NOTES AND CORRESPONDENCE

The Combined Effects of Gulf Stream–Induced Baroclinicity and Upper-Level Vorticity on U.S. East Coast Extratropical Cyclogenesis

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ABSTRACT

The Atlantic Surface Cyclone Intensification Index (ASCII) is a forecast index that quantifies the strength of low-level baroclinicity in the coastal region of the Carolinas. It is based on the gradient between the coldest 24-h average air temperature at Cape Hatteras and Wilmington, North Carolina, and the temperature at the western boundary of the Gulf Stream. The resulting prestorm baroclinic index (PSBI) is used to forecast the probability that a cyclone in the domain will exhibit rapid cyclogenesis. The initial ASCII study covered the years 1982–90. This dataset was recently expanded to cover the years 1991–2002, which doubled the number of cyclone events in the sample. These additional data provide similar position and slope of the linear regression fits to the previous values, and explain as much as 30% of the variance in cyclone deepening rate.

Despite operational value, the neglect of upper-tropospheric forcing as a predictor in the original ASCII formulation precludes explanation of a large fraction of the deepening rate variance. Here, a modified index is derived in which an approximate measure of upper-level forcing is included. The 1991–2002 cyclone events were separated into bins of "strongly forced," "moderately forced," and "weakly forced" based on the strength of the nearest upstream maximum of 500-mb absolute vorticity associated with the surface low. This separation method reduced the scatter and further isolated the contributions of surface forcing versus upper-level forcing on extratropical cyclogenesis. Results of the combined upper-level index and surface PSBI demonstrate that as much as 74% of the deepening rate variance can be explained for cases with stronger upper-level forcing.

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1. Introduction

The coastal region offshore of the Carolinas and Virginia is known to be a favorable setting for the development of extratropical cyclones (ETCs; e.g., Zishka and Smith 1980; Sanders and Gyakum 1980). Cyclones that track northward along the East Coast of the United States can produce gale-force winds, heavy wintry precipitation, and coastal storm surges that result in severe beach erosion and major property damage. This region is favorable for cyclogenesis because of (i) its position adjacent to the warm waters of the Gulf Stream, and (ii) the frequent passage of mobile upper-tropospheric disturbances embedded within the upper jet stream. Extensive research has been conducted on the prestorm marine boundary layer and air–sea interactions associated with extratropical cyclones forming in this region (e.g., Bosart et al. 1972; Sanders and Gyakum 1980; Bosart 1981; Rogers and Bosart 1986; Kuo and Reed 1988; Grossman and Betts 1990; Holt and Raman 1990; Kuo and Low-Nam 1990; Reed et al. 1992; Reddy and Raman 1994).

Studies by Cione et al. (1993) and Cione et al. (1998) presented an index related to the magnitude of the lower-tropospheric baroclinicity associated with the western Gulf Stream boundary; this Atlantic Surface Cyclone Intensification Index (ASCII) has been used as objective guidance to compliment other forecasting tools for the prediction of coastal cyclone development. However, the original ASCII scheme did not include any measure of upper-tropospheric forcing. The objective of this study is to extend the original ASCII concept through the inclusion of an approximate measure of upper-tropospheric forcing, and by using a vastly expanded storm dataset.

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The mutual interaction of upper-tropospheric cyclonic disturbances and lower-tropospheric thermal gradients forms the basis of the Sutcliffe–Petterssen self-development paradigm for extratropical cyclones (e.g., Sutcliffe and Forsdyke 1950; Uccellini 1990). From a potential vorticity (PV) perspective, self-development can be described as the mutual amplification of counterpropagating thermal waves on the tropopause and lower boundary (e.g., Hoskins et al. 1985; Morgan and Nielsen-Gammon 1998). The strength of the interaction is determined not only by the characteristics of the boundary disturbances themselves, but is also related to the static stability of the intervening tropospheric air and to the character and strength of lower-tropospheric, diabatically generated PV maxima (e.g., Davis and Emanuel 1991; Davis et al. 1993; Stoelinga 1996). This framework provides a convenient dynamical interpretation for the role of the lower thermal gradient in cyclone growth rate.

The Gulf Stream's influence on the lower troposphere is a major factor in determining the nature of the cyclogenesis process. A climatological study investigating the relation between the atmospheric thermal gradient induced by the western Gulf Stream boundary and coastal cyclogenesis was conducted by Cione et al. (1993). This study demonstrated that approximately 30% of the variance in sea level deepening rate can be explained by quantifying the near-surface atmospheric thermal gradients. However, this study was not designed to account for variations in the strength of the upper-tropospheric cyclogenetic precursor disturbance. For example, Sanders (1986) found that a relatively simple measure of the strength of the upper-tropospheric precursor disturbance could explain as much as 75% of the variance in sea level deepening rate for "strong bombs." The 12 strong bomb cases, as defined by Sanders (1986), had a mean deepening rate of 24 mb in 12 h.

Within a hundred kilometers offshore of the North Carolina coast lies the Gulf Stream, which in the fall, winter, and spring months, has a sea surface temperature 12°–15°C warmer than that of the near-coastal waters. The distance of the Gulf Stream from the coast can fluctuate several kilometers in 24 h. These variations are caused by the lateral or cross-shelf meandering of the Gulf Stream front (GSF; e.g., Brooks and Bane 1978; Pietrafesa et al. 1978; Rooney et al. 1978; Pietrafesa et al. 1985). Large horizontal temperature gradients occur during winters off the mid-Atlantic coast because of the presence of the Gulf Stream with a sea surface temperature between 24° and 28°C. During the occurrence of coastal fronts and wintertime cold-air outbreaks, air temperatures in eastern North Carolina generally range from −5° to 5°C.

The Carolina coastal region is highly baroclinic in the marine boundary layer especially when the Gulf Stream is closer to the coast. The degree of marine boundary layer baroclinicity is related to the distance of the GSF to the coast. The enhanced baroclinic energy and reduced static stability can result in rapidly deepening winter cyclones (e.g., Bunker 1976; Chou et al. 1986; Kocin and Uccellini 1985a,b; Dirks et al. 1988; Raman and Riordan 1988; Kuo et al. 1991).

a. Atlantic Surface Cyclone Intensification Index

The ASCII is a forecast index that quantifies the amount of low-level baroclinicity off the coast of the Carolinas during a cold-air outbreak. ASCII is based on the gradient between the coldest 24-h average air temperature at the coast (T) during a cold-air outbreak and the temperature at the GSF (T_{GSF}). The resulting prestorm baroclinic index (PSBI) is

$$\text{PSBI} = \frac{T_{GSF} - T}{d}, \qquad (1)$$

where d is the distance of the GSF from the coast. The surface PSBI can be used to forecast the probability that a cyclone in the domain will exhibit rapid cyclogenesis.

The initial ASCII climatological study conducted by Cione et al. (1993) investigated winter coastal cyclonic events from 1982 to 1990 during the months November–April. The objective of their research was to investigate the potential effects of Gulf Stream induced low-level baroclinicity on cyclonic deepening within the U.S. mid-Atlantic coastal zone.

A measure of the low-level prestorm baroclinicity was obtained using the surface air temperatures at Wilmington and Cape Hatteras, North Carolina, and the corresponding Gulf Stream front SST east of these locations. It should be noted that Cione et al. (1993) assumed the surface air temperature over the Gulf Stream to be the same as the SST, and the SST was assumed to be constant over the 12-h observed deepening period for each storm.

Cione et al. (1993) show that the prestorm baroclinicity, which includes the prestorm GSF, sea surface temperature, and coastal air temperature, has a correlation coefficient of 0.56 with the sea level deepening rate of coastal cyclones. Results from this study reveal that both the thermal structure of the continental air mass and the position of the GSF, in relation to land, are linked to the rate of surface cyclonic intensification, and can explain as much as 32% of the storm deepening rate variance.

b. Upper-tropospheric forcing

It has long been known that upper-level divergence is required for surface cyclogenesis (e.g., Sutcliffe 1939; Bjerknes and Holmboe 1944), and that this divergence is associated with regions of cyclonic vorticity advection aloft. Although differential vorticity advection is the factor linked to cyclogenesis, if the low-level vorticity advection is assumed to be weak in the majority of cases, then the forcing is primarily a function of the strength of the upper-level vorticity advection. This assumption is considered to be valid for most, but not all cases, and is a foreseen limitation of cyclogenetic events with strong low-level vorticity advection. Sutcliffe (1947) shows that there is a strong correlation between the absolute vorticity advection at the 500-mb level and surface cyclogenesis. Climatological studies of rapid extratropical cyclogenesis verify that the magnitude of cyclonic vorticity advection downstream of a trough at the 500-mb level is highly correlated to the deepening rate of the surface cyclone (e.g., Sanders and Gyakum 1980; Sanders 1986, 1987; Kocin and Uccellini 1990; Uccellini 1990). Climatology of explosive cyclogenesis from 1981 to 1984 studied by Sanders (1986) included 48 storms stratified into three bins based on the surface cyclone's deepening rate. Results from the study by Sanders (1986) show that the mean 500-mb absolute vorticity advection associated with the surface cyclone averaged over 12 h versus the surface cyclone's 12-h deepening rate can explain as much as 75% of the deepening rate variance for cyclones with pressure falls greater than 1.9 mb h^{-1}. Sanders (1986) also concluded that the largest mean deepening rate of 24 mb in 12 h occurred while cyclones crossed a region of strong SST gradient associated with the GSF.

2. Data and methodology

A domain between 38°–32°N and 79°–72°W (Fig. 1) was used for this study, similar to the domain employed by Cione et al. (1993). Closed isobar circulations at sea level pressure were considered storm events. All East Coast winter storms during the months of October–April between 1991 and 2002 that remained within this region for a period exceeding 6 h were analyzed. Past storm data were obtained from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) 6-h reanalysis maps, which are archived on a 2.5° × 2.5° latitude–longitude grid (Kalnay et al. 1996). The 1.1-km SST data and maps were obtained from the National Oceanic and Atmospheric Administration (NOAA) Coastwatch program. Since these are single-pass images, if
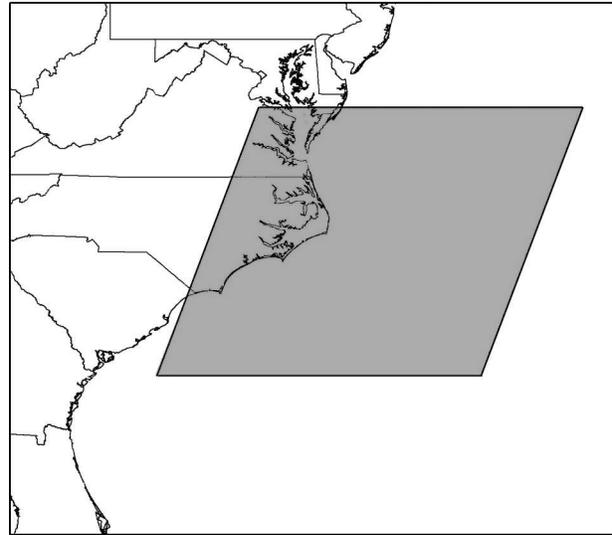
FIG. 1. Map of the southeastern United States. The domain used to study East Coast cyclogenesis or cyclone redevelopment using climatological data is shaded in gray.

the SST was less than 50% visible because of cloud cover, the first acceptable preceding pass was chosen. In most cases an acceptable image was obtained within the preceding 48 h. A limit of 7 days was imposed, but never needed, as the longest duration required for a particular case was 4 days. The imagery was then processed through an interpolation routine to filter out the remaining cloud cover. The air temperature data at the coastal stations were obtained at 3-h intervals through the State Climate Office of North Carolina.

Surface air temperatures recorded every 3 h were averaged over the coldest 24 h within a 48-h window preceding the storm for Cape Hatteras and Wilmington. This isolates the time with maximum low-level baroclinicity. The SSTs were assumed to be constant throughout the 24-h period over which surface air temperature was averaged. The horizontal air temperature gradient was computed using the location of the western edge of the GSF that was obtained via Advanced Very High Resolution Radiometer (AVHRR) imagery. The horizontal thermal gradient was then calculated using (1). Storm intensification was taken to be the 12-h surface central pressure decrease of any extratropical cyclone within the study area using the NCEP–NCAR reanalysis. Extratropical storms that began as tropical systems were not included in this study.

The 500-mb maximum absolute vorticity values were obtained from the same NCEP–NCAR reanalysis as those used for the surface data. The method for determining the maximum absolute vorticity value was based on the 12-h time window defined by the maximum

deepening rate of the surface low. During this 12-h period, three (0, 6, and 12 h) 500-mb vorticity fields, superimposed on sea level pressure, were analyzed for each storm event. During this period, the maximum value of absolute vorticity at the 500-mb level upstream of the surface disturbance was recorded. An upper limit of horizontal distance separation between the 500-mb absolute vorticity maximum and surface low center of 1000 km was imposed. However, in the majority of the cases, the associated absolute vorticity maximum was within 750 km. In rare cases where two maxima were located at the same distance (± 100 km), the stronger of the two was chosen.[1]

For this study, it is assumed, for operational simplicity, that the value of maximum vorticity at the 500-mb level is directly related to the 500-mb vorticity advection. However, the same criteria were applied to the selection of maximum positive vorticity advection (PVA) at the 500-mb level. The results obtained when maximum PVA was used in place of vorticity were similar to those obtained from the simpler vorticity classification, except that the former produced a much noisier signal, as well as inconsistencies in localized maxima. The complications related to grid resolution yielded a wide range of numerical values, thus making the binning procedure less accurate. In addition to these obstacles, multiple regions of equal PVA sharing the same horizontal displacement were linked to the surface low pressure during the 12-h selection window. This made for a more subjective process in identifying the most appropriate upper-level forcing. Therefore, the results presented below will be based on the vorticity classification.

3. Results

The extension of the ASCII dataset covered an additional 11 yr and 4 months (1991–2002) beyond the original Cione et al. (1993) study. This 20-yr climatology almost doubled the number of storms to 231. A linear regression of the (dependent) observed surface cyclone central pressure decrease for the 231 cyclonic events that occurred from 1982 to 2002 on the (independent) PSBI is shown in Fig. 2. These additional data provide similar position and slope of the linear regression fit verifying the previous threshold values defined

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[1] The authors chose this method for determining the maximum absolute vorticity value based on its simplicity within a future operational setting, but acknowledge that other measures of forcing, such as **Q**-vector convergence, or vorticity advection by thermal wind directly over the surface cyclone, would yield more accurate results.
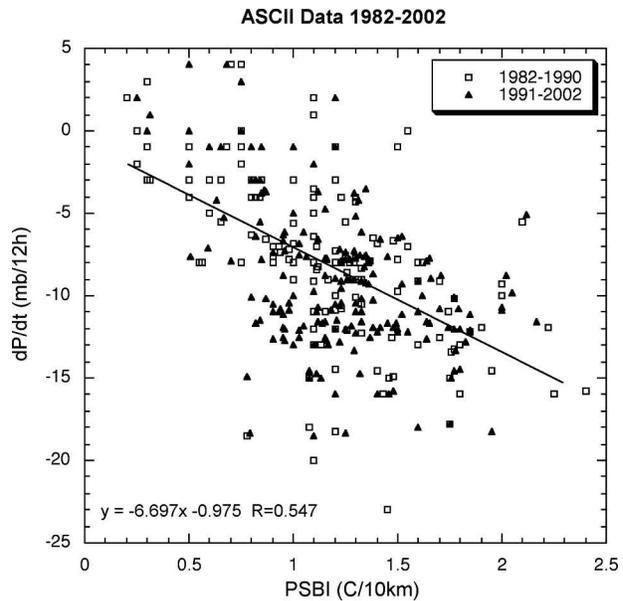
FIG. 2. The updated ASCII dataset (1982–2002) of ETC ΔP $(12 \text{ h})^{-1}$ vs PSBI. The linear regression fit combines both sets of storms (1982–90 and 1991–2002).

in the PSBI. The combined results from this study and the previous one by Cione et al. (1993) yield a regression coefficient (r) of 0.55 between the prestorm baroclinicity and storm development that explains 30% of the total deepening rate variance. The remaining 70% of the variance is assumed to be due to other contributing factors such as upper-level forcing.

One of the objectives of this study is to test the hypothesis that the unexplained variance (i.e., $1 - r^2$) observed in Fig. 2, is a result of other important contributing cyclogenetic processes such as variability in the strength of the upper-tropospheric forcing. Using the values of maximum absolute vorticity at the 500-mb level recorded for 111 out of the 115 cyclonic events (1991–2002), the storms were separated into three bins. The remaining four storms were not included due to missing data. The bins are defined by storms with 500-mb maximum absolute vorticity values equal to or greater than 19×10^{-5} s^{-1} or "strongly forced" (24 storms), values between 15×10^{-5} s^{-1} and 19×10^{-5} s^{-1} or "moderately forced" (44 storms), and values equal to or less than 15×10^{-5} s^{-1} or "weakly forced" (43 storms).

To objectively distribute the number of storms per bin, the span of absolute vorticity values covered by each bin are greater at both extremes. This was done by dividing the absolute vorticity of the dataset in half at the mean (17×10^{-5} s^{-1}), and setting the moderately forced bin limits to the mean of the upper half (19×10^{-5} s^{-1}), and the mean of the lower half (15×10^{-5} s^{-1}).

Thus, several storms with a maximum absolute vorticity greater than 15×10^{-5} s^{-1} and less than 19×10^{-5} s^{-1} fell in the moderately forced bin. Likewise, bins strongly forced and weakly forced were grouped by default because of the lack of storms with maximum absolute vorticity above 20×10^{-5} s^{-1}, and below 14×10^{-5} s^{-1}. By using the mean instead of the median, the strongly forced bin, albeit fewer cases, isolated the extreme rapid cyclogenic events from the more typical coastal storms.[2]

Linear regression fits were computed for each bin of the observed surface cyclone central pressure decrease for the 111 cyclonic events that occurred from 1991 to 2002 on the PSBI (Fig. 3). The slopes for the strongly forced, moderately forced, and weakly forced bins are -15.1, -10.3, and -6.1, respectively. Not only do the slopes of the regression fits decrease at a nearly linear rate as seen in Fig. 4, but the bins are found to be naturally stratified in the order of increasing vorticity. The correlation coefficients for the strongly forced, moderately forced, and weakly forced bins are 0.84, 0.86, and 0.59, respectively. For the moderately forced bin, the average deepening rate was 9 mb (12 h)$^{-1}$, accounting for 74% of the variance. The correlation coefficient for the strongly forced bin, which had an average deepening rate of 11 mb (12 h)$^{-1}$, was 0.84 explaining 71% of the variance. This was slightly lower than the correlation coefficient for the moderately forced storm bin, but considering there were half the number of storms, and of those storms many were extreme events, it is comparatively high. This suggests that for stronger cases, the deepening rate is more sensitive to changes in PSBI thus increasing the slope of the regression fit. For the weakly forced bin, where the average deepening rate was 7 mb (12 h)$^{-1}$, the correlation coefficient of 0.59 explaining 35% of the variance. This is likely related to the fact that weaker disturbances are more easily influenced by various other forcing mechanisms not accounted for in this study such as tilt, moist diabatic processes such as convection, and Gulf Stream front curvature, thus increasing the scatter. However, the correlation coefficients for all three bins are substantially higher than the nonbinned correlation coefficient of 0.55.

Predicted deepening rates for the events in the 1991–2002 dataset were calculated using the updated regression equation shown in Fig. 2. These predicted deepening rates are compared to the observed deepening rates for the 1991–2002 dataset in Fig. 5a. Figures 5b,c,d show
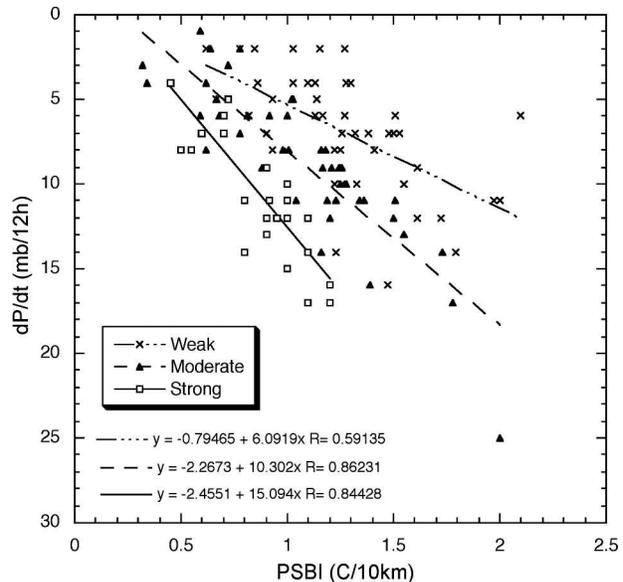
FIG. 3. The ASCII dataset (1991–2002) of ETC [ΔP (12 h)$^{-1}$ vs PSBI] broken down into bins of 500-mb vorticity (10^{-5} s^{-1}).

the same comparison stratified by bin. It is evident from Fig. 5d, that ASCII, based on PSBI alone, breaks down in cases where upper-level forcing is the primary influence. However, it is the forecasting of moderately forced cases, seen in Fig. 5c, where the ASCII provides the best fit to the observations. These findings verify the outcome of the binned regressions discussed above.
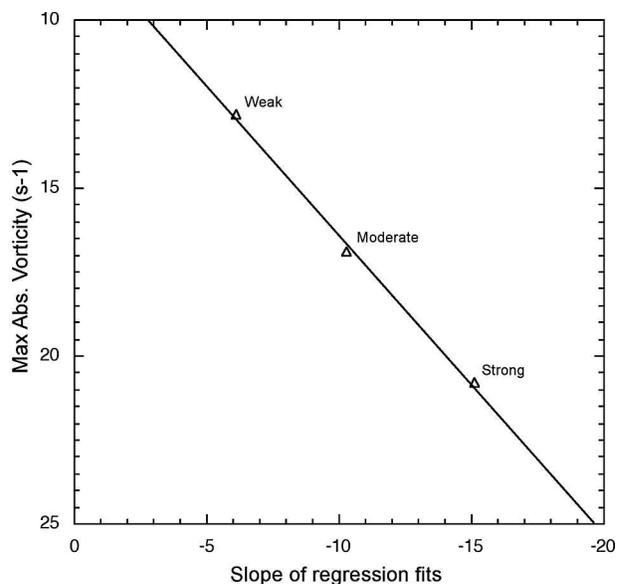
FIG. 4. The maximum absolute vorticities (s^{-1}, averaged for each bin) plotted against the corresponding slope of the linear regressions seen in Fig. 3.

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[2] Experiments with different binning strategies demonstrated that the results are not strongly sensitive to these choices.
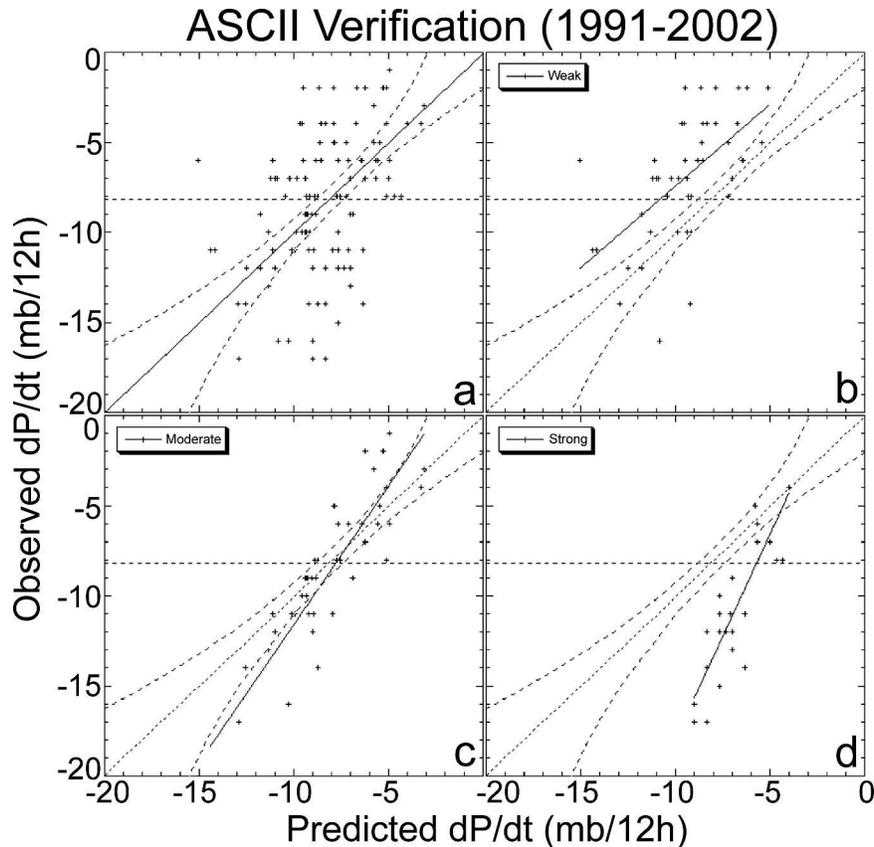
FIG. 5. The observed deepening rate $[\text{mb} \ (12 \ \text{h})^{-1}]$ of cases from the 1991–2002 dataset plotted against the predicted deepening rate $[\text{mb} \ (12 \ \text{h})^{-1}]$ from the updated ASCII regression equation seen in Fig. 2. The center line shows a perfect correlation bound on both sides by a 95% confidence interval calculated for the entire dataset. The horizontal line marks the mean deepening rate for the entire dataset. (a) The full distribution, as well as (b) the weakly forced, (c) moderately forced, and (d) strongly forced bins are shown.

Figures 5b (5d) also reveal a trend for ASCII to "over-predict" ("underpredict") the deepening rate of storms involving weak (strong) upper-level forcing. In other words, storms with greater upper-level cyclonic vorticity are characterized by more rapid deepening, regardless of PSBI.

The corrected predictions for the deepening rates using the separate regression equations of the respective bins are seen in Fig. 6. Since the entire 1991–2002 dataset (Fig. 6a) has the same regression, this prediction was unchanged. However, the weakly forced (Fig. 6b), moderately forced (Fig. 6c), and strongly forced (Fig. 6d) deepening rates are independently verified. Although the scatter within each bin is left mostly unchanged, the trend, discussed above, for ASCII to overpredict (underpredict) the deepening rate of storms involving weak (Fig. 6b) [strong (Fig. 6d)] upper-level forcing has been rectified by the use of the separate regression equations. The prediction improvements of

the moderately forced cases (Fig. 6c) are less substantial, although still noticeable, because this bin's separate regression equation is similar to the average of the entire dataset.

4. Conclusions

The objective of this study is to extend the original ASCII concept by incorporating an approximate measure of upper-tropospheric forcing. Inclusion of 11 yr and 4 months of data from 1991 to 2002 added 115 storms to the original 10 yr (116 storms) ASCII dataset compiled by Cione et al. (1993). Application of the same methods employed by Cione et al. (1993) for the first climatological study verified the original regression fit. The slope of the fit $[-6.7 \ \text{mb} \ (12 \ \text{h})^{-1}]$ was 0.1 mb $(12 \ \text{h})^{-1}$ less than that in the original study. The correlation coefficient of the new 231 storm dataset was 0.55. This decreased the explained variance by an insignifi-

ASCII Verification (1991-2002)
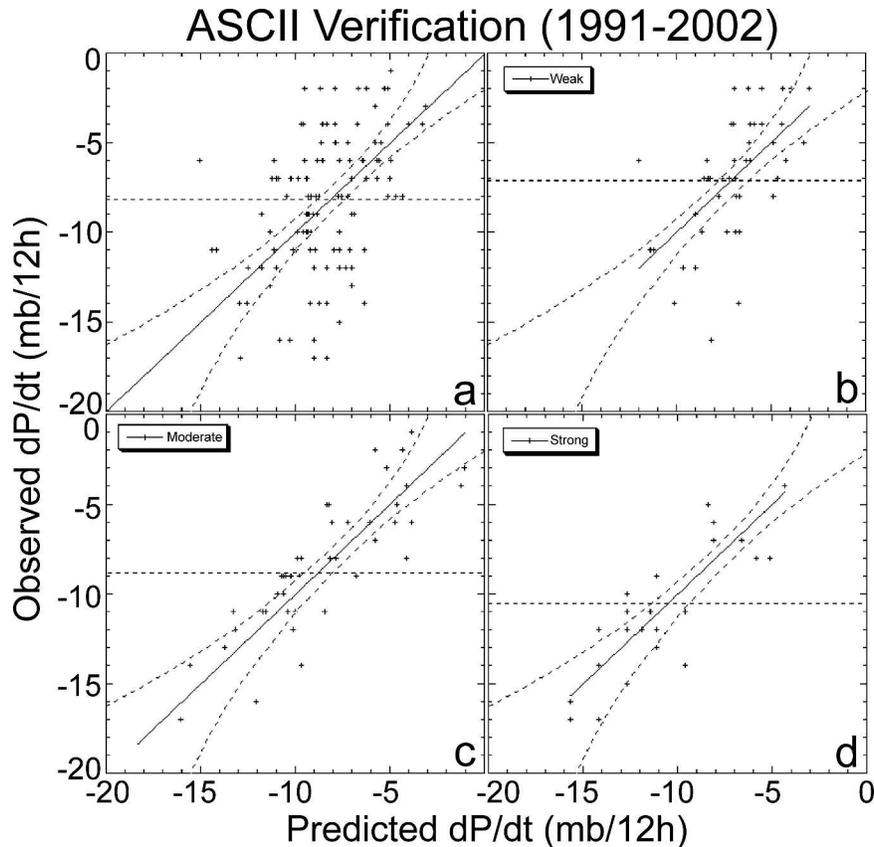
Fig. 6. Same as Fig. 5, but from the separate regression equations of the respective bins.

cant 1.7%. Doubling the size of the original ASCII dataset verifies threshold values defined in the PSBI by the statistically insignificant changes in the regression fit. However, the variance explained by the PSBI remains low, approximately 30%. In this study, we address a major limitation inherent in the original ASCII study by adding an approximate measure of upper-tropospheric forcing.

The additional grouping of storms within the 1991–2002 dataset based on 500-mb vorticity significantly reduced the scatter, and further isolated the contributions of surface forcing versus upper-level forcing on extratropical cyclogenesis. The decrease in slope for cases with less upper-level forcing, as well as the stratified bin positions, suggest that there is a shifting degree of dependency on lower-tropospheric forcing. Correlation coefficients for the "strongly forced," "moderately forced," and "weakly forced" storms are 0.84, 0.86, and 0.59, respectively. However, all these values are higher than the nonbinned correlation coefficient of 0.55. There is a definite trend for stronger correlation among the storms that are linked to larger upstream upper-level vorticity maxima, as demonstrated by the less sub-

stantial improvement in correlation for weakly forced storms. Additionally, as much as 74% of the variance can be explained for stronger upper-level forcing cases. This is a marked improvement over the 30% of explained variance from the original ASCII dataset, as well as the entire updated climatology.

Employment of the 500-mb vorticity parameter in an operational setting would require the analysis of 24–48-h 500-mb forecasted fields of absolute vorticity on a coarse grid (e.g., 2.5° × 2.5°) to ensure consistency with the current study, and to reduce noise. To determine the correct bin, an automated script can radially search for the region of maximum absolute vorticity. Following the binning procedure, the correct forecast regression fit of strongly forced, moderately forced, or weakly forced can be used to predict the deepening rate of the impending storm.

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