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Evaluation of Extratropical Cyclone Precipitation in the North Atlantic Basin: An analysis of ERA-Interim, WRF, and two CMIP5 models

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Abstract

The representation of extratropical cyclones (ETCs) precipitation in general circulation models (GCMs) and a weather research and forecasting (WRF) model is analyzed. This work considers the link between ETC precipitation and dynamical strength and tests if parameterized convection affects this link for ETCs in the North Atlantic Basin. Lagrangian cyclone tracks of ETCs in ERA-Interim reanalysis (ERA-I), the GISS and GFDL CMIP5 models, and WRF with two horizontal resolutions are utilized in a compositing analysis. The 20-km resolution WRF model generates stronger ETCs based on surface wind speed and cyclone precipitation. The GCMs and ERA-I generate similar composite means and distributions for cyclone precipitation rates, but GCMs generate weaker cyclone surface winds than ERA-I. The amount of cyclone precipitation generated by the convection scheme differs significantly across the datasets, with GISS generating the most, followed by ERA-I and then GFDL. The models and reanalysis generate relatively more parameterized convective precipitation when the total cyclone-averaged precipitation is smaller. This is partially due to the contribution of parameterized convective precipitation occurring more often late in the ETC life cycle. For reanalysis and models, precipitation increases with both cyclone moisture and surface wind speed, and this is true if the contribution from the parameterized convection scheme is larger or not. This work shows that these different models generate similar total ETC precipitation despite large differences in the parameterized convection, and these differences do not cause unexpected behavior in ETC precipitation sensitivity to cyclone moisture or surface wind speed.

1. Introduction

Extratropical cyclones (ETCs) are responsible for the majority of wintertime precipitation in the midlatitudes (e.g., Hawcroft et al. 2012). For general circulation model (GCM) projections of this midlatitude precipitation to be useful, the models should accurately

capture ETC precipitation in the current climate. One process that may be a particular issue for GCM is latent heating within the cyclones (Willison et al. 2015, Hawcroft et al. 2016), which is related to cyclone precipitation and can affect the dynamical strength of the cyclone (e.g., Emanuel et al. 1987; Stoelinga 1996), and this change in dynamics can feedback on the precipitation amount. Recent work suggests that parameterized convection in models can impact the moisture content within a cyclone's warm conveyor belt (WCB; e.g. Carlson 1998, p. 305) by transporting the moisture upward and out of the WCB at the WCB entrance region (Boutle et al. 2011; Booth et al. 2013). Following this chain of reasoning, the present study examines ETC precipitation and the precipitation generated by the convection scheme in reanalysis data, GCMs, and a regional climate model. The research is focused on determining the skill of the reanalysis and the different models, relative to each other, in generating ETC precipitation and determining if the contribution of precipitation from the convection scheme impacts the relationship between the cyclones and their water vapor content and surface winds.

The analysis will utilize cyclone-centered compositing, which is a useful tool for bulk comparisons of ETCs across datasets that do not have identical ETC tracks. Previous work has shown that GCMs with horizontal resolution of less than 1° are capable of generating realistic winds and precipitation composites (Field et al. 2008; Bengtsson et al. 2009; Catto et al. 2010; Hawcroft et al. 2015). The Bengtsson et al. (2009) study also found that a model with approximately 2° resolution did not produce strong enough ETCs in terms of both winds and precipitation. The present work seeks to extend those previous analyses by considering two models with 2° by 2.5° resolution, the Coupled Intercomparison Project 5 (CMIP5) Geophysical Fluid Dynamics Laboratory (GFDL) model and the NASA Goddard Institute for Space Studies (GISS) model. This analysis is part of a project in collaboration with the modeling centers focused on testing and improving moist processes in their GCMs. Of particular interest is the impact of parameterizations on ETCs; here we will focus on parameterized convection.

In both the GFDL and the GISS GCM, there is a single convection parameterization used globally, meaning the schemes in the models are usually designed with attention on the tropics. In contrast, the Weather Research and Forecast (WRF) model (Skamarock et al. 2008) was developed originally for forecasting midlatitude weather. These different constraints on parameterized physics motivate us to compare ETC precipitation between GCMs and WRF. Herein, we analyze ETC precipitation from integrations in which WRF was configured as a regional climate model (Willison et al. 2015; Michaelis et al. 2017).

As part of the comparison of the datasets, we will test model ETC precipitation sensitivity to changes in cyclone moisture and wind speed. This is motivated by the warm conveyor belt (WCB) rain model of Field and Wood (2007; hereafter FW2007). Given the observational data available, FW2007 developed the following model:

$$R_{\text{WCB}} = k^* \text{PWV}^* \text{WSPD}. \quad (1)$$

In (1), PWV and WSPD are cyclone-averaged values of precipitable water vapor and surface wind speed. This model has been used for analyzing GCM precipitation (Field et al. 2008), and showing precipitation changes in ETCs in a GCM global warming projection are mainly related to changes in PWV (Yettella and Kay 2016). The fit of the R_{WCB} model can vary with cyclone life cycle and latitude (Pfahl and Sprenger, 2016), and this will be considered in our analysis.

As mentioned above, there is reason to ask if parameterized convection impacts the relationship between ETC precipitation and surface wind speed. Boutle et al. (2011) and Booth et al. (2013) show that if parameterized convection is active in the equatorward region of a modeled ETC's warm sector, it can remove moisture from the WCB. In addition, the different vertical distribution of heating profiles typically associated with convection and isentropic ascent can impact cyclone development (Tierney et al., in revision). Therefore, the analysis herein uses cyclone-centered compositing to analyze the relationships between dynamical strength, precipitation, and parameterized convection within ETCs. However, in the feedback loop between precipitation and surface wind speed, we will only focus on one direction: the response of precipitation to changes in wind speed.

The results section of the paper is organized as follows: first we analyze the distribution of ETC strength, which is motivated by the fact that latent heating associated with precipitation can impact cyclone strength. This is followed by analyses of the composite means and distributions of ETC precipitation rates as well as the precipitation generated by the convection scheme. We find that total precipitation is similar for the most of the datasets, despite large differences in the precipitation amount generated by the convection scheme. Therefore, we characterize the behavior of convective precipitation across the different datasets. Finally, we examine the sensitivity of modeled ETC precipitation to changes in cyclone water vapor and surface wind speed, and whether the sensitivity is affected by precipitation from the convection scheme. This work provides information on both the behavior of parameterized convective precipitation in ETCs and its potential impact on the ETC precipitation, and to our knowledge, it is the first direct comparison of ETC precipitation between GCMs and WRF.

2. Data and Methods

Table 1 provides a summary of the datasets used in this analysis. The WRF data were produced for a limited regional domain and a specific season and time period. Therefore the same domains and time periods are used for reanalysis and GCM output when possible.

Two configurations of a WRF regional climate model (RCM) are used, both of which have been described in detail in Willison et al. (2015). One configuration has a horizontal resolution of 120 km (hereafter, WRF-120km). The second version has a horizontal resolution of 20 km (hereafter, WRF-20km). These resolutions were chosen because they are typical resolutions of GCMs (i.e. the 120 km model) and regional climate models (20 km). The WRF domain covers the North Atlantic Ocean extending from 15° N to 72° N and 96° W to 46° E. The model lateral boundary conditions and surface conditions are the NCEP Final Analyses (NCEP/NWS/NOAA/U.S. Department of Commerce, 2000). Starting in

2001 and ending in 2010, model runs begin on Dec. 24 and continue until Apr. 7 of the following year. The first week of each winter's integration is not used, to avoid issues with model spin-up, and so the analysis focuses on JFM for 2002–2011. See Willison et al. (2015) for a discussion of model setup, spin-up, and sensitivities.

The reanalysis used is ERA-Interim (Dee et al. 2011), which will be referred to as ERAI. The time period used is 2002 – 2011, and the months used are Jan. – Mar. ERAI has been shown to compare well with other reanalysis data for ETC dynamical strength, and spatial distribution (Hodges et al. 2011). Based on daily means, ERAI precipitation compared reasonably well (Hawcroft et al. 2012) with Global Precipitation Climatology project dataset (Adler et al., 2003). Based on recent analysis of ETC precipitation composites based on instantaneous satellite data, it appears that ERAI might slightly underestimate ETC precipitation, however the ERAI bias is no larger than differences between multiple satellite platforms (Naud et al., 2017, submitted to J. Appl. Meteorol. Climatol.).

As mentioned in Section 1, the GCMs used for this study are GFDL CM3 and GISS ModelE2. For GFDL, we use the first physics configuration (i.e., *r1i1p1*) of the coupled model CM3 (Donner et al. 2011) for the historical CMIP5 experiment. The data were downloaded from the GFDL NOMADS portal. This model integration ended in 2005, therefore the Jan. – Mar. data for the years 1996 – 2005 are used in the analysis. For the NASA GCM, we use ModelE2 (Schmidt et al. 2014). As with GFDL, we use the *r1i1p1* version of the model. GISS submitted two versions of the model to the CMIP5 catalog; here we analyze the version using the NASA GISS Hycom Ocean model (Bleck 2002; i.e., GISS ModelE2-H in CMIP5). To match GFDL, the Jan. – Mar. data for 1996 – 2005 are used. These models will be referred to as GFDL and GISS respectively.

Before doing any cyclone tracking, statistics, or compositing analysis, the reanalysis and WRF RCM data are regridded to the $2^\circ \times 2.5^\circ$ horizontal resolution grid used by the GCMs. The regridding is accomplished using CISL's NCAR Command Language (NCL) tools. This method uses an inverse distance squared weighting of the four points in the WRF grid that are closest to each point in the GCM grid. Although this scheme makes an “area-mean” assumption, it is non-conservative. This can lead to the possibility of more extreme values (Chen and Knutson, 2008). However, we ran comparisons of the precipitation distributions for the original and regridded data and found that the impact of regridding on the largest precipitation rates are less than 1% for the distributions we analyze. For the regridded data, there is a 4% increase in the occurrence of smaller precipitation rates, i.e., the 0 to 1 mm day⁻¹ range, and a corresponding decrease in the occurrence of zero precipitation. However, the overall shapes of the distributions do not change before and after regridding. Given the availability and portability of NCL, we chose to use its regridding scheme because it allows for easy reproducibility of the analysis.

The variables analyzed here are precipitation, convective precipitation, sea level pressure (SLP), specific humidity at 850 hPa (Q850), and 10-meter wind speed. For precipitation, WRF and ERAI provide accumulated data every 6 hours. In the case of ERAI, we do not use the data generated during the first 6 hours of the forecast (referred to here as the reanalysis version), as it has been found to have a spin-up bias (Hawcroft et al. 2015). By using the

forecast product for precipitation and reanalysis version for the cyclone locations for ERAI, we may introduce small differences in the location of the cyclone center relative to the precipitation. We bare this in mind in the interpretation of the results. GFDL provides 3-hourly time-averaged precipitation that we average into 6-hourly data. GISS provides 6-hourly time-averaged data. We multiply the 6-hourly data by four to obtain units of mm day⁻¹, for consistency with FW2007.

For our analysis of the WCB rain model, we use Q850 not PWV (as in FW2007), because the CMIP5 data archive does not include 6-hourly PWV data. We use ERAI to test if this replacement is reasonable. For the Northern Hemisphere, for the latitudes between 20° and 65°, we calculate the spatial correlation of 6-hourly snapshots of PWV and Q850 for a set of 100 randomly selected dates. For these cases, the correlation between PWV and Q850 has an average value of 0.92 and is never less than 0.9. If the land is excluded the average correlation value is 0.94. We also create a linear estimate of PWV from Q850 and find that large biases rarely occur and do not systematically affect specific cyclone regions. Therefore, given the availability of data, the analysis reported here will use Q850 in the WCB model.

Extratropical cyclone tracks in the models and reanalysis are identified using the Lagrangian tracking algorithm of Bauer et al. (2016), which is an update of the algorithm in Bauer and Del Genio (2006). The algorithm identifies low-pressure centers, using 6-hourly SLP fields, and then the cyclones are linked into tracks. Bauer et al. (2016) show that the skill of their algorithm compares well with multiple other tracking programs summarized in Neu et al. (2013). The term cyclone refers to 6-hourly snapshots, and track refers to the full life cycle.

For the GCM and reanalysis, the tracking algorithm can be applied to global data, whereas the RCM only has data for its specified domain. Therefore, a set of criteria is used to homogenize the GCM and ERAI tracks, in order to minimize biases associated with the RCM's limited domain. To account for the fact that the RCM might have biases in track genesis near its edges, we remove any tracks in which all of the cyclone centers are: (a) north of 55° N, (b) south of 36° N, (c) west of 72°W, or (d) east of 5° E. Also, any individual cyclones outside of the RCM domain are removed (the remainder of the track is retained). Then, we check that the portion of the track that remains would have been retained by the Bauer et al. (2016) tracker, based on its duration and propagation distance (otherwise the equivalent tracks would not be in the RCM track data). Any tracks total distance traveled less than 500 km are presumed to be cut-off lows associated with topography and are removed (see Bauer et al. 2016).

Our preliminary analysis identified a large difference in WSPD for WRF cyclones over land, in both WRF models, as compared to the reanalysis and GCMs. This may be due to differences in the models' surface layer schemes. Therefore, we masked land points, and only analyzed cyclones for which at least 50% of the region within 1000 km of the center is over ocean, hereafter, ocean cyclones. To accomplish this, we test per track for ocean cyclones and remove those that are not. Then we test that the track still has at least 5 cyclones adjacent in time. If so, we retain the new track consisting only of the ocean

cyclones that are adjacent in time. These tracks are used for the remainder of the analysis and summarized in Table 1.

Figure 1a shows cyclone density for ERAI. Note that the region shown is smaller than the WRF domain. The maximum near the Gulf Stream region and the SW to NE tilt in the cyclone density exists for all of the models (not shown). The reanalysis and GCMs have 5–15% more tracks on the western half of the ocean basin than the WRF models. To test if this affects the results, we randomly sub-sampled the tracks from all of the models to have a matching number: 200. The results using this subset are very similar to the results using the full set of cyclones, and therefore we report the results using all cyclones. Figure 1b shows that the models and reanalysis have similarly distributed cyclones with respect to latitude, however the maxima for the GCMs are south of that of reanalysis. This issue in GCMs could be related to cyclone steering (for details on steering see Booth et al. 2017), and the steering biases may be associated with model representation of orographic drag (Pithan et al. 2016). To account for the differences in latitudinal distribution of the cyclones, we randomly subsampled cyclones per 4° latitude bin, so that each dataset had the same number of cyclones per bin, and repeated our analysis. This also did not have a noticeable impact, and therefore we use the cyclones shown in Fig. 1b.

To calculate cyclone-centered averages, we identify all data within 1000 km of each cyclone's center, using the 2 by 2.5 regrided data. For cyclone-centered averaging, we calculate area-weighted averages of the data on the geographic grid. The distance of 1000 km differs from FW2007, who use 2000 km. The choice of a smaller radius is motivated by the fact that latent heating close to the cyclone center (where potential vorticity tends to be stronger) can have a larger impact on the dynamics (e.g. Martin, 2006, p.293). As discussed above, we mask out areas over land. For composite figures, we show results extending out to 2000 km, for ease of comparison with FW2007. We project cyclone-centered data to a stereographic projection, taking into account the different distances from the cyclone center for different latitudes. For the composites, we do not rotate the fields relative to the cyclone propagation direction, as we found that it had only minimal impact on the results. We note that small differences in the location of the peak precipitation relative to the cyclone center will not be a focus of this study, as they might relate to issues of using ERAI forecast products for precipitation but not for SLP.

Significance tests for the distributions are conducted using the Kolmogorov-Smirnov goodness-of-fit test, at a 99% significance interval. This tests the null hypothesis that two distributions are drawn from the same population. Therefore, in cases in which we consider multiple distributions, we compare each pair individually.

3. Results

The analysis is separated into three sections. First, cyclone dynamical strength and precipitation strength are examined, both to compare the models with reanalysis and to provide a bulk analysis of the relationship between latent heating associated with cyclone precipitation and cyclone circulation strength. Then, motivated by the potential impact of convection on ETC latent heating, the role of precipitation from convective

parameterizations is analyzed. Finally, ideas from the first two sections are brought together in an analysis of the sensitivity of total precipitation to cyclone surface wind speed and moisture for subsets with different levels of convective activity.

3.1 Cyclone Dynamical Strength and Precipitation

As discussed above, in-cyclone-latent heating, which is associated with the cyclone's precipitation, can strengthen the cyclones dynamically. Therefore, we begin with an analysis of cyclone dynamical strength based on WSPD. We choose WSPD because it relates to storm damage (e.g., Shimkus et al 2017; Walz et al. 2017 and references therein) and 850-hPa relative vorticity, which is a common metric in cyclone tracking studies (e.g. Zappa et al. 2013). WRF-20km has the highest frequency of strong cyclones, followed by ERAI (Fig. 1c). WRF-20km's WSPD distribution is shifted towards stronger values relative to those of the other models' based on the Kolmogorov-Smirnov goodness-of-fit test. By the same test, ERAI cyclones also tend to be stronger than GFDL, GISS, and WRF-120. These model-to-model differences in WSPD can have big impacts because storm damage relates to the cube of wind speed (e.g., Leckebusch et al. 2008). In an analysis of the distributions of cyclone central SLP also reveals that ERAI and WRF-20km have deeper cyclones more frequently than the other models (not shown). Both the WSPD and SLP results look similar when we subsample the datasets to account for the differences in their latitudinal distributions, and therefore they are not shown.

Next we consider cyclone-centered precipitation composites using cyclones that have the strongest cyclone-averaged precipitation rate per cyclone track. We focus on this snapshot in the life cycles because of the two-way link between precipitation and dynamical strength, which we do not want to lose by averaging the different precipitation patterns that emerge throughout the life cycle (Rudeva and Gulev 2011). Figure 2 shows reanalysis and models all generate a similar spatial pattern: a comma shape with a maximum near the cyclone center extending slightly east. The southwestward extension of precipitation from the cyclone center indicates the location of the cold fronts. Cyclone-average values at 500, 1000, and 2000 km are included on the figure to help quantify model-to-model similarities and differences. ERAI, GFDL, GISS, and the WRF-20km models have good agreement in magnitude, the differences are less than 10% based on 500-km-cyclone-average), but there are some differences. GFDL generates more precipitation than ERAI towards the cyclone center and less in the cold frontal region within 1000km of the center. In contrast, GISS matches ERAI near the center but generates more precipitation than ERAI in the cold front region. WRF-120km model has too little precipitation everywhere. WRF-20km generates the most precipitation; Bengtsson et al. (2009) also found that their model that had finer spatial resolution produced more ETC precipitation than reanalysis. As discussed in section 2, the differences between ERAI and WRF-20km are within the range of uncertainty of observations based on satellite data.

The spatial distribution of precipitation in the composite means is not representative of most individual cyclones, which tend to have thinner cold frontal precipitation regions and more inhomogeneity in the precipitation rates near the fronts. This point is made clear in Figure 3, which shows the standard deviation for the composited cyclones. The maximum in cyclone-

to-cyclone variability is coincident with the maximum in the composite mean. As in Fig. 2, GFDL has more precipitation activity near the center and less along the cold front, indicating that this model concentrates its ETC precipitation in the warm sector. The larger standard deviation in the WRF-20km model is indicative of the model's well-resolved fine-scale frontal precipitation.

Composite means can sometimes hide differences, because they involve averaging a large set of data. As such, we examine frequency distributions of precipitation rates for the data used to calculate the means (Fig 4). For points within 1000 km of the cyclones' centers, the models all generate a similar distribution, with a maximum at weak precipitation rates (i.e., 0 – 1 mm day⁻¹). ERAI and WRF-20km have larger relative frequencies of zero precipitation, and WRF-20km has the largest relative frequency of the strongest precipitation rates (Fig 4a). If we consider points within 500 km of the cyclones' centers (Fig. 4b), the peak in the distribution shifts to larger values, between 8 and 16 mm day⁻¹ for all models except in WRF-20km. As discussed in Section 2, the peak in weak precipitation in WRF-20km is not a result of regridding. WRF-20km again has the largest frequency of strong rates, suggesting a stronger potential impact of latent heating in conditions where latent heating would be expected to be large. If we compare the distributions for precipitation rates greater than 8 mm day⁻¹, the WRF-20km model significantly differs from the others based on the method described in Section 2. The propensity for WRF-20km to have stronger precipitation rates than the other models may be related to its finer resolution (e.g., Champion et al. 2011, Li et al. 2011).

The WRF-20km model has stronger cyclones dynamically and in terms of precipitation, consistent with the idea of latent heating interacting with cyclone circulation. However, a similar relationship is not found across the other datasets. ERAI has the stronger WSPD, but nearly equal precipitation rates as GISS. The GFDL model has stronger precipitation rates near the cyclone center, but not stronger WSPD. The lack of a relationship between model-to-model differences in precipitation and dynamical cyclone strength could be the result of multiple factors, such as surface boundary conditions, dry baroclinic forcing, or biases in the modeled latent heating within the cyclone. Here we explore the latter factor, based on the hypothesis discussed in the introduction: it is possible that parameterized convection is interfering with the thermodynamic link between precipitation and cyclone strength. Therefore the next analysis focuses on understanding the behavior of ETC precipitation from the convections schemes.

3.2 ETC Precipitation Generated by Convection Parameterizations

The reanalysis and models each use a different convection scheme (Table 1), and each saves convective precipitation as a standard output variable. We note that the convective precipitation output saved by models might only provide a minimum estimate of convective activity in the model. This is because: (1) a convection scheme may activate and then pass moisture to the large-scale microphysics scheme where precipitation is generated, and (2) a model may resolve some of the convection. Nonetheless, precipitation from the convective scheme serves as a conservative indicator of convective activity and highlights vertically unstable regions in cyclones. To improve the flow of the text, we refer to the precipitation

from the convection scheme as the parameterized convective precipitation for the remainder of the results section.

For all models, parameterized convective precipitation is at most 1/3 the strength of the total composite mean precipitation (Fig. 5). However, model-to-model differences in the amplitude of precipitation from the convective scheme are large compared to total precipitation (e.g., 20% differences in the 500-km average). In terms of spatial distributions, all models have parameterized convective precipitation near the cold front, which is expected based on observations (e.g., Browning and Roberts, 1996). However, for GISS, parameterized convective precipitation has a maximum coincident with the maximum for total precipitation, in the warm sector. Precipitation rates in the convection composite are smallest in WRF-20km, perhaps because the model has a spatial resolution that can resolve some aspects of convection. Analysis of the distributions for convective precipitation (not shown) confirms the results shown in the composite mean analysis: (i) convective precipitation rates are smaller than the total precipitation rates, and (ii) ERAI and GISS, and to a lesser extent GFDL, more frequently have stronger parameterized convective precipitation as compared to the WRF RCMs.

To better understand if parameterized convective precipitation impacts ETC precipitation, we analyze its behavior. This work will include analysis of convective precipitation during cyclone life cycles; therefore it considers all cyclones per track. We define a new metric for this analysis, convective fraction, as the cyclone-averaged precipitation from the convective scheme divided by cyclone-averaged total precipitation for each cyclone.

Figure 6 shows two-dimensional joint frequency distributions of cyclone-averaged precipitation and convective fraction. For ERAI, the most frequent precipitation rates have a convective fraction that ranges from 0 to 1, and most often is 0.4. At larger precipitation rates, the range and modal values of the convective fraction both decrease. The relationship between convective fraction and total precipitation in GFDL and WRF-120km is similar to ERAI. However, for WRF-120km the peak in frequency at weak precipitation rates occurs closer to zero. WRF-20km has an even smaller contribution from the convection scheme. The GISS model is unique because the convective fraction is most often near 0.4, and the range of convective fraction values is smaller than any of the other datasets. Thus, the GISS model regularly has 40% of its precipitation generated by the convection scheme regardless of the overall precipitation rate. Despite this unique behavior, the composite and distribution for total ETC precipitation for GISS is similar to ERAI.

Next we examine if convective fraction relates to ETC life cycle. We designate each cyclone (i.e., the 6-hourly snapshots) with a life cycle age that is relative to the time of peak WSPD for the track, i.e., for each track the cyclone with the maximum cyclone-averaged WSPD has age zero; cyclones in the track that occur prior to peak WSPD have negative ages. Then we divide each model's cyclone dataset in half using the median value of convective fraction per dataset (see Fig. 6), and plot the distribution of cyclone life cycle age for the half of the cyclone with large convective fraction and the half with small convective fraction (Fig. 7). For all datasets, cyclones with larger convective fraction occur more frequently after the timing of peak WSPD (Fig. 7). These differences in the distributions are statistically

significant. However, the separation between the sets is more obvious for ERAI, GFDL and WRF-120km. This analysis shows that the relative contribution of the convection scheme increases when the cyclone is decaying, for a life cycle defined by WSPD. If we define life cycle using SLP, as in Pfahl and Sprenger (2016), we find a similar result. Also, for each model the peak WSPD per tracks typically occurs coincident with, or 6–12 hours after peak precipitation for these datasets (not shown). Thus, Fig. 7 implies that larger convective fraction occurs more often when cyclone tracks are not generating peak precipitation. The peak in convective fraction during decay is associated with the evolution of the cyclone fronts, as we will discuss in the next section.

This section has revealed that the models have similarities and differences in the characteristics of parameterized convection in ETCs. The relative contribution of the convection scheme to total precipitation varies across the models, but on the other hand all of the models dictate the behavior of the parameterized convection based on the large-scale evolution of the tracks. With this in mind, we test sensitivity of ETC precipitation to cyclone dynamics and thermodynamic conditions and check if the sensitivity is impacted by convective fraction strength.

3.3 Sensitivity of Precipitation to Q850 and WSPD

Following FW2007, we use cyclone-averaged variables to subset the data and analyze how composite precipitation varies with cyclone moisture and surface wind speed. Following FW2007, we: (1) calculate distributions of cyclone-averaged Q850 and WSPD, (2) divide each of the distributions into terciles, and then, (3) find the cyclones that fit into each of the 9 resulting subcategories (Fig. 8). To link the analysis to convective fraction, we first divide the cyclones in half based on strength of convective fraction, and then carry out the WSPD/Q850 subsetting for the strong and weak convective fraction cyclone sets separately, per model. Thus, the thresholds for the WSPD/Q850 analysis are defined separately for each convective fraction subset. Both WRF models differ from the other datasets by having few cyclones with large Q850 values (Fig. 8). This is mainly because it has fewer cyclones in the southern portion of the basin (Fig. 1b.) The differences between the joint distributions of WSPD and Q850 for ERAI, GFDL, and GISS are small, as are the differences between the large and small convective fraction subsets for each of the datasets.

The composite precipitation for WSPD/Q850 subsetting is displayed as follows: in a 3-by-3 panel, moving left to right the columns have subsets with increasing WSPD; moving from the bottom to top, the rows have subsets with increasing Q850. Figure 9 shows two of these 3-by-3 panels, for the ERAI dataset split in half based on convective fraction. The sensitivity to Q850 and WSPD is similar for both the smaller and larger convective fraction subsets: ETC precipitation increases with both Q850 and WSPD (Fig. 9). Fixing Q850 and increasing WSPD leads to an increase in the size of the comma structure of the composite. Fixing WSPD and increasing PWV leads to increases in the precipitation rates close to the cyclone center, but less of a change spatially. These results are consistent with FW2007.

Figure 9 also shows that for ERAI the cyclones with less convective fraction have: (1) stronger precipitation rates, and (2) a more-defined comma shape. These results can both be related to the cyclone life cycle result (i.e., Fig. 7): convection occurs more frequently after

peak precipitation when the cyclone track is reaching an occluded stage with a less well-defined comma structure. In this stage, there is the potential for more convectively generated precipitation (relative to the precipitation near the warm front generated by isentropic lift) near and behind the cold front because the spatial extent of cold advection over warm ocean water increases, and because the cold front has caught up to the warm front decreasing the size of the warm sector at the expense of the growing cold sector.

Figures 10a and 10f summarize the results shown in Figure 8 for ERAI. For these figures, each horizontal bar is a cyclone-average precipitation value for one of the 3-by-3 panels. The figure shows results based on the 500 km cyclone average, however the same result holds for the 1000- and 2000 km cyclone averages. By displaying the results of the WSPD/Q850 subsetting in this manner, it is possible to compare the relative changes in cyclone average precipitation with respect to changes in Q850 (by focusing on a specific color in each panel) versus changes with respect to WSPD (by focusing on a subset of three horizontal bars per panel). The figure shows that these relative changes are similar both on a per model basis and across multiple models.

Figure 10 shows the monotonic increase in precipitation with WSPD and Q850 occurs in both convective fraction subsets. This result is important for two reasons: (1) it shows that ETC precipitation for these datasets co-vary with moisture and dynamical strength in a manner similar to observations, and (2), this covariability is not influenced by parameterized convective precipitations. We also carried out this analysis for cyclone-averaged parameterized convective precipitation only. As with the total precipitation, composites of parameterized convective precipitation have monotonic increases in cyclone-averaged precipitation rates with increases in either WSPD or Q850, and this is true for both of the convective fraction subsets (not shown). Thus, the contribution of parameterized convective precipitation has the same sensitivity to cyclone WSDP and Q850 as the total cyclone precipitation.

Figure 10 also shows that for all models the half of the set with weaker convective fraction has smaller precipitation rates. Thus, the relationship between cyclone life cycle, total precipitation and parameterized convective precipitation that was discussed for ERAI applies to all of the models. Given that all of the models and reanalysis have similar relationships between convective fraction and cyclone life cycle. This result provides a robust suggestion that convective fraction is dictated by the evolution of the cyclone life cycle, rather than the scheme dictating specific behavior in the cyclones or their life cycles.

4. Conclusion

The analysis herein compared extratropical cyclone precipitation for the ERA-interim reanalysis, two GCMs and a WRF regional climate model, integrated at 120 and 20 km resolution. Cyclone-centered composite analysis reveals that the GCMs generate a similar spatial distribution and amplitude of ETC precipitation as the reanalysis and the 20 km WRF model, with the latter generating slightly more ETC precipitation than the other models. By comparison, the 120 km model had noticeably less ETC precipitation. Given that ERAI reanalysis is a numerical weather model run in hindcast mode while assimilating

observations, the fact that the GCMs generate similar composites implies the models represent ETC precipitation with reasonable skill.

This conclusion is made more interesting by the second main result of the analysis: the relative contribution of precipitation from the convection schemes differs between the reanalysis and GCMs by a larger fraction than the total precipitation differences. Thus, the GCMs and ERAI produce similar total composite precipitation accumulations despite differences in the role of the convection scheme. Composite analysis reveals that in all models the convection scheme generate precipitation in the region of the cyclone cold fronts. The WRF-20km model generates the least precipitation through its convection scheme, presumably because it partially resolves convection. ERAI, the GCMs, and the WRF-120km model also have differences in the relative contribution of the convection scheme to total precipitation, as seen in the composites and joint histograms of total precipitation and convective fraction. In particular, the GISS model stands out for having a convective fraction of 40% even in cyclones with heavy precipitation. The unique behavior of the GISS model is also evident in the composite mean plot for the precipitation from the convection scheme, as it has the strongest rates in the warm sector near the cyclone center. Despite these differences, the overall performance of the GISS model in generating ETC precipitation matched ERAI and GFDL.

The non-negligible contribution of the convection scheme to total precipitation in ERAI cannot yet be compared with observations. With the recently released NASA Global Precipitation Measurement (GPM; Skofronick-Jackson et al., 2017) radar-microwave radiometer combined product (Grecu et al., 2016), this may change in the near future. However, the work presented here focused on the relative similarities and differences in the precipitation generated by the convection schemes for ERAI, the GCMs, and WRF, and examined if the differences affected the link between precipitation and cyclone surface wind strength.

For each model, we find that the contribution of precipitation from the convection scheme increases later in the cyclone life cycle, and typically this occurs after the time of peak precipitation per life cycle. As a result, cyclone composites comparing subsets with more and less convective fraction show that convective fraction is lower when more precipitation is present. However, we interpret the differences in total precipitation as a response of the ETCs to changes in the dynamical life cycle, rather than a response to differences in convective precipitation. This conclusion is based on the next result we will discuss: the sensitivity analysis of precipitation relative to cyclone moisture and surface wind speed.

Based on a subsetting analysis, the cyclone-averaged ETC composite precipitation increases in response to increases in cyclone-averaged moisture or surface wind speed. This result holds for the reanalysis and all of the models, and matches the results found in FW2007 for observations. Thus, the modeled ETC precipitation exhibits the correct response to changes in cyclone thermodynamic and dynamics conditions. This result holds true regardless of the strength of the contribution of the precipitation from the convection scheme, which gives another indication that the convection scheme does not have a significant impact on cyclone behavior.

We see the main results of the work as follows: the GCMs are capable of producing realistic ETC precipitation on average; the GCMs and ERAI generate different amounts of precipitation with their convection schemes and it does not affect the total precipitation; the ETC precipitation in GCMs and WRF co-vary with cyclone moisture and surface wind speed in a manner that matches reanalysis and observations; the precipitation generated by the convection scheme is noticeably influenced by cyclone life cycle and cyclone moisture and wind speed conditions, and a forcing in the opposite direction, from convection scheme to ETC behavior is not found. This result is based on composite analysis, and in individual cases the difference in the convection scheme may have a bigger impact. Furthermore, the heating from the convection scheme might impact storms in a manner not analyzed here (e.g., Hawcroft et al., 2016). However, in terms of the hypothesis described in the opening paragraph, the work here suggests that forcing on the ETC associated with changes in the warm conveyor belt due to the convection change is small.

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Figure 1.

(a) Cyclone density for ERAI, per 4° by 4° grid, (b) latitudinal distribution of cyclones per model, and, (c) distribution of cyclone-averaged surface wind speed.

Figure 2.

Cyclone-centered composite mean precipitation. Cyclones used in each composite at the time of cyclone-averaged precipitation maximum per track. Black circles indicate 500 km and 1000 km radii. Values given above each panel are the cyclone-averaged precipitation for 500, 1000, and 2000 km in mm day^{-1} .

Figure 3.

Cyclone-centered composite standard deviation for precipitation, using the same cyclones as in Figure 2. Black circles indicate 500 km and 1000 km radii. Values given above each panel are the cyclone-averaged precipitation for 500, 1000, and 2000 km in mm day⁻¹.

Figure 4.

Distribution of precipitation rates for all points in all cyclones that are in Figure 2. Panel (a) shows all data within 1000 km of the cyclones' centers. Panel (b) shows all data within 500 km of the cyclones' centers. The bars to the left of 0 indicate a 0 precipitation rate, otherwise the bars indicate precipitation rates in the range between the values shown on the x-axis.

Figure 5.

Cyclone-centered composites of convective precipitation, using the same cyclones as in Figure 2. Black circles indicate 500 km and 1000 km radii. Values given above each panel are the cyclone-averaged precipitation for 500, 1000, and 2000 km in mm day⁻¹. Note the scale of this colorbar is much smaller than in Figure 2.

Figure 6.

Joint distribution of cyclone-averaged precipitation and convective fraction using all cyclones in all tracks. Units on contours are cyclone counts per 1.1 mm day^{-1} by 0.055 convective fraction bins. The gray dashed line cuts each set in two halves: one half with larger convective fraction and one half with smaller convective fraction.

Figure 7.

Life cycle distributions relative to maximum WSPD for cyclones separated into two halves: those with larger convective fraction (dashed) and those with smaller convective fraction (solid).

Figure 8.

Cyclone-averaged WSPD versus cyclone-averaged Q850 for half of cyclones with smaller convective fraction (left) and half with larger convective fraction (right). Gray lines separate the data into equal-sized partitions for WSPD and Q850 separately. The resulting set of nine quadrants make up the regions used for the partitioned analysis.

Figure 9.

Cyclone-centered precipitation composites for ERAI, subset based on area-averaged WSPD and Q850 for half of cyclones with smaller convective fraction (top) and half with larger convective fraction (bottom). Black circles indicate 500 km and 1000 km radii. Values given above each panel are cyclone-averaged precipitation for 500, 1000, and 2000 km in mm day⁻¹.

Figure 10.

Summary of the WSPD/Q850 subsetting analysis for half of cyclones with smaller convective fraction (left) and half with larger convective fraction (right). The length of each bar is the 500-km cyclone-averaged precipitation rate for an individual precipitation composite from the subsetting analysis. QLO refer to the bottom row, QMID the middle row and QHI the top row. For each Q set, green corresponds to small WSPD, blue corresponds to medium WSPD, and magenta corresponds to large WSPD. Panel (a) corresponds to the top 3-by-3 set of panels in Figure 9. Panel (f) corresponds to the bottom 3-by-3 set of panels in Figure 9.

Table 1
Reanalysis and Model Overview

Details for models and track and cyclone counts.

	Atmosphere Resolution (lat. × lon.)	Convection Scheme	Track Count	Cyclone Count
ERA-Interim (Dee et al. 2011)	$0.7^{\circ} \times 0.7^{\circ}$ (T255 spectral model)	Tiedke (1989)	353	4446
GFDL CM3 (Donner et al. 2011)	$2^{\circ} \times 2.5^{\circ}$	Donner (1993)	310	4210
GISS ModelE2-R (Schmidt et al. 2014)	$2^{\circ} \times 2.5^{\circ}$	Yao and Del Genio (1989); Kim et al. (2011)	282	4093
WRF RCM (Willison et al. 2015)	120 km × 120 km	Zhang-McFarlane (1995)	224	2836
	20 km × 20 km		266	3057