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On the Relationship Between Atmospheric Rivers, Weather Types and Floods in Galicia (NW Spain)

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Abstract.

Atmospheric Rivers (ARs) -long and narrow structures of anomalously high water vapor flux located in the warm sector of extratropical cyclones- have been shown to be closely related to extreme precipitation and flooding. This paper analyzes the connection between ARs and floods in the Spanish region of Galicia under different synoptic conditions represented by the so-called “weather types”, a classification of daily sea level pressure patterns obtained by means of a simple scheme that adopts the subjective procedure of Lamb. Flood events are identified from oficial reports of the Spanish Emergency Agency from 1979 to 2010. Results suggest that although most flood events in Galicia do not coincide with the presence of an overhead atmospheric river, the latter are present in the majority of severe cases, particularly in coastal areas. Flood events associated with ARs are connected to cyclonic weather types with west and southwesterly flow and occur mostly in winter months. The link between ARs and severe flooding is not so apparent in inland areas or summer months, in which cases heavy precipitation is usually not of frontal nature but convective. Nevertheless, our results show that, in general, the amount of precipitation in flood events in Galicia more than doubles when an AR is present.

1 Introduction

Atmospheric Rivers (ARs) are narrow, elongated structures that carry high quantities of water vapor in the lower troposphere. The climatological characteristics of ARs have been recently published by Guan and Waliser (2015), who showed that they exhibit a mean length of about 3700 km, and have an average integrated vapor transport (IVT) of 375 $\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$. ARs are usually found in the warm sector of extratropical cyclones, and are associated with the meridional transport of latent and sensible heat from the (sub)tropics to mid-latitudes (Newell et al., 1992; Zhu and Newell, 1998; Gimeno et al., 2010; Ralph and Dettinger, 2011; Lavers and Villarini, 2013; Matrosov, 2013; Neiman et al., 2013; Rutz et al., 2014; Gimeno et al., 2014; Garaboa-Paz et al., 2015; Gimeno et al., 2016; Waliser and Guan, 2017).

There has been a rise in the development of detection algorithms of ARs over the past few years, with significant contributions made by numerous authors (e.g. Lavers et al., 2012; Guan and Waliser, 2015; Eiras-Barca et al., 2016; Brands et al., 2016). Despite the fact that discrepancies in the finer details of their detection remain, all algorithms in the literature rely on an

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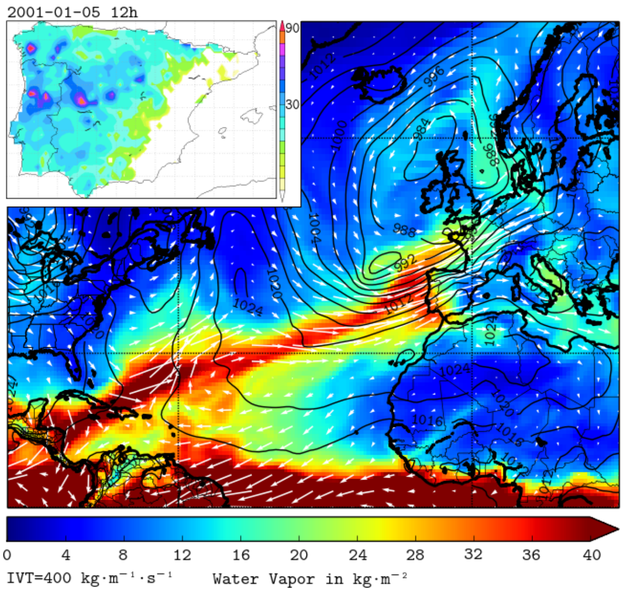

Figure 1. Example of an AR landfalling in Galicia (NW Spain). The background field is the total column of water vapor (IWV, $\mathrm{kg \cdot m^{-2}}$) and arrows represent integrated water vapor flux or integrated vapor transport (IVT, $\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$). Accumulated extreme precipitation (more than 90 mm in 24h) over the Iberian Peninsula is shown in the upper left corner.

analysis of the integrated water vapor column (IWV) and integrated vapor transport fields (IVT). ARs are always characterized by highly enhanced values of both variables when compared with surrounding areas.

A major natural disaster that humans are faced with today are flood events (FEs), and extensive socioeconomic impacts and fatalities are usually associated with flooding episodes worldwide.

The correlation and causality between ARs and extreme precipitation events has been soundly demonstrated in many parts of the world, including the Iberian Peninsula (Ramos et al., 2015; Eiras-Barca et al., 2016). Nevertheless, few studies have used flood databases to analyze how the impact of ARs is reflected in people's daily lives. In this regard, the connection between ARs and floods has been extensively shown for the West Coast of the United States of America (e.g. Ralph et al., 2006; Dettinger, 2011), as well as for some European regions (e.g. Lavers et al., 2011). An example of a well-defined AR landfalling the Iberian Peninsula coast, together with the associated extreme precipitation, can be found in Figure 1.

The region of Galicia is located in the northwestern part of Spain. The Galician climate is highly influenced by its location within the North Atlantic storm track, where a continuous passage of baroclinic structures increases the possibility of heavy rain episodes (Nieto et al., 2011). This is especially true in winter and fall, whereas in spring and summer, as the storm track moves poleward, intense precipitation associated with convective episodes plays a more prominent role (Eiras-Barca et al., 2016).

The interannual variability of rainfall in Galicia is mostly linked to certain modes of the atmosphere (e.g. Lorenzo and Taboada, 2005; Lorenzo et al., 2006, 2008, 2011), in particular the North Atlantic Oscillation (NAO), which modulates the

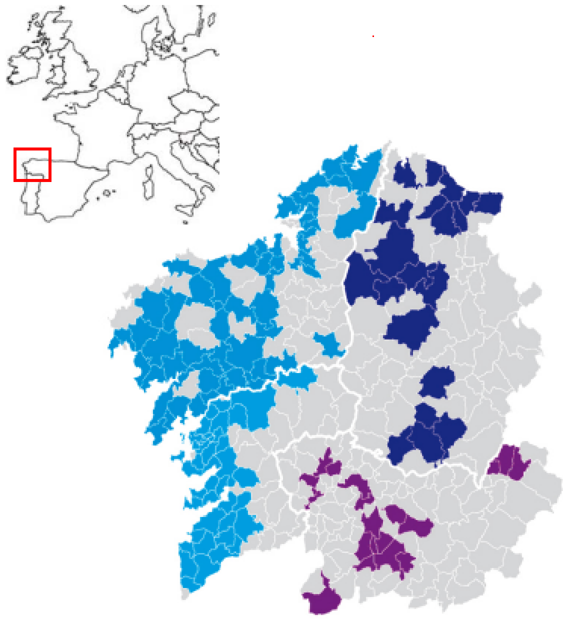

Figure 2. Municipalities of Galicia that are at risk of flooding. Source: Regional Government and Miño-Sil river authority.

position of the storm track and its impact in this region. Therefore, higher correlations that explain the variability in precipitation correspond to this index (Trigo et al., 2008). Notwithstanding, other teleconnection patterns such as the Eastern Atlantic (EA) or the Scandinavian Pattern (SCA) should also be taken into account when explaining the inter-annual variability in precipitation and AR-activity in Galicia (e.g. Bueh and Nakamura, 2007; Lorenzo et al., 2006; Ramos et al., 2015).

Extreme precipitation, anomalous winds and FEs are the most frequent climate risk in Galicia. In coastal towns, floods are more common (Figure 2) and socioeconomic impacts are maximized (Martínez and Ezpeleta, 2000). Fatalities and serious damage to transportation and communication systems are by no means abnormal when FEs occur. Because of this, a better understanding of the meteorological conditions that produce FEs is crucial for the people and economy of this Atlantic region (Cabalar-Fuentes, 2005).

One way to integrate different meteorological parameters, such as rainfall, direction and wind intensity, or temperature, into a single index is the classification of synoptic situations (i.e. weather types, WT). Using data such as the sea level pressure (SLP) or geopotential height for classification, each considered time period is assigned a WT, which allows one to study the associated meteorological variability and its consequences in different fields in a simple and easy-to-interpret way. In this paper, we will look at the occurrence of flood episodes and their related WTs in Galicia.

This study will analyze the connection between ARs and FEs under different WT synoptic situations. The scope of this paper is twofold. First, we identify the relationship between ARs and FEs under different synoptic conditions in the studied region. Next, we show that this study may be useful to properly understand and predict the damages caused by FEs. Hence, no ordinary precipitation databases have been used here, but instead we have employed a flooding events database published by the Spanish Emergency System (Protección Civil de España), where only occurrences with serious implications, in terms of damage, are considered. As the main flood database, the rainfall database has been used only to quantify the exact amount of precipitation on flooding days.

The structure of the paper is as follows: In Section 2 we present our analysis methods, while in Section 3 we outline our obtained results, and give a brief analysis. Finally, our conclusions are presented in Section 4.

2 Data and Methods

FEs were gathered from official reports published by the Spanish Emergency Service. This database registers FEs over an extended period, i.e. from 1979 and 2010 (Interior, 2014). Two different areas were separately analyzed: the Galician Coast (COSTA) and the Miño-Sil (SIL) hydrological units (river basins). Whereas the former unit encompasses all smaller Atlantic basins and is representative of coastal towns, the latter corresponds to the Miño-Sil river basin, and depicts conditions inland of Galicia.

The database published in Guan and Waliser (2015) was used in the detection of ARs. This is an advanced AR database, which is able to identify ARs by complex considerations regarding the characteristics of IWV and IVT fields in terms of coherence and continuity (Waliser and Guan, 2017). Equations 1 and 2 represent the methodology for the integration of the IWV and IVT fields, respectively, where q is the specific humidity, g is the gravitational force, and the integration covers the whole troposphere.

$$IWV = \frac{1}{g}\int_{P_0}^{P_f} q \cdot dp \qquad (1)$$

$$IVT = \left|\frac{1}{g}\int_{P_0}^{P_f} q \cdot \boldsymbol{u} \cdot dp\right| \qquad (2)$$

Only days with an AR landfalling on the Galician coast (from 41.5°N to 44°N at 9°W) have been taken into consideration in this analysis.

The classification of synoptic situations was done by adopting the procedure developed in (Trigo et al., 2000), which was adapted from Jenkinson and Collison (1977) and Jones et al. (1993). The southerly flow (SF), westerly flow (WF), total flow (TF), southerly shear vorticity (ZS), westerly shear vorticity (ZW) and total shear vorticity (Z) were computed using sea level pressure (SLP) values collected for the 16 grid points shown in the supplementary material Figure A1.

For the index calculations, we applied the equations outlined in Lorenzo et al. (2008). The conditions established to define the different WTs are those obtained from Trigo et al. (2000). For the sake of simplicity, only WTs that appear with a frequency over 3% are considered in this study. Under this condition, the total number of WTs is nine in the extended winter months

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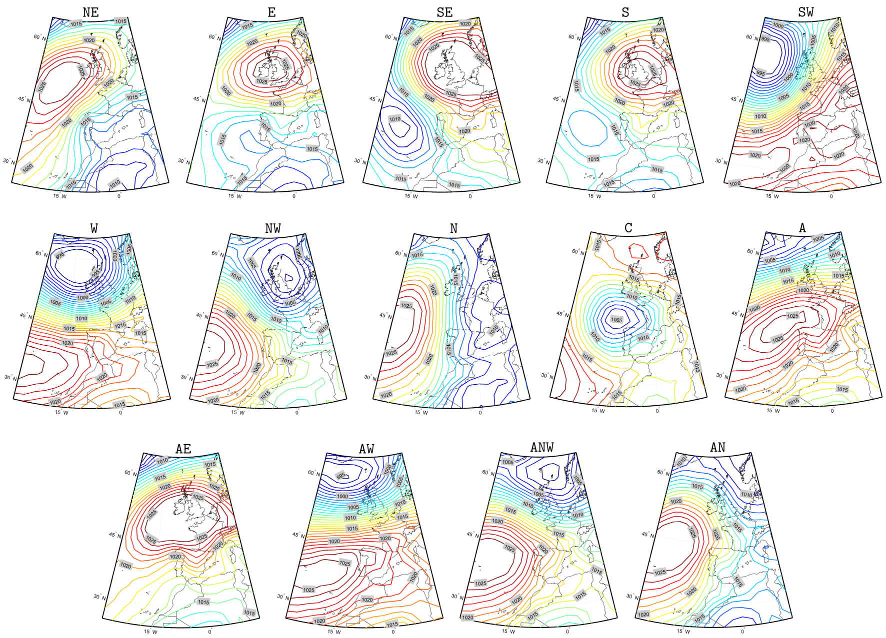

Figure 3. SLP composites for all the WTs considered in this analysis.

(ONDJFM), and 12 in the extended summer months (AMJJAS). SLP composites for each of the considered WTs are shown in Figure 3.

Finally, ECMWF Era-Interim reanalysis data (Dee et al., 2011) were used to make composites of the SLP, IVT and IWV variables on days with or without The occurrence of ARs and FEs.

3 Results

The connection between WTs and FEs has been studied via two different procedures. First, Section 3.1 refers to the aforementioned connection in terms of the corresponding WTs that they are associated with it. Then in Section 3.2, the anomaly composites for different variables show whether or not an AR is detected together with a FE. Finally, the set of meteorological stations stated in Table A3 was used to quantify the amount of precipitation that occurred throughout the FEs.

3.1 Weather Types

Figure 4 shows the frequency of occurrence for each of the winter and summer WTs during the FEs, for both (COSTA and SIL) regions. When a FE is observed in coincidence with an AR event, they are represented by a filled red bar. In contrast, when a FE was observed but no AR was detected over the cited region, the event is represented by a black lined bar. For both regions, ARs primarily correlate to FEs in winter months. FEs during summer months are mostly associated with anticyclonic

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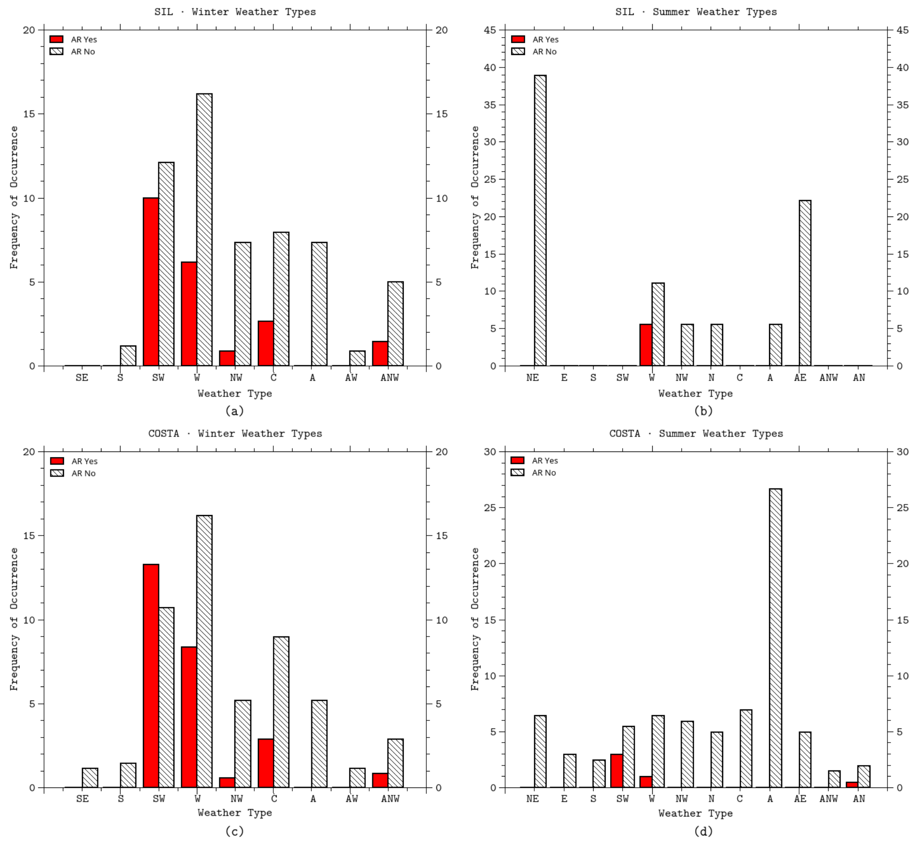

Figure 4. Frequency of occurrence for each WT with FE for the SIL region in the extended winter (ONDJFM, a) and extended summer (AMJJAS, b) months, as well as for the COSTA region in the extended winter (c) and extended summer (d) months. Red bars represent WTs associated with FEs when an AR has been simultaneously detected, while black lined bars refer to flood events without an associated AR event.

situations (NE, A, AE) that block the arrival of fronts, and thus ARs. This is in line with the convective character of extreme precipitation in the extended summer months for these regions. In winter months, however, FEs are mostly associated with WTs W, SW, C, and NW. All of them are associated with cyclonic synoptic situations or situations with humid west flux. Under these conditions, the arrival of fronts to the Galician coast is very likely. Especially remarkable is the case of the SW, which registers as many floods associated with AR events as floods associated to ordinary weather events [meaning unclear please clarify]. As Figure 3 indicates, this WT is characterized by the presence of a cyclone on the western British Isles, which enhances the arrival of fronts to the Iberian coast. The same applies, though to a lesser extent, with the W, C and NW types.

However, it is necessary to consider that periods of flooding do not always coincide with periods of extreme rainfall, since one or two days of heavy rainfall can produce floods and these can be maintained over time simply with rainfall quantities that are closer to normal amounts. Therefore, to study in more detail the relationship between floods and the presence of ARs, we have chosen the day with the highest rainfall in each flood period and looked for the presence of ARs on that specific date. Most flood events do not occur in coincidence with an AR when all days of a FE are considered. However, Table 1 indicates that for the COSTA basin, 16 out of the 23 days with the highest rainfall in the flood events (70%) took place with the presence of an AR over Galicia. In the SIL case, 7 out of 17 (41%) existed in coincidence with an AR. However, if only the extended winter is analyzed in the same database, ratios of 15 out of 19 (79%) and 7 out of 13 (54%) appear for the COSTA and SIL basins, respectively. Once again, our results point to the key role that ARs play in FEs in the COSTA. This role is diminished in the inner points, due to the more likely convective character of extreme precipitation over them.

Figure 5 shows, for each WT and each region, the precipitation ratio occurring when an AR is (or is not) detected, in the context of all the precipitation that occurred in the corresponding WT when there was flooding. In other words, this quantifies how much precipitation should be expected when a FE coincides with an AR, with respect to a FE that is not accompanied by an AR for one of the WTs considered. In general, the expected rainfall on a day with an AR within a flood period is more than double that on the same day without an AR. Especially noteworthy is the case of the NW and ANW types, for the SIL and COSTA regions, respectively, where the expected rainfall was five times larger than if the FE coincided with an AR (relative to when no AR was detected). The same occurs, although to a lesser extent, for types S, W, C and ANW for the winter precipitation in SIL, and with types SW, W, NW and C for the winter precipitation in COSTA. In the summer months, the same occurs with W types for the interior region (SIL) and AN for the coastal region. The exception is the occurrence of the SW type in the coastal region, which represents the fact that few fronts with ARs arrive to the coasts of Galicia in summer. It is uncommon to observe AR precipitation from WTs other than W or SW in the summer months.

3.2 Anomaly Maps

Figure 6 shows anomaly composites with regard to the mean sea level pressure for each point in the Atlantic Ocean, which delineates when an AR is and is not detected in Galicia, as well as when a FE is and is not detected over the same region for both the extended winter and summer months. With regard to the winter maps, and always speaking in terms of the most probable situation, for an AR to be detected on the coast of Galicia, there would have to be a convergence of a high-pressure center to the south of it, and a low-pressure center to the north. For an AR to be detected with a FE, the previously described situation would have to occur, and the low-pressure center would have to occupy a very large space over the North Atlantic. Flooding alone, with no AR presence, would occur with any similar situation to that which was described above, but both pressure centers would be weakened. On the days that neither ARs nor floods were detected, a well-developed anticyclone over the Azores was identified as influential in blocking the passage of baroclinic systems.

In the case of the summer months, the situation is similar to the winter months as far as AR detection is concerned, except with FEs that occurred concurrently with a well-developed anticyclone over the Azores islands. This peculiarity shows that floods in the summer months are not as closely related to the arrival of baroclinic structures as they are to convective precipitation, which is compatible with the idea that the Azores anticyclone forms a blockade.

Figure 7 is analogous to Figure 6, but shows anomalies in the IVT fields instead of the SLP. The results indicate that the detection of an AR is contingent on the presence of an intense IVT field over Galicia. These results are intensified when the AR

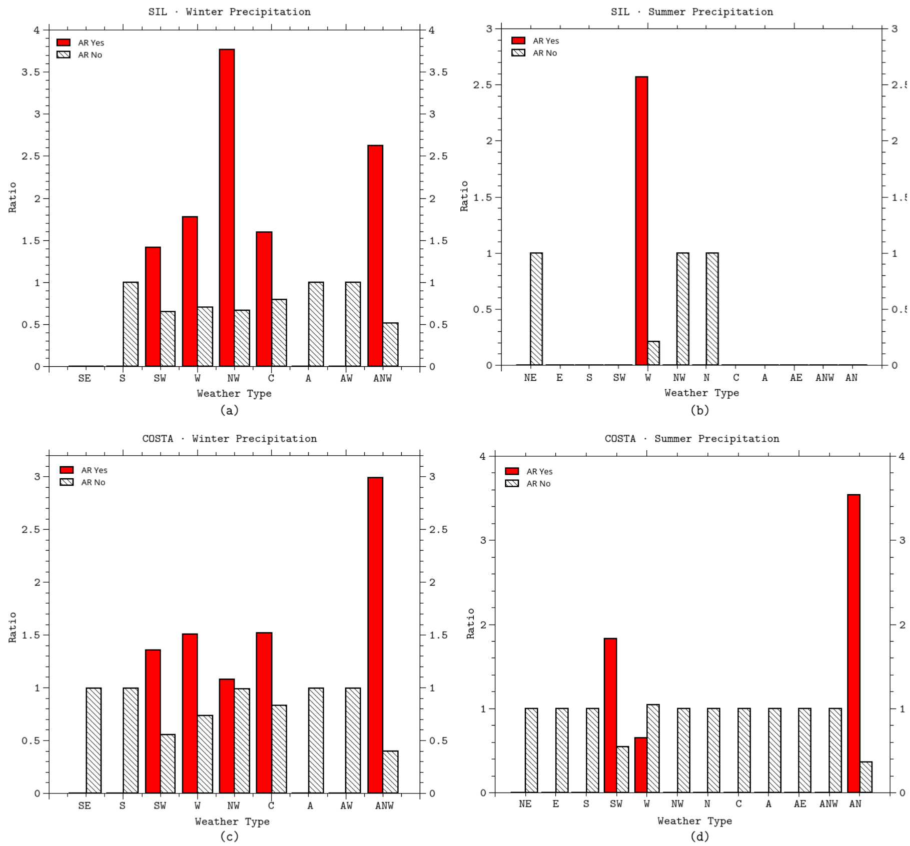

Figure 5. Frequency of occurrence for each WT with FE for the SIL region in the extended winter (ONDJFM, a) and extended summer (AMJJAS, b) months, as well as for the COSTA region in the extended winter (c) and extended summer (d) months. Red bars represent WTs associated with FE when an AR has been detected as well, while black lined bars refer to FEs not associated with an AR event.

is accompanied by a FE. In cases where no AR is detected, no intense IVT fields are observed over the study region, especially when a FE is also not detected. With respect to the summer months, no significant qualitative differences are detected in relation to the winter months.

Figure A2 is comparable to Figures 5 and 6, but the IWV field is represented. With respect to this figure, both for the summer and winter months, more pronounced IWV anomalies were observed for Galicia when an AR was detected. It is also of note that the floods were associated with disturbances of the IWV fields. These conclusions are similar to those drawn from Figure 6. The results are much less pronounced, however, since the IWV fields are much more stable than the IVT fields. Additionally, the presence of an AR implies a disturbance in the IWV fields that is much more spatially localized than in the case of IVT, and therefore the imprint it leaves on the climatic composite is much lower.

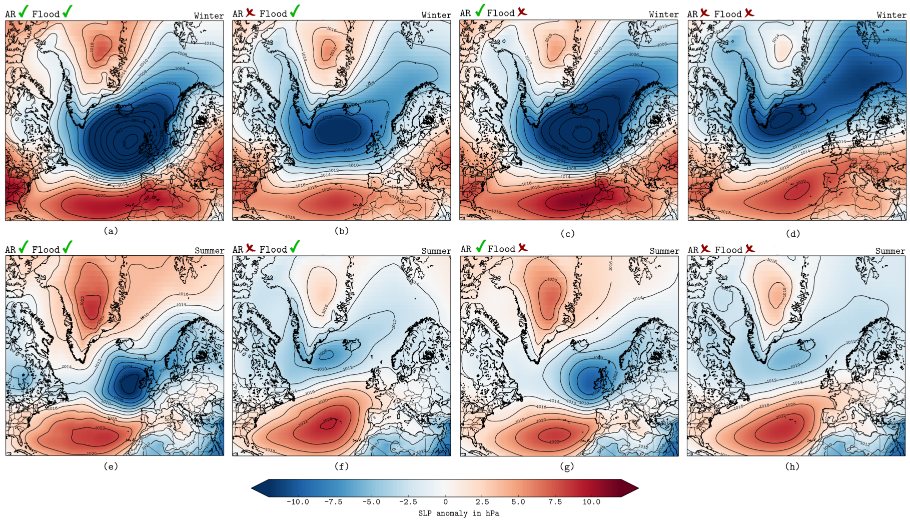

Figure 6. SLP composites for all events in the extended winter months depending on whether both AR and a FE have been detected (a), for FEs only (b), for ARs only (c) for neither (d). (e), (f), (g), (h) respectively represent the same except for the extended summer months. The background field depicts anomalies, and the isolines show mean values. The composites correspond to the period 1979-2010.

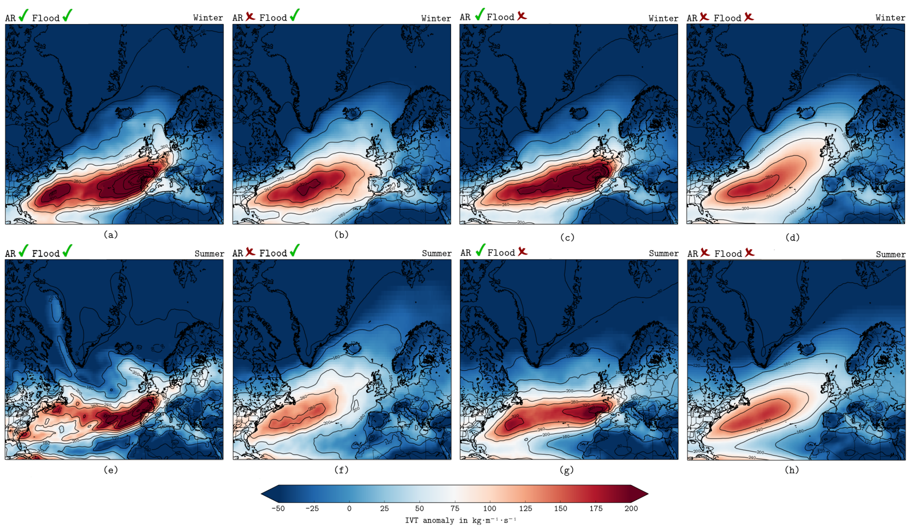

Figure 7. Same as Figure 6 but with IVT values.

4 Conclusions

The flooding episodes in the months between October and March in the coastal areas of Galicia (SW Spain) are associated with WTs of W, SW and C. These WTs are related to an inbound of baroclinic structures, Atlantic storms and atmospheric rivers to the Galicia coast. Our results support the critical role that ARs play in the intensification of flood episodes, which are present in 70% of the most important FEs in coastal areas, and provide enough moisture to increase the accumulated rainfall.

The link between ARs and FEs is not so evident in coastal areas during the summer months or for the inland basin during any season. It is likely that this is due to a more convective nature of precipitation in extreme events far from the coast, and in the extended summer months. It should be noted that most of the FEs in Galicia do not coincide with an AR, in both coastal and inland areas and in both summer and winter months. However, the expected precipitation of a FE is more than doubled if an AR is detected, under any synoptic condition.

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Appendix A: Supplementary material

Table A1. Most important flood events in terms of damage for the COSTA region.

Event	Region	Day of Max. Prec.	Amount of Prec. (mm)	AR Detection	WT
13/10/87-16/10/87	Costa	14/10/87	286.8	1	W
19/12/89-21/12/89	Costa	19/12/89	253.7	1	SW
07/09/99-09/03/99	Costa	08/03/99	253.6	1	C
20/10/00-10/01/01	Costa	06/12/00	202.8	1	SW
02/10/06-25/10/06	Costa	21/10/06	189.1	1	SW
11/11/02-31/12/02	Costa	12/11/02	185.0	0	W
13/11/09-29/12/09	Costa	05/12/09	182.1	1	SW
21/02/10-01/03/10	Costa	21/02/10	181.2	1	CNW
19/10/01-23/10/01	Costa	21/10/01	179.9	1	SW
03/10/10-09/10/10	Costa	08/10/10	160.0	0	S
21/12/95-23/01/96	Costa	23/12/95	156.9	1	W
05/01/88-05/01/88	Costa	05/01/88	145.9	1	CW
18/11/06-07/12/06	Costa	27/11/06	139.2	1	SW
19/03/01-24/03/01	Costa	20/03/01	105.2	1	CW
24/04/00-25/05/00	Costa	24/04/00	103.9	1	CW
28/10/05-02/11/05	Costa	29/10/05	103.0	1	SW
12/01/10-23/01/10	Costa	22/01/10	88.2	0	W
10/11/97-13/11/97	Costa	10/11/97	83.0	1	W
30/04/98-01/05/98	Costa	30/04/98	66.0	0	N
09/06/10-11/06/10	Costa	10/06/10	63.6	0	C
04/04/04-08/09/04	Costa	04/09/04	62.6	0	AE
06/11/94-06/11/94	Costa	06/11/94	41.7	0	CW
23/01/09-25/01/09	Costa	24/01/09	40.8	1	W
15/06/88-21/06/88	Costa	15/06/88	27.9	0	NE

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Table A2. Most important FEs in terms of damage for the MIÑO-SIL region.

Event	Region	Day of Max. Prec.	Amount of Prec. (mm)	AR Detection	WT
14/10/87-16/10/87	Miño-Sil	15/10/87	95.4	1	C
31/12/94-01/01/95	Miño-Sil	31/12/94	88.7	1	NW
12/12/89-24/12/89	Miño-Sil	16/12/89	69.2	1	WC
01/01/94-17/01/94	Miño-Sil	05/01/94	68.1	1	W
24/12/95-02/01/96	Miño-Sil	30/12/95	66.6	0	WC
01/11/96-30/11/96	Miño-Sil	22/11/96	60.2	0	W
10/01/91-12/01/91	Miño-Sil	10/01/91	58.4	1	W
14/12/99-16/12/99	Miño-Sil	14/12/99	56.8	1	NC
06/01/96-13/01/96	Miño-Sil	06/01/96	50.2	0	WC
15/06/88-21/06/88	Miño-Sil	15/06/88	46.4	0	NE
30/10/00-31/03/01	Miño-Sil	21/11/00	36.5	1	W
05/12/00-13/12/00	Miño-Sil	07/12/00	29.9	0	WC
30/04/98-04/05/98	Miño-Sil	30/04/98	26.6	0	N
01/11/02-31/12/02	Miño-Sil	20/11/02	24.7	0	SW
01/12/03-31/12/03	Miño-Sil	09/12/03	12.6	0	C
27/12/03	Miño-Sil		12.6	1	C

Table A3. Information regarding the meteorological stations.

Estation	**Province**	**Latitude**	**Longitude**	**Agency**	**Type**	**Region**
Coruña	Coruña	43°22'1"N	8°25'9.9"W	AEMET	Manual	Costa
Louriz	Pontevedra	42°24'37.8"N	8°39'46.1"W	MeteoGalicia	Automatic and Manual	Costa
Lugo	Lugo	43°0'40.0"N	7°33'17.0"W	AEMET	Manual	Miño-Sil
Orense	Orense	42°19'40.0"N	7°51'37.0"W	AEMET	Manual	Miño-Sil
Santiago	Coruña	42.87N	8.55W	AEMET	Manual	Costa

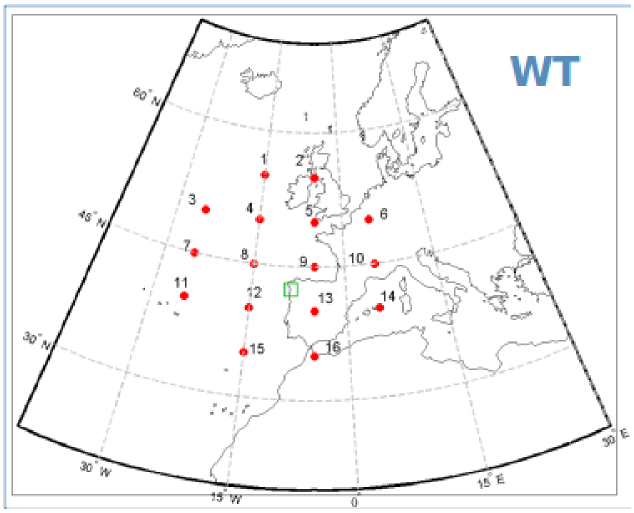

Figure A1. Pressure grid points used in the characterization of the WTs.

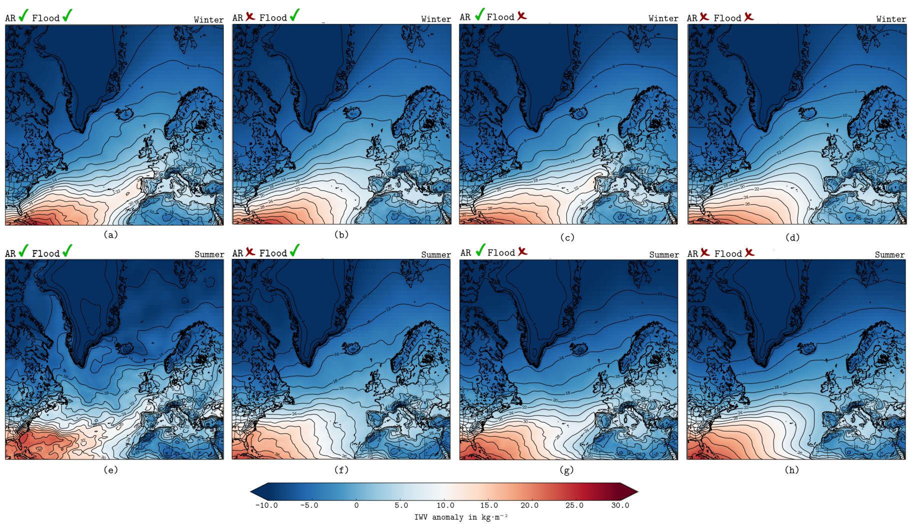

Figure A2. Same as Figures 5 and 6, but with IWV values.