A. Speranza (Referee #1)
antonio.speranza@unicam.it

In this paper, the concurrence of atmospheric rivers and explosive cyclogenesis over the North Atlantic and North Pacific Basins is analysed using ERA-Interim reanalysis data for 1979-2011 (for the extended winter months ONDJFM). Atmospheric rivers are identified in concurrence with almost 80% of explosive deepening cyclones and only in about 40% of the cases of non-explosive cyclones. The Conclusion is offered that "The above results strongly indicate that the presence of an AR near the developing cyclone is related with a higher probability of an explosive cyclogenesis occurrence. A detailed analysis of the time evolution of the high values of water vapour flux associated with the AR during the cyclone development phase leads us to hypothesize that this fact is a fingerprint of a physical mechanism that raises the odds of an explosive cyclogenesis occurrence and not merely a statistical relationship. . . .. This insight can be potentially helpful to enhance the predictability of high impact weather associated with explosive cyclones and atmospheric rivers."

Dear Antonio Speranza, thank you for your valued time dedicated to reviewing this paper. We believe that these modifications will improve the manuscript. Here you can find the response to your comments, questions, and suggestions.

There are some minor errors like, for example:

Pag.6 line 7 "Whereas for the Atlantic storm track has a clear SW-NE orientation is found, reaching values of 0.8 events"; either "has" or "is found" should be omitted;

The text was corrected accordingly.

Pag.4 line 8 "*. . .*statistics changes over time (Table S1), as not all systems have the same life time."; "Table" is probably "Figure"; but overall the text is adequately written.

In this specific case we are actually refereeing to the Supplementary Table S1. In Table S1, we show the number of explosive cyclones (EC) and non-explosive cyclones (NEC) in each time step used for the computation of Figures 3 to 5 and Supplementary Figures S1, S3 and to S4 for the North Atlantic domain (a) and for the North Pacific domain (b). We agree that the original text was not clear regarding the differences between Supplementary table and figure. Therefore, we have changed the text in the new version of the manuscript in order to highlight when we are referencing a Supplementary Table and when to the Figure.

The object of the study is interesting and I believe the analysis can be extended to the role of localized flows of atmospheric water also in other types of adverse weather development. For example, in the analysis of the event which led to the disaster in Giampilieri (October 2009) a concentrated southerly flow of atmospheric water channeled between Sicily and Calabria was the source of intense precipitation which eventually caused the deadly landslide.

We agree with the reviewer that localized flows of atmospheric water (called Atmospheric Rivers) can lead to huge socio-economic impacts in different regions of the Globe. In fact, the authors contributed to several recent studies analysing extreme precipitation and floods associated with ARs in the Iberian Peninsula

(Ramos et al., 2015; Eiras-Barca et al., 2016, Pereira et al., 2016, Liberato et al. 2013, Trigo et al., 2014). In addition, other studies (as mentioned in the introduction) show the importance of the Atmospheric Rivers in extreme precipitation not only in the west coast of the USA, but also for Europe, including the UK (Lavers et al., 2012), Norway (Sodemann, H. and A. Stohl, 2013) and also another example in Italy as point out by reviewer #2 (Malguzzi et al., 2006). We have included a new reference to support the Italian event Malguzzi et al (2006).

Additional references:

Malguzzi P., G. Grossi, A. Buzzi, R. Ranzi, R. Buizza 2006 The 1966 “century” flood in Italy: A meteorological and hydrological revisitation. Journal of Geophysical Research: Atmospheres 111, D24

Sodemann, H. and A. Stohl, 2013: Moisture Origin and Meridional Transport in Atmospheric Rivers and Their Association with Multiple Cyclones. Mon. Wea. Rev., 141,2850–2868

Pereira, S., Ramos, A. M., Zêzere, J. L., Trigo, R. M., and Vaquero, J. M. (2016) Spatial impact and triggering conditions of the exceptional hydro-geomorphological event of December 1909 in Iberia, Nat. Hazards Earth Syst. Sci., 16, 371-390, https://doi.org/10.5194/nhess-16-371-2016

Trigo, R. M., Varino, F., Ramos, A. M., Valente, M., Zêzere, J. L., Vaquero, J. M., Gouveia, C. M., and Russo, A.: The record precipitation and flood event in Iberia in December 1876: description and synoptic analysis, Front. Earth Sci., 2, 1–15,

However, I have the feeling that the above mentioned conclusions are pushed too far with respect to the real achievements of the analysis reported in the paper: the simultaneous occurrence of different events is in itself no proof of a cause-effect relationship between them and, even less, of a predictive potential.

My scepticism is based on personal experience in trying to identify “precursors” of relevant tropospheric developments. Specifically: in early seventies, following Ed Danielsen (1964,1968,1970), I participated in the search for correlation between tropospheric folding and alpine cyclogenesis (Nanni et al. 1975), but studies on the subject eventually revealed that although stratospheric air enhances signals (due to its very low density) it is too tenuous to exert any real “forcing” on the troposphere below and, in fact, its analysis does not improve the prediction skill of intense Mediterranean cyclones; a few years later we went through a similar experience in studies concerning the relationship between stratospheric warming and blocking: sudden stratospheric warming eventually resulted to be the consequence and not the cause of tropospheric blocking.

In conclusion, my feeling is that the conclusive statements of the paper are too generic and I would suggest either to moderate the expectations or be more specific about the physical mechanism alluded to and the associated enhancement in the predictability of high impact weather associated with explosive cyclones.

This is a fair comment, which we partially agree with. Also following the comments by the other reviewers, we have changed the pertinent text and made an effort to “moderate the expectation” regarding the content of the paper.

Danielsen, E. F.: Report on Project Springfield, Headquarters, Defense Atomic Support

Agency, Washington D. C. 20301, 15 July 1964.
Danielsen, E. F.: Stratospheric-Tropospheric Exchange Based on Radioactivity, Ozone and Potential Vorticity. J. Atmos. Sci., 25, 502 (1968).
Danielsen, E.F., R. Bleck, J. Shedlovsky, A. Wartburg, P. Haagenson, and W. Pollock: Observed Distribution of Radioactivity, Ozone and Potential Vorticity Associated with Tropopause Folding. J. Geophys. Res., 75, 2353 (1970).
Nanni T., A. Speranza, A. Trevisan and 0. Vittori, 1975: "Precipitation of stratospheric tracers and cyclogenesis in the Western Mediterranean". Arch. Met. Geoph. Biokl., A 24, 321-328.

Anonymous Referee #2

The paper is well written and easy to follow, and the subject is relevant. The paper should be published with minor corrections. Minor points follow.
Thank you for your valued time dedicated to reviewing this paper. We believe that these modifications will improve the manuscript. Here you can find the response to your comments, questions, and suggestions.

Beginning of page 4: the "historical" flood of Florence in 1966 was also a consequence of an atmospheric river (Malguzzi P., G. Grossi, A. Buzzi, R. Ranzi, R. Buizza: The 1966 "century" flood in Italy: A meteorological and hydrological revisitation. Journal of Geophysical Research: Atmospheres 111, D24, DOI: 10.1029/2006JD007111, 2006)
We have included the reference in the text. Thank you very much for point out this very interesting study which we were unware of.

Page4 line 20: the formula has a misprint (/ instead of =).
We have rephrased the sentence in order to become clear.

Page 4 line 26: for instead of For.
The typo was corrected.

Page 6 line 7: delete has.
The sentence was corrected.

Page 6 line 12: . . .to detect ARs . . . .can broadly be divided into. . .
The sentence was corrected.

Page 7 line 7: word should be world.
The typo was corrected.

Page 8 line 12: graphs b) and d) are too flat to identify a minimum.
We agree with the reviewer that it is difficult to identify a minimum pressure after the MDP in Figure S1. We have changed the text accordingly the reviewer's suggestion.

Page 9 lines 5-8: are you referring to the general trend of NEC cases from -36h to 36h? Please clarify.
The sentence was clarified and is in the present form clearly states that the specific lines mentioned by the reviewer are referring to NEC cases.

Page 9 line 12: . . .methodologies. However,. . . .
The sentenced was corrected.

Page 9 line 20: . . .moisture flux near the cyclones. .
The sentence was rephrased.

Page 10: figures S3 and S4 are really not needed.
We understand the reviewer's concern about Supplementary Figures S3 and S4 since the results are similar to the ones found for the Atlantic Basin. However, we believe that its inclusion Supplementary Figures are important for the potential readers outside the North-Atlantic-European domain. For this reason, and since the Supplementary Figures S3 and S4 do not influence the size of the main manuscript we choose to maintain them.

Page 10, last paragraph of section 4: hypothesis instead of hypothesized. The evidence that the AR is already present at MPD-36h for EC may be a strong argument to support the conclusion, since it may be considered as a precursor.
We have replaced hypothesizes by hypothesis.

Page 11 line 3: of the is repeated.
The typo was corrected.

Page 11, line 18: the sentence "This insight can be potentially helpful to enhance the predictability. . .." is too vague and difficult to be sustained given these results (in my opinion). Please try to be more specific.
This is a fair comment, which we partially agree with. Also following the comments by the other reviewers, we have changed the pertinent text and made an effort to "moderate the expectation" regarding the content of the paper.

Anonymous Referee #3

In this article the authors study the relationship between atmospheric rivers and explosive cyclogenesis through the objective identification of both large-scale features. The topic is interesting and within the scope of the journal. However, there are several details in the study and the interpretations of results that require attention before I can fully recommend the article for publication in ESD. These details are listed below in the specific comments followed by a list of purely technical correction.

Thank you for your valued time dedicated to reviewing this paper. We believe that these modifications will improve the manuscript. Here you can find the response to your comments, questions, and suggestions.

Specific comments

P1L14: I'm not convinced by the assertion that the occurrence of atmospheric rivers are characteristic features of baroclinic atmospheres. Are there atmospheric rivers on Mars?

We agree with the reviewer that the use of the word "atmospheres" is misleading since we are referring to the Earth atmosphere. Therefore we change the change it to: "The explosive cyclogenesis of extra-tropical cyclones and the occurrence of atmospheric rivers are characteristic features of a <u>baroclinic atmosphere</u>,……..".

P3L16-24: These lines are taken verbatim from Dettinger et al. (2015). Please rephrase or use quotation marks to indicate that you are using the words already published by another author. (To the editor: I didn't actively look for pieces of text taken without appropriate attribution from other sources.)

We are aware that these words were taken verbatim from Dettinger et al. (2015), but we didn't realize that quotation marks were needed, as we provided a clear reference to the author at the beginning of the lines "Recently, some agreement has been achieved (Dettinger et al., 2015) regarding the relationships between ARs, warm conveyor belts (WCBs), and tropical moisture exports (TMEs). The term WCB refers……". And in addition, we repeated the reference to Dettinger et al. (2015) at the end of the paragraph. We will re-phrase the text in the revised manuscript and we apologize for the misunderstanding. There are no other pieces of the text being taken without the appropriate attribution from other sources as proven by the iThenticate.com Similarity Report provided by the Journal.

On the other hand, I don't agree with the clarification on the terms warm conveyor belt (WCB), tropical moisture exports (TME) and ARs made by Dettinger et al. (2015). The main drawback in Dettinger et al.'s clarification is the lack of an explanation as how ARs are formed. In my opinion, they are the footprint of WCBs and possibly other frontal jets, which extract moisture from wetter regions (originally the tropics) to moisten drier regions. From this point of view ARs are a consequence of frontal dynamics. Dettinger et al. state that "[water] vapour is often transported to the WCB by an AR". However, a WCB is an air stream that develops as a consequence of the baroclinic development of a cyclone and frontal structure. Being an air stream, it's the WCB itself the entity that transports the moisture. The moisture would be present or absent depending on whether previous WCBs or other frontal jets transported it.

We fully acknowledge that there is no consensual definition on how atmospheric rivers relate to WCBs, TMEs, etc, and also on the controversial discussion on how atmospheric rivers are formed. There are some recent works that try to prove the origin of the moisture sources of the ARs by means of Lagrangian analysis:

a) Sodemann and Stohl (2013) showed that in December 2006 several ARs reached from the subtropics to high latitudes, inducing precipitation over western Scandinavia. The sources and transport of water vapour in the North Atlantic storm track during that month were examined, and they reveal that the ARs were composed of a sequence of meridional excursions of water vapour. Different moisture sources were found: (1) in cyclone cores, the rapid turnover of water vapour by evaporation and condensation was identified, leading to a rapid assimilation of water from the underlying ocean surface; (2) in the regions of long-range transport, water vapour tracers from the southern edges of the midlatitudes and subtropics dominated over local contributions.

b) Ramos et al., 2014 showed moisture sources for the major ARs affecting western European coasts between 1979 and 2012 over the winter half-year (October to March). The major climatological areas for the anomalous moisture uptake extend along the subtropical North Atlantic, from the Florida Peninsula (northward of 20º N) to each sink region, with the nearest coast to each sink region always appearing as a local maximum. In addition, during AR events the Atlantic subtropical source is reinforced and displaced, with a slight northward movement of the sources found when the sink region is positioned at higher latitudes. In conclusion, the results confirm not only the anomalous advection of moisture linked to ARs from subtropical ocean areas but also the existence of a tropical source, together with mid latitude anomaly sources (associated with convergence of moisture along the fronts).

c) More recently, Jorge Eiras-Barca et al. 2017, analysed two extreme ARs events by using a 3D Tracer tool coupled to the WRF model. Results show that between 80% and 90% of the moisture advected by the ARs, as well as 70% to 80% of the associated precipitation have a tropical or subtropical origin. Local convergence transport is responsible for the remaining moisture and precipitation.

It may also be useful in this context to emphasise that a new definition of ARs was recently included in the AMS glossary (http://glossary.ametsoc.org/wiki/Atmospheric_river) which states that: ARs are "a long, narrow, and transient corridor of strong horizontal water vapour transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapour in atmospheric rivers is supplied by tropical and/or extratropical moisture sources. Atmospheric rivers frequently lead to heavy precipitation where they are forced upward—for example, by mountains or by ascent in the warm conveyor belt. Horizontal water vapour transport in the midlatitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere."

Therefore it is appropriate to state that the authors are particularly active (in other works) in trying to understand the origin of the moisture and how it is transported by the ARs to the mid latitudes. Nevertheless we partially agree with the reviewer that the definition provided by Dettinger et al., 2015 can be slightly misleading and further studies need to be undertaken in order to better understand the connection between the TME and how is advected by the ARs to the mid-latitudes. *However from our point of view this discussion is out of the scope of the present manuscript.*

In the particular paragraph mentioned by the reviewer based on Dettinger et al. (2015) we choose to delete it and rephrase it as follows:
"According to the AMS glossary ARs are: "A long, narrow, and transient corridor of strong horizontal water vapour transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone". The definition also affirms that the water vapour in ARs is supplied by sourced of both tropical and/or extratropical origin (e.g. Ramos et al.2016a; Eiras et al., 2017) and that ARs can lead to heavy precipitation whenever these systems are forced upward— either by mountains or by ascent in the warm conveyor belt. Horizontal water vapour transport in the midlatitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere."

Regarding TMEs, Knippertz and Wernli (2010, doi:10.1175/2009JCLI3333.1) explicitly included what was called AR in the set of TMEs. Therefore, all ARs are TMEs. The authors of the present paper seem to subscribe to this view at times: For instance, in P4L7-10, they seem to use the terms AR and TME as synonyms.
The authors do not agree that the term ARs and TME are synonyms. It was our mistake to include TME on that particular sentence therefore we have replaced TME by ARs in this sentence.
From our understanding of the study from Knippertz and Wernli, 2010 you can have TME but not necessarily the formation of ARs.

All this is not to say that the authors should not be studying ARs. They provide a good definition of ARs (P3L11-13, however see also the comment to P7L20). However, if the authors are willing to enter the debate, this is a good opportunity to provide a better clarification of terms.
Please see the previous comments. We agree with reviewer that the exact mechanism leading to how the ARs are formed is still an open topic for some authors however this debate is out of the scope of the present manuscript.

P5L16-17: Whether a trigger happens just prior to its effect or long before it is not something that can be guaranteed. Please rephrase.
We agree with the reviewer that the sentence was misleading, therefore the sentence was re-written.

P7L20: I'm not convinced there is a region with high IVT values extending from the Caribbean to the British Isles. This is precisely where the confusion in the interpretation of ARs arise as it is not IVT, but IWV what extends between these two locations in Fig.1. Even the two AR-detection methods show that strong IVT is confined in its most southern and western extreme to $30^\circ - 35^\circ$N and about 30°W, whereas the Caribbean is a long way from this (around 20°N, 60°W). Please, rewrite this description.
In this particular example the reviewer is right that the IVT does not extend back till the Caribbean region due to the presence of a high pressure system that was located East of Florida. That high pressure location hampered the supply of water vapour to the ARs

(since the IVT is southwards). Therefore the text was changed accordingly to the following:

“The overall IWV pattern is clearly compatible with the presence of an AR-like structure located in the North Atlantic Ocean, showing an extensive region with high IWV values extending from the Caribbean to the British Isles (Fig. 2a). In this case, the IVT preferred direction along the high IWV region is directed from SW to NW between the sub-tropic and the cyclone center. However it seems that for these particular time steps the supply of water vapor from the tropics is cut off by the presence of high pressure system located East of Florida that make the IVT direction from the sub-tropics to the tropics.”

We would like to show an example where we have an ARs clearly visible in the IVT field (values above 400kg/m/s), and thus the water vapour transport from the tropics is documented. This AR struck directly over the Iberian Peninsula for several time steps. Still, ARs do not need to be directly connected from the tropics to the mid-latitudes.

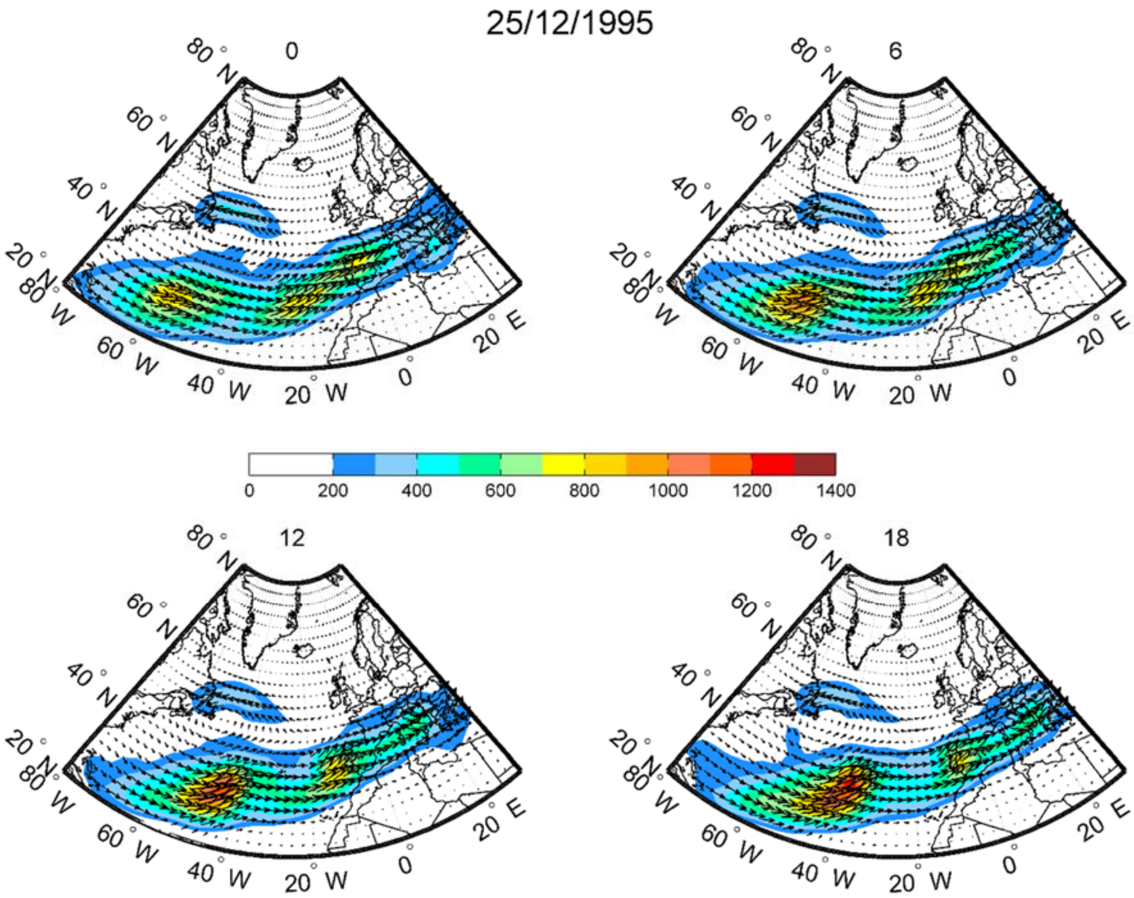
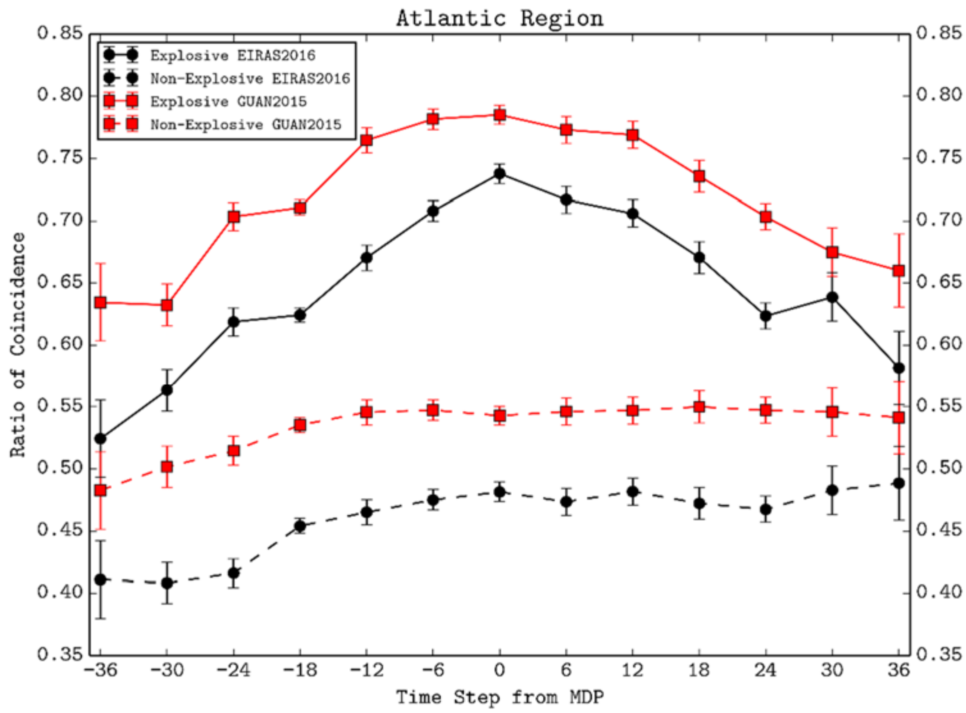


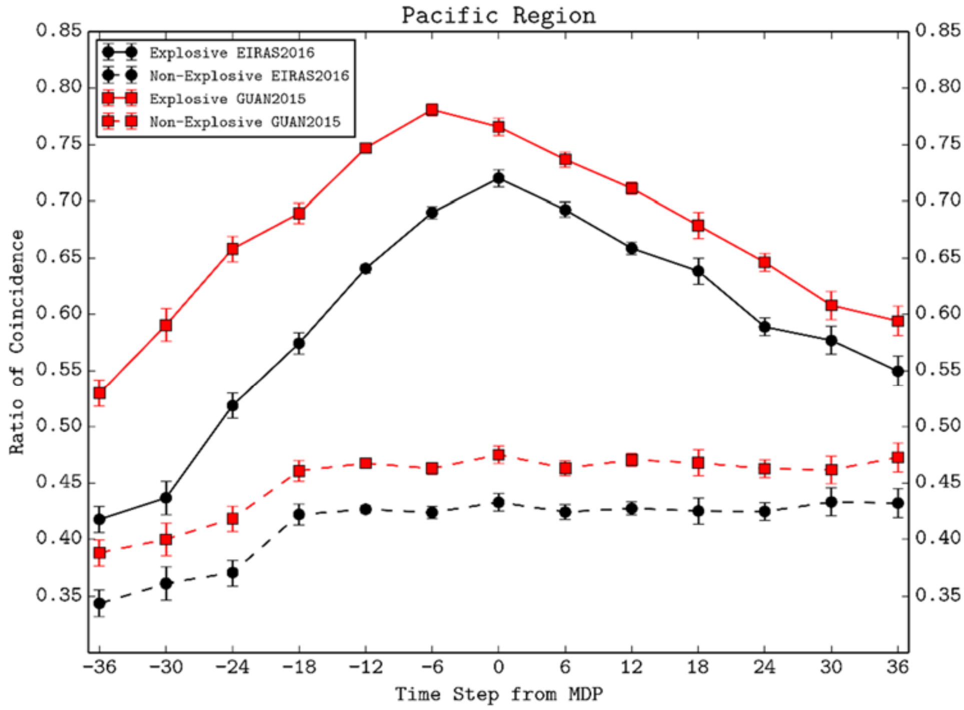
Figure R1. IVT direction (vectors) and intensity (kg/m/s; colour shading) fields at (a) 0000, (b) 0600, (c) 1200, and (d) 1800 UTC 25 December 1995.

P9L5-9: Is there really an increase? There is an increase between -36 h and -24 h but after that the lines are essentially flat. The lines in Fig. 3 must include error bars. This might reveal whether the increase is within the error or not. Also, please elaborate on the relationship of this increase and the frontal moisture convergence as it's not clear.

We agree with the reviewer that Fig. 3 should display also the uncertainty range for each time step. Therefore we will include the *variance* as an error bar for each MDP time step. The new version of the Figure 3 is shown below:



(a)



(b)

P9L11: What is a quasi-linear relationship? Even if it was a line, I don't see how it helps in the interpretation of results. This term also appears in P11L1.

We agree with the reviewer that the use of the term quasi-linear relationship is not very clear. Therefore, in the new revised section 3 the text was changed to "While a clear peak is identified close to the MDP for EC, for NEC a stable relationship with the ARs is identified in both methodologies with almost no changes of the ratio of coincidence when analysing the different 6h time frames."

In the conclusion section it was changed to "While a clear peak is found for EC, a stable relationship is identified for NEC"

P9L20-26: This part of the study produced the expected results, which is good, but it can go beyond that. What the composites are showing are the 80

We believe that this comment by the reviewer was somehow cut in half. In the pdf of the revision (shown below) the sentence stops abruptly in "....are showing are the 80". Can the reviewer clarify it?

P9L20-26: This part of the study produced the expected results, which is good, but it can go beyond that. What the composites are showing are the 80

P10L17: I don't see how your description goes beyond a statistical relationship. This is also stated in P11L16. However, to truly remove the statistical character the evolution of whole ARs would need to be studied too so that changes in cyclones can be related to changes in ARs.

We agree with the reviewer this would be a very nice idea, but it is in our opinion out of scope for the present study. We aim to do additional analysis along this direction in a follow-up study, namely by using a high resolution RCM to model the effect of introducing (or removing) an AR in the evolution of different EC and NEC events.

Technical comments

P2L18: Delete 'that'.

The word has been deleted.

P2L21: Delete 'the most'. Or how are you measuring the quality of being maritime?

The words have been deleted.

P4L8: Delete 'the' in front of Ferreira et al.

We have deleted it according to the reviewer suggestion.

P5L7: Use period instead of colon in $0 : 75^{\circ} \times 0 : 75^{\circ}$.

The typo was corrected.

P5L9: It says '...lasting more than 24 hours'. Should it be less, i.e. '... lasting less than. . .'?

The text was corrected according to the reviewer suggestion.

P5L13: I don't understand what the authors meant by 'attained'.

We agree with the reviewer that "attained" was not the best choice of word. We have replace it by "was computed".

P5L14: Use 'rather than' instead of 'over'.
We have changed the text accordingly.

P5L26: 'For' should not start with capital.
The entire sentence was re-written in order to become clear. The new version is as follows: "Two wide domains over both ocean basins have been selected: for the Atlantic domains latitudes between 25ºN and 65ºN and longitudes between 80ºW and 10ºE are considered, while for the Pacific domain considered longitudes span between 120ºE and 105ºW."

P5L27-P6L2: There is no need to give approximate figures. Give the actual percentages.
The text was re-written for clarity.

P6L7: Change 'Whereas' for 'While' and delete 'has'.
The text was changed according to the reviewer's suggestion.

P6L12: Delete the second 'be'.
The "be" was deleted from the text.

P6L15: Delete 'For' and start the sentence with 'Methods'.
We have changed the text accordingly.

P6L16: Delete ', they'
The word was deleted.

P6L17: '... combination of IWV and IVT estimated reanalysis datasets' is not clear. Please rewrite.
The sentence has been re-written for clarity.

P6L23: Change 'cf.' to 'see'. Cf. indicates comparison, which is not the case here.
We have replaced the "cf "to "see".

P7L1-2: Plural of radius is radii
We have changed the text accordingly.

P7L4: Delete 'et al.'
The "et al." was deleted from the text.

P7L4-5: Are Guan and Waliser (2015) also studying ERA-Interim to produce their dataset?
Indeed, Guan and Waliser (2015) also used ERA-Interim in their algorithm. This information has been included in the text.

P7L7: Should it say 'world' rather than 'word'?
The typo was corrected.

P8L24: I'm not sure what 'temporal association' means. Change to 'temporal coincidence'.
We have changed the word according to the reviewer's suggestion.

P9L1: The verb 'reduce' implies that it was once high and now it's low. Perhaps change to 'smaller'.
We have changed the text accordingly.

P9L27-28: What is a 36h wind-frame?
We have replaced "wind-frame" to "time-frame".

P10L15: Delete 'of this'.
We have delete it according to the reviewer's suggestion.

P10L25: Delete 'reduced to'.
We have delete it according to the reviewer's suggestion.

P11L7: Should it say '-36 hours' rather than '-30 hours'?
The typo was corrected.

P11L8: Change 'Afterword's' to 'Afterwards'.
We have changed the text accordingly.

Anonymous Referee #3
Received and published: 9 November 2017
Thank you very much for adding the comment that was incomplete.

Looking into the response from the authors to my comments, they've pointed out that one of my comments was incomplete. The complete comment is the following:
P9L20-26: This part of the study produced the expected results, which is good, but it can go beyond that. What the composites are showing are the 80% ECs associated with ARs and the 60% NECs not associated with ARs.

Figure 4 and Figure 5, are showing the composites for the entire EC and NEC dataset respectively. The reviewer is right to assume that the composites are dominated by the 80% ECs associated with ARs (Figure 4) and the 60% NECs not associated with ARs (Figure 5).

What is more interesting is to find out why there are some EC that are not associated with ARs. Why these cyclones still develop explosively? Or why are there NECs that are associated with ARs? Why these cyclone do not develop explosively? These questions could be at least partially addressed by separating the cyclones in four categories, namely EC-AR, EC-nonAR, NEC-AR, NEC-nonAR, and producing composites for each one of these. Are there noticeable differences between EC-AR and NEC-AR, or between EC-nonAR and NECnonAR? Changing this analysis will also require changing the last bullet point in the conclusions (P11L10-11).

The questions raised by the reviewer are relevant, but difficult to assess in a "climatological framework" such as the one we are developing here. However we agree with the reviewer that such an analysis is a very pertinent suggestion. Therefore, we have decided to try to address partially the problem. With this aim, we have separated the cyclones in four categories, namely EC-AR, EC-nonAR, NEC-AR, NEC-nonAR and produced the composites for each case for both **Atlantic basin** (Figure A.1 and A.2) and **Pacific basin** (not shown, but the results are very similar) using the results obtained with GUAN2015 (results obtained with EIRAS2016 database are again similar). The results presented on Figure A.1 and A.2 are only for the time frames MPD+36, MDP and MDP-36 but they illustrate well the differences between the EC-AR, EC-nonAR (Figura A.1), NEC-AR and NEC-nonAR (Figure A.2).

As could be expected, there is a considerable difference in the composites between EC-AR and EC-nonAR, with high values of IVT being found on the EC-AR and considerable lower values in the case of the EC-nonAR.

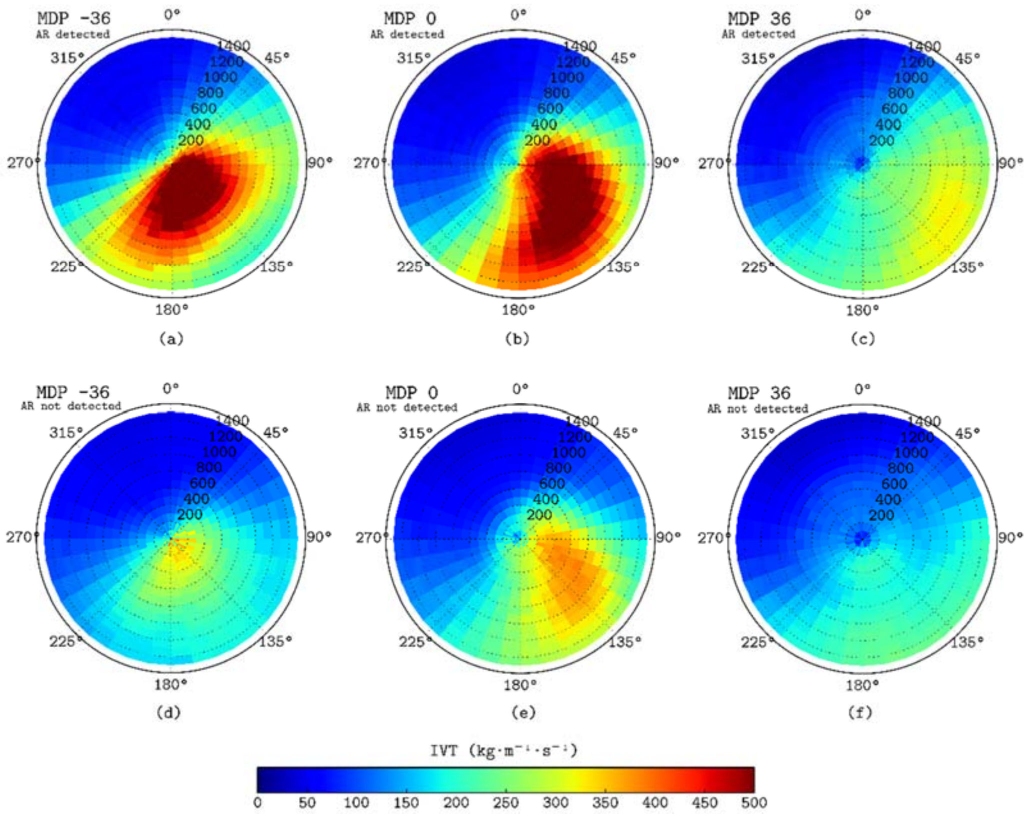


Figure A.1. Composite of the integrated vapour transport (IVT, colours, $kg.m^{-1}.s^{-1}$) within a 1500km radius around the cyclone core for EC-AR (upper panel) and EC-nonAR (lower panel) for the North Atlantic basin for the period 1979-2011 for +36 hours do the MDP, for the MDP and for -36h of the MDP. These results are based on the AR database developed by GUAN2015 (see Figure 3 of our manuscript).

Regarding the NEC-AR, NEC-nonAR (Figure A.2.) the composites reveal that for the NEC-AR the presence of relatively higher IVT when compared with the NEC-nonAR. However when compared with the EC-AR and even with the EC-nonAR (Figure A.1) these values are much lower (EC-AR) or relatively lower (EC-nonAR).

This apparent contradiction when comparing the NEC-AR and the EC-nonAR (since higher values of IVT are found for the EC-nonAR) results in our opinion from two main effects:

1) the detection of the ARs is based on the IVT percentile threshold climatology, with means higher values of IVT are required in the south than in the north (GUAN2015 and EIRAS2016), therefore the position (latitude, longitude) of the bomb will have influence of the value of IVT required in the detection of the ARs.
2) The sample of the cyclones in the NEC-AR and the EC-nonAR is very different, being considerably higher in the NEC-AR than in the EC-nonAR (see Figure 3 and supplementary Table S1), therefore the IVT composite is very smoothed in the NEC-AR.

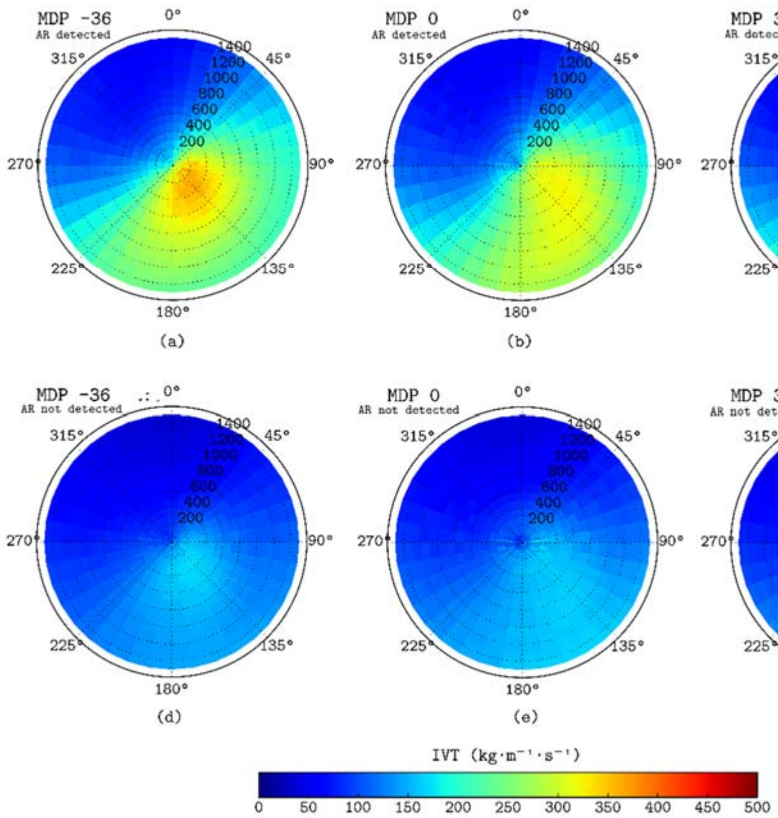


Figure A.2. Composite of the integrated vapour transport (IVT, colours, kg.m^{-1}.s^{-1}) within a 1500km radius around the cyclone core for NEC-AR (upper panel) and NEC-nonAR (lower panel) for the North Atlantic basin for the period 1979-2011 for +36 hours do the MDP, for the MDP and for -36h of the MDP. These results are based on the AR database developed by GUAN2015 (see Figure 3 of our manuscript).

Taking these into account, when analysing the EC-AR, EC-nonAR, NEC-AR, NEC-nonAR composites, and despite they are some noticeable differences between them, we do not think that they were unexpected. Thus, we do not think that this additional analysis leads to new / different conclusions. Still, we have decided to include a short reference to the differences between EC-AR and EC-nonAR in section 3 and include Figure A1. in the supplementary material (new supplementary Figure S3 . A more detailed analysis is left for future work.

"While the EC samples are dominated by systems associated with an AR (cf. Fig. 3), this is not always the case. In order to evaluate this in more detail, we analysed additional composites by separating the EC cyclones in two categories, namely EC with AR (EC-AR) and without AR (EC-nonAR; Supplementary Fig. S3 for the North Atlantic Ocean). As expected, results show that there is a considerable difference in the composites between EC-AR and EC-nonAR, with high values of IVT identified for EC-AR and considerable lower values for EC-nonAR. The figures for EC-nonAR are more similar to NEC systems (not shown)."

The concurrence of Atmospheric Rivers and explosive cyclogenesis in the North Atlantic and North Pacific basins

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Abstract. The explosive cyclogenesis of extra-tropical cyclones and the occurrence of atmospheric rivers are characteristic features of a baroclinic atmosphere~~s~~, and are both closely related to extreme hydrometeorological events in the mid-latitudes, particularly on coastal areas on the western side of the continents. The potential role of atmospheric rivers in the explosive cyclone deepening has been previously analysed for selected case studies, but a general assessment from the climatological perspective is still missing. Using ERA-Interim reanalysis data for 1979-2011, we analyse the concurrence of atmospheric rivers and explosive cyclogenesis over the North Atlantic and North Pacific Basins for the extended winter months (ONDJFM). Atmospheric rivers are identified for almost 80% of explosive deepening cyclones. For non-explosive cyclones, atmospheric rivers are found only in roughly 40% of the cases. The analysis of the time evolution of the high values of water vapour flux associated with the atmospheric river during the cyclone development phase leads us to hypothesize that the identified relationship is the fingerprint of a mechanism that raises the odds of an explosive cyclogenesis occurrence and not merely a statistical relationship. These~~is~~ new insights on~~can be helpful for the predictability of~~ the relationship between~~high impact weather associated with~~ explosive cyclones and atmospheric rivers~~.~~ may be helpful to a better understanding of the associated high impact weather events.

1 Introduction

Intense extra-tropical cyclones are one of the major natural threats in mid-latitudes and are often responsible for large socioeconomic impacts (Munich Re, 2015). Their impacts include strong winds, heavy precipitation and in some cases storm surges (e.g., Lamb, 1991) In particular, cases associated with explosive cyclogenesis (Sanders and Gyakum, 1980; pressure decrease larger than 24 hPa in 24 hours at 60ºN, or equivalent) are associated with particularly large impacts and often with low predictability (e.g. Wernli et al., 2002; Fink et al., 2009). Such systems are often referred in the literature as "bombs". According to Shapiro et al. (1999), explosive cyclogenesis result from different mechanisms that include upper-level cyclonic vorticity advection, low-level warm air advection, and latent heat release. This may be supported by upper-tropospheric Rossby wave breaking, which constraints and intensifies the upper-level jet stream and thus contributes to intense cyclone developments (e.g. Hanley and Caballero, 2012; Gómara et al., 2014). According to Aubert (1956), the latent heating influence is significant not only in the pressure distribution, but also in the vertical motion field. In particular, Aubert (1956) states that this mechanism lowers the heights of isobaric surfaces in the lower troposphere, and raises them in the upper. In agreement, Tsou et al. (1987) found that even for cases with strong vorticity advection and the differential thermal advection, ~~that~~ latent heat release is still primary cause of the pressure falling below 900 hPa during the period of most abundant precipitation. The release of latent heat contributes to increase the storm's available potential energy, deepening the cyclone while decreasing the horizontal scale of the region of ascent particularly in ~~the most~~ maritime cyclones (e.g., Emanuel, 1987; Snyder and Lindzen, 1991; Davis, 1992)

Several studies have confirmed the occurrence of a maximum of latent and sensible heat availability in the lower troposphere near the warm sector of the cyclone, and documented the contribution of moist diabatic processes such as latent heat release by cloud condensation processes to the intensification of extratropical cyclones (Pinto et al., 2009, Liberato et al., 201~~3~~2; Ludwig et al., 2014). However, the relative contribution of diabatic processes to the cyclone deepening may differ considerably from case to case. For example, Fink et al. (2012) showed for selected explosive cyclogenesis cases that while diabatic processes played a key role for storms such as Xynthia and Klaus, other storms are largely baroclinic driven (e.g. Kyrill and Martin). This results has recently been extended by Pirret et al (2017), which provided evidence that baroclinic processes generally dominate the majority of storms. On the other hand, the contributions from diabatic processes varies strongly from cases to case, and are only dominant for 10 out of 58 cases. The role of the diabatic contribution is strongly related with the period of time that a storm remains equatorward side of the jet, where warm, moist air is present.~~For example, Fink et al. (2012) showed for selected explosive cyclogenesis cases that while diabatic processes played a key role for storms such as Xynthia and Klaus, other storms are largely baroclinic driven (e.g. Kyrill and Martin). The recent study by Pirret et al. (2017) quantifies the role of the different mechanisms for the deepening of 60 severe European windstorms based on the methodology by Fink et al. (2012). This objective assessment shows that baroclinic processes dominate the majority of storms, such that deepening is closely related to warm advection ahead of the cyclone centre. Contributions from diabatic processes vary strongly from cases to case and exceed those from horizontal temperature advection in 10 out of 58 cases, with values of up to 60%. In addition, the diabatic contribution is significantly correlated with the period of time a given storm spends on the equatorward side of the jet, where there is greater potential for diabatic processes in the warm, moist air.~~

The higher moisture availability in the north Pacific and north Atlantic basins are controlled by so-called Atmospheric Rivers (AR; e.g. Newell and Zhu, 1994; Zhu and Newell 1998; Bao et al., 2006; Ralph and Dettinger, 2011; Gimeno et al., 2017). ARs are relatively narrow (on average 500 km) corridors of enhanced water vapour (WV) transport in the lower troposphere that can extend for thousands of kilometers. According to the AMS glossary ~~the~~ARs are:~~-~~ “~~a~~A long, narrow, and transient corridor of strong horizontal water vapour transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone”. The definition also affirms that ~~T~~the water vapour in ARs~~atmospheric rivers~~ is supplied by sourced of both tropical and/or extratropical origin (e.g. Ramos et al.2016a; Eiras et al., 2017) ~~moisture sources.~~ ~~A~~and that ARs ~~Atmospheric rivers frequently~~can lead to heavy precipitation whenever these systems ~~re they~~ are forced upward~~—~~ ~~for example,~~ either by mountains or by ascent in the warm conveyor belt. Horizontal water vapour transport in the midlatitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere.~~This phenomenon is associated with tropical moisture exports (TME; e.g., Knippertz and Wernli, 2010) and occurs often in combination with the passage of extratropical cyclones (Dacre et al., 2015). Recently, some agreement has been~~

~~achieved (Dettinger et al., 2015) regarding the relationships between ARs, warm conveyor belts (WCBs), and tropical moisture exports (TMEs). The term WCB refers to the zone of dynamically uplifted heat and vapour transport close to a mid-latitude cyclone. This vapour is often transported to the WCB by an AR, and the result of the uplift is heavy rainfall that generally marks the downwind end of an AR, provided that the AR has not experienced orographic uplift (upslope flow), accompanied by rainout over mountains earlier on its approach to the WCB. TMEs are zones of intense moisture transport out of the tropics, vapour that is frequently conducted by ARs towards cyclones and WCBs. TMEs can provide important vapour sources for ARs, but most ARs also incorporate mid-latitude sources and convergences of vapour along their paths (Dettinger et al., 2015; Sodemann and Stohl, 2013, Dacre et al., 2015)~~. ~~A comprehensive assessment of moisture sources feeding Atlantic ARs bound for different sectors of Western Europe can be found in Ramos et al. (2016)~~. The importance of ARs in extreme precipitation events and floods has been analysed in detail for the west coast of the USA (particularly for California) over the last decade (e.g., Ralph et al., 2004; Neiman et al., 2008; Dettinger et al., 2011). Similar conclusions have been reached for Europe (e.g. Malguzzi et al., 2006; Lavers et al., 2012; Liberato et al. 201~~3~~2; Ramos et al., 2015; Eiras-Barca et al., 2016; Brands et al., 2017) and other regions of the world (e.g. Viale and Nuñez, 2011; Mahoney et al., 2016; Blamey et al., 2017).

Given the role of latent heat release in the development of explosive cyclogenesis, this suggests that explosive cyclogenesis in the mid-latitudes may be influenced by the presence of an AR. Additionally, the release of sensible heat in the vicinity of the cyclone will enhance the convective instability of the AR. Previous studies showed for selected case studies that explosive development can indeed be driven by the presence of an AR (Zhu and Newell, 1994, Ferreira et al., 2016). For example, ~~the~~ Ferreira et al (2016) have provided evidence on the role of ARs ~~a TME~~ over the western and central (sub)tropical Atlantic towards cyclone development, which converged into the cyclogenesis region and then moved along with the storm towards Europe. However, to the best of our knowledge, no ample assessments analysing the role of ARs in the explosive deepening have been performed from the climatological perspective. The main objective of this study is to provide a comprehensive evaluation on the role of the ARs in the explosive deepening of North Atlantic and North Pacific extratropical cyclones between 1979 and 2011 for the extended winter months (ONDJFM), focusing on the spatial concurrence and the timing of both features.

The manuscript is organized as follows: Section 2 described the data and methods, while the results are presented in section 3. Finally, the conclusions are given and discussed in section 4.

2 Data and Methods

We use ECMWF ERA-Interim Reanalysis (Dee et al., 2011) between 1979 and 2011 for our study. For the cyclone detecting and tracking methodology (see section 2.1), 6-hourly instantaneous 1000 hPa geopotential height fields at a resolution of 0.75º × 0.75º are considered. For the detecting and tracking of the ARs structures (see section 2.2), we used moisture and wind values at multiple vertical pressure levels to compute the integrated water vapour column (IWV) and the vertically integrated horizontal water vapour transport (IVT) at the same resolution.

2.1 Cyclone Detecting and Tracking Methodology

We have applied an automatic procedure to identify and track extratropical cyclones (Trigo, 2006). This particular cyclone detecting and tracking algorithm was first developed for the Mediterranean region (Trigo et al., 1999, 2002), later extended to a larger Euro-Atlantic region (Trigo, 2006) and finally generalized for both hemispheres (e.g. Neu et al. 2013). The scheme is applied to the ERA-Interim geopotential height at 1000 hPa (Z1000) fields. Cyclones are identified and tracked at a 6-hourly basis at the spatial resolution available of 0.~~:~~75º × 0~~:~~.75º for the entire northern hemisphere. Results from this method compare well with other similar methods (Neu et al., 2013). Storms with minimum central pressure higher than 1010 hPa over their entire lifecycle and lasting ~~more~~ less than 24 hours are discarded from the subsequent analysis. For each cyclone, the maximum deepening rate ΔP per cyclone track is determined by the maximum pressure drop at the centre of the cyclone on the basis of all the 6-h successive time steps ((P (t − 6) − P (t)) in its life cycle. The maximum deepening point (MDP) corresponds to the point P(t) and ~~is~~ was ~~attained~~ computed for each cyclone in order to analyse the influence of the ARs on its maximum deepening rate. We choose the maximum deepening point ~~over~~rather than the minimum pressure point of the cyclone because it is in this time frame of the cyclone development that an influence from AR may be expected. ~~the minimum pressure point may not guarantee that trigger for its deepening occurred in the 6 hours previous to it. On the contrary, b~~By choosing ~~in~~ the MDP, we guarantee that the potential trigger effect for its maximum deepening occurred ~~just prior to it~~at the same time or just prior to it. From this database, the sub-set of explosive cyclogenesis (EC) is selected for further analysis. Following Bergeron (1954) and the generalization by Sanders and Gyakum (1980), explosive cyclones are defined as cyclones with deepening rates (NDR) ~~exceeding 24~~exceeding 24 hPa in 24 hours for a reference latitude of 60°N, where NDR is defined as: $NDR=(\Delta pc \sin 60) / (24 |\sin \varphi|)$, where Δpc is the change in central pressure in 24h and ~~(24 * sin(φ)= sin(60º)) hPa / 24 hours, where~~ φ is the latitude of the cyclone core at MDP. All remaining cyclones are included in the sub-set non-explosive cyclones (NEC). In addition, for the ARs analysis, all the cyclones below 25ºN were filtered in order to avoid tropical storms and hurricanes in our analysis.

Two wide domains over both ocean basins have been selected: for the Atlantic domains ~~for~~ latitudes between 25ºN and 65ºN~~. For the Atlantic domain,~~ and longitudes between 80ºW and 10ºE are considered, while for the Pacific domain longitudes are between 120ºE and 105ºW. Regarding the extended winter months, ~~For~~ for the North Atlantic basin, a total of 7315 cyclones were detected, from which 733 were classified as EC (~~close to~~ 10.02% of the cases). Regarding the Pacific domain, a total of 10890 cyclones where identified, in which 1115 classified as EC (~~close to~~ 10.~~3~~24% of the cases).

Fig. 1 shows the spatial distribution of the positions where EC reached their minimum core pressure during lifetime. Depicted are the number of events per extended winter (ONDJFM) season per 5ºx5º grid box, normalized to the corresponding area for 50ºN (about 200x10^3 km^2). The density maps of cyclone positions provide a good overview of the distribution of explosive cyclones in both basins. While~~Whereas~~ for the Atlantic storm track ~~has~~ a clear SW-NE orientation is found, reaching values of 0.8 events per extended winter near the American continent, over the Pacific Basin the storm track is more zonal and reached values of 0.9 events per extended winter over the central-western basin.

2.2 Atmospheric Rivers Detection

There are several methodologies to ~~the~~ detect ARs, which can ~~be~~ broadly be divided into two groups considering the nature of the main dataset used, either satellite data or reanalysis data (Gimeno et al., 2014). ~~For m~~Methods using satellite data, the different approaches consider the IWV, obtained mainly from the SSM/I sensor (e.g., Ralph et al. 2004; Guan et al. 2010; Ralph and Dettinger 2011). For methods based on reanalysis data, ~~they~~ focus on the IVT (e.g., Zhu and Newell 1998; Lavers et al. 2013) or the method of Eiras-Barca et al (2016) that use a ~~a~~ combination of IWV and IVT from ERA-Interim reanalysis. ~~estimated reanalysis datasets (e.g Eiras-Barca et al., 2016)~~. An overview of the different methods to identify ARs can be found in Gimeno et al. (2014). Given the different approaches to identify them, and in order to estimate the sensitivity of the results for the choice of identification method, we employ two different methods to identify them.

The first method is an adaptation of Eiras-Barca et al. (2016) approach (hereafter EIRAS2016) which uses not only IWV but also the IVT to identify ARs. For each cyclone, the location and timing of the MDP (~~cf.~~see section 2.1) along the cyclone track is used as a starting point. In 6 hourly time-steps and for a ±36 hour window-frame around the MDP, we search within a radius of 1500 km surrounding the centre of the cyclone location at that time for the maximum values of IWV which are above the local 85th monthly percentile. If a grid point is selected, the neighbouring grid points are also investigated. This procedure continues as long as the threshold conditions are met, building 2-D features. A feature must have a minimum extension of 2000km to be considered an AR. The search radius of 1500 km has been selected to take the shape and geometry of ARs and cyclones into account. While smaller radii~~radius~~ of search may be in some cases insufficient to detect ARs in the vicinity of large cyclones, larger radii~~radius~~ of search could detect other ARs which are unrelated to the analysed cyclone, leading to a false detection.

The second ARs detection scheme was developed by Guan and Waliser ~~et al.,~~ (2015) (hereafter GUAN2015) using also the ERA-Interim Reanalysis.~~.~~ The database used here (shape boundary and axis of the ARs) were provided by the authors. For this method, there is no need of a reference starting point to search for the ARs. Instead, the method isolates contiguous regions of the world of enhanced IVT exceeding a certain IVT threshold (> 85th percentile or 100kg m^{-1} s^{-1}, whichever is greater). Each of these regions will be subsequently analysed for the geometry requirement of length >2000km, length/width ratio >2 and other considerations indicative of ARs conditions (~~cf.~~see Guan and Waliser, 2015). Both algorithms operate using variable spatial and time dependent thresholds. The assignment of the cyclones to the GUAN2015 ARs is performed in an identical way as for EIRAS2016 to warrant comparability. Both methodologies were applied to both EC and NEC sub-sets in order to quantify the role of the ARs for the development of explosive cyclones.

2.3 Example of detection

A good example of a well-defined AR can be found in Fig.2. The selected case corresponds to an explosive cyclone where the MDP occurred on the 31 January 1988 at 18 UTC west of Ireland (approximately at latitude 51ºN and longitude 20ºW, red dot in Fig. 2b and Fig. 2c). The overall IWV pattern is clearly compatible with the presence of an AR-like structure located in the North Atlantic Ocean, showing an extensive region with high IWV values extending from the Caribbean to the British Isles (Fig. 2a). In this case, the IVT preferred direction along the high IWV region is directed from SW to NE between the sub-tropic and the cyclone centre. However it seems that for these particular time steps the supply of water vapour from the tropics is cut of be the presence of high pressure system located East of Florida that make the IVT direction from the sub-tropics to the tropics. This preliminary visual assessment of the presence of an ARs is confirmed using the GUAN2015 algorithm in Fig. 2b, where the two highlighted regions that are distinguished corresponds to the "shape" region (reddish) which is the region where the AR can exist, and the blue line depicts the central axis of maximum intensity of the AR detected by the GUAN2015 method. Similarly, in Fig. 2c the results for the EIRAS2016, for the same case, is shown, where it shows the detection of the central axis of the AR (blue crosses) event stated in Fig. 2a.

3 Results

Both AR detection methodologies were applied to the entire cyclone database. The obtained information was used to estimate the relevance of the ARs in the occurrence of explosive cyclogenesis and compare it with the corresponding NEC results. First, we analyse the samples of cyclones in each sub-set in terms of the evolution of core pressure over time. Supplementary Fig.~~ure~~ S1 depicts the distributions of core pressure values from - 36 hours until +36 hours from MDP, for both the North Atlantic and North Pacific basins and for EC and NEC. Please note that the number of cyclones included in the statistics changes over time (Supplementary Table S1), as not all systems have the same life time. EC systems typically deepen around 30 hPa during its lifetime and attain a minimum core pressure around MDP+6 or +12 hours. Afterwards, occlusion advances and the systems fill in and consequently core pressure slowly increases with time. On the other hand, the pressure changes for NEC is typically much smaller (around 10 hPa) and the minimum peak intensity is difficult to identify since the core pressure more or less is stable ~~sometimes attained~~ after MDP~~+12 hours~~. The increase of core pressure over time after MDP+6h is thus not identifiable for NEC systems.

Regarding the concurrence of these events with ARs, Fig.~~ure~~ 3 shows the ratios of observed coincidence between the EC and the presence of an AR within a 1500km radius of the cyclone for the North Atlantic (Fig. 3a) and for North Pacific (Fig. 3b) including the variance as the error bars for each MDP. The first prominent result is high ratios of coincidence between ARs for EC, peaking between 70% and 80% for time lags MDP-6h to MDP+6. When focusing on the North Atlantic region (Fig. 3a), the maximum (~78%) is found for the MDP+6h using the GUAN2016, while using the EIRAS2016 the maximum (~74%) is at the MDP timing. Likewise, for the Pacific Basin (Fig. 3b) the ratios of coincidence with the ARs reach a maximum of 78% when using the GUAN2016 on the MDP-6, while when using the EIRAS2016 its maximum (~72%) is found at the MDP. The results for the EC are in line with those found by Zhu and Newell (1994) and Ferreira et al. (2016) for a few selected case studies, where ARs were identified near the cyclones during an explosive cyclogenesis. In addition, we show here that the temporal coincidence~~association~~ between the ARs and explosive deepening of the cyclone takes place primarily between -6h to +6h around the MDP. Our results support the findings by Pirret et al. (2016), as the presence of the ARs will enhance the warm advection ahead of the cyclone core during the development phase.

For NEC, the concurrence of ARs during the development phase is strongly ~~reduced~~smaller. For the North Atlantic Region (Fig. 3a), the values for NEC range from about 55% with the GUAN2015 and close to 45% with the EIRAS2016 method. For the North Pacific basin (Fig. 3b), results for the NEC are similar (but lower ratios) to those found for the North Atlantic basin ranging from approximately 46% in the GUAN2015 and nearly 42% when using EIRAS2016. In addition, for the NEC, there is apparently an increase in the ratio of coincidence between the position of the ~~cyclone~~ NCE and the presence of the ARs from -36h to +36h. This can be associated with the convergence of moisture along the frontal system of the cyclones (Dacre et al., 2015) along with tropical moisture export episodes (Knippertz and Wernli (2010) which can potentiate the formation of an AR in the latter stages of the NEC.

The conclusions attained with both methodologies are very similar. While a clear peak is identified close to the MDP for EC, for NEC a stable ~~quasi-linear~~ relationship with the ARs is identified in both methodologies with almost no changes of the ratio of ~~-~~coincidence when analysing the different 6h time frames. ~~h~~However, the ratio of coincidence is always higher when using the GUAN2015.

Regarding the spatial distribution of the EC-AR coincidences, no conclusions can be achieved based on our results. Supplementary Fig. S2 shows the position of the EC during the MDP if the AR coincidence was detected (red dots) and if it was not (black crosses). At first sight, the coincidences and non-coincidences of explosive cyclonenesis with ARs seem to be roughly equally distributed throughout the Atlantic and Pacific domains. However, on the downstream end of the storm tracks, cases with concurrent AR seem to dominate (e.g. over the British Isles). Still, no general conclusions can be taken on a possible relation on the location of explosive cyclogenesis and concurrence (or non-concurrence) with anomalous moisture flux near the cyclones. ~~ARs.~~

In order to analyse the flux of moisture in near the cyclones within ±36 hours of the MDP, spatial composites of the IVT within radius of 1500km from the cyclone core were computed for each time step, for the EC and for the NEC and for both domains. Fig. 4 shows the composites of the IVT in the surroundings of EC between -36h and +36h from the MDP at 6h time steps for the North Atlantic, while Fig. 5 shows the same fields but for NEC. One key difference between both Figures is noticeable differences in the IVT fields, which implies the presence of intense IVT values akin to ARs-like structures in explosive cyclogenesis when compared to the NCE events.

Since ARs are commonly spatially associated to the warm sector of the cyclone, the evolution of the IVT fields throughout the 36h ~~wind~~time-frame adjacent to the MDP frame depicts the general frontal evolution over the cyclogenesis event. Note that the AR is already quite prominent at MDP-36h for EC events, and its position slowly rotates around the cyclone core MDP with slightly increasing intensities. Also noteworthy is the fact that after the MDP point the AR not only strongly weakens but its central axis tends to be detached from the cyclone with increasing time, corresponding to the detachment from the warm sector from the cyclone core at later stages of cyclone development (occlusion is initiated). This conclusion is in line with that obtained by Zhu and Newell (1994) for a much smaller number of cases. While the EC samples are dominated by systems associated with an AR (cf. Fig. 3), this is not always the case. In order to evaluate this in more detail, we analysed additional composites by separating the EC cyclones in two categories, namely EC with AR (EC-AR) and without AR (EC-nonAR; Supplementary Fig. S3). As expected, results show that there is a considerable difference in the composites between EC-AR and EC-nonAR, with high values of IVT identified for EC-AR and considerable lower values for EC-nonAR. The figures for EC-nonAR are more similar to NEC systems (not shown).

Supplementary Figs. ~~-~~S4 and S5 show the composites for EC and NEC events but for the North Pacific domain. No meaningful differences can be observed between the North Atlantic and the North Pacific basins, and thus the conclusions are the same for the North Atlantic. The results suggest the importance of latent heat released when the cyclones encounter the ARs leading to intense condensation process, thus providing an important source of energy when the cyclone is in its deepening phase (e.g. Danard, 1964; Bullock and Jonhson, 1971, Whitaker and Davis, 1993).

The results presented in this section have revealed two main new insights. First, the highest ratio of the present of the ARs in the vicinity of EC is found within ±6 hours of the MDP. Second, it is apparent for EC events that the AR is located very close to the cyclone centre prior to MDP, while the AR becomes detached from the EC core once the cyclone stops deepening. As a result~~ of this~~, we confirm the hypothesis~~hypothesizes~~ that the presence of an AR raises the odds of an explosive cyclogenesis occurrence and is thus not only a merely a statistical relationship as suggested by Ferreira et al., (2016) for three modelled EC case studies.

5 Conclusions

We investigated the importance of ARs in the development of explosive cyclogenesis on both North Atlantic and North Pacific basins using two different algorithms for AR identification. With this aim, the concurrence of the presence of AR in the vicinity of developing cyclones was quantified over different time lags. The main results are summarized in the following:

- ARs are present very frequently within the vicinity of cyclones undergoing EC, reaching a maximum values close to 80% near the MDP (+/- 6 hours) for both domains. The concurrence of ARs with NEC is ~~reduced to~~ 42-46% for NEC.
- While slightly different results are obtained with the two AR methodologies, the results are consistent, both in terms of the general numbers and the time evolution of concurrences between AR and cyclogenesis over time. While a clear peak is found for EC, a stable ~~quasi-linear relationship is~~relationships identified for NEC. The obtained conclusions are thus robust and largely independent ~~of the~~ of the detection ARs algorithm used
- Since ARs are commonly associated to the warm sector of the cyclone, the evolution of the IVT fields throughout the ±36h frame surrounding the MDP point depicts the general frontal evolution over the cyclogenesis event. Prior to the MDP, high values of IVT are already present at -~~30~~ 36 hours, with the maximum values of IVT appearing around the MPD (±6h). Afterwards'~~Afterword's~~, the IVT values quickly decrease and the central AR axis tends to be detached from the cyclone.
- The analysis of NEC composites reveals much lower values of IVT during development. This is a clear indication of the unusual characteristics of the IVT for EC cases.

The above results strongly indicate that the presence of an AR near the developing cyclone is related with a higher probability of an explosive cyclogenesis occurrence. A detailed analysis of the time evolution of the high values of water vapour flux associated with the AR during the cyclone development phase leads us to hypothesize that this fact is a fingerprint of a physical mechanism that raises the odds of an explosive cyclogenesis occurrence and not merely a statistical relationship. Given the previous work of Zhu and Newell (1994) on selected case studies, our analysis allows for a systemization of results from a climatological perspective. This insight ~~can be~~can be potentially helpful ~~to enhance the predictability of~~to a better understanding of the occurrence of high impact weather associated with both explosive cyclones and atmospheric rivers. A detailed analysis of the changes in terms of cyclone structure and intensity would enable a further step forward towards a better predictability of such extreme events.

Regarding future climate projections, Ramos et al. (2016b) showed that most models from the CMIP5 project a coherent increase of IVT values over the North Atlantic Basin and an increase in the number of ARs that hit the Western Europe by the end of the XXI century, although more evident with emissions scenario RCP8.5 than with scenario RCP4.5. When such climate change scenarios are considered simultaneously with the new insights of the current paper, this implies that the probability of occurrence of intense extra-tropical explosive cyclones will increase in future decades.

Author Contributions

JEB, AMR, JGP developed the concept of the paper and wrote the first manuscript draft. JEB performed the data analysis and prepared the figures. MLR provided the cyclone track data. All authors contributed with ideas, interpretation of the results and manuscript revisions.

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Figure Captions

Figure 1. Spatial distribution of the location where explosive cyclogenesis reach their minimum core pressure for: a) Atlantic Ocean and b) Pacific Ocean. Contours correspond to the average number of events per extended winter (ONDJFM) season, detected per 5ºx5º area normalized for 50ºN. The spatial distribution was smoothed with a 5° averaging radius.

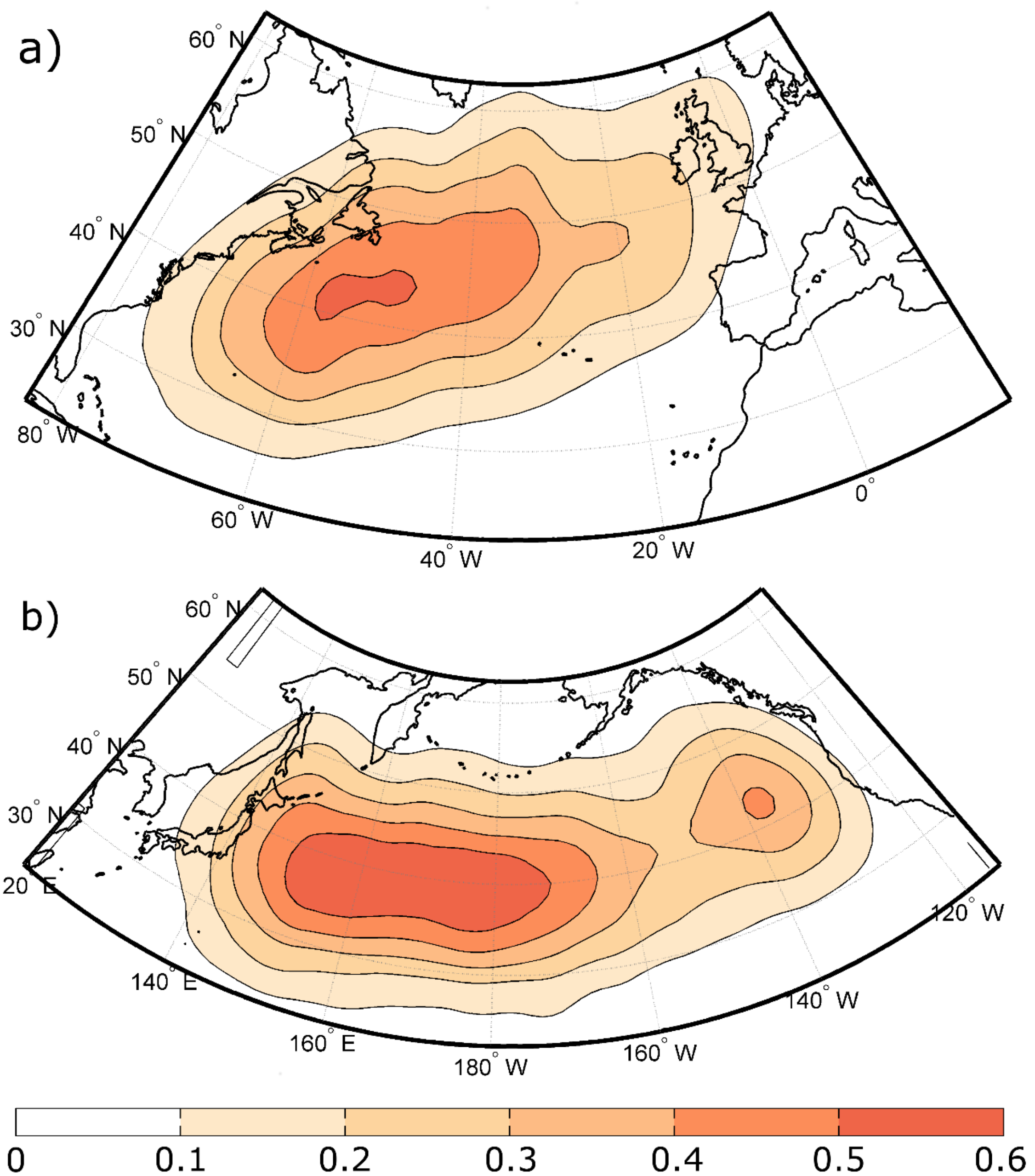
Figure 2. Example of a well-defined Atmospheric River associated to an explosive cyclone development land-falling the British Isles on 31 January 1988, 18 UTC. Mean Sea Level Pressure field (hPa) is indicated as black isolines in all panels. (a) total integrated column of water vapor (IWV, colours, $kg.m^{-2}$) and integrated vapour transport (IVT, arrows, $kg.m^{-1}.s^{-1}$). (b) Shape region (red) and central axis of the Atmospheric river (blue) for the GUAN2015 algorithm. (c) as a) but showing only IVW values above 10 $kg.m^{-2}$ and the blue crosses highlights the central axis of the Atmospheric River detected by the EIRAS2016 algorithm. In addition the location of the MDP is highlight with a red dot.

Figure 3. (a) Ratio of coincidence between the position of the cyclones for the North Atlantic basin and the presence of an Atmospheric River in a 1500 km radius. The maximum deepening point (MDP) is fixed as time-reference and results are shown for ±36 hours of the MDP. Red lines correspond to the GUAN2015 method and black lines to the EIRAS2016 method. Solid lines refer to explosive cyclogenesis (EC) and dotted lines refer to Non-Explosive events (NEC). (b) as a) but for the North Pacific basin. In addition the variance of each time step is also shown.

Figure 4. Composite of the integrated vapour transport (IVT, colours, $kg.m^{-1}.s^{-1}$) within a 1500km radius around the cyclone core of an explosive cyclogenesis (EC) cyclone for the North Atlantic basin for the period 1979-2011. The maximum deepening point (MDP) is fixed as time-reference and results are shown for ±36 hours of the MDP.

Figure 5. Same as Figure 4, but for Non-Explosive cyclogenesis (NEC).

Figures



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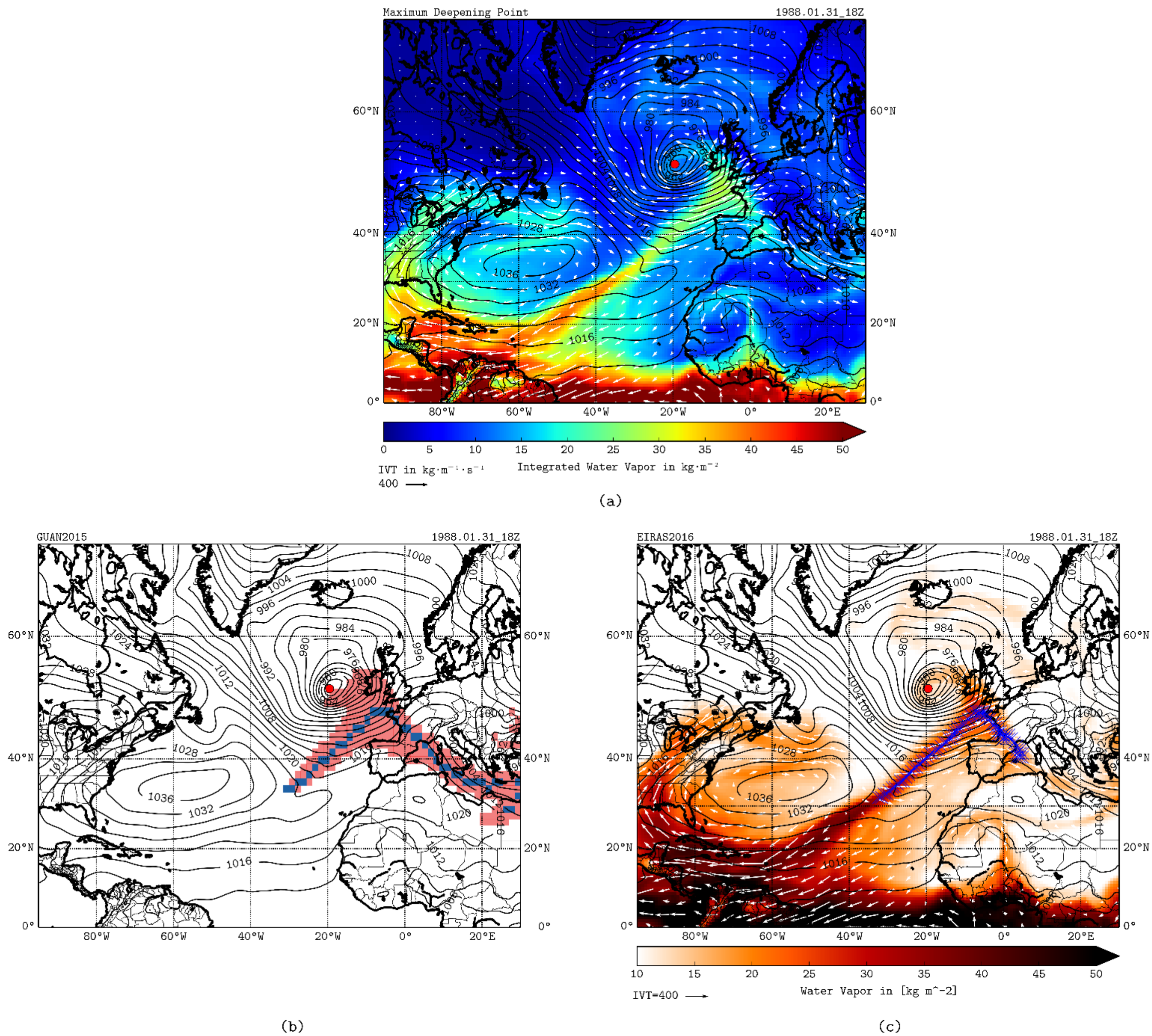

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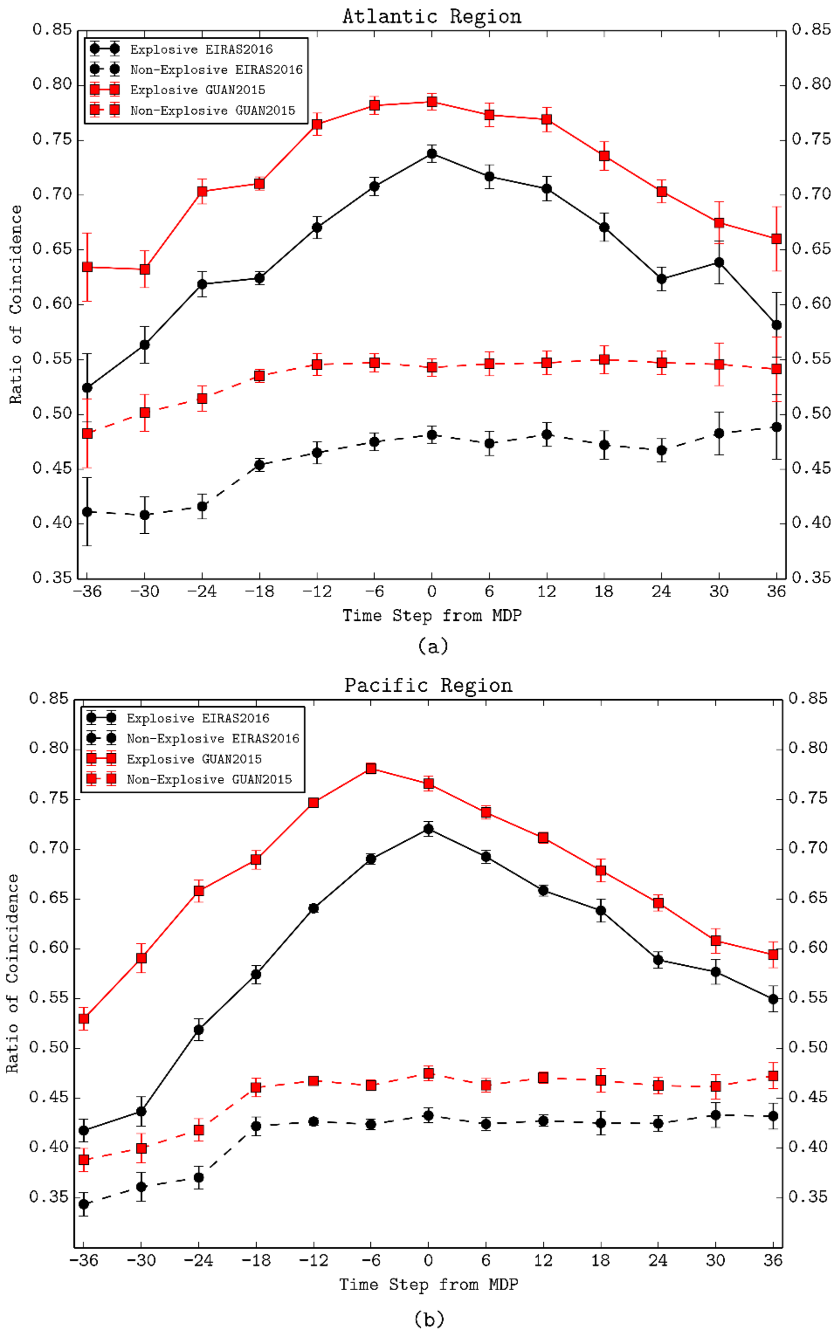

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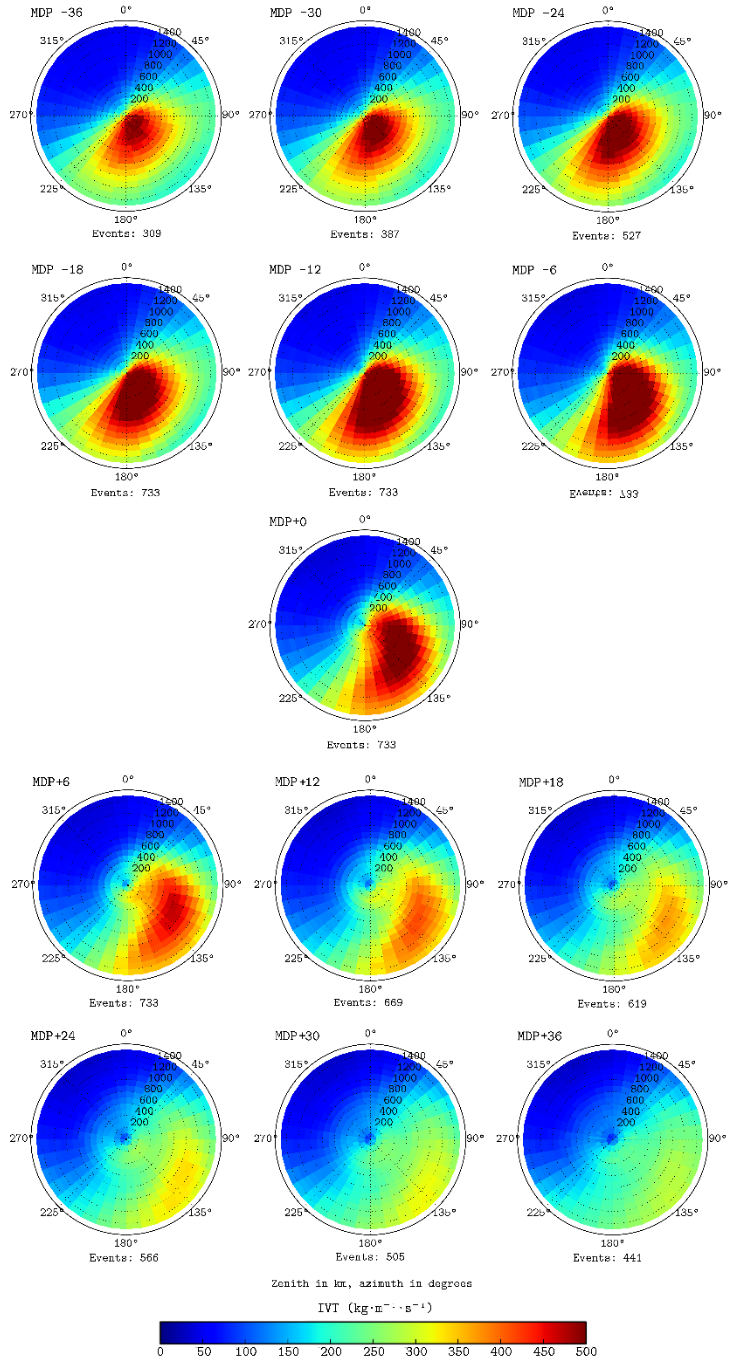

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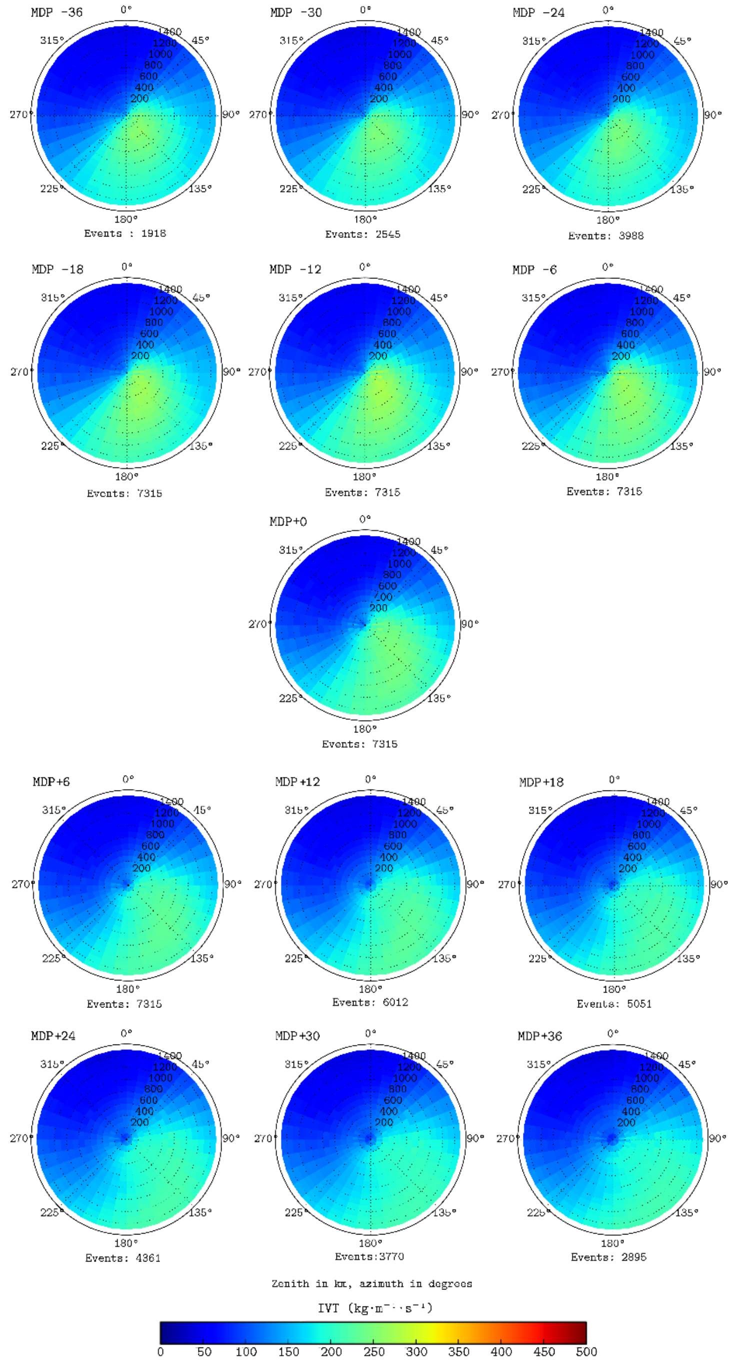

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