A Comparison of Extra-tropical Cyclones in Recent Re-analyses; ERA-INTERIM, NASA-MERRA, NCEP-CFSR and JRA25.

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Abstract

Extra-tropical cyclones are identified and compared using data from four recent re-analyses for the winter periods in both hemispheres. Results show the largest differences occur between the older lower resolution JRA25 re-analysis when compared with the newer high resolution re-analyses, in particular in the Southern Hemisphere (SH). Spatial differences between the newest re-analyses are small in both hemispheres and generally not significant except some common regions associated with cyclogenesis close to orography. Intensities are generally related to spatial resolution except NASA-MERRA which has larger intensities for several different measures. Matching storms between re-analyses shows the number matched between ERA-Interim and the other re-analyses are similar in the Northern Hemisphere (NH). In the SH the number matched between JRA25 and ERA-Interim is lower than in the NH, but for NASA-MERRA and NCEP-CFSR the number matched is similar to the NH. The mean separation of the identically same cyclones is typically less than 20° geodesic in both hemispheres for the latest re-analyses, whereas JRA25 compared with the other re-analyses has a broader distribution in the SH indicating greater uncertainty. The instantaneous intensity differences for matched storms shows narrow distributions for pressure while for winds and vorticity the distributions are much broader indicating larger uncertainty typical of smaller scale fields. Composite cyclone diagnostics show that cyclones are very similar between the re-analyses, with differences being related to the intensities, consistent with the intensity results. Overall, results show NH cyclones correspond well between re-analyses, with a significant improvement in the SH for the latest re-analyses, indicating a convergence between re-analyses for cyclone properties.
1. Introduction

Re-analyses are an important means of producing observationally constrained data for studying atmospheric circulation systems. They are produced using Numerical Weather Prediction (NWP) systems producing analyses (initial conditions for a forecast) at sub-daily frequency. This is done by combining historical atmospheric observations with a comprehensive model of the atmosphere using data assimilation to produce homogenous 4-dimensional data. As NWP systems are continuously improving with the introduction of new data assimilation methods and models (Kalnay 2003), it is important to continuously redo the re-analyses to extract more information from the available observations and to provide us with better long term data for climate studies (Bengtsson and co authors 2007).

Re-analyses have been popular for a wide range of studies of the atmosphere due to their homogenous nature compared to raw observations. One of the areas where re-analyses are important is in the study of extra-tropical cyclones. Re-analyses are important, not only to provide information on the properties, climatology and variability of extra-tropical cyclones (Hoskins and Hodges 2002, 2005), but also to provide a means of validating climate models with respect to these storms, e.g. Bengtsson et al. (2006) and Bengtsson et al. (2009). However, to have confidence in such studies it is important to understand the uncertainties in the representation of cyclones in the re-analyses.

One way to explore the uncertainties is to inter-compare the re-analyses. For extra-tropical cyclones this can be achieved by identifying them and their full lifecycles in each re-analysis and then comparing their spatial distribution and properties. Several previous
studies have performed these types of studies including that of Hodges et al. (2003, 2004), Bromwich et al. (2007), Wang et al. (2006), Hanson et al. (2004) and Trigo (2006). These earlier studies made use of the older re-analyses, such as the Goddard Earth Observing System version 1 (GEOS-1) (Schubert et al. 1993); National Centers for Environmental Prediction (NCEP-NCAR and DOE) (Kalnay 2003); European Centre for Medium-Range Weather Forecasts (ECMWF) 15-yr Reanalysis (ERA15) (Gibson et al. 1997) and 40-year re-analysis (ERA40) (Uppala and Coauthors 2005); and Japan Meteorological Agency and Central Research Institute of Electric Power Industry 25-year reanalysis (JRA25) (Onogi et al. 2007). These relied on earlier forms of data assimilation and were also at relatively low resolution compared with the latest re-analyses.

Earlier studies have shown that in the Northern Hemisphere (NH) the older re-analyses generally compare well in terms of their spatial distribution and the number of cyclones that can be matched between re-analyses, including the mean separation distances of matched storms (Hodges et al. 2003, 2004; Wang et al. 2006). In the Southern Hemisphere (SH) larger differences were found, indicating a higher degree of uncertainty in the representation of extra-tropical cyclones there. This is likely related to how the available observations, which in the SH are dominated by satellite observations, are assimilated. In fact for the older re-analyses with direct assimilation of radiances, such as ERA40 and JRA25, cyclones compare better in the SH, but still not as well as in the NH.

The production of re-analyses is an ongoing program in several NWP centers with new re-analyses being produced as new models and data assimilation methods are introduced. It is important to continually evaluate new re-analyses to determine where improvements
have been made and to highlight continuing deficiencies, in particular due to changes in the observing system and resolution. In this study three new re-analyses and one of the older re-analyses are explored for extra-tropical cyclone activity for the modern satellite period (1979-2009). The re-analyses studied are JRA25 (Onogi et al. 2007); the ECMWF Interim Re-analysis (ERA-Interim) (Simmons et al. 2007); the NASA Modern Era Retrospective Re-analysis (NASA-MERRA) (Bosilovich 2008); and the NCEP Coupled Forecast System re-analysis (NCEP-CFSR) (Saha and Co-authors 2010; Saha et al. 2006).

This paper essentially repeats the original analysis of Hodges et al. (2003, 2004) with these more recent re-analyses. The scientific aims of the paper are two fold; firstly to determine how well the new re-analyses inter-compare with respect to cyclones, and hence indicate the degree of uncertainty in their properties; secondly to see if there any improvements over the older re-analyses. The focus is on synoptic scale cyclones in both hemispheres for the winter periods. Smaller scale systems such as mesocyclones are likely to be more sensitive to available observations, as well as the model and data assimilation.

The paper continues in section 2 with a brief description of the data and methodology used. Section 3 presents results of the spatial differences of cyclone densities, frequency distributions of cyclone intensities and results of the direct matching between cyclones between different re-analyses including composites. Finally, a summary and conclusions are given in section 4.
2. Data and Methodology

The four re-analyses explored for extra-tropical cyclones are JRA25, ERA-Interim, NASA-MERRA and NCEP-CFSR. The JRA25, NASA-MERRA and NCEP-CFSR start in 1979 and have a similar length (1979-2009), whereas ERA-Interim begins in 1989 (1989-2009). Whilst all four re-analyses produce analyses every 6 hours, the NCEP-CFSR actually has data available hourly. However, this is achieved by placing the forecasts, which are available hourly, that are produced from the analyses as initial conditions, in between the analyses. In this study, only the 6 hourly analyses are used to be consistent with the other re-analyses.

A brief summary of each re-analysis follows with a focus on the components of the different systems that may impact the representation of extra-tropical cyclones:

(a) JRA25 (Onogi et al. 2007) uses a spectral model integrated at a T106 (125km) horizontal resolution with 40 hybrid sigma-pressure vertical levels. The prognostic equations are solved in Eulerian form (semi-Lagrangian after 2005) with finite differences in the vertical. The data assimilation is 3-Dimensional Variational (3D Var.) assimilation with 6 hour cycling. A full range of observations are assimilated following quality control and bias correction, including satellite radiances from TOVS/ATOVS and precipitable water from SSM/I.

(b) ERA-Interim (Simmons et al. 2007) also uses a spectral model (Integrated Forecast System, cycle 31R1) integrated at a T255 (80km) horizontal resolution with 60 ver-
tical hydrid levels. The prognostic equations are solved using the semi-Lagrangian method with a finite element method in the vertical. A 4-Dimensional Variational (4D Var.) data assimilation system with 12 hour cycling (Thépaut et al. 1993) is used with output every 6 hours. Flow dependant structure functions are used which have the potential to extract more information from the observations, thereby improving the quality of the analyses. A new humidity analysis (Hólm et al. 2002) has reduced the problems found in ERA40 with the assimilation of humidity observations from satellites (Bengtsson et al. 2004). A full range of observations are bias corrected before assimilation, in particular a variational scheme is used for satellite radiances.

(c) The NASA-MERRA re-analysis uses the Goddard Earth Observing System, Version 5 (GEOS5) model and data assimilation system (Rienecker and co-authors 2008). This has a finite volume model, integrated at a resolution of $2/3^0$ longitude by $1/2^0$ latitude ($\sim 55$km) with 72 Lagrangian vertical levels (Lin 2004). The data assimilation used is the Gridpoint Statistical Interpolation (GSI) system originally developed by NCEP (Wu et al. 2002) with 6 hour cycling. This is a 3D Var system formulated in physical space to enable the implementation of flow dependent anisotropic, inhomogeneous background error covariances (Purser et al. 2003a,b). As with all the re-analyses, observations are quality controlled and bias corrected before assimilation including the satellite radiances. The NASA-MERRA re-analysis additionally assimilates rain rates from SSM/I and TRMM satellites.

(d) The NCEP-CFSR re-analysis (Saha and Co-authors 2010) uses the NCEP coupled
forecast system model. This consists of a spectral atmospheric model (Saha et al. 2006) at a resolution of T382 (38km) with 64 hybrid vertical levels and the GFDL Modular Ocean Model, version 4p0d (Griffies et al. 2004) which is a finite difference model at a resolution of \( \sim 1/2^9 \) with 40 levels in the vertical. The atmosphere and ocean models are coupled with no flux adjustment. The NCEP-CFSR uses the GSI data assimilation system for the atmosphere. Flow dependence for the background error variances is included as well as first order time interpolation to the observation (FOTO) (Rančić et al. 2008). Variational quality control of observations (Andersson and Järvinen 1999) is also included. An ocean analysis for SST is also performed using Optimal Interpolation (OI). A full range of observations is used as in the other re-analyses which are quality controlled and bias corrected, including satellite radiances. Observations of ocean temperature and salinity are also used.

The analysis methodology used in this study has been used in several previous studies of extra-tropical cyclones, e.g. (Bengtsson et al. 2009, 2006; Hodges et al. 2003, 2004; Hoskins and Hodges 2002, 2005) and is based on the tracking scheme developed by Hodges (1994, 1995, 1999). Cyclones are identified as maxima or minima by the tracking scheme depending on the field chosen for the identification, in this study both Mean Sea Level Pressure (MSLP) and 850hPa relative vorticity \( (\zeta_{850}) \) at 6 hourly frequency are used to provide the traditional MSLP perspective as well as the vorticity perspective. As part of the identification, the large-scale background is first removed as discussed in Hoskins and Hodges (2002) and Anderson et al. (2003). The resolution is also decreased to reduce noise in the identification process, this is more important for vorticity, which is a very
noisy field at high resolution, than for MSLP which is generally smoother. In this study a T63 resolution for MSLP and T42 for vorticity are used. Even though a higher resolution is used for MSLP than for vorticity, in general more cyclones are identified for vorticity than for MSLP with the chosen characteristics of lifetime and displacement distances, due to the smaller scale nature of the vorticity field. In fact, even identifying cyclones in much higher resolution MSLP data does not necessarily result in a larger number of cyclones with the chosen characteristics than identified in the T42 vorticity. The fact that each re-analysis is reduced to the same resolution for the identification means that identification is performed at the same spatial scale which in this case focusses on the synoptic scales. The $850$ is the preferred field for reasons discussed in the previously mentioned studies, namely a weaker influence of the large-scale background than is the case for MSLP, less extrapolation below orography and the focus on smaller spatial scales.

Before analysing the tracks they are filtered to retain only those storms that last at least 2 days and travel further than 1000km, so that the emphasis is on mobile cyclones. Since ERA-Interim data is available for the shortest time period this is chosen as the base re-analysis for the comparison with the other re-analyses. The main focus will be on the winter period in both hemispheres, December to February (DJF) in the Northern Hemisphere (NH) and June-August (JJA) in the Southern Hemisphere (SH). Also, since the interest here is on extra-tropical cyclones, any storms that have the major part of their lifecycle within the tropics are excluded, where the tropics are defined as the zonal region (30S, 30N).

Spatial statistics are computed from the cyclone tracks for each re-analysis using the
spherical kernel approach (Hodges 1996). Selected spatial statistics, namely the track and genesis densities, are differenced to highlight where differences in the distribution of cyclones between the re-analyses occur. These differences are tested using a Monte-Carlo significance test (Hodges 2008). In addition the cyclone tracks will be referenced back to the full resolution fields of MSLP, 925hPa winds and ξ850. The 925hPa winds are used as opposed to the 10m winds because they represent the wind field above the surface boundary layer and are specifically calculated by the model. The full resolution intensities are used to construct maximum intensity distributions to compare between the re-analyses. A more direct comparison between the cyclone tracks from the different re-analyses is also performed by matching the identically same storms between the re-analyses in the same way as in Hodges et al. (2003, 2004). The identically same storms are identified by finding the tracks with minimum mean separation distance which is less than some prescribed value, chosen here to be 4° (geodesic), and which overlap in time by at least 50% of their points. From the tracks that match, maximum intensity distributions are derived, this is also done for the tracks that do not match. From the matched tracks, statistics for the mean separation distances and instantaneous intensity differences are computed. For the storms that match a selected number of extreme storms are used to explore and compare their lifecycles and structure based on compositing, as described and used in Bengtsson et al. (2009) and Catto et al. (2010).
3. Results

a. Climatology

Before presenting the results comparing the cyclones in the different re-analyses, the climatology of cyclones are shown for the ERA-Interim re-analyses, to provide a frame of reference.

The track and genesis densities for the NH and SH winters for $\xi_{850}$ are shown in Figure 1. This shows cyclone distributions very similar to that obtained from older re-analyses based on the same field (Bengtsson et al. 2006; Hoskins and Hodges 2002, 2005). In particular, in the NH the two main oceanic storm tracks are well defined by high values of track density, as is the Mediterranean storm track, extending through the Middle East and the Siberian storm track. The NH cyclogenesis (Figure 1b) shows the well known active regions in the lee of the Rockies, the Tibetan plateau and the Alps (Gulf of Lyon), and over the main baroclinic regions off Cape Hatteras and East of Japan (Kuroshio current region). Other more extended secondary cyclogenesis regions are also apparent in the Atlantic and Pacific oceans. These features have been well documented in previous studies, e.g. Hoskins and Hodges (2002).

In the SH (Figure 1c), the main oceanic storm track is seen extending from South America and spiralling in to the Antarctic coast, then extending to the Antarctic peninsula. The weaker Pacific storm track extending from Australia can also be seen. The main cyclogenesis in the SH (Figure 1d) occurs in the lee of the Andes with two centers,
the poleward center associated with where the Pacific storm track meets the Andes and the equatorward center associated with where the sub-tropical jet crosses the Andes (this pattern is similar to that seen in the lee of the Rockies). Another major center is seen on the Antarctic coast associated with the decay and cycloysis of cyclones spiralling in to the coast from higher latitudes, these bring warm, moist air which combined with the flow of cold air from the continent, results in enhanced local baroclinicity and re-invigoration of storms or development of new storms. Other regions are also apparent in the oceanic storm tracks associated with secondary cyclogenesis and downstream development (Chang 1993; Hoskins and Hodges 2005). These cyclone distribution features in the SH have also been documented in previous studies, e.g. Hoskins and Hodges (2005). If MSLP is used to identify cyclones (not shown), the distributions are in general very similar albeit with lower density values due to the lower number of identified cyclones.

The results that follow comparing the re-analysis from the perspective of extra-tropical cyclone properties are presented as several different types of diagnostics starting with numbers and spatial statistics. This is followed by distributions of maximum intensities for different measures of intensity, determined at full native resolution. Next, to explore which storms are common to the re-analyses and to perform a more direct comparison of intensities, results are shown based on cyclone matching. Finally results will be shown comparing the composite cyclones.
b. *Numbers and Difference in Spatial Distribution*

The number of cyclones identified shows fewer storms are identified in JRA25 than in either of the other three re-analyses and that ERA-Interim and NCEP-CFSR in general have the most storms for both MSLP and $\xi_{850}$ in both hemispheres. More cyclones are identified using the $\xi_{850}$ field than the MSLP field, with the chosen lifetime and displacement properties, for all seasons. This is the case even though the identification is performed at a lower resolution for $\xi_{850}$. In fact if the MSLP is used at an even higher resolution this would still be the case (Froude 2010). In general the differences in numbers between the re-analyses are relatively small, a summary is given in Table 1. Larger differences are expected when focusing on smaller scale mesocyclones.

To explore the differences and similarities between the cyclone spatial distributions the differences of track and genesis densities are determined between ERA-Interim and the other re-analyses for $\xi_{850}$ for the NH and SH winters. Results for MSLP (not shown) indicate similar results. The regions where the distributions are statistically different are indicated where the p-values (Hodges 2008) for the differences are below 0.05 (significance level of 95%). From the "frequentist" view point, this is where the hypothesis should be rejected, that the two distributions (from which the differences are computed) are drawn from the same underlying distribution.

The results for the comparison in the NH winter are shown in Figure 2. For the ERA-Interim comparison with JRA25 the track density shows relatively small differences (Figure 2a), which are not statistically significant at the 95% level. There are some
regions which show larger differences which are significant, with the largest of these seen at the end of the Mediterranean storm track. This is a similar result to that seen in the older re-analysis (Hodges et al. 2003) and are associated with weak systems that are sensitive to the observations and their assimilation. For the genesis differences (Figure 2b) there are relatively large differences which are significant associated with the orographic regions in the lee of the Rockies and the Himalayan massif as well as at the end of the Mediterranean storm track. This may be expected due to the different representation of the orography and orographic processes at the two different resolutions of the ERA-INTERIM and JRA25.

For the differences between ERA-Interim and NASA-MERRA in the NH (Figure 2c, d) it is apparent that, in general, the differences are smaller than those between ERA-Interim and JRA25. This might be expected as the resolutions are more similar between ERA-Interim and NASA-MERRA. The differences in track density (Figure 3c) are similar to those seen in the JRA25 comparison with the largest significant region of differences at the end of the Mediterranean storm track. For the cyclogenesis (Figure 3d) there is an obvious improvement in the agreement in the lee of the Rocky Mountains, with much smaller differences compared with the JRA25 comparison. This is likely due to the fact that the representation of the orography is similar at the more similar resolutions of ERA-Interim and NASA-MERRA. The difference in the genesis in the Middle East is also smaller in this comparison though still large enough to be significant at the 95% level. The largest difference in genesis occurs on the eastern side of the Himalayas, though shows some improvement over the JRA25 comparison, in particular the southern Mongolian genesis.
The reason why this difference persists even between re-analyses of similar resolution is unclear, the Altai mountains in this region are relatively high reaching up to 6000m, but the differences may be due to the fact that these systems are relatively weak and more sensitive to the model, observations and data assimilation similar to the Middle Eastern region.

The differences between ERA-Interim and NCEP-CFSR in the NH are shown in Figure 2e and f. These show the smallest differences, compared to the comparisons with NASA-MERRA and JRA25. The track density differences (Figure 2e) are almost zero in the main oceanic storm tracks, and even at the end of the Mediterranean storm track through the Middle East the differences are much reduced though still significant. The differences in the cyclogenesis (Figure 2f) are also the smallest of all the comparisons, in particular in the lee of the Rockies. However, the Mongolian region still stands out as a region with significant differences in genesis.

The difference statistics for the SH winter are shown in Figure 3. For the difference in track density between ERA-Interim and JRA25 (Figure 3a) larger differences can be seen than was the case in the NH winter, in particular through the Atlantic and Indian ocean sectors with large regions with p-values below 0.05%. The genesis also shows large differences (Figure 3b) again in association with the orography, in particular in the lee of the Andes similar to that seen in the NH in the lee of the Rockies. In comparison with previous studies with the older re-analyses (Hodges et al. 2003, 2004; Wang et al. 2006), these results do not show any major changes or improvements in agreement in the SH. For the difference between NASA-MERRA and ERA-Interim the track density
(Figure 3c) shows more obviously smaller differences than for the JRA25 comparison, with smaller and fewer regions that are significant. For the cyclogenesis (Figure 3d), the differences are similar to those shown for the JRA25 comparison, in particular the lee of the Andes still shows relatively high and significant difference values with ERA-Interim showing higher levels of genesis. This in part maybe due to the narrow and sharp Andes being more difficult to represent compared to say the broader Rocky mountains in the NH, even at the resolutions of ERA-Interim and NASA-MERRA. The track density differences between NCEP-CFSR and ERA-Interim (Figure 3e) are small and comparable with those in the NH and much less than the for the other two comparisons. The differences in cyclogenesis (Figure 3f) also show the smallest differences compared with the other two comparisons including in the lee of the Andes.

These spatial comparisons highlight a general convergence between the newer high resolution re-analyses in terms of cyclone numbers and distribution. This is particularly the case in the SH which shows a significant improvement between the newer higher resolution re-analyses compared to the older re-analyses. The ERA-Interim comparison with NCEP-CFSR in the SH is as good as in the NH. This likely reflects the general improvement in the data assimilation and forecast models, in particular the use of satellite observations, which has resulted in a significant improvement in recent years in forecast skill in the SH to a level that it is comparable to the NH (Thépaut and Andersson 2003).
c. Intensity Distributions

The maximum intensity distributions of the cyclones referenced to full resolution for MSLP, 925hPa winds and $\xi_{850}$ fields are determined as described in Bengtsson et al. (2009). Values are determined within a prescribed radius of the cyclone center. The radius is taken as $5.0^\circ$ (geodesic) for MSLP and vorticity and $6.0^\circ$ for winds. The maximum attained intensity is obtained for all tracks excluding those in the tropics.

The distributions for MSLP referenced to the MSLP tracks provide the more traditional perspective and are shown in Figure 4a and b for the NH and SH winters respectively, the insets show the extreme tails scaled to 90 months. For the NH winter, Figure 4a shows that the distributions for the four re-analyses appear very similar, with a skewed distribution. However, it is apparent that NASA-MERRA has deeper extreme systems than the other three re-analyses and JRA25 has the weakest extremes. For the SH winter, shown in Figure 4b, the distributions are also very similar but are more heavily skewed to deeper systems associated with the circumpolar pressure trough. Similar to the NH, NASA-MERRA has the deeper extreme systems and JRA25 the weakest systems, this appears more apparent in the SH. As the distributions are very similar a two-sided Kolmogorov-Smirnov test is performed to test when and if they are statistically different. Table 2 shows the Kolmogorov-Smirnov statistic $D$ (the maximum distance between the cumulative distributions) and the associated p-values. The distributions are considered statistically different if the p-value is below 0.05, i.e. significant at the 95% level, this occurs for relatively high values of $D$. Table 2 shows that in the NH winter, the NASA-MERRA
distribution is statistically different from those of the other re-analyses. For the SH winter, NASA-MERRA is also statistically different from the other re-analyses as is JRA25. The other seasons are also shown in Table 2 for completeness and show that NASA-MERRA and JRA25 are statistically different for other seasons as well.

For the 925hPa winds referenced to the $\xi_{850}$ tracks, the maximum intensity distributions are shown in Figure 4c and d for the NH and SH winters respectively. These show much larger differences between the re-analyses than was the case for MSLP. In the NH (Figure 4c) it is apparent that NASA-MERRA still has the more extreme cyclones followed by NCEP-CFSR, then ERA-INTERIM and the weakest extremes are found in JRA25. In many ways these results are not too surprising for NCEP-CFSR, ERA-INTERIM and JRA25 with the intensities following the resolution. The fact that NASA-MERRA shows more extreme cyclones than the other re-analyses, even though it is not the highest resolution re-analysis, is perhaps more surprising but is likely a consequence of the deeper systems in NASA-MERRA. In the SH (Figure 4d) a similar picture is seen, although the distributions are perhaps even more different with different shapes. NASA-MERRA still has the strongest extremes, whilst ERA-INTERIM has a narrower distribution and NCEP-CFSR has a broader distribution.

The maximum (minimum) vorticity distributions for the vorticity tracks referenced to full resolution for the NH (SH) winter periods are shown in Figure 4e and f respectively. Note, in the SH values are multiplied by $-1$. Vorticity is more sensitive for measuring intensity as it essentially depends on second order derivatives. The results for this field show that intensities are as would be expected, with the maximum intensities being highest
in the highest resolution re-analysis of NCEP-CFSR and lowest in the lowest resolution re-analysis of JRA25 for winters in both hemispheres. This is different from the results for winds and pressure and indicates that the resolution is the more important factor in determining the small scale structure. The distributions for both winds and vorticity are so obviously different between the re-analyses that no significance test is performed.

d. Track Matching

Since the re-analyses will in general assimilate the same observations over the same time period, they should simulate the same storms. This makes it possible to also compare the same storms between re-analyses (Bromwich et al. 2007; Hodges et al. 2003, 2004; Wang et al. 2006). This allows a more detailed comparison of the cyclones between the different re-analyses to be performed. This is done using a track matching algorithm (Hodges et al. 2003, 2004), as described in section 2, and constructing statistics based on these matches.

Results for the number of matches for each pair of re-analyses and for both MSLP and $\xi_{850}$ are shown in Table 3. This shows that in the NH winter and using the ERA-Interim as the base re-analysis the largest number of matches occur for the NCEP-CFSR re-analysis for both MSLP (81%) and $\xi_{850}$ (81%) with a lower number for NASA-MERRA (79%, 76%) and JRA25 (80%, 76%). For the 10% most intense systems in ERA-INTERIM the number of matches rises to 97% for $\xi_{850}$. For the SH winter (JJA), again using ERA-Interim as the base re-analysis, the comparison with NASA-MERRA (81%, 75%) and NCEP-CFSR (84%, 81%) show a similar number of matches per month that are
comparable to those in the NH winter, whilst for the comparison with JRA25 (67%, 66%) there are a much lower number of matches. To see what types of systems match and don’t match the maximum intensities of each system are used to determine the distribution for the matching and non-matching systems, this is done based on the T42, ξ_{850} intensities. Figure 5 shows that in the NH the storms that match cover a broad range of intensities for each comparison, whilst those storms that don’t match tend to be the weaker storms. The best comparison occurs for the ERA-Interim matched against NCEP-CFSR. In the SH it is apparent that as well as having a lower proportion of matches, JRA25 has a broader distribution of intensities for the storms that don’t match. This was also found to be the case with the older re-analyses (Bromwich et al. 2007). For the newer re-analyses there is a significant improvement in the SH in terms of the matched storms compared with the older re-analyses.

This comparison can be extended further to look at the differences in more detail for the matched tracks by computing the distributions of mean separation distances, and the instantaneous intensity differences for all pairs of points that match. The distribution of mean separation distances for the storms that match are shown in Figure 6 as a probability density function (PDF) distribution for the NH and SH winters. For the NH winter, Figure 6a shows the results are similar to those obtained for the older re-analyses (Hodges et al. 2004; Wang et al. 2006), namely the matched storms do so predominantly for mean separation distances less than 2.0° (geodesic). However, there is a significant improvement over the older re-analyses with the majority of matches now occurring for mean separation distances less than 1.0° and with more similar distributions between the
different re-analyses. The best matches occur between ERA-Interim and NCEP-CFSR with a distribution shifted to smaller mean separation distances. In the SH, Figure 6b shows that the comparison for the matches between JRA25 and the other re-analyses have a fairly broad distribution compared with the NH indicating a larger uncertainty in location between the cyclones in JRA25 and the other re-analyses, this is similar to previous results (Hodges et al. 2004; Wang et al. 2006). However, for the comparison between the newer re-analyses, Figure 6b shows that there is a significant improvement over the older re-analyses with the mean separation distances generally as good as in the NH with the smallest values occurring for the ERA-Interim comparison with NCEP-CFSR. This improvement between the newer re-analyses indicates a reduction in the uncertainty in location that is consistent with the results shown for the track density differences in section 3 b.

The instantaneous intensity differences for matched tracks are shown in Figure 7 for MSLP, 925hPa winds and $\xi_{850}$. This diagnostic is useful for indicating both the bias and uncertainty in the intensities, the location of the mode or mean, indicates the bias and the breadth of the distribution the uncertainty. All matched points along the tracks are used. The distributions of differences for MSLP are shown in Figure 7a and b for the NH and SH winters, respectively. In the NH the distributions are fairly narrow, indicating that differences between the re-analyses are relatively small. The location of the distributions are centered on zero for all comparisons except those with NASA-MERRA again highlighting NASA-MERRA as having deeper cyclones than the other re-analyses. In the SH the distributions are broader in nature than in the NH highlighting a greater
uncertainty in the intensities. The NCEP-CFSR comparison with ERA-Interim still shows a distribution centered on zero and narrower than the other distributions highlighting the greater similarity between these two re-analyses. NASA-MERRA still shows the deepest cyclones and JRA25 the shallowest. These results are consistent with the maximum intensity distributions shown in section 3c.

For the 925hPa winds (Figure 7c and d) the distributions indicate fairly similar distributions in the NH and SH for the same compared re-analyses, although the SH distributions are slightly broader. JRA25 consistently shows the weakest extreme winds compared with the other re-analyses, although it appears more similar to ERA-Interim in the NH than with the other re-analyses. In general these results are consistent with the results shown in Figure 4. For the $\xi_{850}$ intensity difference distributions (Figure 7e and f) the results are similar to those for winds except that the distributions are much broader, indicating the larger uncertainty at the smaller spatial scales represented by vorticity. The distributions are also broader in the SH than in the NH though biases are similar between the two hemispheres. These results are consistent with those for the maximum intensity distributions shown in Figure 4.

e. Composite Lifecycles and Structure

In this section the matching analyses are extended to cyclone lifecycles and structure. This is done by identifying a set of intense cyclones in the ERA-Interim re-analysis and then finding the identically same systems in the other re-analyses using the matching
methodology as used in the previous section. This is done for both the NH and SH winters. The selected cyclones are then used to construct composite lifecycles based on the MSLP, 925hPa winds and $\xi_{850}$ as discussed in Bengtsson et al. (2009), and horizontal composites of MSLP and system relative winds as discussed in Catto et al. (2010). The 100 most extreme cyclones are selected in ERA-Interim in the same way as discussed in Bengtsson et al. (2009), based on the T42 $\xi_{850}$ and with lifetimes greater than 4 days.

Since the composite lifecycles generally reflect the intensity results already discussed, they are only briefly discussed and not shown. In the NH winter there is very little difference between the lifecycles of the composite cyclones with very similar deepening rates which are greater than 1hPa/hr. The deepest composite lifecycle occurs for NASA-MERRA and the shallowest for JRA25 consistent with the results discussed above. In the SH winter the composite lifecycles are deeper than in the NH related to the circumpolar pressure trough, with growth rates greater than 1hPa/hr, as in the NH. The composite lifecycles using 925hPa winds are also very similar in shape for the different re-analyses but indicate that the NASA-MERRA has a more intense lifecycle with respect to the winds and JRA25 has the weakest lifecycle, ERA-Interim and NCEP-CFSR have very similar lifecycles. This is true for both the NH and SH winters. For the $\xi_{850}$ lifecycles, again the shapes are very similar but there are larger differences between the intensities, consistent with the maximum intensity distributions shown previously.

The horizontal composites are computed in the same way as described in Bengtsson et al. (2009) and Catto et al. (2010). The method is based on sampling the fields on a radial grid centered on the storm centers, with the grid preferred direction rotated to
the propagation direction of the storms. This results in the sampled fields appearing to be relative to the storms all moving in the same direction, making storm structural characteristics easier to be identified. The stage of the lifecycle at which the composites are produced is chosen as the maximum intensity in the T42, $\xi_{850}$, although any stage can be chosen. A more detailed view of storm structure can be obtained, including the vertical structure, as has previously been performed by Catto et al. (2010), here only a limited view is presented based on the MSLP and 925hPa winds. For the winds, the system relative winds are determined before compositing by subtracting the system velocities.

The horizontal composite results for the NH winter for the re-analysed are shown in Figure 8 with the direction of the composite indicated by the large arrow (left to right). This shows that, at least in terms of the variables used here, the structure of the composite cyclones are remarkably similar, in particular for the same features of conceptual models such as discussed by Catto et al. (2010). This includes the general structure of the MSLP field with an extension to the upper right which possibly indicates the presence of a parent low, this was also discussed by Wang and Rogers (2001). The depth of the composite MSLP cyclones are consistent with the results discussed in previous sections with NASA-MERRA having a deeper composite when compared with the other re-analyses. The system relative winds show structures that are very similar between the re-analyses with relatively weak winds to the right of the direction of motion, with a flow orthogonal to the direction in the bottom right quadrant associated with the warm sector flow. The strongest winds occur to the left of the storm direction with a flow of air rearwards relative to the storm motion which turns cyclonically around the storm center, this is different from
the Earth relative winds which generally occur behind and to the right of the direction of motion (Catto et al. 2010). These wind structures are similar to those previously discussed by Catto et al. (2010). The intensities of the system relative winds are consistent with the previously discussed results, with NASA-MERRA having the larger values. The results for the SH winter are shown in Figure 9. These show the same features as those for the NH, albeit the intensities in terms of the depth of the composite cyclone and the system relative winds appear weaker than in the NH. In particular, the warm sector flow in the top right quadrant appears weaker than in the NH composites. The differences between the high resolution re-analyses also appear weaker but with JRA25 showing the shallower depth and weaker winds, consistent with the previously discussed results.

In general the results for the composites are consistent with the results discussed in the previous sections in that there is a good agreement between the re-analyses in both hemispheres but with JRA25, whilst showing the same lifecycle and structure, being weaker than for the other re-analyses, in particular in the SH and NASA-MERRA being stronger.

4. Summary and Conclusions

Comparisons have been made between cyclones identified in four recent re-analyses, with the focus being on synoptic scale cyclones, with the aim of determining how well cyclones compare between the re-analyses and any improvements over older re-analyses.
A summary of the results are outlined as follows:

i. The numbers and spatial distribution of extra-tropical cyclones compare well in the new high resolution re-analyses and better than with the lower resolution JRA25 re-analysis. This is particularly the case in the NH and also in the SH where the comparison between ERA-Interim and NCEP-CFSR is comparable with the NH. This is an improvement over the comparison of the older re-analyses. The largest differences are seen for cyclogenesis in the vicinity of orography, though this improves in the newer re-analyses.

ii. Greater differences occur between the re-analyses in terms of their maximum intensities, with NASA-MERRA having more extreme cyclones in terms of MSLP and winds. For vorticity the intensities are more closely related to the resolution of the models, with NCEP-CFSR having the larger intensities. JRA25 consistently has the weakest intensities for all variables. Differences between the re-analyses becomes progressively more pronounced going from MSLP to winds to vorticity.

iii. Comparing cyclones between the re-analyses using matching shows significant improvements over the older re-analyses with greater than 80% matches in the NH. The systems that do not match tend to be the weaker storms. For the 10% most intense storms the number of matches increases to greater than 97%. The SH shows the most significant improvement over the older re-analyses with the number of matches for the newest re-analyses being almost as good as in the NH, with the comparison of ERA-Interim with NCEP-CFSR being the best. The number of matched storms
are much less for JRA25 in the SH similar to the older re-analyses.

iv. Using the matched storms to explore the uncertainties in the mean separation distances and instantaneous intensity differences indicates that in the NH all four re-analyses have matches with mean separation distances predominately less than $2^\circ$ (geodesic), with the lowest mean separation distances occurring for the ERA-Interim comparison with NCEP-CFSR. In the SH the comparison of JRA25 with the other re-analyses shows results similar to the older re-analyses with a much broader distribution of separation distances than in the NH. However, for the new re-analyses in the SH the separation distances are comparable with the NH, with the ERA-Interim comparison with NCEP-CFSR being the best. The instantaneous intensity bias results are consistent with the maximum intensity distributions, the uncertainty (spread) increases going from pressure to winds to vorticity.

v. The composite cyclones indicate that for the different re-analyses these are very similar, with the main differences reflecting the intensity differences seen in the intensity distribution statistics. Similar structures to those discussed by Catto et al. (2010) are found.

The results have shown there is a considerable improvement in the agreement between the new high resolution re-analyses compared with older re-analyses or with the lower resolution JRA25 re-analyses. This is consistent with the improvement in models, observations and data assimilation in NWP systems such that predictive skill is now as good in the SH as in the NH. It is in the vicinity of the orography that large differences in the cy-
clogenesis are seen which improves considerably for the newer high resolution re-analyses, though problems still persist in the vicinity of the high but narrow Andes. One spatial difference seen between the older re-analyses that persists with the newer re-analyses occurs at the end of the Mediterranean storm track in both track density and cyclogenesis though this reduces in the newer re-analyses in particular for the ERA-Interim comparison with NCEP-CFSR. This is likely due to the fact that these storms are relatively weak and more dependent on the forecast model, observations and data assimilation methods. The fact that the weaker systems agree less well between the re-analyses is also apparent in the track matching analysis.

One of the big improvements in assimilating observations has been the direct assimilation of satellite radiances, this was shown to have an impact for the older re-analyses (Bromwich et al. 2007), however there was still larger differences in the SH, where satellite data dominates, than in the NH. This might suggest that the satellite observations on their own are insufficient to constrain the whole of the troposphere. However, for the new high resolution re-analyses the fact that the differences in the SH are comparable with those in the NH indicates that more information is being extracted from the available observations by the new data assimilation methods supplemented by new observations such as scatterometer winds and improved microwave sounder observations.

Perhaps the most surprising results occur for the intensities, in particular that of the larger number of extremes in NASA-MERRA for MSLP and winds compared with the other re-analyses. It is difficult to explain why NASA-MERRA should have more and larger extremes of pressure and winds than the other re-analyses, but the fact that the
storms are deeper is likely to lead to stronger geostrophic winds. The intensity in terms of vorticity is perhaps more clearly understandable as it is closely linked to the resolution of the different re-analysis systems with the small spatial scales represented by the vorticity being more sensitive to resolution.

The matching results further confirm the agreement between the new high resolution re-analyses such that in the NH the cyclones compare to a high degree both in terms of numbers and location, with the systems that do not match tending to be the weakest ones; this is also true for the lower resolution JRA25 in the NH. The biggest improvement in agreement occurs in the SH where comparisons between the high resolution re-analyses are almost as good as in the NH. The composite analysis of the matched storms further highlight the similarity of cyclones between the re-analysis in particular for the structure. There is much scope to extend the composite analysis to the full 3D structure and to verify the cyclone properties directly against observations, in particular from satellites (Field et al. 2008; Naud et al. 2010).

Whilst the focus of the study has been on the ERA-Interim period (1989-2009), using the longer periods from 1979 of the other re-analyses gives similar results with only a small degradation in results for the earlier periods.

We have inter-compared the different re-analyses and showed that there is an improvement in their agreement with respect to extra-tropical cyclones, in particular in the SH, compared with the older re-analyses. The convergence of the newer high resolution re-analyses provides some confidence that the re-analyses are representing these storms at
least equally well. However, it does not tell us that extra-tropical cyclones are being correctly represented in every respect as differences are still apparent for the intensities of storms and it is not possible to tell from a simple inter-comparison which one is closest to reality. This has to be done by comparing directly with observations, ideally independent from the assimilated observations. However, this is made difficult by the inhomogeneous nature of the observations. This in part can be reconciled by using the available satellite observations which provide much better coverage than terrestrial observations. This is an area of current work.

5. Acknowledgements

The authors would like to acknowledge the Global Modeling and Assimilation Office (GMAO) and the GES DISC for the dissemination of the MERRA data. The JRA25 data was produced and supplied by the Japan Meteorological Agency (JMA) and the Central Research Institute of Electric Power Industry (CRIEPI). The ERA-Interim data has been produced by ECMWF and obtained as part of a member state special project. The CFSR data was developed by NOAA’s National Centers for Environmental Prediction (NCEP). The data for this study are from NOAA’s National Operational Model Archive and Distribution System (NOMADS) which is maintained at NOAA’s National Climatic Data Center (NCDC).
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2. Kolmogorov-Smirnov statistic (D) and associated p-value for the comparison of the MSLP intensity distributions in both the NH and SH for the respective winter periods. The bold values in the table indicate p-values below 0.05, i.e. significant at 95%.

3. The number of storms per month that match between the re-analyses for the 1989-2009 period and for the different seasons for both MSLP and $\zeta_{850}$ in both hemispheres excluding the tropics.
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Table 1. Number of cyclones per month for each season, field and re-analysis that are found in the extra-tropics, (30, 90)°N and S for the period 1989-2009.
### Table 2

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Table 2. Kolmogorov-Smirnov statistic (D) and associated p-value for the comparison of the MSLP intensity distributions in both the NH and SH for the respective winter periods. The bold values in the table indicate p-values below 0.05, i.e. significant at 95%.
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Table 3. The number of storms per month that match between the re-analyses for the 1989-2009 period and for the different seasons for both MSLP and $\xi_{850}$ in both hemispheres excluding the tropics.
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1 Extra-tropical cyclone climatology based on the ERA-Interim re-analysis (1989-2009), $\xi_{850}$, (a) NH, DJF track density, (b) NH, DJF genesis density, (c) SH, JJA track density, (d) SH, JJA genesis density. Densities are in units of number density per month per unit area where the unit area is equivalent to a 5 degree spherical cap ($\sim 10^6km^2$).

2 Difference in $\xi_{850}$ extra-tropical cyclone track and genesis densities between ERA-Interim, JRA25, NASA-MERRA and NCEP-CFSR for the NH, DJF for the period 1989-2009. Left column shows the track density differences (a) ERAI-JRA25, (c) ERAI-MERRA, (e) ERAI-NCEP. Right column shows the genesis density differences (b) ERAI-JRA25, (d) ERAI-MERRA, (f) ERAI-NCEP. The white lines delineate regions where p-values for the differences are below 0.05. Densities are in units of number density per month per unit area where the unit area is equivalent to a 5 degree spherical cap ($\sim 10^6km^2$).

3 Same as Figure 2 but for SH, JJA.
Maximum intensity distributions based on full resolution MSLP, 925 hPa winds and $\xi_{850}$ for the winter periods in the NH (DJF) and SH (JJA), (a) NH, DJF, MSLP referenced to MSLP tracks, (b) SH, JJA, MSLP referenced to MSLP tracks, (c) NH, DJF, 925 hPa winds referenced to $\xi_{850}$ tracks, (d) SH, JJA, 925 hPa winds referenced to $\xi_{850}$ tracks, (e) NH, DJF, $\xi_{850}$ referenced to $\xi_{850}$ tracks, (f) SH, JJA, $\xi_{850}$ referenced to $\xi_{850}$ tracks. Values are number per month for the 1989-2009 period and the bin widths are 10 hPa for MSLP, 5 $ms^{-1}$ for winds and $10 \times 10^{-5} \text{s}^{-1}$ for vorticity. SH vorticity is scaled by $-1$.  

Maximum intensity distributions for cyclones that match and those that don’t match based on the T42, $\xi_{850}$ intensities for (a) NH, INTERIM-MERRA, (b) SH, INTERIM-MERRA, (c) NH, INTERIM-JRA25, (d) SH, INTERIM-JRA25, (e) NH, INTERIM-NCEP, (f) SH, INTERIM-NCEP. Bin widths $1.0 \times 10^{-5} \text{s}^{-1}$.  

Probability Density Distributions for mean separation distance for $\xi_{850}$ tracks that match for (a) NH and (b) SH. Units are geodesic degrees and bin widths are $0.25^\circ$. 


### Tables

#### Table 7
Probability Density Distributions for instantaneous intensity differences for the tracks that match, (a) NH, MSLP (hPa), MSLP tracks with bin widths of 0.5hPa, (b) same as (a) but for SH, (c) NH, 925hPa winds ($ms^(-1)$) with bin widths of 0.5$m/s^1$, $\xi_{850}$ tracks, (d) same as (c) but for SH, (e) NH, $\xi_{850}$ ($\times10^{-5}s^{-1}$), $\xi_{850}$ tracks, bin widths of $1.0 \times 10^{-5}s^{-1}$, (f) same as (e) but for SH.

#### Table 8
Horizontal composites of the 100 most intense cyclones identified in ERA-Interim and matched to the other re-analyses for the NH of MSLP and system relative winds at 925hPa. Colour contours with interval 2.5$m/s^1$ show the system relative wind speeds with the white lines indicating the highest values starting at $30m/s^1$. The vectors show the system relative wind vectors and the black contours show the MSLP with contour interval 5hPa. (a) ERA-Interim, (b) JRA25, (c) NASA-MERRA and (d) NCEP-CFSR. The large blue arrow indicates the direction of the composite storm.

#### Table 9
Same as Figure 8 but for SH.
Fig. 1. Extra-tropical cyclone climatology based on the ERA-Interim re-analysis (1989-2009), $\xi_{850}$, (a) NH, DJF track density, (b) NH, DJF genesis density, (c) SH, JJA track density, (d) SH, JJA genesis density. Densities are in units of number density per month per unit area where the unit area is equivalent to a 5 degree spherical cap ($\sim 10^6 \text{km}^2$).
Fig. 2. Difference in $\xi_{850}$ extra-tropical cyclone track and genesis densities between ERA-Interim, JRA25, NASA-MERRA and NCEP-CFSR for the NH, DJF for the period 1989-2009. Left column shows the track density differences (a) ERAI-JRA25, (c) ERAI-MERRA, (e) ERAI-NCEP. Right column shows the genesis density differences (b) ERAI-JRA25, (d) ERAI-MERRA, (f) ERAI-NCEP. The white lines delineate regions where p-values for the differences are below 0.05. Densities are in units of number density per month per unit area where the unit area is equivalent to a 5 degree spherical cap ($\sim 10^6 km^2$).
Fig. 3. Same as Figure 2 but for SH, JJA.
Fig. 4. Maximum intensity distributions based on full resolution MSLP, 925 hPa winds and $\xi_{850}$ for the winter periods in the NH (DJF) and SH (JJA), (a) NH, DJF, MSLP referenced to MSLP tracks, (b) SH, JJA, MSLP referenced to MSLP tracks, (c) NH, DJF, 925 hPa winds referenced to $\xi_{850}$ tracks, (d) SH, JJA, 925 hPa winds referenced to $\xi_{850}$ tracks, (e) NH, DJF, $\xi_{850}$ referenced to $\xi_{850}$ tracks, (f) SH, JJA, $\xi_{850}$ referenced to $\xi_{850}$ tracks. Values are number per month for the 1989-2009 period and the bin widths are 10 hPa for MSLP, 5 m s$^{-1}$ for winds and $10 \times 10^{-5}$ s$^{-1}$ for vorticity. SH vorticity is scaled by $-1$. 
Fig. 5. Maximum intensity distributions for cyclones that match and those that don’t match based on the T42, $\xi_{850}$ intensities for (a) NH, INTERIM-MERRA, (b) SH, INTERIM-MERRA, (c) NH, INTERIM-JRA25, (d) SH, INTERIM-JRA25, (e) NH, INTERIM-NCEP, (f) SH, INTERIM-NCEP. Bin widths $1.0 \times 10^{-5}$ s$^{-1}$. 
Fig. 6. Probability Density Distributions for mean separation distance for $\xi_{850}$ tracks that match for (a) NH and (b) SH. Units are geodesic degrees and bin widths are $0.25^0$. 
**Fig. 7.** Probability Density Distributions for instantaneous intensity differences for the tracks that match, (a) NH, MSLP (hPa), MSLP tracks with bin widths of 0.5 hPa, (b) same as (a) but for SH, (c) NH, 925hPa winds ($m s^{-1}$) with bin widths of 0.5 $m s^{-1}$, $\zeta_{850}$ tracks, (d) same as (c) but for SH, (e) NH, $\zeta_{850}$ ($\times 10^{-5} s^{-1}$), $\zeta_{850}$ tracks, bin widths of $1.0 \times 10^{-5} s^{-1}$, (f) same as (e) but for SH.
Fig. 8. Horizontal composites of the 100 most intense cyclones identified in ERA-Interim and matched to the other re-analyses for the NH of MSLP and system relative winds at 925hPa. Colour contours with interval 2.5$m/s^{-1}$ show the system relative wind speeds with the white lines indicating the highest values starting at 30$m/s^{(-1)}$. The vectors show the system relative wind vectors and the black contours show the MSLP with contour interval 5hPa. (a) ERA-Interim, (b) JRA25, (c) NASA-MERRA and (d) NCEP-CFSR. The large blue arrow indicates the direction of the composite storm.
FIG. 9. Same as Figure 8 but for SH.