

Global Distribution of the Intensity and Frequency of Hourly Precipitation and their Responses to ENSO

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Online Electrical Supplementary Information

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Supplementary Information

1. Distribution of hourly precipitation gauges

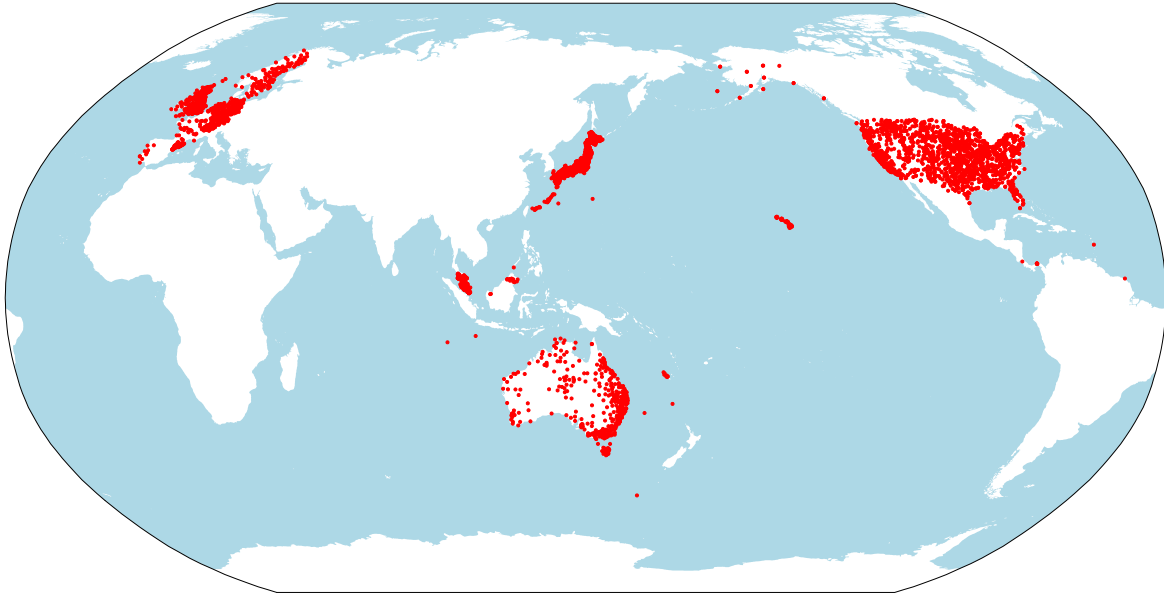


Figure S1 Spatial distribution of 4,663 hourly precipitation gauges. The gauges span the period January 1998-February 2008, containing less than 30% missing values.

2. Land-sea contrast of precipitation intensity in daily precipitation

As an example, we show the climatological mean and extreme daily precipitation intensity (DPI) in Figure S2 and S3. Comparing global distribution of intensity between daily and hourly precipitation (Figure 1 vs Figure S2, Figure 2 vs Figure S3), we can see the climatological mean and extreme DPI centers in most seasons over the mid-east part of Northern America are weaker than over tropical or sub-tropical oceanic areas, opposite to the distributions of the mean and extreme HPI (Figure 1,2). The mean and extreme DPI centers over tropical mid-west Africa and the south-east of Southern America in the mid-high latitudes are still remarkable in some seasons, but are barely distinguishable from the DPI over tropical oceans, i.e. we can not see DPI in the tropical oceans are remarkable lower than these land areas. Notably, for annual mean and extreme DPI, we do not observe the clear land-sea contrast seen in HPI (Figure 1e vs Figure S2e, Figure 2e vs Figure S3e). Actually, the spatial distribution of mean and extreme DPI is more like the accumulated precipitation total (APT) (Figure S2 VS Figure S4). This may be due to the intermittency of precipitation being better represented in hourly precipitation compared with daily or coarser resolution data. This unclear land-sea contrast in mean and extreme intensity at daily timescales is also consistent across all four seasons.

Climatological Daily Precipitation Intensity (mm day^{-1})

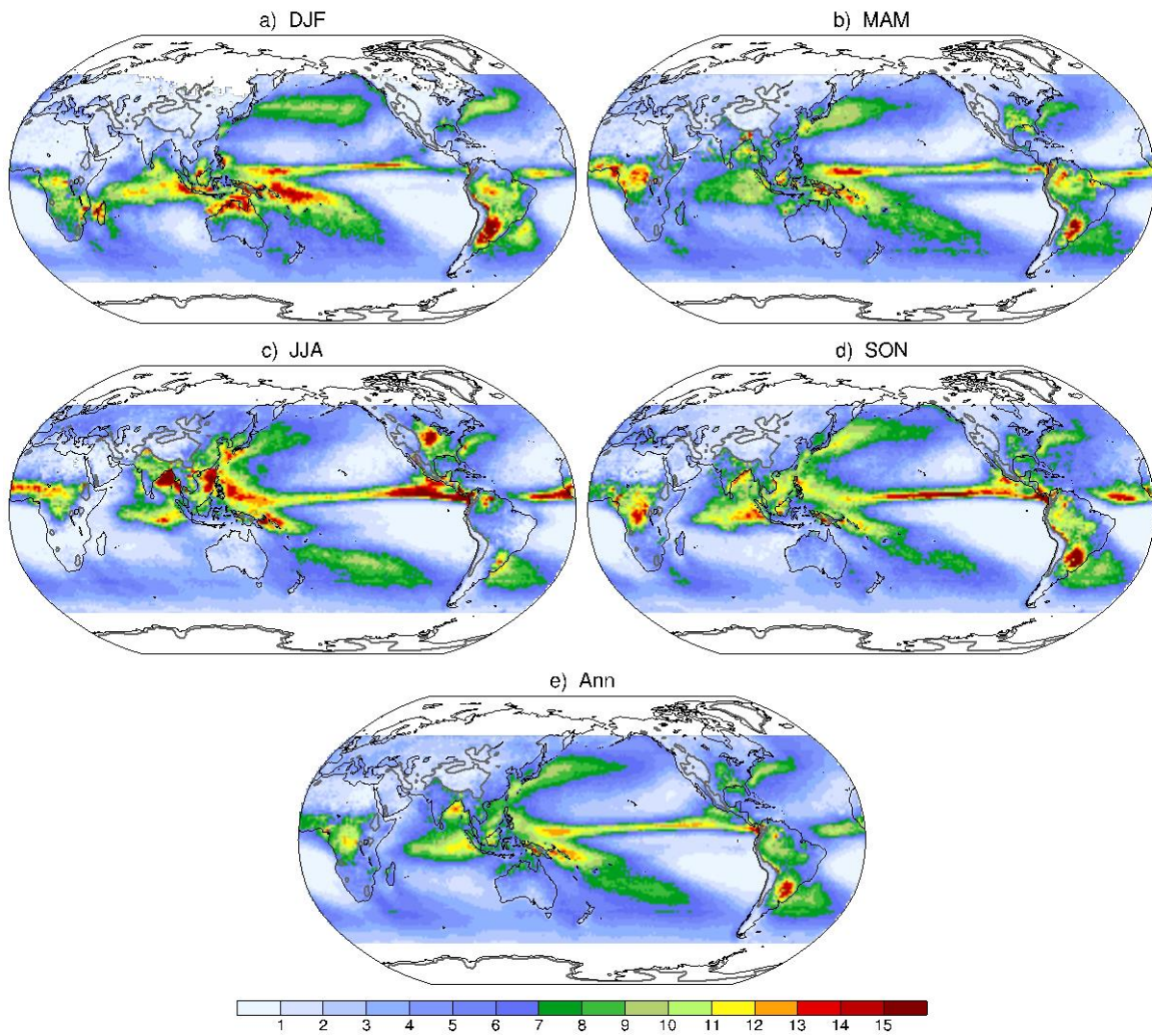


Figure S2 Climatological-averaged daily precipitation intensity (mm day^{-1}) retrieved from CMORPH daily precipitation data for the period January 1998-February 2017 for a) winter (DJF), b) spring (MAM), c) summer (JJA), d) autumn (SON), and e) the annual mean.

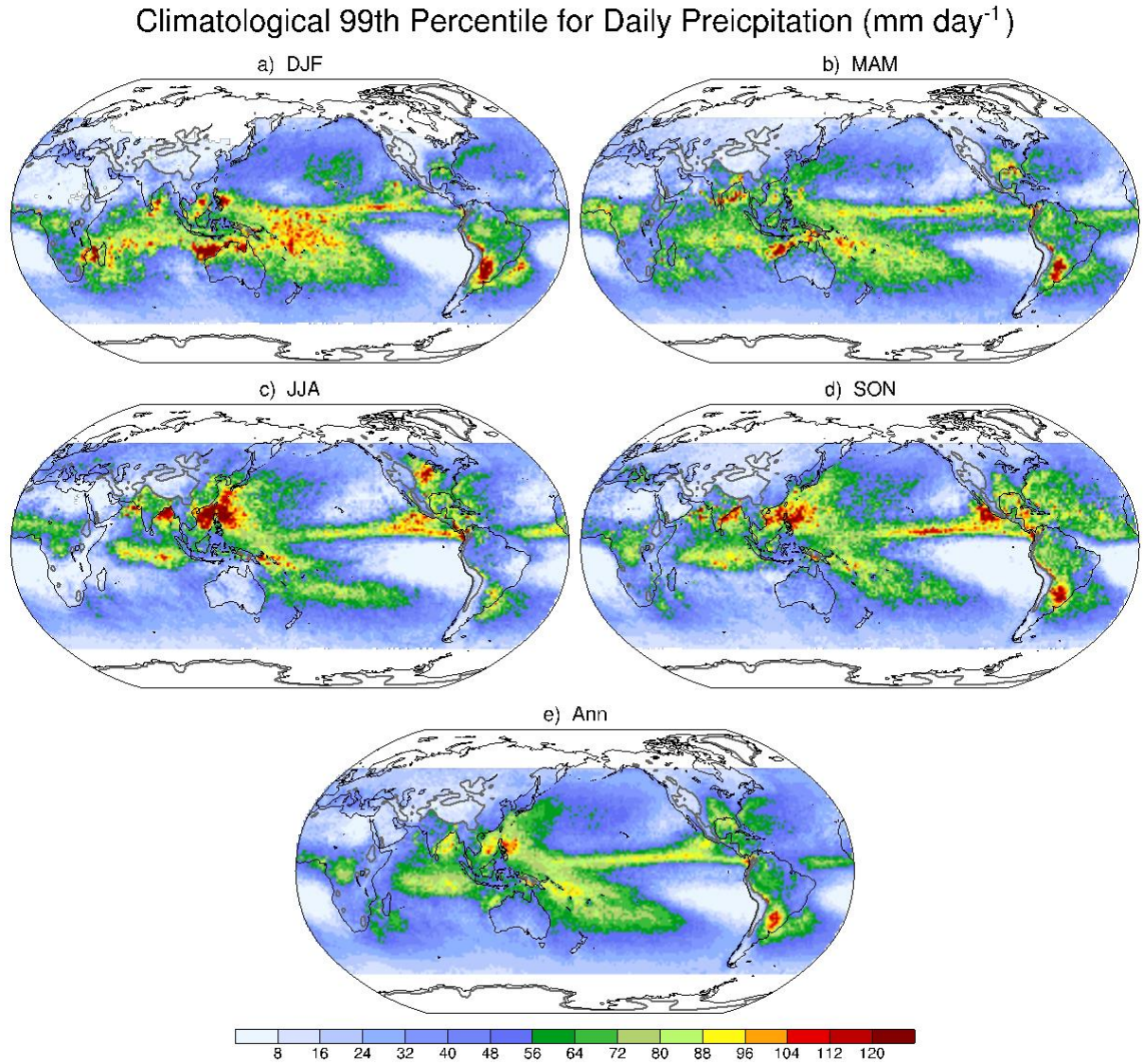


Figure S3 Climatological extreme daily precipitation intensity at 99th percentile level (mm day^{-1}) of CMORPH for January 1998-February 2017 for a) winter (DJF), b) spring (MAM), c) summer (JJA), d) autumn (SON), and e) the annual mean.

3. Climatological-averaged accumulated precipitation total (APT)

Initially, we examine the distribution of climatological-averaged APT by using CMORPH satellite data, which is a reference for the climatological-averaged HPI and NWH to be compared with later. The climatological-averaged APT of CMORPH (Figure S4, for definitions also see Section 2.3) shows that the seasonal and annual mean APT is much greater over ocean than land areas in both the tropical and mid-high latitudes. We can also see that the highest APT occurs in the tropics ($30^{\circ}\text{S}\sim 30^{\circ}\text{N}$), with lower APT in the mid-high latitudes

(60°S~30°S and 30°N~60°N). Annually, ~1040 mm (~87 mm month⁻¹) of rainfall on average falls over each square meter of the tropical region: this is equivalent to about 278 trillion tons

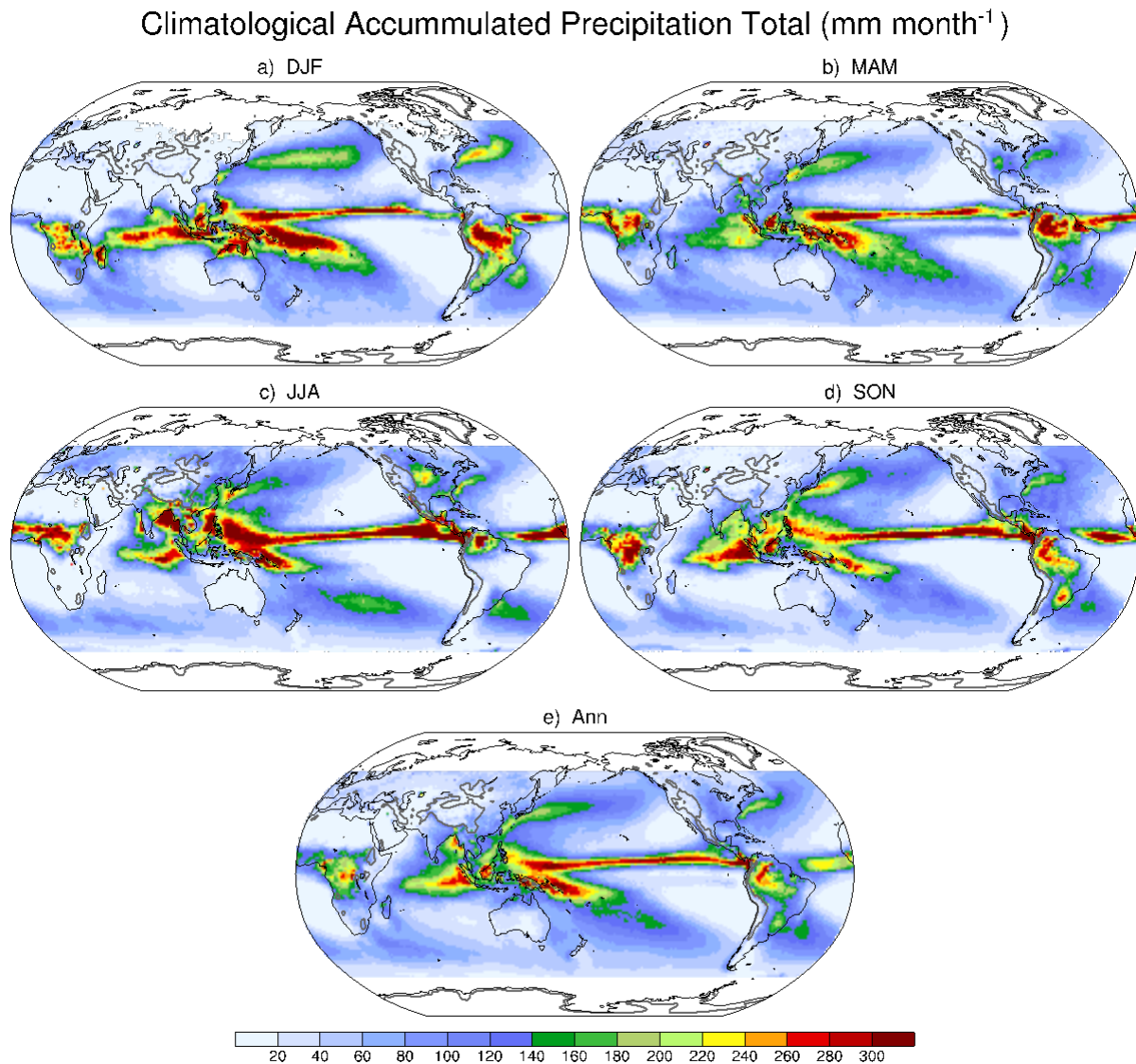


Figure S4 Climatological-averaged accumulated precipitation total (APT; mm month⁻¹) retrieved from CMORPH hourly precipitation data for the period January 1998- February 2017 for a) winter (DJF), b) spring (MAM), c) summer (JJA), d) autumn (SON), and e) the annual mean. Gray lines denote the altitude at 1,500 meters.

(2.78×10^{14} m³) of precipitation received by the tropics. This is also >2.2 times the APT received annually by the entire mid-high latitudes of the globe. In the mid-high latitudes over oceanic areas, higher APT mainly occurs in the locations where storm tracks prevail, while within the tropics, the maximum APT is mainly observed within the central locations of the Inter-Tropical Convergence Zone (ITCZ, see Waliser et al. 1993) along the equator. The seasonal north-south wandering of the ITCZ causes the north-south movements of the high rainfall centers over the

tropics. Overlapping the ITCZ, there are three high APT centers observed along the equator - the tropical Indo-Pacific warming pool, tropical Africa, and tropical South America. These three centers are coincident with the locations of three rising branches of the global Walker Circulation (e.g. Julian and Chervin 1978; Lau and Lim 1982), a string of vertical circulation cells along the equator.

In short, the climatological-averaged APT illustrates: 1) the land-sea contrast with higher APT over oceans; 2) the tropical-extratropical contrast with higher APT in tropical regions along the ITCZ; and 3) the seasonal migration of the ITCZ within the tropics across the year brings high tropical APT, overlapped by three high APT centers caused by rising branches of the Walker Circulation. These features are generally consistent with previous studies (e.g., Xie and Arkin 1996; Huffman et al. 1997; Xie and Arkin 1997; Huffman et al. 2001; Huffman et al. 2007; Kubota et al. 2007).

4. Global patterns of precipitation in responding to ENSO

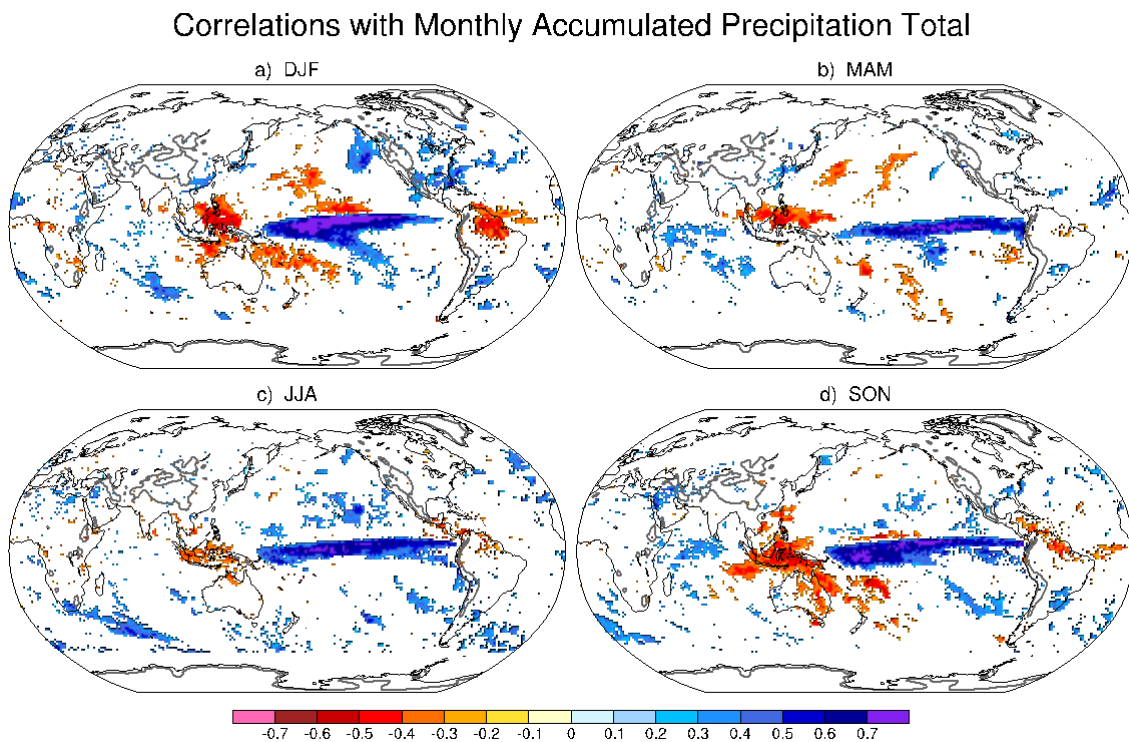


Figure S5 Pearson correlations between the Niño3.4 index and monthly accumulated precipitation total (APT) of CMORPH for the period January1998- February 2017. a) is for winter (DJF) months, b) is for spring (MAM) months, c) is for summer (JJA) months, d) is for autumn (SON) months. The colour-shading only denotes correlations significant at 0.05 level, and the sample size for each season is 57 months.

A strengthened (weakened) ENSO is usually associated with a weakened (strengthened) global Walker Circulation, which causes rainfall decreases (increases) over the rising branches of these circulations and rainfall increases (decreases) at their sinking branches. This is verified

well by the seasonal correlations between ENSO and monthly precipitation totals (Figure S5) based on CMORPH, with significant positive (negative) correlations between the Niño3.4 index and APT observed over the tropical mid-eastern Pacific (the Indo-Pacific warming pool and tropical South America). Further, the tropical rainfall response to ENSO is stronger in autumn and winter than in other seasons, as these are respectively the developing and mature stage of the ENSO life cycle.

5. Contrasting responses of the mean and extreme NWH and HPI in composites of ENSO events from NOAA

Independently, we also employ composite analysis to examine the contrasting responses of the mean or extreme NWH and HPI to ENSO variability. These responses are represented well by the composited difference between El Niño and La Niña events. The composited difference is defined as the mathematic mean of the frequency or intensity of hourly precipitation in El Niño events subtracted by La Niña events, which is tested by the student's-t test. Note that the seasonal cycle is removed before deriving the composites, i.e. the seasonal cycle of the mean or extreme NWH and HPI are removed by subtracting the 14-year-mean of them at each month during the period of 1998 and 2012. The definition of El Niño and La Niña events is derived from Oceanic Niño Index (ONI) by NOAA, as same as the definition used by Guerreiro et al. (2018): 5 consecutive months where the 3-month rolling mean of Niño3.4 anomalies (against the climatological mean for the period 1950-2000) are above (below) or equal to +0.5 (-0.5) °C (Guerreiro et al. 2018). As shown in Table S1, there are 15 El Niño months and 40 La Niña events available during the period 1998 to 2012.

Table S1 Number of ENSO events and dates used in the composite analysis.

	Number of Events	Dates
El Niño	15	01/1998 02/1998 03/1998 10/2002 11/2002 12/2002 01/2003 11/2004 12/2004 12/2006 10/2009 11/2009 12/2009 01/2010 02/2010
La Niña	40	10/1998 11/1998 12/1998 01/1999 02/1999 03/1999 04/1999 05/1999 06/1999 07/1999 08/1999 09/1999 10/1999 11/1999 12/1999 01/2000 02/2000 03/2000 04/2000 05/2000 06/2000 01/2001 11/2007 12/2007 01/2008 02/2008 03/2008 04/2008 02/2009 09/2010 10/2010 11/2010 12/2010 01/2011 02/2011 03/2011 04/2011 11/2011 12/2011 01/2012

Composited difference between ENSO's warm and cold phases (Nino-Nina)

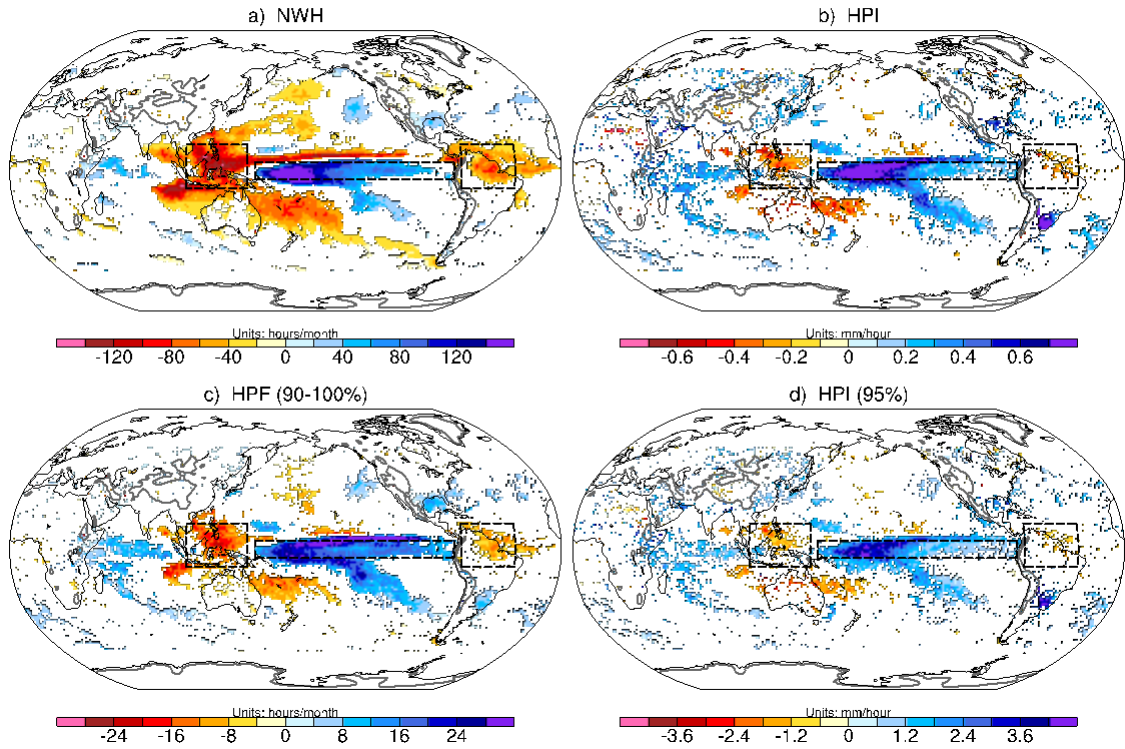


Figure S6 Composited difference of (a) monthly mean NWH (hour month⁻¹), (b) monthly mean HPI (mm hour⁻¹), (c) extreme HPF (hour month⁻¹) represented by monthly number of hours at the percentile bin of 90%-100%, and (d) extreme HPI (mm hour⁻¹) represented by the monthly 95th percentile between El Niño and La Niña events (ensemble mean in El Niño events minus that in La Niña events) in CMORPH hourly precipitation data. The colour-shading denotes composited difference significant at the 0.05 level of student t-test.

Figure S6a and b are separately the patterns of the composited difference between the El Niño and La Niña events of the NWH and HPI. These are very similar to the correlation patterns of NWH and HPI with the NINO3.4 index in Figure 5a,g and Figure 5b,h. Unsurprisingly, the signals of composited difference of the frequency is more pronounced than the intensity of both mean and extreme hourly precipitation over Tropical Western Pacific and Tropical Southern America (Figure S6a vs S6b, Figure S6c vs S6d), the rising branches of the Pacific and Atlantic Walker Circulations. Therefore, the contrasting responses to ENSO variability between mean and extreme frequency and intensity of hourly precipitation is not dependent on the method of analysis which can be represented well by both correlations and composites.

6. Contrasting responses of frequency and intensity of daily precipitation to ENSO variability

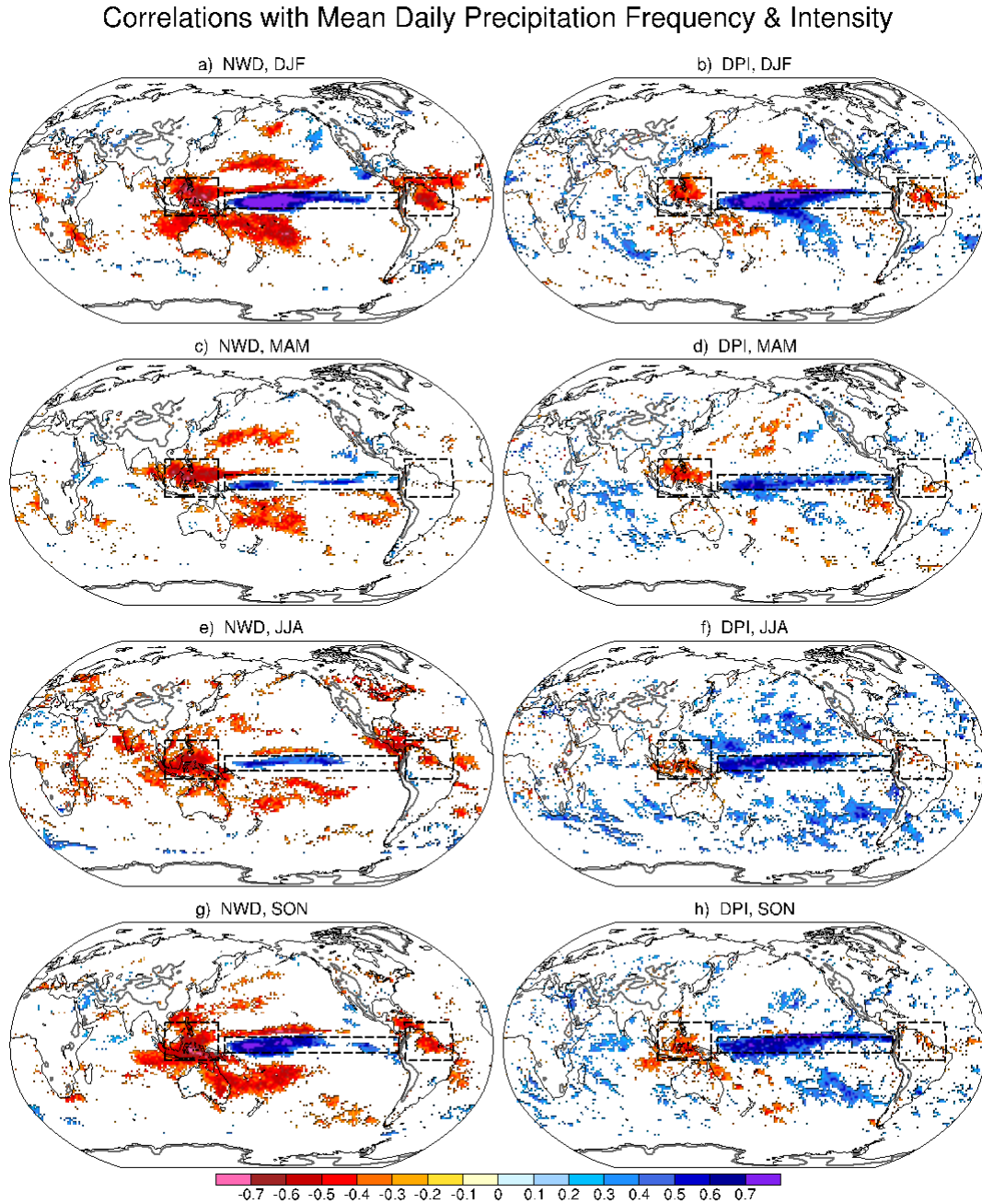


Figure S7 Pearson correlations between the Niño3.4 index and monthly mean number of wet days (NWD, day month⁻¹, left column), and monthly mean daily precipitation intensity (DPI, mm day⁻¹, right column) for the period January 1998-February 2017 in CMORPH data. a) and b) are for winter (DJF) months, c) and d) are for spring (MAM) months, e) and f) are for summer (JJA) months, g) and h) are for autumn (SON) months. The colour denotes correlations significant at the 0.05 level. The three black dashed boxes in each panel respectively represent the tropical western Pacific (TWP; 10°S~15°N, 105°E~145°E), tropical mid-eastern Pacific (TMEP; 5°S~5°N, 150°E~280°E) and tropical south America (TSA; 10°S~15°N, 285°E~320°E) domains. Same as Figure 5, but using daily data here.

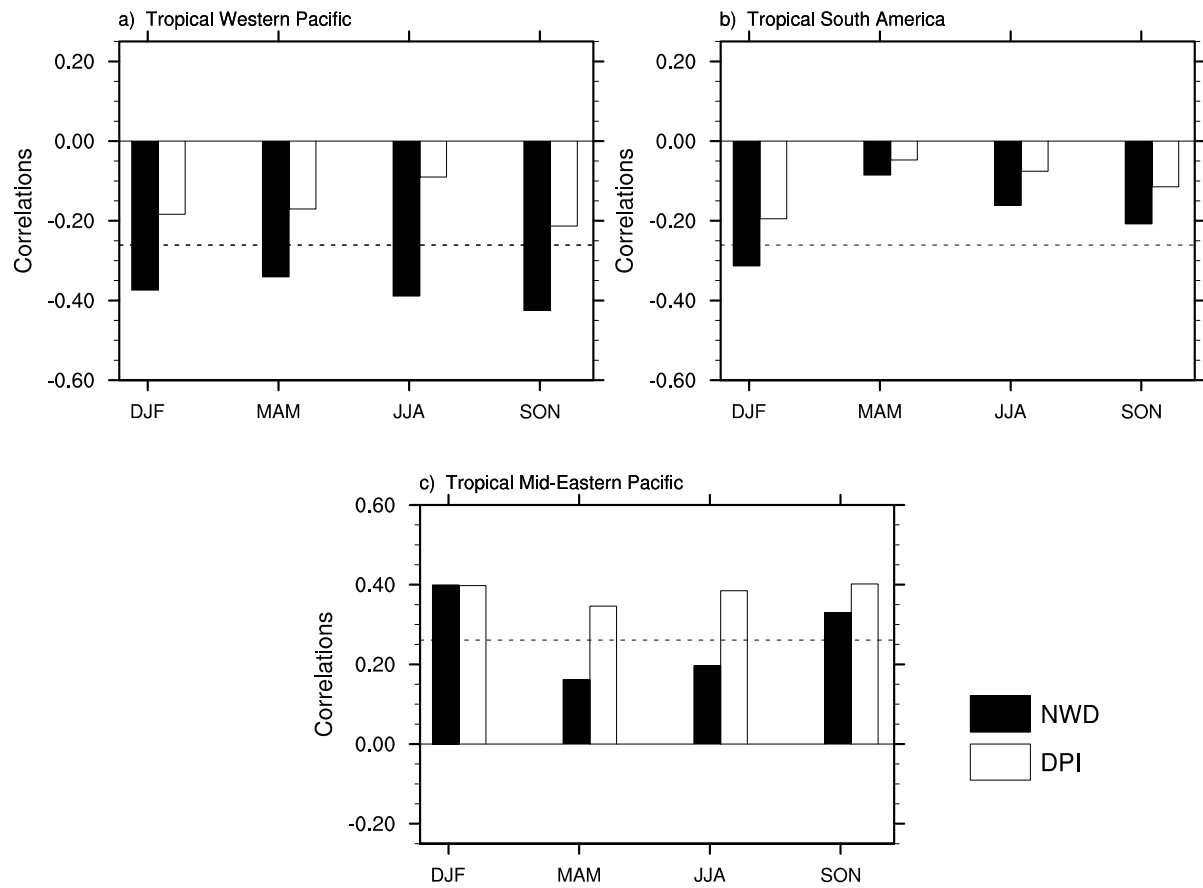


Figure S8 Average Pearson correlations between the Niño3.4 index and monthly NWD (black bar) and monthly mean DPI (white bar) for a) tropical western Pacific (TWP), b) tropical south America (TSA), and c) tropical mid-eastern Pacific (TMEP) domains for the period January 1998-February 2017 in CMORPH data. The three areas are denoted in Figure 6. The horizontal dashed line in each panel denotes the correlation value significant at the 0.05 level. Same as Figure 6, but using daily data here.

7. Spatial Distributions of the Contrasting Responses in USA, Japan and Europe in GSDR gauges

Here, we provide the results calculated by using GSDR gauge data in extra-tropical land areas (Figure S9-S14), which are generally consistent with the results over sub-regions of land areas calculated by using CMOPRH data (figures not shown). Although ENSO impacts APT mainly through its influence on NWH over these areas, we find the spatial patterns of ENSO's impacts vary in different seasons over some areas (Figure S9-S14), suggesting the complexity of the associations of hourly precipitation frequency and intensity with ENSO over extra-tropical areas.

7.1 USA

El Niño (La Niña) brings more (less) rainfall to the southern USA in autumn and winter (Figure S9), the developing and mature phases of ENSO. It is unsurprising to observe that the

correlation pattern between APT and the Niño3.4 index is highly similar to that between NWH and Niño3.4 during autumn and winter as their correlations are both above 0.8 in both seasons (Table 2). In contrast, the correlations patterns of Niño3.4 with APT and with HPI are dissimilar, as their correlations in autumn and winter are lowest - only 0.36 and 0.21 respectively (Table 2). So, in these seasons, El Niño (La Niña) brings more (less) APT to the southern USA mainly through higher (lower) NWH.

In spring, El Niño (La Niña) mainly brings more (less) APT to the western USA, however, this is due to both increases (decreases) of NWH and mean HPI, as both show significant positive correlations with Niño3.4 over this area.

In summer, the correlation patterns of NWH and APT with Niño3.4 index are not spatially coherent and are dissimilar, their correlation being only 0.69 (Table 2), the lowest of the four seasons. This indicates that in summer the impacts of ENSO on APT mediated through NWH are lowest.

7.2 Japan and Europe

ENSO's impacts on HPI over Japan and Europe are much higher relative to over the USA. This is evidenced by the higher similarities (Table 2) between the correlation patterns of Niño3.4 with HPI and APT over Japan and Europe in all four seasons.

Over Japan, ENSO's impacts on HPI is particularly strong in winter and spring. As shown in the first row of Figure S10, El Niño (La Niña) brings heavier (lighter) precipitation over most of Japan in winter, evidenced by significant positive correlations between HPI and Niño3.4. The heavier (lighter) wintertime HPI is an important contributor to higher (lower) wintertime APT over south and east Japan associated with El Niño (La Niña), apart from the contributions of NWH changes. In spring, patterns of significant correlations of Niño3.4 with APT and HPI are highly similar, in contrast to the nearly non-significant correlations between Niño3.4 and NWH, suggesting the vital role of HPI changes in ENSO's modulation of springtime APT over northern Japan. However, in summer and autumn, the significant correlations of Niño3.4 with APT and NWH are highly similar to each other, suggesting ENSO's significant influences on APT are mainly through the modulation of precipitation frequency in these two seasons.

Over Europe, the impacts of ENSO are also complicated. To provide more details, we examine data for the UK (Figure S11), northern (Figure S12), central (Figure S13) and southern (Figure S14) Europe. It is quite reasonable that ENSO impacts the APT mainly through impacts on NWH over most of sub-regions of Europe as revealed in Table 2, where we can confirm from Figures S11 - S14 that the spatial similarities of ENSO's impacts on NWH are more

similar to its impacts on APT than those on the HPI over most areas. Some clear examples to support Table 2 are autumn and winter UK, winter northern Europe and autumn central Europe.

However, for some sub-regions of Europe, ENSO has a significant impact on the HPI. For example, over southern UK in winter, summer and autumn, significant positive correlations with the Niño3.4 index are detected for all three variables, i.e. APT, NWH and HPI, demonstrating the nearly equivalent contribution of the HPI and NWH in modulating changes in the APT by ENSO variability. In addition, we find ENSO can significantly impact precipitation mainly through the impacts on HPI during the summer over west France (Figure S13) and Catalonia (Figure S14). Then, ENSO even shows significant impact on HPI that is independent of both APT and HPI over Europe, for example, it has significant impacts on only HPI over northeastern Germany in winter (Figure S13). Moreover, we also find ENSO's impacts on HPI are the opposite of its impacts on either the APT or the NWH over northern Sweden in summer and winter (Figure S12).

Therefore, ENSO generally influences the precipitation total over extra-tropical land gauges mainly by modulating NWH. But, in sub-regions of the USA, Europe and Japan, the impacts of ENSO on both HPI and NWH are important components of its modulation of the precipitation total or even independent or opposite to its impacts on either APT or NWH. The results based on the precipitation gauges are generally consistent with the major results based on CMORPH satellite data over the same areas (figures not shown), although there are biases (smaller over tropics and larger over mid-high latitudes) in CMORPH data compared with gauges.

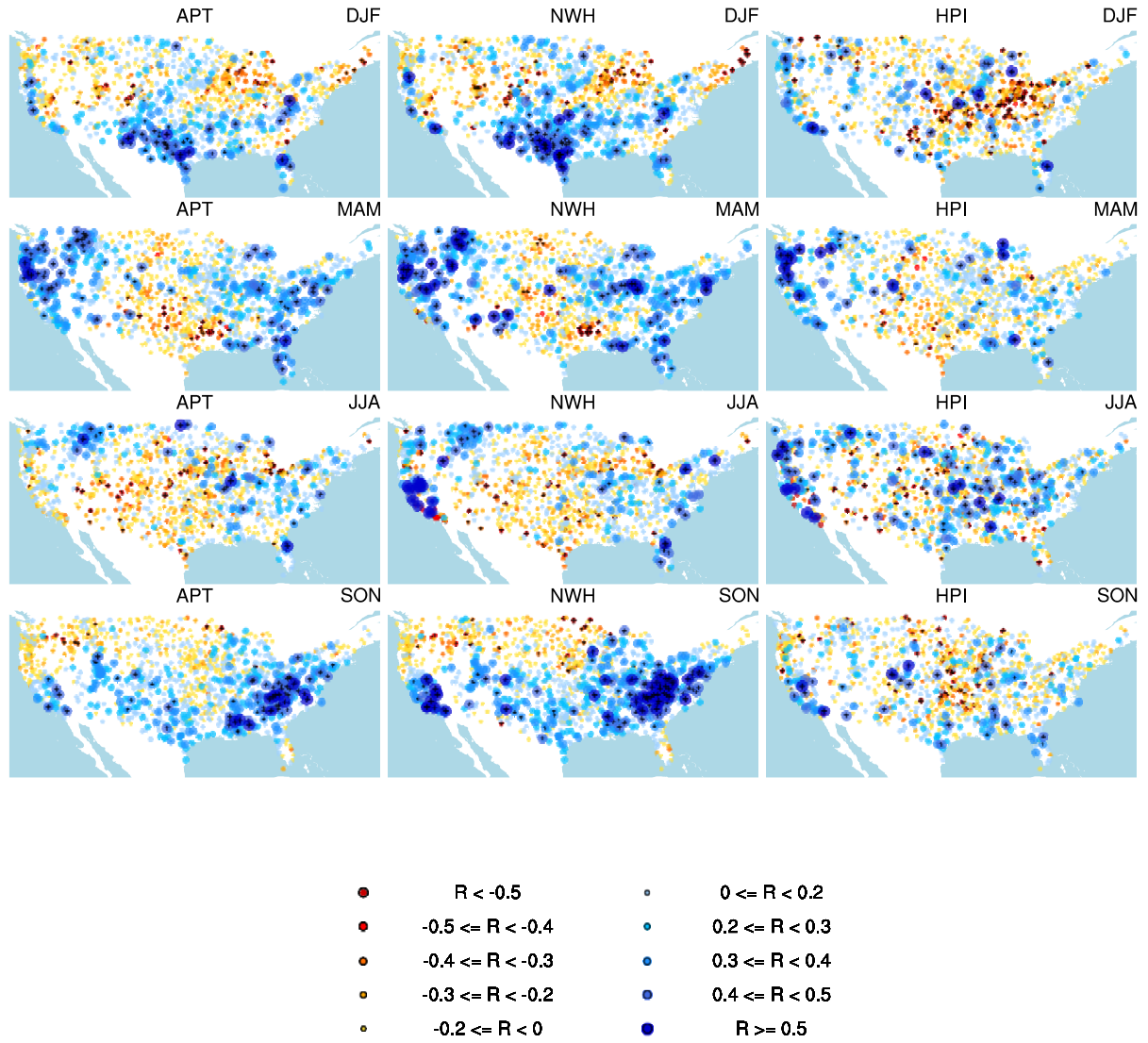


Figure S9 Pearson correlations between the Niño3.4 index and accumulated precipitation total (APT, mm month⁻¹, left column), mean number of wet hours (NWH, hour month⁻¹, middle column), and c) mean hourly precipitation intensity (HPI, mm hour⁻¹, right column) over the USA for the period January 1998-February 2008 in GSDR gauge data. Rows are results for different seasons. The black “+” symbols denote significant correlations at the 0.05 level, and the sample size for each season is 57 months, and for the annual case is 228 months.

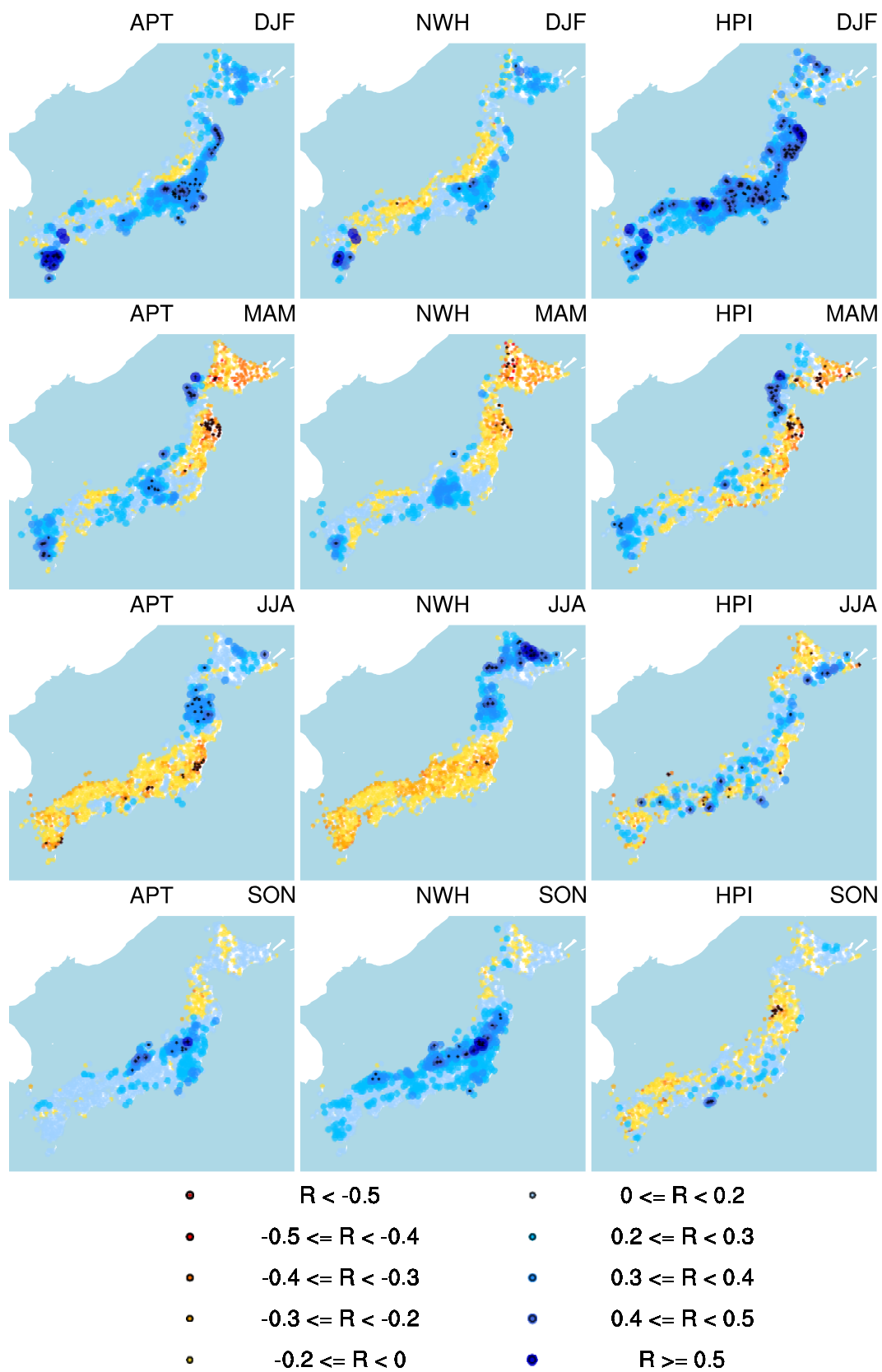


Figure S10 Same as Figure S9 but for Japan.

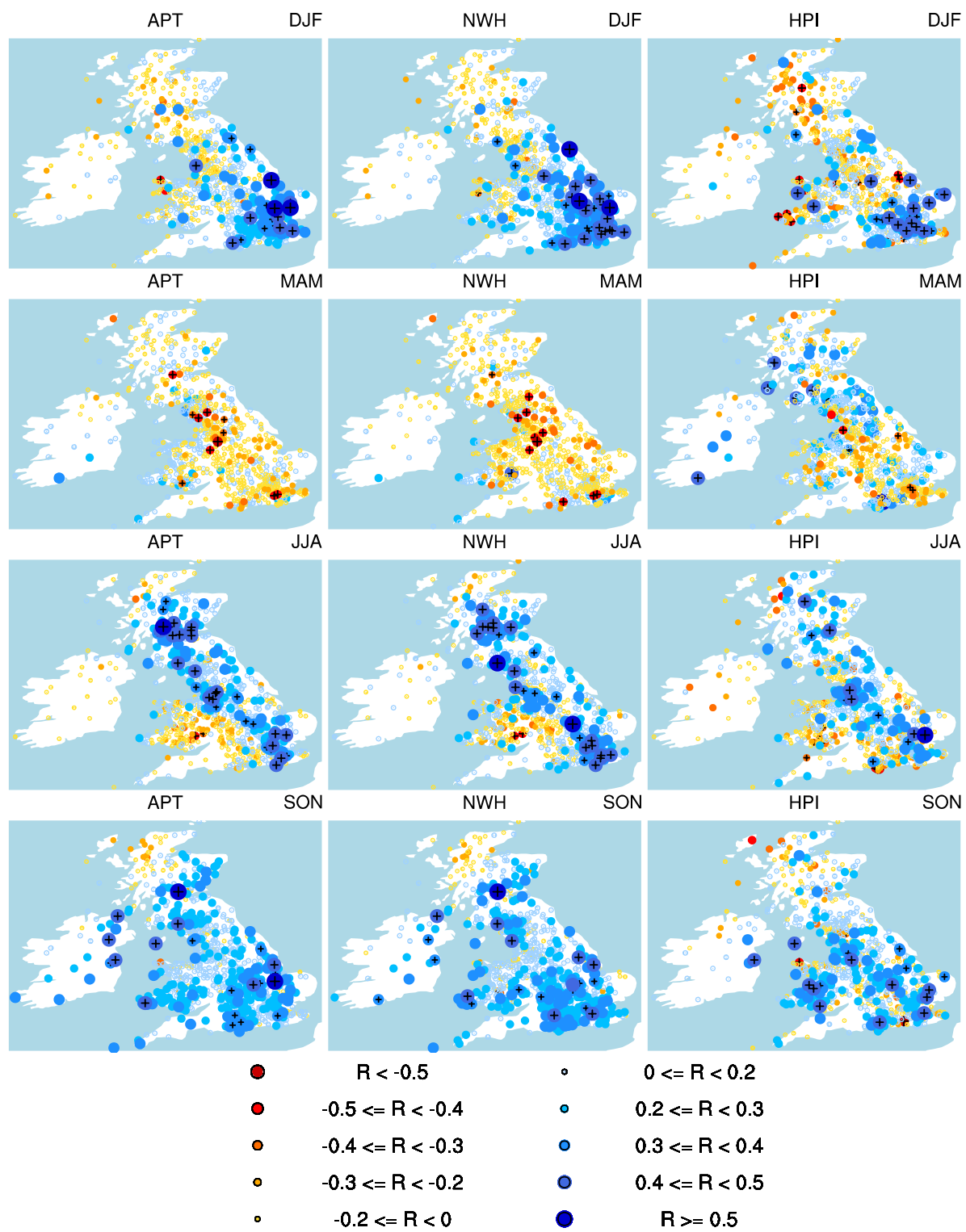


Figure S11 Same as Figure S9 but for UK.

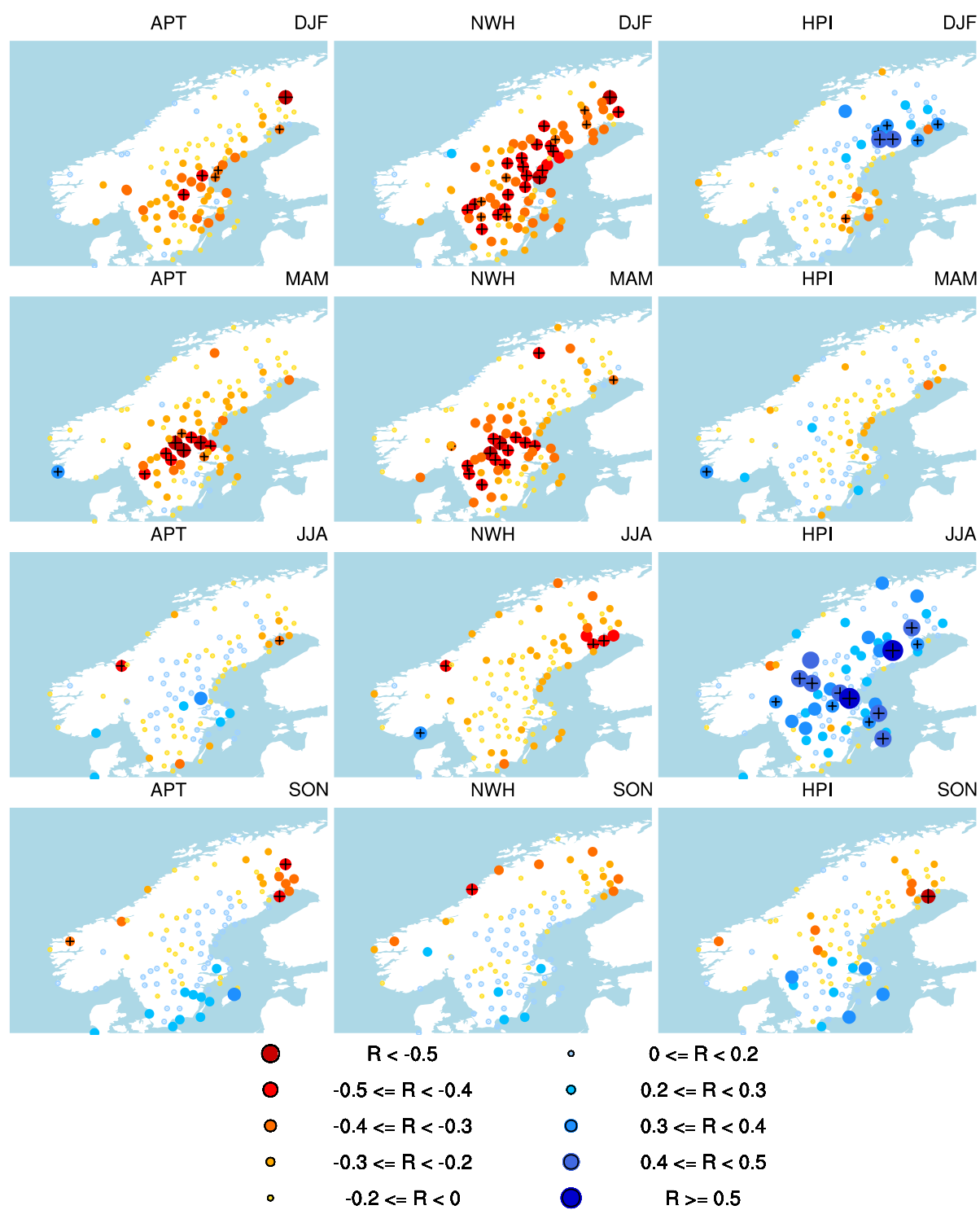


Figure S12 Same as Figure S9 but for northern Europe.

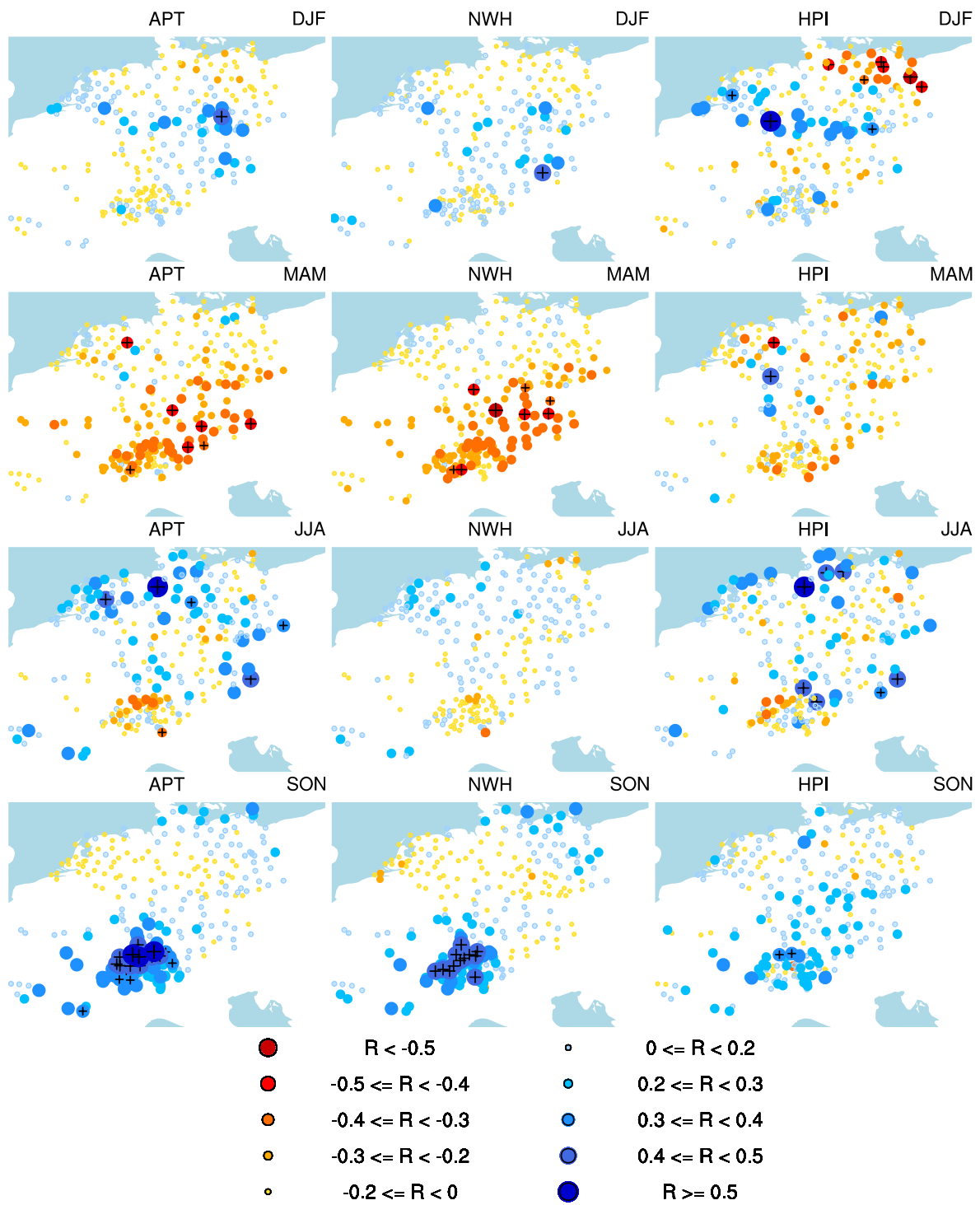


Figure S13 Same as Figure S9 but for central Europe.

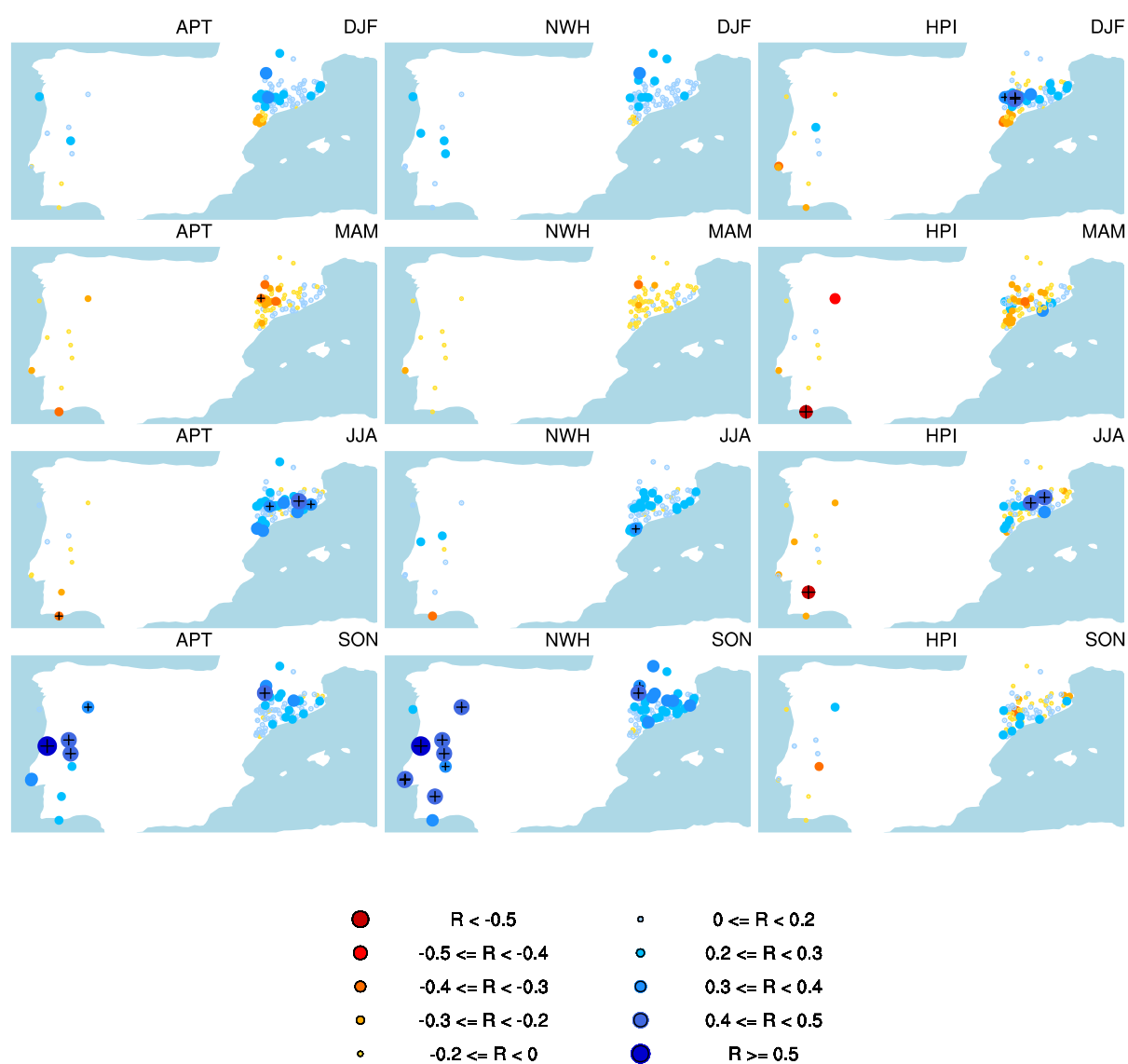


Figure S14 Same as Figure S9 but for southern Europe.