# TSUNAMI

## TROPICAL CYCLONE PREDICTION SYSTEM PRODUCT

## Dynamical Model Research

**By**

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# Summary

Exciting opportunities exist to improve on purely statistical approaches to seasonal forecasting of tropical cyclone activity in the Atlantic. This work is an important first step towards utilising the skill that is available now from the UKMO dynamical forecast model.

It has been shown here that seasonal tropical cyclone activity is strongly negatively correlated with the observed wind shear that is present in the main development region (MDR) for tropical cyclones. The linear correlation coefficient between the MDR shear and the number of tropical cyclones is -0.79. We have also shown that the current UKMO dynamical model shows significant skill in predicting the MDR shear. We recommend therefore that the predicted MDR shear be used now as a stand-alone forecast of likely tropical cyclone activity. The forecast of the MDR shear made at the beginning of June suggests that the 1999 Atlantic tropical cyclone season will be more active than normal.

It has also been shown that the seasonal tropical cyclone activity is negatively correlated with MDR relative humidity although more weakly than with the MDR shear. The UKMO dynamical model has also shown encouraging skill in the seasonal prediction of this field. At present though, we do not have sufficient confidence in the analysis of this field to recommend its use as a predictor of tropical cyclone activity. We would encourage further work in this area.

It has been shown that, in some years, prominent steering flow anomalies have been present in the Atlantic which have either encouraged or discouraged landfalling hurricanes. Preliminary analysis indicates though that dynamical models are expected to have little skill in predicting these anomalies. This is not due to inadequacies in the models but due to the more chaotic behaviour of high latitude weather patterns.

To further the development of a more skillful forecast of tropical cyclone activity we recommend two avenues for future research:

(i) Continue to improve the UKMO dynamical model, paying special attention to why the model underestimates the impact of El Nino on the MDR shear.

(ii) Develop a methodology for forecasting Atlantic sea surface temperatures, both for initialising the UKMO model and using directly as a predictor.

# 1. Background

An exciting opportunity exists now for improving on purely statistical approaches to seasonal tropical cyclone activity prediction by using the rapidly developing skill of dynamical models on seasonal timescales.

Most attempts at seasonal forecasting of tropical cyclones have been purely statistically based. As recently discussed in an article on seasonal weather prediction in Nature by Stockdale et al (1998) this type of approach is likely to be superseded in the future by dynamical forecasts. To quote them "....dynamical methods offer the best long-term hope for making seasonal forecasts because of their greater generality and precision: that is, because of their ability to handle unprecedented situations and to treat non-linear combinations of factors which cannot be extracted empirically from the short observational records available to us".

The present study focusses on the large-scale environmental factors that are known to affect tropical cyclone activity and which can be forecast by dynamical models. It will assess the ability of the current UKMO atmospheric general circulation model (AGCM) to reproduce and predict these large-scale factors. Hence, the prospects of using such information to enhance statistical models as well as long-term prospects for purely dynamical forecasts will be examined.

Previous, mainly empirical work, has identified several environmental factors that influence Atlantic tropical cyclone activity. Many of these may be predictable using dynamical models, including El Nino , West African rainfall (WAR) and, related to these, vertical wind shear and relative humidity in the Atlantic. The vertical wind shear will serve as a particular focus in this study together with relative humidity. Both are known to have important influences on tropical cyclones and are linked to the state of El Nino and the WAR (see Jones and Thorncroft, 1998).

Another important component of this research is the consideration of regional-scale-circulation anomalies and their predictability. Skill in this area may allow a prediction of likely tropical cyclone track and hence landfall.

The aim of this study is to first analyse the interannual variability of the large-scale factors that are known to affect tropical cyclone activity and second to assess the skill of the UKMO AGCM in predicting this variability.

# 2. Development of Analysis Dataset

## 2.1 Background

Previous, mainly empirical, studies (e.g. Gray 1984, Landsea and Gray, 1992) have shown that Atlantic tropical cyclone activity is affected by meteorological events occuring remotely from the Atlantic where the tropical cyclones form. Most importantly, these include El Nino and West African rainfall (WAR). It is important to understand though how these remote events can affect the Atlantic tropical cyclones. Gray (1984) and many others have shown that vertical wind shear in the MDR is very important; that is the difference in wind velocity high up in the atmosphere and that at low-levels. There is an inverse relationship between MDR shear and north Atlantic hurricane activity. It was recently shown by Goldenberg and Shapiro (1996) (GS) that in El Nino years the shear is strengthened, consistent with the reduced tropical cyclone activity in those years, and in wet WAR years the shear is weakened, consistent with increased tropical cyclone activity in those years.

As well as wind shear, it is generally accepted that the large-scale Atlantic relative humidity may also have an influence on tropical cyclone activity, with dryness acting to inhibit tropical cyclone development. This parameter, unfortunately, is less well observed than the wind shear and is also less well handled in AGCMs. Relative humidity is included in this study, but the errors in this field must be kept in mind.

The 1995 Atlantic tropical cyclone season was the busiest this century (Landsea et al 1998). Despite this, there were relatively few U.S. landfalls. It has been suggested that this may have had something to do with a semi-permanent large-scale circulation feature off the coast of Florida which acted to steer the tropical cyclones northwards before they could reach the U.S. mainland.

We will examine whether such circulation features are coherent in other years and whether they can be related to increased or decreased likelihood of landfall.

In section 3 of this report the skill of the UKMO AGCM in predicting the variability presented in section 2 will be examined.

## 2.2 Datasets used and region of study

### a. ECMWF analyses

For the analysis presented in this section we use the ECMWF reanalysis dataset for 1979-1993 together with ECMWF operational analyses for 1994-1998.

### b. Rainfall

The rainfall dataset used to diagnose the West African rainfall variability is that produced by Xie and Arkin (1997) and is based on a merging rainguage and satellite data. The West African region used is defined as that between 12$^{o}$N and 17$^{o}$N and between 15$^{o}$W and 5$^{o}$W.

### c. Nino-3 sea surface temperatures

The sea surface temperature (SST) index used to diagnose the status of El Nino is the average SST for the region between 5$^{o}$S and 5$^{o}$N and between 150$^{o}$W and 90$^{o}$W.

### d. Region of study

Following GS we focus on the so-called ‘main development region’ (MDR) for tropical cyclones. This represents the region where most of the Atlantic tropical cyclones develop. Figure 1 shows the MDR on a map of the region. Since we hypothesise that the eastern part of the MDR will be more influenced by the WAR variability and the western side more by El Nino variability we also divide the MDR into two halves and in some parts of the work consider the two separately.

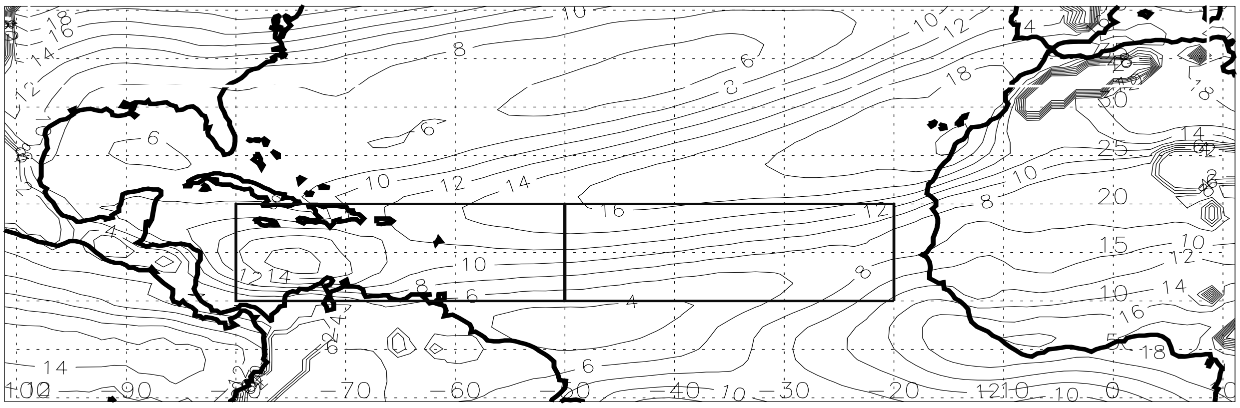



Figure 1. The Mean vertical wind shear between 200mb and 925mb for July-September (averaged for 1979-1998).

## 2.3 Vertical Wind Shear

### a. Analyses

Figure 1 shows the mean vertical wind shear between 200mb and 925mb (about 10km and 750m). Contours are of the difference in wind speed between these levels. GS based their shear parameter on the 200mb and 700mb levels, but our work shows that this gives slightly weaker correlations with tropical cyclone activity. Note that much of the MDR is characterised by shears greater than $10ms^{-1}$ . This implies that climatologically the MDR region is not a good environment for tropical cyclones and especially the western MDR. This may be one contributing factor to the weaker tropical cyclone activity in the Atlantic than in the Pacific.

Figure 2(a) shows the seasonal cycle of the shear for the MDR, west-MDR and east-MDR. The minimum in the summer months is striking. Figure 2(b) shows the variance of the shear in these regions. The variance in the summer months in the west-MDR is particularly strong. This suggests that although the mean shear seen in Figure 1 would be expected to inhibit tropical cyclones, some years may exhibit much weaker shear thereby reducing this inhibition. It is important to know if this hypothesis is true.

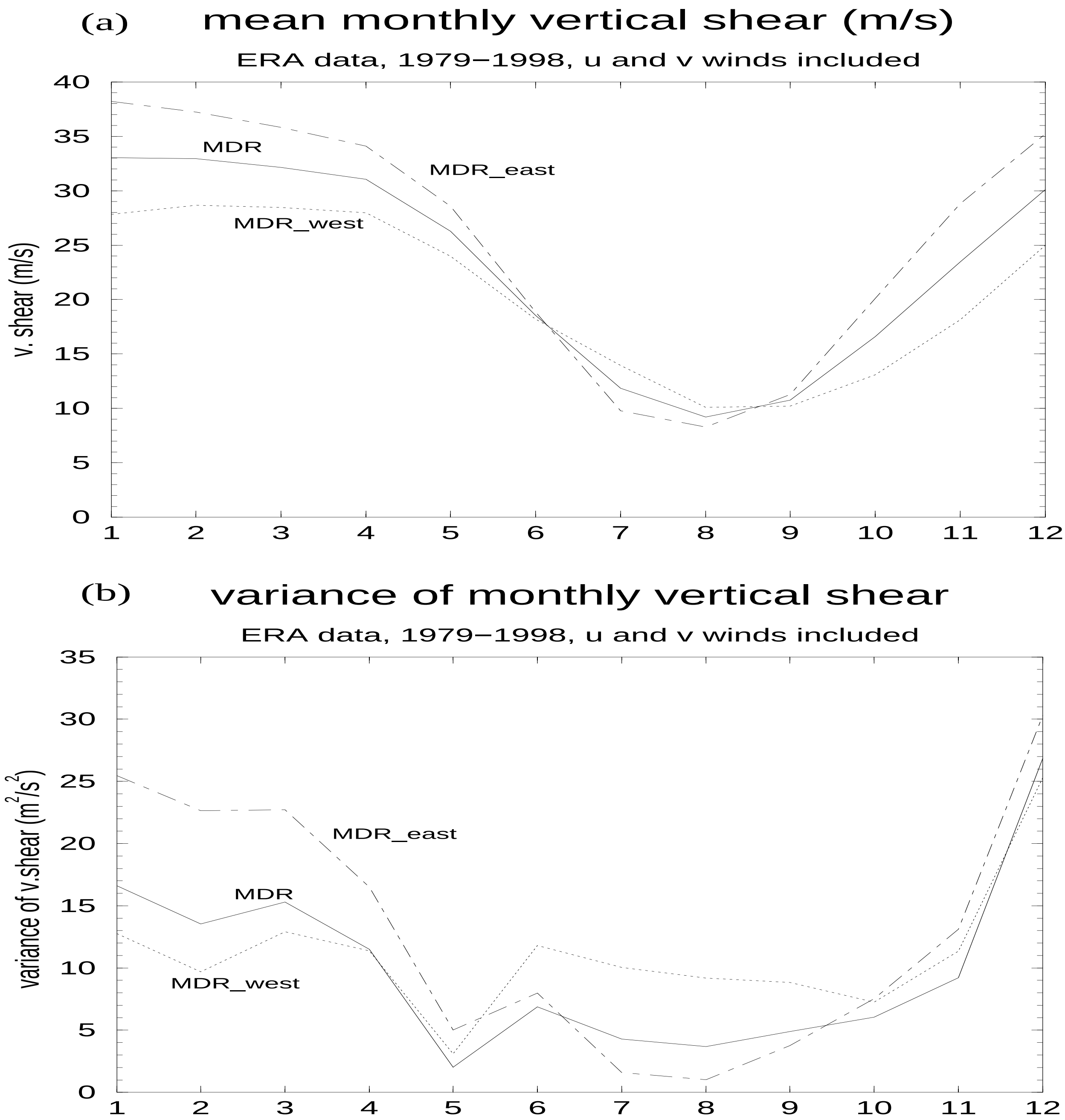
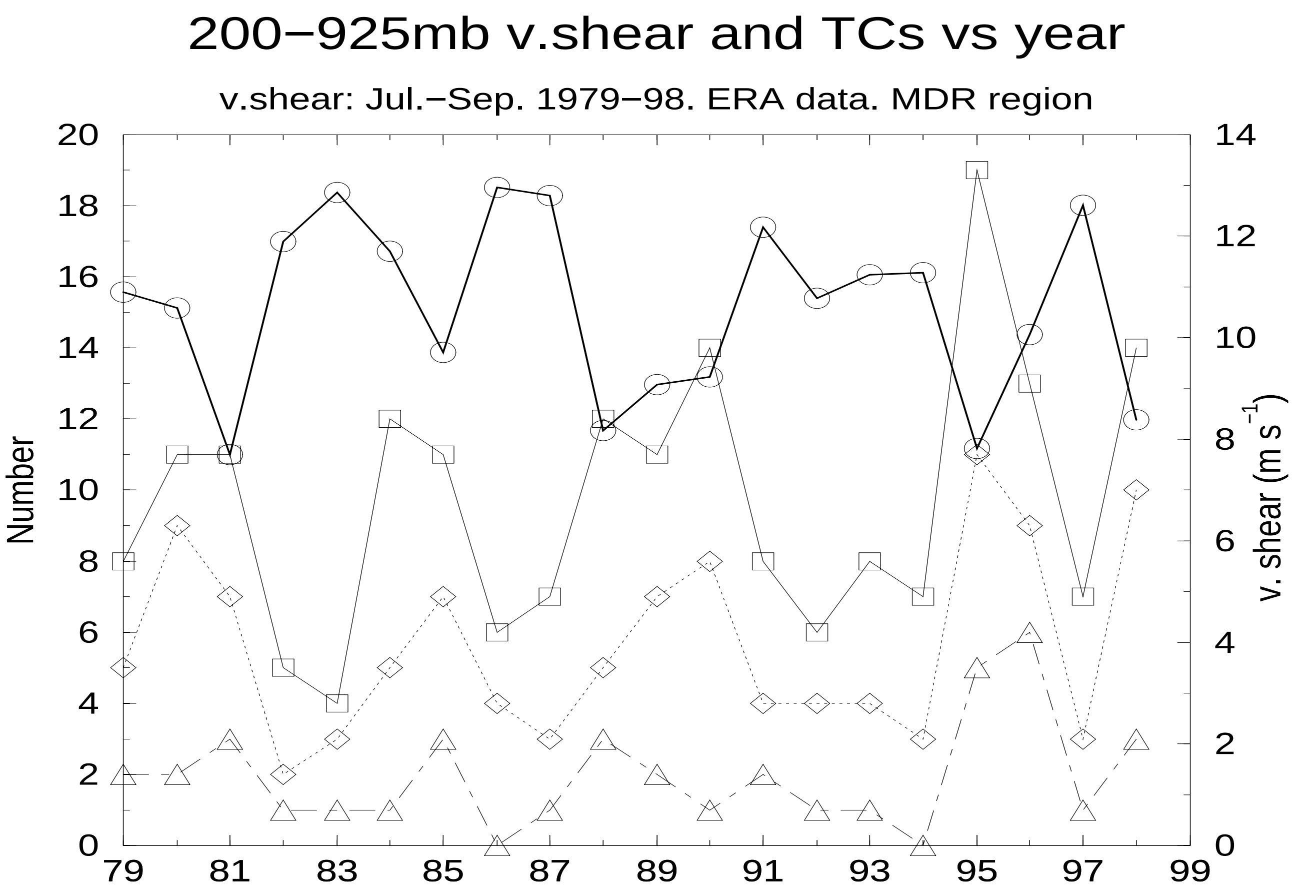



Figure 2.(a) Seasonal cycle of the vertical shear for the MDR, west-MDR and east-MDR and (b) variance of the vertical shear in these same three regions.

Figure 3 shows the year-to-year variability of the July-September mean MDR shear (circles) together with the number of tropical cyclones, hurricanes and intense hurricanes. The first thing to note is, as expected, the MDR shear exhibits considerable year-to-year variability with very low shear in 1981, 1988 and 1995 for example and very high shear in 1997. If we now compare this time series with that for the number of tropical cyclones (squares), we notice a very strong negative correlation. As expected, generally, years when the shear was weaker than normal, for example 1995, were characterised by high tropical cyclone activity and vice-versa. The linear




r(v.shear_MDR, TC number)=-0.79
(explains 64% of variance)
r(v.shear_MDR, Hurricane number)=-0.76
(explains 58% of variance)
r(v.shear_MDR, Intense Hurricane number)=-0.65
(explains 42% of variance)

Figure 3. Time-series showing tropical cyclone activity versus vertical shear in the MDR.

correlation coefficient between the MDR shear and number of tropical cyclones is -0.79 and thus can explain 64% of the variance. This result is extremely encouraging since it suggests that if we could predict the MDR shear, we would have a very good forecast of tropical cyclone activity. It should be noted, that the shear also correlates strongly with the number of hurricanes and the number of intense hurricanes.

**b. Auto-correlations**

Before considering how well dynamical models can forecast the MDR shear, it is first worth considering if there is any skill in persistence. For example, if we know that the MDR shear is strong in April or May will it be strong in August? Figure 4 shows the monthly mean shear anomalies for 12 years of this study (1979-84 and 1991-96). From an examination of these graphs, persistence is not a good guide. The weak skill in using shear anomalies from earlier months to predict the shear in summer months is further illustrated in fig. 5. For example, the correlation coefficient between the shear in August with the shear in previous months is indicated by the dotted line. Apart from July, the correlation with previous months is below 0.3 making it a useless predictor. It should be noted though that in both 1983 and 1995 (fig. 4), the least active and most active tropical cyclone seasons in the record respectively, the shear anomalies (positive in 1983 and negative in 1995) were strong as early as May in 1983 and April in 1995. This suggests that the shear in the MDR should be continually monitored and that large anomalies present before the summer may be an indication of extreme events. This hypothesis should be examined further.

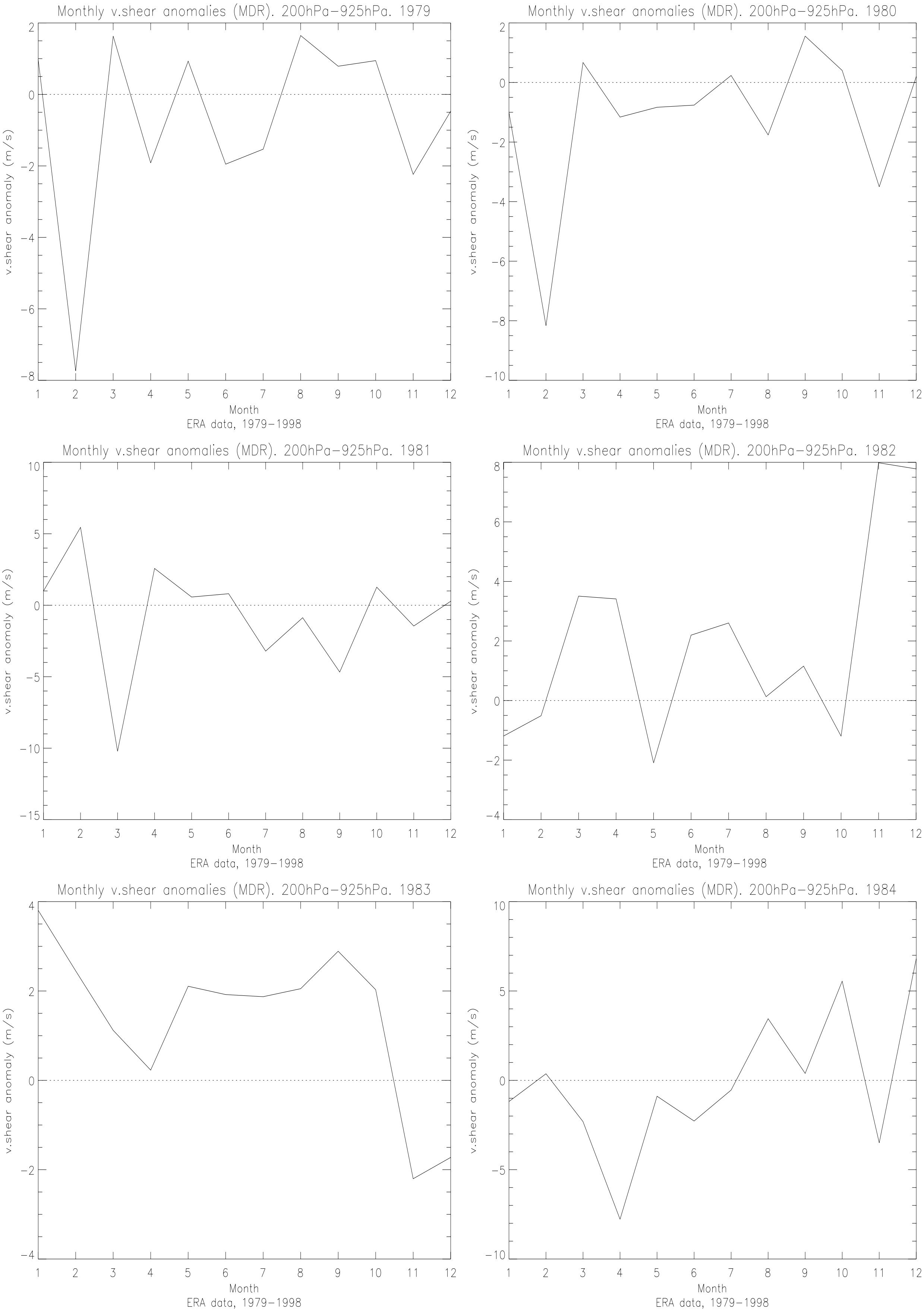



Figure 4 Time-series of monthly mean vertical shear anomalies in the MDR for 12 different years.

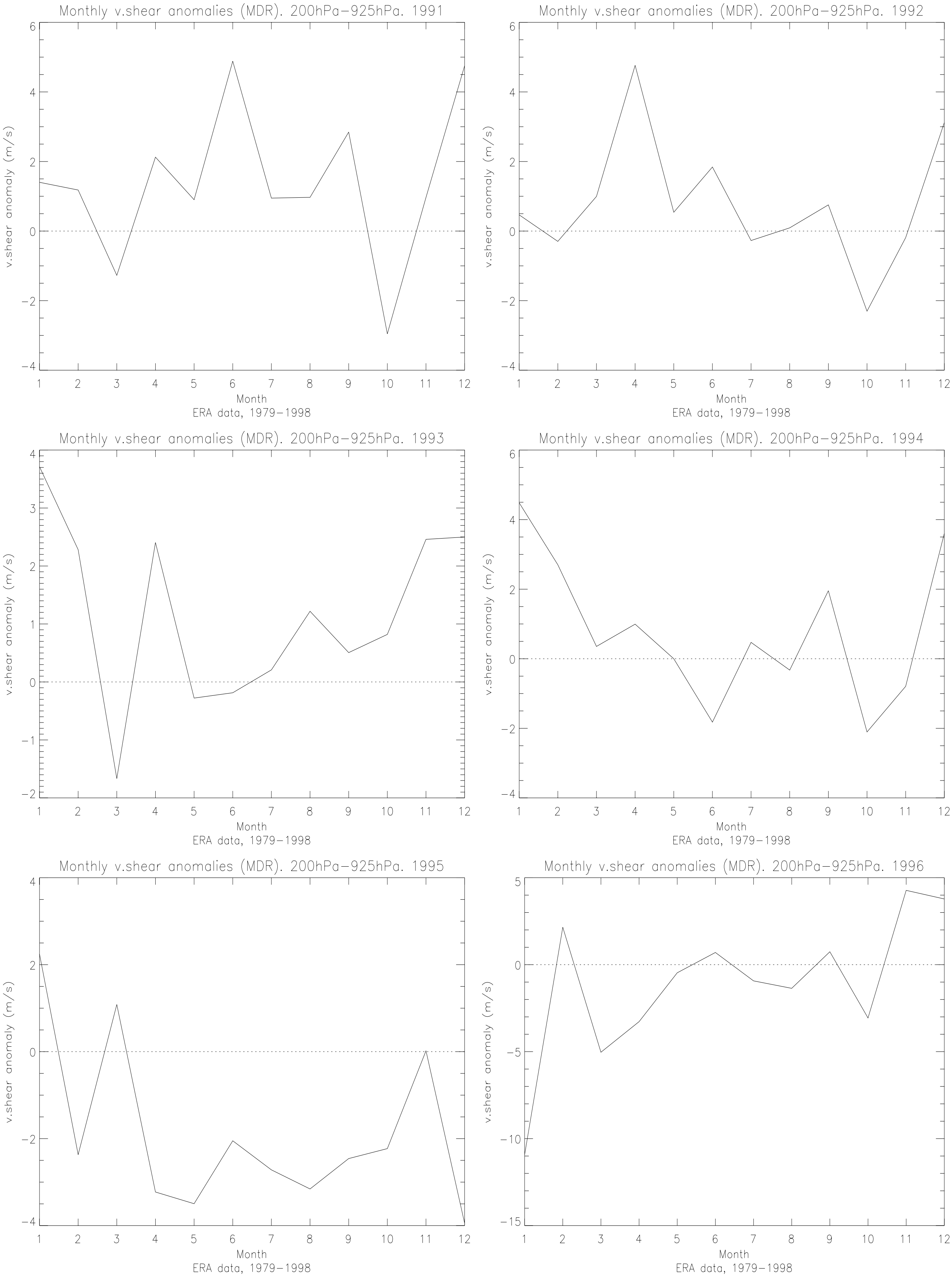



Figure 4 continued.

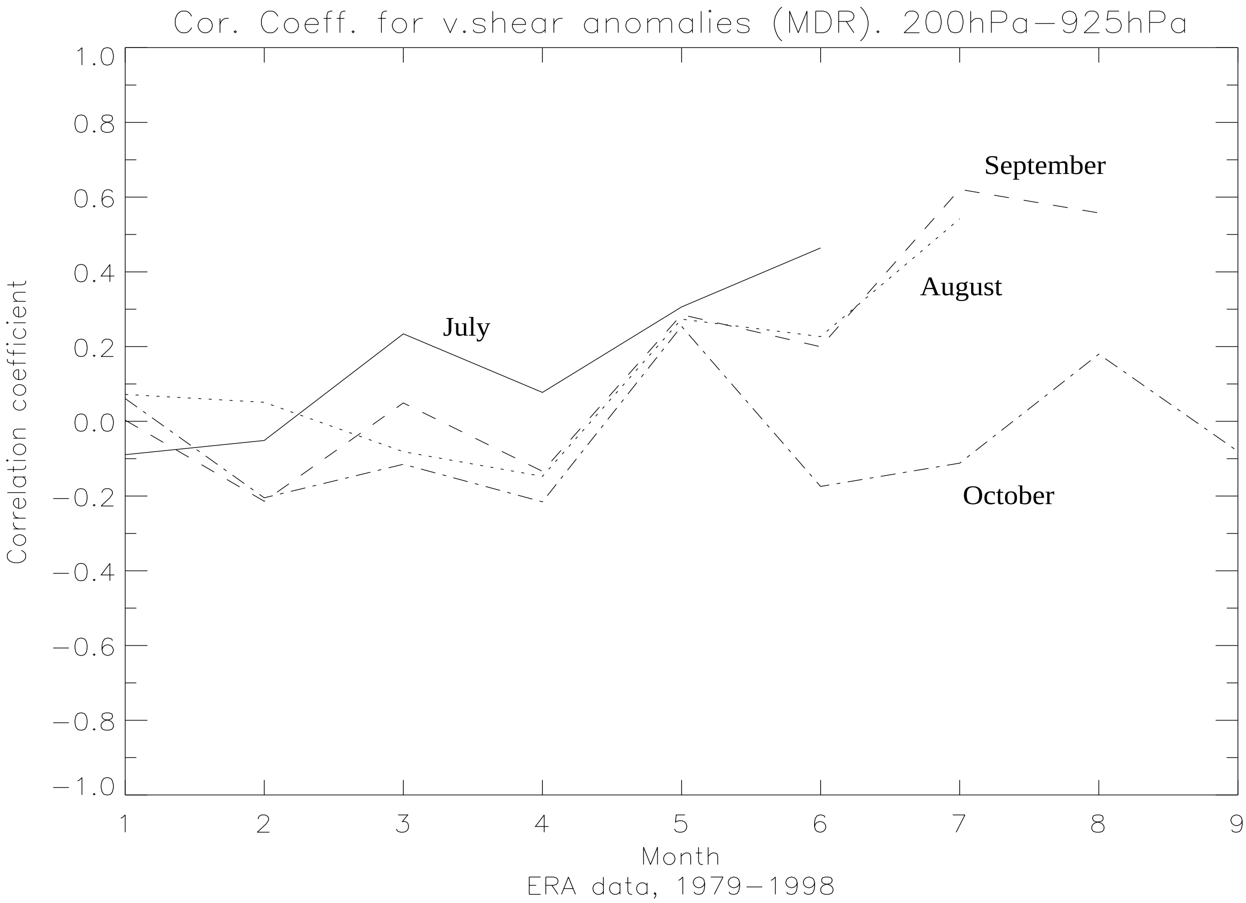



Figure 5. Linear correlation coefficients between mean MDR vertical shear for individual months and the months previous to it.

**c. Relationship with El Nino and West African Rainfall**

The following linear correlation coefficients were found between the MDR shear and the Nino3 sea surface temperature (SST) and West African rainfall:

| | |
|---|---|
| Nino3 SST: | +0.74 |
| West African rainfall: | -0.49 |

This suggests that for our period, El Nino has had a bigger influence on the MDR shear than West African rainfall. This is the opposite result to that found by GS. The reason for this is that they considered a different and earlier period to us (1968-1992). Along with this, it is well known (e.g.

Janicot et al 1996) that there is strong decadel variability in the remote impacts of El Nino. This is confirmed here in table 1 which shows the linear correlation coefficients between Nino 3 SSTs and tropical cyclone activity.

**Table 1: Linear correlation coefficients between Nino3 SST and the number of tropical cyclones, hurricanes and intense hurricanes.**

| | 1979-1997 | 1944-1997 |
|---|---|---|
| Tropical Cyclones | -0.58 | -0.38 |
| Hurricanes | -0.57 | -0.34 |
| Intense Hurricanes | -0.49 | -0.38 |

From the table it can be seen that El Nino has had a stronger impact on the tropical cyclone activity in the more recent period compared with the whole record. We conclude from this that it is important to take into account the decadel variability that is present in the coupled atmosphere-ocean system.

It should also be noted that tropical cyclone activity correlates more strongly with the vertical shear (-0.79) , which directly and locally impacts on tropical cyclones, than with Nino3 SST (-0.58) which indirectly impacts on tropical cyclones remotely.

The contrast in the correlations of Nino3 SST and MDR shear with tropical cyclone activity is illustrated further in fig. 6 which show scatter plots of these parameters against the number of tropical cyclones. Figure 6(a) shows clearly the two extreme years of 1995 and 1983. These are the only years in the time-series that have tropical cyclone activity more than one standard deviation more and less than normal respectively and both are extreme years in terms of vertical shear. Figure 6(b), in contrast shows that neither 1983 nor 1995 were extreme years with regards to Nino3

SSTs both falling within one standard deviation of the mean SST. This suggests that if a good forecast of MDR shear was available forecast skill may be increased compared to a forecast just based on Nino3 SST, especially for extreme years.

**(a)**

**(b)**

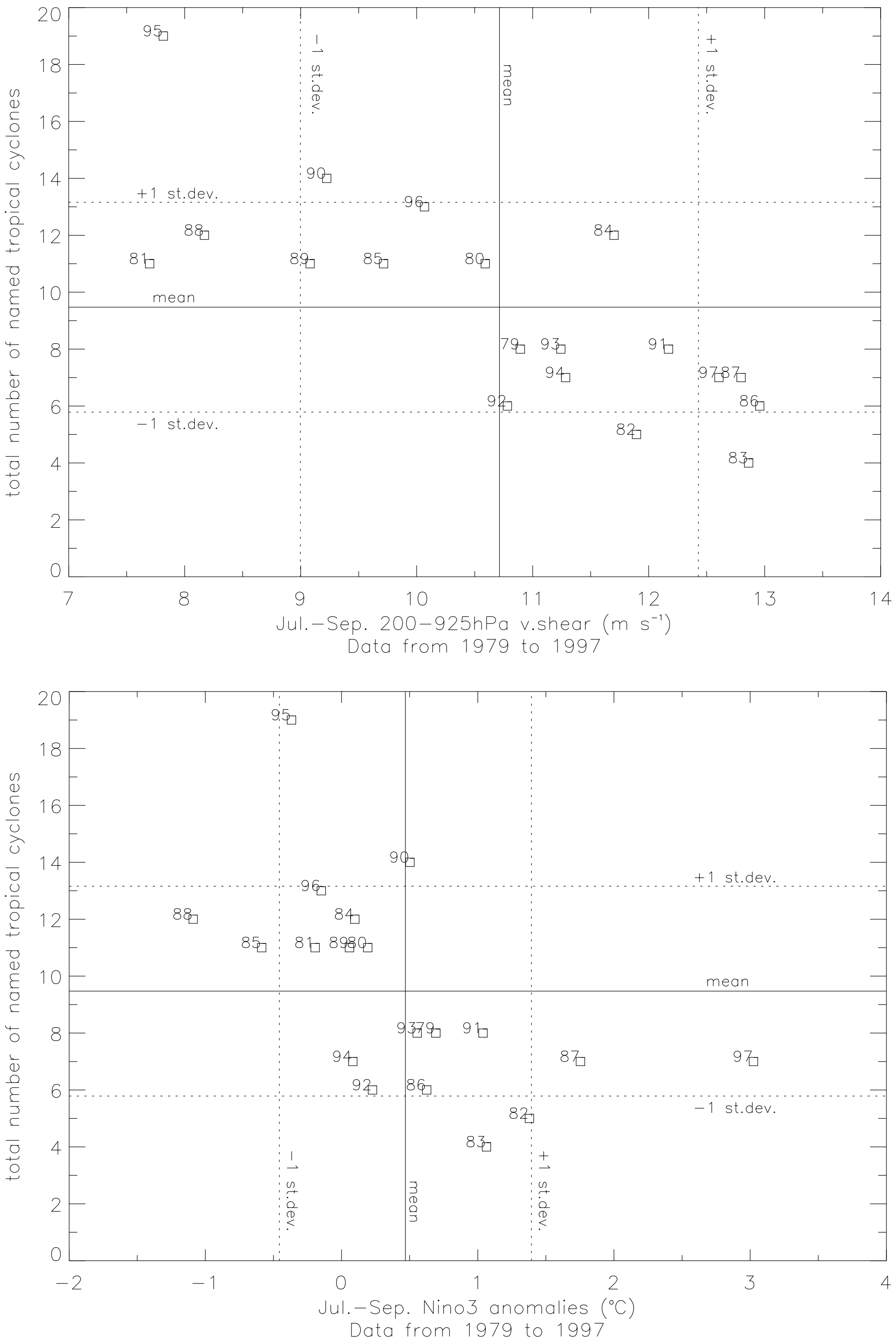
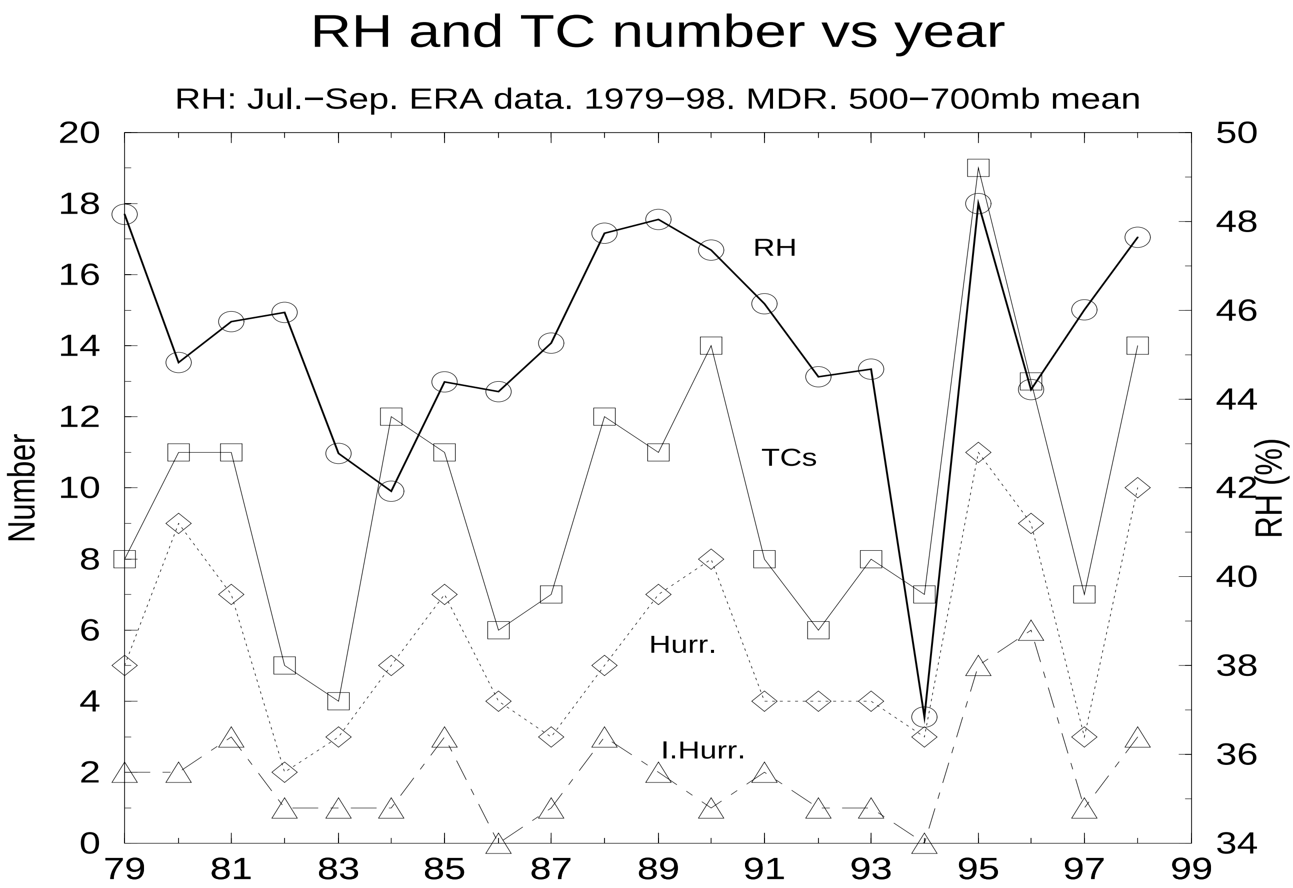



Figure 6. Scatter plots showing (a) number of named storms vs MDR shear and (b) number of named storms vs Nino 3 SST anomalies. Also indicated on the plots are the means and standard deviations.

## 2.4 Relative Humidity

Figure 7 shows a time-series of the MDR relative humidity (circles) averaged over the layer between 500mb and 700mb together with the time series of tropical cyclones, hurricanes and intense hurricanes. We average over this layer, which is about 5km above the surface, because it is known that any anomalous dryness there is likely to inhibit cloud formation and hence inhibit tropical cyclone activity. Figure 7 indicates some variability in this parameter but the linear correlation coefficient with tropical cyclone number is only 0.41, explaining just 17% of the variance. It should




r(v.shear_MDR, TC number)=0.414
(explains 17% of variance)

r(v.shear_MDR, Hurricane number)=0.413
(explains 17% of variance)

r(v.shear_MDR, Intense Hurricane number)=0.412
(explains 17% of variance)

Figure 7. Time-series showing tropical cyclone activity versus mid-level relative humidity in the MDR.

be remembered however that this parameter is difficult to analyse and so has larger errors than the vertical shear. So, the small correlation coefficient may not be a true reflection of reality. It is striking though that in the more recent period, the year-to-year variability appears to be stronger and well correlated with the tropical cyclone activity. This may be consistent with recent improvements in how this parameter is observed and analysed. We conclude therefore that further monitoring of this parameter is required before we can be confident in using it to forecast tropical cyclone activity.

### 2.5 Steering Flows

This work was inspired by the active season of 1995, because although there were many tropical cyclones there were relatively few landfalls. This can be seen dramatically in fig. 8 which shows the tracks for that year. Note that the cyclones that formed in the MDR all tended to recurve polewards before reaching 70$^{o}$W. This was associated with a persistent circulation anomaly illustrated in fig. 9. Figure 9(a) shows in red the anomalous meridional wind at 500mb (solid means stronger than normal wind from the south), together with, in black, the streamfunction at 500mb which is a rough guide to wind direction with air blowing roughly parallel to the lines in the Atlantic region. The striking feature in this figure is the strong wind anomaly around 65$^{o}$W, 32$^{o}$N. This anomaly has been blamed for the poleward steering of the tropical cyclones seen in fig. 8. To illustrate this more clearly the meridional wind anomaly averaged between 20$^{o}$N and 30$^{o}$N is shown as a graph from 80$^{o}$W to 20$^{o}$W in fig. 9(b). The positive anomaly is clearly seen around 65$^{o}$W. The question remains as to whether this was a one-off year or whether similar anomalies can help to explain the tracks in other years. More years are presented to examine this.

In 1996 the tracks shown in fig. 10 show that the tropical cyclones developing in the MDR tended to reach further west than in 1995, thus making landfall more likely. The graph of anomalous mer-

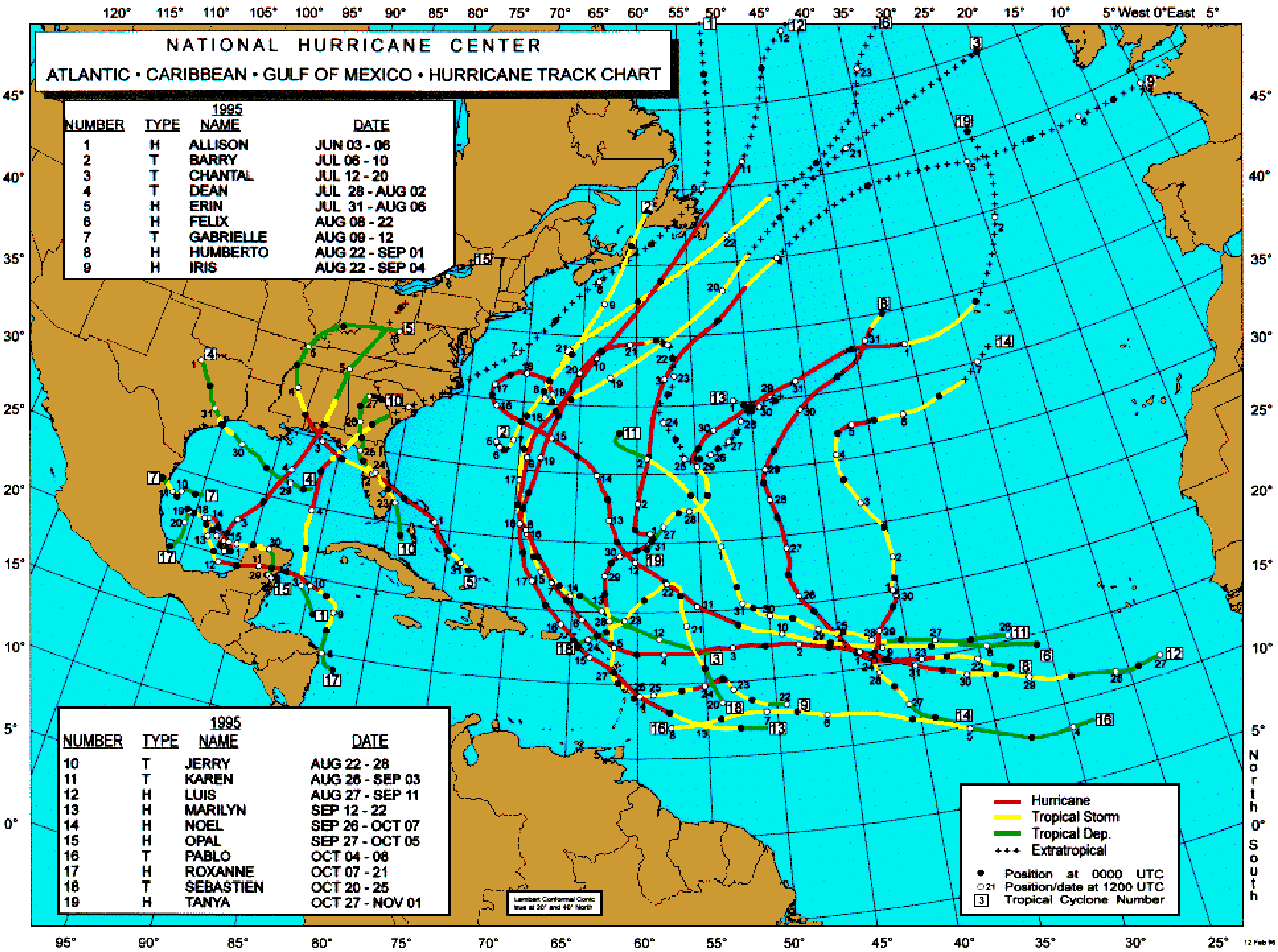


Figure 8.Tropical cyclone tracks for 1995, from the National Hurricane Centre, Miami..

idional wind is shown in fig. 11. The strong meridional wind anomaly which steered the tropical cyclones polewards in 1995 was not present in 1996, consistent with the more westward reaching tracks.

To further illustrate this fig. 12 shows the tracks in 1988 and 1989. The tracks in 1988 tended to track more westwards into the Caribbean whereas those in 1989 tended to recurve before. The meridional wind anomalies for these two years are shown in figs. 13. Consistent with the recurving tropical cyclones in 1989, a broad meridional wind anomaly greater than 0.5ms$^{-1}$ was present around 60$^{o}$W whereas only weak anomalies were present in 1988.

We conclude that some years are associated with persistent steering flow anomalies which make recurvature more likely. The active 1995 season is a particularly good example. We hypothesise that years without such strong anomalies will result in increased likelihood of landfall. The question remains as to whether these steering flow anomalies are predictable or not. This will be investigated in section 3.5 below.

**(a)**

**(b)**

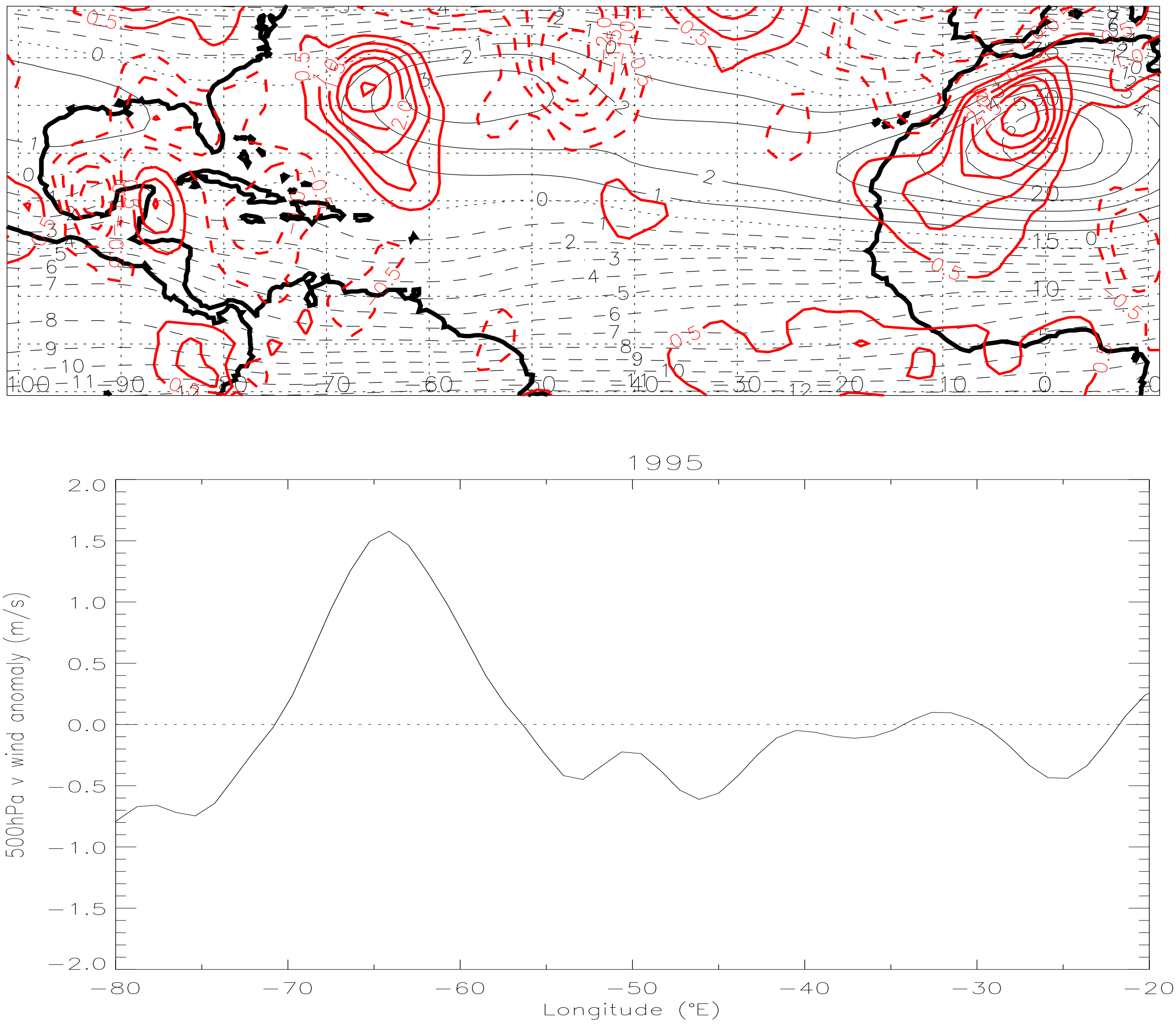



Figure 9 (a) 500mb streamfunction in black and meridional wind anomalies in red ($ms^{-1}$) for July-September 1995. (b) 500mb meridonal wind anomalies for July-September 1995 averaged between $20^oN$ and $30^oN$.

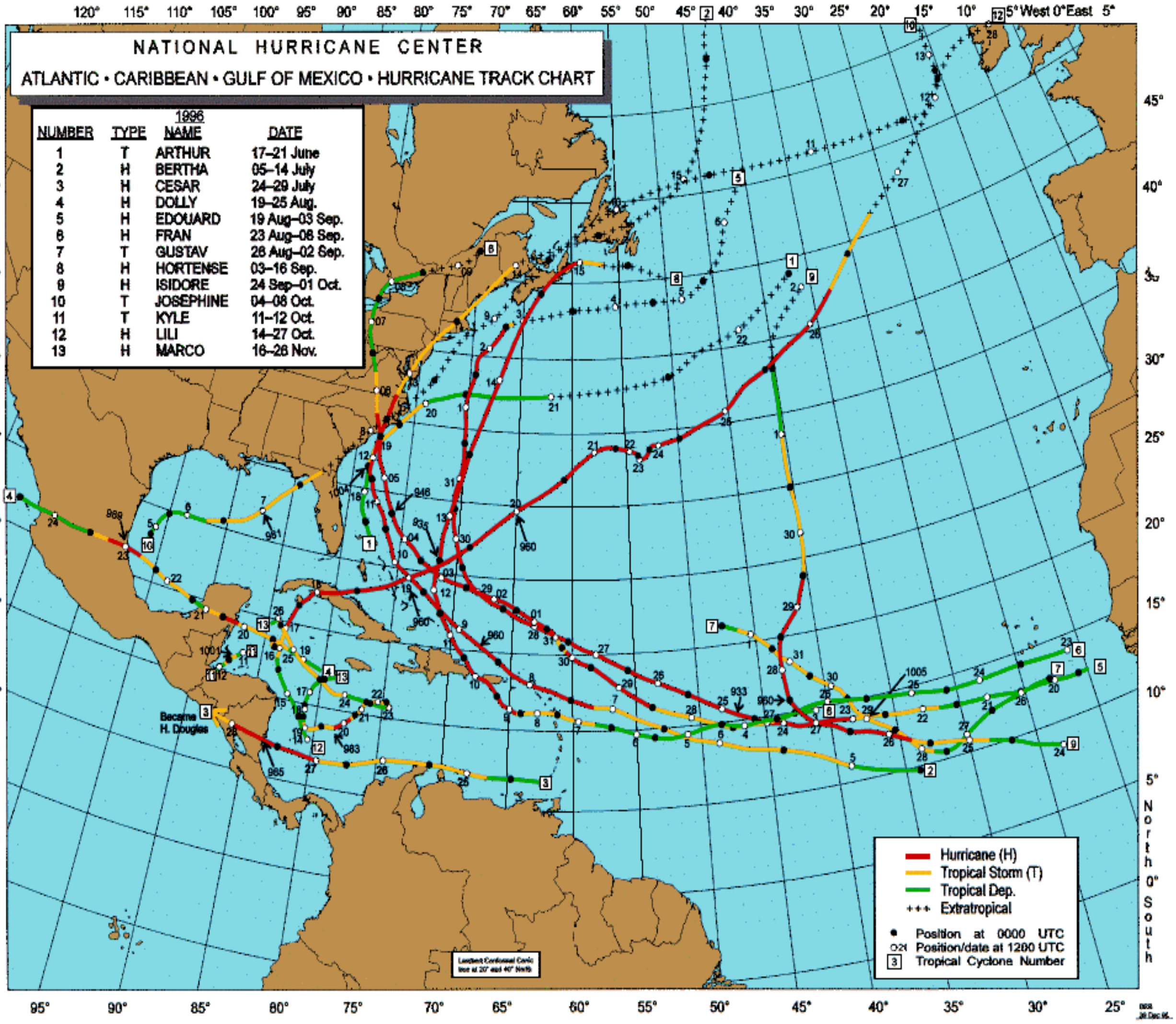



Figure 10.Tropical cyclone tracks for 1996, from the National Hurricane Centre, Miami..

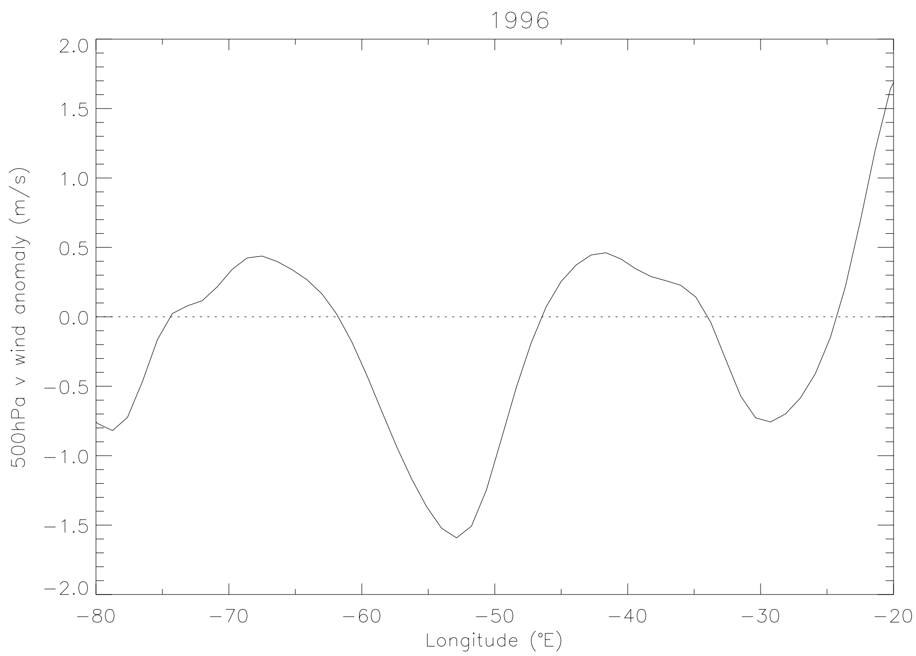
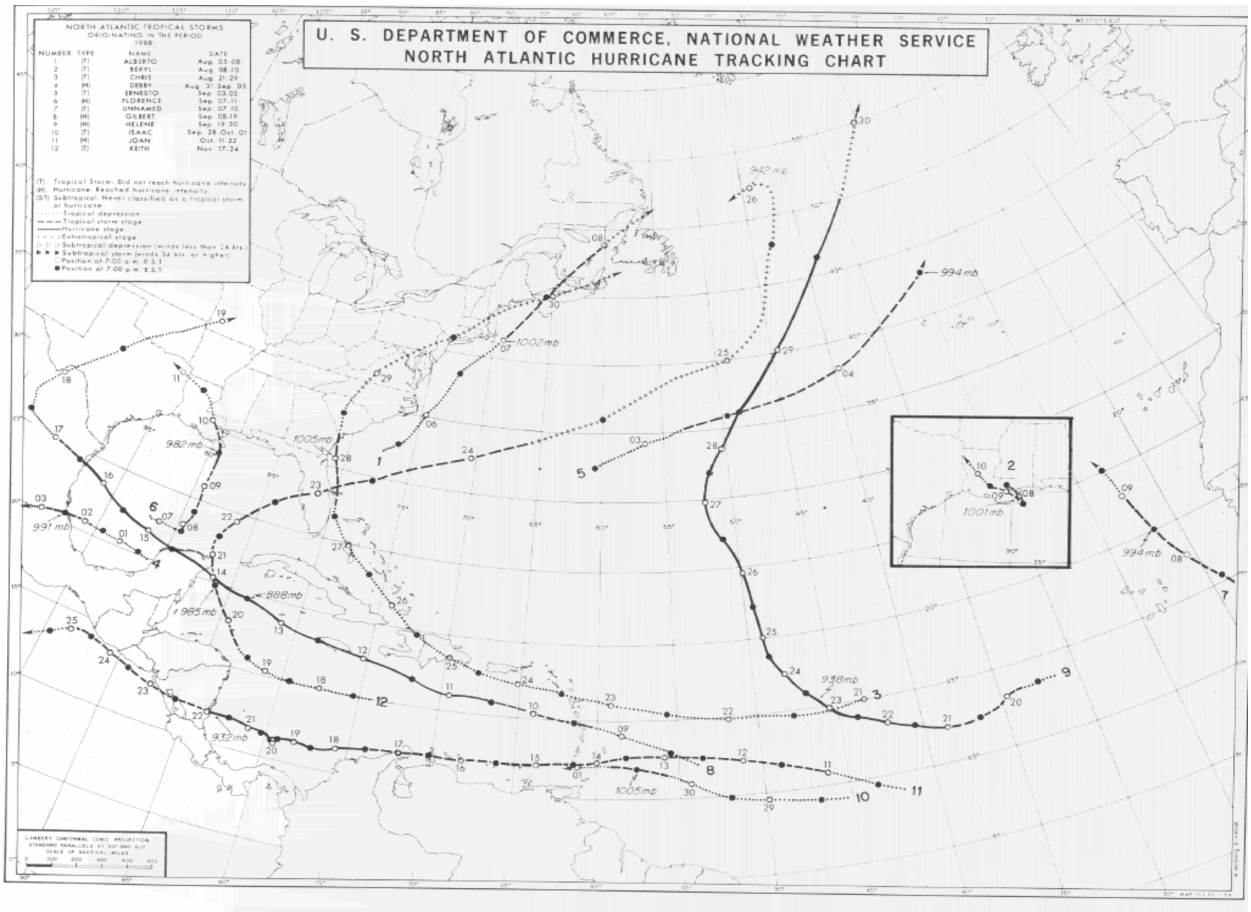



Figure 11. 500mb meridonal wind anomalies for July-Septemver 1996 averaged between 20$^{O}$N and 30$^{O}$N .

(a)




(b)

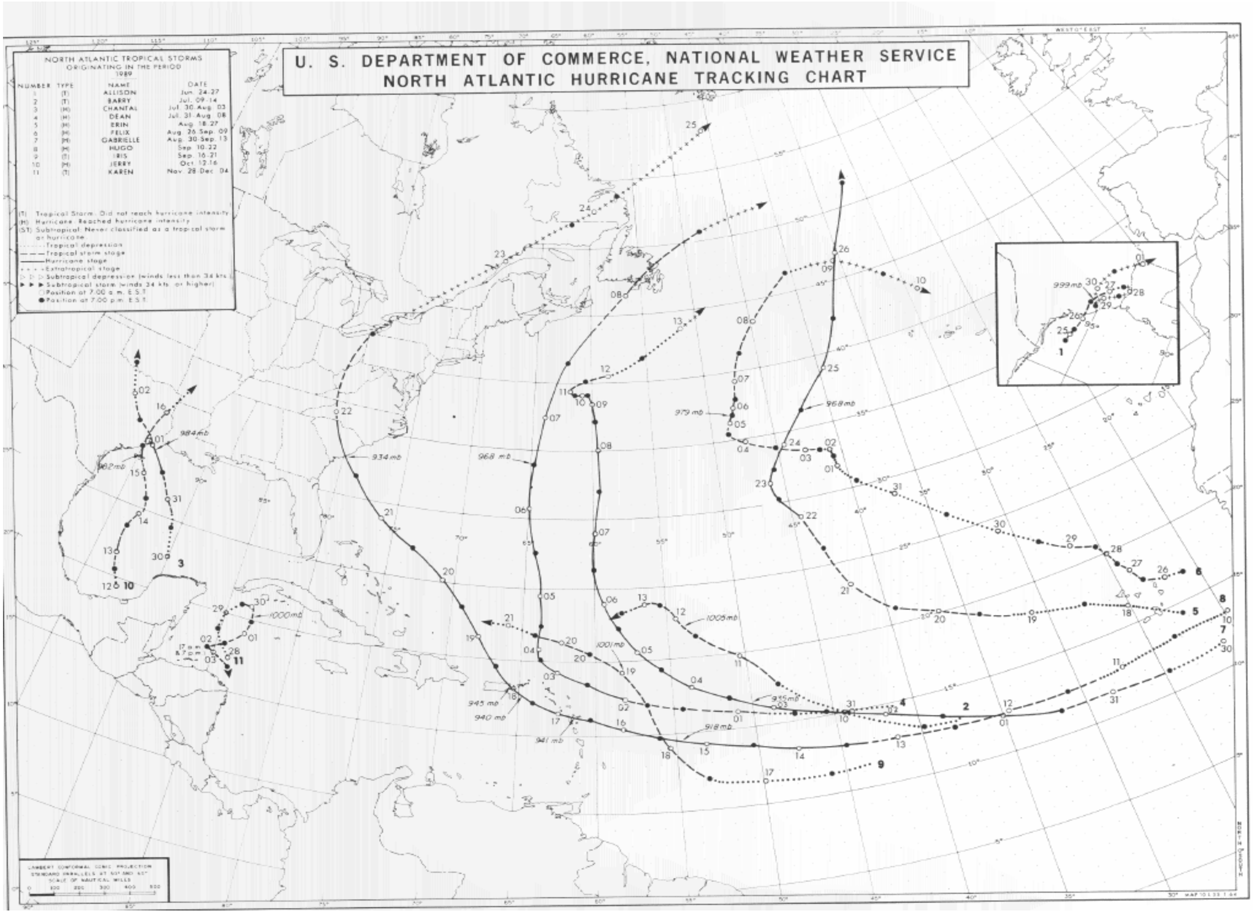
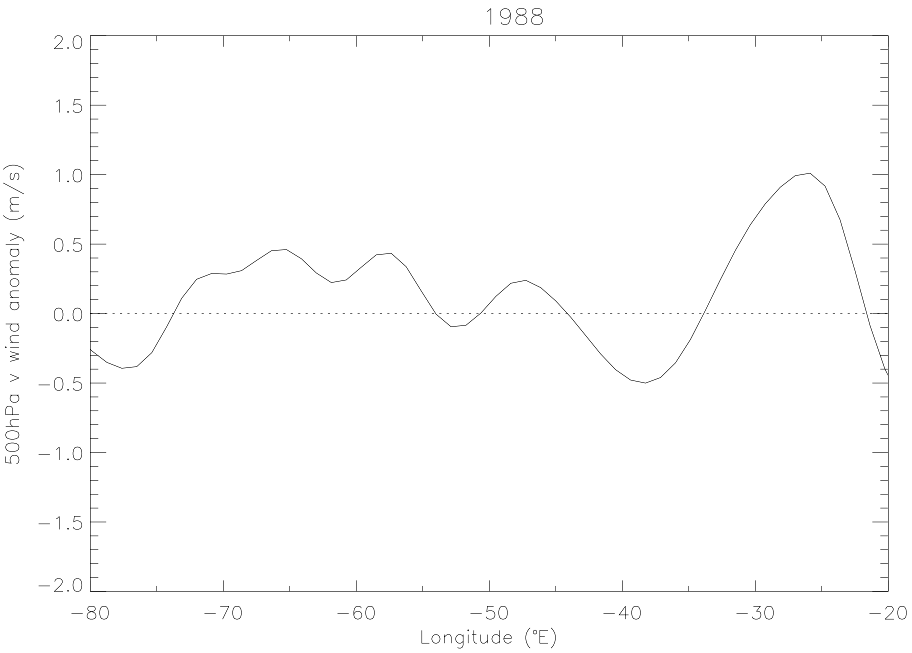



Figure 12.Tropical cyclone tracks for (a) 1988 and (b) 1989, from the National Hurricane Centre Miami.

(a)




(b)

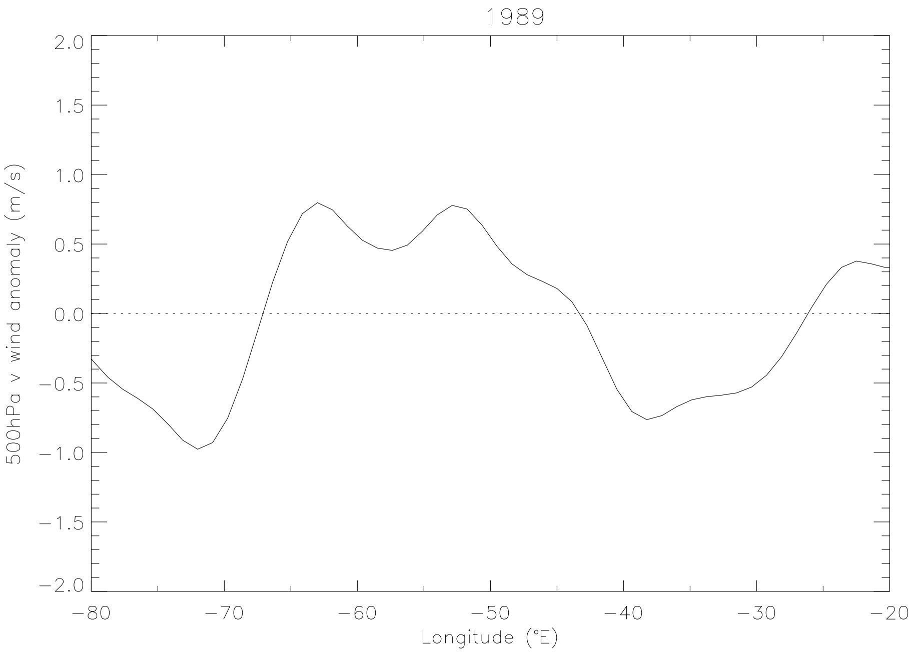



Figure 13. 500mb meridonal wind anomalies averaged between $20^{o}$N and $30^{o}$N for July-September (a) 1988 and (b) 1989.

# 3. Analysis of Forecasts

### 3.1 Background

The most important result in the previous section was that there is a very strong relationship between MDR shear and tropical cyclone activity. It is clear therefore that if we are able to predict the July-September MDR shear with a 4 month lead time, then a useful forecast of tropical cyclone activity will be possible. The main aim of the present section is to assess the skill of the UKMO atmospheric general circulation model (AGCM) in predicting the parameters analysed above and in particular the MDR vertical shear.

### 3.2 Datasets used

The tropical climate is strongly influenced by the tropical sea surface temperatures (SSTs). The SSTs are therefore an important boundary condition used in running the AGCM. The forecasts analysed here are made using the UKMO AGCM for the years 1979-1997 and are based on the observed SSTs for each year. In this sense they are not true forecasts, since in order to be a true forecast the SSTs themselves must also be predicted. We examine these so-called ‘hindcasts’ because if the AGCM is unable to give useful predictive skill with the observed SSTs it has little hope of doing so with the forecast SSTs. Each forecast is made from the end of May and we consider the July-September average.

In the section 4 below, we also provide a real forecast of the MDR shear for 1999. The SSTs used in this forecast are predicted by using persistent SST anomalies present at the end of May when the forecast was made.

Each seasonal forecast is made of 9 members. These are forecasts made with the same SSTs but different atmospheric initial conditions. This ‘ensemble’ approach is used to assess the level of predictability. If the 9-member ensemble has a large spread then predictability is low whereas if it is small the predictability is higher and our confidence in the forecast is therefore higher.

### 3.3 Vertical Wind Shear

#### a. Hindcasts

Figure 14 shows the analysed shear (circles) based on the 200mb and 950mb levels together with the forecast shear from the 9 members of each ensemble. The 950mb level was used instead of 925mb because the forecasts did not output on the 925mb level. Superimposed on this are the forecasts. It needs to be stressed here that the agreement between the analysed shear and the forecast shear is extremely good. The correlation between the ensemble mean shear and the analysed shear is 0.66 (significant at the 99% level). This suggests that the current UKMO AGCM, given good SSTs has good skill in predicting the MDR shear and hence tropical cyclone activity. Also, the correlation between the mean ensemble forecast shear with observed tropical cyclone activity is -0.5 and with hurricane activity is -0.65; both lower than the analysed shear but this is to be expected.

The results depicted in fig. 14 are extremely encouraging. They tell us that the UKMO AGCM is capable of forecasting MDR shear to a reasonable accuracy. Of course, this is assuming that the SSTs used are accurate and in this case they are. Operationally these SSTs will themselves need to be predicted.

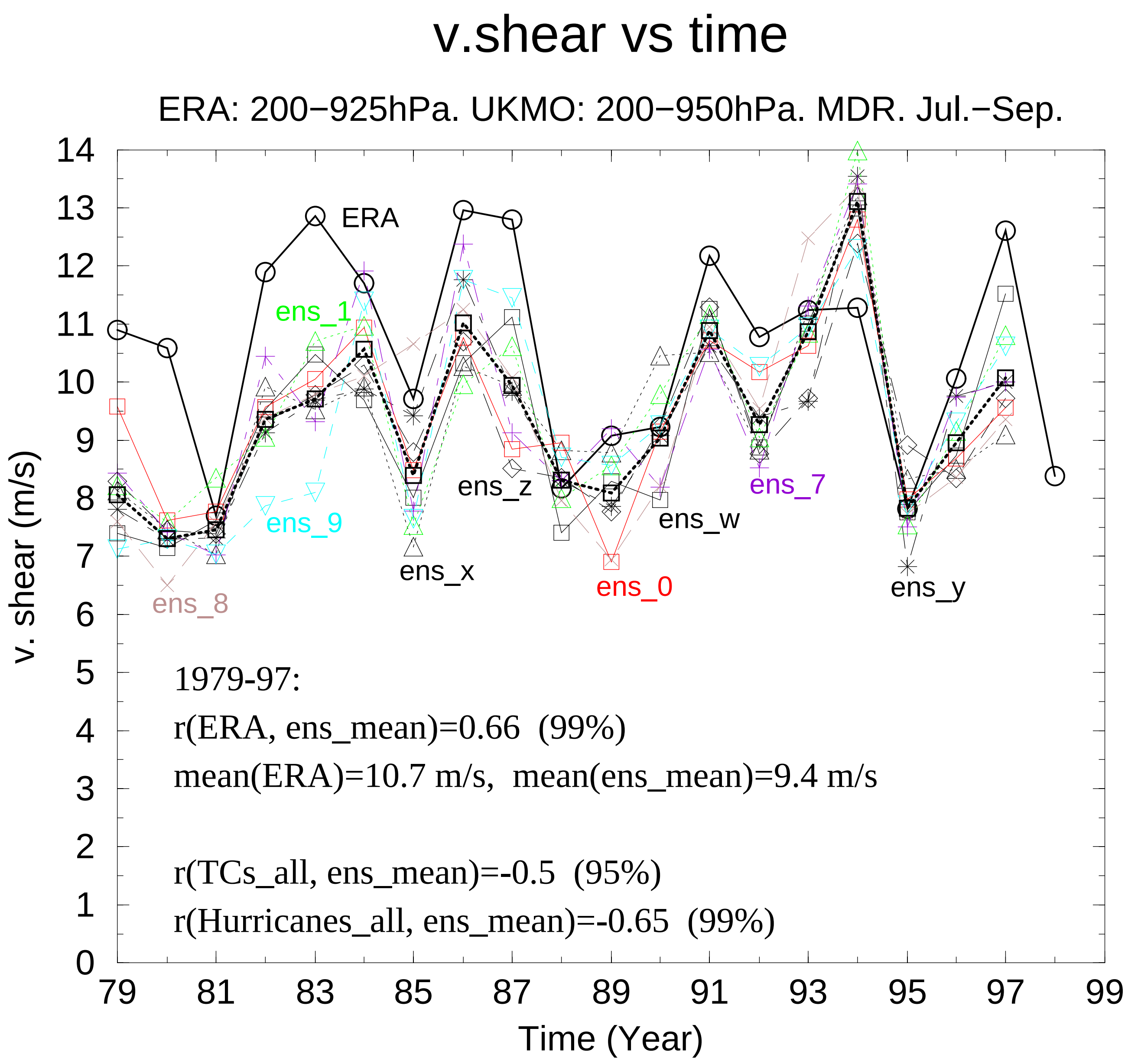



Figure 14. Time-series of analysed MDR vertical shear (black lines) together with the forecasts from each member of the ensemble forecast (coloured lines).

Analysis of the shear for the west and east MDR regions are shown in Appendix A. This reveals that the skill is greater in the west MDR than the east MDR. Future work should consider why this is the case.

Analysis of the shear for the regions used by the UCL group are included in Appendix B together with a map of their regions. Skill in forecasting skill is good for UCL's MDR and Caribbean region, but it is low for their Gulf and their north Atlantic region.

**b. Relationship with El Nino and West African rainfall**

In section 2.3.c above the relationship between analysed MDR shear and El Nino and West African rainfall (WAR) was examined. It is important that the UKMO AGCM reproduces the observed relationships. Table 2 below summarises the relationships between MDR shear and Nino 3 SSTs and WAR. What can be seen is that although the relationship between MDR shear and WAR in the model is reasonably well reproduced, the model underestimates the relationship with El Nino. This gives us a clue to why the forecast MDR shear does not match perfectly with the observed MDR shear and suggests an important area for future research.

**Table 2: Correlations July-September 1979-97**

| Linear correlations | ECMWF analyses | UKMO AGCM |
|---|---|---|
| MDR shear and Nino3 SST | +0.74 | +0.34 |
| MDR shear and WAR | -0.49 | -0.41 |

**c. Seasonal Evolution**

Figure 15 shows the evolution of the analysed MDR shear anomalies for 12 of the years studied (as previously shown in fig. 4), but now superimposed on this are, for each year, the 9 forecasts. The forecast anomalies are relative to the analysed shear and because of the slightly weaker mean shear in the forecasts (c.f. fig. 14) the lines tend to fall below the observed shear lines. The purpose of presenting these figures though is to examine the evolution from June-September to see if analysed trends are reproduced. Examining fig. 15 reveals some notable successes, for example the marked upward trend observed in 1984 is reproduced. Inspection of these graphs shows that qualitatively the seasonal evolution is handled reasonably well.

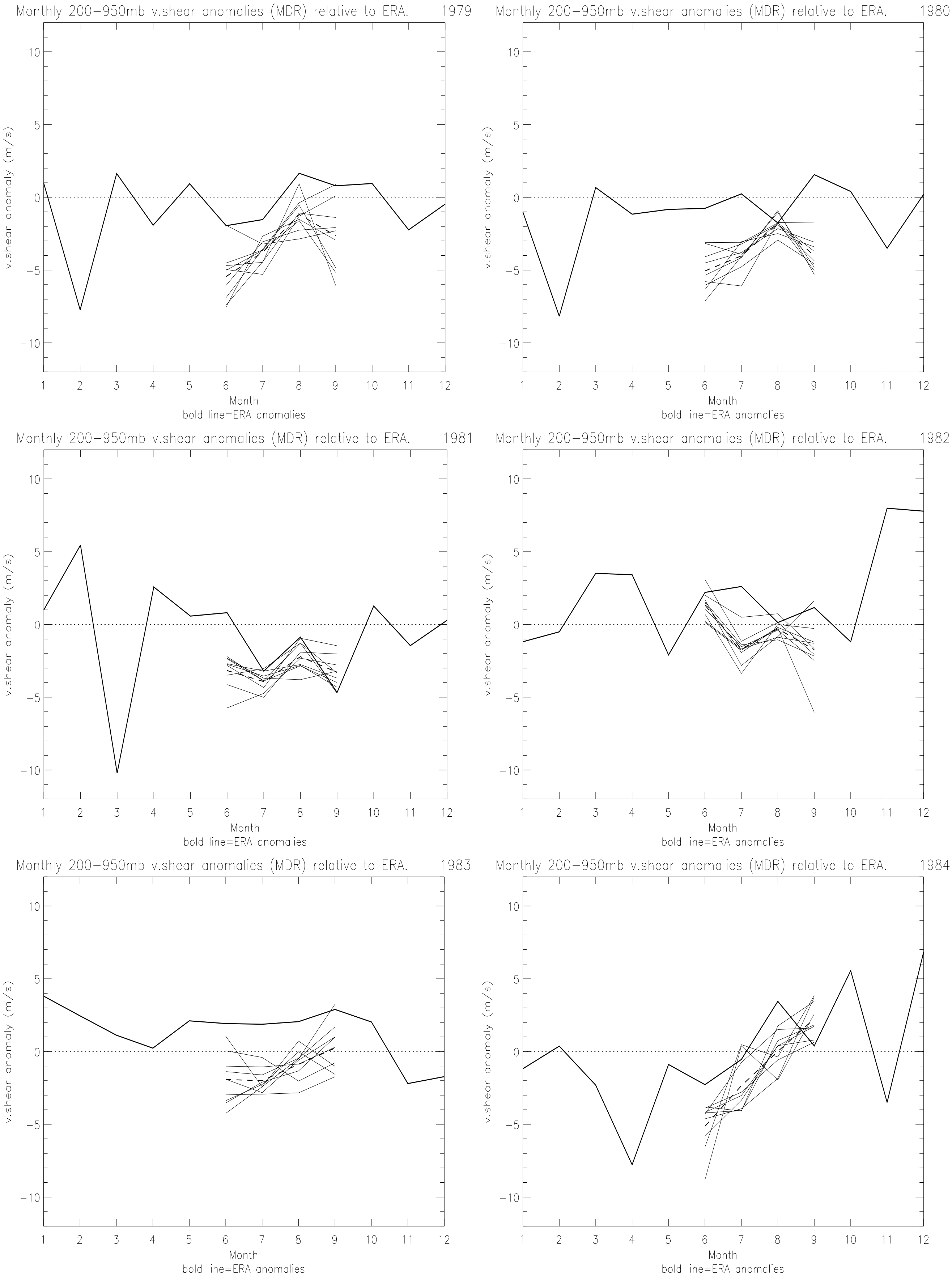



Figure 15. Forecasts of monthly mean MDR vertical shear anomalies together with the ERA anomalies (continuous line).

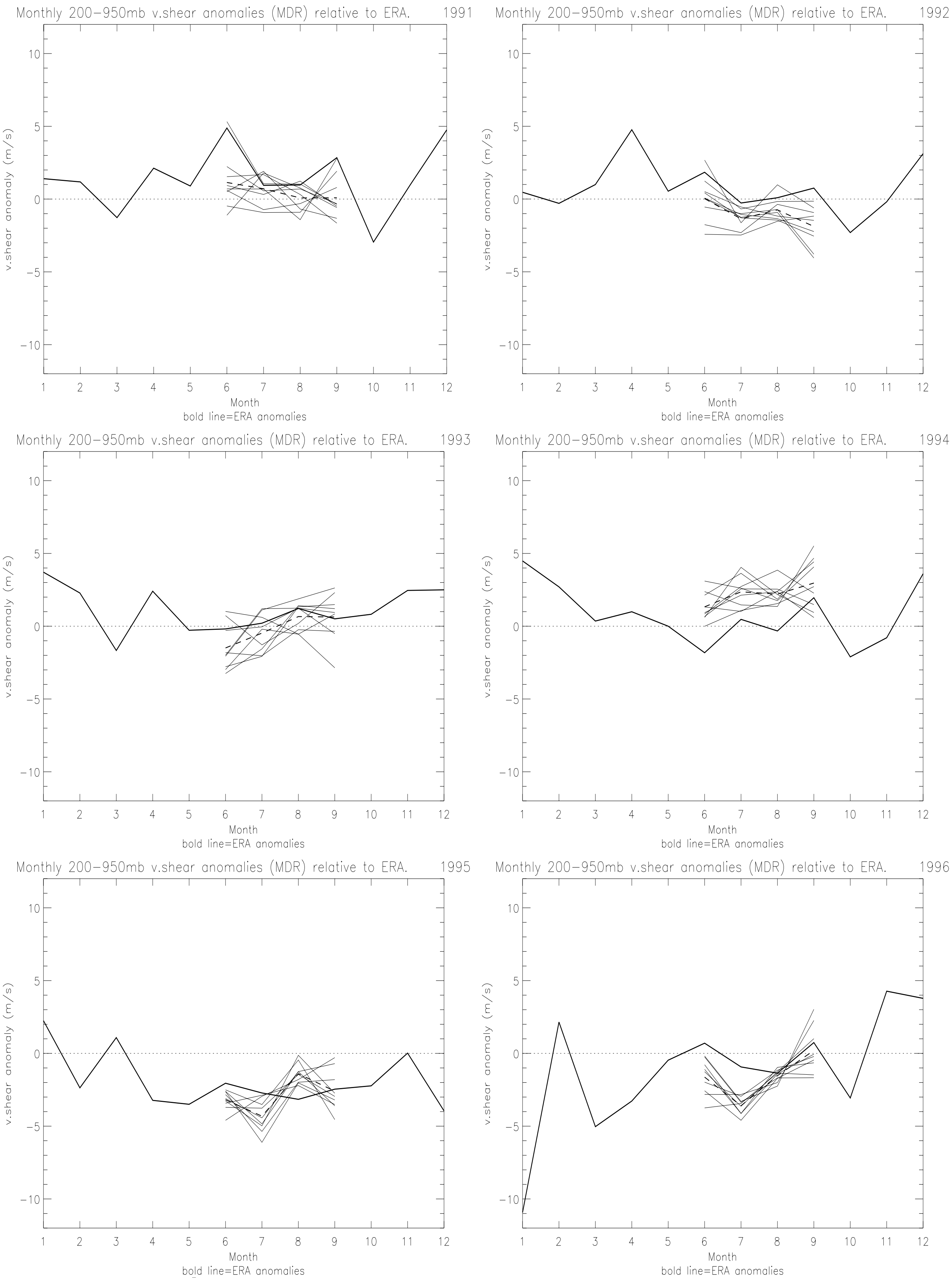


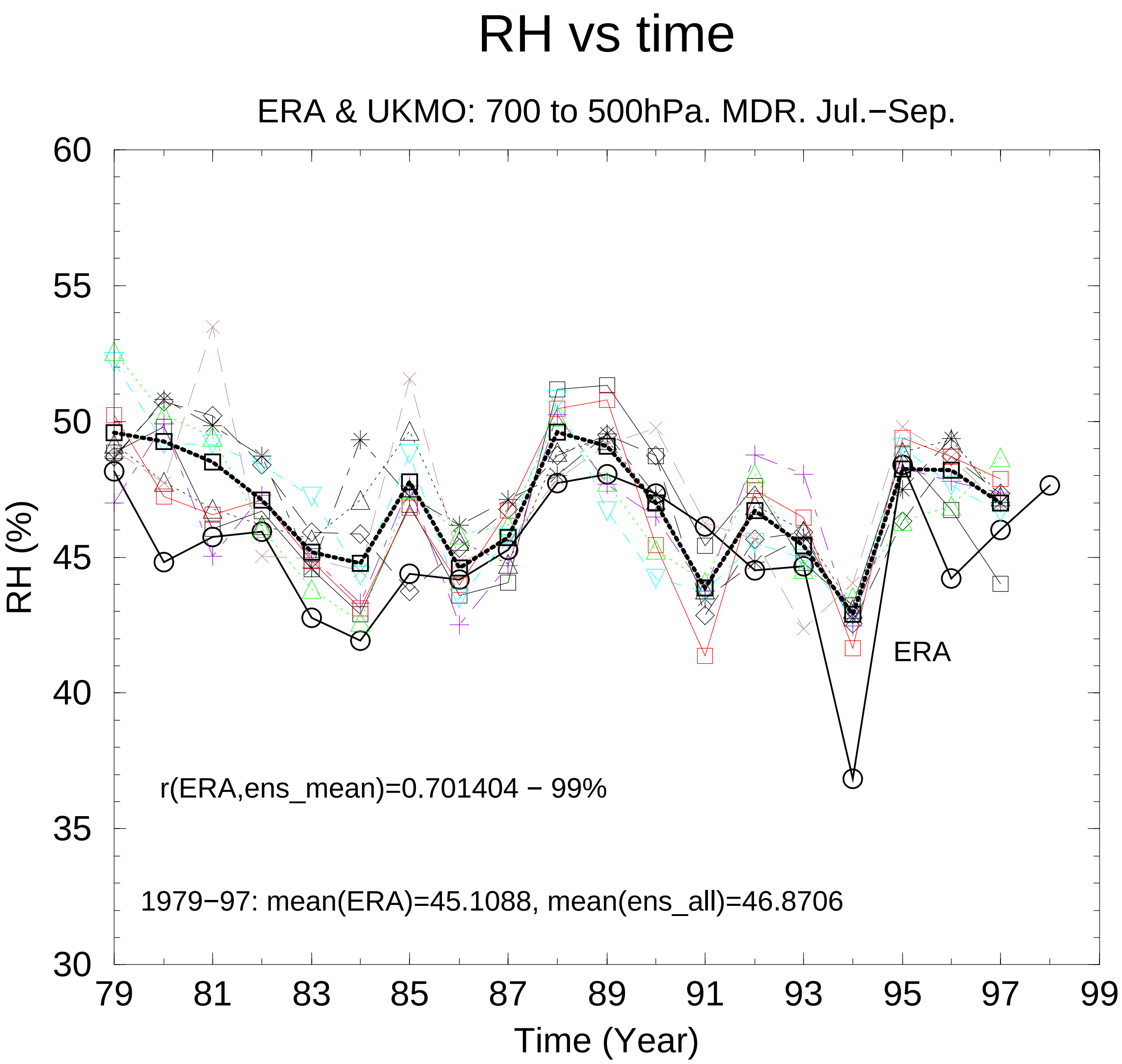

Figure 15 continued

Further analysis of this data is required to assess whether there is any relationship between the seasonal evolution of the MDR shear and seasonal evolution of tropical cyclone activity. The fact that the trends are reasonably well captured in the forecasts suggests that if there is a seasonal relationship with tropical cyclone activity a useful forecast may be possible.

### 3.4 Relative Humidity

Figure 16 shows the analysed relative humidity (circles) based on the 700mb and 500mb layer average together with the forecast relative humidity from the 9 members of each ensemble. The correlation between the ensemble mean relative humidity and the analysis is again extremely good, with a linear correlation coefficient of 0.7. This is a surprising result, since our confidence in analyses and forecasts of relative humidity is usually very low. This is because the field is very difficult to observe and also very difficult to predict. It is particularly encouraging to see the change from a dry season in 1994 to the moist season in 1995

The linear correlation between the ensemble mean relative humidity and the tropical cyclones and hurricanes is 0.47 and 0.57 respectively. Both values are slightly lower than those found with the ensemble mean shear. It should be noted though that the shear and relative humidity fields are not necessarily independent and including both in a forecast may not increase the forecast skill. A comparison, for example, of the ensemble mean MDR shear variability (fig. 14) and ensemble mean MDR relative humidity (fig. 16) shows a marked negative correlation between the two fields.




r(TCs_all, ens_mean)=0.47 (95%)

r(Hurricanes_all, ens_mean)=0.57 (95%)

Figure 16. Time-series of analysed MDR mid-level relative humidity (black lines) together with the forecasts from each member of the ensemble forecast (coloured lines).

The conclusion from this section is that relative humidity could well be a useful field to consider in producing a forecast of tropical cyclone activity; however it is recommended that further work be done before it is incorporated; including an assessment of the confidence in the analysis of this field and to what extent the field can be considered independent of the shear.

### 3.5 Steering Flows

In section 2.5 above we noted that in some years there are pronounced steering flow anomalies which can be linked to the tropical cyclone tracks. The most obvious case was that of 1995 which had persistent anomalous winds blowing from the south which helped to steer the many tropical cyclones away from the U.S. coastline (c.f. figs 8 and 9). The question we wish to answer here is whether such steering flow anomalies can be predicted. In order to do this we consider the 1995 season. Figure 17 presents the meridional wind anomalies at 500mb (about 5km high) for each of the members of the ensemble; again solid lines represent anomalous winds blowing from the south, and dashed lines anomalous winds blowing from the north. What we must note from this is that the forecasts vary a lot. For example, the 9th member does show pronounced anomalous winds in the same sense as that which was observed, but the 7th and 8th members show the opposite. This suggests that a strong role is played by high latitudes in the setting up of the anomalous flows that we have discussed, indeed this is not surprising since the maximum anomalous winds in question are located at around 32$^{o}$N. Since high latitude weather patterns are inherently less predictable than those in the tropics the important steering flow anomalies which appear to be important for determining the tropical cyclone tracks are also less predictable. Other years have been examined (not shown) but lead us to the same conclusion.

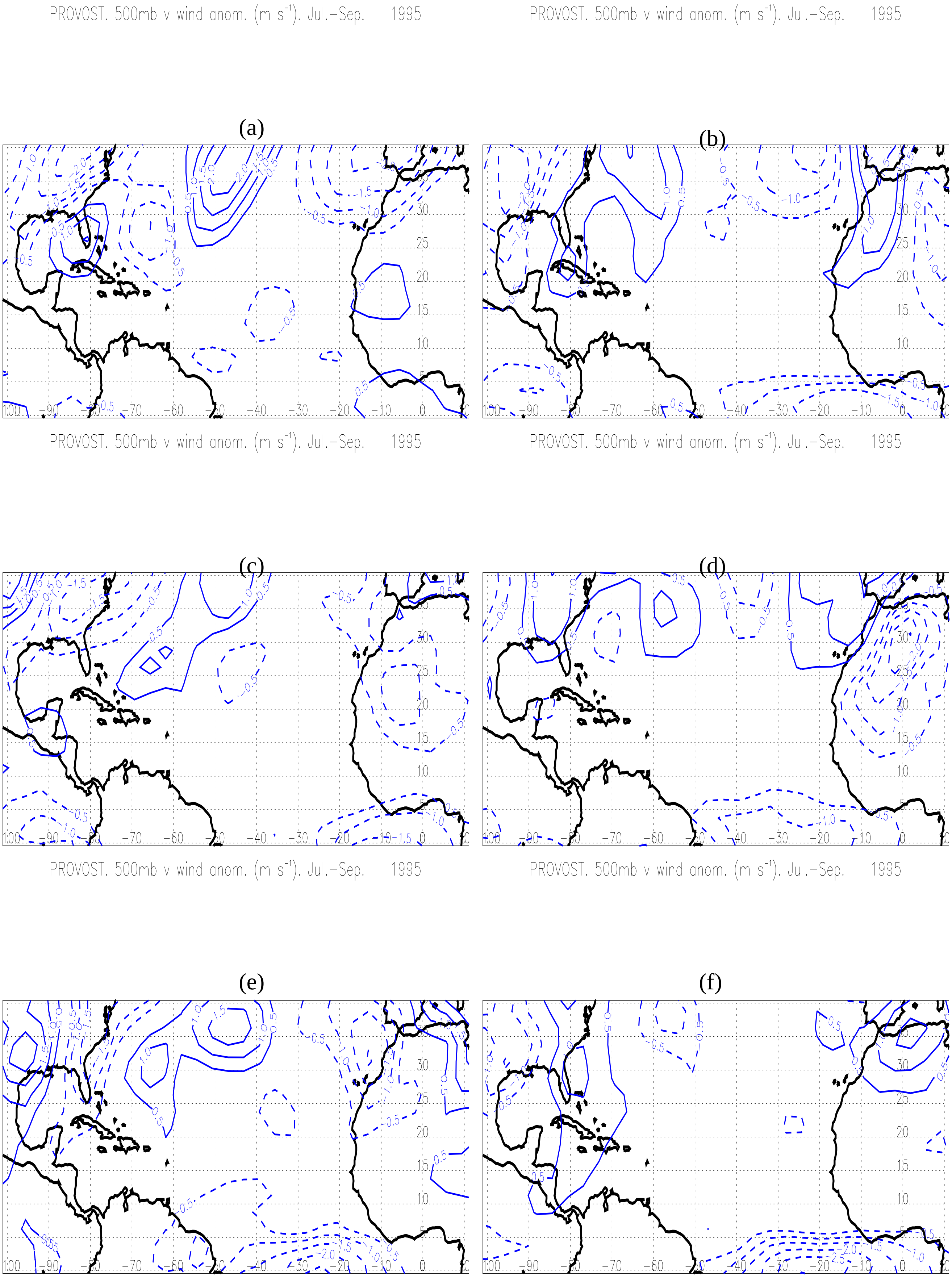
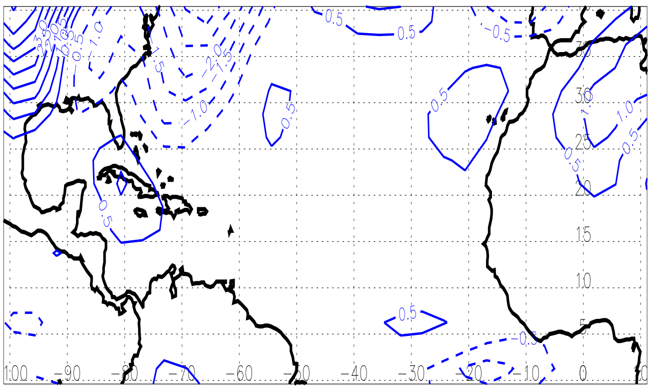



Figure 17 500mb meridional wind anomalies ($ms^{-1}$) for each member of the 1995 ensemble forecast. Solid lines indicate winds from the south.

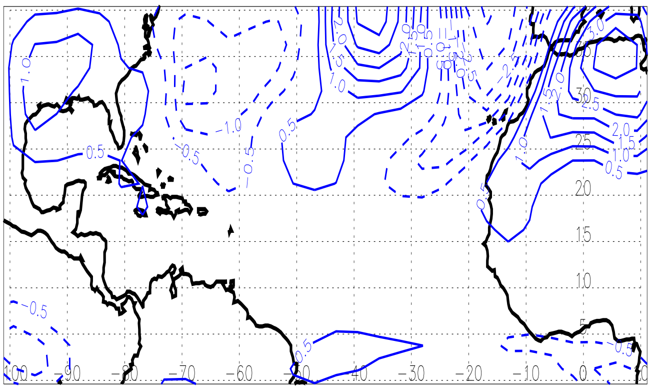
PROVOST. 500mb v wind anom. ($m\ s^{-1}$). Jul.–Sep. 1995

(g)




PROVOST. 500mb v wind anom. ($m\ s^{-1}$). Jul.–Sep. 1995

(h)




PROVOST. 500mb v wind anom. ($m\ s^{-1}$). Jul.–Sep. 1995

(i)

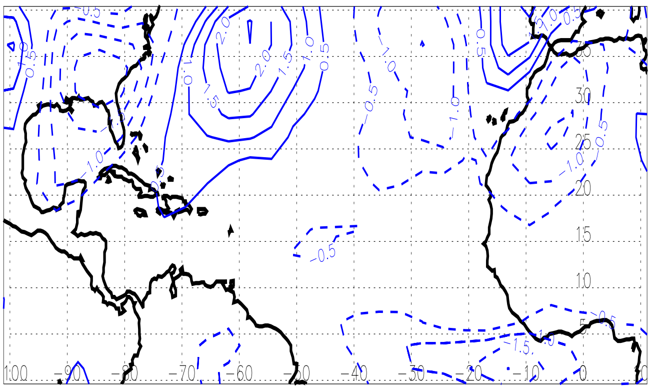



Figure 17 continued

# 4. The Dynamical Forecast for 1999

The UKMO operationally run their AGCM to produce seasonal forecasts; that is the dynamical model is run to produce a 4 month forecast. We therefore used this opportunity to examine the 4 month forecast made at the beginning of June for the 1999 Atlantic tropical cyclone season. In this case the forecast is a true forecast, since in this case the SSTs are not known but have to be predicted. At present the SST prediction is based on persisted SST anomalies superimposed on the seasonal cycle.

The forecast is included in fig. 18 which shows the MDR shear for the years 1979-1998. Highlighted are those years which deviate from the mean by more than one standard deviation. Alongside those years is the number of tropical cyclones that occurred in those years. It is again confirmed here that should the shear deviate from the mean by more than a standard deviation we expect to see either very active or very inactive tropical cyclone seasons depending on the sign of the anomaly. The 9 members of the forecast ensemble are included in the figure together with the mean of the ensemble (marked by a black circle). The mean ensemble shear is predicted to be anomalously weak and so **we expect to have an active tropical cyclone season**. The spread of the forecasts, indicated by the standard deviation of $0.58ms^{-1}$ , is small and so our confidence in the forecast is high.

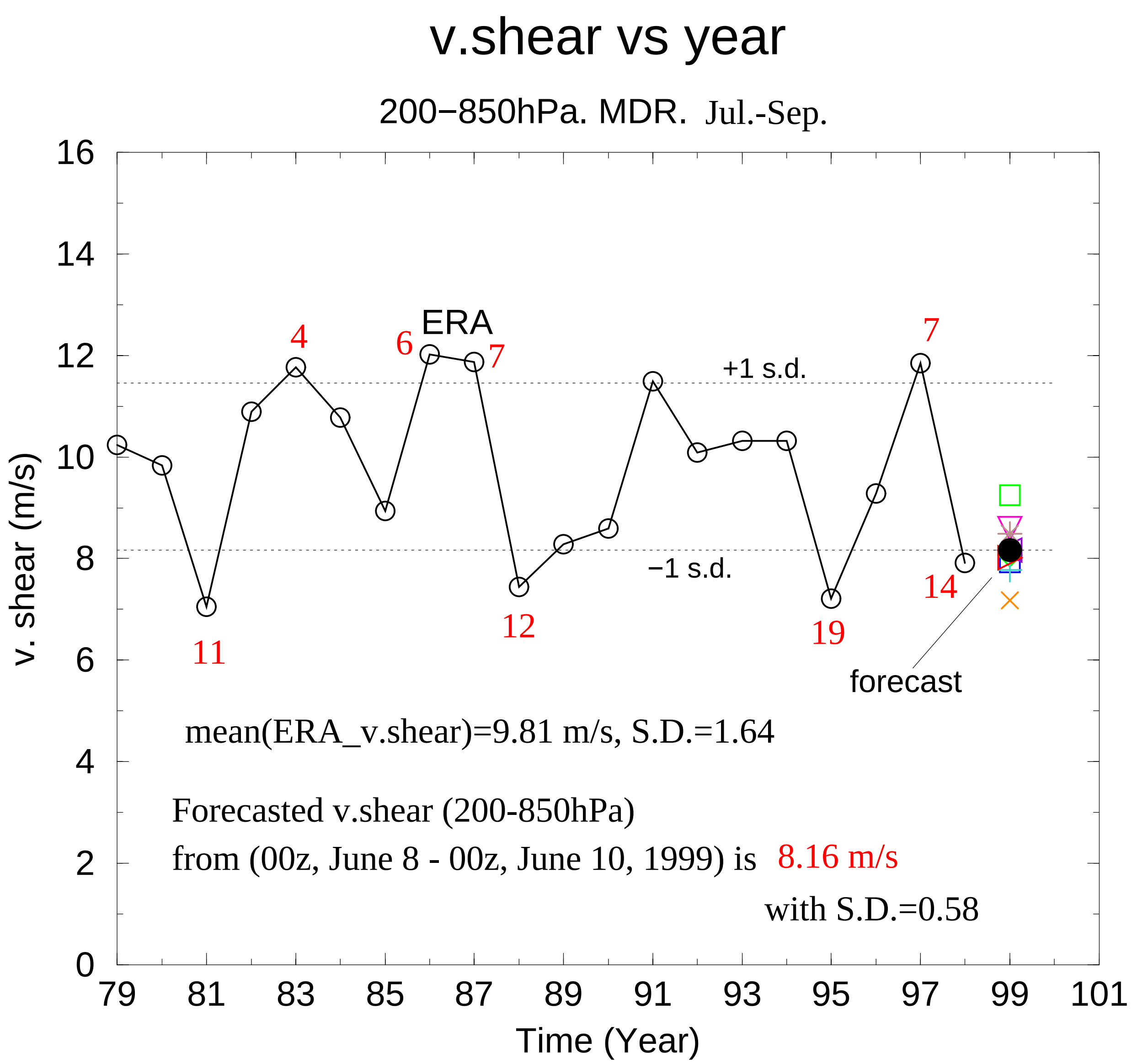



Figure 18 Time-series of MDR vertical shear together with the forecasts for 1999. Included in red are the numbers of named storms in years where the MDR shear is more than one standard deviation greater or smaller than the mean.

# 5. Conclusions and Recommendations

We have mainly focussed here on the shear, because this is the parameter which is local to the region where the tropical cyclones form and is known to directly affect the nature of the tropical cyclones. We have shown clearly that the analysed MDR shear is strongly and negatively correlated with Atlantic tropical cyclone activity thus confirming this hypothesis. We have shown that it is linked to both El Nino and West African rainfall although the relationship it has with these two remote features is likely to vary on decadel timescales. It should also be noted that the MDR shear correlates more strongly with the Atlantic tropical cyclone activity than does El Nino (based on Nino 3 SSTs) for the period of our study.

If a dynamical model could forecast this shear a useful forecast of Atlantic tropical cyclone activity would be obtained, either as a stand-alone forecast or combined with more traditional statistical approaches.

We have shown that the current operational UKMO AGCM has significant skill in predicting the MDR shear, given the observed SSTs. We are extremely encouraged by this result and strongly recommend that future forecasts of Atlantic tropical cyclone activity include the information coming from such dynamical forecasts.

Since it is known that tropical cyclones are also sensitive to the relative humidity in mid-levels of the atmosphere, we have also considered the variability of this field, its relationship with tropical cyclone activity and its predictability. We have shown that the analysed relative humidity is negatively correlated with tropical cyclone activity but much more weakly than with the shear. We must be aware though that our confidence in the analysis of this field is lower than that for the shear. The current UKMO AGCM does have some skill in predicting the relative humidity though which, bearing in mind the known difficulties in modelling this field, was surprising. There is a scientific question which needs to be addressed here in future work and it is: to what extent are the MDR shear and MDR relative humidity independent? There are scientific arguments for their dependence which would suggest that combining shear with relative humidity may not lead to gains in forecast skill. This must be investigated further.

As well as tropical cyclone activity there is a lot of interest in the likelihood of landfall. We have shown that in 1995, although there were many tropical cyclones, most were steered polewards by anomalous persistent winds blowing from the south. A qualitative analysis of other years showed that a lack of such wind anomalies was more likely to lead to landfalling tropical cyclones. Unfortunately, it appears that these wind anomalies are not well predicted in the UKMO model. This-may not be due to any deficiency in the UKMO model, but could simply be due to the important role of high latitude processes, which are inherently less predictable, in determining these anomalies. This should also raise important questions about the likely usefulness of statistical forecasts of landfalling tropical cyclones. If wind anomalies, such as those which occurred in 1995, are important for determining the number of landfalling tropical cyclones, and if these winds are influenced by processes occurring at high latitudes, a statistical forecast is unlikely to be useful.

We conclude with some final recommendations.

**1.** A stand-alone forecast based simply on vertical shear is possible now as guidance to likely Atlantic tropical cyclone activity and should be made available. This should be provided alongside the analysed shear from previous months. Since forecasts are made every week, these forecasts can be compared as the season progresses.

**2.** Efforts should be made to combine the information obtained from the dynamical forecast model with other predictors such as Atlantic SSTs. This should include the development of an Antlantic SST forecast.

**3.** Model development should continue in particular to determine why the relationship between MDR shear and El Nino is not as strong as that observed.

**4.** The relative roles of shear and relative humidity on the tropical cyclone activity needs to be determined.

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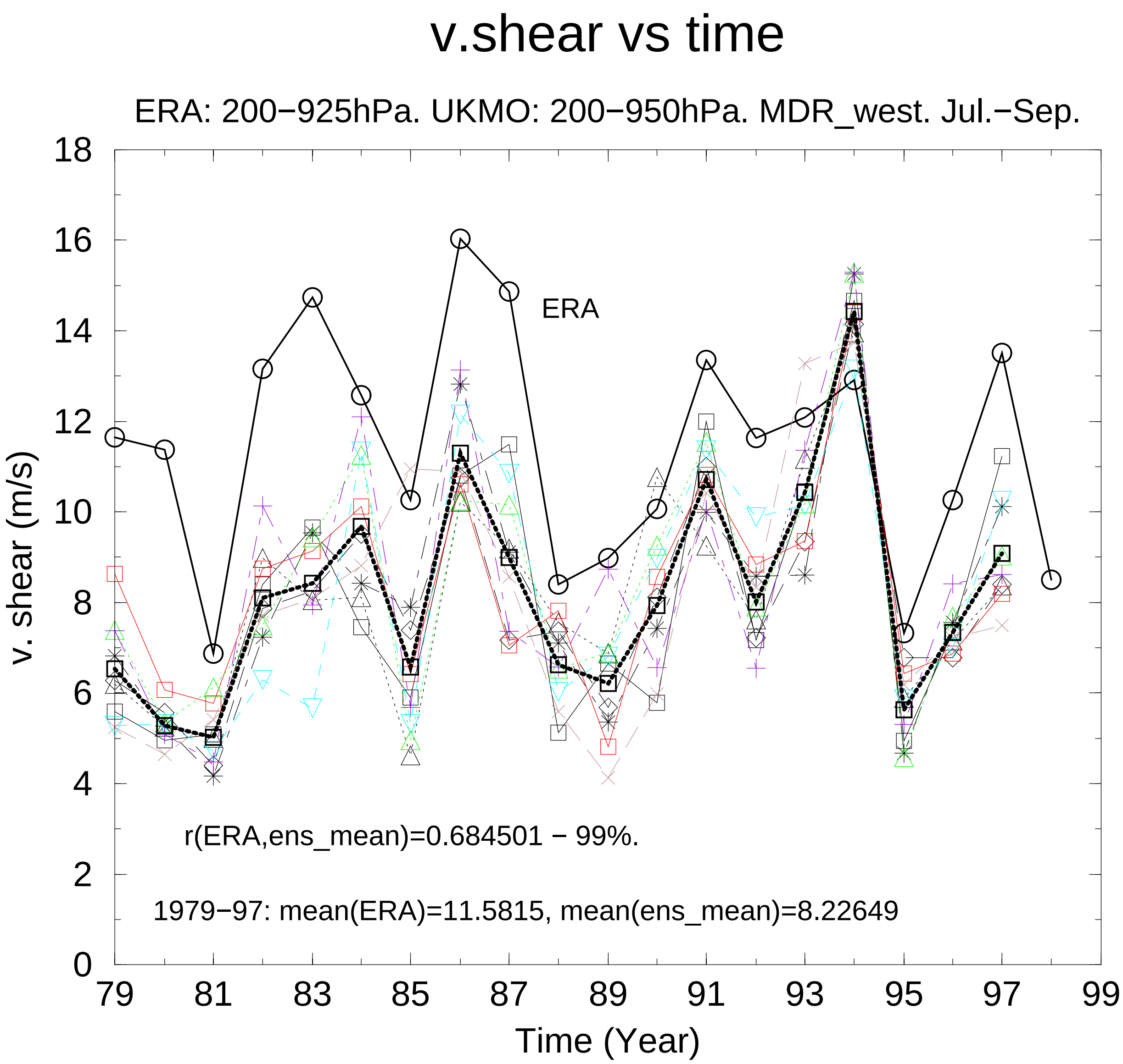
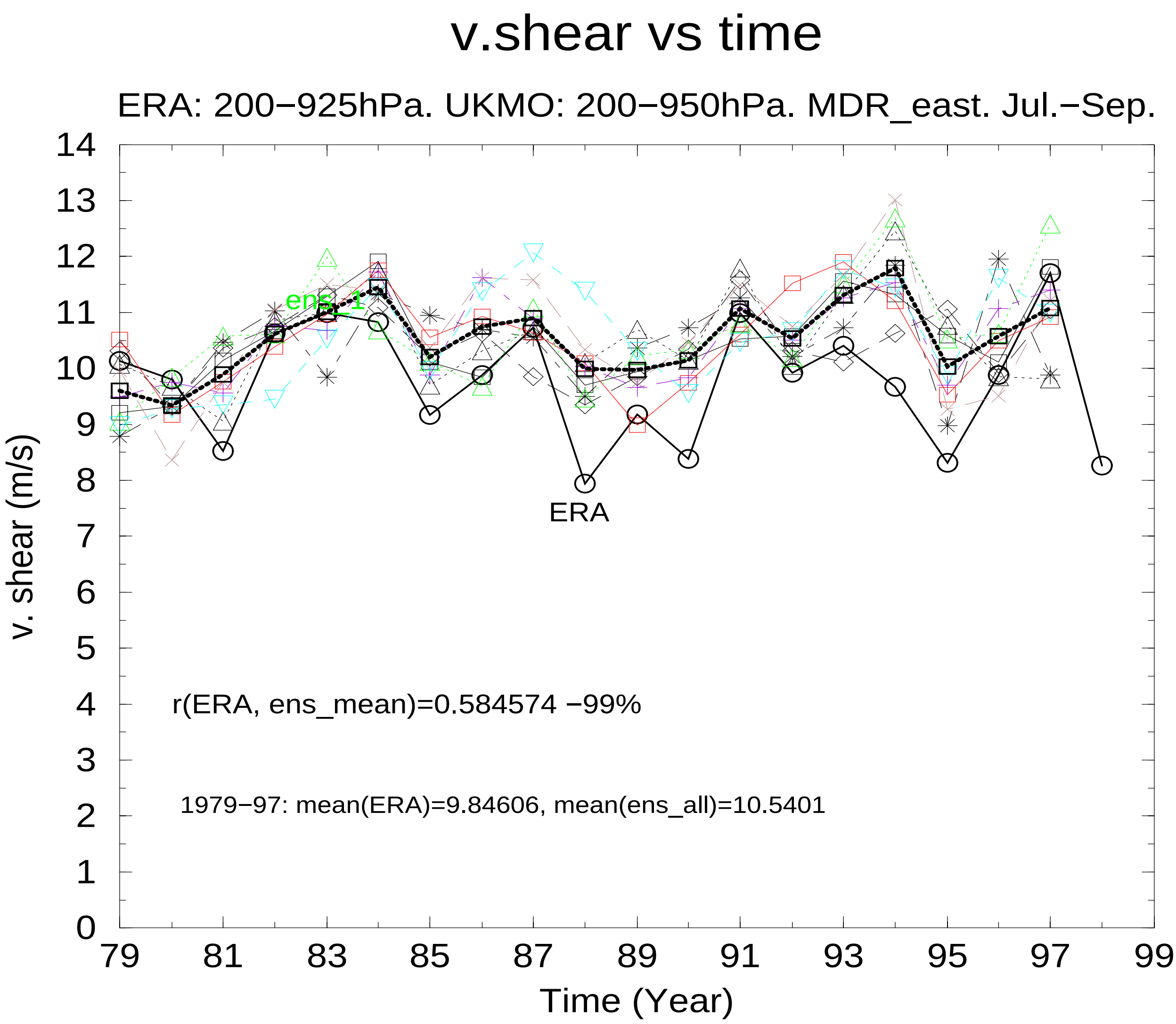
# Appendix A

## Analysed and forecast shear for West MDR and East MDR




r(TCs_all, ens_mean)=-0.5 (95%)

r(Hurricanes_all, ens_mean)=-0.64 (99%)

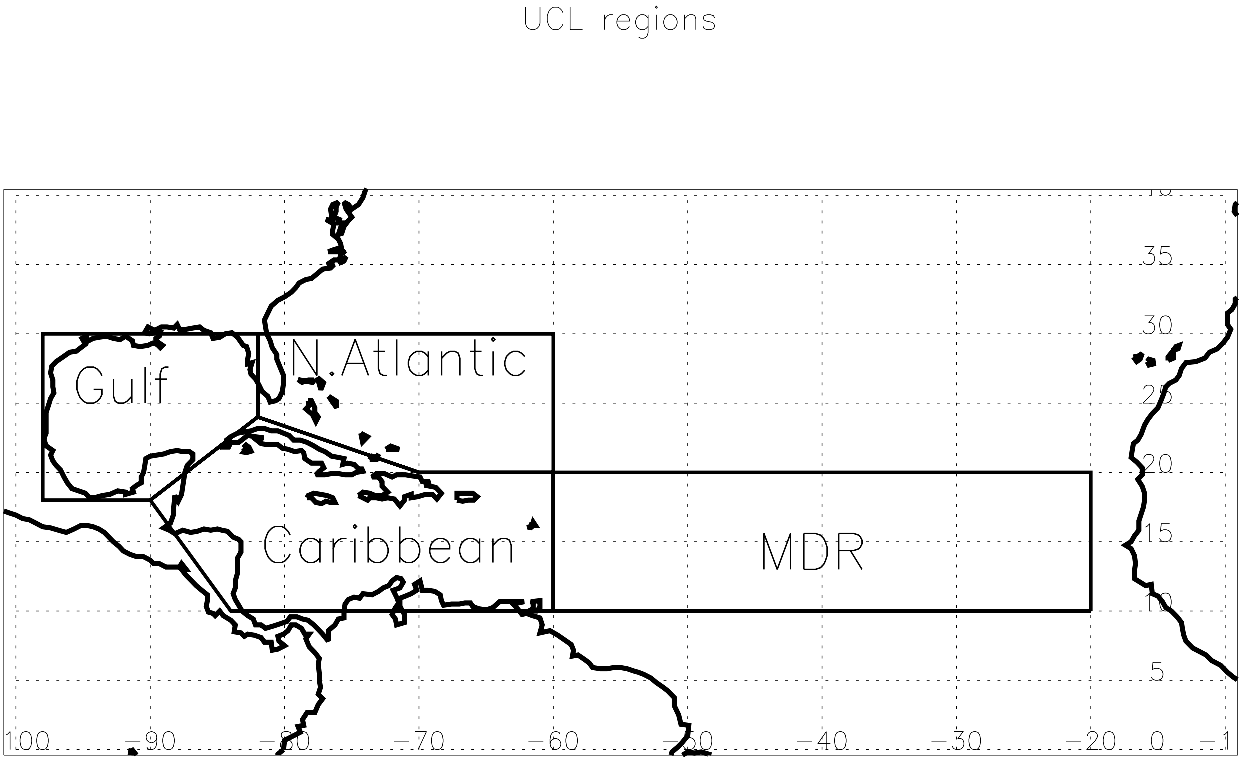


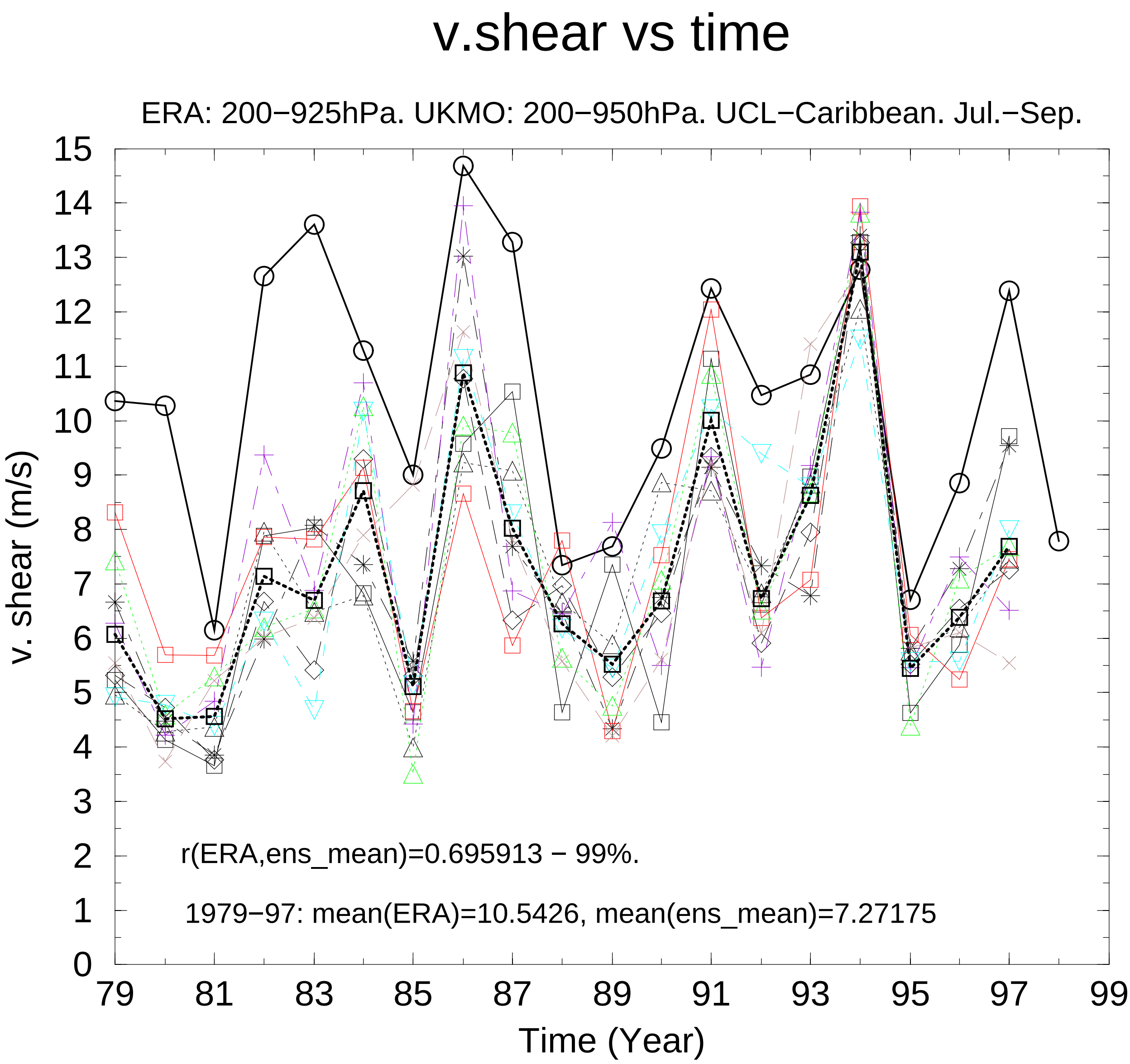

r(TCs_all, ens_mean)=-0.44 (90%)

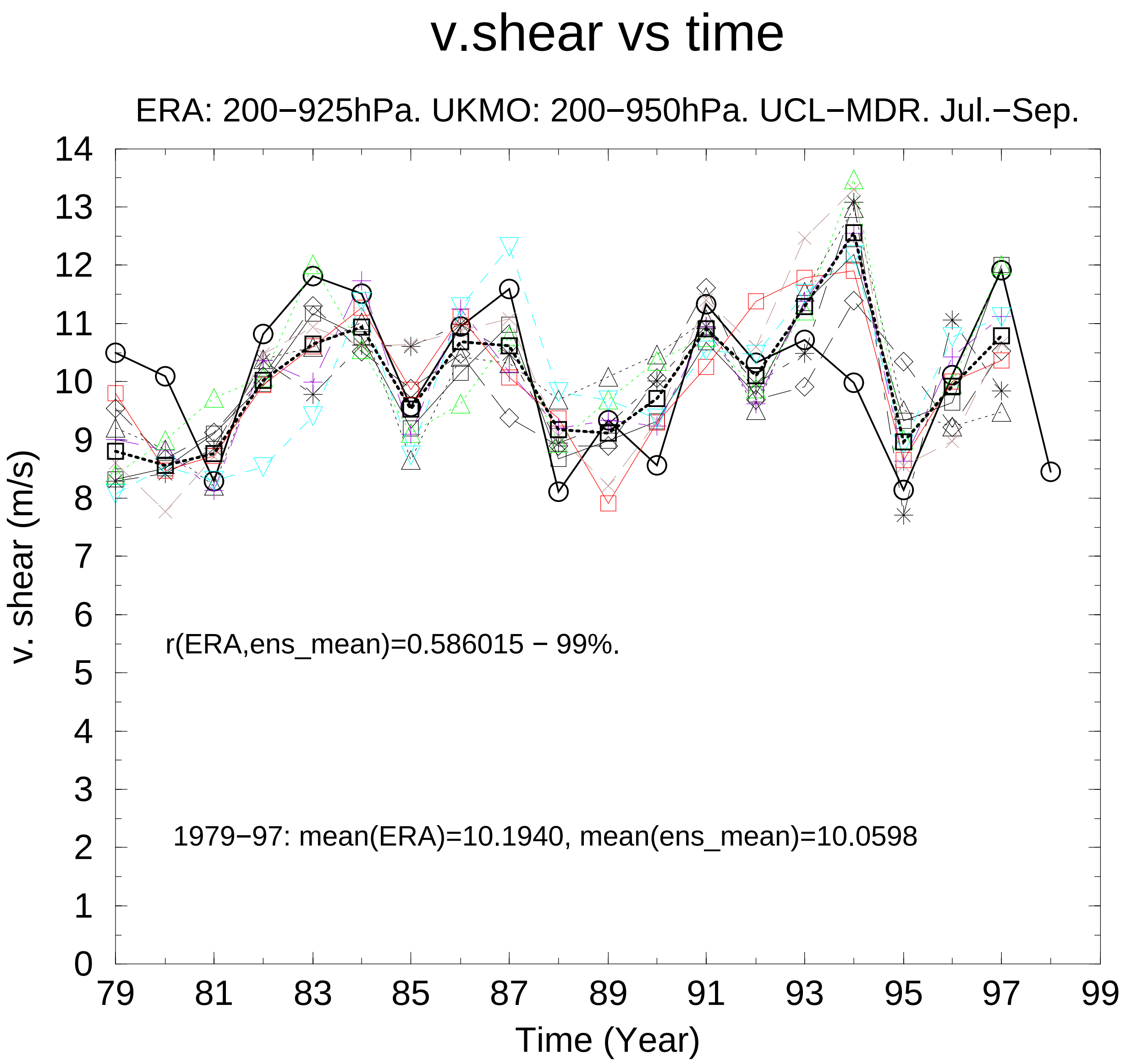
r(Hurricanes_all, ens_mean)=-0.63 (99%)

# Appendix B

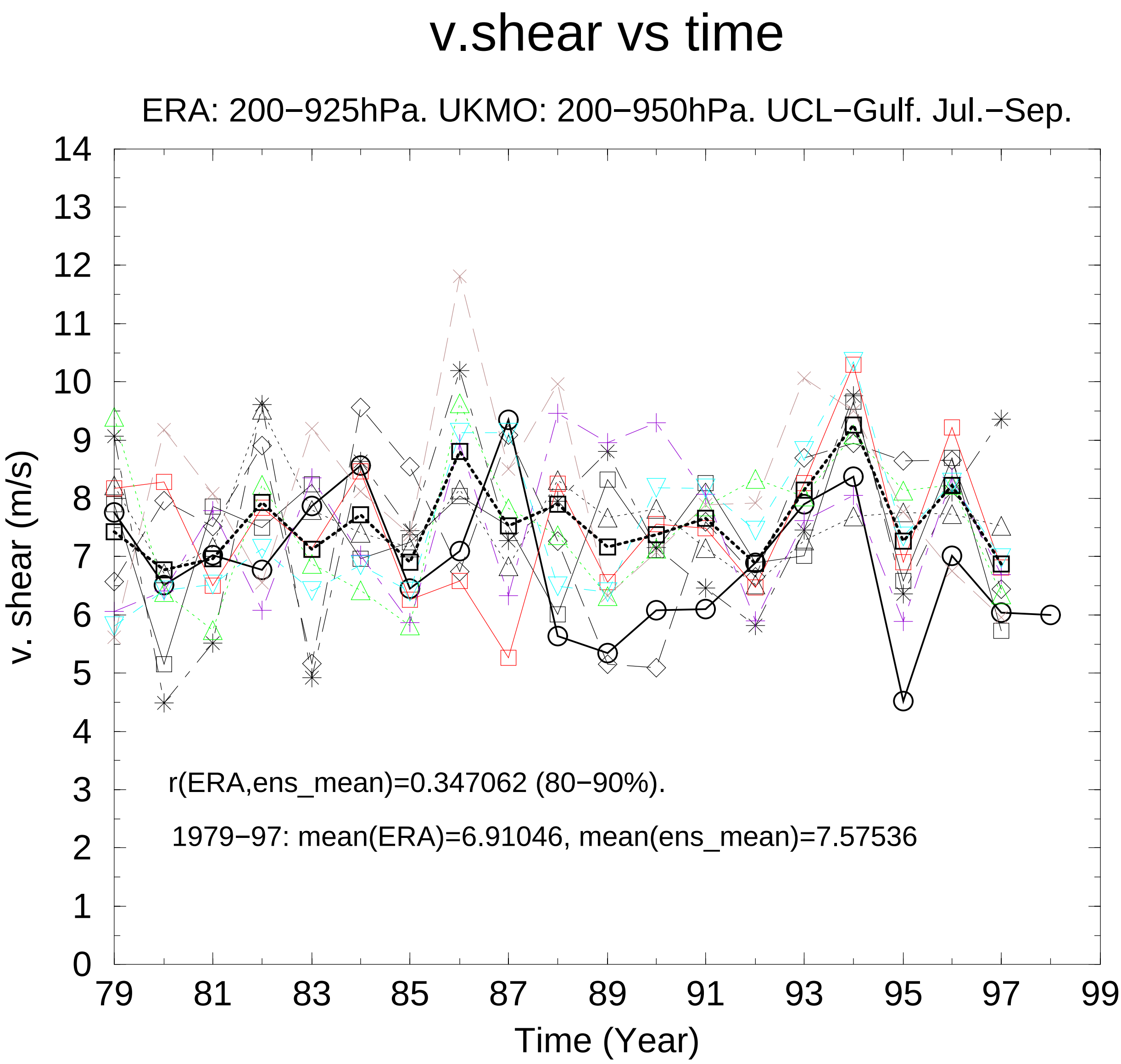
## Analysed and forecast shear for UCL's MDR, Caribbean, Gulf and North Atlantic.

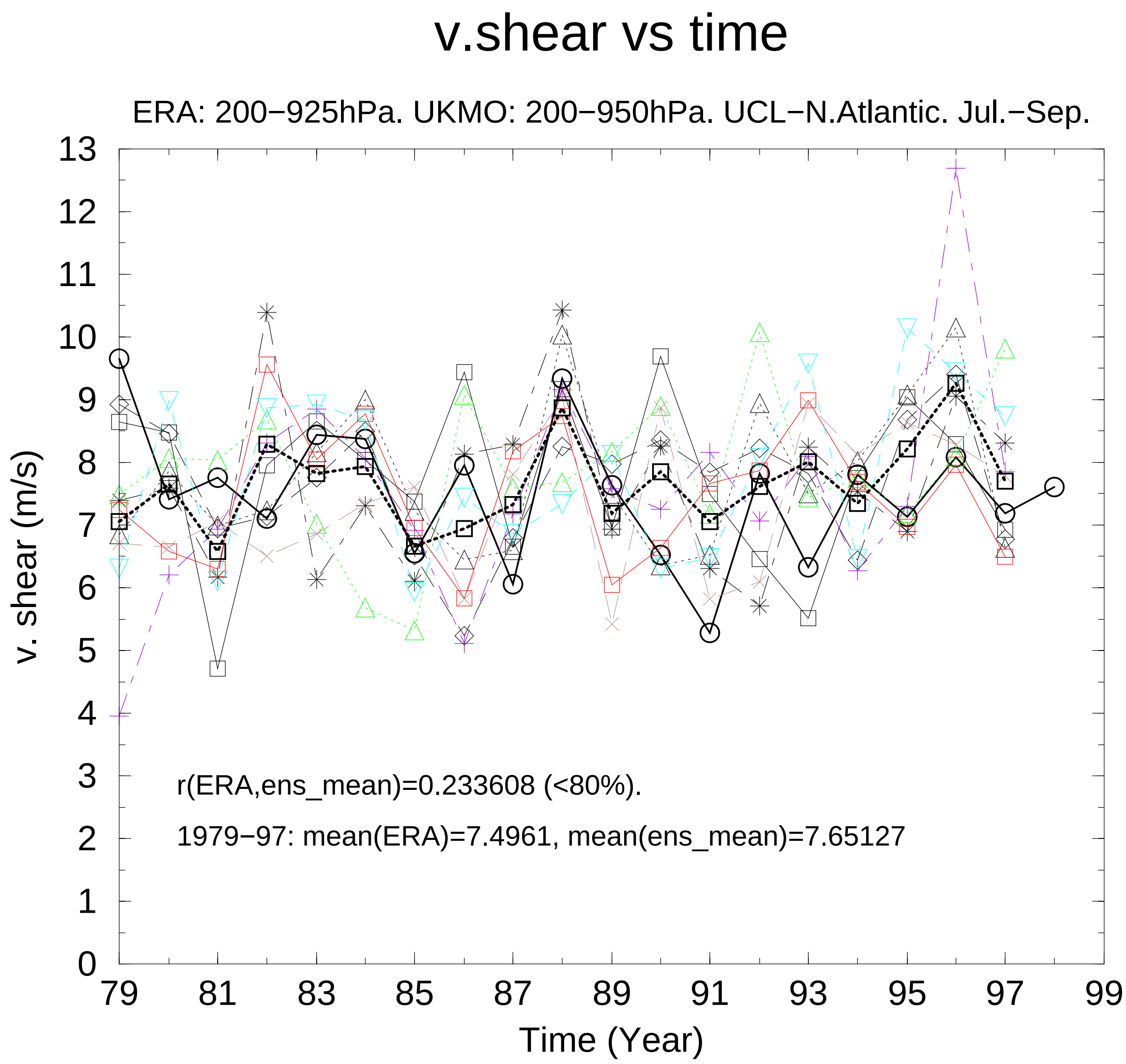



v.shear vs time
ERA: 200−925hPa. UKMO: 200−950hPa. UCL−Caribbean. Jul.−Sep.
v. shear (m/s)
Time (Year)
r(ERA,ens_mean)=0.695913 − 99%.
1979−97: mean(ERA)=10.5426, mean(ens_mean)=7.27175



v.shear vs time
ERA: 200−925hPa. UKMO: 200−950hPa. UCL−MDR. Jul.−Sep.
v. shear (m/s)
Time (Year)
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
79
81
83
85
87
89
91
93
95
97
99
r(ERA,ens_mean)=0.586015 − 99%.
1979−97: mean(ERA)=10.1940, mean(ens_mean)=10.0598


v.shear vs time
ERA: 200−925hPa. UKMO: 200−950hPa. UCL−Gulf. Jul.−Sep.
v. shear (m/s)
Time (Year)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
79
81
83
85
87
89
91
93
95
97
99
r(ERA,ens_mean)=0.347062 (80−90%).
1979−97: mean(ERA)=6.91046, mean(ens_mean)=7.57536



v.shear vs time
ERA: 200−925hPa. UKMO: 200−950hPa. UCL−N.Atlantic. Jul.−Sep.
v. shear (m/s)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
r(ERA,ens_mean)=0.233608 (<80%).
1979−97: mean(ERA)=7.4961, mean(ens_mean)=7.65127
79
81
83
85
87
89
91
93
95
97
99
Time (Year)