AN UPDATED CLIMATOLOGY OF SOUTHERN HEMISPHERE EXPLOSIVE CYCLOGENESIS

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1. INTRODUCTION

The rapid development of extra-tropical cyclones has been thoroughly investigated in the Northern Hemisphere, however the dynamics and formative characteristics of such systems in the Southern Hemisphere have received limited attention. Sanders and Gyakum (1980) (hereon SG80) first described explosively developing cyclones ('bombs') as extratropical systems in which the central pressure falls 24hPa in 24 hours relative latitude, based on investigations of Northern Hemisphere systems. The rapid intensification of this special class of extra-tropical cyclones can result in hurricane force winds (SG80), intense rainfall (Seluchi and Saulo 1998, Leslie et al. 2005) and dangerous oceanic conditions (Buckley and Leslie 2000).

Southern Hemisphere (SH) bomb events comprise about one-third of the global annual cyclone population (Lim and Simmonds 2002 (LS02)), which regularly influence the continents that lie in the midlatitudes. In applying the concepts of Sanders and Gyakum to the SH, Sinclair (1997) and Lim and Simmonds (2002) noted that the failure to account for changes in the climatological pressure field in the Southern Hemisphere resulted in systems that were not explosive being categorised as bombs. LS02, '*identified that an introduction of a climatologically relative pressure drop concept was found to remove these climatological gradient bombs'*, more accurately reflecting the definition of climatologically relative explosive systems. The study of Lim (2000) contributed significantly to the climatological study of explosive systems, covering the period 1959-1999 using the NCEP reanalysis for both the Northern and Southern Hemispheres. This study seeks to update the results of both Lim (2000) and LS02 using new reanalysis data.

To describe the process of extratropical cyclogenesis several conceptual models have been proposed. The first of these was the Norwegian model of Bjerknes and Solberg (1922) which describes the growth of unstable growing waves in a baroclinic region. A second model was that of Shapiro and Keyser (1990), who proposed a model more effective description of genesis in a confluent and weak amplitude environment which requires a distinct lack of topography such as the ocean, as compared to the Norwegian model (Figure 1), which develops in diffluent high amplitude flow (Schultz et al. 1998).

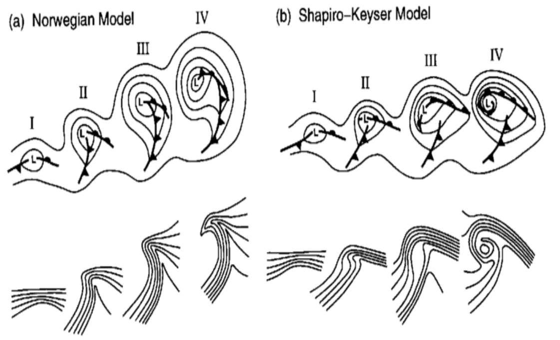

Figure 1: Comparison of the Norwegian Model (a) and the Shapiro-Keyser model (b), both models are similar in phase I, whereas in (b) frontal fracture occurs in phase II, the warm front becomes bent back in phase III, and phase IV sees a secluded warm core. (Schultz et Al 1998)

To consider the applications of these models to explosive development, Wakimoto et al. (1992) provided evidence that the explosive process follows a non-occluded mechanism similar to the Shapiro-Keyser model. While this finding was found to be reflective of a large number of NH systems, the description of SH systems has yet to be considered.

Lim and Simmonds (2002) found that SH bombs appear to display less seasonality than those of the NH, which was suggested arise from a weaker variation in baroclinicity due to the lower proportion of land to ocean, and thus producing weaker thermal contrast between seasons. Transitioning tropical events have been studied more extensively in the NH (Harr and Elsberry 2000a,b), however the studies in both hemispheres suggest that the rapidity of deepening that follows extra-tropical transition corresponds to the development of a warm-seclusion structure similar to explosive development and significantly lower sea surface temperatures, generating instability (Hart et al. 2006). The damaging winds and heavy rainfall commonly associated with explosive SH systems have motivated several regional based climatologies. Leslie et al. (2005) constructed a climatology of systems affecting New Zealand and assessed their impacts, while Seluchi and Saulo (1998) considered heavy rainfall implications for South America. Sinclair (1995,1997) examined hemispheric explosive development for 7-year periods using a vorticity condition, which produced similar results to LS02. While such focused regional and temporal studies are useful, the implications of climatic change on the processes of rapid extra-tropical development necessitate the

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** Corresponding author address:* John T. Allen, Dep. of Earth Sciences, The University of Melbourne; e-mail: JohnTerrAllen@gmail.com ongoing study of the annual frequency of systems on both a synoptic and hemispheric scale.

2. METHOD AND DEFINITIONS

To construct a comprehensive climatology of extra-tropical cyclones the latest data from the NCEP2 reanalysis was used by way of comparison with the Japanese reanalysis (JRA25). Previous Southern Hemisphere climatological studies (Lim (2000), Lim and Simmonds (2002)) used the NCEP2 and NCEP reanalyses. In this study, the NCEP2-DOE AMIP-II reanalysis was used in comparison with the earlier studies. In addition to this updated climatology, the JRA25 (JCDAS) was used to produce a new climatology from the latest available reanalysis. The JRA25 improves resolution and employs a greater range of input data to produce high quality precipitation data an improved resolving of tropical cyclones (Onogi et al. 2007).

In order to effectively identify explosive development within the reanalysis pressure data a method of identifying and tracking is required. The Melbourne University cyclone tracking scheme (Murray and Simmonds 1991) is used to identify and track low pressure centres. Subsequent advances in the methods used for both identification and tracking (Simmonds et al. 1999) have produced a tracking scheme that reliably identifies and tracks low pressure systems as detailed by Leonard et al. (1999).This tracking scheme consists of a two-step process of identification and tracking. The scheme uses an input of gridded reanalysis data and interprets using a bi-cubic spline fit to a 90x90 polar stereographic array. Using this pressure field, minima are identified using a minimum laplacian relative to a specified threshold for the 8 neighbouring grid points. Inflexions in the pressure surface are used to identify centres which lack a distinct pressure minimum. The second stage of the scheme then tracks centres using a prior movement and probability weighted identification of centres between analyses. Tracking data is then compiled for the identified cyclones, and descriptive statistics recorded. This tracking scheme therefore provides a comprehensive identification and tracking of low pressure centres from pressure reanalysis data.

To identify bombs from the cyclone tracking data, a method of sorting systems for those which contain bomb developments is required. To construct this climatology the pressure changes over 24-hour periods between bomb genesis and lysis were considered. The definition of Sanders and Gyakum (1980) can be interpreted as the concept of a Normalised Deepening Rate of central pressure:

$$NDR_c = \frac{\Delta p_c}{24}\frac{\sin 60}{\sin\theta} \qquad (1)$$

Where Δp_c is the change in central pressure and θ is degrees of latitude. Values exceeding unity incidcate bomb intensifications. In this study the NDR_c definition is used computationally to identify bombs, and forms part of the basis for a new definition. The NDR_c suggests that intense changes in system central pressure allow the identification of explosive development and its associated impacts.

A relative bomb as defined by Lim (2000) can also be interpreted a normalised deepening rate:

$$NDR_r = \frac{\Delta p_r}{24}\frac{\sin 60}{\sin\theta} \qquad (2)$$

Where Δp_r is the change in central pressure relative to the climatological pressure field as defined by:

$$\Delta p_r = p_{climate2} + p_{cyc1} - p_{climate1} - p_{cyc2} \qquad (3)$$

The monthly mean of sea level pressure for the period 1979 to April 2008 was used to construct a climatological pressure field for the respectively reanalyses. Thus bombs are identified when their deepening is significant relative to the climatological pressure gradient in the month of occurrence. This definition provides an important insight into the effects of a climatological pressure gradient on bomb development.

In order to resolve differences arising in bomb identification using both the NDR_c and the NDR_r, we define a new criterion in order to identify a bomb. A Consistent bomb is a 24hPa drop accounting for change of latitude in both central pressure and relative to the climatological pressure gradient. Conceptually this is a system for which both the NDR_c and $NDR_r \geq 1$, or simply the intersection between the set of all bombs and the set of all relative bombs. This criterion resolves the issues noted within relative bombs, and identifies systems with intensification that is significant to the surroundings.

The definition of bombs as extra-tropical systems is an issue of consequence for the construction of climatologies. Rapidly developing tropical cyclones which deepen in central pressure akin to extra-tropical systems may be identified due to the weak climatological pressure gradient in the tropics. Thus we also introduce the concept of a critical latitude for bomb formation. While the prior work of LS02 considered rapid pressure reductions occurring southward of 25 degrees to be the extent of extra-tropical systems, here we consider 20 degrees from the equator to correspond to a maximum extent for bomb development. This approach encompasses systems such as East Coast Lows, and transitioning or hybrid tropical systems which may also exhibit the characteristics of bomb development. This critical latitude is applied such that a bomb pressure drop is only identified if it occurs poleward of 20 degrees for the respective hemisphere. This criterion is applied to both the bomb and relative bomb conditions and therefore implicitly to the Consistent bomb definition. Using the respective definitions described above, cyclone track data of varying time scales was used to identify bomb development and update and expand the climatology of LS02. In this work the mean annual bomb statistics and trends in the number of systems by each definition were examined using both the JRA25 and NCEP2 reanalyses.

3. RESULTS

3.1 Mean Bomb Statistics

To examine the effectiveness of the bomb identification program used by this study, comparison was made to work of Lim and Simmonds (2002). Using the NCEP2-DOE reanalysis, the annual mean number of relative bombs for each hemisphere and the globe as a whole can be seen below in Table 1.

Relative Bombs	LS02	Allen 2008
SH	72.3	83

Table 1: Comparison of the mean annual number of relative bombs identified for the Southern hemisphere by LS02 and the current study. Statistics for comparison adapted from Lim and Simmonds 2002. Adapted from Allen 2008.

Evident from this table there appears to be a disparity for the number of SH relative bombs. This difference in SH numbers in part corresponds to the last 8 years of data not examined by LS02, when the number of relative bombs significantly exceeded the mean 7 out of 8 years.

To consider the mean number of bombs by each definition, the statistics were collated for the Southern hemisphere using the three criteria. The critical latitude was used to remove all systems which did not undergo bomb intensification in the defined extratropical region. The mean annual number of bombs according to the two reanalyses is considered in Table 2.

NCEP2	SH	JRA25	SH
Bombs	116.6	Bombs	124.2
Relative	31.5	Relative	32.5
Consistent	18.1	Consistent	20.7

Table 2: The number of bomb, relative bomb and consistent bombs occurring on a mean annual basis for both the NCEP2 (left) and JRA25 (right) reanalysis data sets. Units are mean number of systems over the 29-year period 1979-April 2008. Adapted from Allen 2008.

Annually 124 bombs occur in the Southern Hemisphere, which as noted by Lim (2000) constitutes a greater proportion of the global population. The mean annual frequency of consistent bombs differs significantly from the mean annual relative bombs, which indicates that not all relative bombs satisfy the NDR$_c$ criterion of rapid intensification. The JRA25 data is found to contain a larger number of bombs and consistent bombs than NCEP2. This may suggest a difference in the number of systems undergoing significant deepening between the reanalyses. These statistics indicate that a significant number of bombs occur annually, however not all these systems meet the falling pressure requirements for explosive development of Sanders and Gyakum (1980). While mean annual statistics are useful, we also consider the inter-annual variability in the occurrence of explosive development according to the previously defined criteria.

3.2 Trends in Bomb Numbers

Trends in the global explosive population were considered using the NDR$_c$ to assess the inter-annual variability of bombs for both the NCEP2 and JRA25 detected systems. A trend analysis is shown below in Figure 2 for the variations in the number of bombs occurring in the SH between 1979 and 2007.

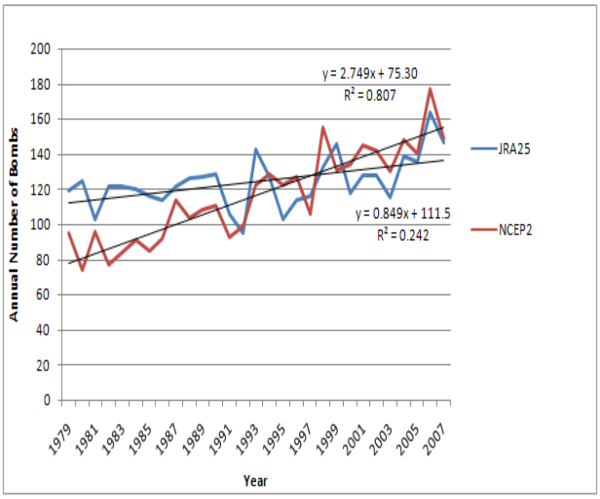

Figure 2: Trend analysis of the annual variability in number of bombs (NDRc) for the JRA25 and NCEP2 reanalyses for the Southern hemisphere. Trend lines are based on least squares method, with the equation and R^2 above the lines describing the NCEP2 reanalysis trend, and that below describing the JRA25.

During the period 1979 to 1991 a difference of 40 systems is noted between the respective reanalyses. This indicates that for the SH, NCEP2 identified fewer bombs This difference does not correspond to a known change in the data used, and therefore further analysis using other recent reanalysis data is required to examine the causes for this anomaly. In the SH, both the NCEP2 and JRA25 show a positive trend in the number of explosive events occurring (with a 99% significance using the student-t test), however the JRA25 trend is only a third of that noted for the NCEP2. The peak number of systems occurred in the SH in 2006 (164 according to JRA25), and in 2000 for the NH (100). In summary the number of explosive events occurring in the SH appears to be increasing according to both reanalyses.

3.3 Trends in Relative Bomb Numbers

The positive trends noted in the number of explosive systems using the NDR_c for the SH pose an interesting question as to whether the climatological pressure gradient has a significant role. To investigate, the inter-annual variability of relative bombs using the NDR_r was considered for both hemispheres (Figure 3).

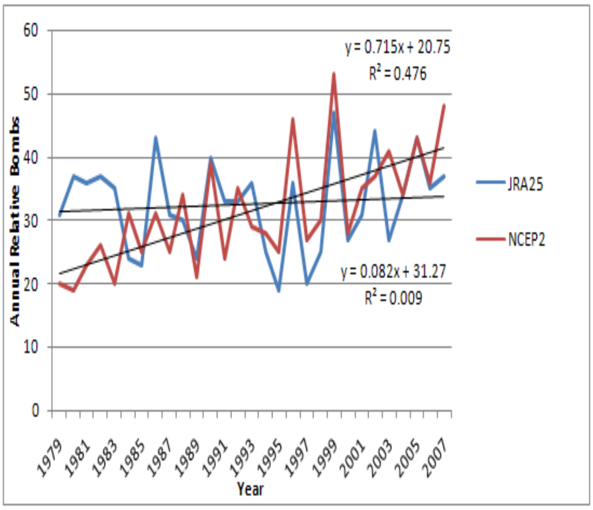

Figure 3: Trend analysis of the annual variability in number of bombs (NDRr) for the JRA25 and NCEP2 reanalyses for the Southern hemisphere. Trend lines are based on least squares method, with the equation and R^2 above the lines describing the NCEP2 reanalysis trend, and that below describing the JRA25.

The NCEP2 displays a positive trend, with a significant correlation in the data points, while the JRA25 once again shows little evident significant trend. The differences in the SH between the reanalyses is also evident for the NDR_r, further suggesting that this is not a statistical anomaly and requires investigation. The interaction of this difference with the significance of trends in the NCEP2 also requires further exploration. The peak number of SH climatologically significant bombs occurred in 1999. This difference from the peak number of systems using the NDR_c criteria suggests that a change in the climatological pressure gradient was likely a major cause of deepening in 2006. This analysis indicates that while the NCEP2 shows a positive trend in the number of relative bombs, the JRA25 displays little long term trend in the data.

3.4 Trends in Consistent Bomb Numbers

To consider the inter-annual variability of the new consistent bomb criterion in comparison to the previously discussed NDR_c and NDR_r criteria, the number of systems was considered over the period 1979-2007 (Figure 4).

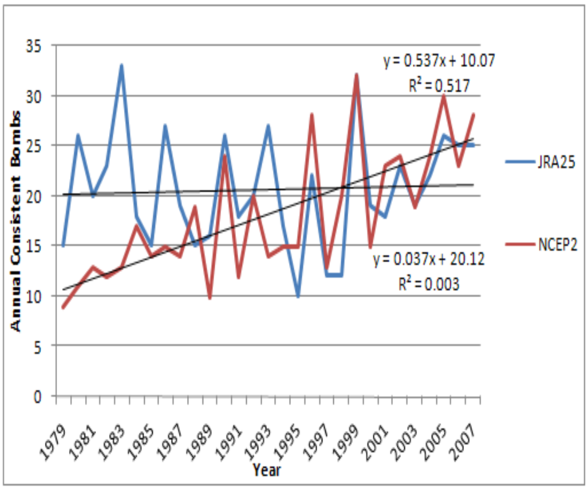

Figure 4: Trend analysis of the annual variability in number of consistent bombs for the JRA25 and NCEP2 reanalyses for the Southern hemisphere. Trend lines are based on least squares method, with the equation and R^2 above the lines describing the NCEP2 reanalysis trend, and that below describing the JRA25.

As noted for the relative bomb trends, the NCEP2 indicates a positive trend with a high degree of significance in the number of SH consistent systems. In contrast, little trend is evident from the JRA25 data, while the previously noted difference between the reanalyses is evident (20 systems).

4. DISCUSSION

The difference between the trends indicated using the NDR_c condition and both the relative and consistent bombs suggests that the differences in definition play a significant role. The increase in the number of systems identified using the NDR_c criteria indicates that pressure decreases of 1B are becoming more common. The lack of significant trend displayed in the JRA25, and the lesser trend in the NCEP2 for both the relative and consistent criteria suggests that there is no corresponding increase in the number of climatologically significant systems. Thus a hypothesis can be formed that the inherent difference between these criteria is changing, suggesting that the climatological pressure gradient in the SH may be changing, which may reflect a changing climate. Such a conclusion has significant implications for the use of reanalysis data, and further investigation using other reanalyses such as the ERA-Interim are required. In summary it appears that the trends evident in inter-annual variability of consistent (and relative) bombs may have important applications in reviewing the understanding of the climatological pressure gradient.

5. SUMMARY

The JRA reanalysis and automated cyclone tracking have been used to produce a detailed climatology of bomb cyclone developments based on a range criteria for both seasonal and annual periods. This has updated and advanced the earlier work of LS02 including the use of the new JRA25 dataset. Expansions of the domain for which bomb systems occur appear to have played a significant role, and this suggests that hybrid systems and transitioning tropical systems may require consideration in the SH bomb population. The application of a new consistent bomb criterion which is defined as a 24hPa drop accounting for change of latitude in both central pressure and relative to the climatological pressure gradient is applied for the first time in this study. This criterion is used to examine the relative bomb criteria and indicated that the NDR_c condition did not always identify systems which met the rapid intensification of central pressure. Further study of the trends associated with the number of systems and the impacts of using the consistent bomb criteria for various reanalyses together with additional data from the Northern Hemisphere will be undertaken in the near future.

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