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The importance of fronts for extreme precipitation

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[1] Extratropical cyclones and their associated frontal systems are well known to be related to heavy precipitation events. Here an objective method is used to directly link extreme precipitation events with atmospheric fronts, identified using European Centre for Medium-Range Weather Forecasts Interim Reanalysis data, to quantify the importance of fronts for precipitation extremes globally. In some parts of the major midlatitude storm track regions, over 90% of precipitation extremes are associated with fronts, with slightly more events associated with warm fronts than cold fronts. On average, 51% of global precipitation extremes are associated with fronts, with 75% in the midlatitudes and 31% in the tropics. A large proportion of extreme precipitation events occur in the presence of both a cyclone and a front, but remote fronts are responsible for many of the "front-only" events. The fronts producing extreme precipitation events are found to have up to 35% stronger frontal gradients than other fronts, potentially providing some improved forecasting capabilities for extreme precipitation events.

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1. Introduction

[2] Precipitation extremes pose a major concern to society [*Easterling et al.*, 2000]. Flooding events associated with heavy precipitation can cause huge socioeconomic loss. For example, the UK summer flooding in 2007 caused three billion GBP in insured losses [*Pitt*, 2008]. Precipitation extremes are widely expected to intensify in a warming climate due to the increased moisture content in a warmer atmosphere [*Allen and Ingram*, 2002; *Trenberth et al.*, 2003; *Allan and Soden*, 2008]. Increased moisture on its own, however, does not produce extremes in precipitation. It is therefore important to understand the mechanisms and atmospheric circulation regimes responsible for such events in order to improve estimates of projected extreme rainfall changes.

[3] Extratropical cyclones and their associated frontal systems have long been known to be associated with rainfall in the midlatitudes [*Bjerknes and Solberg*, 1922]. The importance of these systems for heavy precipitation and flooding has been investigated using various case studies of individual cyclones or fronts [e.g., *Rappaport*, 2000; *Kahana et al.*, 2002; *Ulbrich et al.*, 2003]. Fronts are often related to "atmospheric rivers", which are distinct flows of moist air stretching from the subtropics into the midlatitudes. These atmospheric features also have a large impact on extreme rainfall events as shown in recent studies by *Lavers et al.* [2011] and *Ralph et al.* [2006]. Ten of the worst winter flooding events in the UK since 1970 were found to be associated with atmospheric rivers [*Lavers et al.*, 2011], and *Ralph et al.* [2006] found that the seven flooding events detected since 1997 on California's Russian River were also related to atmospheric rivers.

[4] On a regional scale, there have been estimates made of the relative importance of different synoptic situations on extreme rainfall. For example, *Kunkel et al.* [2012] found 54% of daily events with a 5 year return period over the contiguous United States to be associated with fronts. *Lima et al.* [2010] estimated that 53% of Brazil's summer daily heavy rainfall events (above the 99th percentile at at least 10 of the stations used) were associated with the incursion of cold fronts into the country. The use of different thresholds in the definition of "heavy" or "extreme" events and differences in the methodologies make it difficult to compare and contrast regional studies, and the use of meteorological station data or manual identification of synoptic systems limit their utility for other regions.

[5] In order to investigate the global importance of fronts for extreme precipitation events, it is necessary to use an objective, automated system to identify the fronts and link them with the precipitation events. Recently, *Pfahl and Wernli* [2012] investigated the relationship between cyclones and precipitation extremes on a global scale using data from reanalysis. They found that a huge proportion of precipitation extremes in the midlatitudes is associated with cyclones. *Hawcroft et al.* [2012] used a similar method to show the importance of cyclones for the total precipitation in the Northern Hemisphere. These particular studies did not, however, explicitly consider the impact of the more

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far-reaching features of extratropical weather systems, i.e., fronts. *Catto et al.* [2012] used an objective front identification algorithm [*Berry et al.*, 2011a] to investigate the importance of atmospheric fronts for total global precipitation, finding that up to 90% of total precipitation in the midlatitudes can be associated with fronts.

[6] The goal of this study is to estimate the importance of fronts for extreme precipitation events by combining the methods of *Pfahl and Wernli* [2012] and *Catto et al.* [2012] and to quantify the relative importance of the cyclones themselves and the more far-reaching fronts. While there have been many individual case and regional studies mentioned above, this is the first global study to link extreme precipitation events and fronts. The paper will be set out as follows. The front identification method and the technique used to link fronts with extreme precipitation events are outlined in section 2 along with a description of the data used and the statistical testing applied. Section 3 presents the results of the study including an evaluation of the importance of fronts for extreme precipitation events, any differences between the fronts producing extreme events versus other fronts, and the relative contribution to extreme precipitation events from fronts and cyclones. The paper concludes with a summary and discussion in section 4.

2. Data and Methods

2.1. Front Identification

[7] Fronts are identified from the European Centre for Medium Range Weather Forecasting (ECMWF) reanalysis product, ERA-Interim [*Dee et al.*, 2006], 6-hourly data using the objective methodology of *Berry et al.* [2011a]. This method is based on the work of *Hewson* [1998]. First, the thermal front parameter is calculated, defined by *Renard and Clarke* [1965] as $\mathrm{TFP}(\tau) = -\nabla|\nabla\tau|.(\nabla\tau/|\nabla\tau|)$ where τ is a scalar thermodynamic variable (here the wet bulb potential temperature on the 850 hPa level). Regions where this exceeds some predefined threshold (-8×10^{-12} $\mathrm{Km^{-2}}$) are masked. Frontal points are identified where the gradient of the thermal front parameter is zero and the frontal points are linked into contiguous fronts according to proximity. The fronts can then be split into cold, warm, and quasi-stationary fronts depending on their frontal speed and direction, and are output on a 2.5° grid.

2.2. Precipitation Data

[8] In the study of *Catto et al.* [2012], daily precipitation estimates from Global Precipitation Climatology Project (GPCP) [*Huffman et al.*, 2001] were used and linked to fronts. The relatively short period for which these data are available means that their use in studies of extremes would give very small sample sizes. For this reason, as in *Pfahl and Wernli* [2012], estimates of 6-hourly accumulated precipitation from the ERA-Interim data set are used (here for the extended period of 1979–2011). The ERA-Interim precipitation data were obtained on a 1.5° grid. Since the front information is available on a 2.5 × 2.5° grid, the precipitation data are interpolated onto this same grid. The 99th percentile of precipitation is calculated for each grid point using all available days (including zero precipitation days), and the extreme precipitation events are defined as those events exceeding the 99th percentile. For the 33 years considered, this gives 481 extreme events per grid point. The grid spacing used means that we are considering precipitation extremes which are important in terms of impact over the larger-scale. *Pfahl and Wernli* [2012] showed that in the midlatitudes, the 99th percentiles of precipitation compare well between the ERA-Interim estimates and the high-resolution gridded satellite observation-based precipitation estimates from the Climate Prediction Center Morphing method (CMORPH) data set [*Joyce et al.*, 2004]. The timing of the extreme events in the two data sets matched very well and so the ERA-Interim precipitation data were deemed to be useful for the investigation of the important synoptic features for extreme precipitation events.

2.3. Linking Fronts With Precipitation

[9] The automated method of *Catto et al.* [2012] has been used to link the identified fronts with precipitation estimates. First, the *total daily* precipitation estimates from both GPCP and ERA-Interim have been linked with fronts in order to investigate the sensitivity of the method to the different observational estimates of precipitation. The daily precipitation is associated with fronts if a front lies within a predefined search area (a 5° box around the precipitation location, which includes the precipitation grid box and the surrounding eight grid boxes). As in *Catto et al.* [2012], only regions between 60°S and 60°N are considered due to problems with the convergence of the meridians at high latitudes, and the spuriously identified fronts at the boundary of the Antarctic continent. A comparison between the proportion of annual 24 h accumulated precipitation from GPCP and ERA-Interim associated with fronts is shown in Figures 1a and 1b for the years 1997–2008. In general, the main features are very similar using the two different data sets. Figure 1c shows that there is a higher proportion of precipitation associated with fronts over Japan and the Kuroshio Current, the Arabian Peninsula, and in a band centered on 30°S from the Indian Ocean to the mid-Pacific Ocean when using the ERA-Interim data, and more precipitation associated with fronts over the British Isles and Western Europe, and over the Southern Ocean when using the GPCP data. However, these differences are mostly smaller than 10%, further confirming that the ERA-Interim precipitation can be used for the purposes of this study.

[10] Next, the sensitivity of using the 6-hourly accumulated precipitation is investigated. A similar automated method to that of *Catto et al.* [2012] is used to link the 6-hourly accumulated precipitation with the fronts. The use of 6-hourly precipitation in this study requires small modifications in the method linking the fronts with precipitation. Here the search for a front in the 5° box has been performed at two 6-hourly time points, at the beginning and the end of the precipitation accumulation period (similar to *Pfahl and Wernli* [2012]). The proportion of 6-hourly precipitation associated with fronts for the period 1979–2011, calculated using this modified method, is shown in Figure 1d and the difference between the proportion of 24 h and 6-hourly precipitation from ERA-Interim associated with fronts is shown in Figure 1e. The values are slightly lower for the 6-hourly precipitation accumulations than for the 24 h precipitation. One possible reason for this is that when using the 24 h accumulated precipitation and the fronts from four time points on the same day, some of the precipitation could have

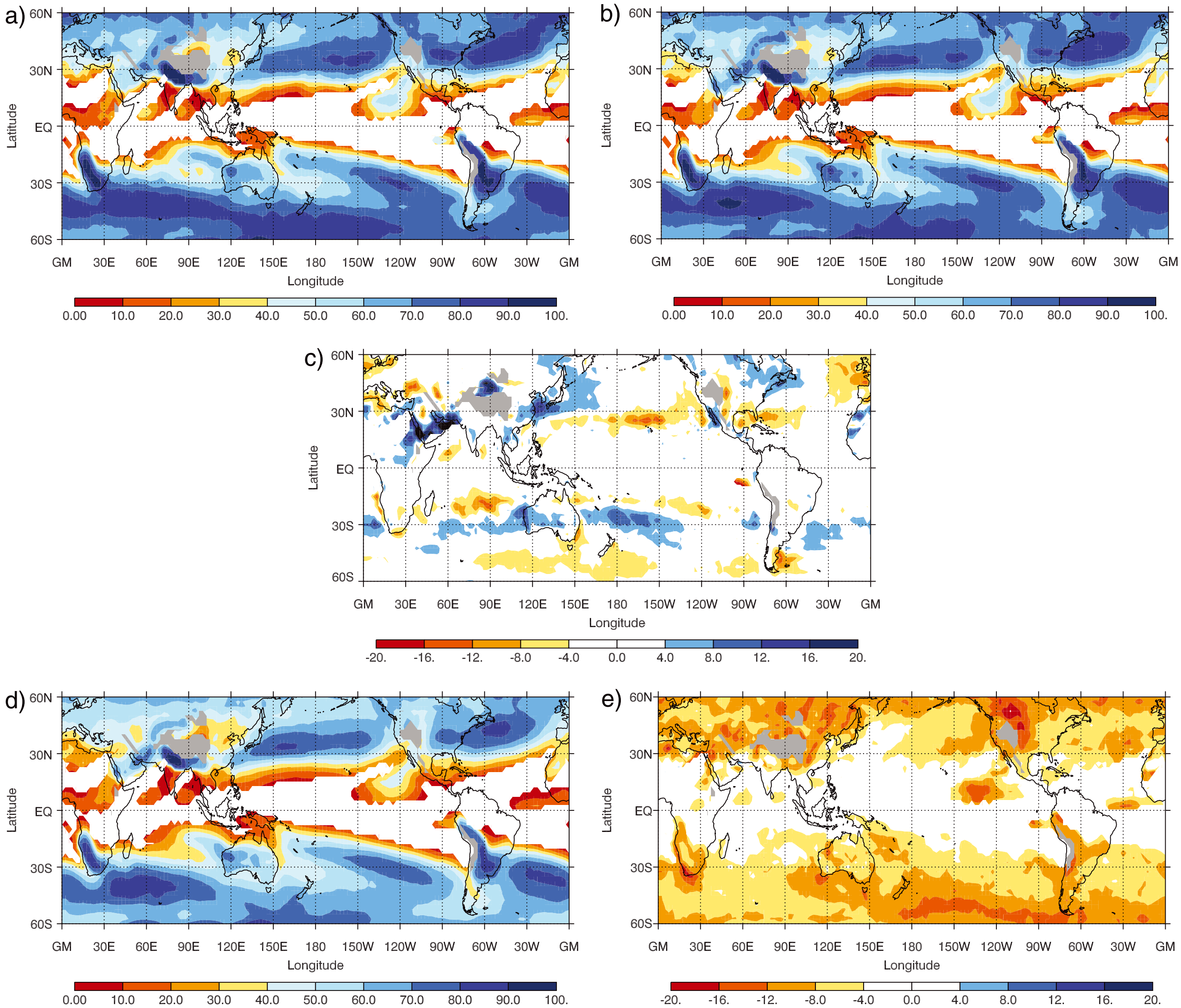

Figure 1. The proportion of precipitation associated with fronts for (a) 24 h precipitation from GPCP (1997–2008), (b) 24 h precipitation from ERA-Interim (1997–2008), and (c) the difference between ERA-Interim and GPCP. (d) The proportion of 6-hourly precipitation from ERA-Interim associated with fronts, and (e) the difference between the 24 h and 6-hourly precipitation from ERA-Interim associated with fronts. Regions where the front frequency is less than 3% are blanked out in white and high orography is blanked out in grey.

accumulated over a short period where there was no front nearby, but during the course of the day a front passed and produced more rainfall. In this case, both the nonfrontal and frontal precipitation would be allocated to a front. Using the 6-hourly precipitation accumulations reduces this type of misallocation. However, it is likely that with all automated methods such as this, where the area of influence of the front may be larger than the front itself, there could be some instances of misallocation. The important aspect of this method is the reproducibility, for example, when using different data sets or model data.

[11] When considering extreme precipitation *events* associated with the different types of fronts (i.e., cold, warm, and quasi-stationary), a method has been devised to allocate the event to one of the frontal types when there is more than one type of frontal point identified within the search area. A weighted random allocation has been performed, and the event is allocated to the front type based on this random allocation weighted by the relevant probabilities. For example, if there are three warm frontal points and one cold frontal point within the search area, the probability of the event being associated with a warm front is 0.75 and with a cold front is 0.25. This differs from the method used in *Catto et al.* [2012] in the allocation of precipitation *volumes* to the different types of fronts, where the precipitation values themselves were weighted before allocation to the appropriate fronts. This new method has been compared with the method used in *Catto et al.* [2012] and found to generate only random differences in the proportion of precipitation associated with the different types of fronts,

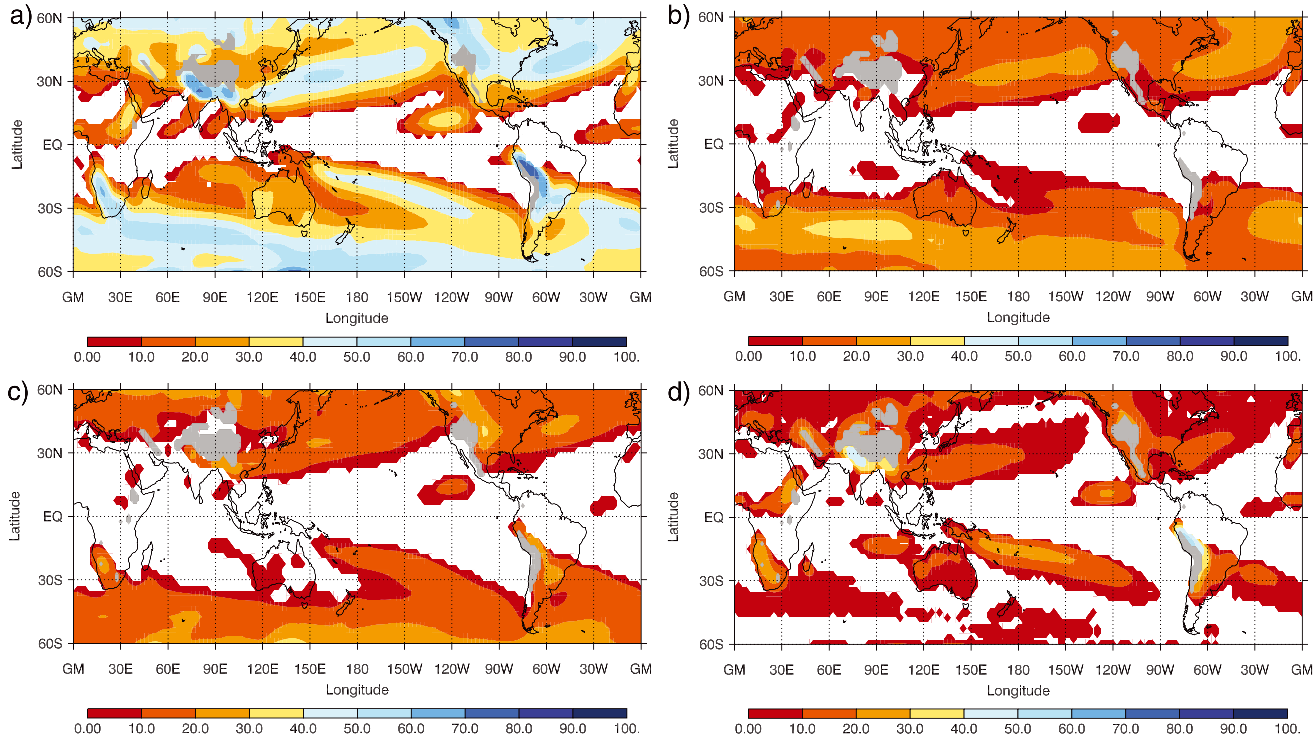

Figure 2. The proportion of 6-hourly ERA-Interim precipitation events with a front in the vicinity (1979–2011). (a) All fronts, (b) cold fronts, (c) warm fronts, and (d) quasi-stationary fronts. Regions where the front frequency is less than 3% are blanked out in white and high orography is blanked out in grey.

with no coherent pattern. This suggests that the results will be insensitive to the exact method of allocation to the different frontal types, but the new method makes physically more sense when considering a single event rather than precipitation volumes.

2.4. Statistical Testing

[12] Regions where the relationship between fronts and extreme precipitation are statistically important have been calculated using the same method as that of *Pfahl and Wernli* [2012]. At each grid point, the dates have been determined during which the point was influenced by a front (i.e., was located within a 5° box around a frontal point). The difference between the relative frequency of this frontal influence and the fraction of precipitation events associated with fronts can be used as a measure for the statistical significance of the relationship between fronts and precipitation extremes. A statistical test has been designed by comparing the occurrence of fronts at 600 selected base grid points with 1000 randomly constructed precipitation event lists each (see again *Pfahl and Wernli* [2012] for more details). The latter have been compiled by combining successive precipitation extremes from randomly selected grid points from the opposite hemisphere (with respect to the base point). In this way, the temporal autocorrelation of the precipitation events is preserved. At each base point, a statistical distribution of matches between fronts and randomly constructed precipitation events has been obtained, and the first and 99th percentiles of these distributions as functions of the frequency of frontal influence have been calculated with the help of a quantile regression method. The relationship between fronts and precipitation at an arbitrary grid point is considered to be highly significant if the proportion of precipitation extremes associated with a front lies outside of these fitted percentiles.

3. Results

3.1. Precipitation Events Related to Fronts

[13] In this study the focus is on precipitation events. Before looking at the importance of fronts for the extreme events, their importance to precipitation events contributing to total precipitation (i.e., events with 6-hourly accumulated precipitation greater than zero) is quantified. Figure 2 shows the proportion of all 6-hourly precipitation events associated with all fronts and with the different types of fronts. The pattern is very similar to that for the proportion of the precipitation amount associated with fronts (Figure 1d). The influence of fronts on precipitation events is greatest in the regions where the front frequency is highest such as over the North Atlantic and North Pacific Oceans, over the Southern Ocean and in the region of the South Pacific Convergence Zone (SPCZ). The proportion of the 6-hourly precipitation events associated with fronts is almost half of the proportion of the precipitation amount associated with fronts, with maximum values of around 50% in the midlatitudes (Figure 2a). This suggests that there are many precipitation events constituting very light precipitation that are not related to a front, for example, drizzle associated with a high pressure system. Cold fronts (Figure 2b) are responsible for a slightly larger proportion of precipitation

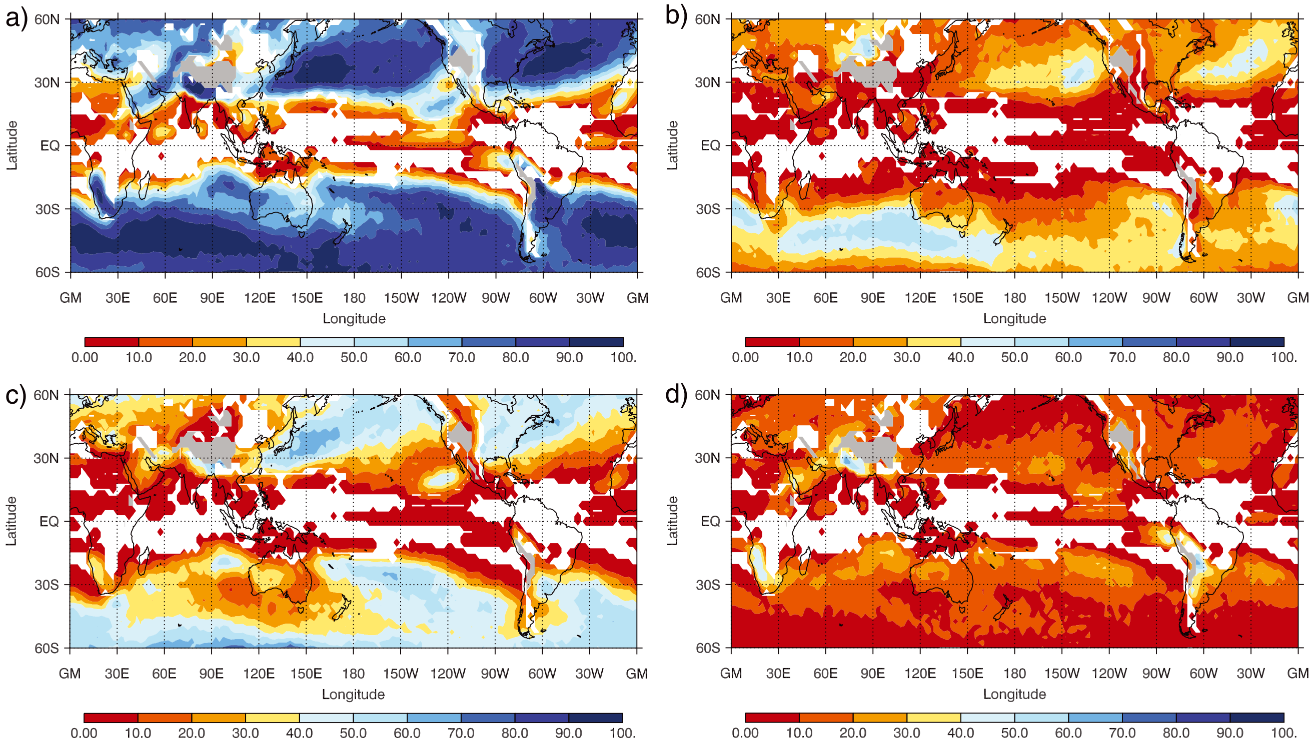

Figure 3. The proportion of 6-hourly ERA-Interim extreme precipitation events with a front in the vicinity (1979–2011). (a) All fronts, (b) cold fronts, (c) warm fronts, and (d) quasi-stationary fronts. Regions where the link between fronts and precipitation is not statistically highly significant are blanked out in white and high orography is blanked out in grey.

events than warm fronts (Figure 2c), and quasi-stationary fronts are responsible for only few events in most regions (Figure 2d).

3.2. Extreme Precipitation Events Related to Fronts

[14] Having established that quite a small proportion of all precipitation events are associated with fronts, we now quantify the relevance of fronts for the extreme precipitation events (6-hourly accumulated precipitation greater than the 99th percentile). Figure 3a shows that fronts are much more important for the extreme precipitation events than for other precipitation events. In the midlatitudes up to 90% of extreme precipitation, events are associated with fronts. The maximum values occur in the major storm track regions of the Northern and Southern Hemispheres, particularly in the west of the Pacific and Atlantic Ocean basins and over the Southern Ocean stretching eastward from South America to the south of New Zealand. There is also a large proportion of extreme events associated with fronts over the SPCZ (up to 80%) and to the northwest of Australia (60–70%; Figure 3a).

[15] Cold fronts (Figure 3b) are responsible for a relatively larger proportion of extreme events toward the east of the Northern Hemisphere ocean basins and in the Southern Ocean midlatitudes. About 40% of extreme precipitation events can be associated with cold fronts over the south of Australia. Warm fronts have a larger impact over the warm currents in the Northern Hemisphere and account for up to 60% of extreme precipitation events over the eastern seaboard of the USA. A region extending from the Indian Ocean into the northwest of Australia has up to 50% of extreme events associated with warm fronts. These warm fronts may be related to other tropical features such as tropical cyclones since *Pfahl and Wernli* [2012] also detected a relatively high frequency of cyclones in this region.

[16] The annual proportion of extreme precipitation events associated with fronts is summarized in Table 1 with the average values over different regions of the globe. Globally (between 60°S and 60°N), 51% of extreme precipitation events are associated with fronts. The difference between cold and warm fronts can be seen clearly in this table with 23% of events being associated with warm fronts, and only 17% with cold fronts and 11% with quasi-stationary fronts. A higher proportion of events are associated with fronts in the Southern Hemisphere (57%) than the Northern Hemisphere (45%), which could be associated with the

Table 1. Average Proportion of Extreme Precipitation Events Associated With Fronts (%)[a]

	All Fronts	Cold Fronts	Warm Fronts	Quasi-Stat Fronts
Global	51	17	23	11
Northern Hemisphere	45	14	20	11
Southern Hemisphere	57	20	25	11
Midlatitudes	76	28	37	12
Tropics	31	9	12	11
Land	45	13	18	15
Sea	53	18	25	10

[a] Global (60°S–60°N), Northern Hemisphere (0–60°N), Southern Hemisphere (0–60°S), Midlatitudes (30–60°N and S), Tropics (30°S–30°N), land (60°S–60°N) and sea (60°S–60°N).

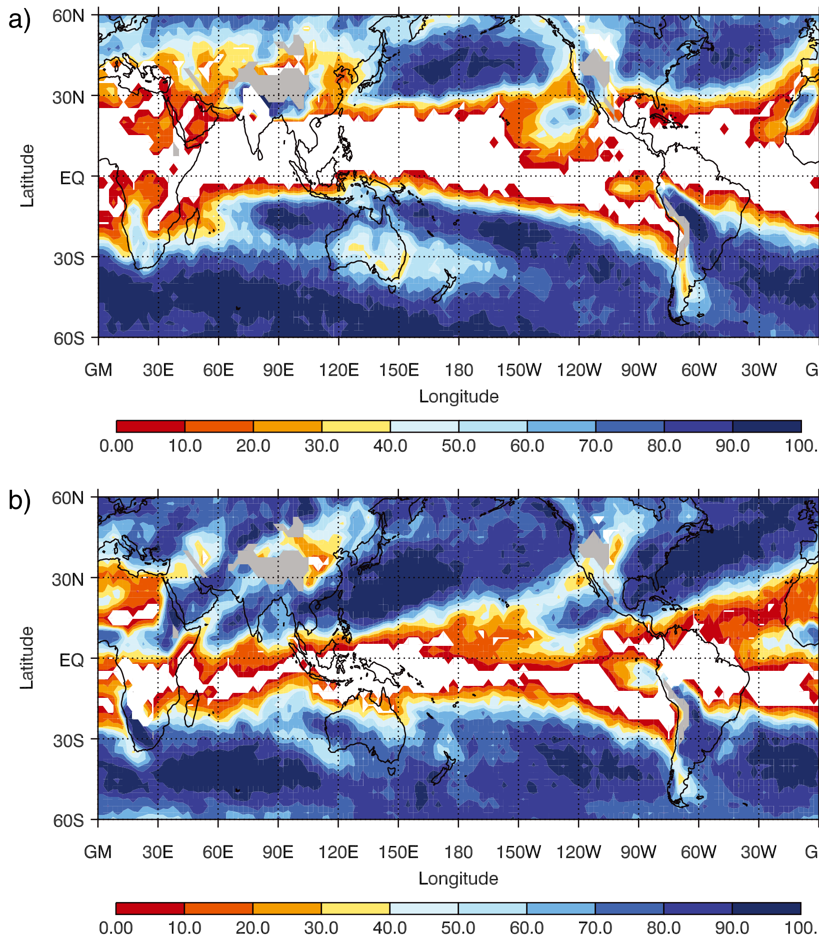

Figure 4. The proportion of 6-hourly ERA-Interim extreme precipitation events associated with fronts (1979–2011) for (a) JJA and (b) DJF. Regions where the link between fronts and precipitation is not statistically highly significant for that season are blanked out in white and high orography is blanked out in grey.

high values seen in the SPCZ region that are not reflected in the Northern Hemisphere. The ratio of warm and cold front events is approximately 0.7 or 0.8 in most regions. The midlatitudes have the highest proportion of extreme precipitation events associated with fronts at 76%, and the tropics have the lowest at 31% as expected from the frequency of fronts identified in these regions [*Catto et al.*, 2012].

[17] In order to calculate the seasonal proportions of extreme precipitation events associated with fronts, the 99th percentile of precipitation is calculated for the seasons individually. This gives only 120 extreme events per grid box per season, making the field rather noisy. The proportion of extreme precipitation events associated with fronts during June, July, and August (JJA), and December, January, and February (DJF) are shown in Figures 4a and 4b, respectively. In the Northern Hemisphere the proportion of extreme precipitation events associated with fronts is much lower in JJA than in DJF, as to be expected from the more frequent occurrence of fronts during the winter. The equatorward shift of the extratropical storm tracks during the winter means there is also a much larger proportion of extreme precipitation events affected by fronts closer to the equator in the Northern Hemisphere during DJF. The wintertime equatorward shift of the maxima can also been seen in the Southern Hemisphere in JJA (Figure 4a). In this season the SPCZ region is a more prominent feature and there are high values to the northwest of Australia. During summer (DJF), over much of the Southern Ocean, the proportion of extreme precipitation events associated with fronts is still as high as 90%, similar to JJA. This is consistent with the observations that the Southern Hemisphere storm tracks have much weaker seasonality than in the Northern Hemisphere [*Hoskins and Hodges*, 2005]. Over Australia, there is a higher proportion of extreme precipitation events associated with fronts during DJF than JJA, suggesting that fronts are a much more important factor in extreme precipitation events during the summer than winter.

3.3. Fronts Related to Extreme Precipitation Events

[18] The preceding analysis has shown that fronts are important for extreme precipitation events. But how many fronts have an influence on the extreme events? Figure 5 shows the proportion of fronts that influence extreme precipitation events. In the midlatitudes where the front frequency is highest, only about 5–10% of fronts contribute to extreme precipitation events (Figure 5a). A larger proportion of

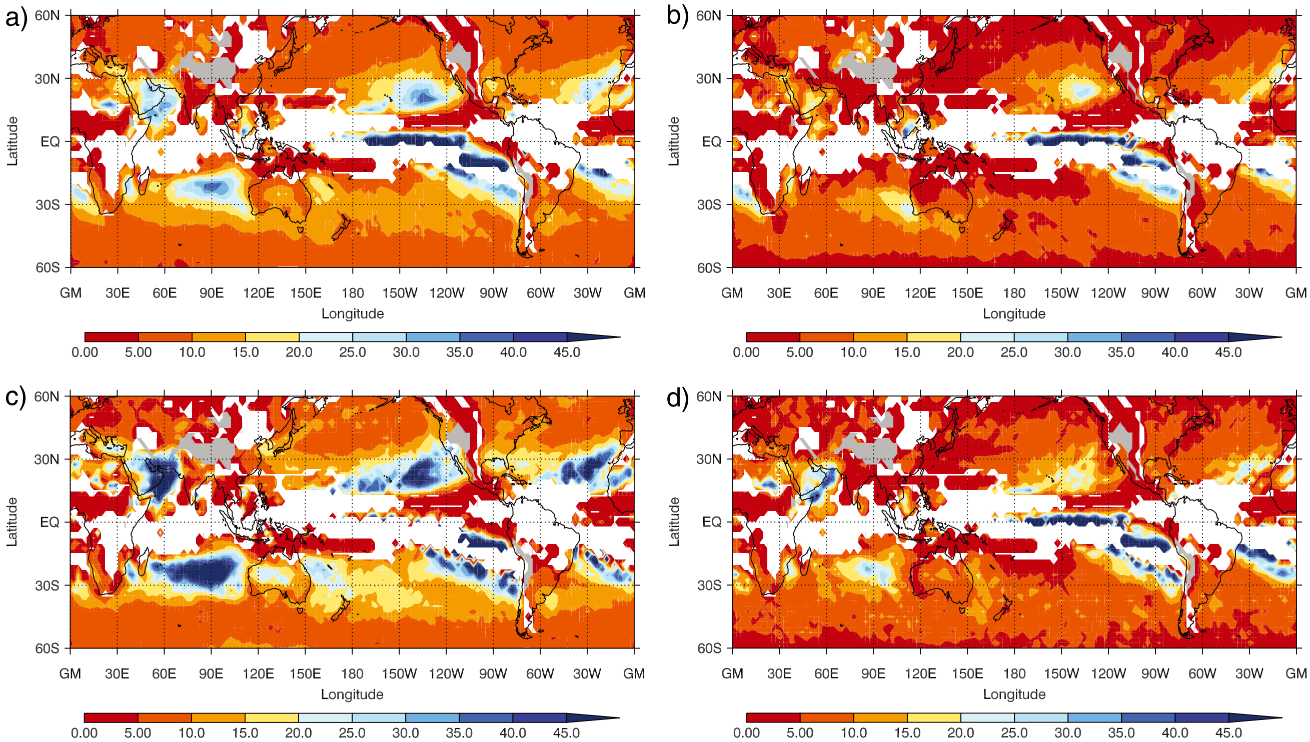

Figure 5. The proportion of fronts that lead to 6-hourly ERA-Interim extreme precipitation events (1979–2011). All fronts (a), cold fronts (b), warm fronts (c), and quasi-stationary fronts (d). Regions where the link between fronts and precipitation is not statistically highly significant are blanked out in white and high orography is blanked out in grey.

fronts contribute to extreme events in regions in the subtropics where the fronts are relatively rarer, such as in the eastern Pacific Ocean, to the west of Australia, and over the Arabian Sea. In general, a higher proportion of warm fronts (Figure 5c) contribute to extreme precipitation events than cold (Figure 5b) or quasi-stationary fronts (Figure 5d).

[19] The gradient of the wet bulb potential temperature [*Berry et al.*, 2011a] is a measure of the strength of the fronts. This has been used to investigate whether the fronts contributing to extreme precipitation events are stronger than other fronts. Figure 6 shows the difference between the average gradient of frontal points contributing to extreme precipitation events minus the average gradient of frontal points contributing to any precipitation. The fronts contributing to extreme precipitation events are up to around 35% stronger than other precipitation-producing fronts in the midlatitudes. In the cyclogenesis regions in the Northern Hemisphere such as over the Kuroshio Current and the Gulf

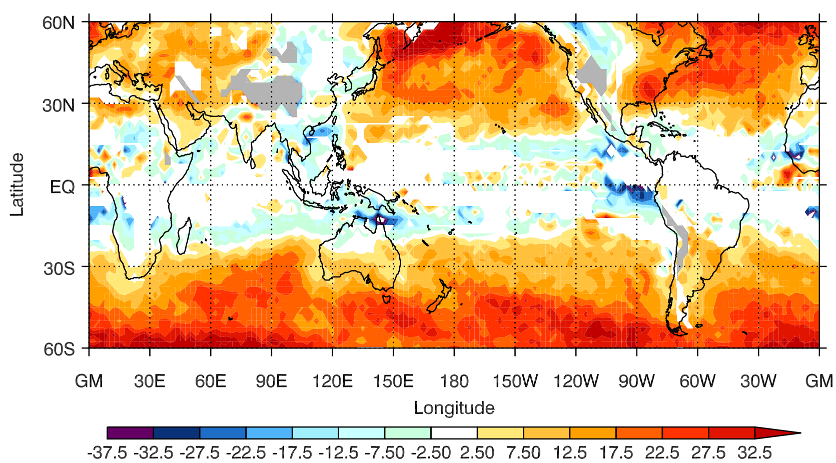

Figure 6. The percentage difference in the strength of fronts that lead to 6-hourly ERA-Interim extreme precipitation events (1979–2011) minus all other fronts associated with precipitation. Regions where the link between fronts and precipitation is not statistically highly significant are blanked out in white and high orography is blanked out in grey.

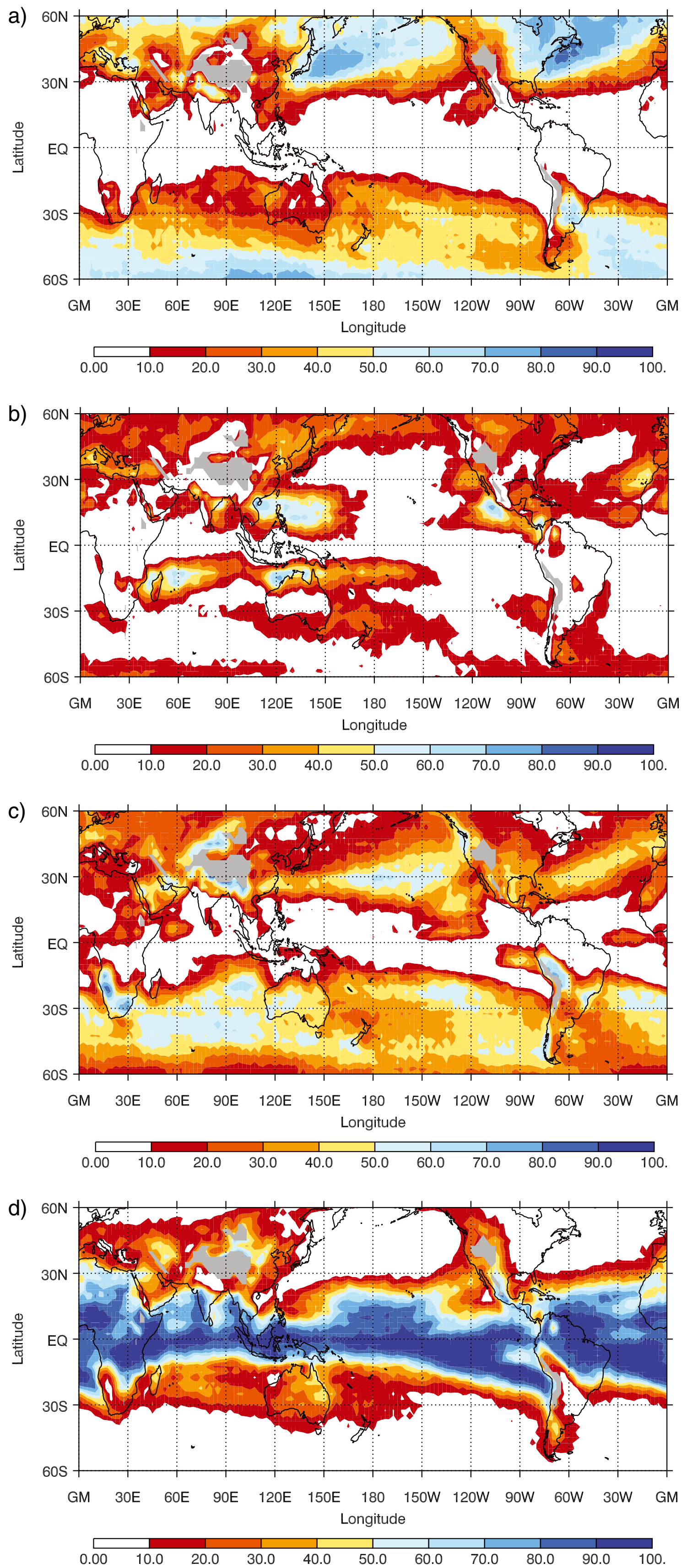

Figure 7. The proportion of 6-hourly ERA-Interim extreme precipitation EVENTS associated with (a) both a front and a cyclone, (b) only a cyclone, (c) only a front, and (d) no front or cyclone. High orography is blanked out in grey.

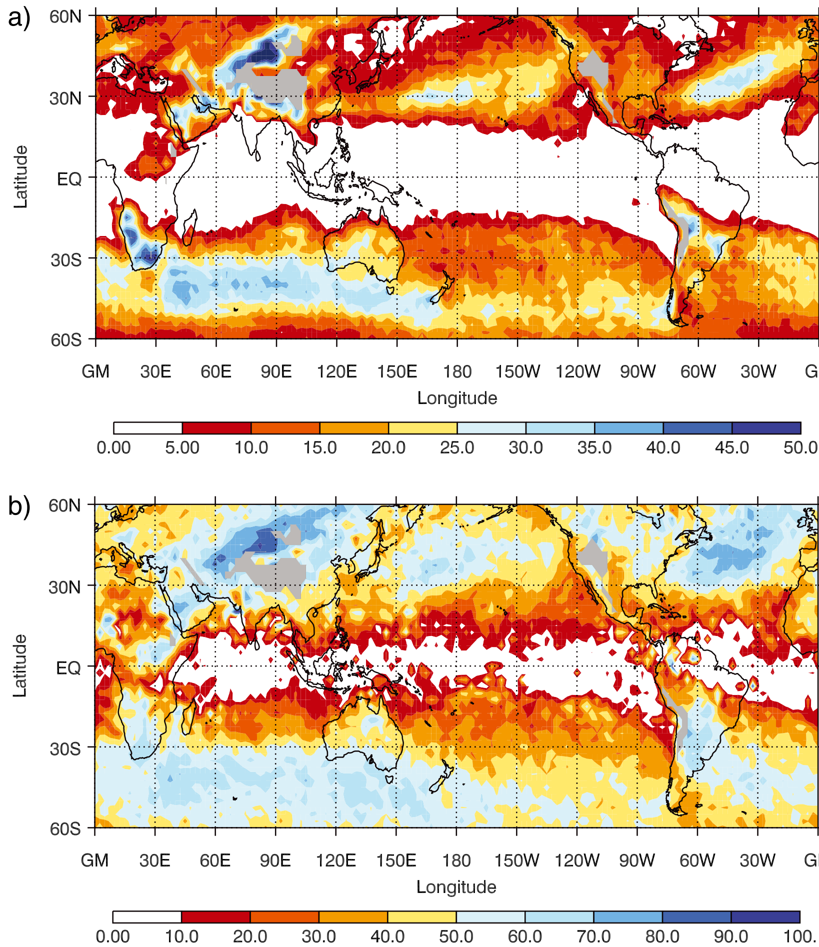

Figure 8. (a) The proportion of 6-hourly ERA-Interim extreme precipitation EVENTS associated with only fronts which are associated with a cyclone at some point along their length (remote fronts). (b)The percentage of the extreme precipitation "front only" events that are related to "remote fronts." High orography is blanked out in grey.

Stream, there are large differences in front strength. In these regions, *Pfahl and Wernli* [2012] show that the cyclones associated with extreme precipitation events do not have significantly lower central pressure than other cyclones, making the precipitation extremes difficult to forecast. Our results show that front strength may offer an opportunity to contribute to this forecasting effort. In the tropics there is very little difference between the fronts producing extreme precipitation and those not, so such opportunities are limited to the midlatitudes. When considering the percentage difference in front strength between the fronts producing extremes and any front (whether it is associated with precipitation or not), the results are very similar.

3.4. Joint Contribution From Fronts and Cyclones

[20] It is clear that fronts and cyclones are intimately related. There are likely to be times when a front lies within a region identified as being influenced by a cyclone. In particular, warm fronts typically have a huge overlap with a cyclone's closed pressure contours. The proportions of extreme precipitation events associated with fronts and with cyclones (shown in *Pfahl and Wernli* [2012]) are quite similar, but are there regions that are only impacted by either one type of feature or the other, or do cyclones and fronts always act together to produce extreme precipitation events? To attempt to answer these questions, the identified cyclone database from *Pfahl and Wernli* [2012] and the fronts from the present study have been combined and linked to the precipitation extremes identified in this study. In *Pfahl and Wernli* [2012], the cyclone area of influence is defined as being within a closed pressure contour where the contours are defined on intervals of 0.5 hPa. Here the 2.5° resolution precipitation extremes are associated with a cyclone if the precipitation extreme lies within the cyclone area of influence at the beginning or the end of the precipitation accumulation period (as with the fronts). By combining the techniques used in the two studies, this is a first attempt to quantify the relative importance of the different synoptic features.

[21] Figure 7a shows the proportion of extreme events associated with both a cyclone and a front at the same location. In the major storm track regions of the Northern Hemisphere, a large proportion (up to 80%) of the precipitation extremes are associated with both synoptic features. In the Southern Hemisphere, poleward of 45°S, between 60 and 80% of extreme events are associated with both cyclones

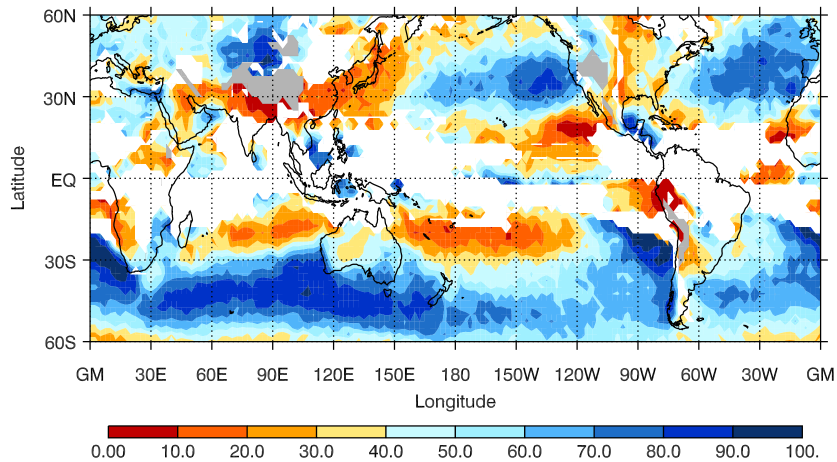

Figure 9. The percentage of front-only precipitation that occur with only a cold front. Regions where the link between fronts and precipitation is not statistically highly significant are blanked out in white and high orography is blanked out in grey.

and fronts. Further equatorward, the values are lower, with about 40% of extreme events in the SPCZ region associated with both fronts and cyclones.

[22] The proportion of extreme precipitation events associated with only cyclones is generally lower (Figure 7b). These events tend to be confined to smaller regions of the subtropics, for example, to the north and northeast of Australia, to the east of Madagascar, and over the South China Sea and the tropical north Pacific Ocean. These maxima are probably due to the presence of tropical cyclones [*Pfahl and Wernli*, 2012]. In the far north Pacific region, there are also relatively high values of up to 40% of extreme events associated with only cyclones. Such events may be related to cyclones in which the front has become displaced from the low pressure center.

[23] There are some regions where up to 60% of extreme precipitation events are associated with only fronts (Figure 7c). These tend to occur equatorward of the maxima of extreme events associated with any occurrence of fronts (Figure 3a). In many regions, you would expect that the fronts that are not co-located with a cyclone (defined as the region within the closed pressure contours) would, at some point along their length, still be associated with a cyclone. Such fronts could be identified as being "remote" fronts. Figure 8a shows that the proportion of extreme precipitation events associated with this type of remote front is up to 35% in the lower latitudes of the midlatitude storm track regions (30–45°). Up to 70% of the front-only extreme precipitation events (shown in Figure 7c) are actually related to the remote fronts (Figure 8b). A large proportion of the front-only extreme precipitation events are also associated with cold fronts (Figure 9). This further confirms that many of the extreme precipitation events associated with only fronts, are sill related to the larger scale low pressure features of the midlatitude storm tracks. In the SPCZ region, over eastern Asia and Australia, the front-only events are more associated with warm or quasi-stationary fronts.

[24] It has been shown that a very large proportion of the extreme precipitation events are associated with synoptic systems, especially in the midlatitudes. Figure 7d shows the proportion of extreme precipitation events that occur with no cyclones or fronts in the vicinity. In the tropics, nearly all of the extremes occur with no synoptic feature, as is to be expected since it is well known that organized convection such as squall lines and the Intertropical Convergence Zone would be responsible for much of the heavy rain in this region.

4. Discussion and Conclusions

[25] In this study, the importance of fronts for precipitation extremes has been evaluated in a similar fashion to the study of *Pfahl and Wernli* [2012]. Fronts in the ERA-Interim reanalysis have been identified using the front identification method of *Berry et al.* [2011a] and combined with the 6-hourly precipitation also obtained from the ERA-Interim reanalysis, similar to the method employed in *Catto et al.* [2012]. The main conclusions of the study are as follows.

[26] 1. In the midlatitudes, fronts are far more important for extreme precipitation events than for any other precipitation events with up to 90% of extreme precipitation events in the midlatitudes associated with fronts.

[27] 2. A larger proportion of the extreme precipitation events is associated with warm fronts than with cold fronts or quasi-stationary fronts in most regions. Averaged globally, 23% of precipitation extremes are associated with warm fronts, 17% with cold fronts, and 11% with quasi-stationary fronts.

[28] 3. There are regions where large proportions of the extreme precipitation events are associated with only cyclones or only fronts. The extreme precipitation events occurring in the main storm-track regions are mostly associated with both fronts and cyclones at the same time.

[29] 4. A large percentage (up to 70%) of the fronts responsible for the "front-only" extreme precipitation events are associated with a cyclone at some point along their length and are therefore still related to the weather systems embedded in the midlatitude westerly flow.

[30] 5. The fronts which produce precipitation extremes have a much stronger wet bulb potential temperature gradient than other fronts, giving a potential for forecasting extreme precipitation events using the strength of the frontal gradient as predictor.

[31] The importance of synoptic systems for global and regional total and extreme precipitation has been highlighted by a number of recent studies [e.g., *Kunkel et al.*, 2012; *Catto et al.*, 2012; *Pfahl and Wernli*, 2012; *Hawcroft et al.*, 2012; *Pfahl et al.*, 2013]. The current study represents a new way of investigating this importance and complements previous work. It is not possible to directly compare the numerical results of the various different methodologies, but here some attempt has been made to investigate the relative importance of both fronts and cyclones by combining two of the techniques. Many regions of the globe are significantly affected by front-related extreme precipitation events. It is clear that in order to provide projections of future total and extreme precipitation, an understanding of how these synoptic systems may change in the future is of utmost importance. In order to be able to do this, the physical processes responsible for producing these systems, and the relationship between them and the precipitation must be well represented in climate models.

[32] A state of the art atmospheric general circulation model has recently been shown to perform reasonably well in the representation of the proportion of precipitation associated with fronts [*Catto et al.*, 2013]. However, there are some issues with the intensity of frontal precipitation being too low, suggesting that precipitation extremes in this particular climate model may not be well represented. To have confidence in future projections of precipitation and precipitation extremes, a systematic analysis of the cyclone- and front-related precipitation in the CMIP5 models must be performed. This will be the subject of a future study.

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