# Explosive Cyclogenesis: A Global Climatology Comparing Multiple Reanalyses

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ABSTRACT

A global climatology for rapid cyclone intensification has been produced from the second NCEP reanalysis (NCEP2), the 25-yr Japanese Reanalysis (JRA-25), and the ECMWF reanalyses over the period 1979–2008. An improved (combined) criterion for identifying explosive cyclones has been developed based on preexisting definitions, offering a more balanced, normalized climatological distribution. The combined definition was found to significantly alter the population of explosive cyclones, with a reduction in ''artificial'' systems, which are found to compose 20% of the population determined by earlier definitions. Seasonally, winter was found to be the dominant formative period in both hemispheres, with a lower degree of interseasonal variability in the Southern Hemisphere (SH). Considered over the period 1979–2008, little change is observed in the frequency of systems outside of natural interannual variability in either hemisphere. Significant statistical differences have been found between reanalyses in the SH, while in contrast the Northern Hemisphere (NH) was characterized by strong positive correlations between reanalyses in almost all examined cases. Spatially, explosive cyclones are distributed into several distinct regions, with two regions in the northwest Pacific and the North Atlantic in the NH and three main regions in the SH. High-resolution and modern reanalysis data were also found to increase the climatology population of rapidly intensifying systems. This indicates that the reanalyses have apparently undergone increasing improvements in consistency over time, particularly in the SH.

## 1. Introduction

The dynamics of rapid cyclone intensification have been intensively studied over the past 30 years, mainly centered on systems in the Northern Hemisphere (NH). Comparatively little attention has been given to thermodynamic and planetary forcing mechanisms associated with this class of cyclone in the Southern Hemisphere (SH). Climatologies of explosive development have rarely been produced for either hemisphere, owing to a combination of data sparsity over oceanic regions and the painstaking nature of identifying cyclone tracks manually from 6-hourly operational analyses, prior to the development of automated tracking schemes. Explosive cyclone development has been traditionally defined by a central pressure fall of 24 hPa over a 24-h period relative to 60° of latitude (Sanders and Gyakum 1980, hereafter SG80). These systems can produce strong winds, heavy rainfall, and dangerous oceanic conditions as a result of this rapid change of central pressure.

Earlier studies established rapidly intensifying cyclones to be predominantly maritime cold season events, which occur preferentially in regions of enhanced baroclinicity with strong surface temperature gradients (SG80; Roebber 1984; Sanders 1986; Gyakum et al. 1989). As studies of explosive cyclogenesis progressed, more restrictive thresholds identified that many of the deepest cyclones were explosive in their development, and that these systems predominantly intensified over the ocean to the east of continental seaboards (Chen et al. 1992; Gyakum et al. 1989). More recently, rapidly intensifying cyclone dynamic characteristics have been found to depend on the mesoscale characteristics of the individual cyclone (Kuwano-Yoshida and Asuma 2008). This highlights the importance of resolution for climatologies of explosive cyclogenesis, with significant improvements to the rendition of mesoscale and boundary layer features possible by using better models and higher-resolution analyses (Sanders 1987). This influence should also not be ignored when investigating the impacts of climate change on these systems, where resolution is often coarser than found in analyses or reanalyses (Kuwano-Yoshida and Asuma 2008).

In the SH, a large proportion of rapidly intensifying cyclones influence the midlatitude continents, despite

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this type of system having a lower frequency of occurrence than in the NH (Lim and Simmonds 2002, hereinafter LS02). The use of MSLP has been found to be problematic in the SH, with rapid spatial changes in the climatological pressure field resulting in nonexplosively developing systems being wrongly categorized as explosive (Sinclair 1994, 1995, 1997). As we will discuss later, the above cyclones are referred to as ''artificial systems'' in this work. With the advent of automated cyclone tracking schemes and quality reanalysis data, longer-term climatologies of rapidly intensification have become possible (Sinclair 1994, 1995; Lim 2000; LS02). These have not only been limited to the SH, but have also contributed to the body of knowledge in the NH, and have used both the first and second National Centers for Environmental Prediction (NCEP and NCEP2, respectively) reanalyses. To address the issues surrounding the climatological pressure gradient, a relative bomb criterion (detailed further in section 2a) was developed (LS02). This climatology established that the frequency of SH explosive events had less seasonality than systems in the NH. Regional climatologies in the SH have also considered the implications of heavy rainfall from explosive cyclones over South America, and the impact of explosive events affecting New Zealand (Seluchi and Saulo 1998; Leslie et al. 2005). While synoptic extratropical cyclones form the bulk of explosive developments, subsynoptic systems and tropical cyclones undergoing extratropical transition may also undergo explosive development. The definitions of hybrid and subsynoptic events have important implications for specifying the domain over which explosive events are potentially identified.

Changes to the interannual variability of extratropical cyclones have a significant potential impact on midlatitude continents, and therefore will also have an impact on rapidly intensifying cyclones. Cyclone frequency in the NH winter has been reported to increase in the high latitudes, and to decrease in the midlatitudes (McCabe et al. 2001), while in the SH a similar shift is evident, with the extratropical cyclone population decreasing markedly since 1970 (Simmonds and Keay 2000b; Fyfe 2003; Pezza and Ambrizzi 2003; Pezza et al. 2007). However, while there appears to be a decrease in the overall population, the intensity of extratropical cyclones is likely to increase in some regions (Pezza et al. 2007; Raible 2007; Ulbrich et al. 2009). In contrast to the findings for extratropical cyclones, the global population of explosive cyclones has apparently steadily increased when considering the NCEP and NCEP2 reanalyses (Lim 2000; LS02).

This study addresses the need for a robust global climatology of explosive cyclogenesis, using a selection of the latest available reanalyses and a quality tracking scheme (section 2a.). Existing definitions for explosive cyclogenesis are refined and explored (sections 2b and 2c). Consideration was made of descriptive cyclone and annual mean statistics together with the implications of an improved criterion (section 3a). The interannual variability was assessed using multiple reanalyses (sections 3b and 3c), while the spatial distribution of system density (section 3d) and depth (section 3e) were identified. This climatology seeks to allow a greater understanding of the distribution of explosive events and the influence of using different reanalysis datasets, while addressing whether earlier criteria accurately identify this special class of cyclone.

## 2. Method

### a. *Selection of tracking scheme and reanalysis data*

It is well established that the identification of cyclones can be influenced by the selection of particular reanalyses, their resolution, and the automated tracking scheme used (Blender and Schubert 2000; Zolina and Gulev 2002; Hoskins and Hodges 2002, 2005; Pinto et al. 2005; Raible et al. 2008; Bengtsson et al. 2009). Indeed in an optimal world the highest-resolution models would be used to resolve all aspects of extratropical cyclones in producing reanalysis data, with an optimal tracking scheme that did not miss any system no matter its size or strength. However, such datasets do not yet exist; there has been suggestion that even models of T255 spectral resolution inadequately resolve extratropical cyclones (Hodges et al. 2003), while automated tracking schemes can be subjective owing to smoothing processes and detection criteria (Pinto et al. 2005). Therefore climatologies of extratropical cyclones produced by these means are always subject to limitations. However, with resolution of T42–T63 capable of reasonable distributions (Pinto et al. 2005; Bengtsson et al. 2009), and automated tracking schemes found to be skilled in producing tracks of individual extratropical cyclones (Pezza and Ambrizzi 2003; Pezza et al. 2007) the climatologies produced using this approach still form a valid assessment. Furthermore, the influence of the problem on cyclones identified seems to be lacking at the extremes of the population in terms of the systems missed; small cyclones, extremes in wind and rainfall close to coastal regions, and weak or marginal systems can easily be missed in the process of tracking (Hodges et al. 2003; Pinto et al. 2005; Jung et al. 2006; Bengtsson et al. 2009). Therefore, in order to produce a robust and comparable set of reanalysis climatologies, several datasets were chosen and a verified and reliable automated tracking scheme was used.

#### 1) Reanalyses

The 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40), NCEP and NCEP2, the 25-yr Japanese Reanalysis (JRA-25), and ERA-Interim reanalyses were used to provide MSLP data from the 30-yr period 1979–2008 for both the NH and SH. Each reanalysis was used for the maximum available extent over this period, with the ERA-40 and ERA-Interim considered over the periods 1979–2001 and 1989–2008, respectively. The ERA-40, NCEP2, and JRA-25 reanalyses were used with 2.5° horizontal resolution. To investigate the extent to which resolution influences the count of explosive events, the ERA-Interim reanalysis was also considered at 1.5° horizontal resolution (Simmons et al. 2007; Uppala et al. 2008; Dee and Uppala 2009). The newer reanalyses (i.e., JRA-25 and ERA-Interim) potentially provide significant advantages for studying explosive systems by using more advanced high-resolution models in their derivation [i.e., four-dimensional variational data assimilation (4D-Var) in the case of the ERA-Interim; Dee and Uppala (2009)]. This may improve the resolving of convection and system dynamics (Sanders 1987; Trigo 2006).

Although the different reanalyses have different spectral resolutions in their original models, we have dealt with this issue internally through the smoothing parameter Rdiff of the tracking scheme as described by Simmonds et al. (1999). A multipass smoother has been applied on the polar stereographic (PS) grid to attenuate the higher wavenumbers without necessarily reducing the number of cyclones found by our analyses. A given amount of smoothing also tends to reduce the difference between the numbers of cyclones in different datasets. As our analyses will show, in the NH there is greater consistency between the different reanalyses both in terms of total number of systems and interannual variability, similar to the findings of Hodges et al. (2003) and Bromwich et al. (2007). This suggests that the different spectral resolution of the reanalyses alone cannot be the only reason for any inconsistencies appearing between the reanalysis.

#### 2) Cyclone identification and tracking

To resolve individual cyclones for explosive analysis, MSLP reanalysis data are used in conjunction with a cyclone tracking scheme. The automated Melbourne University cyclone tracking scheme (Murray and Simmonds 1991; Simmonds et al. 1999; Simmonds and Keay 2000a) was used to produce track data for low pressure systems from the aforementioned reanalyses. The tracking scheme operates by way of a two-step process of identification and tracking. An input of gridded reanalysis data is interpreted using a bicubic spline fit to a 90 × 90 polar stereographic array. Using this pressure field, minima are identified using a specified threshold for a minimum Laplacian relative to the neighboring 8 points. Inflections in the pressure surface are used to identify centers that lack a distinct pressure minimum. The secondary stage of the tracking scheme then uses prior movement and probability weighted identification of centers to track between analyses. Tracking data are then compiled for the identified cyclones, and descriptive statistics recorded. The scheme produces high-quality cyclone data, which reliably tracks and identifies low pressure systems, providing cyclone information remarkably similar to tracks of the same systems identified by manual analysis (Leonard et al. 1999; Pezza and Ambrizzi 2003). The method also performs well compared to other automatic tracking methods (e.g., Raible et al. 2008).

The radius $R$ of a cyclone is taken here to be the weighted mean distance from the cyclone center to the points where $\nabla^2 p$ is zero at the ''edge'' of a cyclone (i.e., at the point of inflection in the pressure field). The depth of a cyclone, given in hectopascals, represents the pressure difference between the edge and center of a cyclone (Simmonds and Keay 2000a). The cyclone depth is related to the intensity and the radius by the equation:

$$\mathrm{DP} = 0.25(\nabla^2 p)R^2.$$

### b. Existing explosive cyclone definitions

The earlier approaches used to identify explosive cyclogenesis relied on changes in the central pressure in the cyclone over 24-h periods. It is recognized that the peak rate of change in central pressure is unlikely to commence exactly from 0000 UTC on one day and 0000 UTC on the next, hence, consideration of the pressure difference for these two points may not capture all explosive events. However, we here follow the earlier definitions and consider 0000 UTC our standard calculation time for simplicity. The normalized deepening rate of central pressure ($\mathrm{NDR}_c$) is defined by SG80 (hereinafter SG cyclones) as

$$\mathrm{NDR}_c = \frac{\Delta p_c}{24}\frac{\sin 60}{|\sin\theta|},$$

where $\Delta p_c$ is the change in central pressure and $\theta$ is degrees of latitude. A bergeron (1B) is defined to be a value from the $\mathrm{NDR}_c$ which equals unity, and values equal to or exceeding this corresponding to explosive events.

An alternative definition for explosive events is that of a relative bomb (hereafter LS cyclones; LS02), which can be defined as above for the normalized deepening rate of relative central pressure ($\mathrm{NDR}_r$):

$$\mathrm{NDR}_r = \frac{\Delta p_r}{24}\frac{\sin 60}{|\sin\theta|},$$

where $\Delta p_r$ is the relative central pressure change, removing the climatological pressure field from the deepening. The LS bomb criterion requires a mean monthly MSLP for the period covered for each reanalysis to provide a climatological pressure field. This definition addresses the issues noted by Sinclair (1995, 1997) regarding the problems associated with using changes in system central pressure, and provides an insight into the influence of the climatological pressure gradient on the interannual variability of explosive cyclone development.

The concept of using pressure change is most appropriate as it implies that explosive cyclones will also have a rapid increase in horizontal pressure gradient. Therefore, explosive cyclones will also have a significant and rapid increase in geostrophic wind speed, which translates into stronger surface winds, even when frictional processes are taken into account (Watson et al. 2000). This is important as wind data both observational and remotely sensed can be unreliable in its distribution over the oceanic regions in which these systems form, and therefore from the perspective of a global climatology, MSLP is preferable.

### *c. An improved criterion for explosive cyclogenesis*

#### 1) Artificial explosive systems

The application of the climatological pressure gradient to explosive cyclone development as proposed in earlier studies results in the identification of systems, which display equatorward motion while experiencing negligible increases in intensity or falling central pressure. To further illustrate this point, two systems were identified from the JRA-25 and ERA-Interim derived cyclone tracks, and the development over the climatological pressure gradient is considered (Fig. 1). The NH case (Fig. 1a) during its explosive development was found to experience a central pressure fall of 9 hPa over the 24-h period, while moving across a climatological pressure gradient in excess of 10 hPa. In the SH case (Fig. 1b) the example is more extreme, with a central pressure increase of 2 hPa over the supposed explosive development. The JRA-25 data indicated that the SH system moved across a climatological pressure gradient of 25 hPa, while the ERA-Interim suggested a more moderate difference of 15 hPa as a result of the displacement of the identified cyclone center at the commencement of explosive development.

These cases are both explosive cyclones according to the LS criterion. However, they do not appear to follow the concept of explosive cyclogenesis defined by SG80, which implies rapid development. The behavior of the respective NH and SH case studies over their life cycles are examined, analyzing the track of each system using depth, $\nabla^2 p$ and surface central pressure (Fig. 2). In both cases there is a relatively high central pressure that varies very little, or even increases over the period of "explosive" development.

The NH case displayed an increase in depth, characterized by little change in the $\nabla^2 p$, suggesting that the radius was the dominant factor in the depth relationship. In the SH case, the explosive development is associated with a similar small increase in $\nabla^2 p$, and a radius increase, which suggests that the depth change was not reflective of an explosive cyclogenesis event. Figures 1 and 2 indicate a close agreement between the cyclone track derived from each of the reanalyses in the NH, while in the SH distinct separations exist in both cyclone parameter values and tracks. The cyclone tracking method may have caused a disparity in center location, as the identification of the nascent cyclone is as a weak open system, but we suggest that the main differences in the SH are a feature of different reanalyses (Bromwich et al. 2007; Raible et al. 2008). This is examined further in section 3. "Artificial explosive systems" are therefore defined to be extratropical storms that are LS cyclones; however, they do not experience explosive intensification as their central pressure values change little (such as demonstrated in the cases studies). This does not mean that these systems are not significant, as they might pose a similar threat as regular extratropical cyclones to coastal areas; however, they are not explosive cyclones in the traditional sense. Artificial explosive systems are not a rarity within the population of LS cyclones. The statistical analysis of these systems is discussed further in examining the mean statistics (section 3a).

#### 2) Improved criterion

To account for the impact of the climatological pressure gradient on systems that move equatorward, an improved criterion that took these effects into account was developed. A "combined" explosive cyclone is identified by a 24-hPa drop relative to latitude in both central pressure and relative to the climatological pressure gradient over a 24-h period. This corresponds to a system that meets the condition that $\mathrm{NDR}_c$ and $\mathrm{NDR}_r$ are less than or equal to $-1$ (i.e., the intersection between the set of all SG and LS cyclones). This criterion identifies systems with intensification that is relative to the climatological pressure gradient while removing artificial explosive systems; however, for completeness and verification both the SG and LS criteria were used to produce the climatology. Unlike earlier studies (Lim 2000; LS02), the latitude value used in the calculation for each of the aforementioned criteria was defined to be the absolute mean of the

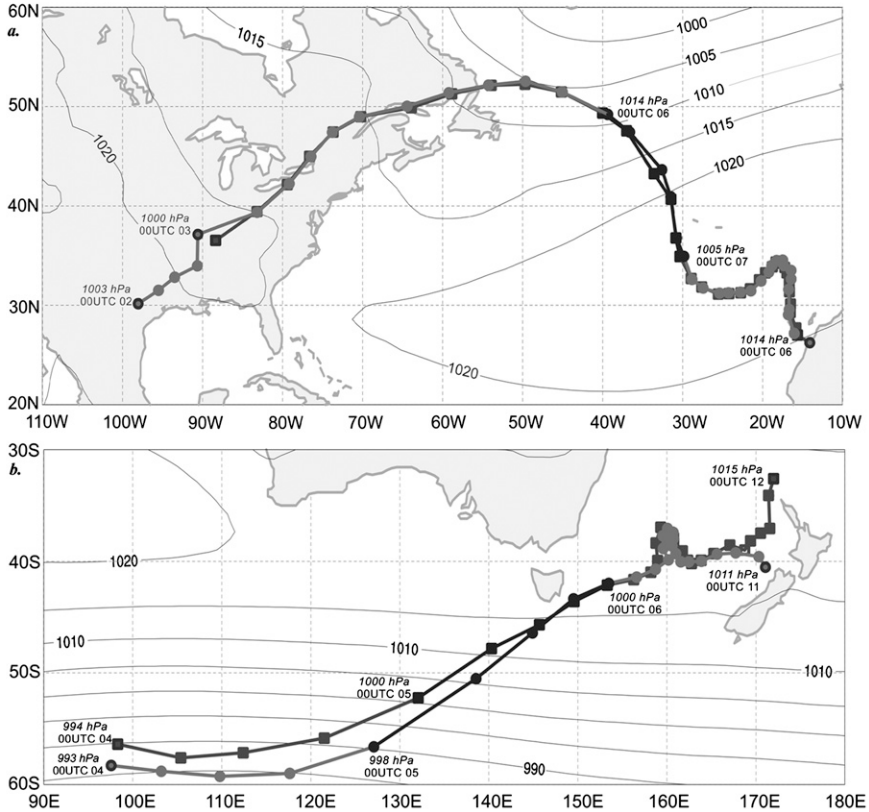


FIG. 1. Cyclone tracks of equatorial-moving relative explosive events. Circular points denote the JRA-25-derived track, while square points the ERA-Interim track. The period over which explosive development occurred is shaded black. Isobars of monthly MSLP are shown at 5-hPa intervals, as determined from the ERA-Interim reanalysis data based on a 20-yr mean (1989–2008). (a) NH case full track length (0000 UTC 2 Feb–0000 UTC 12 Feb 2006), with explosive component from 0000 UTC 6 Feb to 0000 UTC 7 Feb 2006; and (b) SH case full track length (0000 UTC 4 Mar–0000 UTC 12 Mar 1998), with the explosive section from 0000 UTC 5 Mar to 0000 UTC 6 Mar 1998.

latitude at the commencement and termination of explosive cyclogenesis. To exclude tropical cyclones, and provide the potential of capturing hybrid and transitioning systems that can form equatorward of 20° latitude and experience explosive development poleward of this latitude, a $\pm 20°$ latitude threshold was used to define the domain. This approach has the added benefit of removing systems which result from the criterion failure in close proximity to the equator, while assuming that warm-core or hybrid systems such as transitioning cyclones generally experience their explosive deepening upon entering the midlatitudes.

## 3. Results

### *a. Examination of the new combined criteria*

Combined system population as compared to SG cyclones over the respective reanalysis periods was examined to identify the proportion of systems that meet the combined criteria (Table 1). All of the reanalyses indicate that globally approximately 28% of the SG population meets the combined threshold. Hemispherically, this corresponds to 16% in the SH and 46% in the NH, which reflects the larger proportion of NH systems identified by LS02. These values indicate that there is a high ratio of systems that fail to simultaneously satisfy the LS and SG criteria.

In excess of 40% of all SH LS cyclones were found to be artificial explosive systems using the new definition. The reduced climatological pressure gradient in the NH resulted in the proportional artificial systems in that hemisphere being closer to 20%. Considered globally, artificial explosive systems correspond to a 30% change in the population of LS events, highlighting the frequency of artificial explosive systems presented in the case study. We therefore suggest that the implementation of the combined criteria has an important influence on the population of explosive cyclones, and hence is important for any climatology of

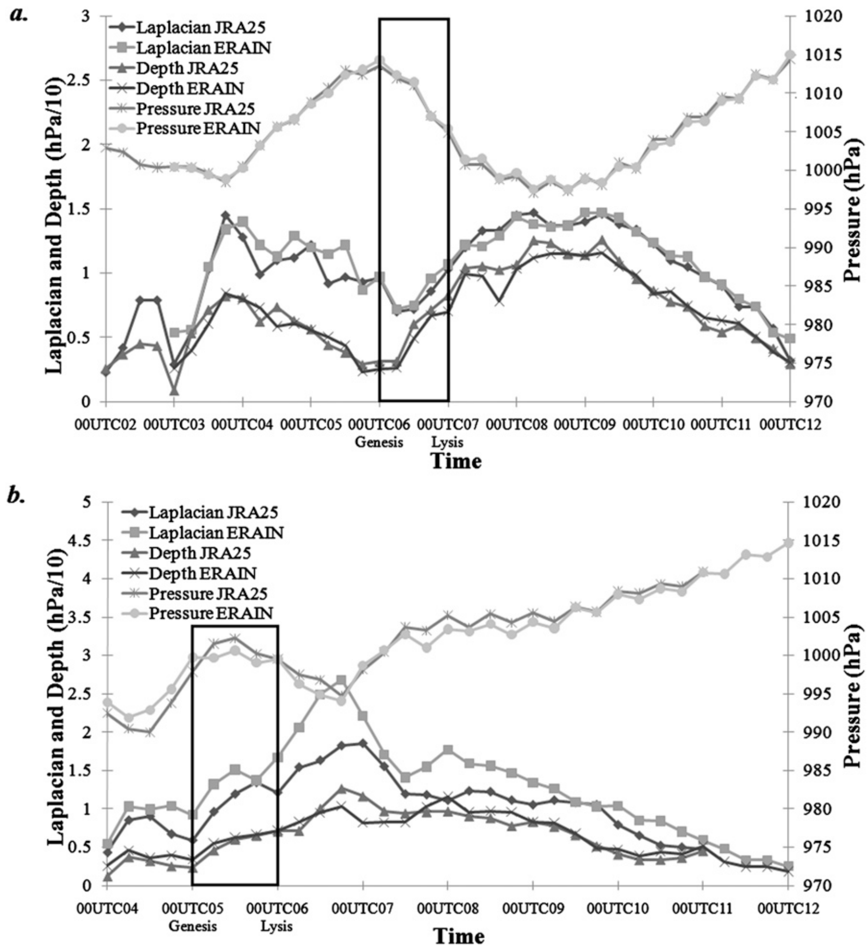


FIG. 2. Evolution of descriptive cyclone statistics during the life cycle of each case study. The right-hand scale corresponds to central pressure (hPa) of the system, while the left-hand scale corresponds to Laplacian [hPa (°latitude)$^{-2}$] and depth [hPa (10)$^{-1}$] for the respective reanalyses. The black boxes indicate the period of artificial explosive cyclogenesis for the (a) NH case, 0000 UTC 2 Feb–0000 UTC 12 Feb 2006, with explosive cyclogenesis at 0000 UTC 6 Feb and explosive lysis at 0000 UTC 7 Feb; and (b) SH case, 0000 UTC 4 Mar–0000 UTC 12 Mar 1998, with explosive cyclogenesis between 0000 UTC 5 Mar and 0000 UTC 6 Mar 1998.

this type of system. Clearly the application of central pressure–based criteria to explosive cyclones should involve either the SG criterion, the new combined criteria, or both depending on whether the user considers the background climatological pressure field to be ''seen'' by the cyclone.

An alternative approach to assessing the rapid intensification of explosive systems is to consider changes in $\nabla^2 p$ such as considered by Pinto et al. (2009). Figure 3 shows the distribution of changes in pressure Laplacian for the SH for a comparison of the earlier LS02 explosive definition and our ''combined'' criteria. The histogram distribution of artificial systems is also included, where ''artificial'' is given by the difference between LS02 and the combined criteria. The figure is very elucidative, showing that the combined definition has a substantially more normal distribution. This makes strong sense physically, when one is dealing with a spectrum of intense cyclones prefiltered by pressure criteria. The LS02 histogram shows a substantial bias toward greater

TABLE 1. Mean annual frequency of explosive events as defined by the respective reanalyses and hemispheres for the SG, LS, and combined criteria. Average values are taken over the period 1979–2001 for the ERA-40, 1979–2008 for the NCEP2 and JRA-25, and 1989–2008 for the ERA-Interim.

| | SG | | LS | | Combined | |
|---|---|---|---|---|---|---|
| Reanalysis | NH | SH | NH | SH | NH | SH |
| ERA-40 | 73.3 | 129.9 | 42.2 | 38.3 | 35.2 | 22.1 |
| NCEP2 | 70.6 | 91.2 | 39 | 27.7 | 30.3 | 14.4 |
| JRA-25 | 67.3 | 99.4 | 37.5 | 30.1 | 29.6 | 16.7 |
| ERA-Interim | 80.1 | 171.1 | 46.3 | 53.5 | 36.5 | 31 |

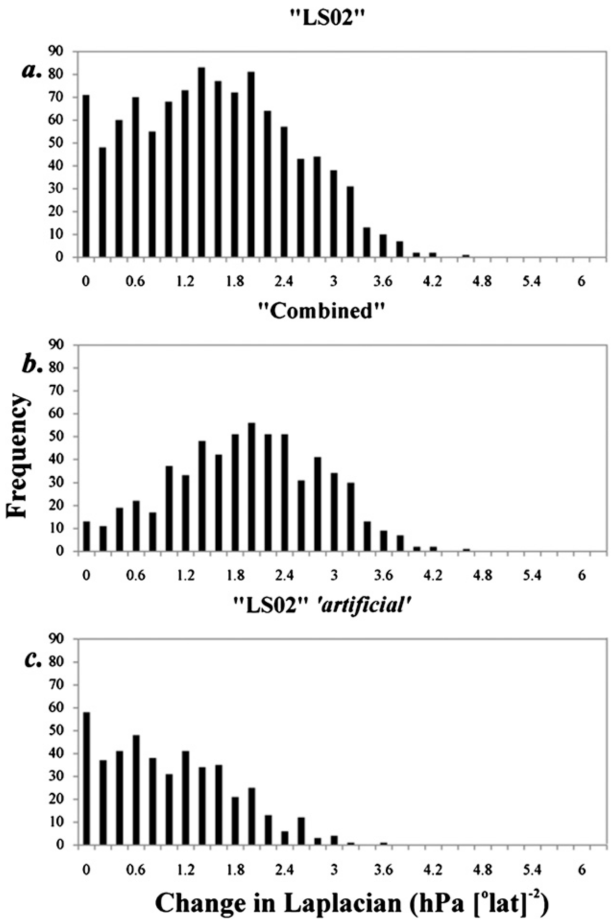


FIG. 3. The change in Laplacian over the 24-h period of explosive development for SH explosive cyclones during 1989–2008. The explosive cyclones are identified using the 24-h pressure change definitions of (a) LS02 and (b) combined criteria. (c) The 24-h change in Laplacian for cyclone events satisfying the explosive definition of LS02 but not SG80 [and hence the differences between (a) and (b)] is shown.

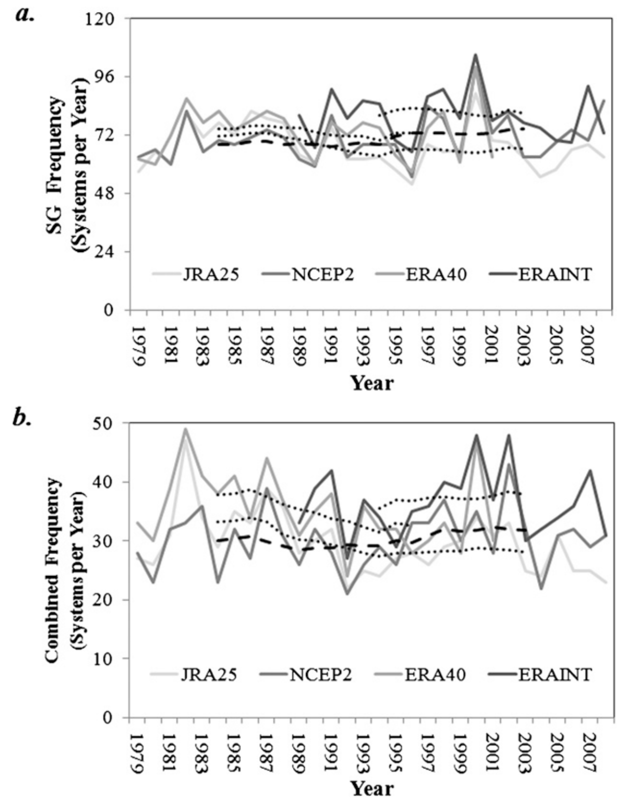


FIG. 4. Time series for the interannual variability of NH explosive cyclones, as defined by the (a) SG criterion over the period 1979–2008 in systems per year for the respective reanalyses. (b) As in (a), but explosive cyclones are defined by the combined [($NDR_c$) and ($NDR_r$) $\leq -1$] criteria. The 11-yr-centered running mean values are shown by the dotted lines for the respective reanalyses, with the NCEP2 shown as a dashed line.

frequency of cyclones with very small changes in the pressure Laplacian, which as discussed in our case studies can be interpreted as artificial explosive systems.

The frequency distribution of artificial cyclones is a highly biased histogram peaking at the minimum Laplacian variation threshold. Our combined criteria effectively remove this bias, providing a much more uniform distribution complementing previous results. Although based on Fig. 3 criteria such as used by Pinto et al. (2009) would pick most of the combined cyclones, our technique imposes a further normalization via removal of the artificial cyclones that can also have relatively large changes of pressure Laplacian (Fig. 3c). In light of these results, for the remainder of this study we consider the SG and combined cyclone populations only.

### *b. Interannual variability of system frequency*

#### 1) NORTHERN HEMISPHERE

The dynamic and baroclinic formative environment of explosive cyclogenesis results in a strong interannual variability in the formation of these systems. Mean system frequency over 11-yr periods was considered for both hemispheres to determine if the system frequency is changing based on available data using the respective reanalyses. Explosive cyclones identified using the SG criterion in the NH display a high degree of interannual variability, with no statistically significant trends or variations in the running mean (Fig. 4a). There is relatively good agreement between the number of systems identified by each of the reanalyses, within the aforementioned limitations of using more modern techniques and resolution in the newer products. This is clearly exhibited by the common representation of the highest-recorded system frequency in 2000 by all reanalyses. No notable or verifiable trends or changes in the running mean were identified for interannual variability in the NH for

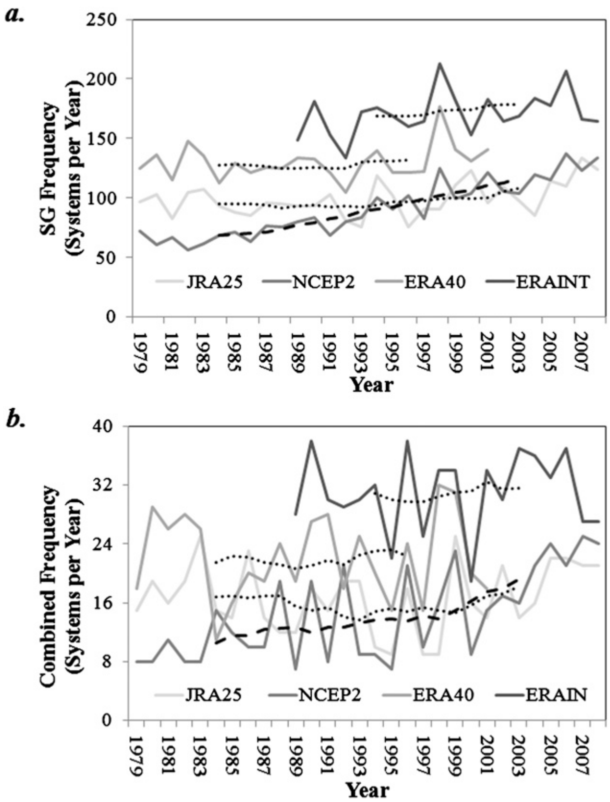


FIG. 5. As in Fig. 4, but for the SH explosive cyclones.

combined systems (Fig. 4b), however, the use of the improved criterion appeared to improve the agreement of interannual variability between the reanalyses.

### 2) SOUTHERN HEMISPHERE

In contrast to the NH, there is a marked disparity in SH system frequency between the reanalyses throughout the climatologies for the SG criterion (Fig. 5a), particularly evident in the period prior to 1991. Separation at the early part of the analyzed period is in excess of 30 systems between the NCEP2 and the JRA-25, and the JRA-25 and ERA-40, respectively. A convergence of the NCEP2 and JRA-25 population occurs in the period following 1991, while throughout the record the ECMWF reanalyses identify a larger number of systems. This may be a result of the greater run resolution and advanced model for the ERA-Interim dataset, while the large number of systems detected by the ERA-40 seems to follow the systemic larger population of cyclones found within that reanalysis (Raible et al. 2008). The overlap period (1989–2001) between the ECMWF reanalyses shows good agreement in the interannual variability, with a larger number of explosive systems identified from the newer reanalysis, suggesting that the higher resolution and/or use of 4D-Var may be important for detection. A large degree of interannual variability characterizes the combined

TABLE 2. Mean seasonal frequency of explosive events as defined by the respective reanalyses and hemispheres for the combined criteria. Seasons are indicated as follows: December–February (DJF), March–May (MAM), June–August (JJA), and September–November (SON). Mean values over the period 1979–2001 for the ERA-40, 1979–2008 for the NCEP2 and JRA-25, and 1989–2008 for the ERA-Interim in all cases excluding DJF, where the reanalyses commencing in 1979 were used from 1980 and similarly 1990 for the ERA-Interim.

| | DJF | | MAM | | JJA | | SON | |
|---|---|---|---|---|---|---|---|---|
| Reanalysis | NH | SH | NH | SH | NH | SH | NH | SH |
| ERA-40 | 19.2 | 2.4 | 7.7 | 4.9 | 0.1 | 8.9 | 7.0 | 5.4 |
| NCEP2 | 17.7 | 1.4 | 6.1 | 3.7 | 0.3 | 5.9 | 6.2 | 3.0 |
| JRA-25 | 15.9 | 2.2 | 6.8 | 4.0 | 0.2 | 6.1 | 6.3 | 4.2 |
| ERA-Interim | 20.7 | 4.2 | 7.5 | 7.7 | 0.35 | 11.4 | 8.2 | 7.3 |

cyclone population by each reanalysis, a result of the small number of systems identified on an annual basis. The NCEP2 is associated with an increase in the running mean over the climatological period using the SG definition (Fig. 5b), which may be a result of the smaller number of systems identified in the early period of the climatology (1979–1991). The population of combined systems shows a longer-term variability, with an overall increase over the length of the climatology. In contrast to the increase of system frequency in the NCEP2 climatology, combined and SG systems have remained consistent over the length of the climatology as determined from the JRA-25 reanalysis. The shorter available period for the ECMWF reanalyses makes identifying changes in running means difficult; however, there is a suggestion of an increase in the frequency of systems after 1991. In each of the JRA-25, ERA-Interim, and ERA-40 reanalysis cases there is an increase in the number of systems toward the end of the running mean for the SG definition, with the system populations thereafter continuing to climb. The small population and resultant statistical instability means that variations in the combined system population are difficult to interpret. However, there is suggestion of an increasing population toward the end of the climatology, particularly in the JRA-25. Clearly there is a significant variation in the trends of population frequency for explosive cyclones depending on the reanalysis chosen [similar to the findings of Hoskins and Hodges (2005)], and the extent to which this variation influences the climatology is examined (section 3c).

### 3) SEASONAL

The SH has a low interseasonal variability in the frequency of explosive cyclones (Table 2), with the trends and interannual differences between the reanalyses being reflected in the interannual variation by season. In contrast, the NH has similar frequency of systems for all

TABLE 3. Correlations for the respective reanalysis pairs for the SG and combined criteria over the climatological period 1979–2008 by hemisphere, with the ERA-40 and ERA-Interim being used for the periods 1979–2001 and 1989–2008, respectively. Correlations are in terms of $R$, with bold values indicating significance exceeding the 99% level and N/S indicating values that do no exceed the 95% level (Student's $t$ test).

| | | Reanalyses | | | | |
|---|---|---|---|---|---|---|
| Criterion | Hemisphere | ERA-40 to NCEP2 | ERA-40 to JRA-25 | JRA-25 to NCEP2 | ERA-Interim to NCEP2 | **ERA-Interim to JRA-25** |
| SG | NH | **0.79** | **0.79** | **0.65** | **0.66** | **0.79** |
| | SH | 0.47 | N/S | 0.40 | N/S | N/S |
| Combined | NH | **0.81** | 0.53 | **0.53** | **0.66** | **0.73** |
| | SH | N/S | N/S | 0.40 | 0.47 | N/S |

reanalyses. Each of the reanalyses identified that for the SH winter is the peak season of explosive development regardless of the criterion, consistent with the peak period of development in the NH winter. However, there is a lower degree of seasonal variability in the SH, reflecting the findings of LS02. There is close agreement between the mean NH seasonal frequency of the JRA-25 and the NCEP2, with the JRA-25 only notably differing in the winter. In the SH, however, the NCEP2 shows a smaller number of mean systems in all seasons, with the greatest differences outside the winter season. The ECMWF reanalyses show a degree of consistency in the system frequency across all NH seasons, even with the differences between the ERA-Interim and ERA-40 in terms of model resolution. In contrast, for the SH the ERA-Interim indicates a much larger population of systems in each season, suggesting that small scale or poorly resolved systems play a more significant role, and this was examined further using spatial distribution (section 3d). A high degree of interannual variability is found in the relatively small population of explosive cyclones detected by season in both hemispheres (not shown). We note that while no significant linear trends are identified by the ERA-Interim reanalysis (or any of the other reanalyses) either hemispherically or seasonally, the relatively short period (20 yr) for which the data is available means that weak trends may be difficult to identify from the natural interannual variability. In the SH, the reanalyses appear to be approaching similar values to the ERA-Interim as the end of the climatology period is reached. This convergence of reanalyses may be of interest to examine in the future. While there is some variation in mean frequency values between the reanalyses, both annually and seasonally there is strong evidence to suggest that there is a high degree of consistency between the reanalyses, particularly in the NH.

### *c. Correlations between reanalyses*

#### 1) HEMISPHERIC 1979–2008

The trends identified in the context of interannual variability suggest an apparent lack of consistency of reanalysis data through time, particularly in the SH. Correlation coefficients were used to assess the similarities between the reanalyses, particularly in the period 1979–91, which shows pronounced differences in the consideration of interannual variability. The NH shows strong positive correlations between the ERA-40 and both the JRA-25 and NCEP2 reanalyses over the period 1979–2001 for all cases (Table 3). The use of the combined criteria appears to considerably remove the noise, consistent with the fact that it was shown to produce a much more normalized climatology expressed by $\nabla^2 p$. Direct comparison between the JRA-25 and NCEP2 suggests that there is a strong correlation between these reanalyses over the entire 30-yr period. The strong positive correlations in the NH suggest that there is good agreement between the reanalyses regarding the interannual variations of explosive systems occurring in that hemisphere.

In contrast to the consistency identified in the NH, there is relatively poor agreement between reanalyses in the SH. Small positive correlations are found between the NCEP2 and the ERA-40 for the SG criterion. When considered in comparison to the JRA-25, a smaller positive correlation was found, which corresponds to the significant differences in the number of systems detected in the period 1979–1989. The combined criteria shows improved correlation between the NCEP2 and ERA-Interim, which reflects the exclusion of both the noise and the period of greatest deviation from each of the other reanalyses. We suggest that the lack of significant correlations in the SH may be a result of the higher variability resulting from a small system population. However, to some degree this may be a product of the differences between the model formulation of the reanalyses identified in examination of interannual variability, a result consistent with earlier findings (Hodges et al. 2003).

#### 2) TEMPORAL CONSISTENCY

To assess the temporal consistency of the reanalyses, three 10-yr periods were used to compare each of the reanalyses using correlation values. The selection of the periods was such that the overlap between the reanalyses was maximized, and coincided with the number of

TABLE 4. Correlations of annual system population using each of the criteria for the various reanalyses over three 10-yr periods, 1979–1988 (ERA-40, NCEP2, and JRA-25), 1989–1998 (ERA-40, NCEP2, JRA-25, and ERA-Interim, broken down into two groups for convenience), and 1999–2008 (NCEP2, JRA-25, and ERA-Interim). The *R* values are used, with all linear least squares regressions shown. Italicized values correspond to correlations exceeding the 95% significance level, while those in bold correspond to correlations exceeding the 99% significance level (Student's *t* test).

| Criterion NH | Period: 1979–1988 | | Period: 1989–1989 (i) | | Period: 1989–1998 (ii) | | Period: 1999–2008 | |
|---|---|---|---|---|---|---|---|---|
| | Reanalyses | Correlation | Reanalyses | Correlation | Reanalyses | Correlation | Reanalyses | Correlation |
| SG | ERA-40 to NCEP2 | **0.74** | ERA-40 to NCEP2 | **0.78** | ERA-40 to ERA-Interim | **0.97** | ERA-Interim to JRA-25 | **0.84** |
| | ERA-40 to JRA-25 | **0.85** | ERA-40 to JRA-25 | **0.72** | ERA-Interim to JRA-25 | **0.81** | ERA-Interim to NCEP2 | 0.58 |
| | NCEP2 to JRA-25 | **0.83** | NCEP2 to JRA-25 | **0.78** | ERA-Interim to NCEP2 | **0.82** | NCEP2 to JRA-25 | **0.78** |
| Combined | ERA-40 to NCEP2 | **0.72** | ERA-40 to NCEP2 | 0.25 | ERA-40 to ERA-Interim | **0.77** | ERA Interim to JRA-25 | **0.72** |
| | ERA-40 to JRA-25 | **0.89** | ERA-40 to JRA-25 | *0.65* | ERA-Interim to JRA-25 | **0.74** | ERA-Interim to NCEP2 | *0.63* |
| | NCEP2 TO JRA-25 | *0.66* | NCEP2 to JRA-25 | 0.51 | ERA-Interim to NCEP2 | *0.66* | NCEP2 to JRA-25 | 0.55 |

| Criterion SH | Period: 1979–1988 | | Period: 1989–1989 (i) | | Period: 1989–1998 (ii) | | Period: 1999–2008 | |
|---|---|---|---|---|---|---|---|---|
| | Reanalyses | Correlation | Reanalyses | Correlation | Reanalyses | Correlation | Reanalyses | Correlation |
| SG | ERA-40 to NCEP2 | −0.56 | ERA-40 to NCEP2 | **0.77** | ERA-Interim to ERA-40 | **0.88** | ERA-Interim to JRA-25 | −0.45 |
| | ERA-40 to JRA-25 | **0.77** | ERA-40 to JRA-25 | 0.22 | ERA-Interim to JRA-25 | 0.18 | ERA-Interim to NCEP2 | 0.46 |
| | NCEP2 to JRA-25 | −0.38 | NCEP2 to JRA-25 | 0.01 | ERA-Interim to NCEP2 | **0.77** | NCEP2 to JRA-25 | 0.13 |
| Combined | ERA-40 to NCEP2 | 0.36 | ERA-40 to NCEP2 | 0.30 | ERA-Interim to ERA-40 | **0.71** | ERA-Interim to JRA-25 | 0.00 |
| | ERA-40 to JRA-25 | 0.41 | ERA-40 to JRA-25 | 0.28 | ERA-Interim to JRA-25 | 0.49 | ERA-Interim to NCEP2 | 0.34 |
| | NCEP2 TO JRA-25 | *0.61* | NCEP2 to JRA-25 | 0.55 | ERA-Interim to NCEP2 | *0.68* | NCEP2 TO JRA-25 | *0.68* |

reanalyses available at that time (Table 4). The NH was found to be relatively consistent in the correlations between the reanalyses, with strong positive correlations using the SG criterion over each of the periods. Considering the combined criteria, there is a stronger correlation over all three periods, with all cases excluding the NCEP2–ERA-40 indicating a greater agreement between the reanalyses. We suggest that the removal of the noise produced by artificial explosive systems explains this improvement in correlation. Correlations are similar to those noted for the SG criterion, and the lower values are a result of the high degree of interannual variability associated with the small population of systems.

We suggest that the differences in the SH, particularly for SG systems are due to significant variation in the individual systems identified. Whether this is a result of various interpretations of changing climate, natural variability in the pressure field, or changes in the input data used for reanalysis requires further examination and is outside the scope of this study. However, ERA-Interim and ERA-40 show a good degree of consistency in the system frequency across all NH seasons in spite of the differences in terms of model resolution. Additionally the relative consensus of reanalyses obtained using the combined criteria suggests that the use of several of these datasets is an important tool for obtaining verifiable results. Thus, reanalysis data despite its deficiencies still provides one of the best sources of MSLP information to examine explosive cyclones in data-sparse regions of the SH. However, care should be taken in considering these correlations, as they are sensitive to both the tracking scheme and the statistical limitations of assessing correlation over 10-yr periods (Pinto et al. 2005; Raible et al. 2008).

### *d. Spatial distribution of system density*

A comparison of the spatial distribution of explosive cyclone tracks was conducted to examine the influence of the high-resolution ERA-Interim dataset and assess spatial differences between the reanalyses. The NH combined cyclone distribution ranges between 30° and 70° latitude, with two main regions of explosive development situated in the northwest Atlantic and Pacific (Fig. 6). Distinct secondary maxima are located equatorward of Iceland and the Aleutian islands for the

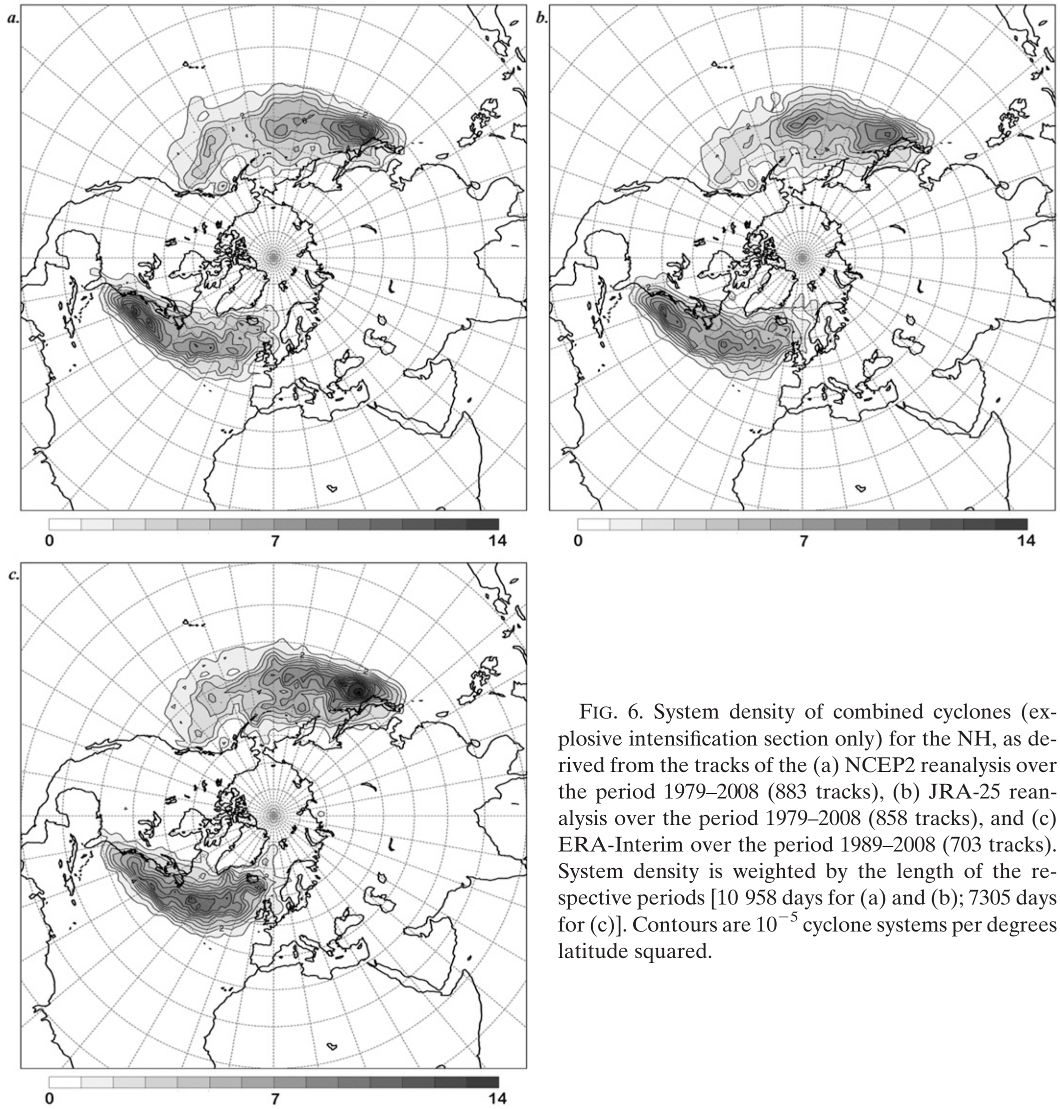


FIG. 6. System density of combined cyclones (explosive intensification section only) for the NH, as derived from the tracks of the (a) NCEP2 reanalysis over the period 1979–2008 (883 tracks), (b) JRA-25 reanalysis over the period 1979–2008 (858 tracks), and (c) ERA-Interim over the period 1989–2008 (703 tracks). System density is weighted by the length of the respective periods [10 958 days for (a) and (b); 7305 days for (c)]. Contours are $10^{-5}$ cyclone systems per degrees latitude squared.

NCEP2 and JRA-25 (Figs. 6a and 6b, respectively) derived system densities. In contrast, the ERA-Interim (Fig. 6c) appears to provide an elongated maximum in the Atlantic basin that extends between 35° latitude at 75°W and 50° at 20°W. In the northwest Pacific the primary maximum near 150°E still appears to be more focused than the maximum in the Atlantic. Peak system density is lower for the JRA-25, as the systems appear to be more widely distributed despite being composed of a similar number of tracks to the NCEP2. A more confined distribution is evident for the ERA-Interim with the majority of systems confined to the regions of peak values. However, as the ERA-Interim is only available for the period 1989–2008 any changes in distribution in comparison to the JRA-25 and NCEP2 may be a result of systems prior to 1989. This distribution is similar to that documented by Hoskins and Hodges (2002) for extratropical cyclones, with a slight bias toward the western continental seaboards, which reflects the greater dependence on strong baroclinicity.

In the SH spatial differences are more pronounced, with considerable variations in number of explosive cyclones identified by the respective reanalyses (Fig. 7). The NCEP2 was found to identify the smallest population, while the ERA-Interim produced approximately 200 additional tracks over only a 20-yr period. All three reanalyses identify a large maximum off the east coast of South America between 70° and 10°W and extending latitudinally between 30° and 50°S, which has the greatest density of systems in the hemisphere. Smaller regions are identified consistently by each reanalysis to the east of the Australian continent and New Zealand, following the genesis maxima found in the NH on eastern continental seaboards. The greatest densities were found using the

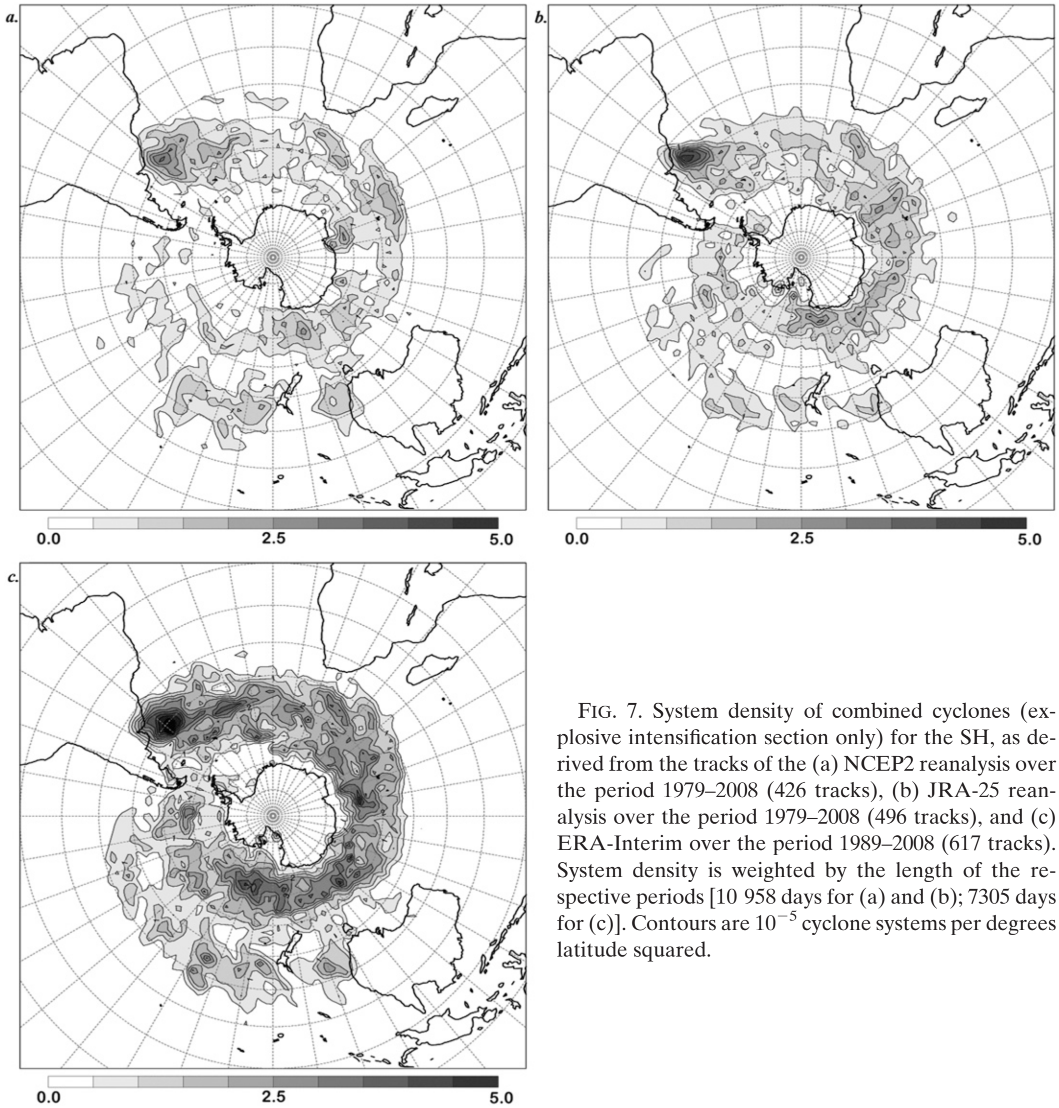


FIG. 7. System density of combined cyclones (explosive intensification section only) for the SH, as derived from the tracks of the (a) NCEP2 reanalysis over the period 1979–2008 (426 tracks), (b) JRA-25 reanalysis over the period 1979–2008 (496 tracks), and (c) ERA-Interim over the period 1989–2008 (617 tracks). System density is weighted by the length of the respective periods [10 958 days for (a) and (b); 7305 days for (c)]. Contours are $10^{-5}$ cyclone systems per degrees latitude squared.

higher-resolution ERA-Interim, suggesting the identification of small scale or transitioning systems may be achieved using increased spatial resolution and is of particular importance to the SH. A maximum earlier noted by LS02 to the southwest of the Australian continent appears to be a region dominated by artificial explosive systems. Other major regions of system density are found in a band between 45° and 90°E and poleward of 40° to near the Antarctic continent, and between 100°E and 150°W in a latitudinal band poleward of 45°–80°S. Once again this distribution of systems was found to be similar to that identified for SH extratropical cyclones (Hoskins and Hodges 2005), with a bias toward continental margins and regions of enhanced baroclinicity. Spatial distributions by the criterion were also considered for each of the reanalyses. However, it was found that the pattern was similar to intercomparison of the reanalyses, despite the less restrictive criteria identifying more systems. These regions of explosive cyclogenesis require further examination to establish the developmental characteristics and dynamical influences of these cyclones in the SH. We note that while for both hemispheres the ERA-Interim identifies a greater system density, in the majority the pattern of spatial distribution is retained by both the NCEP2 and JRA-25, and this spatial distribution of explosive cyclones identified by the reanalyses is robust.

### e. Spatial distribution of system depth

In the NH (Fig. 8), mean depth suggests that the most intense combined systems occur poleward of the major

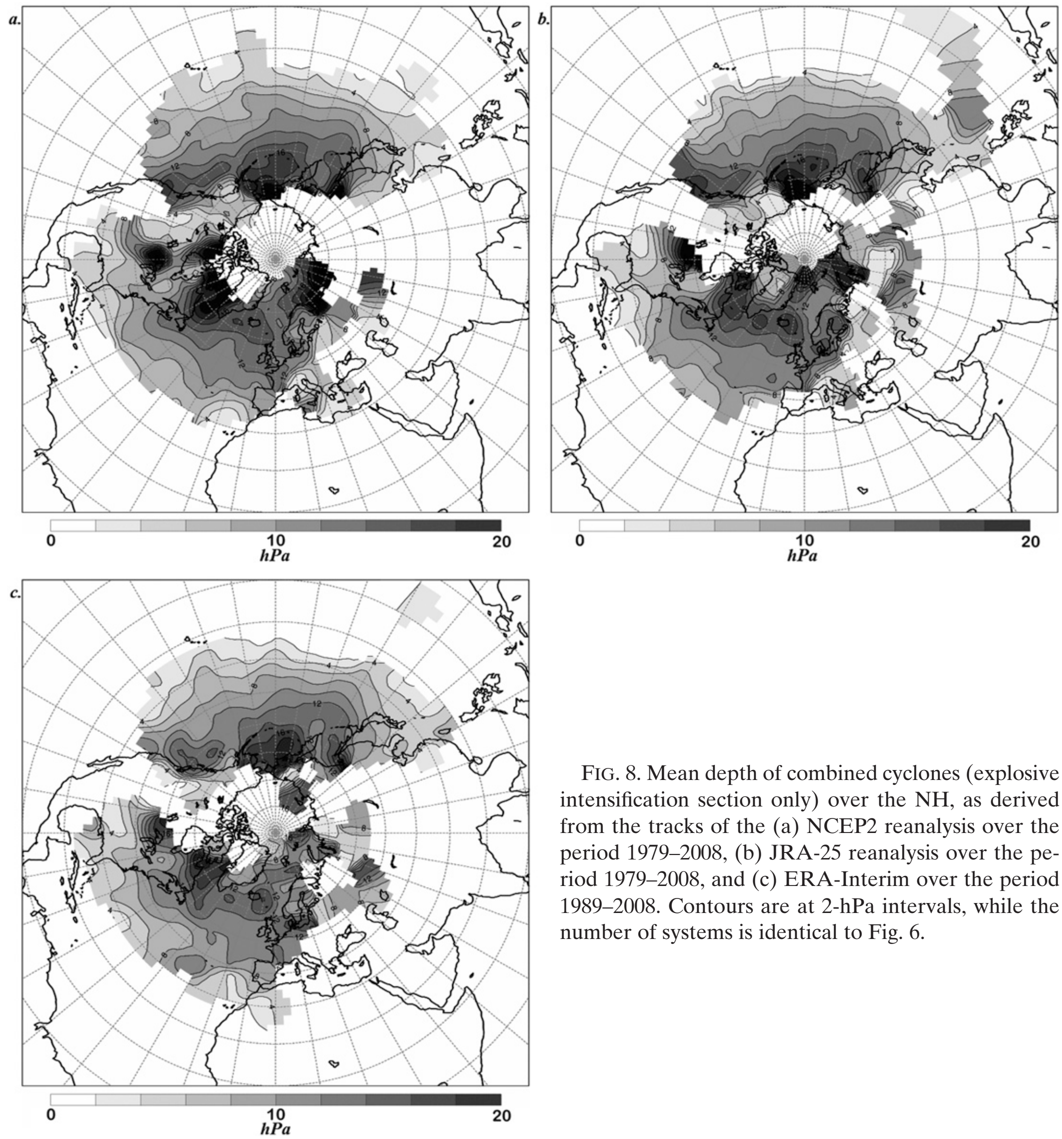


FIG. 8. Mean depth of combined cyclones (explosive intensification section only) over the NH, as derived from the tracks of the (a) NCEP2 reanalysis over the period 1979–2008, (b) JRA-25 reanalysis over the period 1979–2008, and (c) ERA-Interim over the period 1989–2008. Contours are at 2-hPa intervals, while the number of systems is identical to Fig. 6.

regions of system density in both the northern Atlantic and Pacific basins. While system density is greatest in a latitudinal band between 30° and 70°N, system depth is greatest poleward of 50°. The deepest systems in the NH are located near the Aleutians in the northern Pacific, and band poleward of 50°N and between Greenland and Iceland in the northern Atlantic, with similar distributional differences between the reanalyses to system density. The SH displays similarities to the pattern in the NH, with the regions of greatest depth being poleward and eastward of the distribution noted for system density (Fig. 9). We suggest that the poleward and eastward shift in distribution identified by the depth criterion indicates that the greatest intensity occurs toward the end of explosive development, as suggested by Pinto et al. (2009). The robustness of the distribution for system density is further confirmed by the depth, with a high degree of similarity between the reanalyses.

## 4. Discussion and conclusions

A comprehensive global climatology has been presented for explosive cyclones using multiple reanalyses with the Melbourne University automated cyclone tracking scheme over the 30-yr period 1979–2008. Our combined criteria, which identifies a 24-hPa drop relative to latitude in both central pressure and relative to the climatological pressure gradient over a 24-h period normalized to 60° latitude, have been presented here for the first time. This definition is characterized as being

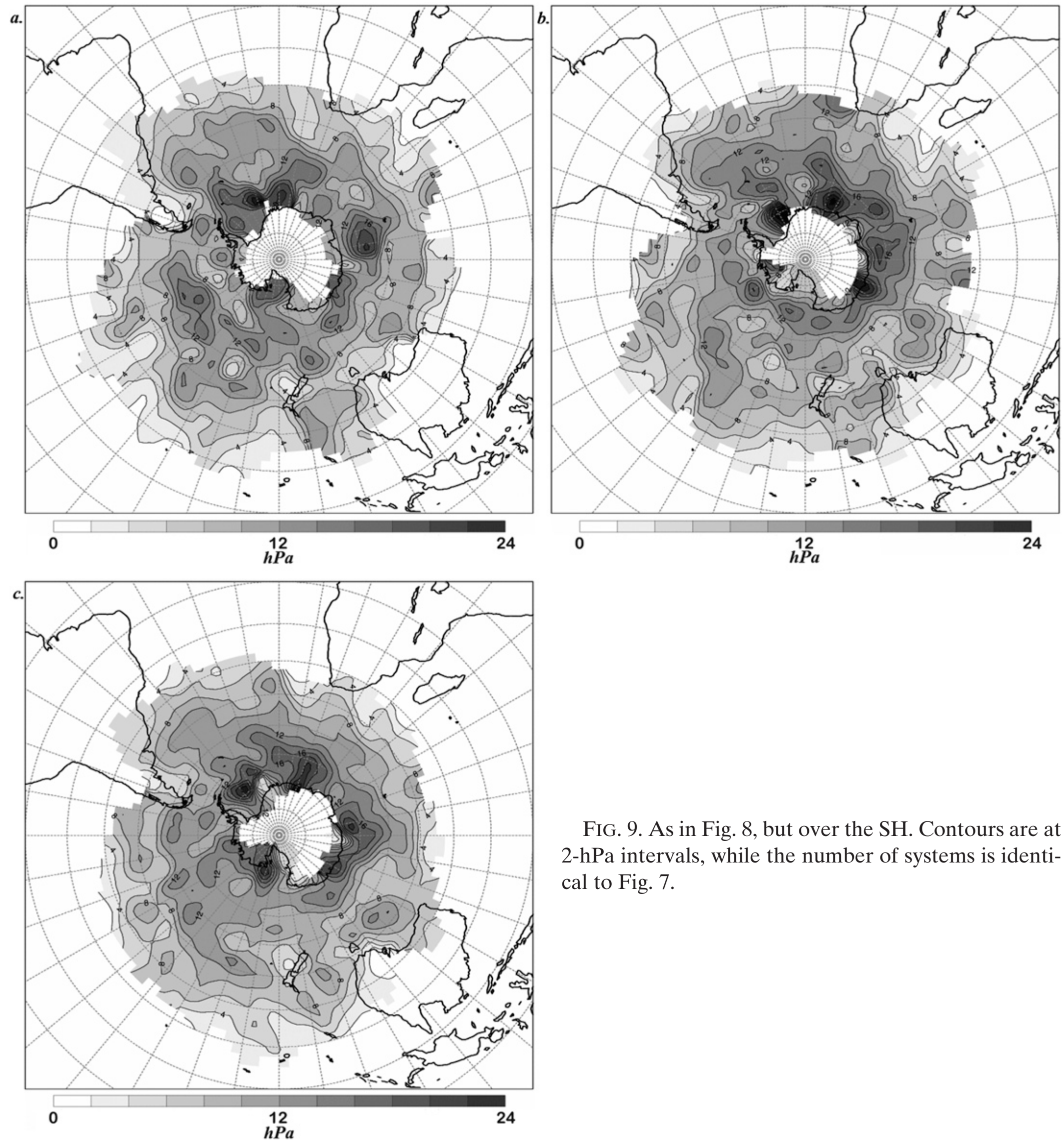


FIG. 9. As in Fig. 8, but over the SH. Contours are at 2-hPa intervals, while the number of systems is identical to Fig. 7.

the intersection between the set of explosive cyclones defined by the SG and LS criteria. The application of the combined criteria was found to remove ''artificial'' explosive systems identified by the LS criterion and identifies the population of explosive cyclones with deepening relative to climatological pressure gradient. Artificial explosive systems were found to compose 30% of the global LS cyclone population, and are particularly influential in the SH where they compose in excess of 40%. Our criteria also offer a climatology that has a frequency spectrum of $\nabla^2$ MSLP significantly more normal than the earlier definitions, making it more appropriate to put explosive development in a climate perspective. Mean annual and seasonal statistics have been examined for each of the ERA-40, NCEP2, JRA-25, and ERA-Interim reanalyses. The NH was found to have a larger population of explosive cyclones than the SH, which reflects the findings of LS02. On a seasonal basis, winter was found to be the dominant period of explosive cyclogenesis, with a smaller degree of seasonal variability in the SH. The impact of the climatological pressure gradient has found to be important in both hemispheres, with our new definition being essential to eliminate artificial explosive systems. The ERA-Interim reanalysis was found to significantly increase the number of systems detected, particularly in the SH. This reflects the possibility of improved detection of explosive development achieved by higher-resolution pressure data and improved model formulation features such as 4D-Var (Dee and Uppala 2009).

A high degree of interannual variability has been identified for the combined criteria in both hemispheres. However, the agreement between reanalyses displays a notable deficiency in the SH, despite consistent mean annual statistics identified from each of the reanalyses. Significant trends or variations in the running mean were not identified in the NH on an annual basis for any of the criteria or reanalyses. In the SH, increases in the running-mean frequency of systems were identified for all reanalyses for both the SG and combined systems. However, these may be questionable given the deficiencies in system numbers for the NCEP2 and short availability of the ERA-Interim. Nonetheless ERA-Interim data displayed a larger population of explosive cyclones in the SH over the period 1989–2008 than the other reanalyses, showing the effect of greater spatial resolution. Correlation coefficients were examined between each of the reanalyses over the length of the climatology and for three 10-yr periods. These were used to establish the consistency of the reanalyses through time for the identification of explosive cyclones. Strong positive correlations have been identified in almost all cases for the NH, with the criteria having little statistical impact on the significance. This was also reflected in the limited analysis period, despite the restriction of the population size producing a higher degree of variability. In both the full period and limited analysis, a lack of significance in the correlation between the reanalyses was identified for the SH, similar to the findings of Hodges et al. (2003) for extratropical cyclones. Weak positive correlations are noted for the combined criteria using the NCEP2 during the first period, while there were positive correlations to the ERA-Interim for all reanalyses for the second period. The third period was found only to have a significant correlation between the NCEP2 and JRA-25, and this was suggested to be a result of the apparent convergence in annual system population noted between the reanalyses in the assessment of interannual variability. The poor correlation values in the early period for the NCEP2 may be a result of the lower-resolution model (Hodges et al. 2003; Trigo 2006) compared to each of the ECMWF reanalyses and the JRA-25.

In the SH, the maximum system density was found east of South America, with two other high-density areas located between 45° and 90°E and poleward of 40°S to near the Antarctic continent, and between 100°E to 150°W in a latitudinal band poleward of 45° to 80°S. This distribution is similar to that found for the total population of extratropical cyclones (Hoskins and Hodges 2005), with a greater bias toward the western margins of ocean basins. The use of the high-resolution ERA-Interim identified a significantly larger number of systems particularly to the east of continental landmasses in the SH at lower latitudes, possibly reflecting a greater population of smaller or hybrid systems.

System depth was found to have a distribution poleward and eastward of the system densities in both hemispheres, reflecting the rapid poleward intensification process of combined systems. A further question important to the establishment of a new future criterion for explosive cyclogenesis that would be regarded as unbiased is whether individual explosive systems "see" the climatological pressure gradient. This is relevant for both the LS and combined criteria, which include the impact of climatological pressure gradient on central pressure, while the climatological pressure gradient is developed on a mean monthly basis consisting of many such systems. A case study by Fink et al. (2009) concluded that the large-scale pressure gradient was largely responsible for the extremely unusual wide area affected by the storm "Kyrill," as the cyclone itself (in terms of core pressure and vorticity) was not so extreme. The conclusion of Fink et al. (2009) suggests that the pressure gradient may have an important effect in influencing the wind field associated with a storm, and less to do with the storms' explosive development. This provides motivation to investigate whether the systems discarded by the use of such criteria are any less rapidly intensifying or influential than those identified. The concept of pressure gradient force, which clearly suggests that a rapid increase in pressure gradient associated with explosive cyclogenesis should be reflective of the dangerous impacts such as strong winds, should be one of the primary considerations in this endeavor. Another future step is the use of the spatial distribution of explosive developments to assess the dynamics and formative characteristics of explosive development in the SH to determine whether central pressure changes are reflecting cyclone intensification in a similar fashion to Kuwano-Yoshida and Asuma (2008) for the northwest Pacific.

Finally, we note that while statistical differences between the reanalyses may pose a significant influence to climatologies of cyclones and explosive cyclones, the use of multiple reanalyses, particularly high-resolution datasets such as the ERA-Interim remains a powerful tool for data-sparse regions (Simmonds et al. 2008). Acknowledging the limitations in the use of reanalysis data allows a greater understanding of midlatitude development, which is particularly important in the SH where reanalysis data has improved significantly in quality, but must improve further to achieve the consistency and reliability found in the NH.

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