Monsoon variability in different versions of the Met Office climate model

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1. Introduction

One of the most stringent tests of a general circulation model (GCM) is its ability to simulate a realistic tropical climate. This includes both the mean climate and its many modes and timescales of variability. One of the major components of the tropical circulation is the Asian Summer Monsoon (ASM), on which the economies and livelihood of the populations of India and southeast Asia depend heavily. Simulation of this system and its variability remains a significant challenge for many GCMs. Previous versions of the Hadley Centre climate model have produced a reasonably good simulation of the ASM, although the monsoon strength, in terms of both circulation and precipitation, is rather overestimated, and the onset is slightly early in comparison with observations.

A new semi-Lagrangian, non-hydrostatic version of the Met Office climate model called HadGEM1 is currently under development. This model incorporates numerous changes to the physical parametrisations in both the atmosphere and ocean components, as well as to the model grid and vertical resolution, and includes additional processes such as the sulphur cycle and cloud aerosol effects. Thus, both the coupled model and its atmosphere-only version, HadGAM1, are very different from the previous versions, HadCM3 and HadAM3.

The aim of this work, which was started as part of the PROMISE (PRedictability and variability Of Monsoons, and the agricultural and hydrological ImpactS of climate change) EU project, is to determine the relative importance to the simulation of monsoon variability of improved dynamics and physics in the atmosphere model against coupling the atmosphere model to an ocean model.

2. Description of model runs

A four-member ensemble of the atmosphere-only model HadAM3 has been used, each differing only in their initial conditions, and covering the AMIP-II period (1979-1995). An ensemble of recent HadGAM1 runs was not available and a single 17-year AMIP-II run of this model has been used. However, a four-member ensemble of a previous prototype version of HadGAM1 was available. In order to check that the analysis of interannual variability of the recent HadGAM1 run was valid, the results were compared with similar analysis of the previous ensemble We use a 60-year period from an equilibrium run of HadCM3 and a 30-year test run of HadGEM.

The changes made between HadAM3/CM3 and HadGAM1/GEM1 are too numerous to describe in detail here. As well as the use of semi-implicit, semi-Lagrangian advection instead of Eulerian advection, new treatments of boundary layer, convection, surface scheme, microphysics and gravity wave drag have been included. The model runs on a Charney-Phillips grid and the vertical resolution is twice that of HadAM3/CM3.The horizontal resolution of all the runs used here is 3.75 by 2.5 degrees.

It should be noted that HadGAM/GEM1 are still under development; the prototypes used in this study do not represent the final versions.

3. Asian Summer Monsoon

3.1. Mean monsoon climatology

The monsoon climatology in HadGAM improves on HadAM3 in terms of the circulation strength (see Figure 1[a,c]), and in some aspects of the precipitation distribution (Figure 2[a,c]), such as over the eastern equatorial Indian Ocean and over the west Pacific. However, the westerly low-level monsoon jet extends too far eastwards across East Asia, and precipitation is underestimated over India and over Indonesia. The monsoon in HadCM3 is rather different from that in HadAM3 (Figure 1[a,b] and Figure 2[a,b]). The monsoon circulation is weaker and there is far less precipitation over and around the Indian peninsula. Instead, precipitation over Indonesia is increased. These changes are associated with errors in the sea surface temperature (SST) climatology of the coupled model, where the northern hemisphere temperatures are colder and the SSTs around Indonesia warmer than observed. The SST errors occur as a result of systematic errors in the atmosphere model, namely too much cloud over the subtropical and midlatitude oceans and too little convection over Indonesia. Similarly, warm SSTs and increased precipitation around Indonesia are seen in HadGEM, although the errors are significantly smaller than those in HadCM3. The northern hemisphere temperature errors are also reduced in HadGEM1, but an equatorial cold bias, which was also seen in HadCM3, remains (though of smaller magnitude) as a result of continuing problems with near-surface winds in the tropics. There is an associated decrease in winds and precipitation over the equatorial west Pacific in HadGEM1 compared with HadGAM1, but little change in the strength of the monsoon circulation.

3.2. Interannual variability

Empirical Orthogonal Function (EOF) analysis was carried out on the seasonal (June-September, JJAS) mean anomalies of 850 hPa winds. The dominant EOFs from each of the models are shown in Figure 3. Both atmosphere-only models have a dominant mode of interannual variability which explains at least 40% of the variance. Despite the vast differences between the two models, their dominant modes are rather similar. Easterly 850 hPa wind anomalies across East Asia and most of the Indian peninsula are associated with decreases in precipitation here, while increased convergence over Indonesia, western India and the Arabian Sea is associated with increased precipitation there. The coupled models, HadCM3 and HadGEM1, have similar dominant modes to the atmosphere-only models (Figure 4), although they explain slightly less of the variance. However, in the case of the coupled models there is an additional contribution from the eastern equatorial Indian Ocean.

These dominant modes resemble the first EOF calculated by Molteni et al. (2002) from the NCEP/NCAR reanalyses, and the second EOF calculated by Annamalai et al. (1999) from the ECMWF Reanalyses. However, in both of the reanalyses, nearly half of the total variance is divided nearly equally between the first two modes, with the other most dominant mode being associated with north/south anomalies over India. Although around half of the total variance is explained by the first two EOF modes in HadAM3/CM3 and HadGEM1 (but only by the first mode in HadGAM1), the first mode is more dominant in the models and the second mode is not represented very well, except in HadGEM1 where it is quite realistic (not shown).

Both of the first two modes from the reanalyses also showed the presence of anomalies over the equatorial Indian Ocean. The presence of such anomalies in only the coupled versions of our models may suggest an improved representation of the Indian Ocean SST dipole mode when the atmosphere and ocean are allowed to interact. However, it is also possible that the appearance of these anomalies may be due to the Indonesian SST errors which occur in both coupled models. In order to investigate this, a test run in which HadAM3 was forced with the SSTs from 20 years of HadCM3 was analysed. This shows a dominant mode of variability (Figure 5) which is more similar to that of HadAM3 than HadCM3, indicating that the changes in HadCM3 are associated, at least in part, with the coupling rather than the SST errors.

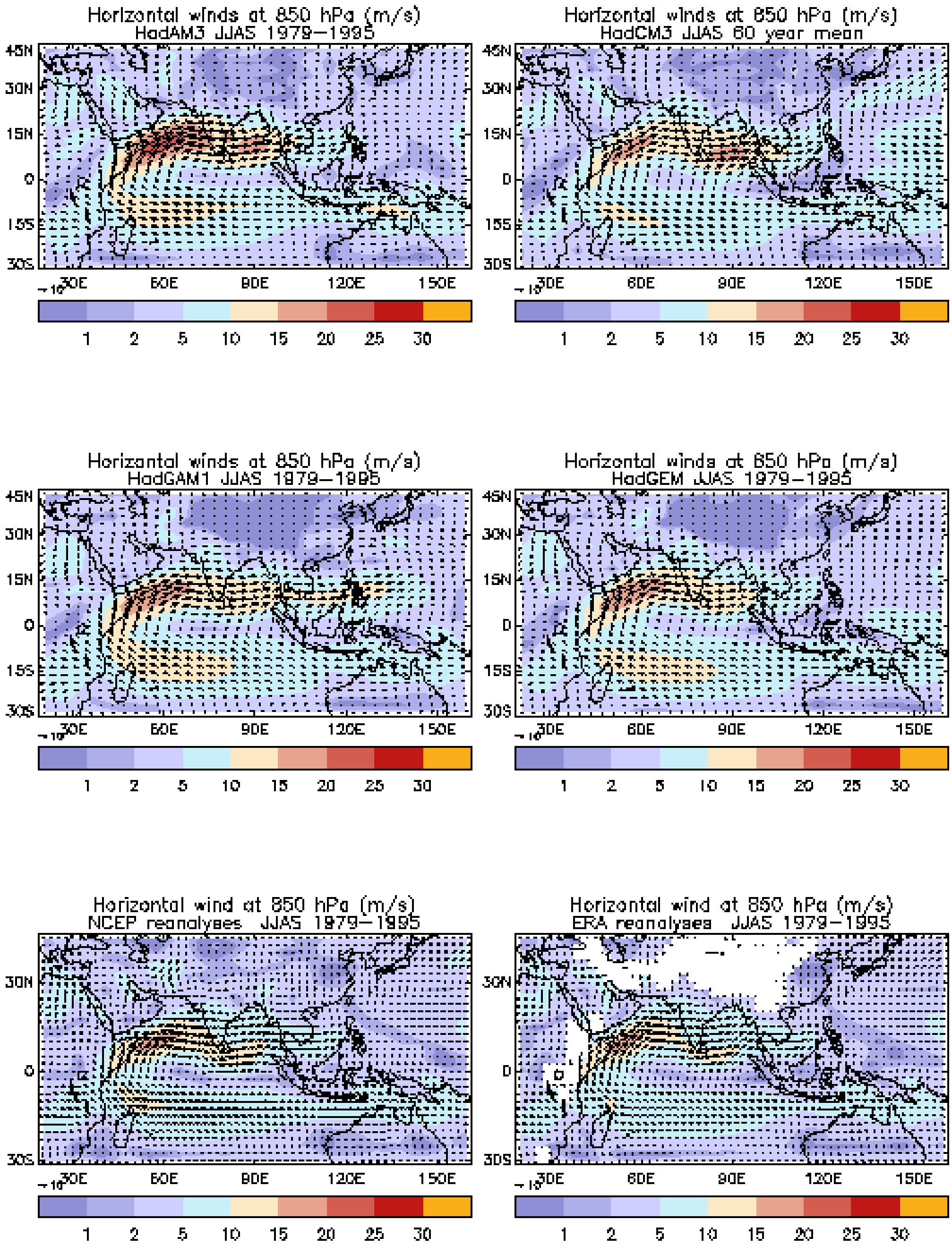

Figure 1: Horizontal winds at 850 hPa in the four models and two reanalysis datasets

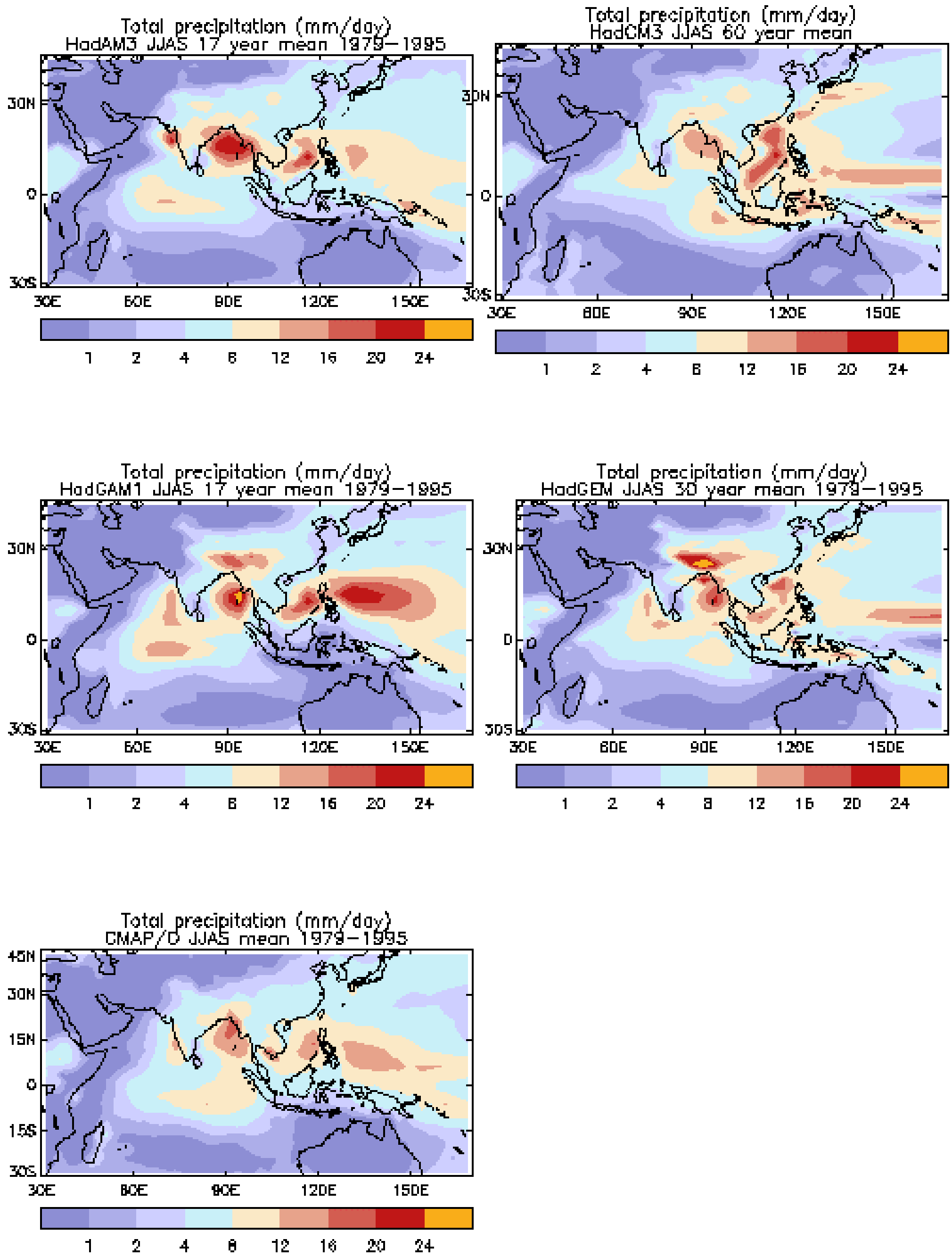

Figure 2: Total precipitation (mm/day) in the four models and CMAP/O dataset

Both the atmosphere-only and coupled configurations of HadAM3/CM3 show significant teleconnections between the dominant mode of interannual variability and SSTs in the central and eastern Pacific. Wind and precipitation anomalies in El Nino years are very similar to the dominant mode of variability in these models (compare Figure 6 with Figure 3[a] and Figure 4[a]). These teleconnections are rather weak in HadGAM1/GEM1, suggesting that internal variability may be prevalent in this model. However, anomalies in El Nino years in HadGAM1 are quite similar to those observed (not shown), suggesting that strong SST forcing can outweigh the internal variability on some occasions. In contrast, HadAM3/CM3 responds too strongly to both local and remote SST forcing, such that teleconnections with SST, and anomalies in El Nino years, are less realistic than in HadGAM1/GEM1.

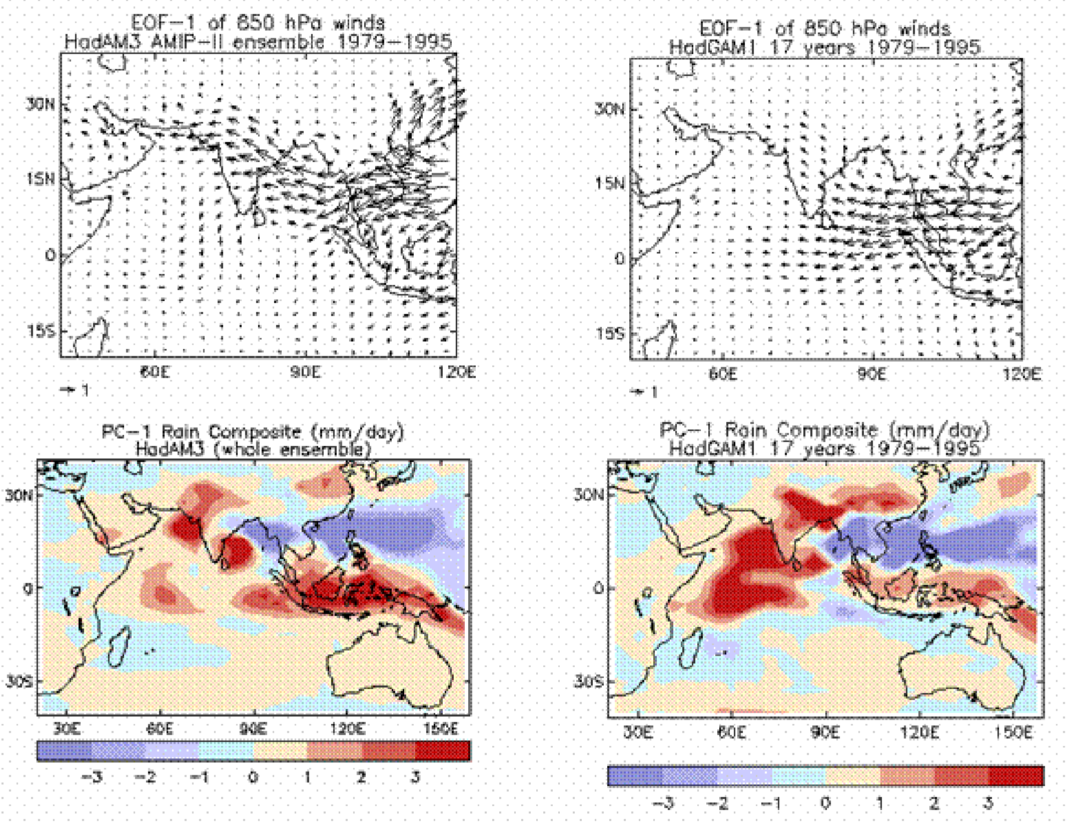

Figure 3: Dominant modes of interannual variability of 850 hPa winds in HadAM3 and HadGAM1. These explain 38% and 42% of the total variance respectively.

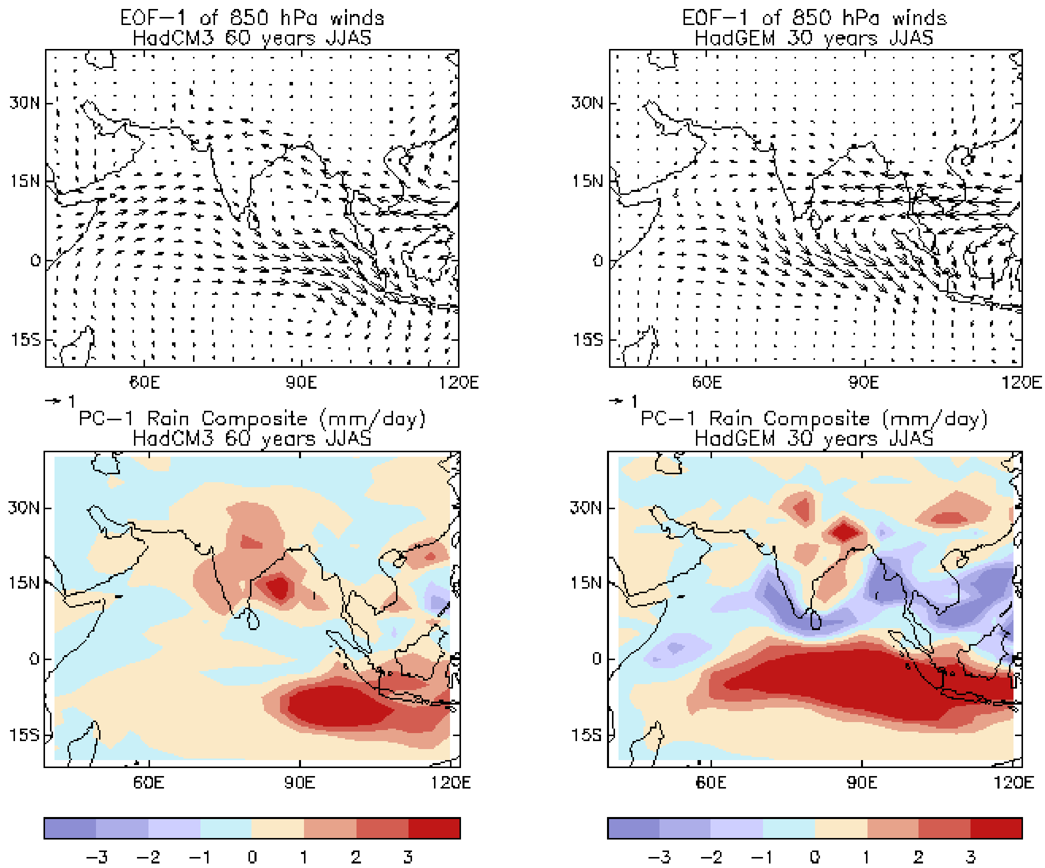

Figure 4: Dominant modes of interannual variability of 850 hPa winds in HadCM3 and HadGEM1. These explain 30% and 36% of the total variance respectively.

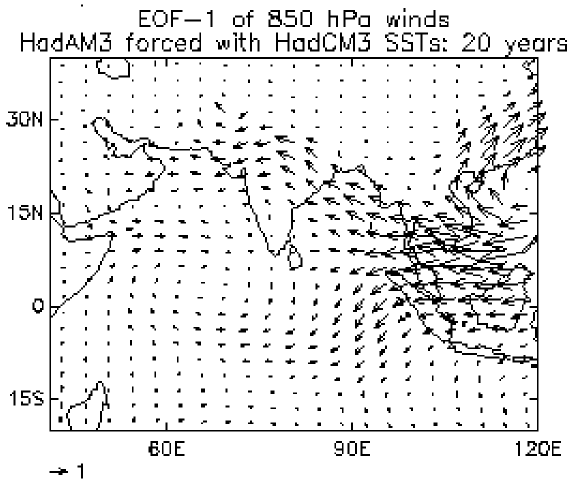

Figure 5: Dominant mode of interannual variability from a HadAM3 run forced by SSTs from HadCM3. (run supplied by Hilary Spencer, CGAM)

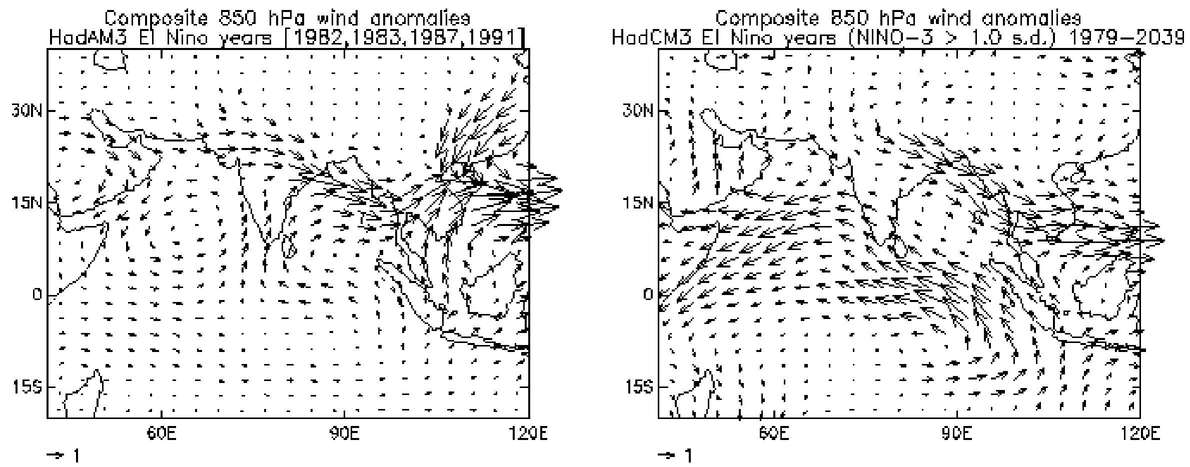

Figure 6: 850 hPa wind anomalies in El Nino years from HadAM3 and HadCM3

3.3. Intraseasonal variability

Analysis of the tropical intraseasonal variability of HadGAM1/GEM1 (personal communication: Pete Inness and Gui-Ying Yang, CGAM, Reading University) shows an increase in the variance of convective activity around the equator in the Warm Pool region on intraseasonal timescales in HadGAM/GEM1 compared with HadAM3/CM3, bringing the new model closer to observations. However, neither atmosphere-only model shows the eastward-propagating signal of the Madden-Julian Oscillation (MJO). Inness and Slingo (2003) showed that coupling between the atmosphere and ocean was important for eastward propagation; Pete Inness (personal communication) has shown that HadGEM1 does indeed produce some eastward-propagating events of comparable magnitude to observations, although there are deficiencies in the MJO simulation. We now investigate whether the apparent improvement in the simulation of tropical intraseasonal variability in the new model extends to that of the monsoon simulation.

EOF analysis of the daily 850 hPa wind anomalies was carried out for a 17-year period of each of the model runs. The anomalies were calculated relative to the long-term average seasonal cycle, which was first low-pass filtered to remove frequencies higher than 65 days. This analysis of the intraseasonal variability in the models shows a strong similarity between the dominant modes from all four models (Figure 7), which describe around 13% of the variance in all cases. This mode is in good agreement with that calculated from

NCEP reanalyses (Sperber et al, 2000). Of the first four modes of intraseasonal variability in the NCEP reanalyses, three represented different stages of the northward propagation of the Tropical Convergence Zone (TCZ). Several of the first few EOFs from the models do appear to represent slightly different positions of the TCZ, and spectral analyses of the principal component (PC) timeseries show preferred timescales which are all in the range 10-50 days, again in agreement with Sperber et al (2000). However, although northward propagating events are seen occasionally in all of the models, the variability between these modes appears to be mainly random. More work is needed to investigate this further.

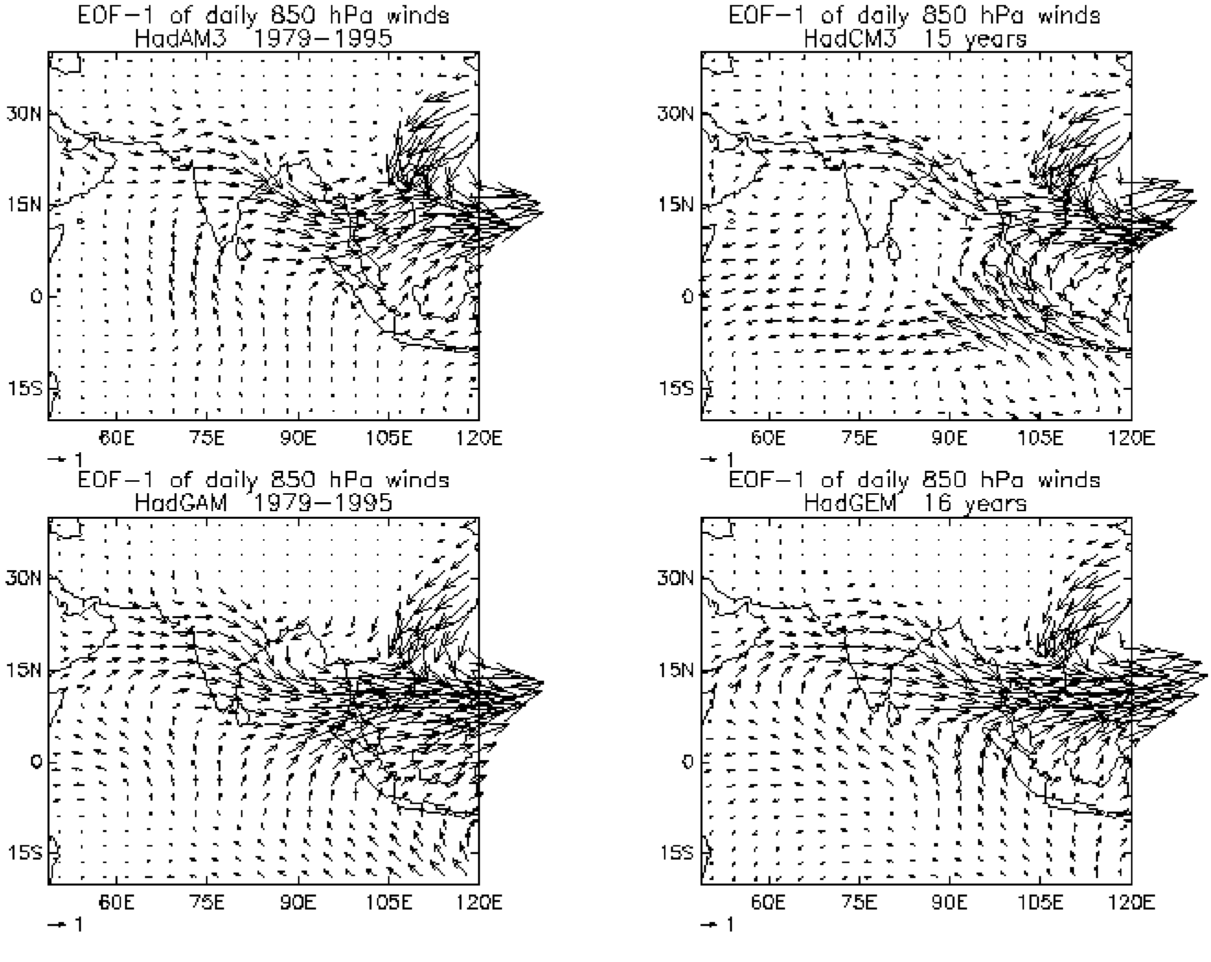

Figure 7: Dominant mode of intraseasonal variability of 850 hPa winds from all four models

One of the primary intraseasonal modes in the NCEP reanalyses (explaining 6.6% of the variance) appeared to be related to the variability of the All-India Rainfall (AIR), and hence associated with active/break phases of the Indian monsoon. HadAM3 and HadCM3 also show evidence of this mode in their third and second EOFs, respectively, explaining 6.5% and 6.8% of the variance (see Figure 8[a,c]), and correlations between daily AIR and the principal component timeseries of these modes (each smoothed with a 5-day box-car average) in 7 out of 17 years are significant at the 5% level. This mode can be identified in HadGAM1 and HadGEM1 (Figure 8[b,d]), although it is not as well isolated and the correlations with AIR are rather weaker.

The link between monsoon interannual variability and external forcings such as ENSO has long been established. It is also interesting to investigate whether there are any significant teleconnections between the intraseasonal variability of the monsoon and intraseasonal variations in global SSTs in the models. This analysis is limited for the atmosphere-only models by the limited time resolution of the SST forcing dataset. Monthly observations are interpolated linearly between the middle of consecutive months to give daily values. In order to allow a sensible comparison, the PC timeseries are therefore smoothed with a 30-day box-car average before the teleconnections are calculated. Although the SSTs in the coupled model show daily variations, the same smoothing is done on the PC timeseries from the coupled models, and the SST fields low-pass filtered to remove frequencies higher than 30 days, in order to make a fair comparison. It is found that calculating the teleconnections using the actual daily values for the coupled models gives the same pattern but generally lower (and mainly insignificant) correlations.

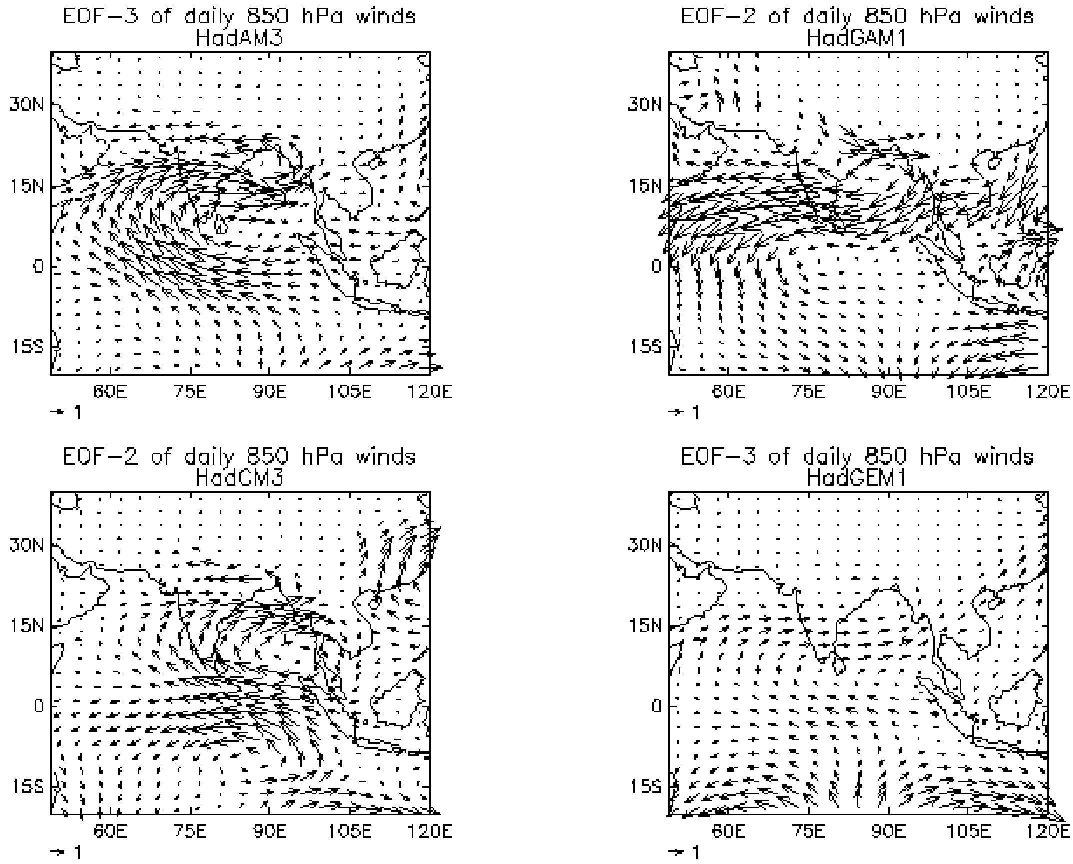

Figure 8: Modes of intraseasonal variability of 850 hPa winds from all four models which resemble the "All-India Rainfall mode" identified by Sperber et al. (2000)

In order to remove interannual variations of SST and monsoon winds, the seasonal means for each year are removed and the EOFs recalculated, before calculating the teleconnections. This has little impact on the EOF analysis (see Section 3.4, Figure 13), although the dominant mode identified in Figure 7 moves to the second EOF in HadGEM1. This analysis was done for HadAM3/CM3 and HadGEM; daily surface temperatures were not available from the HadGAM1 run. Lag-lead correlations at 5-day intervals from -30 days to +30 days were calculated, with "Lag-N" representing the SST lagging the PC by N days.

Figure 9 and Figure 10 show the results from HadCM3 (PC-1) and HadGEM1 (PC-2). For HadCM3, this mode is negatively correlated with SSTs in the subtropical western Pacific and positively correlated with the western equatorial Pacific at negative lags of 10-20 days, whereas in HadGEM1 the strong negative correlation at these lags is with SSTs in the eastern Bay of Bengal, the South China Sea and the western Pacific. The other PCs from HadCM3 and HadGEM1 also show strong negative correlations at 10-20 day lags (those for HadCM3 shown in Figure 11), but in these cases the correlations are noticeably co-located with the monsoon wind anomalies themselves, with positive anomalies (increases in the monsoon circulation) generally correlating with negative SST anomalies.

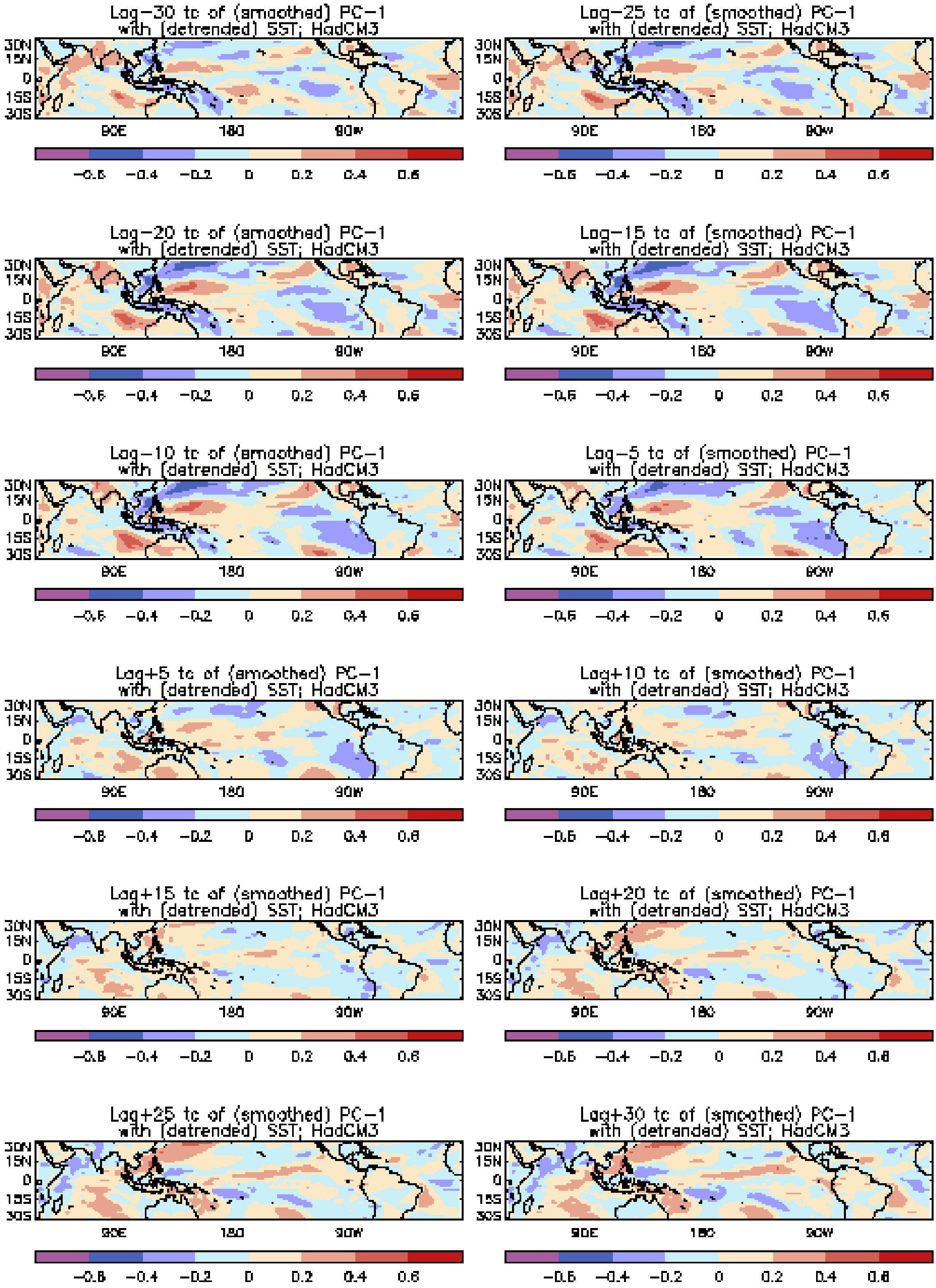

Figure 9: Lag-lead teleconnections of PC-1 from HadCM3 with surface temperatures. Lag-N indicates the PC leading the surface temperatures by N days. See text for further details.

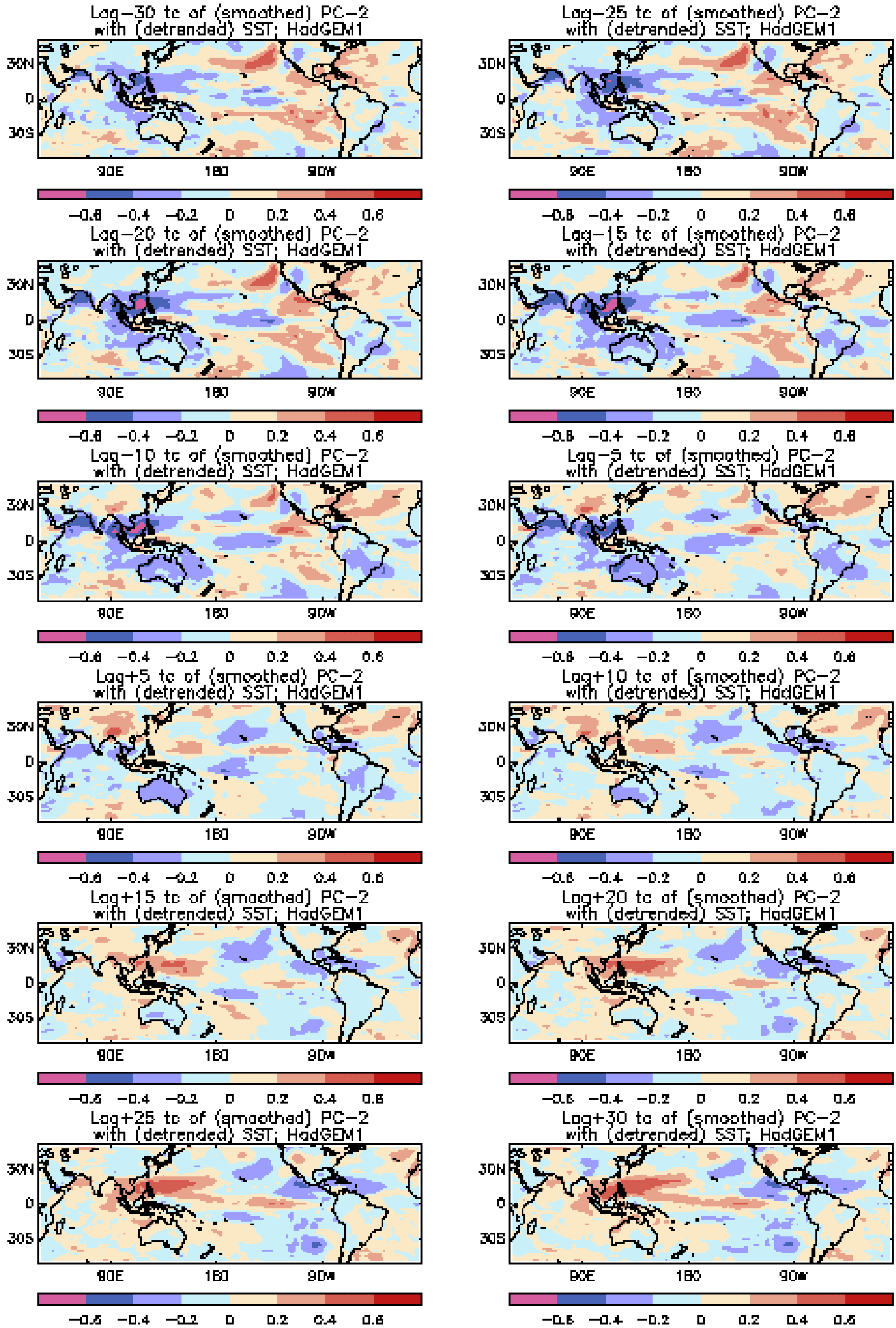

Figure 10: As Fig. 9 but for HadGEM1

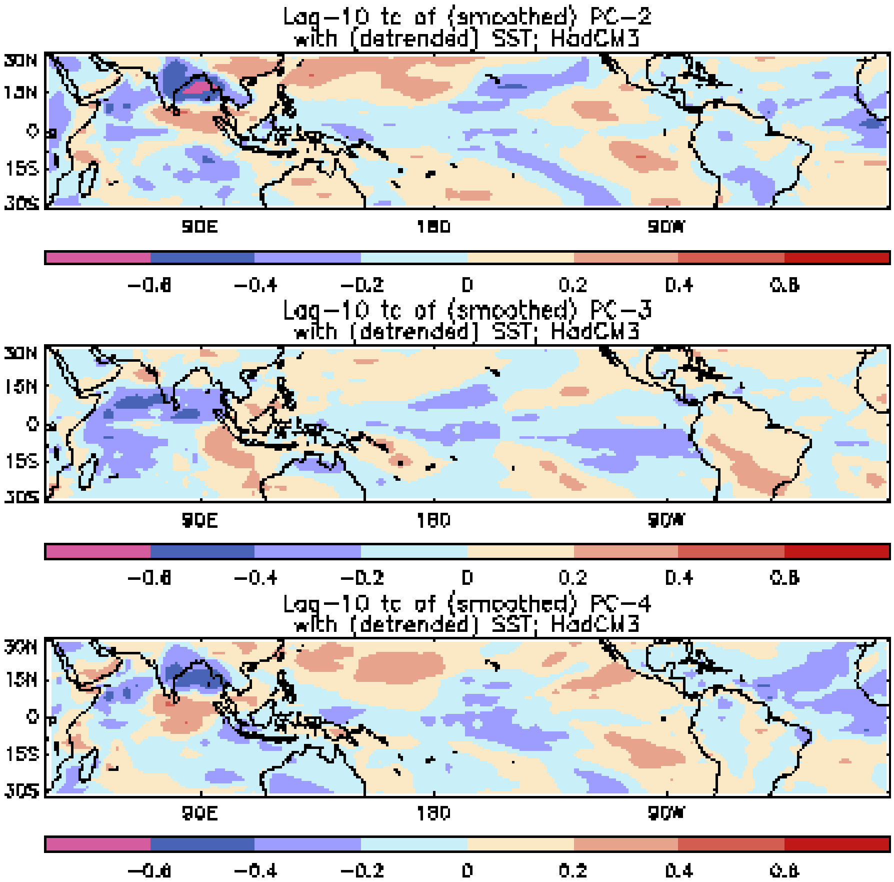

Figure 11: Lag-10 teleconnections between PC-2, PC-3 and PC-4 and surface temperature for HadCM3

Lagged negative local correlations between monsoon wind variability and surface temperatures in the coupled models illustrate the cooling/warming effect of the positive/negative wind anomalies on the surface through increased/decreased surface fluxes. The question remains as to whether there is any subsequent feedback of these SST changes on the monsoon variability. Although Figure 9 shows small positive teleconnections of PC-1 with subtropical west Pacific SSTs at lags+20 to +30, these are barely significant. In contrast, HadGEM1 shows significant positive correlations with west Pacific SSTs at lags +20 to +30. This is to the east of the negative correlations at lags -10 to -20. Similar features are seen in the teleconnections with PC-1 of HadGEM1, and it is not clear if the teleconnections with the two regions at different lag/lead times are connected. Further work is needed to investigate this

Lag/lead correlations for PC-1 of HadAM3 are shown in Figure 12. No significant correlations are seen at any lag/lead times, and this is also the case for the other PCs. Although we would not expect the negative lagged correlations between the monsoon variability and the SST in the atmosphere-only model, the lack of any significant correlation at positive lags suggests that daily variations in the SSTs have little impact on the monsoon variability and that the intraseasonal variability is chaotic. This is in contrast with the results from Section 3.3 which showed that the interannual variability in this model is strongly linked to SSTs. The relationship between intraseasonal and interannual variability is investigated further in Section 3.4.

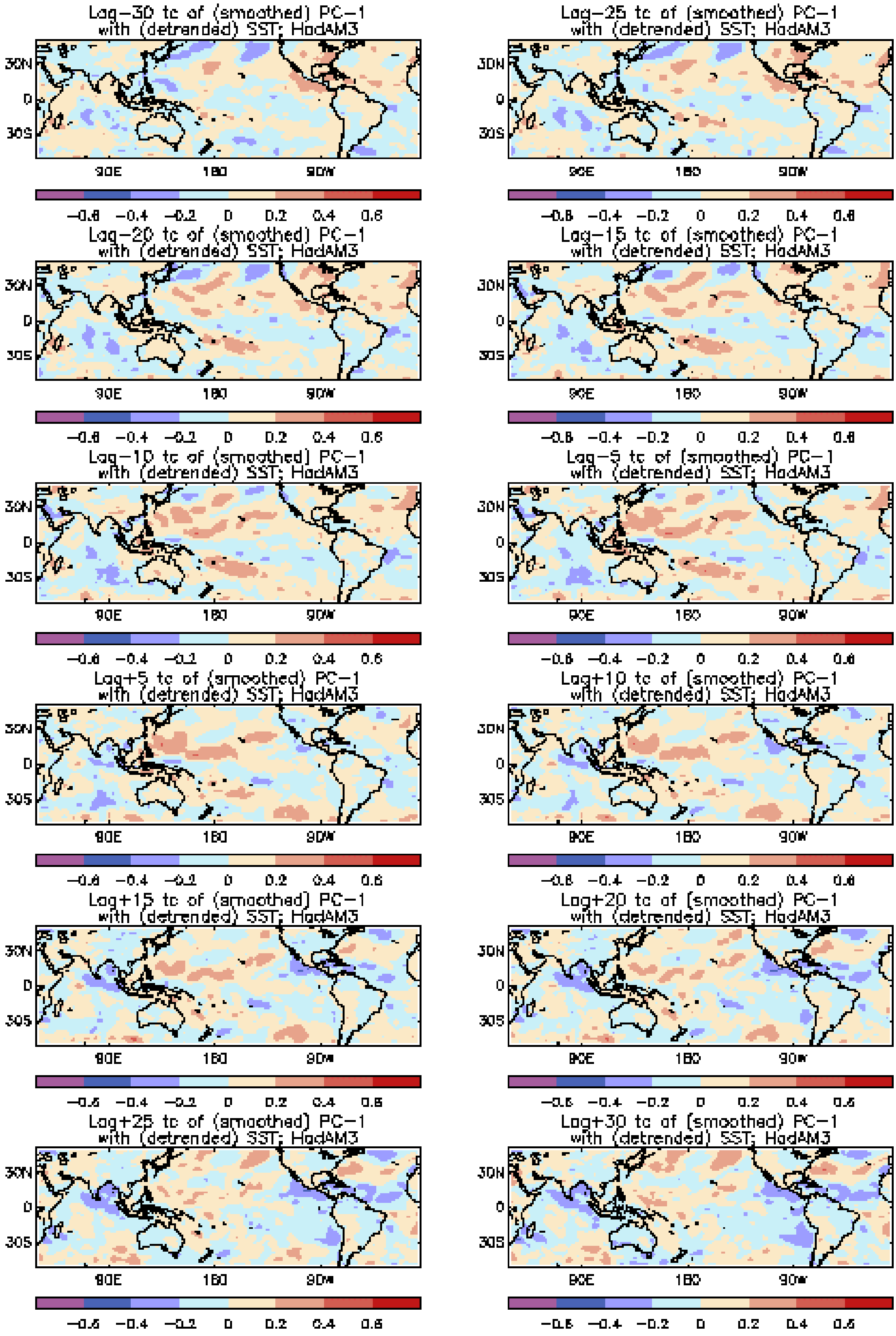

Figure 12: As Figs 9 and 10 but for HadAM3

3.4. Relationships between intraseasonal and interannual variability

Comparing Figs 3, 4 and 7, it is noticeable that the dominant intraseasonal and interannual modes resemble oneanother. The calculation of intraseasonal variability shown in Figure 7 was made without removing the seasonal means from each year, so it includes the interannual variations. However, removing these has almost no impact on the patterns of variability (Figure 13), and merely reduces the variance explained to around 10% for all of the models except HadGEM1, where this mode moves to EOF2 and the variance explained is reduced to 5.5%. Similarity between the dominant intraseasonal and interannual modes of monsoon variability has been noted in other GCMs and is also present in the observations. The present study suggests that this mode is not sensitive to the many model changes between HadGAM1 and HadAM3 or to the ocean/atmosphere coupling. Instead, it is a robust feature of these and many other GCMs.

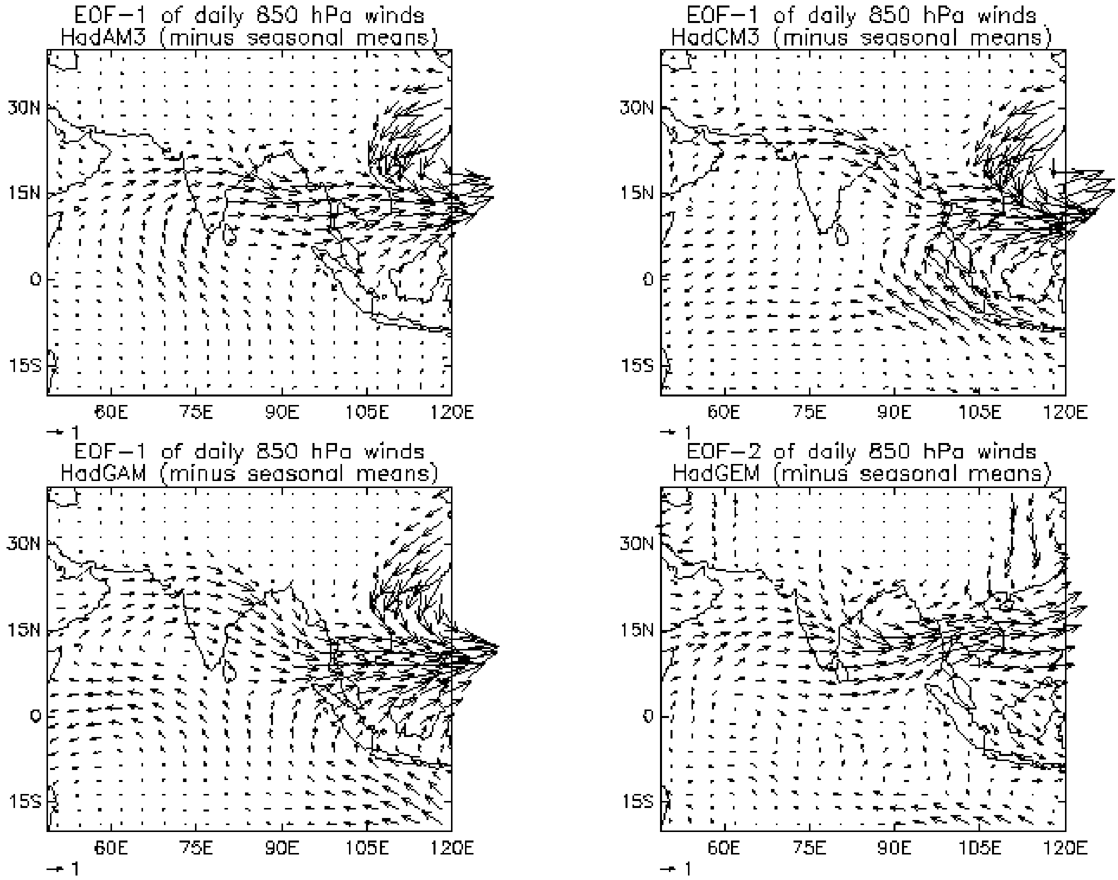

Figure 13: As Fig. 7 with but seasonal means removed from wind timeseries before calculating EOFs.

It was shown in Section 3.2 that the dominant interannual mode in HadAM3/CM3 was strongly linked to ENSO. If these two modes really represent a common mode of variability at the two timescales, we would expect a similar link between ENSO and the preferred state of the dominant intraseasonal mode. Figure 14[a,c] shows the probability Distribution Functions (PDFs) of PC-1 (from the EOFs calculated from the 850 hPa wind anomalies without removing the seasonal means and so including the interannual variability) from HadAM3 and HadCM3 (solid lines), and the dotted and dashed lines show the PDFs of PC-1 from El Nino and La Nina years respectively. In both cases, there is a slight positive bias in El Nino years and a large negative bias in La Nina years. The un-equal biasing of the PDF in the two SST regimes is consistent between the two models, despite the fact that in once case the SSTs are observed and in the other they are calculated by the model. The cause of this interesting feature is unknown. Figure 14[b,d] shows the PDFs of PC-1 from HadGAM1 and HadGEM1. The impact of ENSO in this case is less clear, consistent with the weak teleconnections with eastern Pacific SSTs in these models.

The PDFs of the PCs from the other EOF modes which are associated with the different positions of the TCZ were also partitioned in this way. Of these, only EOF2/PC2 of HadAM3 and PC-3 of HadGAM1 showed a noticeable difference in the PCs from El Nino and La Nina years. Sperber et al. (2000) showed a similar lack of influence of Nino-3 SSTs on all but one of the modes associated with the TCZ. They emphasised that this illustrates the role of internal variability in determining the actual anomalies seen in any particular monsoon season.

Sperber et al. (2000) also showed that the mode of intraseasonal variability associated with variations in All India Rainfall was not biased in ENSO years, in agreement with the lack of correlation between AIR and Nino-3 SSTs. Figure 14 shows that this is also the case for this mode in the models.

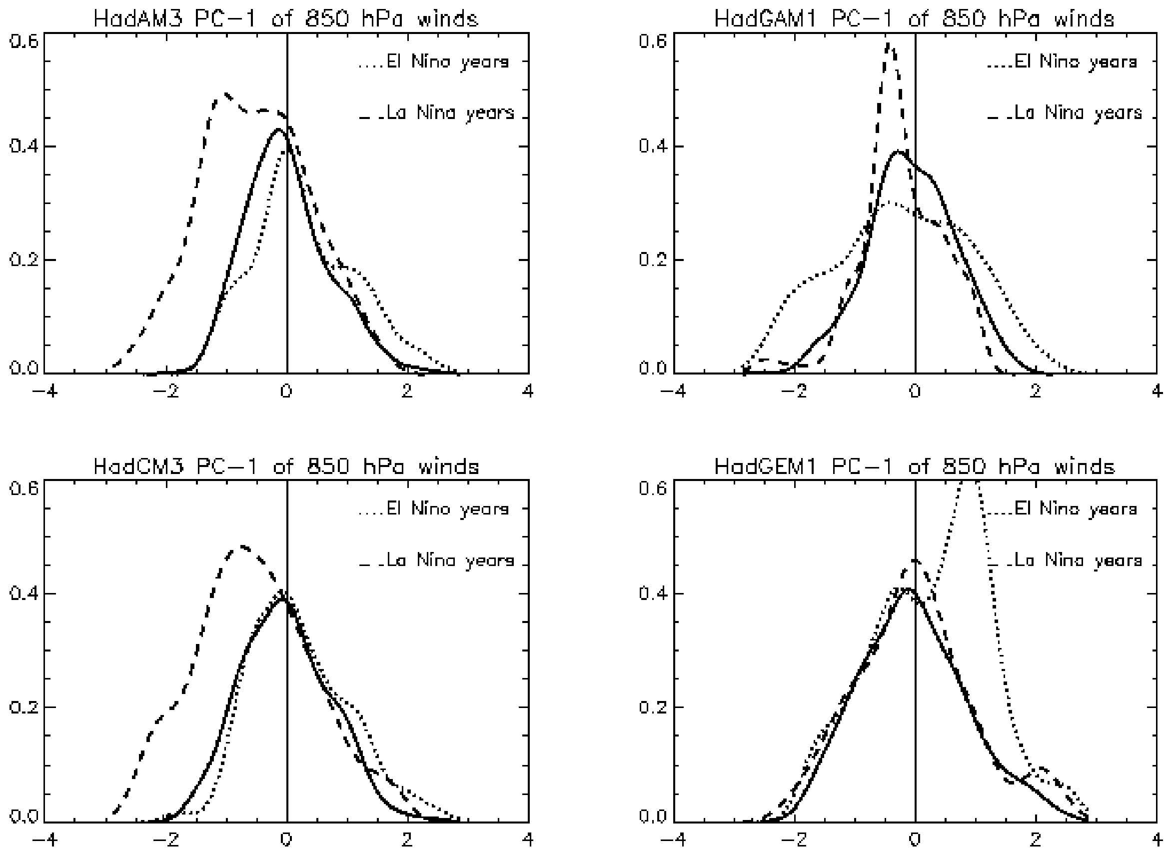

Figure 14: Probability Distribution Functions (PDFs) of the first PC of intraseasonal variability from the four models (solid line). The dotted and dashed lines show the PDFs for El Nino and La Nina years respectively.

4. Summary and Conclusions

In this study, two versions of the Met Office climate model have been compared, in both atmosphere-only and coupled modes. The monsoon climatology is rather different in the two atmosphere model versions, with the circulation strength and some aspects of the precipitation distribution improved in the new model. The impact on the monsoon of coupling the models differs between the two versions, having rather less impact in HadGAM1/GEM1 than on HadAM3/CM3. This may be because the SST errors are larger in HadCM3 than in HadGEM1.

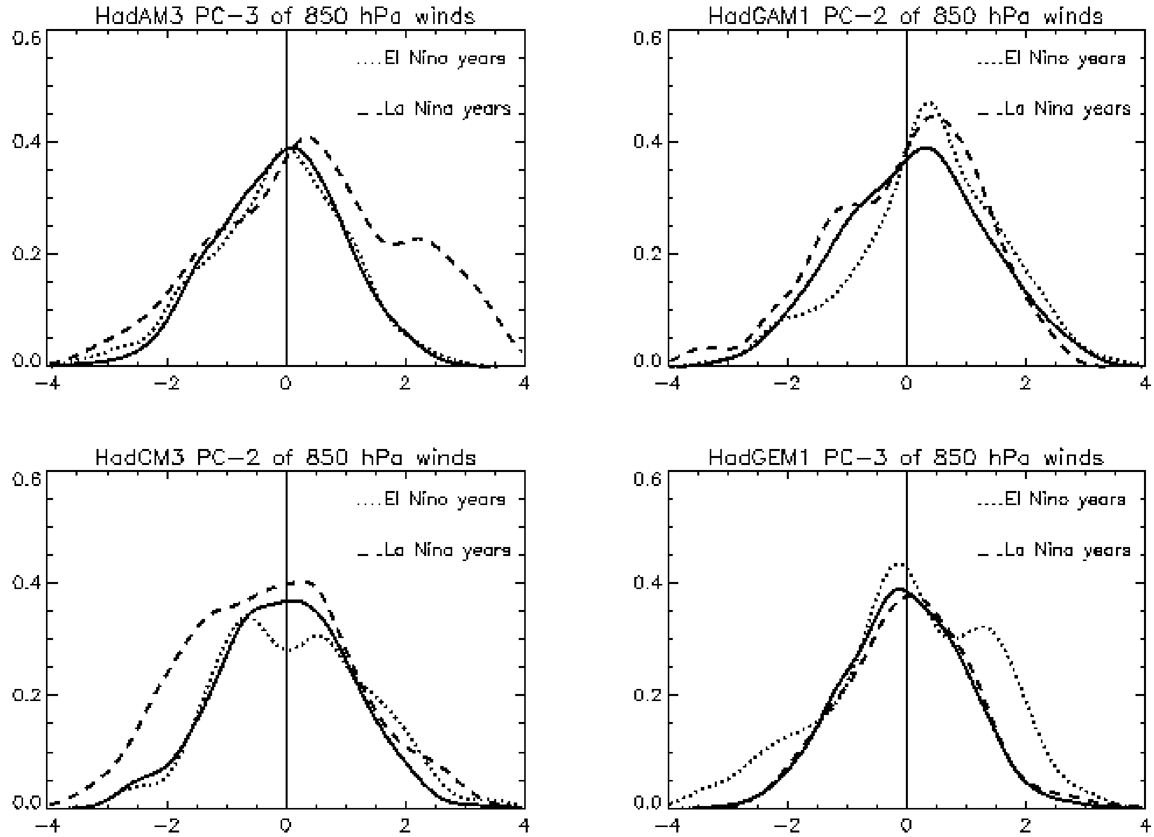

Figure 15: As Fig. 14 but for the PCs corresponding to the EOF associated with AIR variations: (a) HadAM3 PC-3; (b) HadGAM1 PC-2; (c) HadCM3 PC-2; (d) HadGEM1 PC-3.

Despite differences in the monsoon climatologies, the four models show rather similar dominant modes of interannual variability. However, in the case of HadAM3/CM3, the variability is strongly linked to SST forcing, while internal variability dominates in HadGAM1/GEM1. In spite of this, we find that strong SST forcing can outweigh the internal variability in HadGAM1 on some occasions: wind and precipitation anomalies in El Nino years are similar to those observed.

All four models exhibit very similar dominant modes of intraseasonal variability. The similarity in this case is even stronger than for the interannual variability. This dominant mode resembles that of the NCEP reanalyses calculated by Sperber et al. (2000) and has a realistic preferred timescale of variability. The dominant intraseasonal mode resembles that of the interannual variability, a feature which is common to other GCMs and also present in observations. In spite of this, the intraseasonal variations within this mode appear to be stochastically-forced in HadAM3/CM3, whereas there is significant forcing of this mode on the interannual timescale in these models. The coupled model demonstrates an impact of the intraseasonal variability on the local SSTs, but it appears that any potential negative feedback of these changes on the monsoon intraseasonal variability is swamped by the chaotic variations. HadGEM1 shows some evidence of SST forcing of intraseasonal variability, while there is little significant SST forcing of the interannual variability. The apparent forcing of monsoon intraseasonal variability by western Pacific SSTs in HadGEM1 will be investigated further in future work.

Ultimately, the impact on the monsoon simulation of the many changes made to the model between HadAM3/CM3 and HadGAM1/GEM1 is perhaps surprisingly small, and errors still remain. Past experience of model development has shown that the tropical performance is very robust and difficult to improve. The area of the model on which it depends most strongly is the convection scheme. Despite the many changes made to the convection scheme in HadGAM1/GEM1, it is still largely a mass-flux scheme. The errors we see are common to other GCMs, which also use this type of parametrisation. Work is already underway to design a turbulence-based convection scheme which may, at least, change the pattern of errors. Other aspects of the model which also contribute to the tropical performance include the cloud scheme and the treatment of cloud anvils detraining from the top of deep convection, the diurnal cycle of convection over land and the complex circulation patterns generated by land-sea contrasts, and the horizontal and vertical resolution. In the coupled model, the treatment of the ocean mixed layer and the atmosphere-ocean coupling are also important. Many of these aspects are already being tackled, using HadGEM1 as a basis. The improvements made to this model over HadAM3/CM3 provide a more solid framework for developing the next generation of climate models.

References

Annamalai, H., J.M. Slingo, K.R. Sperber and K. Hodges 1999. The mean evolution and variability of the Asian summer monsoon: comparison of ECMWF and NCEP/NCAR reanalyses. *Mon. Weather Rev.,***127,** 1157-1186

Inness, P.M. and J.M. Slingo, 2003. Simulation of the Madden-Julian Oscillation in a coupled general circulation model I: Comparison with observations and an atmosphere-only GCM. *Journal of Climate*, **16**, 345-364.

Molteni, F., S. Corti, L. Ferranti and J.M. Slingo, 2002. Predictability experiments for the Asian summer monsoon: impact of SST anomalies on interannual and intraseasonal variability. *Journal of Climate*, submitted.

Sperber, K.R., J.M. Slingo and H. Annamalai, 2000. Predictability and the relationship between subseasonal and interannual variability during the Asian summer monsoon. *Q.J.R .Meteorol. Soc.*, **126**, 2545-2574.