How much Northern Hemisphere precipitation is associated with extratropical cyclones?

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[1] Extratropical cyclones are often associated with heavy precipitation events and can have major socio-economic impacts. This study investigates how much of the total precipitation in the Northern Hemisphere is associated with extratropical cyclones. An objective feature tracking algorithm is used to locate cyclones and the precipitation associated with these cyclones is quantified to establish their contribution to total precipitation. Climatologies are produced from the Global Precipitation Climatology Project (GPCP) daily dataset and the ERA-Interim reanalysis. The magnitude and spatial distribution of cyclone associated precipitation and their percentage contribution to total precipitation is closely comparable in both datasets. In some regions, the contribution of extratropical cyclones exceeds 90/85% of the total DJF/JJA precipitation climatology. The relative contribution of the most intensely precipitating storms to total precipitation is greater in DJF than JJA. The most intensely precipitating 10% of storms contribute over 20% of total storm associated precipitation in DJF, whereas they provide less than 15% of this total in JJA. **Citation:** Hawcroft, M. K., L. C. Shaffrey, K. I. Hodges, and H. F. Dacre (2012), How much Northern Hemisphere precipitation is associated with extratropical cyclones?, *Geophys. Res. Lett.*, *39*, L24809, doi:10.1029/2012GL053866.

1. Introduction

[2] Extratropical cyclones play a key role in modulating precipitation in the mid and high-latitudes. The importance of these systems to the precipitation of the extratropics has long been known [e.g., *Bjerknes*, 1919; *Bjerknes and Solberg*, 1922]. Precipitation in the extratropics is associated with a variety of phenomena, including extratropical cyclones, convection and orographic uplift. It is not clear that these phenomena will respond to climate change in the same way (e.g., the response of extratropical cyclones may be largely associated with changes in the meridional temperature gradient, whereas convection may be more sensitive to local temperature changes). Decomposing the contribution of each to the total precipitation climatology therefore provides insight into the potential impact that any changes in the intensity or spatial and temporal distribution of these precipitation producing events might have in the future. This is particularly important in light of the current uncertainty in how extratropical cyclones will respond to a change in the background climate [*Bengtsson et al.*, 2006, 2009; *Ulbrich et al.*, 2009; Zappa et al., submitted manuscript, 2012].

[3] In addition to providing an important contribution to the total climatological precipitation, extratropical cyclones are often associated with extreme precipitation and strong winds which can have major socio-economic impacts [*Ulbrich et al.*, 2003; *Pitt*, 2008; *Sibley*, 2010]. In many regions of the extratropics the majority of extreme precipitation events are associated with the passage of an extratropical cyclone [*Pfahl and Wernli*, 2012]. Quantifying the contribution of the most intensely precipitating cyclones to the total climatology provides information on both the current temporal distribution of precipitation in a location and the importance of any possible change in the most intense events under climate change [*Meehl et al.*, 2005; *Finnis et al.*, 2007; *Bengtsson et al.*, 2009; *Champion et al.*, 2011].

[4] Previous studies have produced climatologies of both the fronts associated with extratropical cyclones [e.g., *Berry et al.*, 2011; *Simmonds et al.*, 2011] and frontal precipitation [*Catto et al.*, 2012]. *Catto et al.* [2012] found that up to 90% of precipitation is associated with fronts in certain regions. This study complements the work of *Catto et al.* [2012] through using a different approach to investigate storm associated precipitation, in addition to using multiple datasets and a longer study period. This study adopts a broader approach to characterising extratropical cyclone associated precipitation, which may not be included in an analysis focused on frontal precipitation. For example, frontal detection may not capture occlusions, and the precipitation associated with the occlusion [*Schultz and Vaughan*, 2011], or fronts where the potential temperature gradient is weak [*Naud et al.*, 2010]. The importance of the most heavily precipitating events is also considered, thereby providing further information on storm associated precipitation.

[5] In this study, the contribution of extratropical cyclones to the total precipitation climatology in the Northern Hemisphere is assessed and the contribution of the most intensely precipitating cyclones to the climatology is also investigated.

2. Data and Method

[6] This study uses precipitation estimates from the GPCP merged rain gauge and satellite dataset and the ECMWF ERA-Interim reanalysis dataset. There remains considerable uncertainty in the precipitation estimates derived from satellite observations [*Kummerow et al.*, 2006; *Field and Wood*, 2007; *Stephens et al.*, 2010] and from reanalysis [*Hou et al.*, 2001]. Neither the GPCP or ERA-Interim datasets provide estimates of uncertainty for precipitation, thus the use of multiple datasets allows us to explore the uncertainty in our estimates of how much precipitation is associated with extratropical cyclones.

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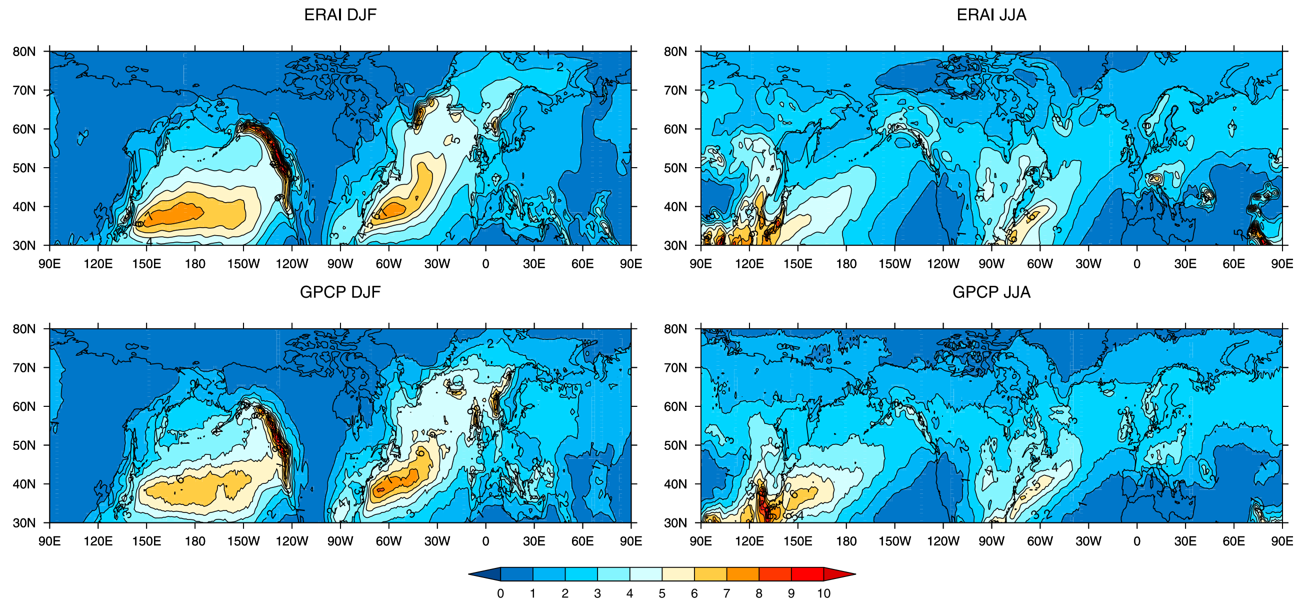

Figure 1. Climatological precipitation (mm/day) from ERAI and GPCP for DJF and JJA.

2.1. GPCP

[7] The Global Precipitation Climatology Project (GPCP) daily precipitation dataset [*Huffman et al.*, 2001; *Adler et al.*, 2003] is a $1^\circ \times 1^\circ$ gridded dataset that combines satellite estimates and rain gauge data to produce daily accumulations centred on 12:00UTC. The GPCP data used in this study is the longest period available, from December 1996 to August 2009. Precipitation rates in GPCP are produced through combining empirical infra-red estimates from geostationary satellites with empirical microwave estimates from polar orbiting satellites. The estimates are adjusted where gauge data is available. Over the oceans, the satellite estimates are not adjusted by gauge data. Comparison studies have shown that the precipitation estimates from the satellite only product perform deficiently relative to the gauge-adjusted product [see, e.g., *Adler et al.*, 2003; *Serreze et al.*, 2005; *Smith et al.*, 2006].

2.2. ERAI

[8] The ERA-Interim (ERAI) reanalysis [*Dee et al.*, 2011; *Simmons et al.*, 2007] uses a 4D-Var data assimilation system to incorporate observations over a 12-hour analysis period, with forecasts commencing at 00:00UTC and 12:00UTC and has spectral resolution T255 (approximately 0.7°). Precipitation is not an analysed field and is therefore taken from short-range forecast accumulations. During the first several hours of the forecast simulation, the precipitation field is affected by spin-up [see *Kållberg*, 2011]. Given the requirement to have daily accumulations centred on 12:00UTC, the forecast periods utilised in this study are accumulations from 12 to 24-hours from forecasts starting at 12:00UTC the previous day and 00:00UTC on the day of interest. The two forecast accumulations are combined to provide daily precipitation estimates. The 12 to 24-hour forecast estimates have previously been found to compare well to gridded gauge data [*Simmons et al.*, 2010] and recent work indicates that the lead time used in this paper offers the best estimates available from ERAI given the daily accumulations required for this study (de Leeuw et al., submitted manuscript, 2012). The ERAI data used in this study is from March 1979 to February 2011. The analysis has been repeated on the 1996–2009 period of GPCP to assess uncertainty which may arise from decadal variability and the results were not materially different.

2.3. Method

[9] Using an objective feature tracking technique [e.g., *Hodges*, 1994, 1995, 1999], Northern Hemisphere extratropical cyclones are identified as features exceeding $1 \times 10^{-5} s^{-1}$ in the 6-hourly ERAI 850 hPa relative vorticity field, truncated to T42 (see *Hoskins and Hodges* [2002] for further discussion). Cyclones with a lifetime of at least 2 days and which travel at least 1000 km are retained as extratropical cyclones and included in the analysis. The sensitivity of the results to these thresholds has been assessed through investigating the impact of a relaxation of either the time or distance criteria. The results were not materially sensitive to changing these thresholds. The feature tracking identifies on average 465 storms per DJF season and 420 in JJA in the Northern Hemisphere.

[10] In order to calculate the storm associated precipitation climatology, the position of all cyclones at 12UTC are identified and the precipitation within a radial cap of the storm centre is extracted. The daily storm associated precipitation estimates are averaged over the period of analysis to create storm associated precipitation climatologies. The sensitivity of the results to the size of this cap have been assessed and for DJF/JJA a cap of 12/10° is selected given the observed variation in typical storm precipitation footprints (for further discussion of sensitivity, see auxiliary material and Section 3).[1]

[11] To assess the contribution of the most extreme storms to the storm associated precipitation climatology, storms were filtered by their maximum precipitation intensity (based on 5° areal average precipitation around the storm centre, which is the location of the peak precipitation). The same

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL053866.

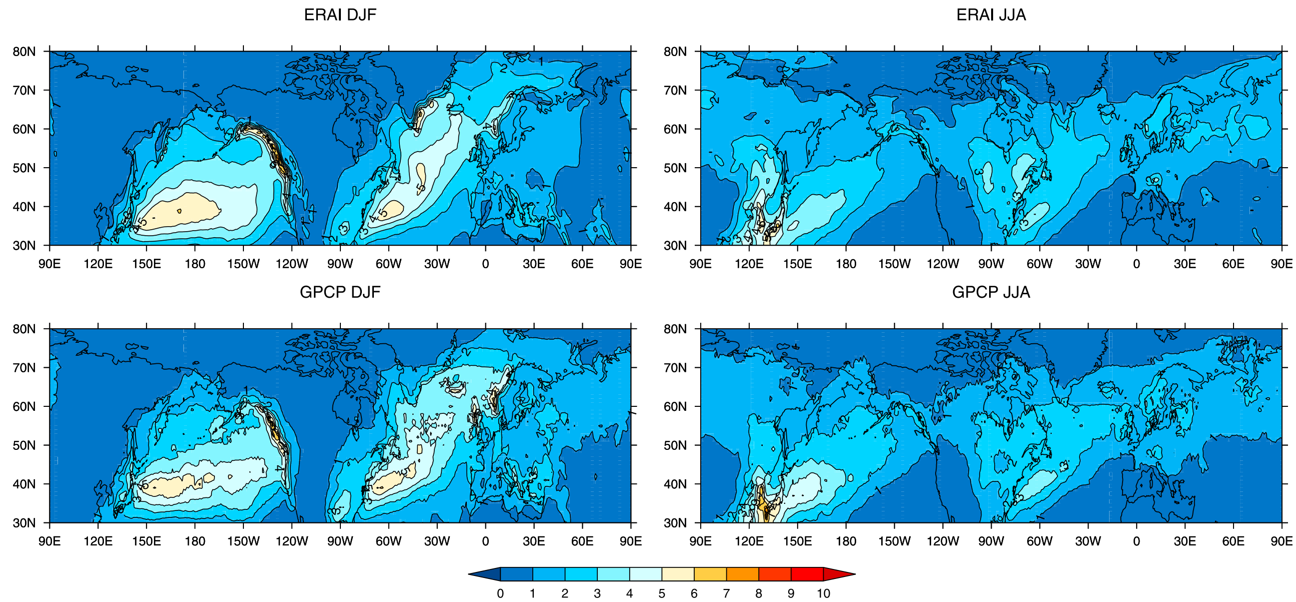

Figure 2. Climatological storm associated precipitation (mm/day) from ERAI and GPCP for DJF and JJA.

methodology was then used to create climatologies with the precipitation associated with, for example, the most intensely precipitating 10% of storms. All four seasons were analysed. The JJA and DJF seasons are discussed in this paper, with the results of the MAM and SON seasons residing between JJA and DJF for the metrics discussed here.

3. Results

3.1. Climatology

[12] In Figure 1 the total precipitation climatology of the Northern Hemisphere is shown. In both seasons there is good agreement between the datasets of the spatial distribution of total precipitation. The seasonal cycle is clearly visible, with the greatest precipitation in the storm tracks in DJF. Across the seasons, the location of the most intense precipitation does not vary greatly, though the magnitude does. The precipitation within the primary Atlantic and Pacific storm tracks reaches 7 mm/day in DJF and 6 mm/day in JJA in both datasets.

[13] In Figure 2 the storm associated precipitation climatologies are shown. The greatest precipitation is in the oceanic storm track regions, with storm associated precipitation contributing up to 5 mm/day in DJF in both the Atlantic and Pacific and up to 4 mm/day in the Pacific and over 3 mm/day in the Atlantic in JJA. The spatial distribution of the storm precipitation is closely comparable in the Atlantic across both seasons and datasets. In contrast, in the Pacific, the storm track is zonal in DJF but has a stronger southwest-northeast tilt in JJA. Local differences in precipitation rates are observed in, for example, the Alps, but the climatologies generally compare well. The precipitation which is not associated with storms is less than 1 mm/day in most regions (not shown), though in the Atlantic and Pacific storm tracks it can reach over 2 mm/day in DJF. Considerable precipitation is observed over the Rockies and Norway in DJF - though this precipitation is associated with the passage of a cyclone, 'orographic effects' [see *Houze*, 2012] may enhance the magnitude of the precipitation. In JJA, few regions in the extratropics exceed 1 mm/day of non-storm associated precipitation.

[14] To illustrate the importance of cyclones to the total precipitation in each location, Figure 3 shows the percentage contribution of cyclones to the total precipitation climatology. In almost all regions, extratropical cyclones contribute over 50% of total precipitation, with this figure exceeding 80/70% in DJF/JJA in the storm track regions, much of North America and parts of Europe. In some locations, such as around Japan, this contribution can exceed 90% in DJF. These figures are comparable in MAM and SON (not shown), demonstrating the importance of extratropical cyclones to total annual precipitation. It is notable that these storms contribute the majority of total precipitation in many regions, not just where the storm tracks are centred, demonstrating how important the precipitation associated with these events is to much of the Northern Hemisphere.

[15] The total storm associated precipitation is highly sensitive to the size of the radial cap which is selected. For example, in DJF in the North Atlantic/Europe the percentage contribution to the total precipitation climatology for 10/12/14° radial caps is 54/71/81% and 58/73/83%, respectively, in GPCP. Given the observed regional variation in average storm precipitation footprint sizes, this generates some uncertainty in the estimates, particularly in those regions with the largest/smallest storm sizes due to the possible exclusion of storm associated precipitation/inclusion of non-storm associated precipitation within the radial cap. This issue is further discussed in the auxiliary material. The results could also be affected by how cyclones are identified [*Raible et al.*, 2008; *Ulbrich et al.*, 2009].

3.2. The Contribution of Heavily Precipitating Cyclones to the Total Storm Associated Precipitation

[16] We also investigate the relative contribution from the most heavily precipitating storms to the storm associated precipitation in Figure 2. Figure 4 shows the total precipitation contribution of cyclones throughout their lifecycle as a

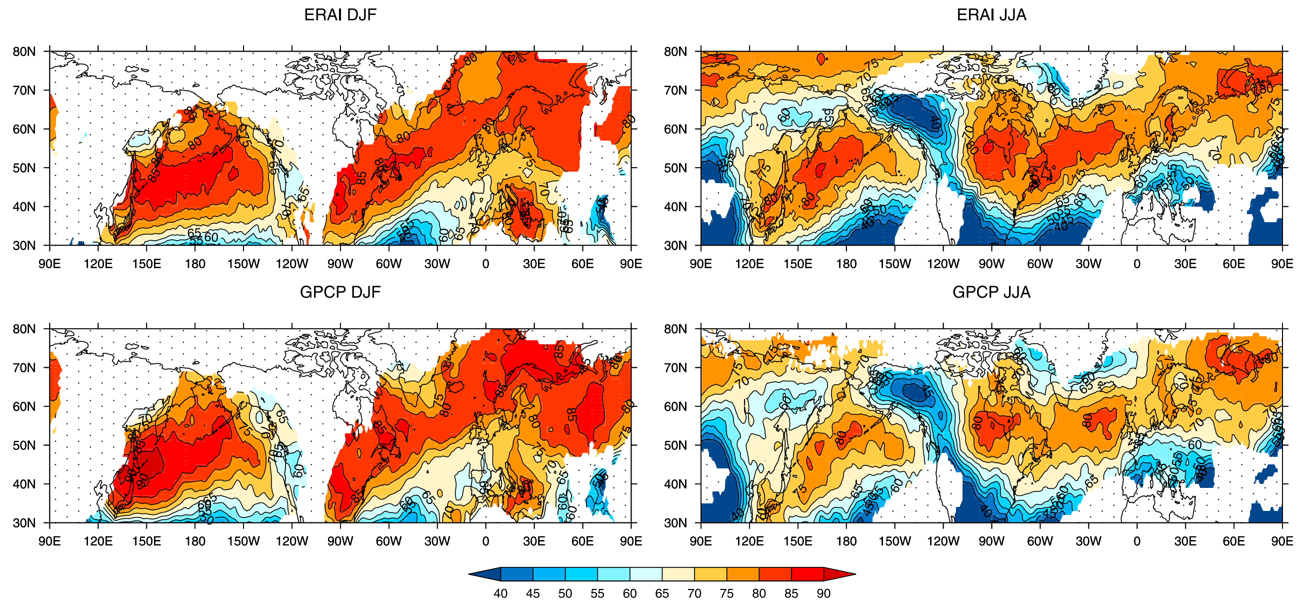

Figure 3. Contribution of storm associated precipitation to the total precipitation (%) from ERAI and GPCP derived from the data in Figures 1 and 2. The masked and stippled areas are where the total climatological precipitation (Figure 1) is less than 1 mm/day. The GPCP data is smoothed over 3-degrees to reduce noise.

function of each storm's maximum precipitation intensity. By construction, it is expected that the storms which have heaviest peak precipitation will have a greater contribution to the climatology than those with low precipitation maxima, but quantifying this is useful particularly given that it is expected that the precipitation intensity of the most severe cyclones will increase [*Held*, 1993; *Trenberth*, 1999] in a warmer climate. The more important the most intensely precipitating storms are to climatology, the greater impact projected changes in their intensity are likely to have on

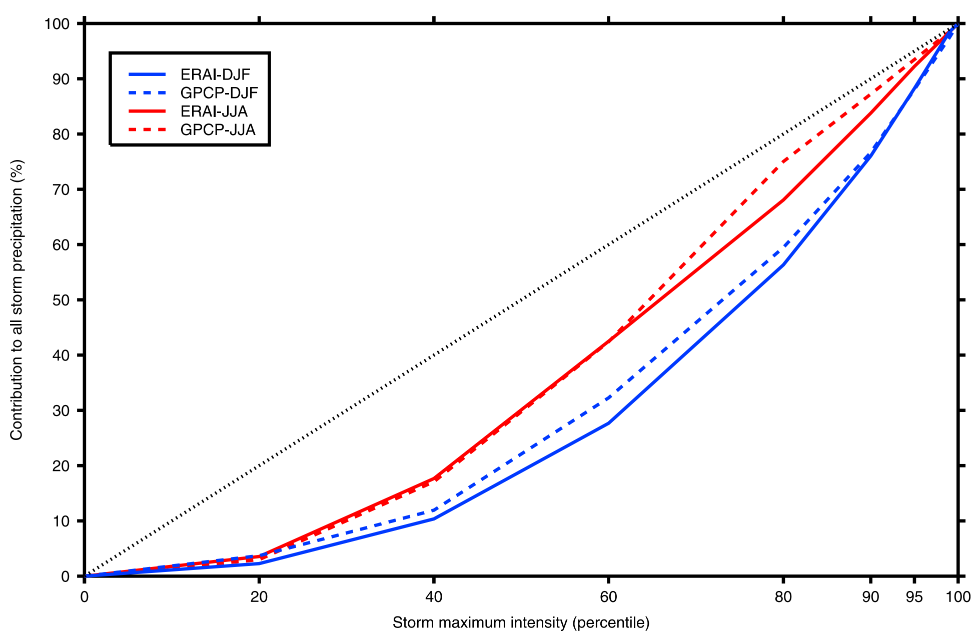

Figure 4. Contribution to storm associated precipitation based on the maximum precipitation intensity of storms. The solid/dashed lines are ERAI/GPCP and are blue/red for DJF/JJA. Maximum intensity is derived from a 5° areal average around the storm centre at the time of peak precipitation. The precipitation associated with storms over their lifetime is then accumulated to derive the importance of storms - based on their maximum intensity - to the total climatological storm associated precipitation. Intensity values are percentiles of all storms in the study period with the contribution shown as a cumulative contribution of all storms below a given percentile threshold. The black dotted line demonstrates the relationship that would exist if all storms contributed equally and demonstrates the importance to the overall climatology of storms of different maximum precipitation intensity.

water management strategies. In DJF, the storms with the highest peak precipitation contribute a relatively greater percentage of the total cyclone associated precipitation over their lifecycles - the most heavily precipitating 10% of cyclones contribute over 20% of total storm associated precipitation. In contrast, the weakest 20% of storms identified in this study contribute less than 4% of the total storm associated precipitation. Given extratropical cyclones contribute approximately 60% of all precipitation north of 30 N, future changes in the most intense DJF cyclones may therefore have a material impact on the total precipitation climatology. In contrast to the DJF storms, the contribution of the most intensely precipitating storms in JJA is smaller, with the most intensely precipitating 10% of storms contributing less than 15% of total storm associated precipitation.

4. Conclusions

[17] This study has investigated the contribution of extratropical cyclones to the total precipitation climatology of the Northern Hemisphere. Decomposing how important different phenomena are to the total precipitation climatology provides valuable insight into understanding how precipitation may respond to climate change. Using an objective feature tracking algorithm, extratropical cyclones have been identified in the Northern Hemisphere. The precipitation associated with these cyclones has been assessed in order to provide an estimate of how important the contribution of these cyclones is to the total precipitation climatology. The regions which are identified as having the greatest absolute storm associated precipitation are in the storm tracks of the Atlantic and the Pacific. It is also shown that in many regions, including parts of Europe and much of North America, over 70% of total precipitation is associated with the passage of an extratropical cyclone.

[18] The two datasets, GPCP and ERAI, used in this study provide comparable values for the metrics analysed here. The ERAI data is analysed for over 30 years and when compared to the shorter period of GPCP data is remarkably similar, suggesting that decadal variability does not strongly affect the contribution of extratropical cyclones to total precipitation in the Northern Hemisphere. Though there are regional differences associated with the approaches and differing methodologies, the results of this work are comparable to *Catto et al.* [2012]. The incorporation of an additional dataset, ERAI, in this study and the longer period of data further enhances confidence in the results of both studies. In addition, this study has investigated the contribution of cyclones to the total precipitation climatology based on their maximum precipitation intensity. It is found that the most intensely precipitating cyclones have a relatively greater importance to the total climatology in DJF compared to JJA.

[19] Verifying whether models can reproduce the observed climate is a necessary, but not sufficient, condition for confidence in future projections and this work will be extended to include a comparison with the output of a high-resolution climate model, HiGEM [*Shaffrey et al.*, 2009]. Few model studies consider the impact of the projected increase in the precipitation intensity of the most severe cyclones [*Held*, 1993; *Trenberth*, 1999] on total storm associated precipitation. *Champion et al.* [2011] found an increase in the magnitude of extreme cyclone associated precipitation in the 21st-century and Zappa et al. (submitted manuscript, 2012) found an increase in the number of strongly precipitating cyclones in DJF in the North Atlantic. These initial results indicate that the importance of these intensely precipitating cyclones to total precipitation may increase, particularly when considered in relation to a likely decrease in the total number of cyclones [*Lambert and Fyfe*, 2006; *Ulbrich et al.*, 2009]. Any changes in the location or pattern of these storms may have major socio-economic impacts, particularly given the importance of cyclone associated precipitation to many regions that has been demonstrated by this study.

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[21] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Adler, R., et al. (2003), The version 2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present), *J. Hydrometeorol.*, *4*, 1147–1167.

Bengtsson, L., K. Hodges, and E. Roeckner (2006), Storm tracks and climate change, *J. Clim.*, *19*, 3518–3543.

Bengtsson, L., K. Hodges, and N. Keenlyside (2009), Will extratropical storms intensify in a warmer climate?, *J. Clim.*, *22*, 2276–2301.

Berry, G., M. J. Reeder, and C. Jakob (2011), A global climatology of atmospheric fronts, *Geophys. Res. Lett.*, *38*, L04809, doi:10.1029/2010GL046451.

Bjerknes, J. (1919), On the structure of moving cyclones, *Mon. Weather Rev.*, *47*, 95–99.

Bjerknes, J., and H. Solberg (1922), *Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation*, Grøndahl, Oslo.

Catto, J. L., C. Jakob, G. Berry, and N. Nicholls (2012), Relating global precipitation to atmospheric fronts, *Geophys. Res. Lett.*, *39*, L10805, doi:10.1029/2012GL051736.

Champion, A., K. Hodges, L. Bengtsson, N. Keenlyside, and M. Esch (2011), Impact of increasing resolution and a warmer climate on extreme weather from Northern Hemisphere extratropical cyclones, *Tellus, Ser. A*, *63*, 893–906.

Dee, D., et al. (2011), The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, *Q. J. R. Meteorol. Soc.*, *137*, 553–597.

Field, P., and R. Wood (2007), Precipitation and cloud structure in midlatitude cyclones, *J. Clim.*, *20*, 233–254.

Finnis, J., M. M. Holland, M. C. Serreze, and J. J. Cassano (2007), Response of Northern Hemisphere extratropical cyclone activity and associated precipitation to climate change, as represented by the Community Climate System Model, *J. Geophys. Res.*, *112*, G04S42, doi:10.1029/2006JG000286.

Held, I. (1993), Large-scale dynamics and global warming, *Bull. Am. Meteorol. Soc.*, *74*, 228–242.

Hodges, K. (1994), A general method for tracking analysis and its application to meteorological data, *Mon. Weather Rev.*, *122*, 2573–2586.

Hodges, K. (1995), Feature tracking on the unit sphere, *Mon. Weather Rev.*, *123*, 3458–3465.

Hodges, K. (1999), Adaptive constraints for feature tracking, *Mon. Weather Rev.*, *127*, 1362–1373.

Hoskins, B., and K. Hodges (2002), New perspectives on the Northern Hemisphere winter storm tracks, *J. Atmos. Sci.*, *59*, 1041–1061.

Hou, A., S. Zhang, A. da Silva, W. Olson, C. Kummerow, and J. Simpson (2001), Improving global analysis and short-range forecast using rainfall and moisture observations derived from TRMM and SSM/I passive microwave sensors, *Bull. Am. Meteorol. Soc.*, *82*, 659–680.

Houze, R. A., Jr. (2012), Orographic effects on precipitating clouds, *Rev. Geophys.*, *50*, RG1001, doi:10.1029/2011RG000365.

Huffman, G., R. Adler, M. Morrissey, D. Bolvin, S. Curtis, R. Joyce, B. McGavock, and J. Susskind (2001), Global precipitation at one-degree daily resolution from multi-satellite observations, *J. Hydrometeorol.*, *2*, 36–50.

Kållberg, P. (2011), *Forecast Drift in ERA-Interim*, Eur. Cent. for Medium-Range Weather Forecasts, Reading, U. K.

Kummerow, C., W. Berg, J. Thomas-Stahle, and H. Masunaga (2006), Quantifying global uncertainties in a simple microwave rainfall algorithm, *J. Atmos. Oceanic Technol.*, *23*, 23–37.

Lambert, S., and J. Fyfe (2006), Changes in winter cyclone frequencies and strengths simulated in enhanced greenhouse warming experiments: Results from the models participating in the IPCC diagnostic exercise, *Clim. Dyn.*, *26*, 713–728.

Meehl, G. A., J. M. Arblaster, and C. Tebaldi (2005), Understanding future patterns of increased precipitation intensity in climate model simulations, *Geophys. Res. Lett.*, *32*, L18719, doi:10.1029/2005GL023680.

Naud, C., A. Del Genio, M. Bauer, and W. Kovari (2010), Cloud vertical distribution across warm and cold fronts in CloudSat-CALIPSO data and a general circulation model, *J. Clim.*, *23*, 3397–3415.

Pfahl, S., and H. Wernli (2012), Quantifying the relevance of cyclones for precipitation extremes, *J. Clim.*, *25*, 6770–6780.

Pitt, M. (2008), Learning lessons from the 2007 floods, interim report, Cabinet Off., London.

Raible, C., P. Della-Marta, C. Schwierz, H. Wernli, and R. Blender (2008), Northern Hemisphere extratropical cyclones: A comparison of detection and tracking methods and different reanalyses, *Mon. Weather Rev.*, *136*, 880–897.

Schultz, D., and G. Vaughan (2011), Occluded fronts and the occlusion process: A fresh look at conventional wisdom, *Bull. Am. Meteorol. Soc.*, *92*, 443–466.

Serreze, M., A. Barrett, and F. Lo (2005), Northern high-latitude precipitation as depicted by atmospheric reanalyses and satellite retrievals, *Mon. Weather Rev.*, *133*, 3407–3430.

Shaffrey, L., et al. (2009), UK HiGEM: The new UK high-resolution global environment model-model description and basic evaluation, *J. Clim.*, *22*, 1861–1896.

Sibley, A. (2010), Analysis of extreme rainfall and flooding in Cumbria 18–20 November 2009, *Weather*, *65*, 287–292.

Simmonds, I., K. Keay, and J. Bye (2011), Identification and climatology of Southern Hemisphere mobile fronts in a modern reanalysis, *J. Clim.*, *25*, 1945–1962.

Simmons, A., S. Uppala, D. Dee, and S. Kobayashi (2007), ERA-Interim: New ECMWF reanalysis products from 1989 onwards, *ECMWF Newsl.*, *110*, 25–35.

Simmons, A. J., K. M. Willett, P. D. Jones, P. W. Thorne, and D. P. Dee (2010), Low-frequency variations in surface atmospheric humidity, temperature, and precipitation: Inferences from reanalyses and monthly gridded observational data sets, *J. Geophys. Res.*, *115*, D01110, doi:10.1029/2009JD012442.

Smith, T., P. Arkin, J. Bates, and G. Huffman (2006), Estimating bias of satellite-based precipitation estimates, *J. Hydrometeorol.*, *7*, 841–856.

Stephens, G. L., T. L'Ecuyer, R. Forbes, A. Gettlemen, J.-C. Golaz, A. Bodas-Salcedo, K. Suzuki, P. Gabriel, and J. Haynes (2010), Dreary state of precipitation in global models, *J. Geophys. Res.*, *115*, D24211, doi:10.1029/2010JD014532.

Trenberth, K. (1999), Conceptual framework for changes of extremes of the hydrological cycle with climate change, *Clim. Change*, *42*, 327–339.

Ulbrich, U., T. Brücher, A. Fink, G. Leckebusch, A. Krüger, and J. Pinto (2003), The central European floods of August 2002: Part 1—Rainfall periods and flood development, *Weather*, *58*, 371–377.

Ulbrich, U., G. Leckebusch, and J. Pinto (2009), Extra-tropical cyclones in the present and future climate: A review, *Theor. Appl. Climatol.*, *96*, 117–131.

Erratum

In the originally published version of this article, a typographical error in the supporting information text file published unaltered. The PDF file has since been corrected and this version may be considered the authoritative version of record.
The following change was made:
In the text S01 PDF file, "CHECK REF" was deleted.