Investigating the Use of a Genesis Potential Index for Tropical Cyclones in the North Atlantic Basin

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ABSTRACT

Large-scale environmental variables known to be linked to the formation of tropical cyclones have previously been used to develop empirical indices as proxies for assessing cyclone frequency from large-scale analyses or model simulations. Here the authors examine the ability of two recent indices, the genesis potential (GP) and the genesis potential index, to reproduce observed North Atlantic cyclone annual frequency variations and trends. These skillfully estimate the mean seasonal variation of observed cyclones, but they struggle with reproducing interannual frequency variability and change. Examination of the independent contributions by the four terms that make up the indices finds that potential intensity and shear have significant skill, while moisture and vorticity either do not contribute to or degrade the indices’ capacity to reproduce observed interannual variability. It is also found that for assessing basinwide cyclone frequency, averaging indices over the whole basin is less skillful than its application to the general area off the coast of Africa broadly covering the main development region (MDR).

These results point to a revised index, the cyclone genesis index (CGI), which comprises only potential intensity and vertical shear. Application of the CGI averaged over the MDR demonstrates high and significant skill at reproducing interannual variations and trends in all-basin cyclones across both reanalyses. The CGI also provides a more accurate reproduction of seasonal variations than the original GP. Future work applying the CGI to other tropical cyclone basins and to the downscaling of relatively course climate simulations is briefly addressed.

1. Introduction

Improving our understanding of the variability of tropical cyclones is important both scientifically and socially, and this becomes more important in a changing climate. With increasing computer power, global and regional climate models are approaching the capacity to reproduce the mesoscale processes occurring in cyclogenesis (Bender et al. 2010; Bengtsson et al. 2007; Gualdi et al. 2008; Knutson et al. 2007, 2008; Oouchi et al. 2006; Smith et al. 2010; Sugi et al. 2002; Zhao et al. 2009). These dynamical models bring in-depth perspective and understanding to the problem but remain expensive and therefore limited in their use. An alternative approach to downscaling tropical cyclone activity involves embedding a 2D hurricane model with ocean interaction into a statistical representation of the large-scale fields (Emanuel et al. 2008). This hybrid statistical–dynamical approach is cheaper to run and has been shown to have skill at reproducing observed tropical cyclone activity (Emanuel et al. 2008). Another alternative discussed here is that of statistical downscaling using empirical relationships.

That the large-scale environment has a role in determining tropical cyclone genesis has been understood since the earliest analyses of the association between cyclones and the general circulation in the tropics (e.g., Palmén 1948; Riehl 1954). Gray (1979) summarized the state of science and demonstrated the potential for assessing genesis potential (GP) utilizing such environmental parameters as ocean thermal content [strictly to a depth of ~60 m to account for ocean mixing by the cyclone, but often sea surface temperature (SST) is used as a proxy], midlevel moisture, a conditionally unstable atmosphere, low-level vorticity, and vertical wind shear through a deep atmospheric layer. It is notable that Gray considered these to be necessary but not sufficient conditions for genesis to occur; nevertheless, a number of subsequent studies have either utilized the Gray parameters
directly in assessing cyclone frequency from analyzed or modeled fields (e.g., Ryan et al. 1992; Watterson et al. 1995) or as a basis for further genesis indices based on the same physical principles (e.g., Emanuel and Nolan 2004).

Emanuel and Nolan (2004; see also Emanuel et al. 2006) used a statistical fitting procedure, based on the seasonal cycle and spatial variation of the mean genesis climatology of the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) Reanalysis Project (NNRP) data (Kalnay et al. 1996) to develop the following refinement of Gray’s genesis parameters into a new genesis potential (GP) index:

\[
GP = |10^5 \eta^{3/2} \left( \frac{RH}{50} \right)^3 \left( \frac{PI}{70} \right)^3 (1 + 0.1 V_{\text{shear}})^{-2}, \tag{1}
\]

where \(\eta\) is absolute vorticity (s\(^{-1}\)) at 850 hPa, RH is relative humidity (%) at 700 hPa, PI is the potential intensity (m s\(^{-1}\); Emanuel 1995), and \(V_{\text{shear}}\) is the vertical wind shear (m s\(^{-1}\)) between 850 and 200 hPa. The normalizing factors render the index dimensionless and the values were selected to keep the individual terms within the same order of magnitude.

Since the GP index was formulated from a number of environmental variables that are known to be associated with tropical cyclone formation (e.g., Gray 1968, 1979), it is reasonable to argue that it would be suitable for use as a predictor in both current and future climate studies. Several studies have examined this approach: Emanuel and Nolan (2004) demonstrated skill with the GP in reproducing the hemispheric seasonal variations in the observed frequency of tropical cyclone genesis; Nolan et al. (2006) investigated hurricane formation under global warming conditions from the GP perspective; and Camargo et al. (2007a,b) and Murakami and Wang (2010) used the GP to assess tropical cyclone genesis in global climate models.

Emanuel and Nolan (2004) developed the GP to reproduce the hemispheric seasonal variations in observed tropical cyclone frequency only. They did not examine its ability to capture interannual variability, nor did they test the GP’s skill in individual basins. Camargo et al. (2007a) showed that the GP has some skill in reproducing El Niño and La Niña impacts on observed annual frequency and location of genesis in several basins.

In recent years Emanuel (2010), Tippett et al. (2011), and McGauley and Nolan (2011) investigated improved generalized GP indices. Emanuel (2010) suggested that the genesis index should not depend directly on relative humidity, but rather on the midlevel saturation deficit. His new index comprises absolute vorticity, potential intensity, shear, and a measure of the moist entropy deficit of the middle troposphere, as discussed further in section 4. Tippett et al. (2011) evaluated the use of a clipped absolute vorticity term and concluded that increased vorticity beyond a defined minimum value does not increase the likelihood of cyclogenesis. They also considered satellite-observed column-integrated relative humidity, SST anomaly relative to the global tropics, and shear, and they suggested prudence with regard to the use of relative humidity. McGauley and Nolan (2011) took the approach of using only threshold values in an index that checked for the fraction of time that thresholds for PI, vorticity, shear, and saturation deficit are exceeded locally. Genesis potential is then derived from the product of these fractional exceedance values.

Our overall goal is to utilize the genesis parameter approach for assessing potential future climate variations and trends in tropical cyclones directly from the data available from coarse-resolution climate models. In this preliminary study we first assess the capacity of the GP and each of its components [Eq. (1)] to describe interannual and longer-term tropical cyclone variations and trends in the North Atlantic when applied to reanalysis data. Based on this assessment we develop a revised genesis parameter that utilizes fewer predictors and is applied to a selected region of the basin. This is shown to provide an improved downscaling to observed climatological tropical cyclone variability compared to the GP. Section 2 describes our method and data used; the index is developed using North Atlantic data in section 3; and a preliminary assessment of its global uses, together with a comparison with the Emanuel (2010) index and some discussion of limitations, is presented in section 4.

## 2. Data and method

### a. Data

We use two reanalysis products: the NNRP (Kalnay et al. 1996) and the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA; Uppala et al. 2005; Simmons et al. 2006). The base data are in 6-h intervals and these are averaged over a range of spatial scales for the period August–October (ASO) to represent the broad climate variability. Monthly averages are used for the analysis of intraseasonal variation. Tropical cyclone observations are taken from the International Best Track Archive for Climate Stewardship (IBTrACS; Knapp et al. 2010), also at 6-h intervals.

The NNRP analysis archive covers the period from 1948 to present and can be divided into three periods corresponding to the evolution of the major observing systems: the early years from 1948 to 1957, when very few upper-air observations were made; the rawinsonde era from 1958 to 1978; and the satellite era from 1979 to 2010.
the present day. Data deficiencies in the early years made the analyses demonstrably less reliable compared to later years (Kistler et al. 2001; Emanuel 2010) and this was also a period of questionable tropical cyclone data (e.g., Knutson et al. 2010). Thus we have restricted our analysis to the years 1960–2009, a period of reasonable data quality that is also sufficiently long to enable a robust climate variability analysis.

The ERA data cover two overlapping analysis periods: the 40-yr ERA (ERA-40) from 1958 to 2001 (Uppala et al. 2005) and the interim ERA (ERA-Interim) from 1989 to 2009 (Simmons et al. 2006). ERA-40 was produced using 3D variational analysis on a roughly 125-km grid, whereas ERA-Interim uses a 4D variational analysis on a roughly 80-km grid. Nevertheless, we consider these to be sufficiently similar to enable merging to a continuous set from 1960 to 2009. In doing this, we arbitrarily spliced the analysis series together at 1997. We also note that the GP was developed entirely on NNRP data, so the ERA provides an independent model and analysis approach, albeit one that is based on the same basic observations.

The atmospheric differences between NNRP and ERA are generally small. Studies comparing them with observations (Mooney et al. 2011; Davey et al. 2008; Chase et al. 2000; Chelliah and Ropelewski 2000) concluded that the average reanalysis trends generally fall within the variance in observational trends. One exception is relative humidity: Daoud et al. (2009) reported unrealistic low-level relative humidity in the ERA-40 but not the NNRP; comparisons among NNRP, ERA-40, and observations also showed markedly different behavior for extreme relative humidity values, with ERA-40 poorly correlated with observations. These inconsistencies are shown to introduce large GP errors in section 3.

In summary, both NNRP and ERA are considered suitable for climate variability and trend analysis and both are similar in character. There are some quality issues and those of importance are addressed in the analysis.

For the purposes of this study, the tropical cyclone data since 1960 are considered to be of good quality and free of major observational bias (e.g., Holland and Webster 2007). A recent study (Landsea et al. 2010) suggested that the upsurge in cyclone activity from 1995 might be due to changing observing practices that now identify a larger number of short-lived tropical cyclones. This finding is controversial and we present evidence that it is incorrect in section 4.

b. Method

Four regions are used in assessing the GP, as shown in Fig. 1: the North Atlantic (American to African coast; 0°–40°N), the main development region (MDR; 10°–20°N, 60°–15°W), an extended MDR (EMDR; 5°–20°N, 60°–15°W), and the Gulf of Mexico (GOM; 17.5°–32.5°N, 100°–80°W). The reasoning behind selection of the subregions is as follows.

The MDR has been shown in a number of studies to be important in the differentiation of long-period tropical cyclone variability across the whole basin and in seasonal forecasting techniques (e.g., Gray 1984a,b; Elsner et al. 2006; Klotzbach 2011). Vimont and Kossin (2007) and Kossin and Vimont (2007) provided strong evidence that the local changes in the MDR region correspond to changes in the Atlantic meridional mode (e.g., Nobre and Shukla 1996; Chiang and Vimont 2004). This provides a further association with a number of other environmental changes known to affect tropical cyclone variability in the North Atlantic. The MDR is also a region of potentially increasing importance with climate change as there has been a migration of cyclone developments to this region in the past couple of decades and models indicate a continuation of this migration in the future (Holland and Webster 2007; Holland et al. 2010; Done et al. 2011a). This migration is potentially associated with the expansion of the Atlantic oceanic warm pool toward Africa (Webster et al. 2005).

Emanuel (2005, 2007) extended the MDR to 6°–18°N, 60°–15°W, similar to our EMDR, for his power dissipation analysis. Power dissipation relates frequency, duration, and intensity into a single seasonal activity parameter, which Emanuel showed to be highly correlated with EMDR SSTs.

The Gulf of Mexico was chosen as the region of highest GP (see section 3) with values well above those in other parts of the basin. It is also the region most affected by intraseasonal variations (Maloney and Hartmann 2000), which could be a contributor to interannual variations.

We considered other potential processes in addition to those encapsulated in Eq. (1): in situ SST, which is included in the PI but examined separately for completeness; relative SST (the difference between Atlantic
and global tropical SSTs; Vecchi and Soden 2007); low and high atmospheric-level vertical wind shear; low- and midlevel temperature, relative humidity, and water vapor; and midlevel moisture saturation deficit (Emanuel 2010; Rappin et al. 2010). Of these, the only terms to show any potential as predictors were in situ and relative SST. In situ SST is a quite good predictor [in agreement with Tippett et al. (2011)] and is already included in the PI. Relative SST provided a good discriminator, in agreement with earlier findings (Vecchi and Soden 2007), but the in situ SST provided a better predictor, and the cyclone-frequency relationship with relative SST largely disappeared when the in situ SST linear correlation was removed. This is a different finding from that of Vecchi and Soden (2007), who suggested that relative SSTs were more important; we are examining this difference in a separate study.

The in situ SST provided nearly the same level of skill as PI for past climate and we suggest that this is a valid substitute for earlier periods when atmospheric information is lacking. We do consider that the atmospheric contribution may become more important for future climate assessments, where there are substantial changes in atmospheric as well as oceanic conditions (Pachauri et al. 2007).

To test the contributions of the genesis parameters as predictors of storm frequency, linear correlations were calculated and tested for significance using a standard two-sided t test.

3. Use of genesis parameters as a proxy for current and past North Atlantic tropical cyclone climatology

a. Application of the full GP

The GP averaged over the entire North Atlantic basin skillfully reproduces the seasonal variation of monthly-mean cyclone frequency (Fig. 2) with $R^2 = 0.87$ for NNRP and $R^2 = 0.95$ for ERA, both at 99% significance level. This is an expected result, as the GP was originally developed for this purpose (Emanuel and Nolan 2004). However, as shown in Fig. 3, the basin-average ASO GP provides a poor predictor of climate variability in observed annual tropical cyclone frequency ($R^2 = 0.21$). The skill is particularly poor before 1975 and there is a wide difference between the two reanalyses, with neither providing a good assessment of the observed cyclone frequency variations or trend. We suggest that there are two major contributors to this lack of relationship: reanalysis errors and large intrabasin variations and inconsistencies in the GP. The reanalysis errors are discussed in relation to the component terms of the GP in section 3b.

The intrabasin variations and inconsistencies in the GP are obvious from Fig. 4, which shows GP values overlaid with genesis locations. Of the local GP values across the basin, 75% are less than one (Fig. 5a), whereas the Gulf of Mexico has GP consistently >6 and occasionally much higher (Fig. 4). Yet the GOM only produces ~20% of the basin cyclones and the maxima in observed genesis frequency are in the eastern tropical Atlantic and off the U.S. east coast, both areas of relatively lower GP values. Thus, proportionally small changes in GP over the GOM may dominate the overall basin average without being associated with a concomitant change in overall genesis frequency.

Kossin and Camargo (2009) noted that the PI along the actual cyclone track was a better indicator of cyclone
intensity than aerial averages. A similar comparison for GP values at actual genesis locations (Fig. 5b) indicates that these values are normally <5, with values of 2–3 being most common. This is even more noticeable when GOM storms are excluded from the analysis (Fig. 5b, gray line).

We thus suggest that skewing of basin-averaged GP by the small area of extreme values in the GOM, combined with the smoothing provided by the large number of GP values less than one, is a major contributor to the lack of a solid relationship between basinwide average GP and annual tropical cyclone frequency in Fig. 3. This is examined further in relation to the individual GP components in section 3b. It also provides one explanation for the finding by Emanuel (2010) that the application of a genesis parameter improved substantially as the scale of the domain of averaging was decreased.

For climate prediction applications it is not feasible to calculate GP at genesis locations, but we can utilize subregions of the most common genesis frequency (Fig. 1; for completeness, a basinwide GP average that excludes the GOM is also included). For each region we compare ASO GP with tropical cyclone annual frequencies for all storms, for storms forming within the MDR or EMDR regions, and for storms moving through the GOM, MDR, or EMDR regions at some point (Table 1).

Clearly, averaging the GP over smaller domains is an improvement on the basinwide average. Comparing domains, the MDR and EMDR regions overall have the highest relationship regardless of storm family and explain 35%–45% of the observed North Atlantic frequency. This improvement is partly due to the MDR–EMDR GP picking up the overall increases in cyclone frequency since 1995 (Fig. 6), a not surprising result as the bulk of this has occurred through increased equatorial developments (Kimberlain and Elsner 1998; Holland and Webster 2007). However, both the EMDR and MDR provide an improved ability to estimate all basin storms over those that just form within the EMDR–MDR region. This implies some downstream impact of favorable conditions in this area, as discussed further in section 4.

There are also examples of substantial differences between the reanalysis sets; for example, GOM storms relate poorly to GOM GP in NNRP, but quite well in ERA. However, the subtleties of the differences across Table 1 are not discussed further here, as the overall results are intended as a benchmark against which we can compare both the individual terms in Eq. (1) (section 3b) and the revised index (section 3c). Reanalysis differences are also discussed further in section 3b.
b. Contributions by each term in the GP

The contributions of the individual terms in Eq. (1), and their products, to explaining storm frequency variations are shown in Table 2 and Fig. 7. For simplicity, we limited Table 2 to just the whole basin and EMDR, as these provided the greatest clarity of comparison.

It is clear that the relative humidity and vorticity terms do not exhibit an association with annual variations in tropical cyclone frequency. The relative humidity term alone has a negative correlation and explains essentially no variance. PI, vertical shear, or their product, explains substantially higher variance in observed annual frequency, and this is significant for all except the basin-wide ERA reanalysis. Thus, variations in the EMDR, specifically PI and shear, dominate tropical cyclone development across the basin, a curious result since both are normally associated with in situ development and intensification rather than the remote association found here (e.g., Kossin and Camargo 2009); possible reasons are discussed in section 4.

The lack of a vorticity relationship is consistent with the finding of Tippett et al. (2011) that increases in the value of absolute vorticity beyond a threshold minimum do not increase the probability of tropical cyclone genesis. That the main role of vorticity is as a limiting factor is consistent with its original inclusion by Gray (1968) based on observations that tropical cyclones do not generally form close to the equator.

The lack of a RH signal also agrees with the findings of Tippett et al. (2011) but appears to be in conflict with other studies that have found a strong relationship (e.g., Gray 1968, 1979; Cheung 2004; Emanuel and Nolan 2004; Emanuel 2010). There are obvious detrimental impacts of very dry air on the ability of deep convection
to develop, and if convection develops on the associated development of cool downdrafts that limit the available boundary layer thermodynamic energy (e.g., Emanuel 1993; Tang and Emanuel 2010). But do these impacts carry over to the interannual variations that are of interest to our study? We suggest not, and we further suggest that the varying findings on the importance of RH arise largely from the differing applications being investigated.

For example, Gray (1968, 1979) and Emanuel and Nolan (2004) were focused on the intraseasonal variation in tropical cyclone formation. There is an obvious

<table>
<thead>
<tr>
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<th>NNRP</th>
<th>EMDR</th>
<th>ERA</th>
<th>EMDR</th>
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</thead>
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<tr>
<td>GP</td>
<td>0.21** (0.29**)</td>
<td>0.27** (0.46**)</td>
<td>0.32** (0.52**)</td>
<td>0.35** (0.44**)</td>
</tr>
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<tr>
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<td>0.40** (0.59**)</td>
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<td>0.01 (0.04)</td>
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<td>0.29** (0.58**)</td>
<td>0.35** (0.69**)</td>
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<tr>
<td>vp</td>
<td>0.05 (0.18**)</td>
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<td>0.11* (0.41**)</td>
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<tr>
<td>vs</td>
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<td>0.00 (0.02)</td>
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<tr>
<td>s</td>
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<td>0.03 (0.00)</td>
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* 95% significance.
** 99% significance.

Fig. 7. A 5-yr running mean of observed annual cyclone frequency (black) together with that estimated by individual ASO GP components—(a) absolute vorticity, (b) relative humidity, (c) potential intensity, and (d) shear—for the NNRP EMDR (red).
and large change as relatively dry winter conditions change over to the moister conditions that prevail during the tropical cyclone season (e.g., Emanuel and Nolan 2004; Cheung 2004; Tippett et al. 2011). We have demonstrated that these large seasonal relationships do not carry over into interannual variations, where the RH changes are much smaller.

The poor interannual relationship cannot be attributed to the RH and vorticity terms as these are simply too small to emerge above the reanalysis noise. As is clear from Fig. 7, the RH term is essentially constant throughout the entire period and there is no relationship with tropical cyclone frequency on any time scale, either interannual or decadal. The vorticity is also very flat, although there could be a weak decadal relationship.

One alternative interpretation for RH is that there is a minimum threshold required to enable sustained deep convection within the incipient disturbances that may become a tropical cyclone. The required moistening of the atmosphere to enable cyclogenesis can then follow in the protected Lagrangian volume where regular convective processes moisten the atmosphere to levels well above the local climatological norm (e.g., Dunkerton et al. 2009). This view is supported by Rappin et al. (2010), who examined the time to genesis in a modeling study using an atmosphere in radiative–convective equilibrium. They found essentially no relationship with either vorticity or midlevel RH, in agreement with our findings. However, there is a strong negative relationship between the time to genesis and PI. This implies that weak precyclone disturbances have a higher chance of development before coming into contact with a region hostile to development. Since PI is highly dependent on SST, it also follows that this is indicative of a more rapid moistening of the Lagrangian environment, also aiding cyclone development.

The use of thresholds as the basis of a genesis parameter has been comprehensively examined by McGauley and Nolan (2011) and will not be examined further here. Rather, we acknowledge that this and previous studies point toward both vorticity and RH being a threshold requirement above which there is little relationship with cyclogenesis, and for which there is essentially zero interannual signal. This leads in the next section to the development of a revised, simplified cyclone genesis index (CGI).

c. A revised cyclone genesis index

Removing vorticity and RH from Eq. (1) gives

\[ \text{CGI} = \left( \frac{\text{PI}}{70} \right)^3 \left[ 1 + 0.1(V_{\text{shear}}) \right]^{-2}. \]  

The CGI is dimensionless and can be converted to cyclone frequency by matching the means of the CGI with the mean annual cyclone count over a defined base period.

As shown in Table 2, line 6, (set apart by the extra spacing), this index explains the greatest variance \( R^2 = 0.83 \) for smoothed annual tropical cyclone frequency of all combinations of the factors in Eq. (1).

However, the implicit assumption in the GP that the contribution from vertical shear is maximized at \( V_{\text{shear}} = 0 \) may not be correct. For Rossby-mode waves the vertical wavenumber following a ray varies according to \( dm/dt = -k\partial U/\partial z \), where \( m \) and \( k \) are respectively the vertical and zonal wavenumbers, and \( U \) is the zonal wind (e.g., Lighthill 1978; Webster and Chang 1988; Done et al. 2011b). For westerly vertical shear \( (\partial U/\partial z < 0) \) wave energy can propagate upward and leak out of the shear layer, but for easterly shear the waves are evanescent and will tend to be trapped in the shear layer. Thus there is a potential asymmetry in the manner in which a disturbance will respond to shear: for easterly shear the trapping of wave energy may counterbalance the detrimental shearing effect, but they complement each other to the detriment of the cyclone for westerly shear. Adding to this asymmetry is the westerly vertical shear that is generated over a cyclone core by the beta effect (Holland 1983). This self-generated vertical shear may be counteracted by an opposite easterly shear in the environment (Ritchie and Frank 2007). From observations, Zheng et al. (2010) also confirmed that easterly shear has a lower effect on cyclone intensification than does westerly shear. To evaluate this potential asymmetry we add a new parameter \( a \) to the shearm term of Eq. (2); that is,

\[ \text{CGI} = \left( \frac{\text{PI}}{70} \right)^3 \left[ 1 + 0.1(V_{\text{shear}} + a) \right]^{-2}. \]  

We varied parameter \( a \) to examine if including the sign of the shear is important and found a small but clear relationship. Changing the maximum impact for the EMDR from westerly shear through to easterly shear by varying \( a \) from 5 to \(-5\) produces a steady increase of variance explained for annual cyclone frequency by \( \sim 8\% \) when shear alone is used. However, the dominance of the PI term means that this effect is minimal for the full CGI. This is an area that warrants further investigation, but for now we set \( a = 0 \) [i.e., defaulting back to Eq. (2)].

As shown in Fig. 8, for both reanalyses CGI reproduces realistic trend lines and very good assessments of decadal variations. The summary results in Table 3 indicate that,
overall, EMDR CGI explains 83% (NNRP) and 74% (ERA) of the observed smoothed interannual storm variance. The CGI applied to either the MDR or the EMDR also explains >50% of the variance regardless of which subset of years is selected. The best relationships are for the satellite era; however, when compared to the GP [Eq. (1)] there is less sensitivity to analysis errors in earlier years. For example, for the 5-yr smoothed NNRP EMDR, $R^2 = 0.92$, 0.83, and 0.81 for the periods since 1980, 1960, and 1950, respectively; this compares to 0.86, 0.29, and 0.15 for the basinwide GP. Unsmoothed annual frequencies also typically have $R^2 > 0.5$. Whether the reduction between smoothed and interannual correlations is due to factors from known relationships, such as ENSO, or to stochastic process requires further investigation.

As shown in Fig. 8, these correlations arise from both a trend across the period of analysis and a number of shorter-period variations. After removing the trend, CGI explains 65% of the smoothed variability (significant at 99%) and 38% of the unsmoothed variability (significant at 95%). This implies that CGI can be used both for analysis of long-term trends and for shorter period fluctuations.

Applying CGI to assessing seasonal changes in the monthly mean frequency of tropical cyclones also provides an improvement over the original GP (Fig. 9). The early season build-up, peak in September, and late season ramp-down are all improved, with the one outlier month being due to an underestimate of the August frequency.

### Table 3. Variance ($R^2$) in annual tropical cyclone frequency explained by ASO GP, for (top) NNRP and (bottom) ERA, with 5-yr running-mean variance in parentheses. The regions are shown in Fig. 1, bold indicates the highest $R^2$ in any given row, bold-italic indicates highest overall $R^2$ for each reanalysis. For simplicity, only $R^2$ values for the North Atlantic basin, MDR, and EMDR regions are shown.

<table>
<thead>
<tr>
<th></th>
<th>Annual TC frequency</th>
<th>Basin</th>
<th>MDR</th>
<th>EMDR</th>
</tr>
</thead>
<tbody>
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<td>NNRP</td>
<td>All storms in NA basin</td>
<td>0.34* (0.64**)</td>
<td>0.49** (0.72**)</td>
<td>0.52** (0.83**)</td>
</tr>
<tr>
<td></td>
<td>Storms that move through the GOM</td>
<td>0.22 (0.53**)</td>
<td>0.25** (0.56**)</td>
<td>0.29** (0.58**)</td>
</tr>
<tr>
<td></td>
<td>Number of storms forming in the MDR</td>
<td>0.15 (0.45*)</td>
<td>0.29** (0.56**)</td>
<td>0.27** (0.49**)</td>
</tr>
<tr>
<td></td>
<td>Number of storms forming in the EMDR</td>
<td>0.17 (0.48)</td>
<td>0.34** (0.58**)</td>
<td>0.32** (0.55**)</td>
</tr>
<tr>
<td></td>
<td>Number of storms that move through the MDR</td>
<td>0.21 (0.56*)</td>
<td>0.38** (0.66**)</td>
<td>0.37** (0.64**)</td>
</tr>
<tr>
<td></td>
<td>Number of storms that move through the EMDR</td>
<td>0.21 (0.56*)</td>
<td>0.38** (0.66**)</td>
<td>0.37** (0.64**)</td>
</tr>
<tr>
<td>ERA</td>
<td>All storms in NA basin</td>
<td>0.29** (0.56**)</td>
<td>0.41** (0.62**)</td>
<td>0.41** (0.74**)</td>
</tr>
<tr>
<td></td>
<td>Storms that move through the GOM</td>
<td>0.23** (0.58**)</td>
<td>0.23* (0.59**)</td>
<td>0.27** (0.66**)</td>
</tr>
<tr>
<td></td>
<td>Number of storms forming in the MDR</td>
<td>0.13* (0.40**)</td>
<td>0.25** (0.49**)</td>
<td>0.20** (0.41**)</td>
</tr>
<tr>
<td></td>
<td>Number of storms forming in the EMDR</td>
<td>0.14* (0.41*)</td>
<td>0.28** (0.49**)</td>
<td>0.25** (0.46**)</td>
</tr>
<tr>
<td></td>
<td>Number of storms that move through the MDR</td>
<td>0.20** (0.55**)</td>
<td>0.34** (0.61**)</td>
<td>0.30** (0.58**)</td>
</tr>
<tr>
<td></td>
<td>Number of storms that move through the EMDR</td>
<td>0.20** (0.55**)</td>
<td>0.34** (0.61**)</td>
<td>0.30** (0.58**)</td>
</tr>
</tbody>
</table>

* 95% significance.
** 99% significance.
Further, there is an interesting bifurcation in the CGI component relationships when the annual number of tropical cyclones exceeds 11 (Fig. 10). For both predicted and observed annual cyclone counts <11 there is little real relationship with either the CGI or its component terms. The PI, and thus CGI, predicts years with >11 cyclones very well, whereas the shear term relationship is nearly flat and contributes little to the overall variance explained.

Consistent with the original GP index [Eq. (1)], the revised CGI is developed from the product of the PI and shear terms. For completeness, we also tested alternative approaches. These included taking the sum of the PI and shear terms as well as using different exponents for each of the PI and shear terms. But none of these produced any significant change in skill.

A further evaluation can be made by comparing CGI with the Emanuel (2010) GPI:

\[ \text{GPI} = \eta^{3} \chi^{-4/3} \max[(\text{PI} - 35), 0]^{2} (25 + V_{\text{shear}})^{-4}, \quad (4) \]

where \( \chi \) is the moist entropy deficit in the middle atmosphere. The GPI has units of rate/unit area, so when it is normalized to fit the mean annual cyclone frequency it assumes the same basinwide frequency character as the CGI.

The GPI retains moisture and vorticity terms that were dropped in the CGI, and it has different normalizations and exponents for the PI and shear terms. Yet its reproduction of historical cyclone frequency on both interannual and decadal time scales is very close to that of the CGI (Fig. 11). Further, removing the moisture and vorticity parameters from GPI (notated as GPIx; dashed green line, Fig. 11) make essentially no difference to its capacity to predict interannual variations, which is consistent with our findings in section 3b.

The lack of real difference in reproducing historical annual cyclone frequency across diverse formulations clearly indicates that, while it is important to include PI and shear in any genesis index formulation, the precise nature of that combination is not particularly important. For historical consistency and parsimony, we opt to retain Eq. (2) as our genesis index.

b. Data quality

In section 2 we referred to the Landsea et al. (2010) study that suggested that the recent upsurge in tropical cyclone frequency in the North Atlantic was due to an anomalous increase in short-lived storms associated...
with improved observing and analysis systems. This is a marked change from a large number of other studies that concluded that the cyclone data have been quite reliable since 1970 (e.g., Owens and Landsea 2003; Chang and Guo 2007; Vecchi and Knutson 2008; Holland and Webster 2007). The close relationship among the CGI, GPI, and storm activity in Fig. 11 (see also Table 3) also argues for the increase being real, as was suggested earlier by Emanuel (2010). Here we note that neither the CGI nor the GPI was tuned to fit the annual cyclone frequency sequence, aside perhaps from some implicit tuning in the selection of averaging area.

That environmental changes occur in association with the observed increase in annual tropical cyclones is evidenced by changes in other cyclone characteristics, such as the marked shift toward more equatorial developments (Kimberlain and Elsner 1998; Holland and Webster 2007). Emanuel (2005) noted a very close relationship between annual power dissipation (which is influenced by frequency, intensity, and duration) and SST [which we have shown to be essentially the basis of the PI term in Eq. (2)]. Emanuel (2007) investigated the observed recent increases in power dissipation in the North Atlantic and concluded that they “strongly covary and are highly correlated with SST.” Knutson et al. (2007) and Chen and Lin (2011) also simulated the recent increases in tropical cyclones lasting >2 days using the GFDL model embedded in reanalysis and with internal nudging, indicating that recent tropical cyclone activity has responded to observed environmental changes.

Further checking reveals that the observed recent change in short-lived storms was mirrored by similar proportional changes in the remaining long-lived storms as is evident from Fig. 12. The only disproportionate change in short-lived tropical cyclones occurred between roughly 1950 and 1960. This was during the introduction of aircraft reconnaissance and we concur there is a strong case for this change to have arisen from observational and analysis changes. However, there has been no observable change in the proportion of short-lived tropical cyclones since 1970. The proportion of short-lived storms has remained relatively constant at ~20% of the total since 1970 and thus their numerical increase is consistent with the changes in CGI and GPI (Fig. 11).

Thus, assuming that short-lived tropical cyclones have increased as a result of observing and analysis changes requires an explanation for why the long-lived cyclones have also increased, and for why so many independent studies have found a real increase associated with observed environmental changes. Invoking Occam’s razor, the most likely explanation is that short-lived tropical cyclones have simply followed an overall real increase in all cyclones.

c. Global and climate change application

The CGI has demonstrated considerable skill in predicting interannual variations in North Atlantic cyclones, but a more stringent test will apply for application to other basins where widely different environments are found. This is a complex task, requiring careful attention to varying data quality and also an understanding of the appropriate subregions that are representative of the basin as a whole. The detailed results will be presented in a companion publication, but some preliminary comments can be made here. We constrain the analysis period to post-1975 because of significant data issues prior to the satellite era, and we normalize the CGI to the average annual global cyclone frequency for this period.

The CGI reproduces the global patterns of cyclone development reasonably well (Fig. 13). These patterns
are close to the observed, but the details are not always so. For example, the central Pacific has too many near-equatorial developments. Nevertheless, the CGI provides a better global assessment than does the GP. Similarly, GPIx (GPI after removal of the moisture and vorticity parameters) reproduces the global cyclone development patterns reasonably well. It is similar to the patterns seen for CGI and is an overall improvement over the patterns for the original GPI.

There is considerable variability in the capacity of CGI applied to different basins in reproducing annual variations and trends, with the Northern Hemisphere basins faring better than those in the Southern Hemisphere. This reflects our experience in the Atlantic where an all-basin average was quite poor at reproducing observed annual frequency. The variability across basins is similar to findings by Menkes et al. (2012), who showed that different indices tend to under- or overestimate different basins. The accuracy increases when specific subregions are selected, again similarly to the findings with the EMDR here, but a full discussion is beyond the scope of this study.

Emanuel (2010), Rappin et al. (2010), Korty et al. (2012), and Tang and Emanuel (2010) all argued that a saturation deficit, although relatively stable for current climates, may play a bigger role under climate change scenarios. We suggest caution with this assessment. While the climatological mean saturation deficit can be
expected to change with global warming, there is no
a priori reason to assume that this will impact cyclone
frequency in any significant way.
Both this climate change aspect and the global appli-
cability details will be reported in a separate publication.

5. Conclusions
Tropical cyclone genesis indices capture the major
environmental controls, or contributors, to cyclone
formation and reduce them to a single parameter that
can provide a valuable way of assessing cyclone changes
from large-scale analyses or model simulations. Our
overall motivation for examining such indices is to es-
build a solid parametric relationship that can be applied
to climate model output in assessing potential cyclone
changes associated with varying and changing future cli-
mate. Here we reported on the first phase to investigate
existing indices and developing a revised index.
Gray’s (1979) work established the benchmark for
those physical and dynamical processes contributing to
the necessary conditions for tropical cyclogenesis in the
first seasonal genesis parameter. His four main param-
eters of SST (or more correctly ocean thermal content),
vorticity, midlevel humidity, and vertical shear of the
wind have formed the basis for all subsequent applica-
tions and developments of genesis indices.

We first examine in detail a recent, widely used gen-
esis potential (GP) index developed by Emanuel and
Nolan [2004; our Eq. (1)], together with a recent re-
vision, the genesis potential index (GPI) developed by
Emanuel [2010; our Eq. (4)]. This examination included
the GP and GPI applicability to seasonal, interannual,
and longer-term cyclone frequency changes in the North
Atlantic. We find that the GP and GPI accurately re-
produce the variation of monthly cyclone frequency
throughout a composite of hurricane seasons, but that
they are far less suitable for interannual or longer-term
variations. There are several potential reasons for this:

- Part of the limitation lies in the choice or area over
which to average the indices. Averaging the whole
basin is a quite poor approach, largely because of the
marked variations in amplitude across the basin, and
we find that for the North Atlantic annual cyclone
frequencies taking the mean in the general area of the
Main Development Region (MDR) offers the best
choice.

- Another problem lies in the inclusion of midlevel
moisture and low-level vorticity as explicit predictors,
which we find to be quite poor predictors of interan-
nual or longer-term changes, adding either nothing or
negative skill to the GP and GPI. We concur with
Gray (1979) and more recent work by Tippett et al.
(2011) that these parameters are more of a necessary
condition in that they must lie in a specific range, but
beyond this they appear to add nothing to interannual
variations.

- The potential intensity (PI) provides the bulk of the
skill in predicting climate variations and trends in
North Atlantic annual cyclone frequency. Once the PI
relationship is removed, shear adds a small, but useful,
level of skill.

- Careful differentiation must be made between this cli-
matological finding and the importance of humidity and
shear in the immediate environment of the developing
tropical cyclone, where there does appear to be a strong
moisture and shear signal (e.g., Tang and Emanuel
2010).

Based on this analysis, we suggest a revised cyclone
genesis index [CGI; Eq. (2)], which is derived from the
GP but includes only potential intensity and vertical
wind shear as predictors, and which is best when applied
to a slight meridional extension of the MDR to assess
basinwide cyclone variability and change. In this con-
figuration, the CGI explains ~50% of the interannual
variance in North Atlantic cyclone frequency for NNRP
reanalysis (~40% for ERA); smoothing the series to re-
move El Niño variations increases these to ~80%
(NNRP) or ~75% (ERA). All are significant at 99%.
These results contain a combination of trend and shorter-
period variability. When the linear trend is removed the
CGI explains ~40% of the interannual variance at 95%
significance level or ~65% of the variance after appli-
cation of a 5-yr running mean (99% significance) when
using NNRP (similar for ERA). The CGI also provides
an improved fit to the monthly changes in cyclone fre-
quency throughout the season compared to the original
GP.

These strong relationships of CGI with annual cyclone
variability and trend point to the presence of a strong
forcing from the large-scale environment on cyclogen-
esis in agreement with Gray (1979). This does not rule
out the role of small scales and stochastic elements for
individual cyclone development (e.g., Holland 1995; Tang
and Emanuel 2010) but, when taken over long periods,
the large scales appear to dominate.

This first phase provides us with confidence that the
CGI can provide a robust way of assessing variations in
changes of tropical cyclone frequency from both re-
analyses and climate model simulations. The next stage
of the work will address the global use of the CGI and its
application to future climate scenarios. We provide some
initial indications here (e.g., Fig. 13) but the full details
will be reported in a follow-up publication.
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REFERENCES


