# Storm Tracks and Reanalyses

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#### ABSTRACT

The hypothesis that extratropical cyclones in different reanalyses are all the same is tested and is shown that this is not necessarily the case.

The spatial and intensity distributions of extratropical synoptic scale cyclones are compared between three reanalysis projects (ERA-Interim, MERRA, JRA-25) using an objective feature tracking method. Objective feature tracking was performed using both relative vorticity ( $\xi_{850}$ ) and MSLP fields. Larger and more significant differences were found when using the  $\xi_{850}$  field which picks out smaller spatial scales. Spatial statistics indicate a high level of correspondence in the Northern Hemisphere (NH), particularly in the main storm tracks but with some differences of location, intensity and density in the secondary tracks. In the Southern Hemisphere (SH) there is less agreement, particularly in the Antarctic circumpolar storm track and in the genesis regions in the lee of the Andes. Overall, the highest track densities were found in ERA-Interim whilst the lowest densities were found in JRA-25. Intensity distributions similarly indicate better agreement in the NH and worse in the SH. Significantly different intensities were indicated between all three reanalyses in  $\xi_{850}$  and MERRA was systematically stronger overall, particularly in the high-intensity tails in both fields.

A direct comparison of the track ensembles using system matching indicates a broad range of intensities that compare well, however there are a number of small-scale weak systems that show no correspondence. A similar proportion of track matches were found between all reanalyses in the NH. In the SH however, a greater proportion were found between ERA-Interim and MERRA (75% for SH  $\xi_{850}$ ) compared with matches against JRA-25 (66% and 65% against ERA-Interim and JRA-25 respectively, for SH  $\xi_{850}$ ) and between older generations of reanalyses in previous studies. Separation distances of directly matched storms show smaller distances between ERA-Interim and MERRA compared with JRA-25 in the NH ( $\leq 2^{\circ}$ ). The direct track comparisons reveal worse matches and larger separation distances between JRA-25 and the other reanalyses in the SH however ERA-Interim–MERRA compares almost as good as in the NH. Life cycle composites of the 100 most intense storms in the NH and SH Atlantic and Pacific indicate very similar life cycles but with more intense deeper composites for MERRA and with JRA-25 the weakest, reflecting the intensity distributions.

The results indicate that the largest differences between the reanalyses is most likely related to the data assimilation process and model resolution, and consequently that ERA-Interim and MERRA have systems of comparable quality. Other differences seen between the three reanalyses may be attributed to model parameterizations and orographic representations. More experimentation is needed however to attribute with greater confidence reasons for the differences observed.

# 1. Introduction

The central hypothesis to be tested in this project is: 'Are the properties of extratropical cyclones in different reanalyses all the same?' This is an important question as reanalyses are often used to study the behaviour and properties of extratropical cyclones which are influential with respect to the day to day weather and general circulation. Reanalyses are also often used to validate climate models (e.g. Bengtsson et al. 2006). Hence it is imporant to understand the uncertainties in the representation of extratropical cyclones. To answer this question, this study aims to investigate the level of uncertainty in how extratropical cyclones are represented in three of the most modern reanalyses. Namely, the European Centre for Medium Range Weather Forecasting (ECMWF) Interim Re-analysis (ERA-Interim); the National Aeronautics and Space Administration (NASA) Modern Era Retrospective-analysis for Research and Applications (MERRA); and the Japan Meteorological Agency (JMA) 25-year Reanalysis (JRA-25). The first two of these are new high resolution reanalyses. Extratropical cyclone intensity and location are the central focus of the paper based on a range of diagnostics, including spatial statistics, intensity probability density functions (pdf's) and composite lifecycles.

The AMS (2000) defines a reanalysis as a procedure to project the state of the atmosphere as known from a finite set of imperfect, irregularly distributed observations onto complete a gridded meteorological database spanning the historical observational data record. Reanalyses are produced using modern Numerical Weather Prediction (NWP) methods to combine observations with a model prediction using data assimilation (Bengtsson et al. 2004b). This is done in such a way that account is taken of the dynamics and physics of the forecast model to ensure the observations are used in a meteorologically consistent way (Andersson and Thépaut 2008). This means any reanalysis is dependent on the observations that are assimilated through their biases and their distribution in space and time; the data assimilation method and the forecast model, via its resolution, and physical parameterizations. For example, changes in the observing system can introduce unphysical discontinuities in fields as highlighted by Bengtsson et al. (2004b).

Earlier reanalyses such as NCEP and ERA-40 (Kalnay and Coauthors 1996; Uppala and Coauthors 2005) facilitated tremendous research into weather and climate (Hollingsworth and Pfrang 2005). To 2006, over 6500 unique users accessed the ERA-40 dataset (Uppala and Coauthors 2006). Reanalyses provide our best homogeneous 4-D view of the atmosphere over decadal periods which justify their use for short-term climate studies, exploration of weather systems and verifying climate models. However, to have confidence in their use the uncertainties in the reanalyses need to be understood. This can be achieved by intercomparing different reanalyses and performing experimentation. Experimentation is outside the scope of this study.

Research efforts highlighting reanalysis weaknesses or uncertainties (e.g Bengtsson and Coauthors 2007) can feed back, identifying future development pathways, leading to improvements in the relevant areas and ultimately to subsequent reanalyses (e.g. Saha and Coauthors 2010). One way to explore differences between reanalyses is to identify cyclones and then track them. There have been several studies using reanalyses and objective feature tracking (e.g. Hoskins and Hodges 2002, 2005), to explore the climatology of cyclones and the differences between reanalyses (e.g. Hodges et al. 2003, 2004; Hanson et al. 2004; Wang et al. 2006; Bromwich et al. 2007). There have also been previous studies into storm tracks based on climate model integrations and comparing with reanalyses (e.g. Bengtsson et al. 2006, 2009).

Objective feature tracking is frequently used to produce information on the spatial distribution and frequency of extratropical cyclones using both reanalyses (e.g. Hoskins and Hodges 2002, 2005; Bromwich et al. 2007) and climate model data (e.g Bengtsson et al. 2006, 2009). A range of algorithms have been used, each with their own drawbacks (Hoskins and Hodges 2002; Raible et al. 2008); tracking pressure minima (e.g. Jung et al. 2006; Löptien et al. 2008), maxima in lower-tropospheric vorticity [geostrophic vorticity (e.g. Sinclair 1994); relative vorticity (e.g. Hoskins and Hodges 2002, 2005)] and geopotential height minima (e.g. Blender and Schubert 2000).

Hoskins and Hodges (2002) explore storm tracks in the Northern Hemisphere (NH) winter (December to February) using a wide range of meteorological fields at multiple levels. These were computed from a combination of ECMWF Reanalysis including the ERA-15 (Gibson et al. 1997) and operational reanalyses up to the year 2000. The focus here was mostly on detailing the storm tracks based on a wide range of fields rather than the differences between the reanalyses. Hoskins and Hodges (2005) repeat the same methodology as Hoskins and Hodges (2002), but this time applied it to the Southern Hemisphere (SH). The primary dataset here changed to the 40+ years of 40-yr ECMWF Re-analysis (ERA-40) (Uppala and Coauthors 2005). This paper again details the nature of the storm tracks overall in a similar style to Hoskins and Hodges (2002), rather than comparing reanalyses.

Comparisons between reanalyses focused on storms helps to indicate differences in how

storms are represented in the reanalyses. Several studies have been performed in the same vein. Hodges et al. (2003, 2004) used the ERA-15, NCEP-NCAR, NCEP-DOE (Kanamitsu et al. 1999) and GOES-1 (Schubert and Coauthors 1995) reanalyses. This is applied to storm tracks of the Northern and Southern Hemisphere. A greater agreement was found between the cyclones in the NH than in the SH. Hanson et al. (2004) focus on the North Atlantic storm track, comparing ERA-15 and NCEP-NCAR reanalyses, concluding ERA-15 reproduces a more comprehensive cyclone climatology. ERA-40 and NCEP-NCAR are compared by Wang et al. (2006), who conclude that significant differences are present in the SH extra-tropics and ERA-40 showing systematically stronger cyclone activity. Bromwich et al. (2007) focus on polar regions comparing ERA-40 with NCEP-NCAR/NCEP-DOE and additionally the JRA-25 reanalysis, also demonstrating the generally better agreement in the NH.

Many of the above papers have demonstrated that comparing reanalyses allows one to assess the uncertainties or differences in the storms between the reanalyses and gain an idea about how different the reanalyses are in general. These differences within and between reanalyses can be due to many factors. Different reanalyses have different atmospheric models with different physical parameterizations, and use different resolutions and data assimilation systems. There can all result in uncertainty in the representation of cyclones in the reanalyses. The distribution of the observations in space and time can also introduce large uncertainties in the representation of cyclones.

Changes in the global observing system are a common cause of differences within and between reanalyses (Bengtsson et al. 2004b). From the middle of the nineteenth century, the global observing system evolved from a surface-based system to include radiosondes following the introduction of the radiosonde network after World War II (Bengtsson et al. 2004b). Observations from satellite platforms become more prevalent after 1979 and now play an increasingly dominant role in the present integrated system. Bengtsson et al. (2004b, 2006) examined the impact of the changes of the observation system on the ERA-40 reanalysis by removing observations to simulate the different eras of observations. It was found that the surface-based system has 'severe limitations in reconstructing the atmospheric state of the upper troposphere and stratosphere' when compared with the full system (Bengtsson et al. 2004b). The 'terrestrial' system of surface and radiosonde observations has 'major limitations in generating the circulation of the SH with considerable errors in the position and intensity of individual systems' but compared well with the full system in the NH (Bengtsson et al. 2004b). The modern space-based system was found to 'analyze the larger-scale aspects of the global atmosphere almost as well as the present observing system but performs less well in analyzing the smaller-scale aspects' (as represented by the vorticity field) (Bengtsson et al. 2004b). All three aspects are clearly needed for a full accurate observing system. Hoskins and Hodges (2005) show that for the SH the number of systems is generally higher in the pre-1979 period but that the maximum intensities are higher in general in the post-1979 period of the ERA-40 reanalysis. Hoskins and Hodges (2005) reason that before the introduction of the satellite data, the SH ERA-40 analyses will be more influenced by the GCM and since these model-generated storms tend to be smoother and longer lived, so more storms pass the selection criteria. The model may also be biased to weaker intensities than when it is better constrained by observations resulting in the stronger intensities shown in the post-1979 period (Hoskins and Hodges 2005).

As indicated above, the spatial distribution of the observations can introduce significant differences within and between reanalyses. The SH has fewer terrestrial based observations compared to the NH. This is due to relatively smaller continental landmass and population with fewer radiosonde launch sites, surface stations and aircraft flights. As a result there is a clear dominance of the satellite observing system in the SH (Bengtsson et al. 2004b). The way these satellite observations are assimilated, either as retrievals or the direct assimilation of the radiances, can lead to greater differences between reanalyses. Before the modern satellite observing period the reanalyses are essentially model dominated in the SH.

The forms of data assimilation used in reanalyses are also varied. Most recent reanalyses have used variational data assimilation. A commonly used version of this data assimilation used in reanalyses is known as the three-dimensional variational (3D-Var) algorithm. In this technique, the observations that have come in over the analysis cycle prior to this analysis step time are compared to the model background. The analysis increment is determined at the end of the interval from the previous analysis step, and all data assimilated within that time are mapped onto the final time. The combined analysis is then used as an initial condition for the next 6-hour forecast of the GCM. An advantage of this technique is that is not so computationally expensive in comparison to more advanced techniques (Andersson and Thépaut 2008). However, it may therefore be less accurate due to problems with nonphysical adjustment processes being introduced at the analysis time as the new added observations can sometimes be a shock to the dynamics in the model. For example an increment due to wind observations must also result in an adjustment to the mass field in order to maintain geostropic balance. A second problem of only introducing observations at the analysis time is the field could have significantly changed from the observation time and additionally quality control procedures can also mistakenly reject observations if the difference is too large relative to the previous analysis step. This problem is particularly prevalent in a fast developing storm where the atmospheric state, for example the pressure drop, is sufficiently different between two observations to be rejected by the quality control procedure.

A more advanced variational data assimilation technique is four-dimensional variational data assimilation (4D-Var). The 4D-Var DAS performs a statistical interpolation in space and time between a distribution of observations and an 'a priori' estimate of the model background over the assimilation period (Andersson and Thépaut 2008). It sweeps forward (called the perturbation model) and backwards (adjoint model) in time continuously reanalyzing over the period, gently moving the model towards the particular observation at a particular time within that period. The technique also aims to minimize the presence of high amplitude, fast moving disturbances such as gravity waves.

The numerical forecast models used in the reanalyses can also be very different in terms of their dynamical cores; spectral or grid point, semi-lagrangian; their physical parameterizations; and the resolutions used. Processes which are subgrid-scale in the GCM use physical parameterization schemes to represent them. These include orographic and convection processes which can all use different schemes between reanalyses (Hodges et al. 2003; Bengtsson et al. 2004b). How some fields are derived from the model output also varies between systems, for example extrapolation techniques around orography required for fields which intersect high orography such as the Himalayan mountains or the Antarctic Plateau.

No studies have previously been made intercomparing the new ERA-Interim and MERRA reanalyses these have been produced at nominally similar high resolutions. The JRA-25 reanalysis will be used as an existing comparison with a reanalysis produced at a much lower resolution. Identifying extratropical cyclones from these datasets and comparing between reanalyses is a good way of identifying the uncertainties in the representation of cyclones in reanalyses and to suggest possible causes.

In section 2 the reanalysis data and cyclone tracking, compositing and analysis methodologies will be discussed, including the feature tracking techniques of Hodges (1994, 1995, 1999). Results are given in section 3 and conclusions are in section 4.

# 2. Methodology

### a. Reanalysis Data

The three datasets used in this reanalysis comparison will now be looked at in turn.

The ERA-Interim project (Berrisford et al. 2009; Dee and Uppala 2009) was intended as an improvement on the previous ERA-40 (1957-2002) reanalysis. It aimed to improve key aspects such as the representation of the hydrological cycle (Andersson and Coauthors 2007; Bengtsson et al. 2004a,b), the quality of stratospheric circulation (Schoeberl et al. 2003; van Noije et al. 2004), and the handling of biases and changes in the observing system (Dee 2005; Bengtsson and Coauthors 2007). To date, the system has involved the use of more than  $29 \times 10^9$  meteorological observations (Dee et al. 2009). The model uses a T255 sphericalharmonic representation for the basic dynamical fields, on 60 vertical levels extending from the surface up to 0.1hPa. The gridded data is available on a N128 Gaussian grid with a latitude spacing of  $0.703125^{\circ}$  (~ 70km) The temporal resolution of 6 hours is available for the output products. The reanalysis covers the data-rich period since 1989, and continuing in near-real time. Data used for this paper runs from 1989-2006. The data assimilation uses a 4D-Var with a 12-hour window of observations that includes the adaptive estimation of biases in satellite radiance data (Dee and Uppala 2009). Uppala et al. (2008) notes that this system makes better use of synoptic observations than the 6-hour 3D-Var used in ERA-40, especially for certain 'relatively sparse' satellite measurements in the early 1990s.

The MERRA project (Bosilovich and Coauthors 2006) was created with the aim of studying the hydrological cycle on a broad range of weather and climate time scales, and places the NASA Earth Observing System (EOS) suite of satellite observations in a climate context. The model is run only in gridpoint space (finite volume), unlike either of the other two datasets which are spectral models. MERRA has a native resolution of  $2/3^{\circ}$  longitude by  $1/2^{\circ}$  latitude (~ 56km× ~ 74km; 540 × 361 global gridpoints), with observational analyses every 6 hours. MERRA has 72 terrain following model coordinate levels, extending to 0.01hPa, and 42 output pressure levels Bosilovich (cited 2010). It focuses on the satellite era from 1979-current. Due to data availability and MERRA production times, data used in this paper runs from 1979-2006. MERRA is based on a major new version of the NASA Goddard Earth Observing System Data Assimilation System (GOES DAS) (Version 5.2.0). This system is based on the GOES-5 Atmospheric General Circulation Model (AGCM) with the new NCEP unified Gridpoint Statistical Interpolation (GSI) Analysis. The GSI analysis is a 3D-Var system applied in grid-point space to facilitate the implementation of anisotropic inhomogeneous covariances (Rienecker and Coauthors 2008). The GSI produces an analysis increment using 3D-Var which is then used with an Incremental Analysis Update (IAU) procedure (Bloom et al. 1996) to incorporate the analysis increment gradually to prevent shocks at the analysis times. This technique gently and continually forces the model forecast via 6 hour 'time tendencies' of 'analysis increments' coming from the data assimilation of observations throughout the 6 hour period (3 hours either side).

The JRA-25 project (Onogi and Coauthors 2007) also aimed to improve upon ERA-40, particularly in the tropics with improved satellite data assimilation, and to contribute to climate research and the operational seasonal prediction in Japan and Asia. The model has a T106 spectral resolution ( $\sim 120$ km;  $320 \times 160$  Gaussian global gridpoints), on 40 vertical levels extending from the surface up to 0.4hPa. Data is available on a latitude-longitude grid in  $1.125^{\circ}$  (288 × 145 global gridpoints). The temporal resolution of 6 hours is available for the output products. The reanalysis period covers 1979 to 2004 for the first release and then continues in near-real time. Data used for this paper runs from 1979-2006. The DAS uses a 3D-Var system on 6-hourly cycles.

Observations used in these reanalyses comes from many sources. These include the basic sources such as surface data from stations and ship, additional terrestrial data from aircraft and radiosondes. Finally a large amount of data comes from satellites, remote sensing fields such as temperature, moisture, radiation and winds through the atmosphere and further surface variables including snow cover. The three reanalyses used for this intercomparison all use direct assimilation of satellite radiances which avoids problems with assimilating retrievals with complicated error structures. Satellite observations of moisture have had very little impact on tracked systems relative to the other fields assimilated (Bengtsson et al. 2004a).

ERA-Interim, MERRA and JRA-25 intercomparisons will be made for the common years of 1989-2006. Additionally some intercomparisons are made between MERRA and JRA-25 for the period of 1979-1988. For the seasonal analysis, the usual meteorological seasons are chosen (DJF, MAM, JJA and SON), ignoring lag (e.g. Hurrell et al. 1998) and oscillation complexities (van Loon 1967) in the SH. Mean sea level pressure and vorticity fields will be used for the cyclone tracking. Wind data will also be used in the cyclone evaluations of intensity.

## b. Cyclone Identification and Feature Tracking

The feature tracking algorithm used here is that of Hodges (1994, 1995, 1999); Hoskins and Hodges (2002) using both Mean Sea Level Pressure (MSLP) and 850hPa relative vorticity  $(\xi_{850})$  to identify features. The use of these two fields allows a contrast to be made between features of different scale. Additionally, there are various benefits and drawbacks in using each field. For example MSLP is strongly influenced by large spatial scales and strong background flows and identification of features tends to be dominated by large-scale, slow moving synoptic features (Hoskins and Hodges 2002). Additionally, the MSLP is an extrapolated field and may be sensitive to how the extrapolation is performed and the representation of orography in the model (Hoskins and Hodges 2002), particularly at coarser resolutions. Relative vorticity has been found to be a better field for identifying synoptic systems as it allows systems to be identified much earlier in their life cycle as it is less influenced by the background flow since it focuses on smaller spatial scales (Hoskins and Hodges 2002). Missing data values due to high orography at the level of the 850hPa winds are accounted for via interpolation. The  $\xi_{850}$  is calculated from the zonal and meridional wind fields at 850hPa ( $u_{850}$  and  $v_{850}$ ). To avoid projection issues and loss of data quality it is calculated directly on the sphere, in spherical coordinates as shown in equation 1, where  $\phi$  is latitude,  $\lambda$  is longitude and r is the radius of the Earth.

$$\xi_{850} = \frac{1}{r\cos\phi} \left[ \frac{\partial v_{850}}{\partial\lambda} - \frac{\partial (u_{850}\cos\phi)}{\partial\phi} \right]$$
(1)

High-resolution data in the vorticity field can be very noisy, so reducing the resolution before tracking is preferred. Geostropic vorticity computed from the MSLP (Sinclair 1994) could be used but still has the drawback of being dependent on an extrapolated field.

Before performing the tracking the large-scale background is first removed from the data using a spherical harmonics filter, which removes total wavenumbers  $n \leq 5$ . This is performed on the MSLP as it is found to be beneficial to remove the planetary scale waves (Anderson et al. 2003). It is also performed on  $\xi_{850}$  for consistency (Hoskins and Hodges 2002). Additionally, the vorticity field is spectrally truncated at 42 wavenumbers (T42) on a Gaussian grid for the tracking analysis to exclude very small-scale structures (Hoskins and Hodges 2002). It also means datasets of differing resolution can be truncated to the same resolution for tracking therefore identifying a common spatial scale for fairer comparisons. The MSLP field is also reduced in resolution to T63 for this reason. Both fields also have their spectral coefficients smoothed with a tapering filter to reduce any Gibbs noise (Sardeshmuch and Hoskins 1984). There are other points of view about filtering methods, such as the comparative advantages of temporal filtering (e.g. Donohoe and Battisti 2009) in relation to system intensities, however due to referencing back to full resolution, and the additional negligible effect on  $\xi_{850}$ , such limitations have been negated here.

The feature points (i.e. pressure minima, vorticity maxima/minima—in the NH/SH respectively) of the cyclone are identified and are initialized into tracks using a nearest neighbor approach. These are then improved by minimizing a cost function for the ensemble track smoothness to obtain the minimal set of smoothest tracks. The minimization is performed subject to adaptive constraints on the track smoothness and displacement distance (Hodges 1999). This is done directly on the sphere to avoid the need to use projections which can introduce biases (Hodges 1995). In order to make sure the tracks are mobile and not to introduce noise into the analysis from very short tracks, a post-tracking filter is applied. The tracks that are kept for further analysis must last for more than 2 days and travel further than 1000km. The full-resolution properties of the cyclones are added back onto the tracked storm trajectories to get the full resolution intensities (Bengtsson et al. 2009). For MSLP a minimization of the full resolution field is performed to find the closest true minima to the track center and for 925-hPa winds and  $\xi_{850}$  a grid point search is performed for the maximum or minimum value in the vicinity of the storm center. The search radius is set to  $5.0^{\circ}$ .

### c. Statistical Analysis and Techniques

Once the tracking process has been completed, the cyclone tracks can be analyzed and a series of statistical diagnostics created.

### 1) Spatial difference statistics

Spatial statistics are produced showing the spatial distribution of the storms in each season and reanalysis. This uses the approach described by Hodges (1996, 2008) where the statistics are computed directly on the sphere using spherical kernel estimators with local kernel functions. This prevents the kinds of biases that can be introduced when using histogram type methods on projections (Hoskins and Hodges 2002).

The spatial statistics comprise the track mean intensity, track density, and genesis and lysis densities for the storms. A high genesis density shows locations where it is preferential for systems to originate and high lysis density shows locations where it is preferential for systems to disappear. Differences can be taken between the spatial statistics for different reanalysis to show where the locations of differences occur (Hodges et al. 2003). The track density is computed using a single point from each track that is closest to the estimation point. The genesis density is computed from the starting points of the tracks excluding any tracks that start at the first time step. Similarly, the lysis density is computed from all the end points of the tracks excluding any tracks that end at the last time step (Hodges et al. 2003). The raw density statistics are scaled to number densities per month per unit area, equivalent to a 5° spherical cap (~  $10^6$  km<sup>2</sup>). The statistical diagnostics are calculated for  $\xi_{850}$  and MSLP fields from each dataset, hemisphere and season.

To find areas where the differences are statistically significant, a permutation test using a Monte Carlo approach is used following the methodology of Hodges (2008). This is based on the construction of 'new' pairs of resampled datasets, by repeatedly resampling the pooled tracks without replacement and computing the sampling distributions for the statistic from which the 'p' values are obtained. In this case the null hypothesis  $(H_0)$  is that the two datasets are drawn from the same population and hence the two statistical values obtained from the two separate data samples are consistent with  $H_0: s_1 - s_2 = 0$ . If this test statistic is not consistent with this hypothesis it is rejected. The calculated sampling distribution and p values determine the probability that a more extreme value of the test statistic (difference) is possible than that obtained from the original pair of samples (Hodges 2008). The p values are calculated as described above from 2000 sets of difference statistics. A two-tailed test is assumed because in general there is no reason to prefer a one tailed test. A p value of 0.05 is typically chosen as a significance level. In order to make this Monte Carlo approach as efficient as possible to use a sufficiently large sample size, an estimation scheme based on spherical quad trees is used (Hodges 2008). Nevertheless, this technique is computationally very expensive due to the large number of times the resampling is repeated. As a result the University of Reading Campus Grid was used for these calculations, using up to 300 nodes (Spence 2009).

### 2) INTENSITY DISTRIBUTIONS

Intensity distributions are a clear and useful method for comparing differences in the strength of systems in different regions and between seasons and datasets. The statistics are again calculated for  $\xi_{850}$  and MSLP fields from each dataset, hemisphere and season by

finding the maximum intensity along each track and binning the values.

Many of these distributions are sufficiently different so that statistical significance tests are not required. However, where the distributions are not obviously very different a statistical test for the goodness of fit is required. The Kolmogorov-Smirnov test (K-S test) is used here to determine if two datasets differ significantly. This test has the advantage of making no assumptions about the distribution of the data (e.g. it is normally distributed) and it is sensitive to the location and shape of the empirical cumulative distribution functions (CDFs). The methodology of this hypothesis test is similar to the permutation test used for the spatial difference statistics. The null distribution of this statistic is calculated under the null hypothesis that the samples are drawn from the same distribution. A significance level of p = 0.05 again tests the distribution differences to see if the null hypothesis can be rejected. This would indicate a sufficiently large discrepancy and therefore the distributions are statistically different. This test is also carried out as a two tailed test as there is no knowledge if one CDF is greater than or less than the other CDF. The K-S test statistic,  $D_n$ , looks for the largest difference, in absolute value, between the two distributions, and is calculated by equation 2:

$$D_n = \max_{x} |F_n(x) - F_m(x)| \tag{2}$$

where  $F_n(x)$  is the empirical cumulative probabily of distribution n, estimated as  $F_n(x_i) = i/n$  for the  $i^{th}$  smallest data value and likewise  $F_m(x)$  is the empirical cumulative probabily of distribution for m. The K-S test is usually preferred over the  $\chi^2$  test as it is usually more powerful for continuous distributions (Wilks 2006). The statistics package 'R' (Crawley 2005) was used to compute the K-S test statistics.

### 3) TRACK MATCHING: DISTRIBUTIONS AND SEPARATION DISTANCES

Since the reanalyses should be simulating identically the same meteorological events for the same analysis period, a direct comparison of track ensembles is computed. The methodology follows closely that of Hodges et al. (2003, 2004). Each track in the first ensemble is compared with those in the second by first finding tracks in the second ensemble that overlap in time with the track in the first ensemble. If the number of points that overlap is greater than or equal to 50% of the number of points in the tracks, this is considered a possible good match in time. Since there will occasionally be more than one track in the second ensemble that satisfies the temporal matching threshold, the best match is taken to be the two tracks that match for the largest number of points and that have the smallest mean separation less than 4.0°. The mean separation on the unit sphere is computed. Intensity distributions for the storms that match and those that do not match are computed using the T42 maximum intensities as these show smaller differences than the full resolution fields and make it easier to see differences in numbers and distribution shape.

### 4) LIFECYCLE COMPOSITES

Lifecycle composites are determined from the single-value properties along the selected tracks, centered relative to the time of maximum intensity in the T42  $\xi_{850}$  field (Bengtsson et al. 2009). These were computed for full resolution  $\xi_{850}$ , MSLP and additionally for 925hPa winds for the top 100 most intense storms in each of the Atlantic and Pacific extratropical basins for the NH and SH. These were computed for the winter season in each hemisphere (DJF and JJA in the NH and SH respectively) to focus on the most intense season.

### 3. Results

In this section results are presented detailing and comparing reanalyses for the NH and SH extratropical (30° to 90°N and S) storm tracks based on  $\xi_{850}$  and MSLP and additionally for 925hPa winds in the intensity distributions and lifecycle composites. The results from the ERA-Interim reanalysis will be used as the base dataset throughout as this has the shortest time period but is one of the higher resolution analyses.

# a. The $\xi_{850}$ and MSLP reanalysis climatologies

In this section the ERA-Interim climatology track and genesis density statistics will be described to orientate the results discussion. NH winter (DJF)  $\xi_{850}$  spatial statistics are shown in figure 1a,c for track and genesis density, respectively. This shows the type of distribution of storms seen in previous studies (e.g. Hoskins and Hodges 2002; Hodges et al. 2003).

There are regions of high track density across both the Pacific and Atlantic ocean basins. The Pacific storm track extends from east Asia coming to an abrupt end on the upslope side of the coastal mountains of British Columbia. The genesis density indicates two main source regions to this Pacific storm track. One group of storms is initiated in east Asia, over Mongolia and China with strong downslope cyclogenesis associated in the lee of the Himalayas. A secondary genesis peak is seen to the east of Japan. The main track extends to the northeast and most cyclones then occlude and decay in the central North Pacific region (lysis density not shown). The second group originates in a secondary development region in the mid-Pacific with cyclones occluding with strong cyclolysis in the Gulf of Alaska-Vancouver region. There is a high level of activity over the continent of North America associated with strong genesis and growth rates in the lee of the Rockies. Many of these storms then undergo lysis on the eastern seaboard of the U.S.A. A further genesis region is situated just to its east and together these storms move across the Atlantic in the second main NH storm track with lysis over northwestern Europe.

Other storm tracks include the Siberian and Mediterranean storm tracks. The former initiates over the Scandinavian and Caspian regions and decays over central and eastern Siberia and the latter track originates in the western end and decays in the eastern end of the Mediterranean region. Cyclones in this region are generally smaller scale as indicated by the mean intensity statistics (not shown).

The ERA-Interim climatology track and genesis density statistics for the SH winter (JJA),  $\xi_{850}$ , are shown in figure 1b,d. This shows the type of distribution of storms seen in previous studies (e.g. Hodges et al. 2003, 2004; Hoskins and Hodges 2005). A region of high track density encircles the SH between latitudes of  $45^{\circ}$  and  $65^{\circ}$ S with maximum activity levels to the south of Australia and New Zealand (between 135° and 180°E). The maximum mean intensity (not shown) is equatorward and upstream of this, covering a band over the Atlantic and Indian Ocean sectors (45°W to 135°E). A further weaker band of track desity exists over the Pacific region (90° to  $180^{\circ}$ W) which is also weaker in intensity than in the Atlantic and Indian Ocean sectors of the SH due to weaker SST gradients (Hoskins and Hodges 2005). There is a large region of cyclolysis (not shown) and strong decay around most of the coastal region of Antarctica and upstream of the southern tip of the Andes. There are three main peaks in cyclogenesis, two in the lee of the southern Andes and off the coast of the Antarctic Peninsula. The most equatorward of the genesis regions is associated with where the subtropical jet crosses the Andes. The more poleward of the Andes genesis regions is associated with storms decaying on the upslope side and re-generating on the downslope side (similar to the pattern seen over the Rocky Mountains). This is associated with the flow over orography leading to compression and expansion of isentropes. The Antarctic Peninsula genesis region is associated with storms spiraling in from lower latitudes bringing in warm moist air, and the advection of cold air from the continent, leading to increased baroclinicity.

The MSLP statistics (not shown) are consistent with those of the  $\xi_{850}$  in both hemispheres,



0.0 1.5 3.0 4.5 6.0 7.5 9.0 10.5 12.0 13.5 15.0 16.5 18.0 19.5 21.0 22.5 0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00 3.25 3.50 3.75

FIG. 1.  $\xi_{850}$  tracked winter distributions of track density (a) and (c), and genesis density (b) and (d). Shown for NH DJF (a) and (b), and SH JJA (c) and (d). Density distributions are number density per month per unit area as defined in the text.

though there are some differences. There are lower levels of activity, particularly in the Mediterranean, Siberia, and the lee of the Rocky Mountains in the NH reflecting the largerscale nature of the features identified in the MSLP field and the smaller scale nature of the features found in these regions. In the SH there is a likewise reduced level of activity at latitudes lower than 60°S, again suggesting these systems are of a relatively smaller scale but also some possible bias due to some residual influence smaller planetary scale waves  $(5 < n \leq 10)$  which were not removed, highlighting the advantages of  $\xi_{850}$ . The NH Atlantic and Pacific summer season storm tracks show lower densities and weaker intensities (not shown). In particular the Mediterranean, Mongolian and North American storm tracks show a large decrease in genesis and lysis densities (not shown). There is again a more marked difference in MSLP than  $\xi_{850}$ .

The SH circumpolar storm track is also decreased in density and intensity (not shown) in the summer (DJF) compared to the winter (JJA). The track density is also shifted further from the Antarctic coast. The Antarctic coastal genesis region maximum to the south of New Zealand in figure 1d is much reduced and the northern most of the two genesis regions in the lee of the Andes has also decreased in density, the southern region has slightly increased. MSLP again shows weaker intensities and densities with a more marked change with the summer season.

### b. Intercomparisons between reanalyses

Table 1 shows the number of storms per month as a summary of the differences in the storms in reanalyses. The data are mean values over the period of 1989–2006, with the values in brackets for the period 1979–2006. It is clear there is a larger number of storms tracked using the  $\xi_{850}$  compared to the MSLP field. This is consistent throughout all seasons and reanalyses and also with the results from comparing the climatological spatial statistics in section 3a. Comparing between hemispheres it is clear to see that the NH has most storms in the DJF winter season and the SH has the most storms in the JJA winter season. It can also be seen, by comparing reanalyses, that ERA-Interim has more storms than JRA-25 and MERRA, in both  $\xi_{850}$  and MSLP fields. Looking at the extended period it can be seen there

TABLE 1. Number of cyclones per month for each season, field and reanalysis for the period 1989–2006 that are found in the extra-tropics (30°–90°N and S). Values in brackets are for the 1979–2006 period for MERRA and JRA-25.

Hemisphere		NH				SH			
Seasons		DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Interim	$\xi_{850}$	130.5	121.3	99.6	112.7	103.3	120.8	130.6	120.6
	MSLP	80.8	80.9	68.0	75.1	66.4	77.8	82.2	79.3
JRA-25	$\xi_{850}$	123.4	118.1	96.8	109.4	97.6	112.0	122.3	113.2
		(124.0)	(118.7)	(96.8)	(109.3)	(97.1)	(111.3)	(123.4)	(113.0)
	MSLP	77.0	77.5	65.8	73.4	60.1	69.6	68.8	62.1
		(77.2)	(77.5)	(65.9)	(72.8)	(59.6)	(69.4)	(70.7)	(64.7)
MERRA	$\xi_{850}$	124.9	117.2	97.3	109.1	100.9	117.0	125.3	118.4
		(125.1)	(118.2)	(97.5)	(109.6)	(101.0)	(117.0)	(126.2)	(118.7)
	MSLP	78.1	81.8	70.1	75.2	64.3	76.0	79.1	76.2
		(78.3)	(81.8)	(64.5)	(74.8)	(70.7)	(75.4)	(79.6)	(76.3)

is a slight increase in the number of storms in the winter seasons ( $\sim 0.7$  per month).

More in-depth statistical comparisons will now be made between the three reanalysis datasets.

### 1) Spatial comparisons for $\xi_{850}$ and MSLP

Figures 2 and 3 show the differences in the track and genesis densities for  $\xi_{850}$  features between ERA-Interim and both JRA-25 and MERRA, respectively.

Firstly comparing winter density differences between ERA-Interim and JRA-25 (Fig. 2a,c). The differences in density of the storms are quite small, typically less than 2–4 per month (per unit area). JRA-25 is generally lower in activity than ERA-Interim except for some regions around the Antarctic coast and the Mongolian storm track. This Mongolian storm track is delineated with a region where  $p \leq 0.05$  which indicates the region is significant at the 95% level in the standard parlance. There are also regions where ERA-Interim is significantly more active to this standard. These include the Mediterranean track (Iraq, Iran, Pakistan), where there is a difference of up to 6 per month more. These storms, associated with the sub-tropical jet, are generally very weak in intensity and hence sensitive to the data assimilation and available observations (see later). The greater strength of ERA-Interim is also apparent along the Mongolian storm track and on the upstream side of the Rocky Mountains over the southern U.S.A–northern Mexico. In the SH differences can be found over most of the Antarctic storm track with significant  $(p \leq 0.05)$  activity increases in a band around 60°S and between 90° to 180°E and south of the southern tip of Argentina with activity increases over 6 per month in ERA-Interim. Other areas with more minor, yet still significant differences run in regions from 50°W to 50°E with an increase in activity of up to around 5 per month.

Despite the ERA-Interim winter season showing slightly more activity overall, particularly in certain locations, when compared with , the spatial intensity distributions (not shown) indicate that JRA-25 has few intensity differences in the NH and no weak overall trend either. In the SH however, there is a clear divide at around 65°S, with JRA-25 being more intense poleward of this, and ERA-Interim, equatorward to about 45°S at the edge of the main storm track, with differences of up to  $0.75 \times 10^{-5} \text{s}^{-1}$  in each region respectively. This is consistent through all seasons in the SH. The full resolution storm intensity distributions will be compared in greater detail in the next subsection.

Comparing the genesis density between ERA-Interim and JRA-25 (Fig. 2b,d) there



FIG. 2. ERA-Interim–JRA-25 difference plots for  $\xi_{850}$  tracked winter distributions of track density (a) and (c), and genesis density (b) and (d). Shown for NH DJF (a) and (b), and SH JJA (c) and (d). Density distributions are number density per month per unit area as defined in the text. Regions with  $p \leq 0.05$  are delineated by the white lines. Regions where the original track density is less than 1 per month per unit area are suppressed.

is no overall dominance by either reanalysis. There are some regions however, that show differences that are significant. In the NH JRA-25 has regions of higher genesis density over Algeria feeding into the Mediterranean storm track and to the east of Japan feeding into the Pacific storm track. ERA-Interim also has a region of significantly larger genesis activity over Iran and the Persian Gulf feeding into the end of the Mediterranean track consistent with the differences in the track density discussed above. The most significant difference is over northern China and Mongolia, southern China into the lee of the Himalayas and in the lee of the Rocky Mountains in ERA-Interim. This again suggests greater differences in representation of orography when comparing against JRA-25 with less comparable resolution. In the SH the most significant differences are the genesis regions in the lee of the Andes and the Antarctic Peninsula. ERA-Interim represents a much higher level of genesis activity in both these regions with 1-2 extra storms per month, whereas JRA-25 has the more active genesis region over the Antarctic Peninsula.

Lysis densities (not shown) correspond similarly with patterns seen above. ERA-Interim indicates more active equatorward lysis at the end of the more equatorward shifted tracks for example over Iraq and Pakistan, at the end of the Siberian track, and around the U.S.A-Canadian border on the upstream side of the Rocky Mountains. In the SH ERA-Interim shows a more active region on the upstream side of the Andes at around 40°S and 75°W). One further region is off the Antarctic coast to the south of Australia at around 60°S and 120°E. Similarly JRA-25 has a more active lysis region in northeast Canada at the end of the North American storm track and upstream of the Antarctic Peninsula showing over 1 cyclolysis per month.

Comparing the spatial statistics across other seasons (not shown) between ERA-Interim and JRA-25 for  $\xi_{850}$  shows less significant differences overall, however there are some exceptions. In the spring season the Mongolian/Chinese and southern China genesis region is still more active for ERA-Interim (~ +1 per month). The SH track densities are all showing the same significantly increased activity for ERA-Interim. The lysis density peak activity found in JRA-25 on the upstream side of the Antarctic Peninsula has now moved to the downstream side in the spring, and there is an additional peak by the Antarctic coast to the south New Zealand. The most significant difference in the summer seasons is an increase in genesis density on the lee side of the Rocky Mountains (over the southern U.S.A.) and the Andes (over southern Argentina). The autumn seasons difference patterns show similar significant regions to the spring genesis and winter lysis densities. There are no significant track differences in the NH, however in the SH indicates greater differences than even the winter season. Larger regions feature greater than 6 storms per month increase in ERA-Interim.

Comparing density differences between ERA-Interim and MERRA (Fig. 3) for with that of ERA-Interim against JRA-25 (Fig. 2) an improvement and a reduction in variation in the differences can be seen. Focusing on track density (Fig. 2a,c) there is again a general



FIG. 3. ERA-Interim-MERRA difference plots for  $\xi_{850}$  tracked winter distributions of track density (a) and (c), and genesis density (b) and (d). Shown for NH DJF (a) and (b), and SH JJA (c) and (d). Density distributions are number density per month per unit area as defined in the text. Regions with  $p \leq 0.05$  are delineated by the white lines. Regions where the original track density is less than 1 per month per unit area are suppressed.

bias of ERA-Interim representing a slightly higher level of activity overall, although quite small, typically less than 2–4 per month (per unit area). In the NH winter (DJF) the pattern of significant differences is fairly similar to that of the previous comparison, with more systems in ERA-Interim over the tail end of the Mediterranean track and the Mongolian track. The MERRA dataset does not feature such significant differences over the Rocky Mountains as seen in JRA-25 suggesting some improvement. Differences in the SH (JJA) regions of significant higher activity are halved when comparing ERA-Interim–MERRA with ERA-Interim–JRA-25. Significant activity in the SH is limited to only a few small regions around the circumpolar track, again indicating improvements, though differences reach up to 6 per month in the most active region.

The spatial intensity distributions (not shown) indicate that MERRA has comparatively more intense storms over both hemispheres. Over the NH the  $\xi_{850}$  field in MERRA are typically 0.25 to  $0.5 \times 10^{-5} \text{s}^{-1}$  more intense based on the T42 intensities; for the SH it is ~  $0.5 \times 10^{-5} \text{s}^{-1}$  more intense. The most significant differences are in the NH Atlantic and Pacific storm tracks with up to  $1.3 \times 10^{-5} \text{s}^{-1}$  more intense storms to the southeast of Greenland and to the east of Japan.

The genesis density ERA-Interim–MERRA difference patterns (Fig. 3b,d) are similar to that of ERA-Interim–JRA-25. Iranian and the Mongolian/Chinese genesis regions are again more active in ERA-Interim. The southern China and Rocky Mountains genesis density differences are not significant unlike when comparing against JRA-25, however, the SH shows all the same regions of significant differences, namely along the Andes ridge and into the Antarctica Peninsula. This may be related to the representation of orography and is more apparent in the SH due to the very narrow and sharp shape of the Andes, whereas the Rocky Mountains are broader and perhaps more similarly represented between MERRA and ERA-Interim. Narrow and sharp mountain ranges are more difficult to represent, particularly at lower resolutions.

Lysis density differences (not shown) show very similar patterns to ERA-Interim–JRA-25 although the most significant areas have slightly less differences in activity, again showing an improved dataset. This is particularly the case for the upsteam side of the Rocky Mountains, in the U.S.A-Canadian border location, at the end of the Siberian track and upstream of the Antarctic Peninsula.

Comparing the spatial statistics across other seasons (not shown) between ERA-Interim and MERRA for  $\xi_{850}$  shows less significant differences overall, however there are some exceptions. In the spring season the Mongolian/Chinese genesis region is still more active for ERA-Interim (~ +1 per month) and there is an additional more active region to the south, over southern China, in the lee of the Himalayas, similar to that seen in comparisons with JRA-25 through all seasons. The SH track densities are all showing the same significantly increased activity for ERA-Interim. Furthermore, the three genesis regions on the lee side of the mountain ridge in Argentina and Antarctica are all more active under ERA-Interim. The summer seasons show no significant differences in the NH and slight storm track activity increases in the eastern half of the circumpolar track around Antarctica. The autumn seasons once more show a more active Mongolia/Chinese genesis region and track, and in the SH the Antarctic track is more active along with its main genesis region in the lee of the Rocky Mountains in southern Argentina.

The differences between reanalyses for MSLP in the NH show relatively small and much less systematic differences in the spatial statistics (not shown). However there are several regions where there are differences. Taking ERA-Interim differences with JRA-25, in the NH the most significant differences are in the lee of the Himalayas in the winter, and to a lesser extent, spring. However MSLP is a derived field so differences in the way this operation is performed may lead to the increased track, genesis and lysis activity in ERA-Interim. The SH also has the same issue affecting the Andes with increased genesis, track and lysis activity across central-northern Argentina. Across all seasons the MSLP intensity distribution is such that ERA-Interim represents stronger storms equatorward of 65°S and JRA-25 represents strong storms poleward. This pattern is strongest in autumn and winter with broad regions of  $\pm$ 3hPa difference either way. This is in contrast to the ERA-Interim–MERRA MSLP difference patterns where ERA-Interim is stronger on the poleward side of around 70°S. ERA-Interim–MERRA also has significant density differences around the Himalayan and Chinese regions in the NH and again with the autumn and winter Antarctic circumpolar track and genesis density differences similar to those seen in ERA-Interim–JRA-25.

# 2) Intensity distribution comparisons for MSLP, 925-hPa winds and $\xi_{850}$

Figure 4 shows the results for system maximum intensity for MSLP, for each reanalysis and for all four seasons. In the NH the distribution peak is consistently around 995hPa for all seasons and reanalyses. The high-intensity tails show MERRA consistently having slightly higher numbers of storms of deeper central pressure across all seasons. The SH has a bimodal distribution where the high-intensity systems predominate at high latitudes in the main storm track region around Antarctica, while the low-intensity systems predominate at low latitudes in the Pacific and Atlantic (Hodges et al. 2003). The proximity of the distributions makes it less clear to see if the results are statistically significant, results of pvalues from the K-S test on these distributions are shown in table 2. From this it is clear to see now that JRA-25 and MERRA are statistically different over both hemispheres and all seasons. ERA-Interim and JRA-25 however are only significantly different in the SH summer



FIG. 4. Distributions of MSLP cyclonic mean intensity for NH (blue lines) and SH (red lines) for (a) DJF, (b) MAM, (c) JJA, (d) SON. Mean intensities in units of hPa relative to the background removed state. Tracking performed on T63 MSLP. Distribution of storm tracks per month.

to winter seasons (December to August). This is somewhat surprising given how different the reanalysis resolution and DA systems are. However MSLP derived intensities are only looking at the larger spatial scales. ERA-Interim and MERRA are significantly different throughout all of the seasons in the NH and only autumn and winter in the SH.

925-hPa wind distributions (Fig. 5) are similar as for MSLP however all distributions are statistically different looking at this smaller spatial scale. The most significant difference are again in the high-intensity tail of the distribution in MERRA where in the winter seasons the tail is up to around 60ms<sup>-1</sup> compared to around 50ms<sup>-1</sup> in ERA-Interim and JRA-25. JRA-25 has significantly different distributions throughout the seasons, being consistently less intense throughout the whole distribution and particularly in the high-intensity tails.

 $\xi_{850}$  system maximum intensity (Fig. 6) shows that all three reanalyses produce very different distributions at this small synoptic spatial scale. Looking at the NH, the ERA-



FIG. 5. Distributions of 925-hPa wind mean intensity for NH (blue lines) and SH (red lines) for (a) DJF, (b) MAM, (c) JJA, (d) SON. Mean intensities in units of ms<sup>-1</sup> relative to the background removed state. Winds referenced to  $\xi_{850}$  tracks. Distribution of storm tracks per month.

Interim distribution peak occurs at between 10 to  $20 \times 10^{-5} \text{s}^{-1}$  in the NH winter and between 15 to  $25 \times 10^{-5} \text{s}^{-1}$  for all other seasons. MERRA however is significantly stronger with a peak at 20 to  $30 \times 10^{-5} \text{s}^{-1}$  across all seasons. JRA-25 conversely has the least intense peak at between 10 to  $20 \times 10^{-5} \text{s}^{-1}$  across all seasons in the NH. Further differences lie in the high-intensity tails of the distributions. JRA-25 appears to be consistently lower than ERA-Interim with both being consistently lower than MERRA. In the winter period in the

TABLE 2. Kolmogorov-Smirnov test p values for differing reanalysis intensity distributions in MSLP. A value of  $p \leq 0.05$  indicates the distribution differences are significant at the 95% level in the standard parlance.

Hemisphere		NH				SH			
Sea	sons	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
Interim	MERRA	0.0001	0.0023	0.0009	0.0022	0.6425	0.0265	0.0005	0.1424
Interim	JRA-25	0.7075	0.2616	0.1926	0.2543	0.0000	0.0045	0.0029	0.0696
MERRA	JRA-25	0.0000	0.0361	0.0027	0.0010	0.0000	0.0000	0.0000	0.0008



FIG. 6. Distributions of  $\xi_{850}$  cyclonic mean intensity for NH (blue lines) and SH (red lines) for (a) DJF, (b) MAM, (c) JJA, (d) SON. Mean intensities in units of  $10^{-5}s^{-1}$  relative to the background removed state.  $\xi_{850}$  tracks referenced to full resolution. Distribution of storm tracks per month.

NH, MERRA has around 1 storm per month with a maximum intensity of  $100 \times 10^{-5}$ s<sup>-1</sup>. Comparing this with the NH winter in both other reanalyses, the JRA-25 maximum intensity for 1 storm per month is around  $45 \times 10^{-5}$ s<sup>-1</sup> and around  $75 \times 10^{-5}$ s<sup>-1</sup> in ERA-Interim. Comparing these distributions with the SH (6), the behavior is seen to be similar but more pronounced, the ERA-Interim distribution peak occurs at 20 to  $30 \times 10^{-5}$ s<sup>-1</sup> across all seasons. MERRA has the same distribution peak in the summer however in autumn and winter it moves to 30 to  $40 \times 10^{-5}$ s<sup>-1</sup>, with 25 to  $35 \times 10^{-5}$ s<sup>-1</sup> in the spring. JRA-25 again appears to represent a lower track mean intensity with the same peaks as the NH. The significant high-intensity tail differences are the same as in the NH. The consistent shift towards higher intensities by ERA-Interim, and more so by MERRA, when compared to JRA-25 across both hemisphere suggest that the higher model resolution used in ERA-Interim and MERRA predominantly explain these differences.

### 3) Comparisons of track ensembles for $\xi_{850}$ and MSLP

Figure 7 shows the maximum intensity distributions based on using the second comparison method where storms are matched between reanalyses for winter (DJF)  $\xi_{850}$ . This shows distributions both for the tracks that do and do not match. For those that do the total number of systems must be identical between any pair of reanalyses, although the distributions may be different. For those systems that do not match there will, in general, be different numbers between any pair of reanalyses (Hodges et al. 2003). The overall impression is that those tracks that match between different reanalyses are typically those with the larger maximum intensities and those that do not match tend to be those with weaker mean intensities. In the NH (Figs. 7a,b,c) it can be seen there are very similar number of matches between the reanalyses. The MERRA matching distributions are slightly broader towards higher mean intensities relative to each of the other two reanalyses, consistent with findings from the spatial statistics and intensity distributions. The distribution of no matches in the SH is much broader than in the NH, particularly when comparing with the JRA-25, with 42.3 and 41 storms per month for ERA-Interim and MERRA respectively (Figs. 7e,f). This may be because the SH is less constrained by observation than the NH, differences then may arise from the different methods the DA systems use to handle the observations. Furthermore ERA-Interim has a larger number of no matches throughout both hemispheres as shown by the statistics and distributions, this is consistent with the spatial statistics shown in figures 3 and 2. ERA-Interim using a 4D-Var may be better able to position a storm compared to the standard 3D-Var in JRA-25 giving rise to the non-matching tracks. The comparative similarities of MERRA with ERA-Interim over both hemispheres and high number of track matches suggests that the GSI/IAU procedure in MERRA is comparable to the 4D-Var DA system of ERA-Interim. A further reason may be the high resolutions common to both reanalyses. Nevertheless, the comparisons in this paper reveal a higher percentage of matching tracks than the previous generations of reanalyses compared by Hodges et al. (2003, 2004) and Bromwich et al. (2007). Bromwich et al. (2007) found that JRA-25 was more comparable with ERA-40 than NCEP-NCAR for the modern satellite era. It was suggested this reflected the greater similarities between ERA-40 and JRA-25 systems in terms of DA and model resolution. Comparing results from this latest generation with the first generation, there are 76% track matches from NH ERA-Interim–MERRA for  $\xi_{850}$ , compared with 62% track matches from NH ERA-15–NCEP-NCAR (Hodges et al. 2003, 2004). It should be noted however that this was based on more stringent matching criteria of  $\leq 2.0^{\circ}$  rather than



FIG. 7. Distributions of maximum intensity for the comparison of the three reanalysis ensembles for (a,b,c) the NH DJF and (d,e,f) SH JJA cyclonic  $\xi_{850}$  for both the tracks that do and do not match: (a,d) ERA-Interim–MERRA, (b,e) ERA-Interim–JRA-25, (c,f) MERRA–JRA-25. Maximum intensities in units of  $10^{-5}$ s<sup>-1</sup> relative to the background removed state. Distribution of storm tracks per month.

 $\leq 4.0^{\circ}$  so this result should be taken with caution, although in the NH most of these storms are within  $\leq 2.0^{\circ}$ , as will be shown later, so the impact of these different criteria is not too large. The equivalent figures for MSLP (distributions not shown) are 79% for both NH ERA-Interim–MERRA and ERA-15–NCEP-NCAR (Hodges et al. 2003, 2004). Comparisons with other seasons (not shown) reveal a larger percentage of track matches in the spring and



FIG. 8. Cyclonic  $\xi_{850}$  frequency distributions of winter mean separation distances for the comparison of track ensembles in (a) the NH DJF and (b) SH JJA.

particularly summer. Additionally, those that do not match are towards the weaker intensity end of the distribution.

Also of interest is the distribution for the winter  $\xi_{850}$  mean separation distances (Fig. 8). This shows that there is a strong bias towards small separation distances for those systems that match for all the reanalysis comparisons in the NH winter (DJF) (Fig. 8a), indicated by the rapid fall in distributions by around  $2.0^{\circ}$  mean separation for each of the comparisons. This highlights that it is reasonable to compare track matches found with these reanalyses with those found in Hodges et al. (2003). The distributions are all similar with marginal differences between MERRA and JRA-25. The similarity in distributions is due to the reanalyses being well constrained by the observations. The SH winter (JJA) mean separation distance distributions (Fig. 8b) are broader than those in the NH, indicating a much larger degree of uncertainty in the location of systems. This is particularly striking for tracks matched against JRA-25 suggesting that when less constrained by observations, it performs less well than ERA-Interim and MERRA at assimilating satellite radiances via the DA system. This is more likely to be a reason than the relatively lower resolution of the JRA-25 due to its good performance in the NH where all the reanalyses are comparable. ERA-Interim–MERRA separation distances in the SH are almost as good as in the NH highlighting the similar performances of the DA systems. The SH is dominated by satellite observations compared to terrestrial observations. Satellite observations have poorer vertical resolution compared to radiosondes, although this resolution has improved over the reanalysis period to present, and scatterometer winds provide some constraint at the surface. The separation distance differences indicate that 4D-Var and GSI/IAU appear to extract more information from these observations than 3D-Var.

 $\xi_{850}$  mean separation distances differences change little between the other three seasons for given reanalysis comparisons (not shown). There is a marginally narrower and sharper distribution in both hemispheres. This may be due to there being less intense storms which are slower moving in the spring, summer and autumn months. None of the interseasonal differences are significant between any of the reanalysis intercomparisons.

### 4) EXTREME STORM LIFECYCLE COMPOSITES FOR MSLP, 925-HPA WINDS AND $\xi_{850}$

The composite life cycles for the NH winter (DJF) and SH winter (JJA) Atlantic and Pacific storms, produced by centering the storms on the time at which they reach their maximum intensity in the T42  $\xi_{850}$ , are shown in figures 9 and 10 respectively. For all three reanalyses the maximum pressure deepening rate can be seen to occur around 24 h prior to when the minimum in surface pressure occurs. We note that the maximum in the fullresolution vorticity occurs prior to the minimum in surface pressure by about 6-12 h. This due to the geostrophic adjustment processes where the wind field is likely to lead the mass field (Temperton 1973), particularly with the scale of intense extra-tropical cyclones seen here. The time scale for this adjustment is broadly proportional to the inverse of the Coriolis force (Cahn 1945).

Looking more closely at the differences between the reanalyses it can be seen that MERRA is more intense in all fields and JRA-25 is the least intense in all fields and across all reanalyses. This is consistent with the previous results already shown. The differences between ERA-Interim and MERRA are clearer in the NH compared to the SH. MSLP deepening rates are shown in table 3. These show very similar deepening rates, and the NH storms can be put into the class of "bombs", where a bomb is defined by Sanders and Gyakum (1980) as an 'extratropical cyclones whose central pressure fall averages at least 1 mb h<sup>-1</sup> for 24 h'. The composite storms look deeper in the SH Atlantic due to the large-scale lower

TABLE 3. Maximum Mean Sea Level Pressure change rates (hPa/6h) for the winter season (DJF in NH, JJA in SH). NH Atlantic region: 80°W–0°, 30°N–70°N; NH Pacific region: 120°E–120°W, 30°N–70°N; SH Atlantic region: 60°W–120°E, 30°S–70°S; NH Pacific region: 160°E–75°W, 30°S–70°S.

	-	~		-	
Hemisphere	NI	Η	SH		
Region	Atlantic	Pacific	Atlantic	Pacific	
Interim	-7.5	-7.6	-7.1	-5.6	
MERRA	-7.8	-7.7	-7.2	-5.3	
JRA-25	-7.4	-7.0	-5.6	-4.2	



FIG. 9. Life cycle composites of the 100 most intense storms, identified in T42  $\xi_{850}$ , for NH DJF for (a,b,c) the NH Atlantic and (d,e,f) NH Pacific. Parameters shown are full resolution (a,d) MSLP (hPa), (b,e)  $\xi_{850}$  (10<sup>-5</sup>s<sup>-1</sup>) and (c,f) 925-hPa winds (ms<sup>-1</sup>).

background pressure field in the Antarctic circumpolar track. Storms often originate at lower latitudes and spiral in to the Antarctic coast thereby moving down the background MSLP field gradient. The three fields are more intense in the SH Atlantic compared with the SH Pacific due to the comparatively larger sea surface temperature (SST) gradient in the SH



FIG. 10. Life cycle composites of the 100 most intense storms, identified in T42  $\xi_{850}$ , for SH JJA for (a,b,c) the SH Atlantic and (d,e,f) SH Pacific. Parameters shown are full resolution (a,d) MSLP (hPa), (b,e)  $\xi_{850}$  (10<sup>-5</sup>s<sup>-1</sup>) and (c,f) 925-hPa winds (ms<sup>-1</sup>).

Atlantic sector Hoskins and Hodges (2005). The added influence of downslope cyclogenesis in the lee of the Andes also adds to this comparative difference. ERA-Interim and MERRA also do a better job of representing the time offset between the peak in  $\xi_{850}$ , 925-hPa winds, and then in MSLP compared to JRA-25, this most noticeable in the NH Pacific where the most intense storms occur. It is apparent that the fields show that the rate of decay of the composite cyclone is nearly as large as the rate of intensification. It is reasoned by Bengtsson et al. (2009) that this is due to the divergence of geopotential height fluxes (Orlanski and Katzfey 1991). It appears that the reanalyses are more similar at representing the intensification stages in both hemispheres compared to the stages of cyclolysis. Bengtsson et al. (2009) compared ERA-Interim with ERA-40 and found ERA-Interim has greater intensities for all variables.

### 5) The early satellite era (1979-1989)

MERRA and JRA-25 both extend back to 1979 so statistics were calculated for the 1979 period to the end of February 1989. Comparing pre and post 1989 spatial statistic differences (not shown), the most significant differences can be seen in the SH winter intensity differences. The  $\xi_{850}$  spatial mean intensity differences (T42) (not shown) reach up to  $\pm 5.0 \times 10^{-5} \text{s}^{-1}$  between MERRA–JRA-25 equatorward and poleward of around 65°S respectively, compared to around a maximum of  $\pm 1.2 \times 10^{-5} \text{s}^{-1}$  bias in MERRA and equatorward of the Antarctic coast. A similar, but less extreme pattern is seen throughout other seasons and in MSLP too. Although in the satellite era, satellites in the earlier 1979–1989 period were of lower quality than modern instruments, with poorer vertical resolution and fewer satellite observations relative to the later period. This provides less constraint on the model in the earlier period resulting in greater locational differences and magnitudes.

Comparing matching statistics for identical storms between MERRA–JRA-25 reanalyses for 1979–89 (not shown) with post 1989 (Fig. 7c,f), the greatest differences can again be seen in the SH winter. The distribution in  $\xi_{850}$  and MSLP of no matches is now nearly identical as the distribution of matches. Focusing on  $\xi_{850}$ , the 1979–89 period has 50.6% of track matches, compared to 65.8% for post 1989. Across other seasons and in the NH the no matches are not identical to the match distributions however they are closer relative to the post 1989 era. Separation distance distributions for 1979–89 for  $\xi_{850}$  and MSLP (not shown) are similar to that of the post 1989 (Fig. 8) period in the NH for all seasons. However in the SH the distributions are broader and flatter, with the peak in distribution at around 1.5° compared to around 1.0° for the post 1989 period. Life cycle statistics were not calculated for this 10 year period.

# 4. Conclusions

To answer the central hypothesis, reanalyses are not necessarily all the same when it comes to the distribution and properties of extratropical cyclones. However the size of these differences is reducing in the latest generation of reanalyses.

A comparison of three different reanalysis datasets has been performed based on feature tracking analysis methods. In general all reanalyses give similar results for NH storm tracks, with most differences in the distribution of storms being small and associated with relatively small spatial scale systems. These differences are most marked where small-scale and weak systems are often found, such as the end of the Mediterranean storm track through the Middle East. These results are similar to the results found in a comparison of older reanalyses by Hodges et al. (2003). Comparisons with JRA-25 lead to more significant differences in some locations such as the Rocky Mountains indicated poorer orography representation as a likely result of its lower resolution. The general consistency of the results in the NH provides us with confidence that any of the reanalyses, particularly ERA-Interim and MERRA, can be used to study cyclones to validate climate models at the synoptic scale. In the SH the comparison between the different reanalyses highlights the greater uncertainty in cyclone representation. The comparison of the distributions for track, genesis and lysis density shows that there are significant climatological differences between the reanalyses due to the relatively lower density of lower-tropospheric observations providing constraint on the model via the data assimilation process. A similar set of differences is seen in the 1979–89 period where there are comparatively fewer satellite observations, and of lower quality, providing less constraint on the model.

For the NH mean system intensity, differences are relatively small but with MERRA appearing to have more intense systems and JRA-25 having the least intense systems. This is seen systematically across both ocean basins for both MSLP and  $\xi_{850}$  and these differences are increased when looking at the 100 most intense storms in each basin. The fact there are consistent differences between the different reanalyses and hemispheres suggests this may be partly related to the spatial integration resolution and also issues around orography interpolation in  $\xi_{850}$  and extrapolation in the case of MSLP along with different parameterizations, such as orographic parameterizations, as also indicated in the spatial differences. The additional intensity differences in the SH may additionally be due to the DA systems assimilating the satellite observations differently whilst there is comparatively less constraint from surface observations. Life cycle intensities for the 100 most intense storms indicate that MERRA is

also the best, and closest to dynamic theory, of the three reanalyses at representing the offset in time of the  $\xi_{850}$  peak followed by the 925-hPa wind peak and lastly the MSLP minimum. The JRA-25 again represented this the least accurately of the three reanalyses.

Direct comparison of the track ensembles in the NH shows that most of the systems that compare well between the reanalyses are those with mean intensities in the moderate to large range, with those that do not match predominately at the weak end of the range. The general impression is of a set of significant systems that compare well for all the reanalyses plus a background of weak intensity systems that do not compare well but that are relatively unimportant to the storm climatologies and much of the uncertainty is small in relation to the storm climatology. The larger degree of uncertainty in the SH is again highlighted by these direct track comparisons. There is a significantly higher number of non matched tracks and larger separation distances, particularly in comparisons against JRA-25 and even more so in the 1979–89 period. The similarity between ERA-Interim and MERRA over both hemispheres is a significant improvement upon any other two reanalyses compared thus far.

The comparative similarities between MERRA and ERA-Interim suggests that the data assimilation systems of 3D-Var with GSI/IAU implementation are comparable with that of 4D-Var. Both are better than 3D-Var, where the observations are introduced at the analysis time, causing a shock to the system.

The significant differences between the different reanalyses in some regions highlights the observational uncertainty inherent in the data. While the lower troposphere in the NH is well observed, elsewhere this is not the case so more care is required. This varying degree of uncertainty does not make the reanalyses unusable for applications, such as GCM validation, however it does mean the quantitative use of reanalyses at the synoptic scale will necessarily carry less significance and have larger error bars due to the observational uncertainty. It also highlights the fact that reanalyses should not be used individually without some quantification of the uncertainty. Or, perhaps, studies should use more than one reanalysis to put the uncertainty in context (Hodges et al. 2003). As differences between reanalyses reduce, such as ERA-Interim and MERRA, with improving DA systems, model resolution and parameterizations, this will become less necessary.

Conducting a study on differences and uncertainties between reanalysis datasets presents limitations and many of these are within the reanalyses themselves. When there is uncertainty it is difficult to quantify which reanalysis is closer to reality due to the lack of truly independent datasets. A further limitation of the nature of this study is that it is also

difficult to attribute components making up a reanalysis that are causing differences. To better understand this, Observing System Experiments (OSEs) could be set up to explore the relationship between observations and the uncertainties affecting reanalyses. A similar methodology similar to Bengtsson et al. (2004b) could be used for these new reanalyses, varying the observations fed into the DA system. In practice it would only be feasible to perform such experiments for a short period of time, say a few years, and compare the results to the full system. As an extension to this, the potential for studying the forecast trajectories of storm tracks based on using the reanalysis (such as ERA-Interim) as initial conditions to investigate the change in predictability of cyclones depending on the quality of the observing system in a similar methodology to Froude et al. (2007). A further line of enquiry to increase understandings of the origins of the uncertainties is to vary the DA assimilation systems to see the resulting changes in storm track location and intensity distribution based on the reanalyses. A similar investigation was carried out by Whitaker et al. (2009) comparing 3D-Var, 4D-Var and an ensemble data assimilation (Ens-DA) system however this used surface-only based observations and used two different models for the reanalysis. Nevertheless it was found that 4D-Var and Ens-DA systems produce analyses of comparable quality and that both are much more accurate than the analyses produced by the 3D-Var system. Finally the resolution and spectral truncation of each reanalysis could be changed to compare its differences on cyclone location and intensity distribution in a study similar to that of Jung et al. (2006).

As an extension to this project, extra datasets of new reanalyses could be employed for further comparison. The 20th Century Reanalysis Project (20CR) (Compo and Coauthors 2010; Compo et al. 2006) was released in January 2010 and jointly led by NOAA's Physical Sciences Division and the University of Colorado CIRES Climate Diagnostics Center. It is a much longer reanalysis dataset than the other three, covering the period from 1891 to 2008 and uses surface-only observations throughout the reanalysis period. This enables the dataset to be used in a similar way to an OSE, to see the consequences of removing all but the surface observations on the location and intensity distributions between the NH and surface-data sparse SH for the period of the other three reanalyses. Two complicating factors of this dataset however are the comparatively much lower resolution of this dataset  $(2.0^{\circ} \times 2.0^{\circ} \text{ gridspacing})$  and the Ensemble Kalman Filter (EnKF) system. The EnKF produces an analysis averaged over an ensemble to produce the reanalysis and it performs poorly for the purposes of cyclone tracking due to the greater spatial inconsistencies of the feature points between analysis times.

A further reanalysis would be the NCEP Climate Forecast System Reanalysis (CFSR) (Saha and Coauthors 2006, 2010) which could be used to explore model improvements compared to the other reanalyses, however this is not available at the time of writing. The CFSR uses a  $\sim 38$ km (T382L64) resolution and uses a coupled model following suggestions by Bengtsson and Coauthors (2007). The CFRS combines models for, and fluxes between, the atmosphere, ocean, land and sea-ice which enables a good experiment to see the additional benefits brought by the extra couplings used in the model.

Further in depth analysis could be performed on the existing reanalyses. In this project the focus has been on extratropical synoptic scale waves ( $5 \le n \le 42$ ) however a further study could investigate the differences in mesocyclones between reanalyses, using a T42 to ~T200 filter. Additionally, studies could extend to tropical easterly waves and upper tropospheric disturbances and looking at the vertical tilt of storms. The vertical tilt is particularly useful in assessing cyclone representation in the SH where satellites (sampling the upper troposphere) have a greater dominance. From the results of this study, one would predict that ERA-Interim and MERRA would better represent the vertical tilt relative to JRA-25. Cyclone composting could also be employed to assess the horizontal structure of cyclones at different vertical levels in these three reanalyses in a similar methodology to Bengtsson and Coauthors (2007); Bengtsson et al. (2009) and Catto et al. (2009). This would allow further intercomparisons between reanalyses and with dynamical theory.

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