A Dynamical Approach to Seasonal Prediction of Atlantic Tropical Cyclone Activity

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ABSTRACT

Analysis of ECMWF reanalyses and operational analyses covering the period between 1979–98 has confirmed that seasonal Atlantic tropical cyclone activity is strongly and negatively correlated with the observed vertical wind shear present in the main development region (MDR) between July and September. In 1983 and 1995, the least active and most active tropical cyclone years, respectively, anomalous shear was shown to be present in spring and to persist throughout each of the tropical cyclone seasons. While monitoring of MDR shear is recommended for highlighting the risk of such extreme events, the springtime MDR shear is not generally a good indicator of shear in the summer months.

Seasonal forecasts of MDR shear made with the U.K. Met Office (UKMO) atmospheric GCM (AGCM) and observed SSTs for the years 1979–97 have been analyzed. The model possesses potential skill for predicting the MDR shear as determined by a consideration of the ensemble mean shear variability and an evaluation of the relative operating characteristics (ROC). The ROC analysis indicates high probabilistic skill, in particular for anomalously low shear events. Analysis of seasonal forecasts of MDR shear made with the UKMO AGCM with persisted SST anomalies for the years 1979–97 was also performed. Skill in predicting MDR shear is reduced but still significant. ROC analysis indicates probabilistic skill for the anomalously low shear events, which may be useful for some applications.

Based on this work, the authors conclude that a dynamical approach to the seasonal forecasting of Atlantic tropical cyclone activity, which combines predicted MDR shear with a statistical model should be developed.

1. Introduction

Most attempts at seasonal forecasting of tropical cyclones are purely statistically based (e.g., Gray et al. 1994) and have made no use of dynamical model outputs. In recent years, as the skill of dynamical forecast models has improved, there has been increased confidence and interest in a dynamical approach to seasonal forecasting of climate (e.g., Stockdale et al. 1998; Kerr 1998). While it is recognized that current dynamical models are often handicapped by systematic errors (e.g., Brankovic and Palmer 2000) and low skill of predicted sea surface temperatures (e.g., Landsea and Knaff 2000), it is important that forecast strategies are developed that make the best use of current skill and any enhanced skill that may arise from future improvements to the dynamical models. The present study considers how an atmospheric general circulation model (AGCM) could be used for the seasonal prediction of Atlantic tropical cyclone activity.

There are two main approaches for using AGCM outputs to predict seasonal tropical cyclone activity. The direct approach involves counting the number of tropical cyclonelike systems that the model simulates (e.g., Vitart et al. 1997; Bengtsson and Esch 1995). While this may seem an obvious approach to take, it assumes that AGCMs realistically represent the nature of tropical cyclones and their interactions with the environment. It is well known that many of the most important processes relating to tropical cyclone formation and to intensity change in reality occur at scales less than 50 km (e.g., Ooyama 1982; Montgomery and Kallenbach 1997; Schubert et al. 1999). Clearly, AGCMs currently being used for seasonal weather prediction, with horizontal grid lengths on the order of 200 km, cannot represent these processes as they occur in nature. The simulated tropical cyclonelike systems are weaker and larger than in reality and so it is unclear whether we should expect AGCMs to realistically represent the observed relationships between tropical cyclones and the large-scale environment known to be important for observed tropical cyclone variability (e.g., Gray 1984). It is intriguing, therefore, to see that some AGCMs do appear to simulate aspects of the observed tropical cyclone variability, as shown by Vitart et al. (1997).

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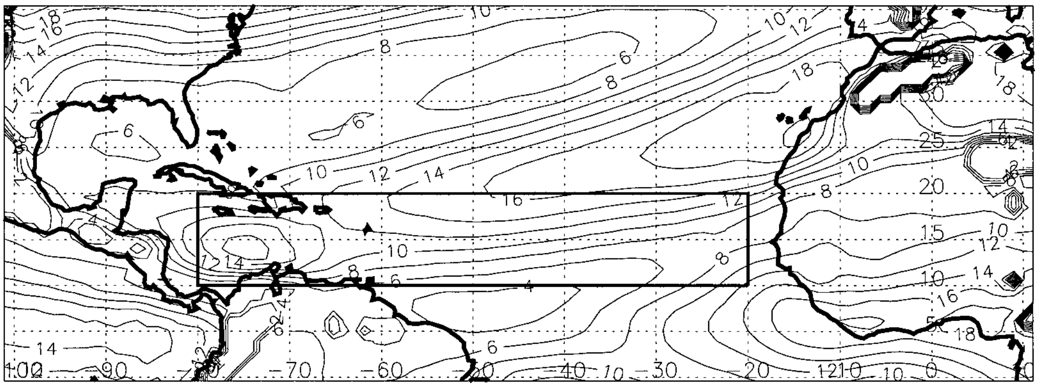

FIG. 1. Mean Jul-Sep vertical wind shear based on ECMWF reanalyses (1979–93) and operational ECMWF analyses (1994–98). The shear is calculated using the total wind difference between 200 and 925 mb. The boxed area represents the main development region (MDR), following Goldenberg and Shapiro (1996), which is used for area averaging in this paper.

The second approach, and that promoted here, is to focus on the dynamical prediction of large-scale environmental factors that are known to affect tropical cyclone activity (cf. Watterson et al. 1995). We should expect AGCMs to have more skill in predicting large-scale factors, especially when averaged in space and time, than in predicting the number of unresolved tropical cyclones. Two large-scale factors commonly used in statistical forecast models are the phase of El Niño and the west Sahelian rainfall since they have a known strong correlation with Atlantic tropical cyclone activity (e.g., Gray et al. 1994). These correlations have usually been interpreted in terms of the remote effects El Niño and west Sahelian rainfall have on the vertical shear in the tropical Atlantic (see Goldenberg and Shapiro 1996; henceforth GS). Anomalous diabatic heating, associated with anomalous overturning circulations, tends to increase the vertical shear in the tropical Atlantic during El Niño years and decrease it in wet west Sahel years (Shapiro 1987; Jones and Thorncroft 1998). Since it is the vertical shear in the tropical Atlantic that is thought to be of direct importance for determining the tropical cyclone activity, it forms the major focus of this study. It should be noted that Vitart et al. (1999, 2001) suggest that the skill exhibited by the AGCMs they considered, in simulating explicitly the interannual variability of tropical cyclones, arises mainly from a skillful simulation of the large-scale environment in which they form. This suggests that the simulated weak and large tropical cyclones interact with the large-scale environment in a similar way to the stronger and smaller observed tropical cyclones. This result gives further motivation for the need to assess predictability of the large-scale tropical Atlantic environment and to improve our understanding of the processes that affect the environment.

If it can be shown that an AGCM can provide skillful predictions of tropical Atlantic shear several months ahead; then this may, in turn, be used to predict tropical cyclone activity by combining this information with a statistical model. Motivated by this, we include in this paper an assessment of the predictability of tropical Atlantic shear in the U.K. Met Office Unified Model (Cullen 1993). The forecasts analyzed here used the same approach as that used for the European Union Prediction of Climate Variations on Seasonal and Interannual Timescales project (PROVOST; e.g., Graham et al. 2000). These were made using observed sea surface temperatures (SSTs) between 1979 and 1997 and will allow us to assess ‘‘potential skill’’ of the AGCM (see Pope et al. 2000 for more details).

This paper focuses on the July–September period since the PROVOST forecasts available for analysis were initiated at the end of May each year and were terminated at the end of September. The month of October was included in forecasts initiated at the end of August and terminated at the end of December. Since the July–September period climatologically encompasses much of the tropical cyclone activity (about 72% during 1979–96), this is not a major problem. Also, the number of tropical cyclones that formed in the main development region (MDR; as defined in Fig. 1) between 1979 and 1996 in June, July, August, September, and October was 1, 5, 29, 26, and 6, respectively, as determined from the National Hurricane Center best track data. Thus, 90% of the tropical cyclones that formed within the MDR in these years occurred between July and September, giving further relevance to the July–September period.

In section 2 of this paper we present analysis of the vertical shear variability based on the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis between 1979 and 1993 and ECMWF operational analyses between 1994 and 1998. This expands on the work of GS and also provides a verification dataset for comparison with dynamical forecasts. In section 3 we compare the analyzed seasonal mean vertical shear with the PROVOST forecasts.

The analysis of forecasts with observed SSTs gives us an assessment of potential skill, but does not tell us about the current skill levels of AGCMs in an operational sense. In order to assess the viability of using the U.K. Met Office (UKMO) AGCM to predict MDR shear in an operational sense, we consider in section 4 forecasts made for the same years but with persisted SST anomalies (SSTAs). As discussed by Graham et al. (2000), this is likely to be a competitive option compared to using a coupled ocean–atmosphere model, especially in light of the poor skill in predicting SSTs using dynamical models (e.g., Landsea and Knaff 2000).

It has been argued that as well as vertical shear, the large-scale tropospheric humidity and thermodynamic instability are also important for determining tropical cyclone variability (e.g., Gray et al. 1994; DeMaria et al. 2001). The main focus of this paper is the variability and predictability of the vertical shear. This is because of the known high correlation with tropical cyclone activity (e.g., GS) and because we expect AGCMs to simulate large-scale dynamical fields better than the notoriously difficult humidity fields (e.g., Emanuel and Zivkovic-Rothman 1999) and more sophisticated thermodynamic instability diagnostics based on, for example, convective available potential energy (CAPE; e.g., DeMaria et al. 2001). Also, since most of the CAPE that is used for developing tropical cyclones arises in association with surface fluxes in individual storms (e.g., Emanuel 1986), it is unclear whether the mean CAPE in the MDR has any significance for observed tropical cyclones. It may, however, be important for simulated tropical cyclones in course resolution AGCMs. (cf. Vitart et al. 2001). In section 5 we briefly consider the variability and predictability of the midlevel tropospheric humidity in the MDR and will address the more complicated issue of thermodynamic instability and its relevance for seasonal prediction of tropical cyclones in future work.

In section 6 we consider the implications and conclusions of the work presented in this paper.

2. Analysis of vertical shear

Figure 1 shows the vertical shear based on the wind difference between 200 mb and 925 mb,[1] averaged for July–September 1979–98. Despite the different levels considered by GS and different averaging period (they considered Aug–Oct) the shear pattern presented here is very similar to theirs (their Fig. 3), with a northeast–southwest-oriented region of high shear. Outlined in Fig. 1, in bold, is the MDR, based on that used by GS, where most Atlantic tropical cyclones form. Most of the MDR is characterized by shear greater than about 10 m s^{-1}. Following Hebert (1978) and DeMaria (1996), this would suggest that, on average, the MDR shear is not conducive for tropical cyclone development.

[1] Whereas GS estimated the vertical shear with 850 mb as the lowest level wind, we use 925 mb since the resulting shear correlates slightly better with the tropical cyclone activity.

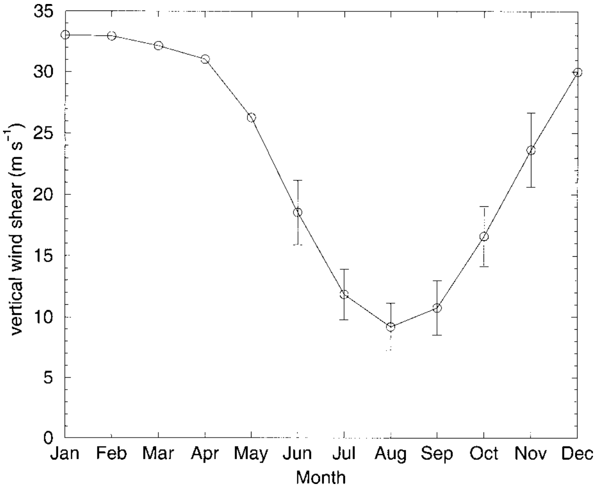

FIG. 2. Mean annual cycle of the vertical wind shear in the MDR shown in Fig. 1, based on ECMWF analyses and the 200- and 925-mb pressure levels. The standard deviation is included for the Atlantic hurricane season, May–Nov.

While it is clear that the climatological average of the seasonal mean shear is not conducive for tropical cyclone development, there is a marked seasonal cycle which implies some months are more favorable than others (Fig. 2). Interestingly, August and September, which have the weakest shear, coincide with the most active tropical cyclone months. It should be noted, however, that July also has a relatively low shear but is characterized by much less tropical cyclone activity than August and September. This means that factors other than shear must limit tropical cyclone activity in July (cf. DeMaria et al. 2001). Of particular relevance to the seasonal prediction of tropical cyclone activity is the interannual variability of the shear. The standard deviation of the shear for each month is illustrated in Fig. 2 by the vertical bars (included for the tropical cyclone season months only). Noticeable reduction in MDR shear in the summer months can occur and is expected to be linked to enhanced tropical cyclone activity.

The interannual variability is further illustrated in Fig. 3, which shows the seasonal mean MDR shear variations between 1979 and 1998. The MDR shear exhibits considerable interannual variability with extreme values varying between 13.0 m s^{-1} in 1986 and 7.7 m s^{-1} in 1981. Also included in Fig. 3 are the total number of tropical storms, hurricanes, and intense hurricanes that occurred in each hurricane season (including those that formed outside the MDR and outside the Jul–Sep period). The anticorrelation between tropical storm activity and the July–September MDR average shear is extremely striking. The linear correlation coefficients between the MDR shear and the number of tropical storms, hurricanes, and intense hurricanes are -0.79, -0.76, and -0.65, respectively, (all significant at the 99% lev-

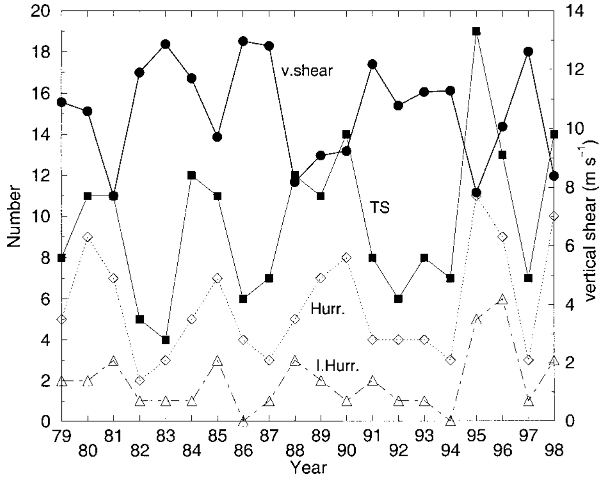

FIG. 3. Time series showing the interannual variability of the mean Jul–Sep vertical wind shear in the MDR in Fig. 1, based on ECMWF analyses (solid circles) and the 200- and 925-mb pressure levels. Also included are the seasonal total of tropical storms (solid squares), hurricanes (open diamonds), and intense hurricanes (open triangles), provided by the National Hurricane Center, Miami.

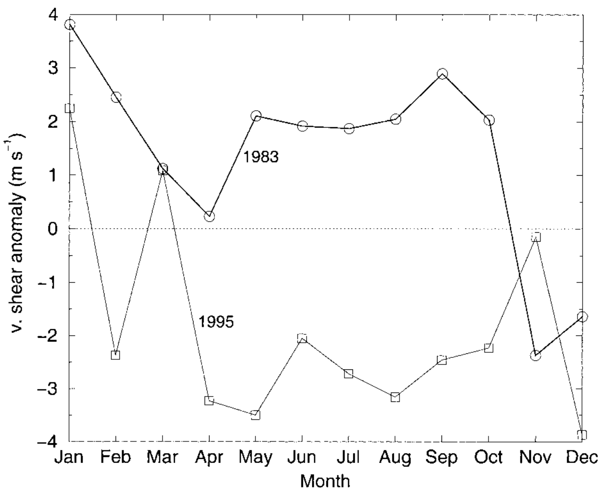

FIG. 4. Time series showing the monthly variation of the vertical wind shear in the MDR in Fig. 1 for 1983 and 1995, based on ECMWF analyses and the 200- and 925-mb pressure levels.

el). These high correlations, consistent with GS, are extremely important and suggest that if a skillful prediction of the MDR shear was available a season ahead, a skillful prediction of Atlantic tropical cyclone activity may also be possible.

A word of caution should be made regarding the interpretation of Fig. 3. In promoting the use of vertical shear as a predictor of tropical cyclone activity, we are assuming that the vertical shear is independent of the tropical cyclone activity. Evidence for this assumption has already been provided by Landsea et al. (1998), who showed that in 1995 the anomalous weak shear was present before the tropical cyclone season started. This is further illustrated here in Fig. 4 which shows how the MDR shear anomaly varies in 1995 and 1983, extremely weak and strong shear years, respectively, and also the most active and least active tropical cyclone years in this record. Consistent with Landsea et al. (1998) the negative shear anomaly in 1995 was present as early as April and persisted through the tropical cyclone season. Also, the positive shear anomaly in 1983 was present in May and persisted until October. While this supports the idea that the shear variability is not affected by tropical cyclone activity, it is not conclusive and further analysis should be considered in this area.

Figure 4 suggests that if we consider the shear anomaly in springtime, by assuming persistence, we should be able to make a prediction of the shear in the summer. While good forecasts would arguably have been obtained in 1983 and 1995, in general, persistence of springtime shear anomalies is not a good indicator of the anomalies in summer. This is illustrated in Fig. 5, which shows the linear correlation coefficients between individual summer months and the preceding months. For example, the August shear has a positive correlation coefficient with the July shear of 0.54, which has a confidence limit of greater than 90%. Although this might be useful, Fig. 5 shows us that the correlation coefficients reduce dramatically as earlier months are considered. To illustrate this, we can consider what the situation is if we want to make a prediction of the July–September shear at the beginning of June. At the beginning of June the shear anomaly in May is known. From Fig. 5 we see that the May shear has a linear correlation coefficient with each of the months of about 0.3, which has a confidence limit much less than 90%. Thus, persistence will not generally be skillful for seasonal prediction of tropical cyclone activity. Despite this, it is noteworthy that in the two extreme years of

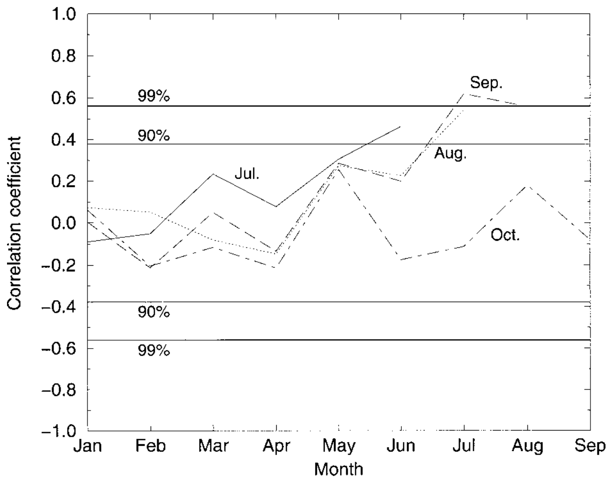

FIG. 5. The linear correlation coefficients between the monthly mean vertical shear in the MDR in Fig. 1 and the mean vertical shear in the preceding months. Correlations are shown for Jul (solid), Aug (dotted), Sep (long dashed), and Oct (dash–dotted). Significance levels at 90% and 99% are indicated.

this study, in 1983 and 1995, persistence would have been a very good guide. It may, therefore, be useful to have real-time monitoring of the MDR shear in any preseason risk assessment.

3. Predictability of MDR shear

a. Background

The analysis presented previously in section 2 showed strong negative correlations between MDR shear and tropical cyclone activity. From this, it is clear that if skillful predictions of July–September MDR shear were available at the beginning of June, then it may be possible to make a skillful forecast of the seasonal tropical cyclone activity by combining this forecast with a statistical model. The aim of this section is to assess the potential skill of the UKMO AGCM at predicting the July–September MDR shear.

The forecasts analyzed were made using the UKMO AGCM for the years 1979–97 and using observed SSTs. The resolution of the AGCM is 3.75° longitude by 2.5° latitude with 30 levels. Nine-member ensembles are used, which were initiated on different starting dates. More details regarding the simulations can be found in Pope et al. (2000).

Since the simulations use the observed SSTs, it should be recognized that they are not true forecasts. They are analyzed in order to assess the potential skill of the UKMO AGCM. The skill of the AGCM is assessed by comparing the ensemble mean MDR shear with the analyzed MDR shear, a measure of the deterministic skill, and also through calculating the relative operating characteristics (ROC; Stanski et al. 1989), which is a measure of the probabilistic skill (e.g., Graham et al. 2000). Assessment of the probabilistic skill is important since it is usually the probabilistic information that is needed by the users of seasonal forecasts. As discussed by Graham et al. (2000) and Palmer et al. (2000), the ROC analysis can be used to assess the value of seasonal forecasts directly.

b. Ensemble mean skill

Figure 6 shows the time series of analyzed mean July–September MDR shear using ECMWF reanalyses (ERA). Since the forecast wind was not available at 925 mb, the shear here is calculated using the wind at 950 mb. This does not significantly affect our results. The circles included on the graph are the forecast MDR shear from the nine members of the forecast ensemble. Also included is the mean of the nine members as a dashed line with filled circles. A qualitative examination of Fig. 6 indicates good agreement. Note, for example, the good agreement in the variability of the MDR shear in the period between 1993 and 1997.

The linear correlation coefficient between the analysed MDR shear and the ensemble mean forecast shear is 0.66 (significant at the 99% level). This suggests that there is potential skill for predicting the MDR shear and, hence, tropical cyclone activity. Indeed, the linear correlation coefficient between the ensemble mean MDR shear and the number of tropical storms, hurricanes, and intense hurricanes is −0.50 (significant at the 95% level), −0.65 (significant at 99% level), and −0.60 (significant at the 99% level), respectively.

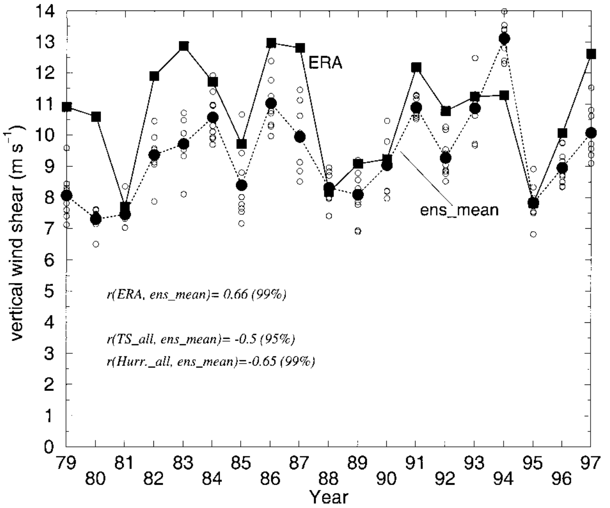

FIG. 6. Time series showing the interannual variability of the mean Jul–Sep vertical wind shear in the MDR in Fig. 1 based on ECMWF analyses (filled squares) and the 200- and 950-mb pressure levels. Also included is the predicted shear from each of the members of the ensemble, based on UKMO model hindcasts initiated at the beginning of Jun (open circles). The mean of the ensemble is also shown with filled circles connected by the dashed line. Included in the figure are the linear correlation coefficients between the ensemble mean shear and ECMWF reanalysis (ERA) shear, the number of tropical storms (TS) and the number of hurricanes (HURR) together with the confidence limits.

Although the results presented are encouraging, it is important to assess if the MDR shear in the model has a similar relationship with the phase of El Niño and west Sahel rainfall that the observed MDR shear has. This is a further test of the model's ability to represent correctly the MDR variability. Regarding El Niño first, the linear correlation coefficient between the Niño-3 area (5°N–5°S, 90–150°W) SST time series between 1979 and 1998, and the observed and model-predicted MDR shear are +0.74 and +0.34, respectively. This suggests that the MDR shear response to El Niño is too weak in the model. The observed west Sahel rainfall, based on the rainfall estimated by Xie and Arkin (1997), has a linear correlation coefficient with the observed MDR shear of −0.49. The linear correlation between the modeled MDR shear and the modeled west Sahel rainfall is −0.41, which suggests that this teleconnection is better represented in the model. Closer examination of the spatial patterns of shear and how this relates to the atmospheric heat sources in the Pacific and over continental Africa is needed in order to understand and assess in more detail the ability of how well the model represents these teleconnections, but this initial analysis suggests a weakness in the model's representation of the teleconnection between the tropical Pacific and the MDR. This work should also consider the role of Atlantic SSTs on MDR shear (cf. Shapiro and Goldenberg, 1998).

c. Probabilistic skill

We present here a ROC analysis that follows the same methodology as that described by Graham et al. (2000) for assessing probabilistic skill of PROVOST forecasts. In this case the ROC for an anomalously low or high shear event is evaluated by considering the hit rates and false-alarm rates at different probability thresholds. Following Graham et al. (2000) we consider probability thresholds of 20%, 40%, 60%, and 80%. The definition of the ROC hit rate and false-alarm rate is included in the appendix. The hit rates and false-alarm rates are normalized and so vary between 0 and 1. A visual assessment of the probabilistic skill is obtained by plotting the hit rate against the false-alarm rate, a so-called ROC curve. In the analysis presented here, we compare observed MDR shear anomalies with simulated anomalies. The simulated anomalies are relative to the simulated mean MDR shear averaged over all ensemble members and years, which, as can be seen in Fig. 6, is a little lower than the observed MDR shear 9.4 m s^{-1} compared to 10.7 m s^{-1}.

Figure 7a shows the ROC curve for MDR shear below average. For orientation, the meaning of the point labelled 20% in this curve is described. It has a hit rate of 1, which means that whenever the observed MDR shear was below average, at least two of the nine ensemble members predicted MDR shear below average. It has a false-alarm rate of 0.545, which means that whenever the observed shear was above normal for about half the years, two or more of the nine ensemble members predicted MDR shear below average. Since it can be seen that hit rates exceed false-alarm rates for all probabilities, the curve indicates that the ensemble has skill in predicting MDR shear below average (and hence above normal too). Whether this is useful information or not will depend on the user application (see Graham et al. 2000).

A quantitative measure of the skill is obtained by calculating the area under the ROC curve, sometimes referred to as the ROC score. A ROC score of 0.5, which would be obtained if hit rates equaled false-alarm rates (the diagonal line included in Fig. 7a) indicates no skill; whereas a ROC score of 1 indicates perfect deterministic skill. The ROC score for MDR shear below normal is 0.92 (significant at the 99% level).[2] This is a high score and confirms that the ensemble has high skill in predicting MDR shear below and above normal. Included in Fig. 7b is the ROC curve for anomalous MDR shear less than 1 m s^{-1}, indicating a more extreme event and potentially a more active tropical cyclone year. The

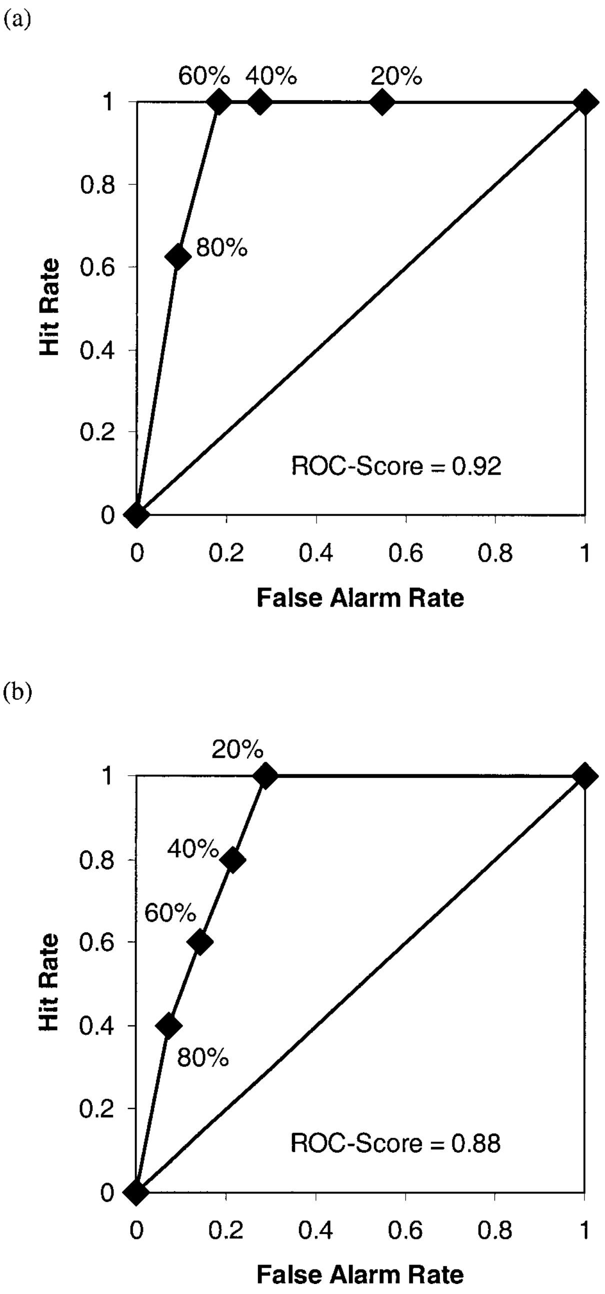

FIG. 7. Relative operating characteristic (ROC) curves for UKMO AGCM Jul–Sep simulations of the events: (a) MDR shear below average and (b) MDR shear 1 m s^{-1} below average. The curves are constructed from hit rates and false-alarm rates (see appendix for definition) at four thresholds on the forecast probability of the event (20%, 40%, 60%, and 80%; see Graham et al. 2000 for more details). The area under the ROC curve is the ROC score and is included in the figure. For reference the diagonal line represents a ROC curve with no probabilistic skill and a ROC score of 0.5.

[2] Significance levels are obtained using a Monte Carlo method following Graham et al. (2000). The ROC calculations were repeated 500 times, each time scrambling the yearly order. This allows an assessment of the probability of achieving ROC scores by chance.

TABLE 1. ROC scores for anomalous MDR shear events of different thresholds.

Anomalous MDR shear event (m s^{-1})	ROC score from PROVOST integrations	ROC score from persisted SSTA integrations
< 0 or > 0	0.92[a]	0.73[b]
<1	0.88[a]	0.71[c]
<1.6	0.78[b]	0.74[c]
>1	0.69[c]	0.39
>1.6	0.51	0.30

[a] Significant at greater than the 99% level.
[b] Significant at greater than 95% level.
[c] Significant at greater than 90% level.

curve and the ROC score of 0.88 (significant at the 99% level) indicate that the ensemble also has high skill at predicting this lower MDR shear event.

Table 1 summarizes the ROC scores for different anomalous MDR shear events. Included in the table are ROC scores for anomalies of ± 1.6 m s^{-1}, which is the standard deviation of the ECMWF-analyzed MDR shear and also the standard deviation of the PROVOST shear based on all the members in Fig. 6. The ROC score for anomalous MDR shear that is more than one standard deviation below normal is 0.78, indicating that the ensemble skill is maintained for this more extreme event. It is of interest to note that the ROC score for the anomalous MDR shear greater than 1 m s^{-1} is 0.69, and greater than 1.6 m s^{-1} is only 0.51. Both indicate lower ensemble skill than for the equivalent low-shear events

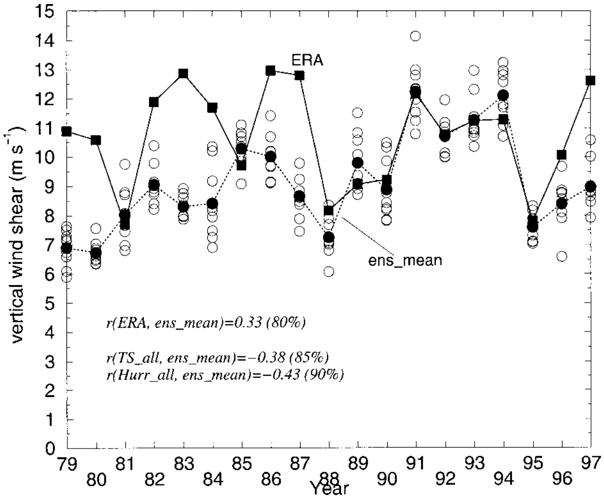

FIG. 8. Time series showing the interannual variability of the mean Jul–Sep vertical wind shear in the MDR in Fig. 1 based on ECMWF analyses (filled squares) and the 200- and 950-mb pressure levels. Also included is the predicted shear from each of the members of the ensemble, based on UKMO model forecasts made with persisted SSTAs initiated at the beginning of Jun (open circles). The mean of the ensemble is also shown with filled circles connected by the dashed line. Included in the figure are the linear correlation coefficients between the ensemble mean shear and ERA shear, the number of tropical storms (TS) and the number of hurricanes (HURR) together with the confidence limits.

with no skill at all for the greater than 1.6 m s^{-1} event. There is no obvious reason that can explain this asymmetry but it may be related to the error in the simulation of the teleconnection acting between the tropical Pacific and the MDR identified above.

4. Forecasts with persisted SST anomalies

The results presented in the previous section indicate that the UKMO AGCM has potential skill in predicting the MDR shear. In order to assess the skill of the model in a more operational mode we must consider forecasts made with predicted SSTs. We do this here by considering forecasts made with persisted SST anomalies (SSTA) superimposed on the climatological seasonal cycle. This offers a cheap method for SSTA prediction and as discussed by Landsea and Knaff (2000) may currently be better than many coupled dynamical model predictions. More details of the method used are included in Graham et al. (2000).

Figure 8 shows the time series of analyzed MDR shear using ECMWF analyses together with the forecast MDR shear using persisted SSTAs. Visual inspection indicates mixed success of the ensemble mean, reflected in a low correlation coefficient of 0.33. During the first half of the period, the ensemble mean is clearly not representing the observed variability well, whereas in the second half there is much better agreement. The conclusion from this analysis however is that deterministic skill is low when using persisted SSTAs. Interestingly as with the PROVOST runs, the ensemble mean shear over all years has a negative bias with a wind difference of 9.1 m s^{-1} between 200 mb and 950 mb compared with 10.7 m s^{-1} from ECMWF analyses.

The ROC scores for prediction of anomalous MDR shear are included in Table 1. They indicate reduced but still significant skill for prediction of anomalously low and high MDR shear events with a ROC score of 0.73 compared with 0.92 for forecasts with observed SSTs. The skill level for the MDR shear greater than 1 m s^{-1} and 1.6 m s^{-1} below normal are comparable to this with ROC scores of 0.71 and 0.74, respectively, indicating that the ensemble has skill at predicting low- and very low shear events. It is of interest to note, however, that the ensemble has no skill in predicting MDR shear greater than 1 m s^{-1} above normal consistent with the weaker ROC scores for these events in the PROVOST simulations.

We conclude from this that while the probabilistic skill is reduced using persisted SSTAs, the ROC scores indicate that there is still significant skill for the events where MDR shear is above or below normal and for the very low shear events. Depending on the user of the forecast there may, therefore, be useful probabilistic information in the forecasts with persisted SSTAs.

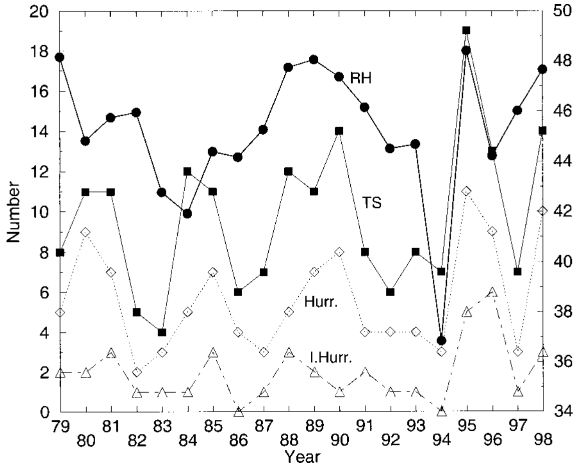

FIG. 9. Time series showing the interannual variability of the mean Jul–Sep relative humidity in the main development region in Fig. 1 based on ECMWF analyses (solid circles) and averaged over the layer between 500 and 700 mb. Also included are the seasonal total of tropical storms (solid squares), hurricanes (open diamonds), and intense hurricanes (open triangles), provided by the National Hurricane Center, Miami.

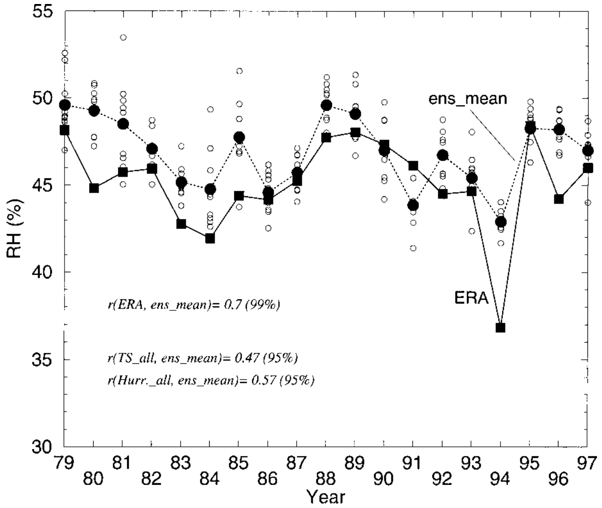

FIG. 10. Time series showing the interannual variability of the mean Jul–Sep relative humidity in the main development region in Fig. 1 based on ECMWF reanalyses (filled squares) and averaged over the layer between 700 and 500 mb. Also included is the predicted RH from each of the members of the ensemble, based on UKMO model hindcasts initiated at the beginning of Jun (open circles). The mean of the ensemble is also shown with filled circles connected by a dashed line. Included in the figure are the linear correlation coefficients between the ensemble mean relative humidity and ERA relative humidity, the number of tropical storms (TS) and the number of hurricanes (HURR) together with the confidence limits.

5. Analysis and predictability of midlevel relative humidity

While shear is the major focus of this paper, we recognize that it is not the only large-scale meteorological factor in the tropical Atlantic that might affect Atlantic tropical cyclone activity. As discussed by Gray (1968), Emanuel (1986), and Bister and Emanuel (1997), the magnitude of the midtropospheric relative humidity may also be important. If midtropospheric levels are drier, for example, downdrafts may be more efficient at decreasing the boundary layer equivalent potential temperature θ_e and hence suppressing tropical cyclone development. It should be realized though that the shear and humidity variability may not be independent. A Walker-type overturning circulation that develops in El Niño years, for example, might be expected to be associated with subsidence and drying in the MDR as well as stronger westerly shear.

One major problem when considering humidity though is that it is neither well observed nor well modeled (see Emanuel and Zivkovic-Rothman 1999). Therefore considerable caution is needed in interpreting the results. We, therefore, only give these results brief consideration.

We consider here the relative humidity averaged over the layer between 700 mb and 500 mb—the expected midlevel source of evaporatively driven downdrafts. Figure 9 shows the mean July–September analyzed relative humidity in the MDR based on the ERA and post-ERA fields. The average is about 45%, with a minimum of 37% in 1994 and a maximum value of 48% in 1995. The variability is clearly very weak, especially for the ERA period and is notably weaker than the shear (cf. Fig. 3) with a coefficient of variation of 0.06 compared to 0.16. Also included in fig. 9 are the numbers of tropical storms, hurricanes, and intense hurricanes. The expected positive correlation between the relative humidity and the total tropical storm activity is weak, confirmed by a linear correlation coefficient of just 0.41.

Following the analysis presented for shear in section 4 above, we present the predicted relative humidity from the ensemble of PROVOST runs, alongside the analyzed relative humidity (Fig. 10). A visual inspection indicates that the ensemble mean curve approximately follows the analyzed curve—consistent with a linear correlation coefficient of -0.70. What is also noticeable in both the forecast and analyzed humidity time series, however, is that the time series are both strongly autocorrelated. For example, between 1979 and 1984 there is a clear downward trend, whereas between 1984 and 1989 there is a clear upward trend. This is followed by a downward trend until 1993. This low-frequency variability is very surprising, especially when it is seen in both the ECMWF analyses and the UKMO forecasts. This suggests that the variability may not be due to any spurious observations, such as a rogue satellite, since satellite data are not included in the UKMO forecasts. A more careful analysis of this variability should be considered in future work including an assessment of the possible role of Atlantic SST variations.

ROC analyses for when MDR RH is less than normal gives ROC scores of about 0.64, significant at the 75% level. This indicates that the ensemble has marginal skill for these conditions. Since the MDR RH is only weakly correlated with the observed tropical cyclone activity and because the potential skill for predicting it is low, we do not currently recommend its use as a predictor.

6. Implications and conclusions

Consistent with GS, it has been shown that the analyzed mean July–September MDR shear is strongly and negatively correlated with Atlantic tropical cyclone activity. We have also shown that the current operational UKMO AGCM has high skill in predicting this shear from forecasts made at the end of May, given the observed SSTs. Skill levels are reduced but still significant when persisted SSTAs are used. Based on these results we recommend that seasonal forecasts of MDR shear using dynamical models, which use persisted SSTAs, should be routinely monitored to give guidance for likely Atlantic tropical cyclone activity a season ahead. They could be used on their own for guidance or merged with a statistical prediction model. ROC analysis also indicates that the ensemble has significant probabilistic skill, particularly for anomalously low shear events, and so depending on the user, there may also be useful probabilistic information in these dynamical forecasts.

It is likely that the skill could be improved by a multimodel approach and should be investigated (e.g., Palmer et al. 2000). Efforts also need to be made at reducing model systematic errors since these are likely to have a detrimental effect on predictability. With regards to the UKMO AGCM and AGCMs in general, particular attention should be given to the teleconnections acting between the tropical Pacific and the MDR, and between West Africa and the MDR. It is also clearly important that efforts are made to improve SST prediction. While skill is obtained with persisted SSTAs, the potential skill is significantly higher and so improved SST prediction should have great benefits.

Alongside the forecasts, we recommend that the analyzed MDR shear be routinely monitored. Although this does not always provide a good indication of the shear in the months ahead, it is noteworthy that in the two extreme years, 1983 and 1995, the shear anomalies that dominated these years were present and persisted from the spring.

The work presented here has concentrated on the analysis and predictability of the MDR vertical shear. This is because of the known strong correlations it has with tropical cyclone activity and because we expect AGCMs to have more skill at predicting this dynamical field than perhaps diagnostics based on thermodynamic fields, which may be more sensitive to the errors in physical parameterizations. A brief analysis has shown that there may be potential skill at predicting midlevel relative humidity, but the observed correlations of this field with tropical cyclone activity are lower, which therefore makes it a lower-priority predictor. Future work should also consider other factors including, perhaps, one related to thermodynamic instability (cf. DeMaria et al. 2001). Also, it must be shown that there is a clear casual relationship between these factors and the tropical cyclone variability.

As discussed in the introduction, there are two approaches for using the outputs from AGCMs to predict seasonal tropical cyclone activity. The one promoted here is to combine predictions of the large-scale environment known to impact tropical cyclone activity with a statistical model. An alternative approach is to use predictions of model-simulated tropical cyclone activity (e.g., Vitart et al. 1997). It is important to note that Vitart et al. (1999) and Vitart et al. (2001) have suggested that much of the skill found using this second approach is due to skillful simulations of the large-scale environment. We conclude, therefore, that a priority for future work is to improve our understanding of the physical processes that determine the large-scale tropical Atlantic environment and its variability, and to assess how well AGCMs simulate this.

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APPENDIX

Definition of ROC Hit Rate and False-Alarm Rate

TABLE A1. This contingency table shows definitions of hit rate and false-alarm rate, for a given forecast probability threshold (X) for a binary event, used in the construction of the ROC curves. Here, H, M, FA, and CR are the total numbers of hits, misses, false alarms and correct rejections at threshold X, following Graham et al. (2000).

		Does ensemble probability for the event exceed threshold X?	
		Yes	No
Is the event observed?	Yes	Hit (H)	Miss (M)
	No	False alarm (FA)	Correct rejection (CR)

Hit rate for probability threshold X is given by $HR = H/(H + M)$.
False-alarm rate for probability threshold X is given by $FAR = FA/(FA + CR)$.

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