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 (≤) 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 occurrance 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 "esembling" 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** AR**s** 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 mˆ2, 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 fontsizes 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

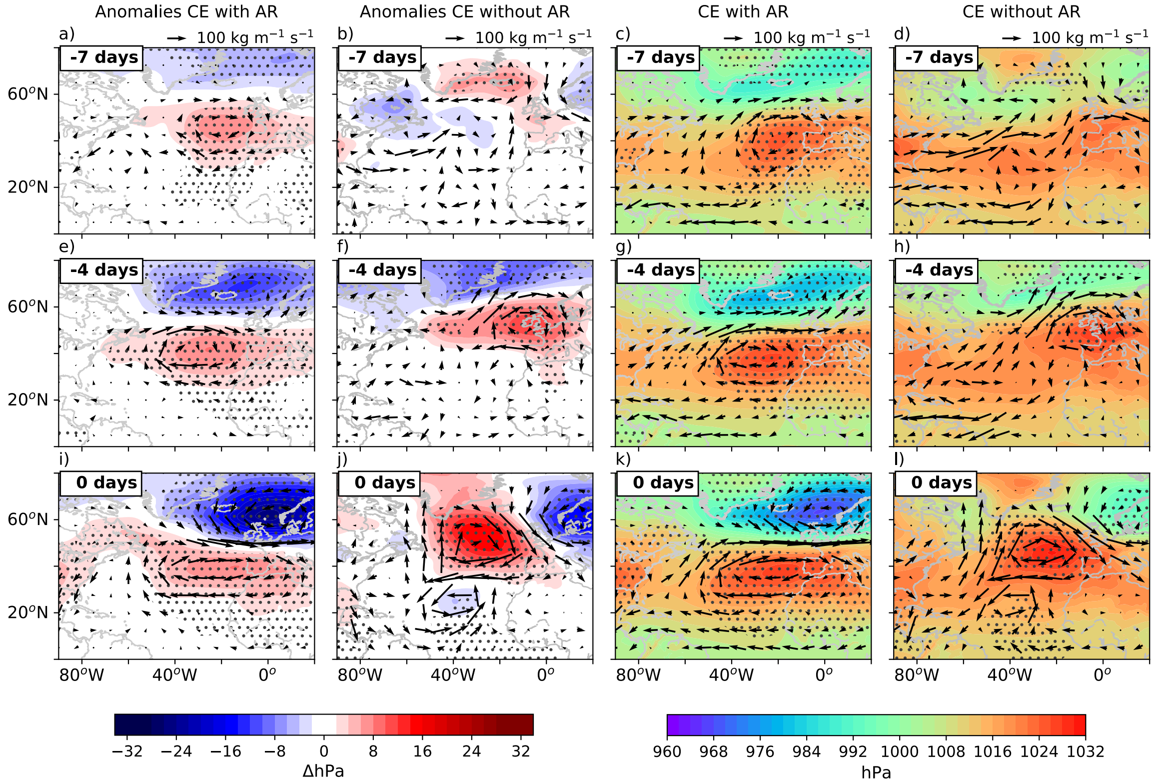


Figure 6: Temporal evolution of mean conditions seven (a-d) and four days (e-h) before a CE at Den Helder and on the day of the event itself (i-l). The left two columns, i.e. panels a, e, i and b, f, j, show the evolution of anomalies in SLP (colour shading) and IVT (vector field) during CEs with and 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.**

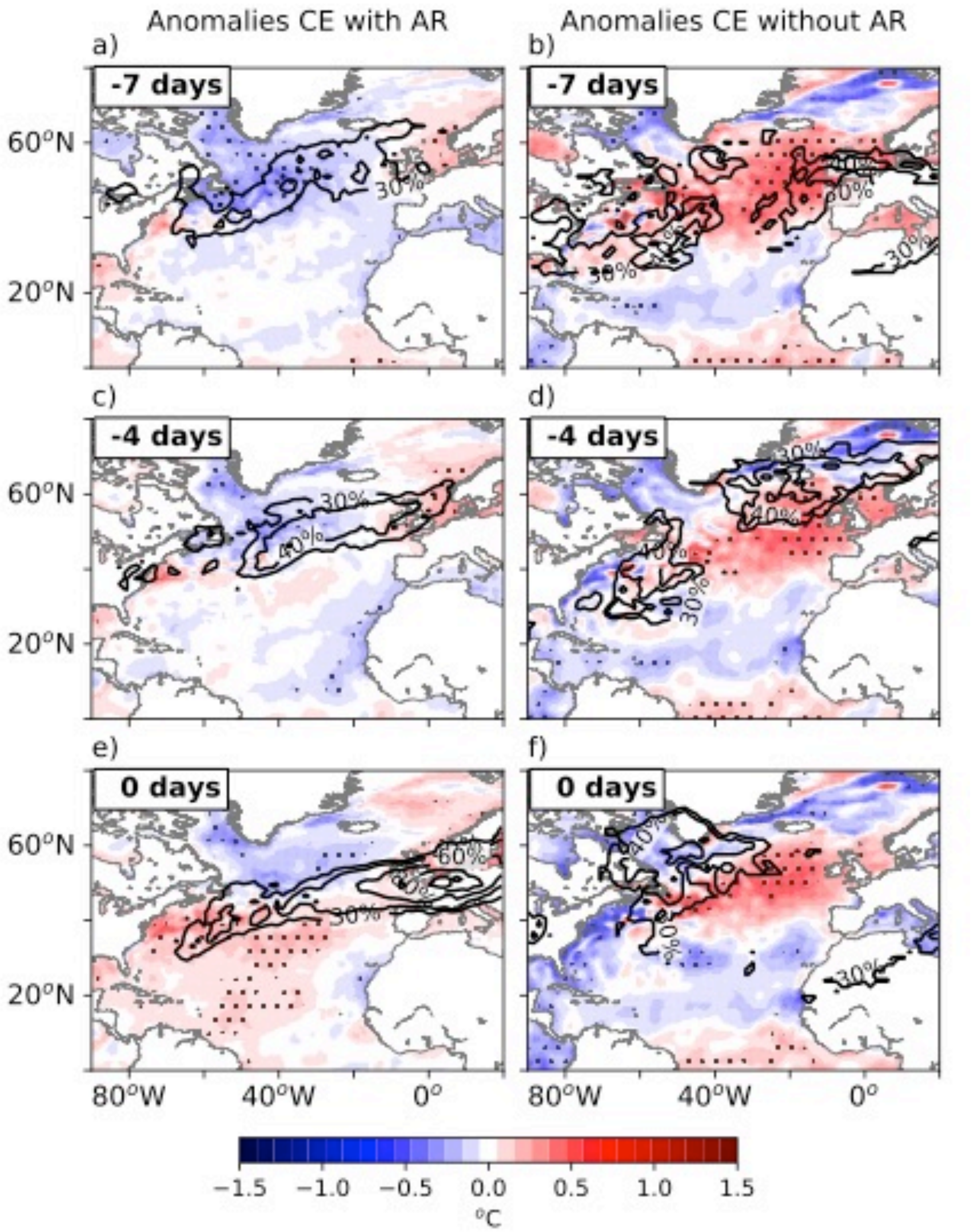


Figure 7: Anomalies in daily mean SSTs (shading) related to CEs with (left panels a, c and e) and CEs without AR association (right panels b, d and f) seven and four days before a CE (a and b; c and d, respectively) and on the day of the event (e and f). Contours mark regions that are occupied by more 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.”**

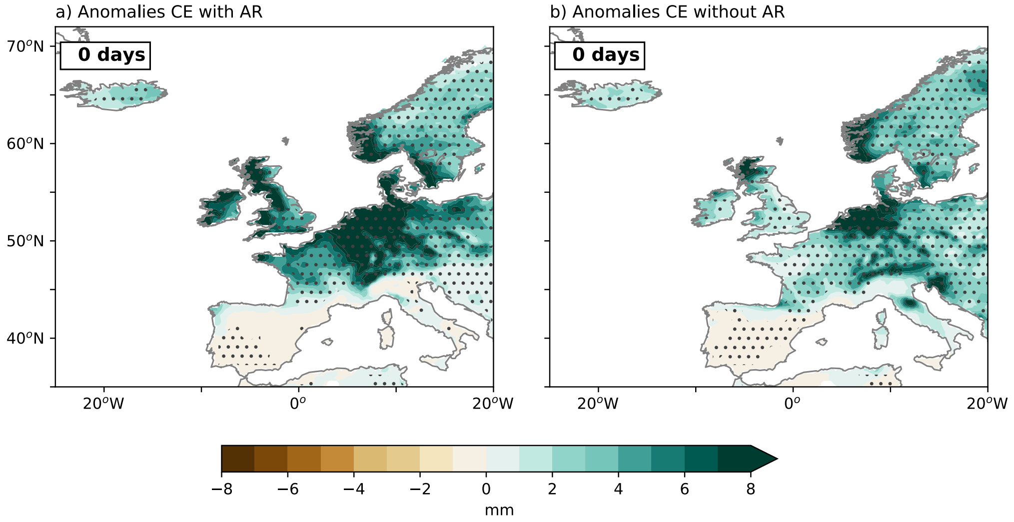


Figure 8: Anomalies of daily mean precipitation sums during CEs with (a) and without (b) AR association. **Stippled areas mark regions with a p-value below 0.05 derived from a student t-test of daily precipitation values during events and the full time series**.

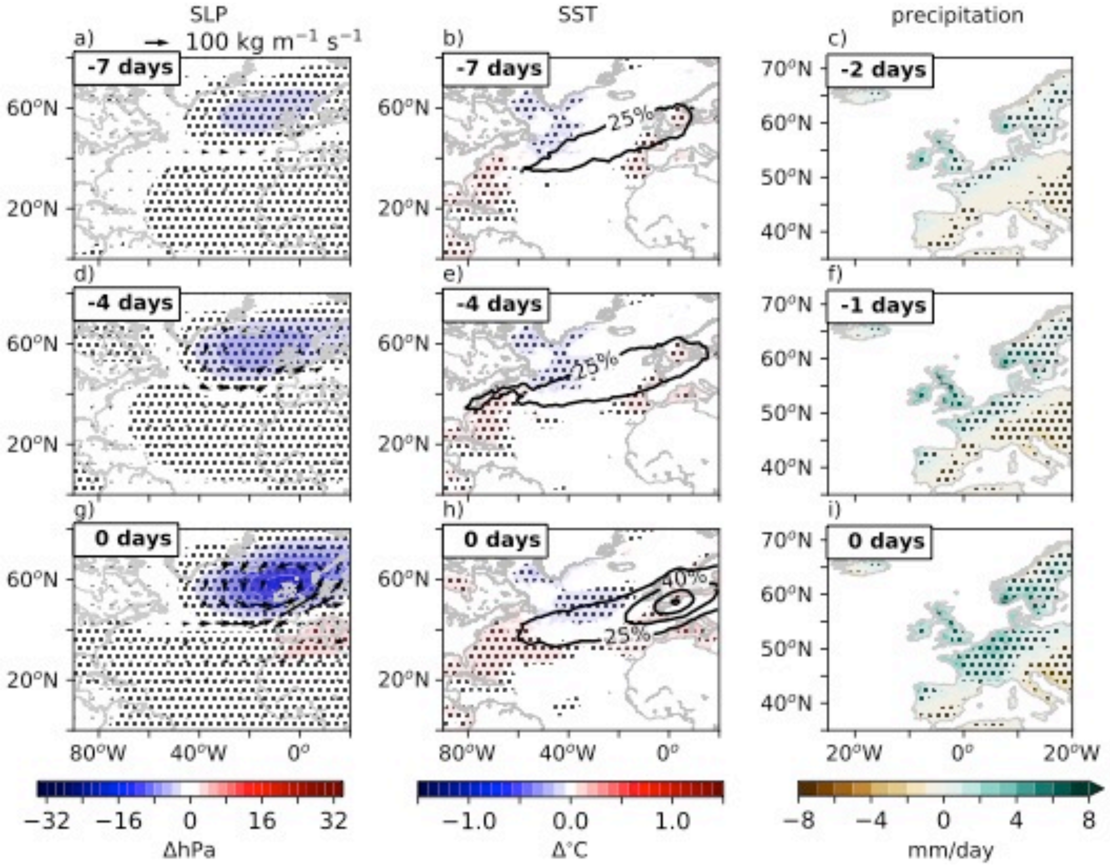


Figure 9: Anomalies of (a) SLP (colour shading) and IVT (vectors), (b) SST (colour shading) and relative number of ARs covering an area, and (c) precipitation on days with an AR over the Netherlands without the occurrence

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.**

We would like to thank Referee #2 for her/his comments. Addressing these comments has helped to improve the manuscript. Below we address each point raised by Referee #2 (*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

My main concern is the statistical strength of the results obtained here. I am not a close friend to complicate the analysis with statistical test when they are not really necessary, but in this case I think they are. For example, in section 4.1, you say that almost 20% of days have AR detections. Then you say that 28% of days in Delfzijl does not show show AR-CE association, but you are analyzing the same day or within +-1, which may become the former 20% in a 60% of the days that are considered in the analysis. So you are claiming that CEs occur 72% of the time in coincidence with a something that exists, in general, up to 60% of the time… can the null hypothesis be rejected with this values? Personally, I doubt it… I strongly suggest to include suitable statistical test in the final version of the manuscript.

If we understand the referee's concerns correctly, the referee is concerned about the significance of our finding in regards to the association of CEs to ARs compared to climatology. The Referee argues that due to the 20% chance of an AR at any given day, the chance of an AR occurring over a three-day period should be 60%. We do not see this in our data. We performed a simple test by counting the days without the presence of an AR over the Netherlands over a three-day period and compared it to the total number of days in the study period. We find that these days make up 61% of the total days, while those days with an AR over a three-day period occur only 39% of the time. Thus, the ratio of days without ARs (including +/-1day) and days with ARs on the day or the day before or after between climatology and CEs is significantly different, i.e. 61:39 (climatology) vs. 28:72 (CEs at Delfzijl). We therefore think that our conclusion that ARs play an important role in the occurrence of CEs is sufficiently supported by our results. To underline this in the manuscript we added the following sentences at the end of the first paragraph of Section 4.1:

"Only a small fraction of 18% (Harlingen) to 28% (Delfzijl) of CEs does not show any association to the presence of an AR over the Netherlands. **This is significantly different to climatology with roughly 61% of days that lack the presence of an AR over a three-day period against 39% of days with an AR detected over the Netherlands either on the day itself or the day before or after. As a result, the chance of having a CE on a random day (ie. without knowledge on presence AR) is a factor three higher than**

that on a day without an AR, whereas the chance on having a CE on a day with AR is a factor three to four higher than on a random day."

Minor Comments:

P2 L14-17 : Please, update this figures regarding the poleward transport of water vapor, and the width/length ratio in ARs with Guan and Waliser, (2015). Guan, B., & Waliser, D. E. (2015). Detection of atmospheric rivers: Evaluation and application of an algorithm for global studies. Journal of Geophysical Research: Atmospheres, 120(24), 12514-12535.

We adjusted the manuscript as follows:

The vast geometric extent of ARs with a typical width of **several hundred kilometres (<1,000 km)** and lengths of over 2,000 km allows them to cover and affect large geographical areas simultaneously (Ralph et al. 2004; Guan and Waliser, 2015).

P2 L25 : Please, consider to add a sentence on the source regions of moisture for Atlantic ARs. Take a look at https://www.earth-syst-dynam.net/7/371/2016/esd-7-371-2016.html.

We added the following sentence to address this:

"[…] They [ARs] typically develop in relation with extra-tropical cyclones and move with the large-scale dynamic phenomena that produce them (hereafter AR system). **In the case of Western Europe, the moisture contained in ARs hitting this region originates from evaporation over an area stretching from the subtropical North Atlantic (north of 20˚N) over the central and western North Atlantic to the West European coast (Ramos et al., 2016).** The vast geometric […]"

P3 L7 : Replace "EOBS" by "E-OBS".

Done.

P3 L21 : Please, add something like "when synoptic forcing conditions are favorable" after "precipitation events".

We added the following:

Nevertheless, it has been shown that those ARs making landfall along the Dutch coast can lead to significant precipitation events **depending on the forcing conditions caused by the prevailing large-scale atmospheric conditions** (Waliser and Guan, 2017).

P3 L23 : Add more information about the stations. To whom they belong?

This section now reads:

[…] and the north-east of the Netherlands (hereafter NENL) for Delfzijl. **All stations are operated by Dutch Ministry of Infrastrcture and Water Management and are located in four different water boards.** The stations were chosen […]

P4 L4-7 : I think that it is completely unnecessary to describe ERA-In. Please, consider to replace this needless description by a citation.

We followed the reviewer's advice and deleted part of the description. The section now reads:

The ERA-Interim reanalysis dataset is produced by the European Centre for Medium-Range Weather Forecast (ECMWF). It is the result of reanalysis simulations performed using a three-component forecast model (Integrated Forecasting System IFS release Cy31r2) for the time period from 1 Jan 1979 to present day (Berrisford et al., 2011; Dee et al., 2011). ~~**The IFS uses the spectral grid T255 ($\sim$80 km) and has 60 vertical levels spanning from the surface up to 0.1 hPa. Analysis time steps are provided every six hours for most atmospheric variables, i.e. each day contains information about atmospheric conditions at 00:00, 06:00, 12:00 and 18:00.**~~ This study uses data for mean sea level pressure, zonal and meridional wind components to force a numerical storm surge model, […]

P5 L23 : "processes" is written two times in the same sentence. Consider to find an alternative.

We replaced the second "processes" with the word "mechanisms".

P6 L24 : replace "winter six months" by "extended winter".

Done.

P10 L6 : Do you mean Fig. 8a?

Reference was adjusted from 8b to 8a.

P10 L27 : Please, consider to rewrite the title of this subsection.

The new section title now reads:

Difference between ARs with and without association to CEs

P12 L14 : "we provide vital information"… consider to replace "vital" by "important", or similar.

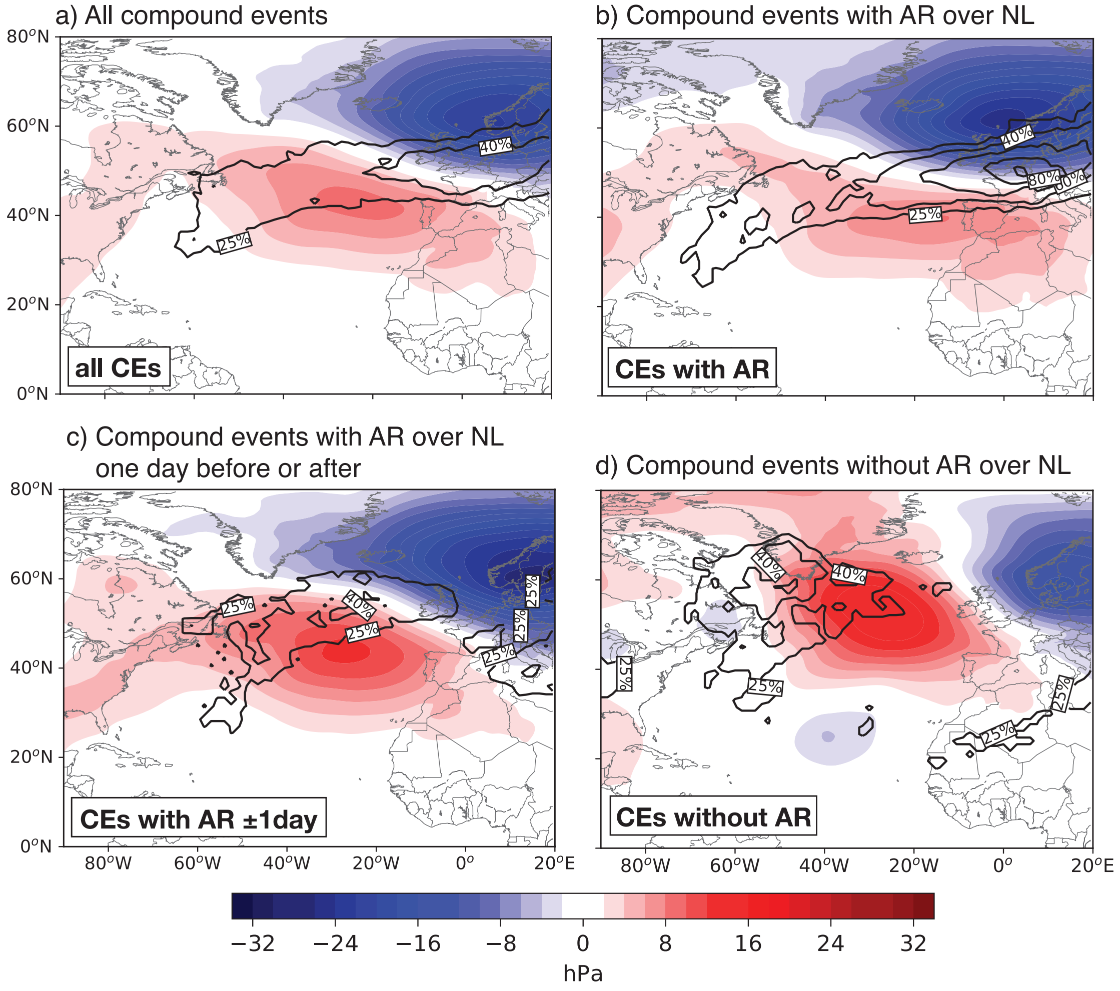
We changed "vital" to "crucial"

Table 1 : Include the period (1979-2015) in the caption.

Done.

Figure 4 : Include “ARCEs”, “no ARCES”, etc… in each box of the Figure.

We added the labels requested by the reviewer to the Figure (see below).



a) All compound events

b) Compound events with AR over NL

c) Compound events with AR over NL one day before or after

d) Compound events without AR over NL

Figure 5 : This figure is very complete and helps a lot to understand the results, but, please, simplify the legend and be consisted. For example, if I understood properly, the only difference between red and black lines is AR and no-AR detection. Then, why do you say "days" for the red line, and "t-series" for the black one? The same applies to the dots.

We adjusted the caption and legend of the figure according to the Referee's suggestion (see below).

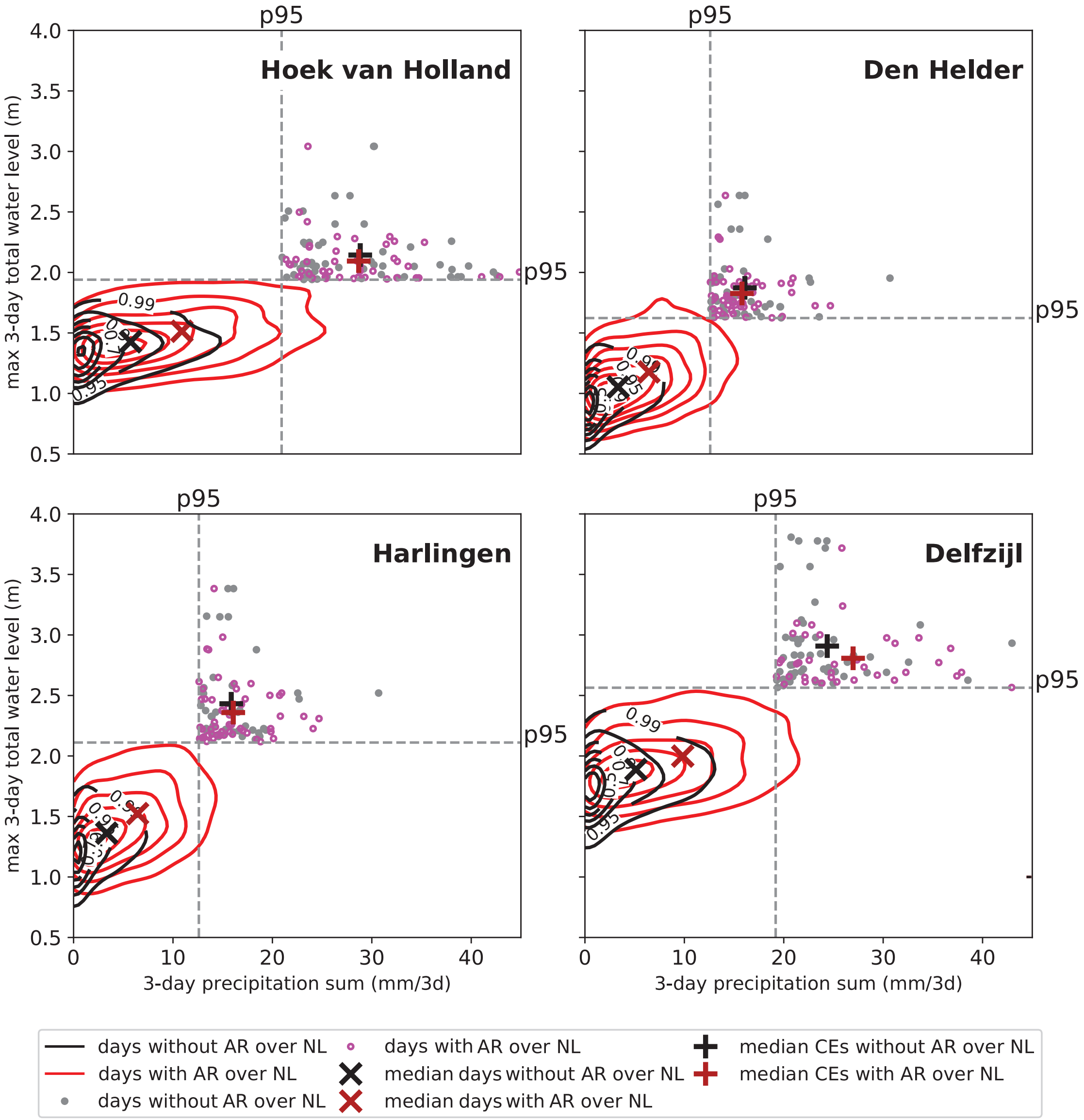


Figure 6 : This results refer to "Den Helder" only. Please, clarify somewhere in the caption.

We adjusted the caption of this figure to the following:

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.**

Figure A1 : Please, rewrite the last sentence in the caption.

The last sentence of the caption now reads:

Dashed horizontal lines indicate the climatological values for the different landfall locations.

The Role of Atmospheric Rivers in compound events consisting of heavy precipitation and high storm surges along the Dutch coast

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Abstract. Atmospheric river (AR) systems play a significant role in the simultaneous occurrence of high coastal water levels and heavy precipitation in the Netherlands. Based on observed precipitation values (E-OBS) and the output of a numerical storm surge model (WAQUA/DSCMv5) forced with ERA-Interim sea level pressure and wind fields, we find that the majority of compound events (CEs) between 1979~~-2015~~ –2015 has been accompanied by the presence of an AR over the Netherlands. ~~By~~ 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~~with and without AR involvement~~, we show that the presence of ARs constitutes a specific type of forcing conditions that (i) resemble the SLP anomaly patterns during the positive phase of the North Atlantic Oscillation (NAO+) with a North-South pressure dipole over the North Atlantic and (ii) cause a ~~warming of the~~ cooling of the North Atlantic subpolar gyre and eastern boundary upwelling zone while warming the western boundary of the North Atlantic. These conditions are clearly distinguishable from those ~~conditions~~ during compound events without the influence of ~~local ARs~~ an AR which occur under SLP conditions resembling the East Atlantic (EA) pattern with a West-East pressure dipole over Northern Europe and are accompanied by a cooling of the West Atlantic. Thus, this study ~~provides~~ shows that ARs are a useful tool for the early identification of possible harmful meteorological conditions over the Netherlands and supports effort for the establishment of an early warning system.

1 Introduction

Currently, policy decisions to respond to flood risk and its increase under global climate change are based on the assumption that coastal flooding is caused by a single, isolated and independent hazard, e.g. heavy precipitation or high river discharge. However, it has become increasingly obvious that this “single-hazard-approach” is insufficient to account for some of the most extreme flooding events observed over the past decades which were in fact often induced by the combined effect of multiple hazards (e.g. Kew et al., 2013; van den Hurk et al., 2015; Vorogushyn et al., under rev.; Zscheischler et al., 2018). These so called “compound events” generally have a more devastating impact than their single-hazard equivalent and exert significant influence on the relevant flood statistics (van den Hurk et al., 2015; Zscheischler et al., 2018). Understanding the underlying dynamics of compound events is therefore paramount to support policymakers to take informed decisions and implement effective coastal protection measures.

In this study we focus on compound events (CEs) in the form of heavy local precipitation and high surge levels (hereafter simply referred to as CEs) along the Dutch coast. For low lying countries like the Netherlands (NL) with a long coastline, understanding CEs related to coastal flooding is of particular importance as these have the potential to cause catastrophic impacts. First assessments of this type of compound events have aimed their attention mostly to the impact of compound events on flood risk in terms of return period (e.g. Kew et al., 2013; van den Hurk et al., 2015). While all these studies conclude that the exclusion of CEs leads to a ~~sever~~ severe underestimation of flood risk along the Dutch coast, which renders the application of current assessments for design standards insufficient, little detail is known about the mechanisms driving the simultaneous occurrence of heavy precipitation and high surge levels. A solid understanding of these processes and their interaction is, however, crucial to understand the implications that future climate change may have on the occurrence of CEs and thus the future development of ~~future~~ flood risk. To close this gap, this study focuses on the large-scale climatologic conditions leading to the simultaneous occurrence of heavy precipitation and high surge levels. In particular, the study aims to identify the importance of one atmospheric phenomenon that has been suggested to potentially be involved in coastal CEs due to its association with high precipitation and strong near-surface winds, namely atmospheric rivers (Waliser and Guan, 2017).

Atmospheric rivers (ARs) are long filaments of high water vapour concentration typically located in the lower troposphere which travel from low to midlatitudes towards the poles in both hemispheres. They play an important role in the hydrological cycle being responsible for over 90% of the poleward water vapour transport at midlatitudes (Zhu and Newell, 1998; Gimeno et al., 2014; Guan and Waliser, 2015; Dacre et al., 2015). They typically develop in relation with extra-tropical cyclones and move with the large-scale dynamic phenomena that produce them (hereafter AR system). In the case of Western Europe, the moisture contained in ARs hitting this region originates from evaporation over an area stretching from the subtropical North Atlantic (north of 20^oN) over the central and western North Atlantic to the West European coast (Ramos et al., 2016a). The vast geometric extent of ARs with a typical width of ~~400 - 600 km~~several hundred kilometers ($<$ 1,000 km) and lengths of over 2,000 km allows them to cover and affect large geographical areas simultaneously (Ralph et al., 2004; Guan and Waliser, 2015). If these water vapour-rich structures make landfall, orographic lifting (Lavers and Villarini, 2013) and, to a minor extent, other synoptic-scale and mesoscale processes (Ralph and Dettinger, 2012) can cause severe precipitation events that have been linked to major floods in many geographical regions (e.g. Gimeno et al., 2014, and references therein). In Western Europe landfalling ARs dominate the high tail of extreme precipitation and their impacts can reach as far inland as Poland (Lavers and Villarini, 2013; Waliser and Guan, 2017). The strong near-surface winds associated with ARs constitute up to half of the events in the highest 98th percentile of the wind distribution along the Western European coastline between 1997 and 2014 (Waliser and Guan, 2017). Thus, AR systems have the potential to play an important role in coastal surge heights a characteristic not previously assessed for ARs affecting Europe (Waliser and Guan, 2017).

The determination of the importance of ARs for and their impact on the conditions during coastal CEs in the Netherlands will pave the way to better understand the underlying risk CEs pose for coastal areas and to a possible early identification of hazardous conditions. This is particularly important in the light of the projected frequency enhancement and intensification of

ARs under global climate change ~~(Ramos et al., 2016a)~~(Ramos et al., 2016b; Espinoza et al., 2018). Despite their importance for flood risk however, even univariate assessments of the impact of ARs and AR-carrying systems in the Netherlands have been incomplete by focusing on the impact of ARs on local precipitation. While these studies have brought valuable insights into the impact of ARs on precipitation in the Netherlands, there have been no equivalent assessments for the impact of ARs on coastal water level extremes or the connection between water level and precipitation extremes. Thus, it is unclear if the strong winds accompanying ARs can induce storm surges along the Dutch coast, where north-northwesterly winds cause the highest storm surges (Kew et al., 2013, e.g.). This puts a constraint on the AR-causing low-pressure systems passing over the Netherlands that is not necessarily met by every one of those.

The study presented here connects the impact of ARs on both ~~,~~ precipitation and coastal surge levels. To achieve this we apply the "bottom-up" approach introduced by Hazeleger et al. (2015), which uses the impact, here the co-occurrence of high water levels and heavy precipitation, as venture point for the analysis and identifies the physical processes driving the particular impact from there. This approach is particularly suited for compound events as it allows the identification of drivers with the largest impacts (Zscheischler et al., 2018). In detail, we investigate coastal water levels derived from a numerical surge model (WAQUA/DCSMv5) driven by reanalysis data and link these to observed precipitation (~~EOBS~~E-OBS) over the Netherlands from 1979 to 2015. From this dataset we identify CEs by isolating those events where both ~~,~~ precipitation and water level, exceed a pre-defined quantile threshold. In a second step we identify days with the presence of an AR over the Netherlands. We then compare mean conditions during CEs with and without the involvement of ARs and identify the driving mechanisms behind these two types of CEs. Finally we determine the difference between conditions during ARs associated with CEs and those that are not (see Section 3). In this way, our study provides a first classification for compound events and presents a detailed assessment of conditions leading to coastal CEs in the Netherlands while focusing on the influence of ARs on their driving mechanisms. This will determine the potential of ARs to aggravate hazards related to coastal CEs in the Netherlands and deliver valuable insight into the atmospheric processes driving these events. The findings of this study could then be used to develop an early warning system using ARs as an indicator for upcoming events.

2 Study area

This study focuses on the possibility and significance of ARs systems causing compound events along the Dutch coast. Located largely at or below sea level, the Netherlands (NL) does not show any significant orographic features (Fig. 1). As a result, ARs passing over the Netherlands do not necessarily cause extreme precipitation (Beukema, 2014). Nevertheless, it has been shown that those ARs making landfall along the Dutch coast can lead to significant precipitation events depending on the forcing conditions caused by the prevailing large-scale atmospheric conditions (Waliser and Guan, 2017).

For the impact assessment, our analysis focuses on a selection of four stations spread along the Dutch coast, namely Hoek van Holland (HvH), Den Helder (DHR), Harlingen (HRL) and Delfzijl (DLZ). The catchment areas associated with these stations are shown in Fig. 1 and include the south of the Netherlands (hereafter SNL) for Hoek van Holland, the Lake IJssel and its surrounding region (hereafter LIJ) for Den Helder and Harlingen, and the north-east of the Netherlands (hereafter NENL) for Delfzijl. All stations are operated by Dutch Ministry of Infrastructure and Water Management and are located in four different water boards. The stations were chosen due to their importance in the Dutch water management system and thus, their significance for flood risk in the Netherlands. Further, they represent a spread of stations along the Dutch coast and cover all its orientations. In this way, our study accounts for stations situated at the westward facing part of the coast (HvH), the northward facing part in the Wadden Sea (HRL, DLZ) and one station facing both directions located at the far west corner of the Dutch mainland (DHR).

3 Data and method

3.1 ERA-Interim reanalysis dataset

The ERA-Interim reanalysis dataset is produced by the European Centre for Medium-Range Weather Forecast (ECMWF). It is the result of reanalysis simulations performed using a three-component forecast model (Integrated Forecasting System IFS release Cy31r2) for the time period from 1 Jan 1979 to present day (Berrisford et al., 2011; Dee et al., 2011). ~~The IFS uses the spectral grid T255 (~80 km) and has 60 vertical levels spanning from the surface up to 0.1 hPa. Analysis time steps are provided every six hours for most atmospheric variables, i.e. each day contains information about atmospheric conditions at 00:00, 06:00, 12:00 and 18:00.~~ This study uses data for mean sea level pressure, zonal and meridional wind components to force a numerical storm surge model, and integrated column vapour and sea surface temperatures for the analysis of differences between AR systems associated with compound events and those without a connection between AR and compound event for the time period from 1979 - 2015.

3.2 Atmospheric river database

Information about ARs occurring in the ERA-Interim reanalysis data between 1979 and 2015 is taken from an online AR database, which is based on the algorithm presented in Guan and Waliser (2015)~~and provided online by Bin Guan~~. The database contains information about the geometrical shape, axis and landfall locations of ARs in the ERA Interim dataset on a global grid with a spatial resolution of $1.5^o \times 1.5^o$. It further provides the land-sea and coastal mask the detection algorithm used to determine AR landfalls. These masks are equivalent to those used in the IFS release Cy31r2 that generate the ERA-Interim reanalysis data.

ARs in the database are identified using the integrated vapour transport (IVT) spreading pressure levels between 1000 hPa and 300 hPa. If the IVT exceeds both an intensity threshold of its local 85^{th} percentile and a minimum of 100 kg m^{-1} s^{-1}, the structure has the potential to be classified as an AR. However, only those structures with a length of at least 2000 km and a length to width ration of two or higher are classified as ARs. Atmospheric IVT structures that do not show a significant poleward component are neglected. For more details about the detection of ARs and a validation of the applied detection algorithm the reader is referred to Guan and Waliser (2015) and Guan et al. (2018).

As mentioned in Section 2 the study presented in this paper isolates ARs in the database that ~~made landfall along the western~~

~~north coast of the European mainland, i.e. at the French, Belgium, Dutch and German North Sea coasts. This choice is based on the potential of ARs to affect large geographical regions due to their geometric characteristics. All assessments are limited to the impact of these AR systems on the Dutch Delta.~~ 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 timesteps. This results in the equivalent treatment of days with an AR over the study area during multiple timesteps and those days with an AR during only one timestep. 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).

3.3 E-OBS precipitation dataset

The E-OBS precipitation dataset provides information of daily precipitation sums over Europe (land only) and spans over a time period from 1950 until present. It is derived from observations at stations across Europe and maps precipitation on a variety of spherical and regular grids. For a detail description of the data set the reader is referred to Haylock et al. (2008).

In this study we use data on a regular grid with a 0.25^o resolution. The time period taken into consideration is equivalent to the one used for the generation of the AR database described in the previous section, i.e. 1979 to 2015 (Section 3.2). Precipitation sums for the different regions under investigation have been derived by isolating precipitation data over the grid boxes within the region SNL, LIJ and NENL as indicated in Fig. 1.

3.4 The Storm Surge Model WAQUA/DCSMv5

In this study water levels along the Dutch coast are determined using the Dutch continental shelf model WAQUA/DCSMv5 (hereafter WAQUA; Gerritsen et al., 1995). Based on the two dimensional shallow water equations, WAQUA calculates water levels in the North Sea basin taking into account sea level pressure, 10-meter wind speeds and the astronomical tide at the domain boundaries using ten harmonic constituents. For selected stations along the coast, WAQUA provides local water level time series with a 10-minute frequency. The output further contains information about the contribution of the tidal component and non-tidal residual (hereafter referred to as surge) to the total water level at each station.

The meteorological fields driving WAQUA in this study are mean sea level pressure and 10-meter wind fields from the ERA-Interim reanalysis database (Section 3.1). In this set up, WAQUA is able to reproduce observations from gauge stations reasonably well (e.g. Sterl et al., 2009; Ridder et al., 2018). However, while generally reliable, WAQUA tends to underestimates extreme water levels, particularly those with long return periods (Ridder et al., 2018). However, this is not considered to be of major significance for this study as the results presented here are based on quantiles and are therefore determined relative to water levels produced within the model. Further, the water levels investigated here lie below the one-year return level, thus the negative bias is not expected to significantly affect the results and conclusions of this study.

3.5 Definition of compound events

Since this study uses local precipitation as a proxy for run-off we need to define a temporal constraint for the definition of compound events that allows enough time for the precipitation water to reach the coast and interact with coastal waters. At the same time, we need to exclude more complex hydrodynamic processes that are caused by ~~processes~~ mechanisms taking place further upstream, i.e. outside of the study area, in large catchment areas. Considering the relatively small catchment areas under investigation here, a run off time of three days seems reasonable. This three-day period should be sufficient to ensure that run-off and other catchment processes have transported the precipitated water close enough to the coastal area to be able to interact with the coastal water level. If precipitation was to occur several days after a coastal water maximum, the collected water in the catchment would reach the coast after the maximum water levels have already ~~subceeded~~subsided, i.e. too late to cause the compounding effect under investigation in this study. Similarly, if a coastal water maximum takes place too long after a high precipitation event, i.e. the time-scale is chosen to be too long, the precipitated water might already be discharged into the sea, again not coinciding with a surge extreme. In this case the local impact would result from one or the other variable in isolation, thus could lead to false positives in the identification of compound events. Also, for long time scales the run off might be contaminated by upstream processes unrelated to the synoptic event causing the local precipitation, e.g. snow melt or isolated precipitation further upstream unrelated to the synoptic system causing the surge. Furthermore, since this study applies daily precipitation sums the selection of a three-day period also ensures the inclusion of extremes that occur closely around midnight of a selected day that otherwise would be associated to a different day and thus falsely considered to not interact with coastal water levels despite the water.

The choice of a threshold to determine whether or not an event is considered to be "extreme" needs to take into account the limited data availability of daily values in precipitation and only 37 years in water levels. Therefore, we need to select a threshold low enough to deliver a reasonable number of events to allow a solid statistical analysis. At the same time, setting the threshold too low would prevent the assessment of the high tail of the multivariate distribution by including events with only moderate impact that are less relevant for the analysis of compound events. Therefore, we choose a relatively low threshold to define extreme precipitation and total water levels, namely the 95th percentile of the respective variable. The choice of rather weak extremes like this ensures numbers of exceedances sufficient for a solid investigation of the relatively short study period.

According to the above argumentation on timing and threshold, in the remainder of this paper, an event is referred to as a compound event (CE) if 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.

4 Results

4.1 Climatology

Throughout the study period with a total of 13,513 days, roughly 17-19% of days display conditions with an AR located over the Netherlands ~~at atleast~~ (NL) at at least one of its four six-hourly reanalysis timesteps (Fig. 2). This shows that ARs are a common phenomenon in this region with an AR passing over the Netherlands roughly every 3-5 days. The number of compound events in the 37 years of ERA-Interim data ranges from 93 (DLZ) to 106 (HvH) events with the majority of CEs coinciding with the presence of an AR over the Netherlands on the same day or within ±1 days of the event (Table 1). Only a small fraction of 18% (Harlingen) to 28% (Delfzijl) of CEs does not show any association to the presence of an AR over the Netherlands. This is significantly different to climatology with roughly 61% of days that lack the presence of an AR over a three-day period against 39% of days with an AR detected over the Netherlands either on the day itself or the day before or after). As a result, the chance of having a CE on a random day (i.e. without knowledge on presence AR) is a factor three higher than that on a day without an AR, whereas the chance on having a CE on a day with AR is a factor three to four higher than on a random day.

Compound events mainly occur in the winter six months (SON and DJF) with a peak in November at HvH and DHR and in January at HRL and DLZ (Fig. 3). CEs associated with ARs occur almost exclusively during the winter six months with the exception of a few events between one (DLZ) and five (HvH) in March. Due to the small total number of CEs with AR association in March and the lack of CEs in the summer months, the remainder of this study will focus the assessment on the ~~winter six month~~ extended winter (SON and DJF) only.

The mean SLP anomaly pattern during all wintertime CEs in the ERA-Interim period shows a distinct difference to the mean ~~climatological~~ climatology with a pressure dipole rover Europe and the eastern North Atlantic ~~esembling~~ resembling the positive positive phase of the North Atlantic Oscillation (NAO+; Fig. 4a). To allow a thorough investigation of the impact of ARs on CEs in this study, we differentiate three types of CEs, namely those events that co-occur with an AR over the Netherlands, either on the day of the event (hereafter ~~ARCEs~~CEs with AR; Fig. 4b) or one day before and/or after (hereafter ~~ARpm1dCEs~~CEs with AR ±1day; Fig. 4c), and those that occur in the absence of an AR in the three days around the event (hereafter ~~noARCEs~~CEs without AR; Fig. 4d). Since the first two types of CEs show very similar atmospheric climatological anomalies (Fig. 4b and c) we will focus our analysis on the difference between ~~noARCEs and ARCEs~~ CEs without AR and CEs with AR only and classify the ~~ARpm1dCEs~~ CEs with AR ±1day as only a slight variation of ~~ARCEs~~CEs with AR. Therefore, all conclusions drawn for ~~ARCEs~~ CEs with AR are qualitatively the same as for ~~ARpm1dCEs~~CEs with AR ±1day. In contrast, the third type of events, i.e. ~~noARCEs~~CEs without AR, occur under a significantly different anomaly pattern compared to ~~ARCEs~~ CEs with AR (Fig. 4b and d). While anomalies during ~~ARCEs~~ CEs with AR resemble the overall anomaly pattern of all CEs ~~regardles~~ regardless of AR occurrence (Fig. 4b), the pressure dipole in case of the ~~noARCEs~~ CEs without AR displays a tilted axes stretching from northwest to southeast, thus resembling the pattern of the second mode of variability of the circulation over the North Atlantic, namely the East Atlantic (EA) pattern (Fig. 4d). In the mean climatology, however, the EA pattern is overpowered by the NAO+ dipole due to the large number of CEs with an AR over the Netherlands compared to those without (Table

1). Thus, only the division of CEs into the two types of ~~ARCEs and noARCEs~~ CEs with AR and CEs without AR reveals the EA pattern and allows a comprehensive analysis of the problem. A detailed analysis of the evolution of the SLP anomalies leading to both types of CEs is discussed in Section 4.3.1.

4.2 Joint Probability Distribution

To assess the impact of ARs on the correlation between precipitation and coastal water levels at the four study locations, Fig. 5 compares the joint probability density distributions of three-day precipitation sums and maximum water levels for days without an AR over the Netherlands (hereafter noARdays; black contours) to the same distribution for days with an AR over the Netherlands (hereafter ARdays; red contours). The median of the distribution considering ARdays (red cross) is significantly shifted to higher precipitation sums compared to the median of the noARday distribution (black cross). The shift to higher three-day maximum water levels is slightly less pronounced, but nevertheless clearly visible. This response in the median reflects the nature of the meteorological phenomenon causing ARs which induces positive precipitation and storm surge anomalies. This can also be seen in the differences between the two distribution with the distribution of ARdays (red contours) reaching further into the part of the graph indicating high precipitation and water levels than the distribution of noARdays (black contours).

In order to understand the influence of ARs on coastal CEs the next step of the analysis focuses on the high tail of the two distributions. For this we select only those days with conditions that fulfil the definition of CE used in this study (grey and magenta scatter plot in Fig. 5). In this region the medians of the two distributions are almost identical (black and red plus) at Hoek van Holland, Den Helder and Harlingen (Fig. 5a-c). This suggests that the conditions during CEs with and without AR over the ~~Netherland~~ Netherlands have caused impacts of similar severity in terms of the joint effect of precipitation and water level at these three stations. Only at Delfzijl the two medians differ significantly (Fig. 5d). Here CEs caused by conditions influenced by an AR tend to have a higher impact on precipitation, while storm surge levels seem to be less affected than in the case of ~~noARCEs~~CEs without AR.

4.3 Difference in meteorological conditions before and during compound events with and without AR association

To determine if ARs significantly alter CEs in the Netherlands this section assesses the conditions during CEs with and without association to ARs. The analysis is focused on CEs at Den Helder. This choice was motivated by the geographical location of this station close to the Wadden Sea and the fact that the station is situated at the north-western corner of the Dutch coastline. Thus, Den Helder borders the North Sea at two sides, the north and west. As discussed in Section 2, this is not the case for the other stations. Thus, choosing Den Helder as representative ensures that the assessment accounts for synoptic systems moving in from the north as well as from the west. Further, most of the compound events at Den Helder occur in close temporal proximity to compound events at (at least one of) the other stations which makes Den Helder a valuable representative for all four stations when it comes to the occurrence of CEs.

4.3.1 Development of sea level pressure and integrated vapour transport

The comparison of the mean anomalies in daily sea level pressure (SLP) and integrated vapour transport (IVT) before and on the day of a CE at Den Helder shows a clear difference in the conditions of CEs with and without association to ARs (Fig. 6 a, e and i; b, f and j, respectively).

CEs associated with ARs (~~ARCEs~~CEs with AR) show little temporal variability in their mean anomaly pattern throughout the week before an event (Fig. 6a, e and i). The overall pattern is comparable to climatology with a high-pressure system over the Azores and a low-pressure system in the North, in this case stretching from the east of Greenland and the Norwegian Sea (Fig. 6c, g and k). The evolution of the atmospheric conditions during this time is mainly limited to changes in the amplitude of the sea level pressure features. Thus, the storm track remains unchanged and is comparable to that under the conditions of a positive North Atlantic Oscillation phase. The low-pressure system develops a stronger anomaly than its positive counter part. This hints to the importance of the storm system as a driving mechanism ~~in the ARCEs~~for CEs with AR. The horizontal dipole that the two pressure systems build and is typical for the North Atlantic Oscillation (NAO), guides the IVT through a small corridor over the UK the north of France before hitting the Netherlands further inland. Therefore, ARs making landfall in the UK, France and the Netherlands itself have the potential to be part of the synoptic system that causes a CEs (Fig. A1).

In contrast, for compound events without the involvement of ARs (~~noARCEs~~CEs without AR) the spatial SLP anomaly patterns vary strongly with time during the week before the event (Fig. 6b, f and j). Seven days before the event, SLP anomalies show two moderate positive maxima, one stretching from Greenland to east of Iceland and one off the coast of the UK (Fig. 6b). The first anomaly maximum is caused by a high-pressure system over Greenland; the latter by a high-pressure system over Spain stretching further north than the Azores high under normal conditions (Fig. 6d). Over the following few days the high-pressure system over Greenland and Iceland temporarily weakens and a low-pressure system moves in from the west (Fig. 6h) leading to a moderate negative SLP anomaly north of 60°N (Fig. 6f). At the same time the high-pressure system over Spain merges with a high-pressure system moving in from the western Atlantic (~~Figures~~ Fig. 6d and h). This causes a strengthening of the positive anomaly west of the UK and increases its extent to cover large parts of Western Europe, Scandinavia and an area over the North Atlantic between 40°N and 60°N reaching up to 55°W (Fig. 6f). On the last days before the CE the Azores high moves back westward ending up in a position that is slightly further north than under normal conditions (Fig. 6l). At the same time, the low-pressure system in the north of the Azores high moves eastwards towards Scandinavia, and the high-pressure system over Greenland strengthens to contribute to the strong positive anomaly seen over most of the northern North Atlantic on the day of the CE. The resulting anomaly pattern resembles the anomalous conditions of the East Atlantic (EA) pattern, the second mode of interannual ~~varibility~~ variability over the North Atlantic (Barnston and Livezey, 1987; Comas-Bru and McDermott, 2014). In this position the Azores high acts as an atmospheric blocking system together with the high-pressure system over Greenland that detains the negative pressure anomaly over Scandinavia (Fig. 6j). These conditions cause a northwards excursion of the storm track. In turn, the resulting meandering of the storm track causes winds and the IVT to hit the Dutch coast with a stronger northerly component than normal conditions. Thus, the conditions during ~~noARCEs~~ CEs without AR favour high surge levels and higher precipitation along the northward facing European coastlines. The reason that the increased IVT in the case of ~~noARCEs~~ CEs without AR cannot be classified as ARs, even if they occurred in long filaments fulfilling the geometric definition of the AR definition, lies in exactly this change of the storm track which forces the IVT to enter the North Sea basin from the north. As a result, the IVT, while significantly increased compared to climatology and in its ~~absolut~~ absolute values comparable to the IVT during ~~ARCEs~~CEs with AR, lacks a distinct poleward component, which is one of the crucial characteristics of ARs according to their most commonly used definition.

4.3.2 Development of Sea Surface Temperature (SST) anomalies

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 the case of ~~ARCEs~~CEs with AR, SSTs respond to conditions that induce gradual, spatially consistent changes due to the small spatial variability of the SLP anomalies in this case as discussed in the previous section (Sec. 4.3.1). 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 most important difference to noARCEs is~~ Another significant feature, which is not present during CEs without AR, is the mean positive SST anomaly off the east coast of North America that ~~, in case of ARCEs, is persitent~~ is persistent throughout the week before an event. This positive anomaly is most likely maintained through the increasing transport of warm tropical waters into the midlatitudes through a ~~strenghtening of the north north-easerly~~ strengthening of the south-southeasterly component of the wind field throughout the week before an event. 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, a detailed account on the driving mechanisms behind the response of SST can only be obtained by an in depth analysis of the complex interplay of changes in Ekman transport, upwelling/downwelling and ocean-atmosphere heat exchange which is beyond the scope of this paper.

In contrast, SLP anomalies during ~~noARCEs~~CEs without AR, and with this the anomalies in 10-m wind fields (Fig. A2) ~~,~~ over the North Atlantic trigger a ~~warm anomaly in~~ warming in parts of the subpolar gyre, the ~~midlatitudes, including the North Sea, and subtropics, with a negative anomaly in the tropics north of the equator and north of 60°N~~ equatorial North Atlantic, and at midlatitudes (Fig. 7~~b, d and f~~a, c and e). Interesting is the negative SST anomaly ~~in the region~~ along the western boundary of the North Atlantic and parts of the (sub-)tropical North Atlantic, i.e. the region from where ARs that hit Europe generally originate~~from, i. e. the tropical North Atlantic. This negative SST anomaly stretches from coast to coast around the 20°N latitude with a strong maximum in the upwelling region off West Africa. While this large-scale SST anomaly pattern broadly remains persistent throughout the week before an event, the changing conditions leading to noARCEs alter local SSTs through a variety of mechanisms resulting in the positive SST anomaly to dissappear in the substropical and western part of the North~~

~~Atlantic (Fig. 7f). This~~. This anomaly pattern is mainly driven by alterations in the Ekman transport across the basin. During the shift of the SLP anomaly pattern from conditions resembling the negative phase of the NAO towards an EA-like pattern closer to the event, the tilt of the North Atlantic pressure dipole ~~over~~ changes. This induces alterations in wind ~~conditons~~conditions, which in turn lead in a flow of cold water from the northeast to the southwest. As a result a cold anomaly off the east coast of North America develops and the warm SST ~~anomly~~ anomaly in the subtropical North Atlantic contracts to the eastern Atlantic. Other changes in SSTs in the case of CEs without AR are mostly statistically insignificant (Fig. 7b, d and f).

4.3.3 Development of precipitation anomaly patterns

The mean anomalies in precipitation during ~~noARCEs and ARCEs~~ CEs without AR and CEs with AR reflect the differences in IVT between the two cases. For ~~ARCEs~~CEs with AR, precipitation anomalies ~~occurr~~ occur on a much larger scale than in the case of ~~noARCEs~~ CEs without AR (Fig. 8). Additionally they show a strong positive anomaly in central Europe reaching as far south as the Alps and far into the east (Fig. 8~~b~~a). Further noteworthy are the strong mean positive precipitation anomalies in Northern Ireland and along the west coast of the UK. Together with the increase in mean precipitation over northern France, this pattern reflects the mean direction with which the IVT and thus the ARs, are moving over Europe. As mentioned earlier when discussing SLP and IVT conditions during ~~ARCEs~~CEs with AR, the IVT is travelling more zonally before and during ~~ARCEs~~CEs with AR. Therefore, ARs have the opportunity to affect larger regions and thus explaining the large-scale precipitation anomalies under these conditions. For instance, the path over land of an air mass travelling zonally over the UK is much shorter than that of its counterpart travelling in a meridional direction and thus crossing the full latitudinal extent of the landmass. As a result the air mass travelling from west to east tends to ~~loose~~ lose less moisture through precipitation. Further, the air mass has the opportunity to replenish lost moisture on its way over the North Sea or while travelling along the English Channel before making landfall on the European mainland and precipitating the rest of its moisture there.

As mentioned earlier, the IVT in the case of ~~noARCEs~~ CEs without AR tends to contain a stronger than normal northerly component which causes them to hit the Netherlands almost straight from the North due to the EA-like pattern of the prevailing mean SLP anomalies (Fig. 6i). Accordingly, the precipitation anomalies reflect this by exhibiting a positive anomaly along the Dutch coast (Fig. 8a). On their way over land the moisture lost through precipitation cannot be replenished as easily as over water which leads to quick drop-off in precipitation southwards of the coastline with the majority of precipitation being dropped north of 50°N. A similar anomaly pattern can also be seen in the north of the UK, where the same mechanism influences precipitation. This results in very localised precipitation anomalies in the northern most regions of Northern Europe. The north coast of France, however, which is located in the lee of the UK in the case of ~~noARCEs~~CEs without AR, shows hardly any anomalous precipitation as water vapour is removed through precipitation over the north of the UK and the English Channel not being sufficiently wide for the moisture to be replenished.

4.4 Difference ~~AR~~ between ARs with ~~CE~~ and ~~those~~ without association to CEs

In order to be able to exploit the potential of AR systems to predict coastal CEs, this section assess the differences in atmospheric and oceanic conditions of AR systems with association to CEs (hereafter ~~CEARs~~ARs with CEs) and those without CEs (hereafter ~~noCEARs~~ARs without CEs). For the comparison of anomalies between the two types of ARs we focus on the ~~days with~~ developments of anomalies within the seven days (for precipitation two days) before an AR over the Netherlands. Here, the mean monthly anomalies in daily SLP, IVT, SST and precipitation in the case of ~~noCEARs~~ ARs without CEs (Fig. 9) are significantly less pronounced than those during ~~CEARs~~ ARs with CEs (Fig. 6~~i, 7e and 8b~~). This is based on the fact that the mean changes in SLP for ~~noCEARs~~ ARs without CEs are not strong enough to create a significant dipole pattern (Fig. 9a, d and g). While the mean negative anomaly over the north of the UK is well established, there is no mean positive anomaly in the location of the Azores High comparable to that evolving in case of ~~CEARs~~ ARs with CEs on the day of the AR over the Netherlands (Fig. 6i). This indicates that the position and strength of the Azores high plays a major role in the determination of whether an AR system can lead to a coastal CE or not.

As a result of the lack of a mean dipole structure, mean wind fields during ~~noARCEs~~ ARs without CEs do not produce a consistent change in surface ocean circulation and thus do not show a strong mean SST anomaly pattern. The same is true for precipitation. This suggests, that overall only strong AR systems, consisting of a strong SLP dipole and carrying high moisture amounts, have coincided with the occurrence of compound events in the Netherlands. However, this does not mean that all strong AR systems, i.e. those with strong SLP anomalies, have been associated with compound events since the mean ~~in the noCEARs case~~ of ARs without CEs is derived from a much higher number of events compared to ~~the CEARs case. Thus~~ ARs with CEs. Therefore some strong AR systems might have failed to induce sufficient precipitation due to the lack of air moisture or the necessary wind conditions in terms of wind direction to induce a compound event at the Dutch coast.

All features that characterise the mean conditions during ARs without CEs and make them different to the conditions during ARs with CEs, as described above, 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.

5 Discussion

This study presents a first classification of coastal CEs by using one specific atmospheric phenomenon as a base resulting in two types of CEs, i.e. (i) events with AR involvement and (ii) events without. This classification can be used to determine the focus of future assessments and deepen the analysis of the driving processes of coastal CEs consisting of heavy precipitation and high coastal water levels. While other coastal CEs might require different categories based on other climatic or even socio-economic factors, the here presented choice of ARs as determining factor is the most suitable considering the purpose of this study, i.e. the investigation of the impact of ARs on coastal CEs in the Netherlands. Thus, it was possible to identify conditions leading to CEs that do not involve AR. These would have been masked if the analysis had only taken into account the mean conditions during CEs which are dominated by the large relative number of CEs with AR involvement. While these atmospheric conditions have been known to potentially cause hazardous conditions for the Netherlands and thus have already been thoroughly studied, conditions with the Azores High acting as blocking system, as realised during the second type of coastal CE, have gotten little attention. With the findings of this study we provide an impulse to extend future investigations into this direction.

Further, by identifying large-scale atmospheric conditions that lead to coastal CEs and comparing them to similar conditions with low impact we provide a tool for the early identification of possible compound events. This is particularly useful in the light of the higher predictability of large-scale atmospheric features, such as SLP patterns and atmospheric moisture content, compared to small-scale events, such as precipitation and wind extremes (Lavers et al., 2014). Therefore, the results of this study could be used for the early identification of compound events that have the potential to cause disruptive impacts in the Netherlands and thus allow an early warning of up to one week in advance.

While this study focused on local precipitation rather than river discharge, we show that the presence of ARs leads to precipitation anomalies that cover large areas of the Rhine catchment. This indicates that, additionally to the chance of the occurrence of CEs in the form of heavy ~~precipitaiton~~ precipitation and high surge, it is likely that ARs are also linked to the co-occurrence of high surge levels and extreme river discharge. These two hazards have been shown to be correlated at a time-lag of several days with storm surge extremes preceding high river discharge (Klerk et al., 2015; Khanal et al., 2018). Our results are in agreement with this, taking into account the time it takes for hydrological processes to transform precipitation over a large catchment into river discharge at the coast or further downstream. As a result, it is possible that ARs aggravate coastal flood risk even further by causing extreme river discharge closely after a compound event consisting of heavy precipitation and high coastal water levels. We leave the investigation of the existence of a statistical connection between these two occurrences and the possible implications for local flood risk to future studies as this falls outside the scope of the work presented here.

We acknowledge that our findings are based on model results and observations and the used data contains the known biases and shortcomings associated with the respective data source. However, the impact of data biases is unlikely to affect the qualitative statements made in this study as most results are based on quantiles, thus dampening the effect of possible biases present in the used datasets.

We also note that the identification of ARs that are analysed in this study is influenced by the applied AR-detection ~~algorithm is determined by a specific definition of ARs~~ algorithm. The particular algorithm applied here was chosen due to the fact that this study was motivated by the work of Waliser and Guan (2017). While the application of other algorithms might introduce some variations in the results of this study, ~~their effect would be marginal and~~ it is not expected to significantly change the conclusions of this study.

However, we would like to remark that our analysis of the conditions during the second type of CEs, namely ~~noARCEs~~CEs without AR, highlights a limitation of the generally accepted condition often used in AR detection algorithms which excludes IVT structures that lack a significant poleward component. We have shown that during ~~noARCEs~~ CEs without AR the IVT reaching the Dutch mainland is significantly ~~incrased~~ increased with absolute values comparable to those in the case of ~~ARCEs~~CEs with AR. Further, we have demonstrated that both types of CEs lead to comparable impacts in terms of precipitation regardless of the inclusion of the underlying IVT structure into the AR catalogue or not. While it is possible that some of the IVT structures during ~~noARCEs~~ CEs without AR were discarded due to the applied geometric constraints, some ARs only failing the poleward transport condition might have been falsely excluded. It is therefore possible that ARs play a much more important role in the occurrence of CEs than identified in this study. We thus suggest that excluding IVT patterns from an AR catalogue based on their lacking of poleward transport, could lead to an underestimation of the risk that ARs pose for coastal regions. Further, if poleward transport should no longer be considered as a detection criterion for ARs, the classification made in this paper of CEs into three types (~~ARCEs, ARpm1dCEs and noARCEs~~CEs with AR, CEs with AR ±1day and CEs without AR) might need to be extended accordingly. Therefore, we advise to apply the AR classification criterion ~~requiering~~ requiring an IVT object to have a considerable poleward component with care and its implications kept in mind when assessing the influence of ARs on CEs.

Nevertheless, our study provides a valuable extension of our understanding of costal CEs and their driving mechanism at one specific geographic location focusing on one particular atmospheric phenomenon. With this, we hope to inspire future work to extend our assessment to include the impact of other phenomena to complement the results of this study. Further, we encourage to apply this and similar assessments to other geographical regions to elaborate on differences in the importance of drivers under different climatological conditions and identify other equally important atmospheric phenomena influencing coastal and other CEs.

6 Summary and conclusions

In this study we used the output of a numerical storm surge model (WAQUA/DCSMv5) and observed precipitation data (E-OBS) throughout the ERA-Interim period (1979-2015) to assess the role of atmospheric rivers in the occurrence of compound events consisting of heavy precipitation and high coastal water levels at four stations along the Dutch coast. Our results show that the majority of past compound events have been associated with the presence of an AR over the Netherlands. Further, we demonstrate that days with an AR over the Netherlands tend to be wetter and have higher water levels than those without. However, this is not realised in the high tail of the joint distribution of the two variables, where the impact of ARs fails to significantly affect the median of the joint distribution (with the exception of Delfzijl). From this we conclude that, while ARs play an important role in the occurrence of compound events, their mean impact is comparable to that of events without AR involvement. Nevertheless, the introduced classification of compound events into two categories, (i) events with AR influence caused by a NAO-like SLP anomaly pattern and (ii) events without AR influence occurring under EA-like SLP anomaly conditions, shows to be useful in order to isolate atmospheric patterns of events that are otherwise masked by the dominance of the number of compound events with AR involvement. Further, in combination with the mean SST anomaly patterns and the NAO- and EA-like SLP patterns specific to each type of event that we identified here, we provide ~~vital~~ crucial information for the possibility to predict compound events. As shown in this study, climatological anomalies leading to the two types of coastal CE are visible at least seven days in advance of an event. It is thus possible to include the atmospheric and oceanographic features leading to CEs that have been identified in this study as indicators in an early warning system for possibly hazardous conditions along the Dutch coast.

Data availability. The data for AR characteristics used in this study are made available by Bin Guan and obtained from https://ucla.box.com/ARcatalog.

Author contributions. NR had the initial idea for the study, performed the surge model experiment, analysed the data and authored the manuscript. HV contributed to bug fixes. HV and SD provided suggestions for analytical metrics and commented on the manuscript.

Competing interests. There are no competing interests present.

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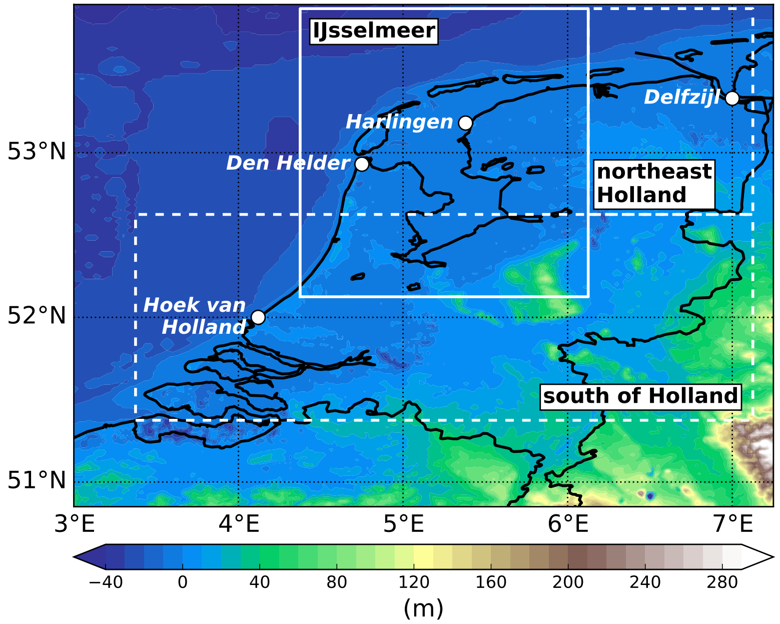

Figure 1. Topographical map of the study area showing the geographic location of the four coastal stations under investigation in this study. White boxes indicate the three regions that were considered for local precipitation, i.e. south of Holland for Hoek van Holland, IJsselmeer for Den Helder and Harlingen and northeast Holland for Delfzijl. Elevation data is derived from the ETOPO1 Global Relief Model(Amante and Eakins, 2009).

Table 1. Number of compound events associated with AR landfall relative to the total number of compound events at the four coastal stations under investigation during the ERA-Interim period (1979 - 2015).

	Hoek van Holland	Den Helder	Harlingen	Delfzijl
all CEs (full year)	106	93	99	93
winter CEs	93	86	90	89
CEs with AR over NL (winter only):				
- on day of event	43	49	52	38
- 1 day before or after event	28	21	23	28
CEs without AR over NL (winter)	22	16	15	23

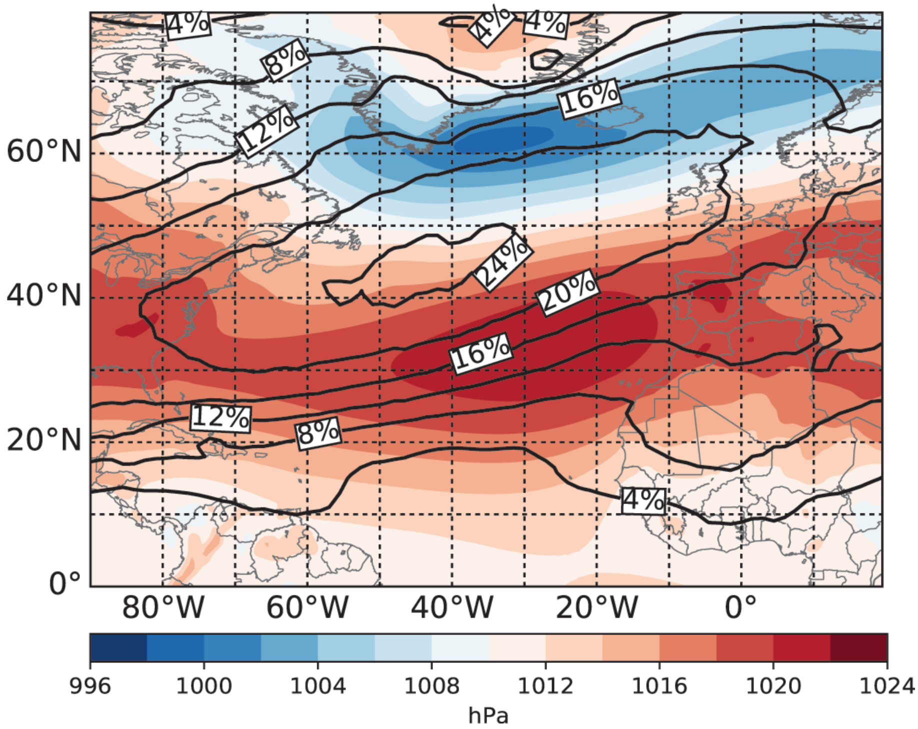

Figure 2. Climatology of daily mean sea level pressure (SLP; colour shading)~~and areas~~. Contours mark regions over which ARs are located. Numbers indicate the relative amount of time that the respective area is covered by ~~AR (contour)~~ an ARs throughout the study period (1979-2015).

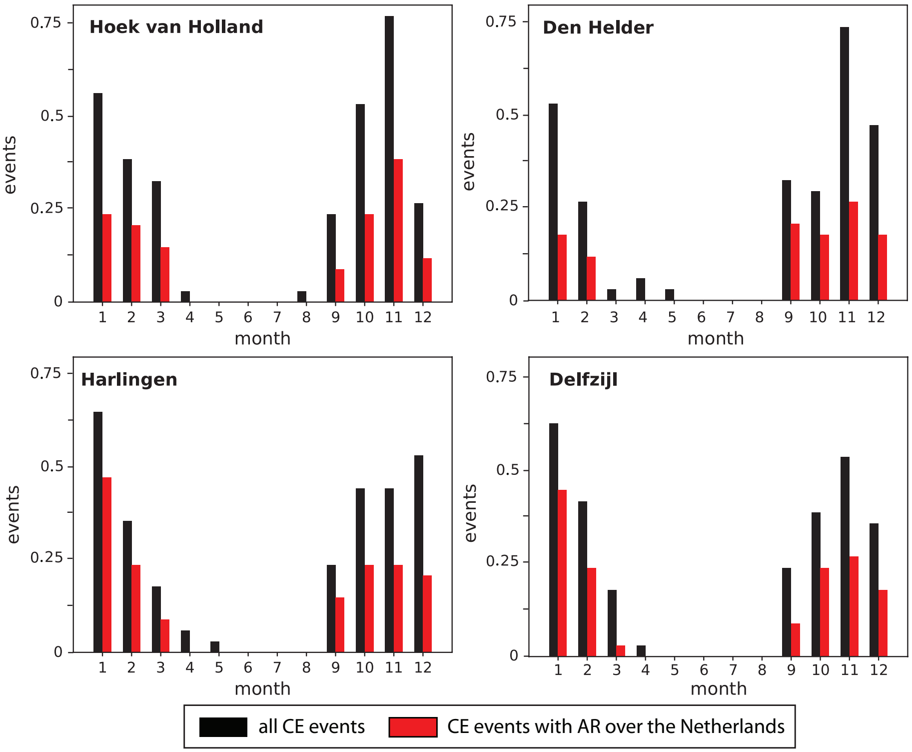

Figure 3. ~~Number~~ Monthly climatological mean number of compound events ~~per month~~ at the four coastal stations assessed in this study. Black columns indicate the number of all CEs (~~ARCEs~~ CEs with AR + ~~noARCEs~~ CEs without AR + ~~ARpm1dayCEs~~CEs without ARs ±1day), while red bars show the number of CEs with association to an AR over the Netherlands (~~ARCEs~~NL; (CEs with AR).

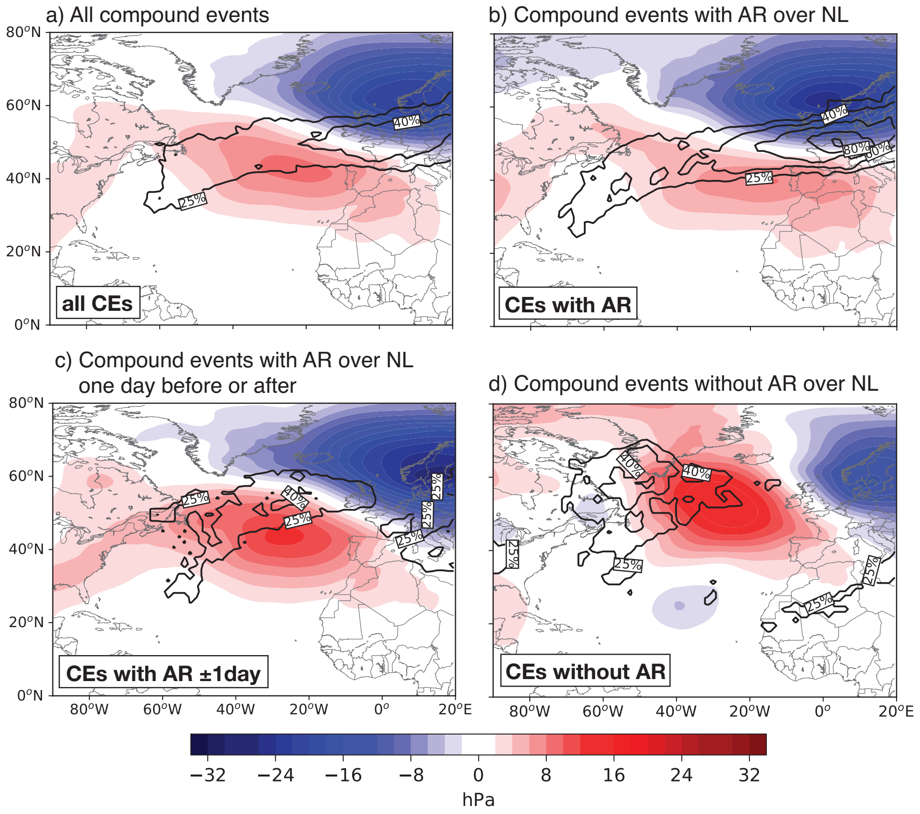

Figure 4. a) Mean anomalies in daily mean sea level pressure (colour shading) and relative area covered by ARs during all compound events at Den Helder during the study period. b), c) and d) as a) but for CEs occurring on days (b) with an AR over the Netherlands, (c) one day before or after a day with an AR over the Netherlands and (d) without AR over Netherlands within a three day period centred around the event.

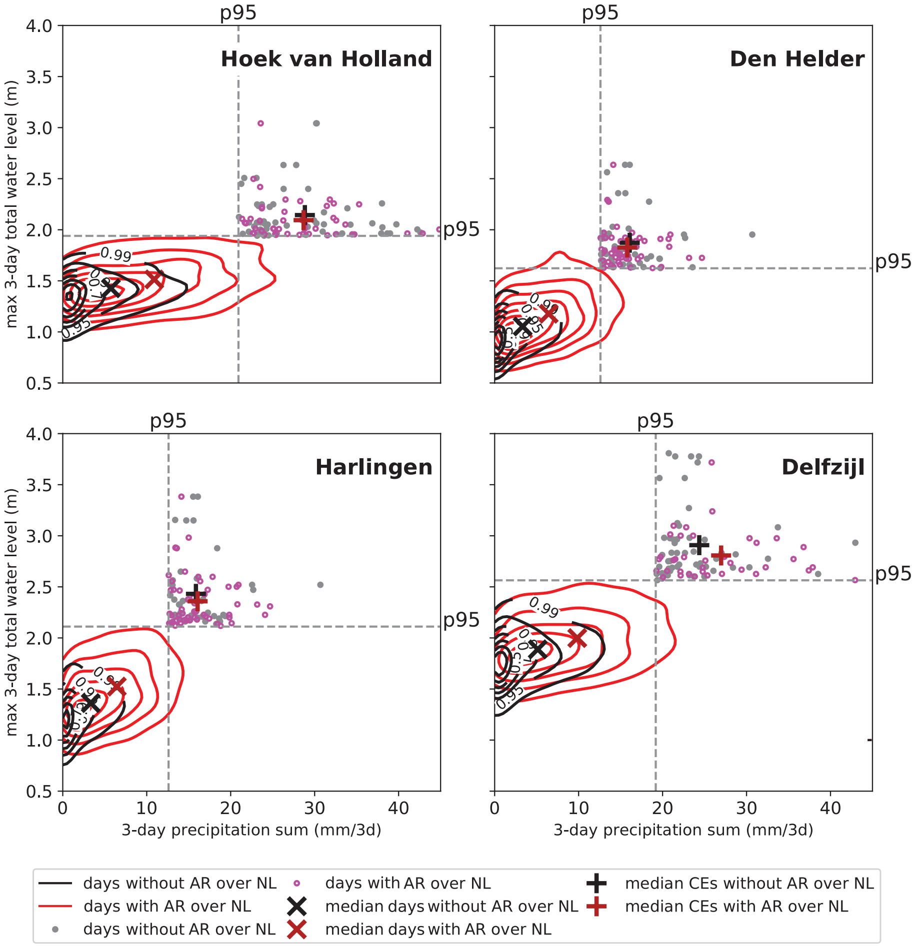

Figure 5. Joint probability distribution of three-day precipitation sums (mm) and three-day maximum total water level (m)~~for days without an AR over~~. Contours denote the ~~Netherlands~~ area enclosing indicated percentage of data (~~dark~~ 30, 50, 70, 90, 95 and 99% contours are shown)~~and~~. Dark/red contours show data for days without/with an AR over the Netherlands~~(red, solid contours)~~. Scatter plot in the in the upper right corner of each subfigure show total water level and precipitation pairs with values higher than the 95th percentile of both variables, i.e. compound events. ~~Compound~~ Data points identified as compound events without an AR over the Netherlands are shown in black, those with an AR over the Netherlands are red. Crosses indicate the position of the mean of the full time series, while plusses show the median of the two variables only taking into account data from ~~CEs~~days with a CE. The colour coding for both markers is the same as for the contours.

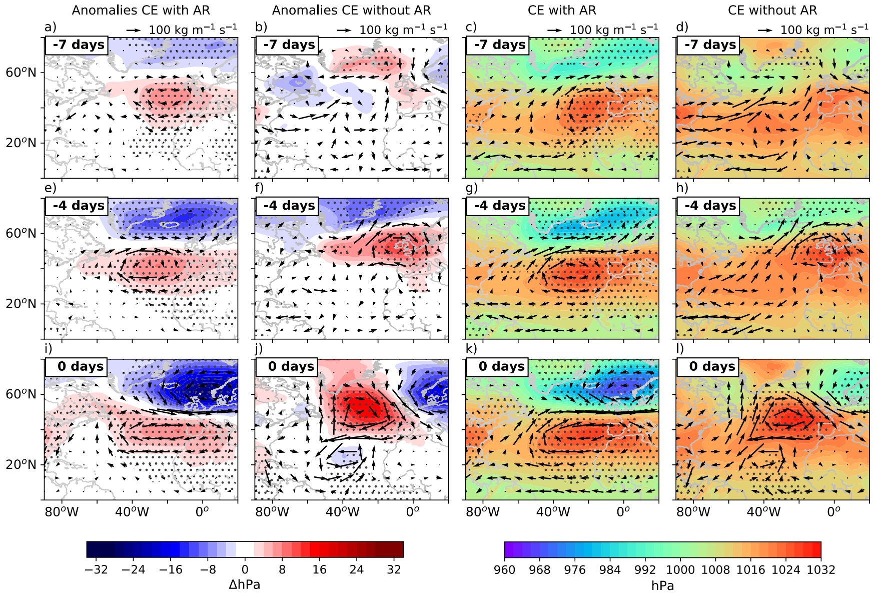

Figure 6. Temporal evolution of mean conditions seven (a-d) and four days (e-h) before a CE at Den Helder and on the day of the event itself (i-l). The ~~right~~ left two columns, i.e. panels a, e, i and b, f, j, show the evolution of anomalies in SLP (colour shading) and IVT (vector field) during CEs 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 a student t-test of daily mean SLP values compared to the daily mean values of full time series.

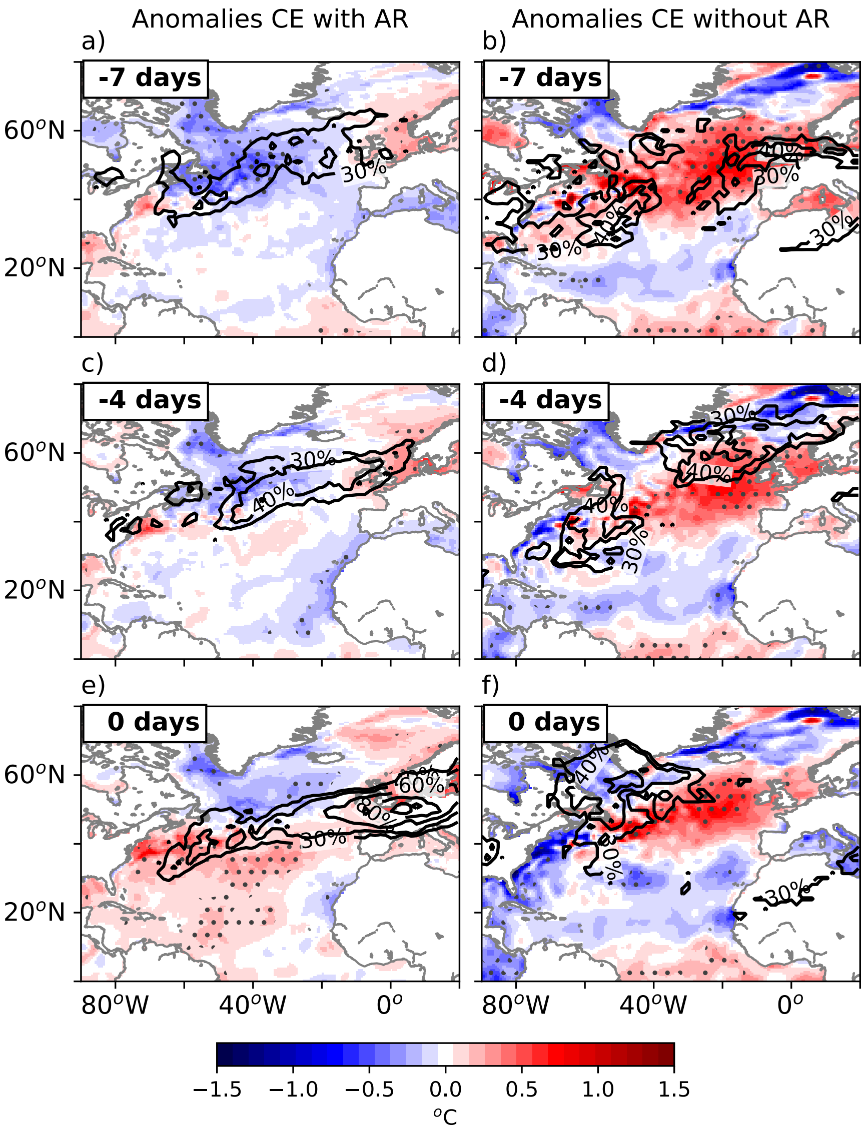

Figure 7. ~~AR location (contours) and anomalies~~ Anomalies in daily mean SSTs (shading) related to CEs with (left panels a, c and e) and CEs without AR association (right panels b, d and f) seven and four days before a CE (a and b; c and d, respectively) and on the day of the event (e and f). ~~Grey~~ 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.

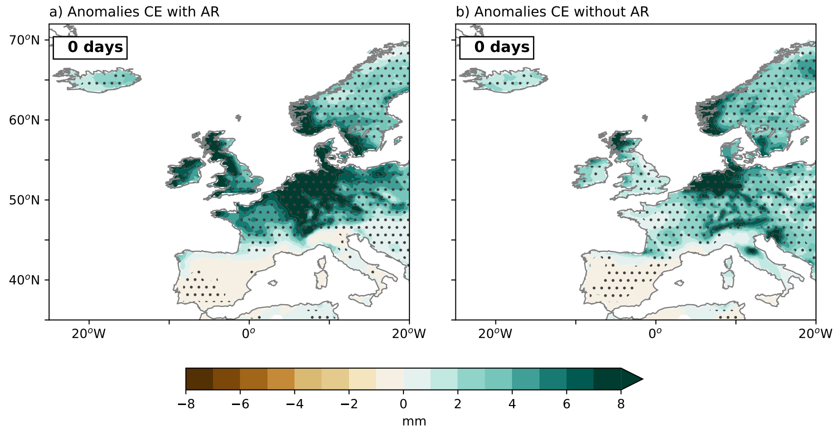

Figure 8. Anomalies of daily mean precipitation sums during CEs with (a) and without (b) AR association. Stippled areas mark regions with a p-value below 0.05 derived from a student t-test of daily precipitation values during events and the full time series.

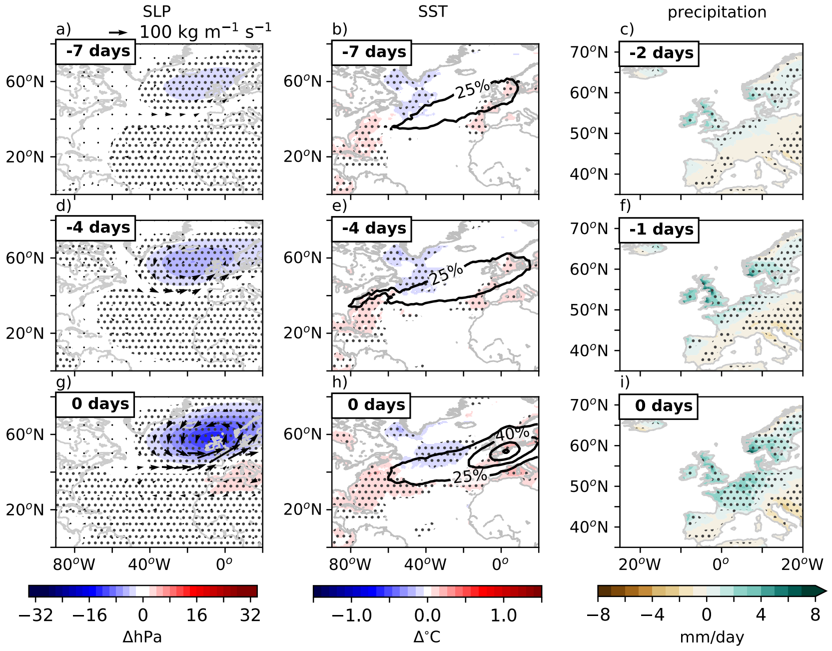

Figure 9. Anomalies of (a) SLP (colour shading) and IVT (vectors), (b) SST (colour shading) and relative number of ARs covering an area, and (c) precipitation on days with an AR over the Netherlands without the occurrence of a CE. Stippled areas indicate regions where the difference in conditions between 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.

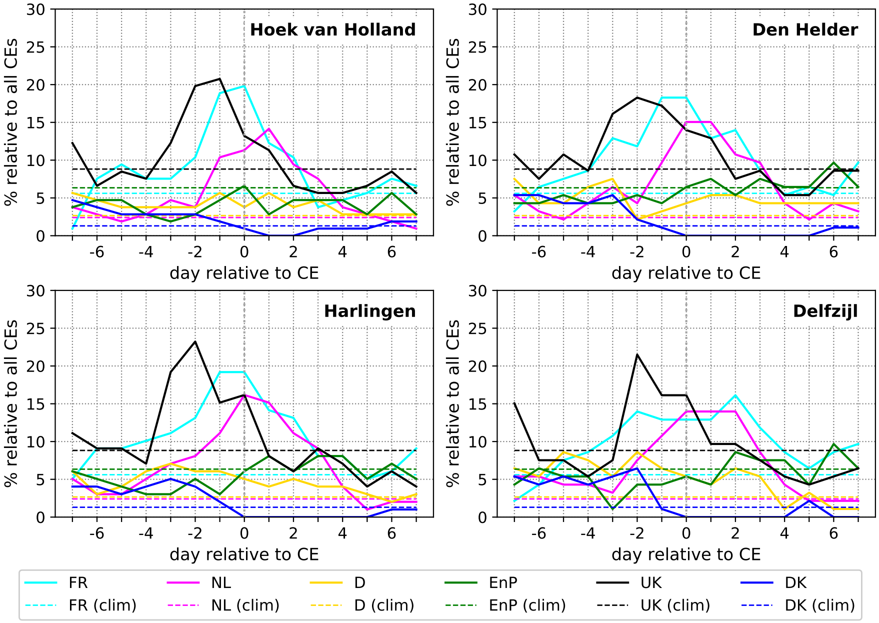

Figure A1. Relative number of compound events associated with AR landfall in the ~~UK~~ United Kingdom (UK; black), France (FR; cyan), the Netherlands (NL; magenta), Germany (D; yellow), Denmark (DK; blue), and Spain and Portugal (EnP; green) at a selection of days before and after ~~an~~ a compound event at HvH (upper left), DHR (upper right), HRL (lower left) and DLZ (lower right). Dashed horizontal lines indicate the ~~numbers~~ climatological values for ~~days with everyday conditions in~~ the ~~full time series and associate it to the respective~~ different landfall ~~location~~locations.

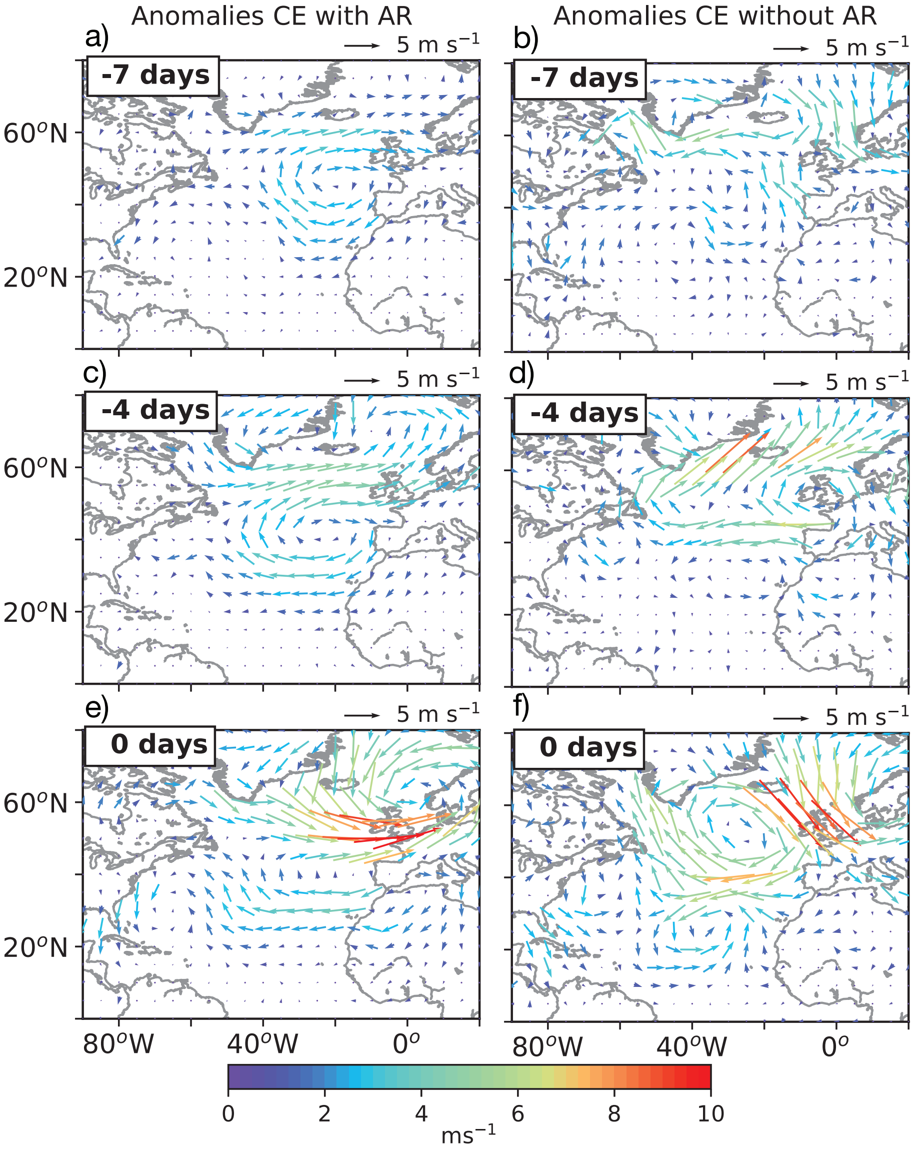

Figure A2. Anomalies in daily mean 10-m wind fields related to CEs with (left panels a, c and e) and CEs without AR association (right panels b, d and f) seven and four days before a CE (a and b; c and d, respectively) and on the day of the event (e and f).