Relating global precipitation to atmospheric fronts

J. L. Catto,[1] C. Jakob,[2] G. Berry,[2] and N. Nicholls[1]

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[1] Atmospheric fronts are important for the day-to-day variability of weather in the midlatitudes, particularly during winter when extratropical storm-tracks are at their maximum intensity. Fronts are often associated with heavy rain, and strongly affect the local space-time distribution of rainfall. A recently developed objective front identification method that distinguishes between cold, warm and quasi-stationary fronts, is applied to reanalysis data and combined with a daily global gridded data set to investigate how precipitation around the globe is associated with atmospheric fronts. A large proportion (up to 90%) of rainfall in the major storm-track regions is associated with fronts, particularly cold and warm fronts. Precipitation over the oceanic storm-tracks is mostly associated with cold fronts, while over the Northern Hemisphere continents precipitation is mainly associated with warm fronts. There are seasonal and regional variations in the proportion of precipitation associated with fronts.
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1. Introduction

[2] Atmospheric fronts are extremely important for the day-to-day weather in the midlatitudes, often bringing strong winds and heavy rain which can have large socio-economic impacts. For example, the severe flooding during the UK summer of 2007 which caused insured losses of around 3 billion GBP [*Pitt*, 2008] was associated with the passage of a front. Ten of the largest winter flood events in the UK have recently been shown to have been associated with "atmospheric rivers", the flows of moist air from subtropical regions into midlatitude frontal systems [*Lavers et al.*, 2011].

[3] Recently there has been considerable effort to produce large-scale climatologies of objectively identified fronts from reanalysis data [*Berry et al.*, 2011a; *Simmonds et al.*, 2011]. *Berry et al.* [2011a] showed that fronts identified in the ERA-40 reanalysis dataset mainly occur in the regions of the major midlatitude storm tracks [e.g., *Hoskins and Hodges*, 2002, 2005], with fronts present in these regions up to 16% of all 6-hourly times analysed. The midlatitudes were also found to be where the frontal intensity is greatest [*Simmonds et al.*, 2011].

[4] Although the regions of maximum annual average precipitation occur in the tropics [*Garreaud*, 2007], there are also large regions of high values of annual average precipitation over the midlatitude storm track regions. Much of the rainfall in the midlatitudes has long been known to be associated with the passage of frontal systems, as shown in *Bjerknes and Solberg* [1922]. The distribution of precipitation around frontal systems has since been investigated using case studies [e.g., *Browning and Roberts*, 1994] and compositing techniques [e.g., *Field and Wood*, 2007]. On regional scales studies have been performed to attribute precipitation to fronts or other synoptic activity [e.g., *Pook et al.*, 2006]. Studies of particular cases or regions are often subjective in nature and as such are not able to be reproduced or extended to global analysis. For this reason the volume of global precipitation associated with fronts has yet to be quantified.

[5] Given the importance of fronts to local weather in many regions, it is feasible that some of the observed trends in weather parameters around the globe, in particular rainfall, could be associated with the frequency of occurrence of fronts. For example, a reduction in the number of fronts has been suggested as a possible reason for the decrease in precipitation over South West Western Australia, however *Berry et al.* [2011b] show that over this region, the front frequency has actually been increasing over the past 50 years. This suggests that perhaps there have been changes to the amount of precipitation that each front produces. In order to investigate such a suggestion further, the amount of precipitation associated with fronts first needs to be quantified. Despite the clear importance of fronts in producing rain, there has as yet been no such quantification on global scales. In this study, the fronts identified in reanalysis data are linked to global precipitation data to investigate how much of the global precipitation comes from fronts, and how this varies regionally.

2. Methodology and Datasets

[6] The objective front identification method of *Berry et al.* [2011a] uses the thermal front parameter of *Hewson* [1998] to identify locations of frontal points. Fronts are located where the gradient of wet bulb potential temperature is a maximum in the direction of the moist isentropes, and they are classed as cold, warm or quasi-stationary depending on the magnitude and direction of front speed. This method has been applied to ERA-Interim [*Dee et al.*, 2001] 6-hourly-fields at 850 hPa for the period from 1997–2008 and provide front locations on a regular 2.5° grid.

[7] Once the fronts are identified, they are combined with the Global Precipitation Climatology Project (GPCP) daily precipitation dataset [*Huffman et al.*, 2001] which combines

[1]School of Geography and Environmental Science, Monash University, Melbourne, Victoria, Australia.
[2]School of Mathematical Sciences, Monash University, Melbourne, Victoria, Australia.

Corresponding author: J. L. Catto, School of Geography and Environmental Science, Monash University, Wellington Road, Clayton, Vic 3800, Australia. (jennifer.catto@monash.edu)

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information from satellites, rain gauges and soundings. First, the GPCP data are interpolated from their original 1° × 1° grid to the same grid resolution as that used for the fronts (2.5°). The GPCP and ERA-Interim data overlap in time for the period 1997–2008, which is used here. Fronts and rainfall are combined as follows. If the daily precipitation at a grid-point is greater than zero, a surrounding box of 5° size is searched for the existence of a front. If a front occurs in the box at any of the four reanalysis time points within that day, then the precipitation is allocated to the front. Often during the day there may be more than one type of front present within the search area. For example, both a cold and warm front may be present close to the center of a midlatitude cyclone. In this case, the precipitation allocated to the fronts is weighted according to the number of times or points at which that type of front occurs. For example, if there is a cold front point present for 4 of the times during the day, and a warm front point present for 2 of the times during the day, then one third of the precipitation is allocated to the warm front and two thirds to the cold front. From this analysis, two key measures are found. First, the rainfall amount associated with a particular type of front at each grid point is calculated by accumulating the rainfall amounts per front type and dividing by the total number of days this front type occurred. Second, the precipitation allocated to each front type is divided by the total precipitation that occurs at that grid point, to give the proportion of precipitation that has an associated front (within a 5° surrounding box).

[8] The choice of a 5° search area may appear somewhat arbitrary, but can be justified by considering the typical speed of fronts and their area of influence as well as the discrete nature and resolution of the data sets. Consider first the case where precipitation is allocated to a front only if the front is located (at one of the 6-hourly times within the 24 hour rainfall period) within the 2.5° by 2.5° grid box carrying the precipitation information. In this scenario a front could be located within close proximity to the boundary of the target grid box but not be considered to contribute to the rainfall in this grid box. Given that the fronts are identified at a single specific level (850 hPa), but their rainfall area often extends well ahead of (in the case of warm fronts) or behind (in the case of cold fronts) the actual front, and since fronts are usually tilted, this would be an unrealistic situation and would lead to an underestimation of the frontal influence on precipitation. Furthermore, typical values for the speed of frontal propagation are around 50–60 km/h. As we only know frontal locations every six hours it is entirely possible that a front crosses the target grid box without ever registering as being located in it, leading again to an underestimation of precipitation associated with fronts.

[9] Widening the search area to the next discrete level beyond 5°, leads to a search area of approximately 1000 km surrounding the target grid box. In this scenario, it is possible that precipitation would be allocated to a front even if the front came no closer than 500 km to the rainfall grid box, thereby leading to an over-allocation of rainfall to frontal influences. The 5° box has been chosen as a compromise between missing fronts for small search areas or counting fronts that are too far removed from the target area for the large search area. The choice of search box has a significant influence on the results; for example, the midlatitude proportion of precipitation found using just the coincident point, a 5° box and a 10° box are 31%, 69% and 86% respectively. Encouragingly though the ratios of frontal rainfall fraction between different regions are found to be largely independent of the choice of search area size.

[10] Polewards of 60°, the convergence of the meridians of the 2.5° regular grid on which the fronts are identified results in the search area becoming smaller and smaller. Since the front frequency at these high latitudes is relatively small [*Berry et al.*, 2011a] and in the Southern Hemisphere the region is dominated by somewhat artificial fronts identified at the edge of the high orography of Antarctica, only the regions between 60°N and 60°S have been considered here.

3. Results

[11] The global distribution of the annual average proportion of precipitation associated with fronts for the period 1997–2008, as well as the frequency of front occurrence, is shown in Figure 1. The proportion of precipitation occurring when any type of front is present is given in Figure 1a. Regions where the front frequency is less than 3% are shaded in grey. In the midlatitudes, a very high proportion (over 90% in some places) of the precipitation occurs with a front present. The maxima are located in the major storm track regions in the North Pacific, North Atlantic, and Southern Ocean where the front frequency is largest. There are also high values in some parts of the subtropics which may not be associated with the classical conceptual picture of a synoptic front as in *Bjerknes and Solberg* [1922], but with features which are nevertheless identified objectively using the gradients of temperature and moisture, such as tropical convergence zones.

[12] Figures 1b–1d show the proportion of precipitation associated with cold, warm and quasi-stationary fronts respectively. The proportion of precipitation associated with cold fronts (Figure 1b) is largest over the midlatitude oceanic storm tracks with values in the North Atlantic above 42% and in the Indian Ocean above 54%. The values over land are relatively small, with less than 24% of precipitation associated with cold fronts over most of North America, Eurasia, and Australia.

[13] A higher proportion of precipitation over land is associated with warm fronts rather than cold fronts, especially over North America with values of 30–58%. Over much of Australia, the frequency of warm fronts annually is very low, but in the west over 24% of precipitation is associated with those warm fronts that do occur. In the midlatitudes, the proportion of precipitation associated with warm fronts is greater further polewards compared to the precipitation associated with cold fronts. This is expected from the structure of midlatitude frontal systems with the warm air advected polewards ahead of the cyclone.

[14] The proportion of precipitation associated with quasi-stationary fronts is generally much lower than for the other types of fronts, as these are less frequently identified. There is a local maximum of approximately 25% in the South Pacific, in a region associated with the South Pacific Convergence Zone (SPCZ) [*Berry et al.*, 2011a].

[15] The average values of the proportion of precipitation associated with the various types of front have been calculated over various regions of the globe and are summarised in Table 1. More precipitation is associated with fronts in the Southern Hemisphere than the Northern Hemisphere. The highest proportion of precipitation associated with any type

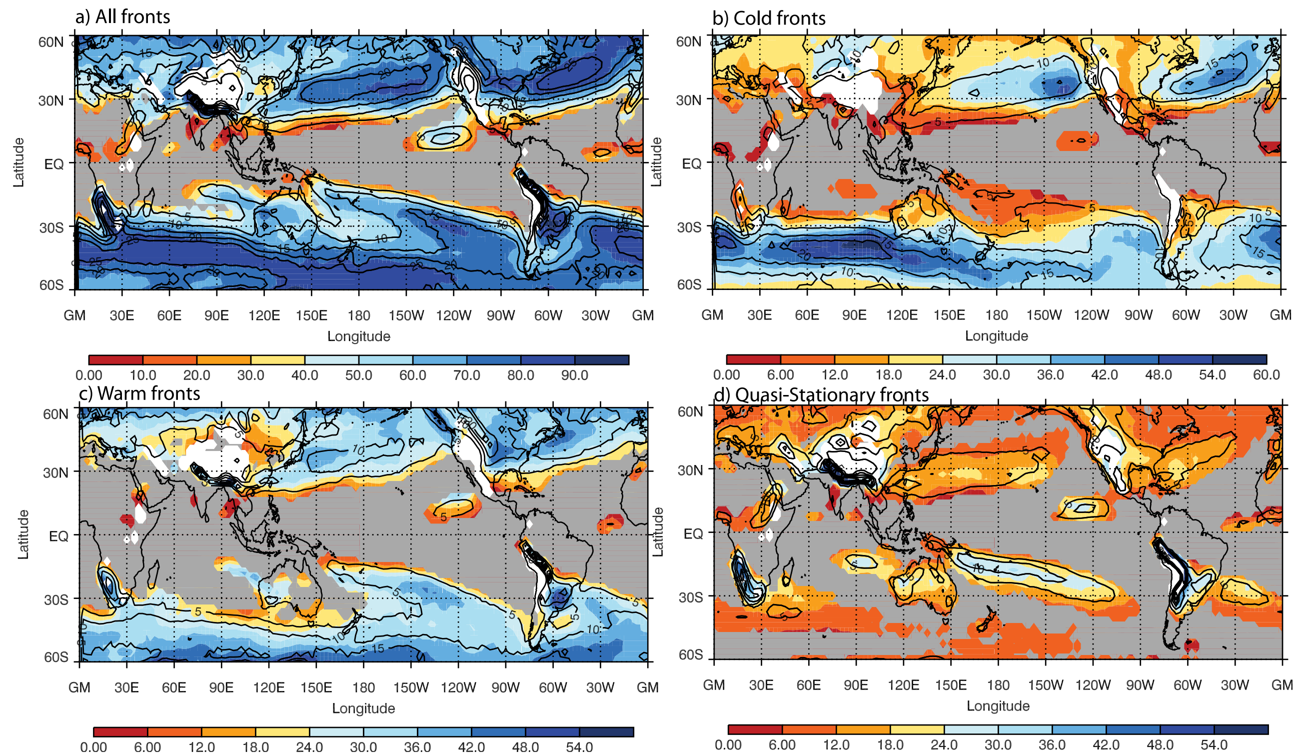

Figure 1. Colors show annual proportion of precipitation that occurs with (a) any front, (b) cold front, (c) warm front, (d) quasi-stationary front within a 5° box. The black contours show the front frequency as a percentage time that a front was located within each grid box. Polewards of ±60° has been cut off due to problems with the convergence of the meridians. Regions where the surface topography is higher than 1.5 km (850 hPa in a standard atmosphere) have been blanked out, and areas where the front frequency is less than 3% have been shaded grey.

of front is in the midlatitudes (from 30° to 60°) with 68% of precipitation occurring with a front. Dividing the results into front types reveals that the total proportion of precipitation associated with warm fronts is greater than with cold fronts, particularly over land where the warm front frequency is higher than the cold front frequency. Cold and warm fronts account for almost the same amount of precipitation in the midlatitudes, where midlatitude cyclones are the dominant weather feature, adding to a total of 57% of midlatitude precipitation occurring with either a warm or cold front. The largest proportions of precipitation associated with quasi-stationary fronts occur over land (and particularly close to orography), where there are sharp gradients in temperature and moisture associated with the boundary layer. The identification of the fronts on the 850 hPa level is problematic near high orography and so these particular results should be considered with that in mind.

[16] The proportion of precipitation associated with fronts varies throughout the year, as can be seen in the seasonal evolution (December–February (DJF) to September–November (SON)) in Figure 2. The proportion of precipitation associated with fronts mainly varies according to the front frequency, which varies in latitude according to the seasonal shifts of the midlatitude storm tracks [*Chang et al.*, 2002]. During the Northern Hemisphere winter season (DJF), up to 60% of precipitation over the North American eastern seaboard and the North Atlantic storm track occurs with an associated cold front, and the values in the North Pacific are over 40% (Figure 2a). These values reduce to a minimum in June–August (JJA) of 30–36% (Figure 2c), then increase again in SON (Figure 2d). For the warm fronts (Figures 2e–2h), the proportion of precipitation associated with the fronts in the Northern Hemisphere does vary over the seasons but not to such an extent.

[17] In the Southern Hemisphere, the seasonal cycle is not as clear as in the Northern Hemisphere. The midlatitude storm tracks over the South Atlantic and Indian Ocean basins maintain their strength through the year [*Hoskins and*

Table 1. Annual Average Values (Calculated Using 12 Years of Data) of the Proportion of Precipitation That Has an Associated Front

Region (All Regions Are Within 60°N to 60°S)	Average Proportion of Precipitation Associated With Fronts (%)			
	All Fronts	Cold Fronts	Warm Fronts	Quasi-stat Fronts
Global	46	17	18	11
Northern Hemisphere	41	14	17	11
Southern Hemisphere	51	20	20	11
Land	46	12	17	16
Ocean	46	18	19	9
NH Land	46	13	18	15
SH Land	46	11	15	19
NH Ocean	39	14	16	9
SH Ocean	52	21	21	10
Midlatitudes (30°–60°)	68	28	29	11
Tropics (30°S–30°N)	28	8	9	11

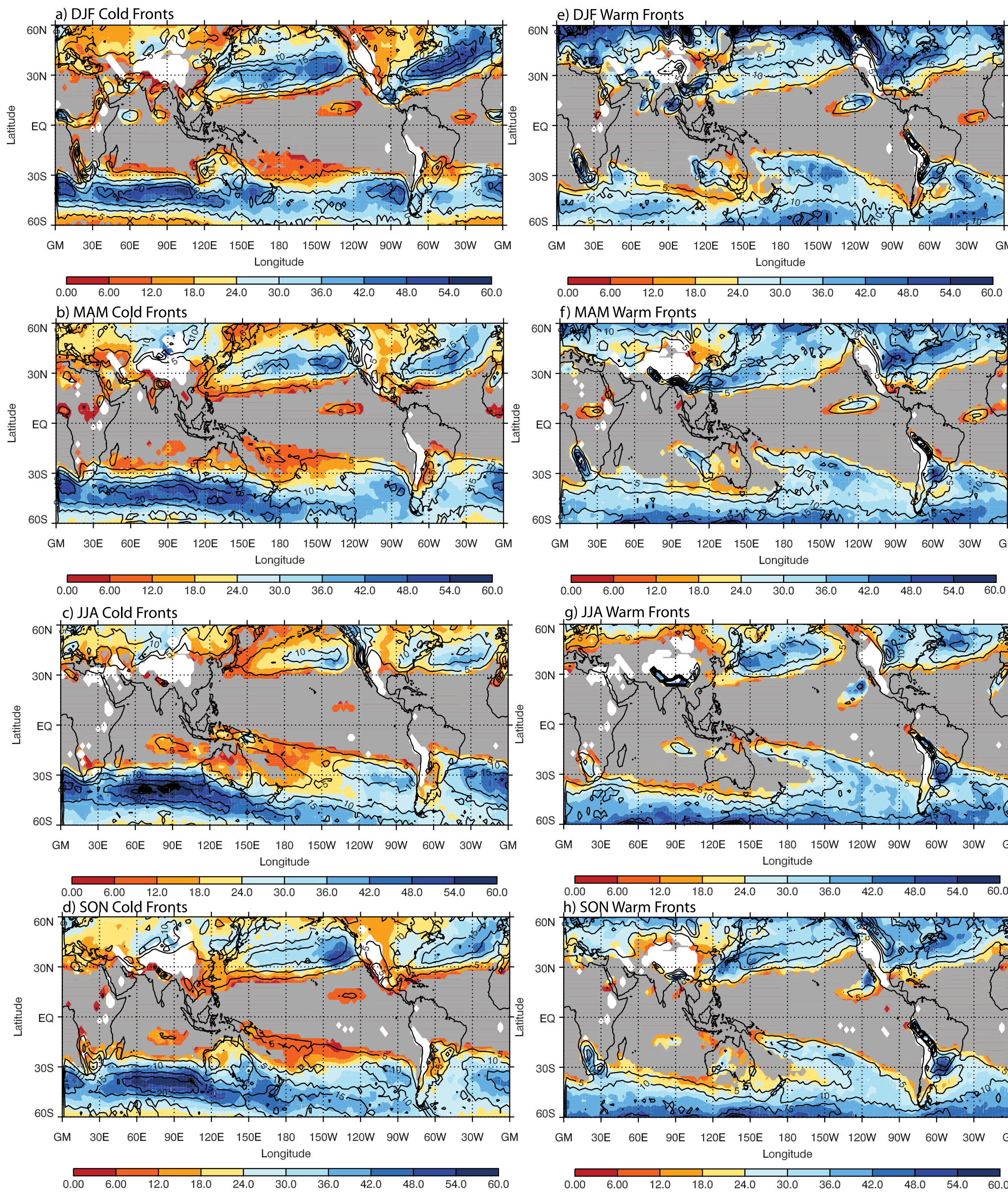

Figure 2. Colors show mean seasonal evolution of the proportion of precipitation that occurs with (left) a cold front and (right) a warm front within a 5° box for (a, e) DJF, (b, f) MAM, (c, g) JJA and (d, h) SON. The black contours show the front frequency as a percentage time that a front was located within each grid box. Polewards of ±60° has been cut off due to problems with the convergence of the meridians. Regions where the surface topography is higher than 1.5 km (850 hPa in a standard atmosphere) have been blanked out, and areas where the front frequency is less than 3% have been shaded grey.

Hodges, 2005]. In these regions, the proportion of precipitation associated with cold fronts is above 50% for most of the year (Figures 2a–2d). Over Australia, the largest proportion of precipitation associated with cold fronts occurs in Spring and Summer (SON and DJF, Figures 2d and 2a), while in Winter (JJA, Figure 2c), only 18–24% of precipitation over the southern parts of Australia is associated with cold fronts. The precipitation associated with warm fronts generally occurs further polewards of the cold fronts, with lower values, and in the region associated with the SPCZ which is a year-round feature (Figures 2e–2h).

[18] The mean precipitation which occurs when a front is present has been calculated. The average precipitation that occurs with a cold, warm and quasi-stationary front in the midlatitudes is approximately 2 mm, 3 mm and 2 mm respectively. The values are higher over oceans than over the land (76%, 72%, and 40% greater for cold, warm and quasi-stationary fronts respectively) For warm fronts in particular, the highest values occur over the warm western boundary currents such as the Gulf Stream and the Kuroshio Current (not shown). The average values in the tropics and the midlatitudes are similar (mainly due to a cancellation in the tropical latitudes of regions of very high values and regions of very low values), however the maximum values in the tropics are much higher since when a front does occur in certain regions (which happens rarely), the associated precipitation is high. In many regions, the average precipitation that occurs on a day when there is *no* front present is lower than if there is any type of front present, e.g., the average precipitation that occurs in the midlatitudes with no front present is approximately 2 mm, compared to 4 mm with any type of front.

4. Discussion and Conclusions

[19] By combining objectively identified atmospheric fronts with satellite derived global precipitation data, we have quantified the proportion of global precipitation that comes from fronts. The regions where most precipitation is associated with fronts are the midlatitude regions of the Northern and Southern Hemispheres. In the major oceanic storm tracks, annually up to 90% of the rain comes from fronts, and particularly from cold fronts. Over parts of the Northern Hemisphere continents, over 30% of precipitation comes from warm fronts during much of the year. There are some interesting seasonal and regional variations, for example, over Australia where there are strong local maxima in the proportion of precipitation associated with fronts over the west and east of the continent.

[20] While the present study has only used 12 years of data, the availability of longer global reanalysis and precipitation datasets would allow this to be extended, and to investigate how the association between fronts and precipitation may have changed in the past. This would be of particular interest to regions that have seen significant declines in precipitation, such as South West Western Australia. Over Australia, for example, the Australian Water Availability Project (AWAP) provides gridded precipitation derived from station data. The overall pattern of the proportion of precipitation from fronts is very similar between the GPCP and AWAP datasets, further analysis of which will be left to a future study.

[21] The results from this study are sensitive to the search box used (as indicated in section 2) and would be sensitive to the use of a different front identification method, such as that of *Simmonds et al.* [2011]. The important aspect of this study is that the method is fully reproducible and can be used globally, thereby making it a useful tool for the evaluation of global climate models. Such models may be able to represent the dynamical structure of extratropical cyclones [*Catto et al.*, 2010], but it is unclear whether the precipitation within these structures can be adequately simulated. Such evaluations will be presented in future studies.

[22] In a warming climate, the locations of the major storm-tracks may change [e.g., *Laîné et al.*, 2009; *Catto et al.*, 2011] which could change how the proportion of precipitation associated with fronts is distributed over the globe. There is also much interest in how precipitation associated with cyclones may change [e.g., *Watterson*, 2006; *Bengtsson et al.*, 2009], and whether individual precipitation events will become more intense. Future studies will be able to make use of the current technique to try to answer these important questions.

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