SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	The role of the Asian Summer Monsoon as a driver of European Summer Circulation Variability
Computer Project Account:	Spgwool
Start Year - End Year :	2017 – 2018
Principal Investigator(s)	Prof Steven Woolnough, Jonathan Beverley, Dr Laura Baker, Dr Antje Weisheimer
Affiliation/Address:	National Centre for Atmospheric Science, University of Reading (SW, JB, LB) and University of Oxford (AW)
Other Researchers (Name/Affiliation):	Stephanie Johnson (ECWMF)

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

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The main objective of the project is to assess the role of the Asian Summer Monsoon as a driver of European Summer Climate Variability, with a particular focus on the circumglobal teleconnection (Ding and Wang, 2005). In initial analysis of forecast skill of the model we have identified errors in both the CGT node in the monsoon region and over Europe and hence we will also to explore the role of European circulation as a driver of the Asian Summer Monsoon

To do this we have performed a set of seasonal hindcast simulations with:

a) relaxation of the circulation in the monsoon region to determine the forced response of the European circulation.
b) Relaxation of the circulation in the European region to explore its role in driving the CGT
c) Imposed heating in the monsoon region to explore the response of the NH circulation to monsoon heating

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Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

None

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Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

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The Special Project Framework has been an excellent way to allow us to work with the latest versions of the ECMWF modelling system. The application process is relatively straightforward and the reporting process is appropriate. The support from technical staff at ECMWF in response to problems has been excellent.

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Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

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Please see attached.

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List of publications/reports from the project with complete references

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Beverley, J. D., Woolnough, S. J., Baker, L. H., Johnson, S. J. and Weisheimer, A. (2018) The northern hemisphere circumglobal teleconnection in a seasonal forecast model and its relationship to European summer forecast skill. Climate Dynamics. ISSN 0930-7575 doi: https://doi.org/10.1007/s00382-018-4371-4 (please note that this paper did not make any use of SP resources)

Beverley J.D., 2019: *The Role of the Asian Summer Monsoon as a Driver of European Summer Climate Variability*. PhD thesis, University of Reading, to be submitted

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Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

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1 ECMWF Special Project Final Report

1.1 Introduction

This project was part of a PhD project at the University of Reading in collaboration with the University of Oxford and within a wider NERC-funded project (SummerTIME). The overall aim of the SummerTIME project is to explore the drivers of variability and change in the European summer circulation. The focus of the PhD project is on the role of the Asian Summer monsoon as one of these drivers. Our ability to predict European climate at extended ranges (sub-seasonal to seasonal and beyond) depends on the ability of our models to correctly represent remote drivers of the European circulation and the teleconnection pathways from those remote drivers.

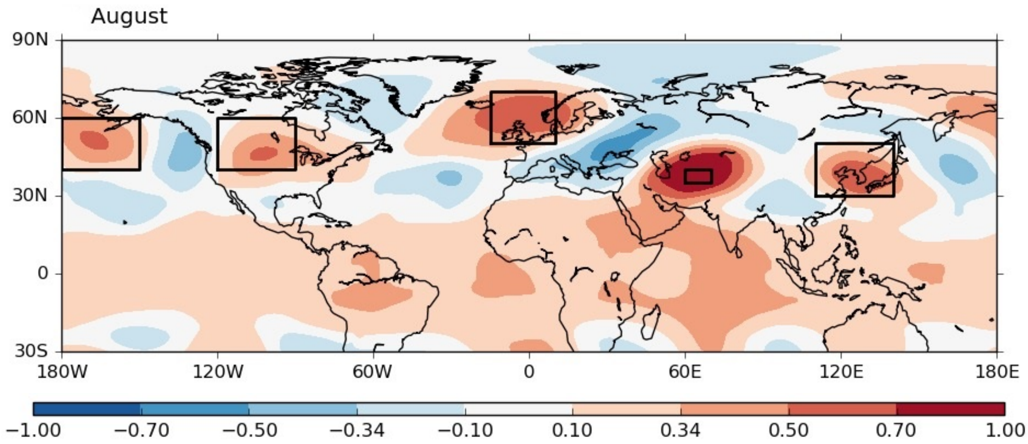

Figure 1: *Correlation between the 200 hPa geopotential height at the base point in west-central Asia (35°–40° N, 60°–70° E) and 200 hPa geopotential height elsewhere for August. The boxes show the regions defined as the "centres of action" of the CGT.*

Two main mechanisms have been proposed for the role of the Indian summer monsoon (ISM) in influencing the climate over Europe. Rodwell and Hoskins (1996) suggested that remote diabatic heating in the ISM region can induce a Rossby wave pattern to the west, which, through interaction with the midlatitude westerlies, can lead to enhanced decent over the Mediterranean. Ding and Wang (2005), and subsequently Ding and Wang (2007), proposed a mechanism whereby strong convection over the northern ISM (NISM) region is triggered by the west-central Asian high pressure associated with a wave train extending from northwest Europe. This convection then reinforces the west-central Asian high through the excitation of Rossby waves, which then propagate downstream to eastern Asia and beyond. They called this teleconnection pattern the circumglobal teleconnection (CGT) and it was shown in both Ding and Wang (2005) and Ding and Wang (2007) that the CGT has significant impacts on both European climate and the strength of the ISM. In addition, the ISM plays an important role in the maintenance of the CGT during the boreal summer. Figure 1 shows the CGT pattern for August, defined as the correlation between 200 hPa geopotential height over west-central Asia and 200 hPa geopotential height elsewhere. The boxes are the regions defined as the "centres of action" of the CGT used for subsequent analysis, which are also given in Table 1.

Table 1: *CGT 200 hPa geopotential height indices*

Index	Abbreviation	Domain
Ding and Wang	D&W	60°-70°E, 35°-40°N
Northwest Europe	NWEUR	15°W-10°E, 50°-70°N
East Asia	EASIA	110°-140°E, 30°-50°N
North Pacific	NPAC	180°-150°W, 40°-60°N
North America	NAM	120°-90°W, 40°-60°N

This project aimed to answer the following questions:

1. How well is the CGT represented in a state-of-the-art seasonal forecast model?
2. What is the role of the Indian summer monsoon in driving the CGT?
3. How does the Indian summer monsoon influence circulation variability over Europe?

The main results and conclusions for these questions are summarised in the following section.

2 Results

2.1 How well is the CGT represented in a state-of-the-art seasonal forecast model?

In order to diagnose the role of the CGT in influencing European summer seasonal forecast skill, it first had to be determined how well the model represents this teleconnection mechanism. To do this, analysis of a set of seasonal hindcasts using Cycle 41r1 was carried out to examine the model performance at representing the CGT. Figure 2 is a histogram of ensemble member pattern correlations of the CGT correlation maps compared to ERA-Interim, calculated between 30°–70°N in the control experiment. The model generally has a weaker than observed CGT wavetrain, and the median northern hemisphere pattern correlation for the wave train is 0.59 when compared to ERA-Interim.

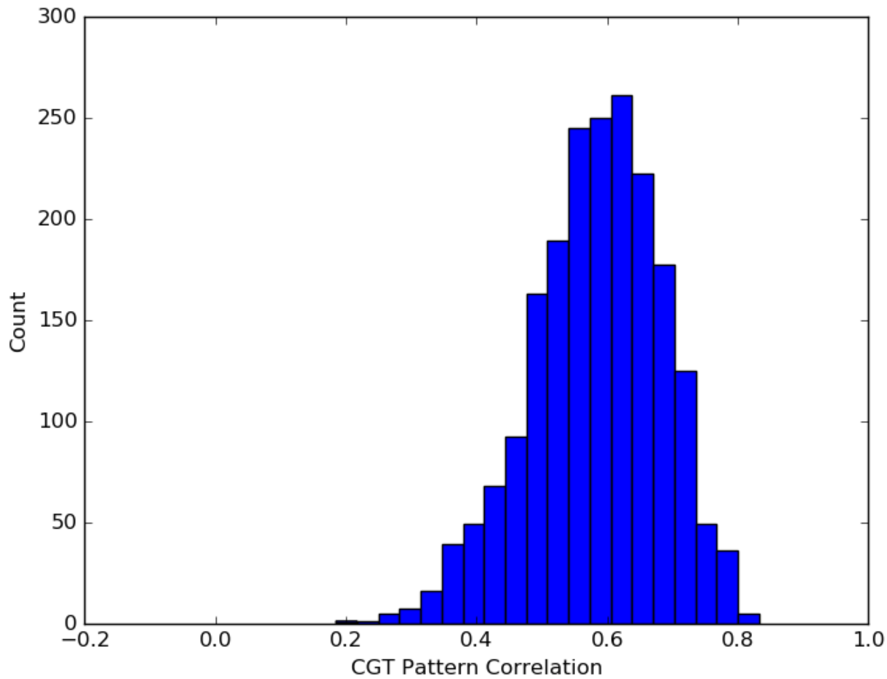

Figure 2: *Histogram of the pattern correlation between model control experiment and ERA-Interim CGT correlations for August, calculated using 2000 timeseries created from the 25 ensemble members. The pattern correlation is calculated for the values between 30°–70°N.*

We also found that the correlations between the D&W Index (the region used as the base-point for the CGT correlations which was proposed by Ding and Wang (2005, 2007) as linking ISM precipitation and the CGT) and other centres of action of the CGT are too weak in August, when the observed wave train is strongest, with the exception of the D&W vs. EASIA region correlations which are well captured (Figure 3). However, beyond EASIA the model wave train becomes weaker. The relationship between the EASIA and NPAC region, which also form part of a teleconnection known as the "Tokyo–Chicago Express" (Wang et al., 2001; Lau et al., 2004) and which have an observed correlation of 0.71, have a weaker than observed relationship in the model, although the majority of members do have a significant correlation between these two regions (not shown).

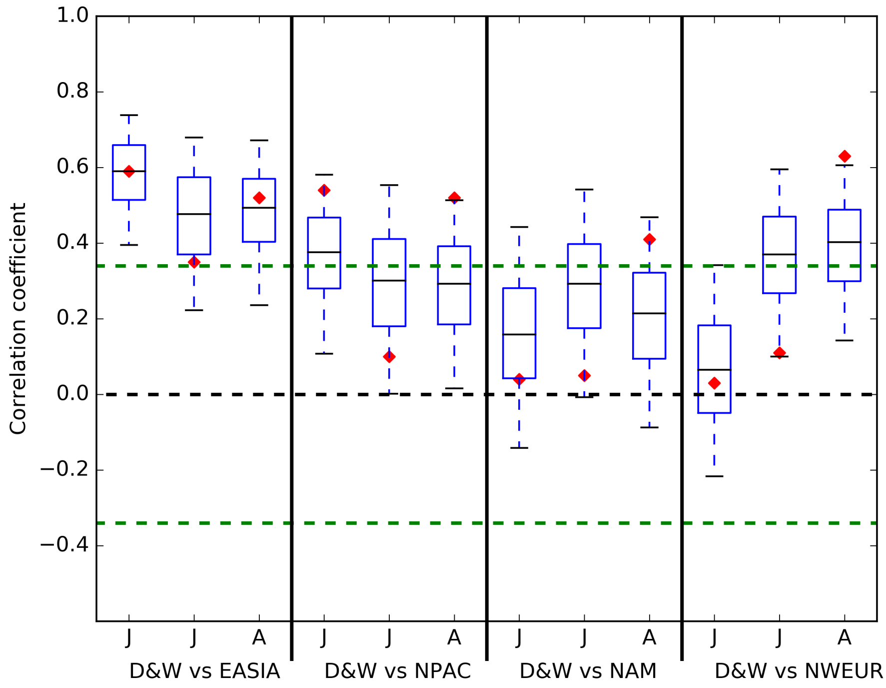

Figure 3: *Distribution of correlation coefficients for the D&W Index correlated against the other centres of action of the CGT, calculated using the multiple samples. The box plots represent the upper and lower quartiles, and the whiskers extend to the 5^{th} and 95^{th} percentiles. The black horizontal line represents the median value and the red diamond the observed correlation coefficient from ERA-Interim. 5% significance levels (±0.34) are indicated by the green dashed lines.*

A number of potential sources for the weak representation of the CGT in the model were investigated. Given the hypothesis of Ding and Wang (2007) that the D&W region plays an important role in the maintenance of the CGT, the skill of the model in this region was investigated. It was found that the variance of the D&W Index is lower than observed in July and August. A possible reason for this lower model variance is a weak representation of the link between ISM precipitation and the D&W Index (Figure 4). In observations there is a significant correlation between these indices in all months, and while this relationship is well captured in June, the correlations in July and August are much weaker. This in turn may be related to lower than observed variance of ISM precipitation in the model, and therefore the poor variance of the D&W Index in July and August may be linked to poor representation of ISM precipitation in the model.

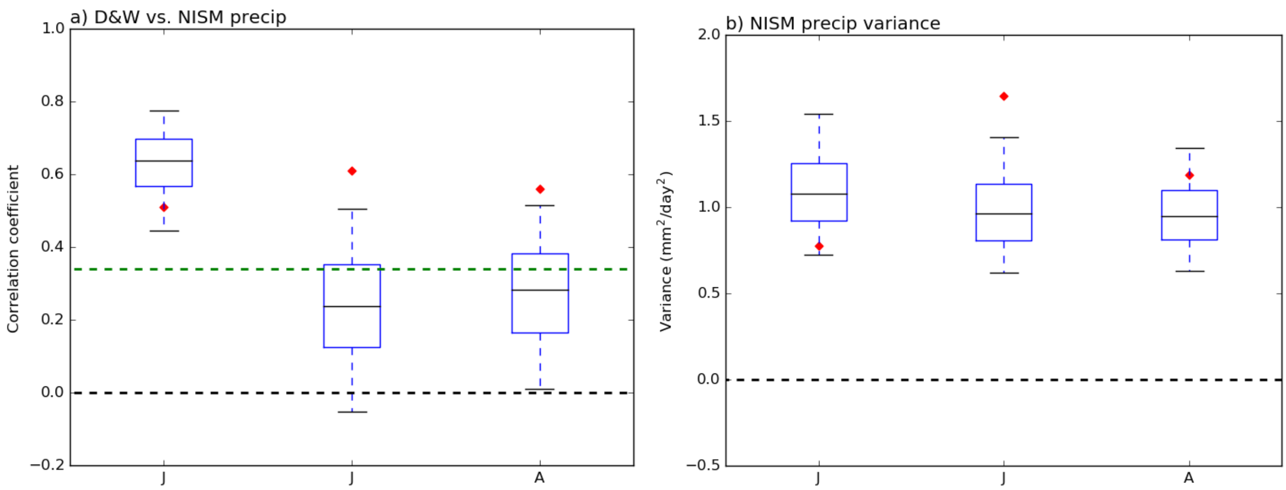

Figure 4: *Distribution of (a) the correlation coefficient between the D&W Index and NISM precipitation and (b) the variance of NISM precipitation. The box plots represent the upper and lower quartiles, and the whiskers extend to the 5^{th} and 95^{th} percentiles. The black horizontal line represents the median value and the red diamond the observed variance from ERA-Interim. The green dashed line on (a) represents the 5% significance level.*

Another possible source of errors in the CGT was found to be the Rossby wave source (RWS), which describes the forcing of Rossby waves by the divergent flow at 200 hPa. It was found that the RWS in the

D&W region is much weaker than in ERA-Interim, associated with a northeastward displacement of the centre of positive RWS near the D&W region in the model. This in turn was shown to be related to a northward displacement of the jet stream in the model over this region by several degrees latitude (Figure 5). The model

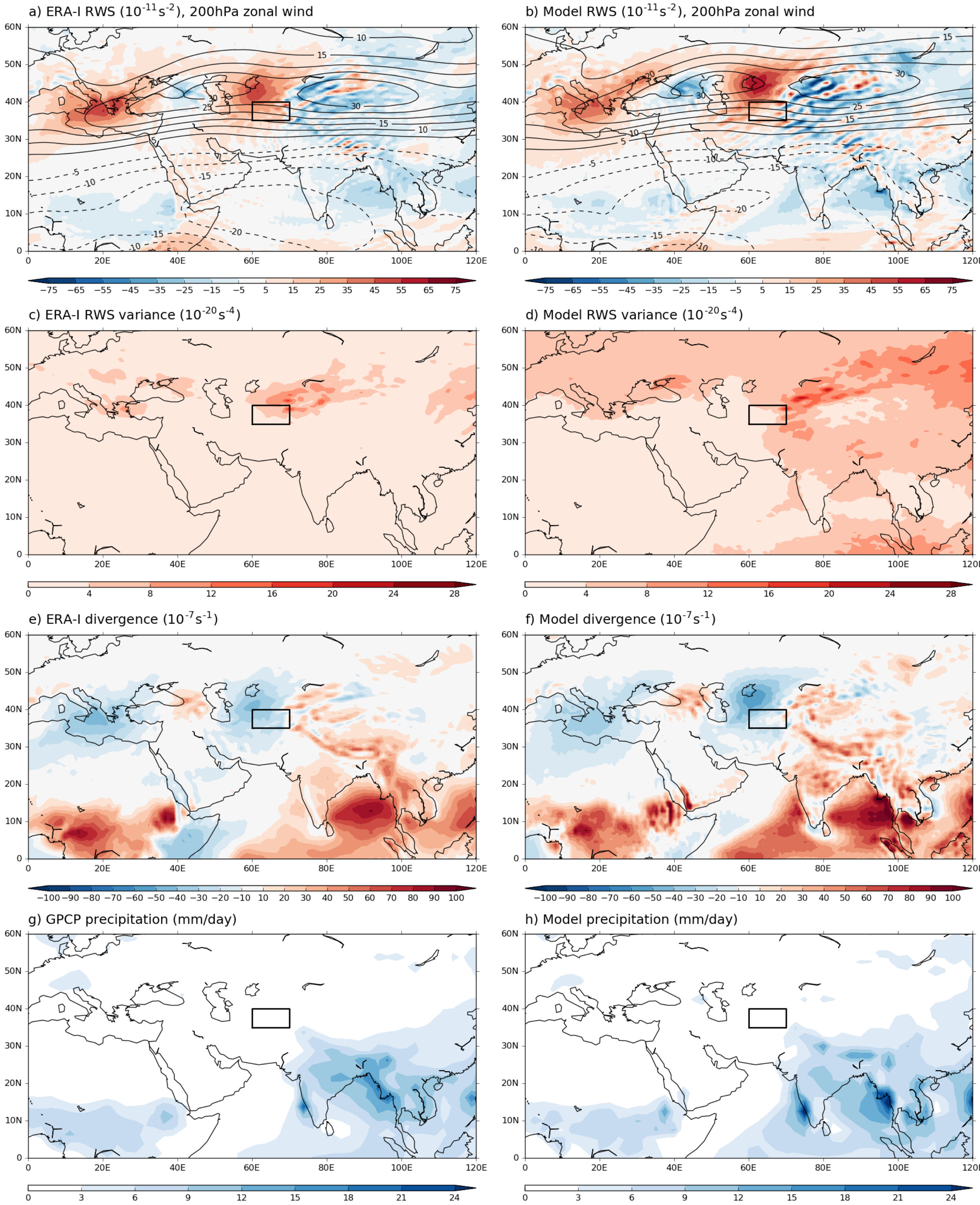

Figure 5: *(a) ERA-Interim and (b) model ensemble mean RWS term (filled contours) and 200 hPa zonal wind (black contours). (c) ERA-Interim and (d) model variance of the RWS term. The model variance is for all members concatenated together. (e) ERA-Interim and (f) model ensemble mean divergence. (g) GPCP and (h) model ensemble mean precipitation. All panels are for August, and the D&W region is marked as a box.*

RWS is also stronger than in ERA-Interim away from the D&W region. Analysis of the divergence and precipitation showed that this difference in magnitude can be attributed to differences in the centre of convergence associated with the centre of positive RWS. This is also greater in magnitude in the model, as well as being displaced northeastwards, again associated with the northward shift of the model jet stream. The magnitude difference may be related to greater model divergence over the Bay of Bengal and the Arabian Sea, which in turn is associated with increased amounts of model precipitation in these regions (Figure 5).

A northward displacement of the jet stream in the model was also found across much of the northern hemisphere. In June, July and August the model jet stream is located several degrees too far north across most of Eurasia and the North Pacific (Figure 6). Rossby waves propagate along the jet stream, which acts as a waveguide, so these biases, which are located along the CGT pathway, are likely to have an impact on the propagation characteristics of Rossby waves associated with the CGT in the model. The combination of the errors in RWS along with the bias in the jet stream location are likely to be important in the weak representation of the CGT in the model.

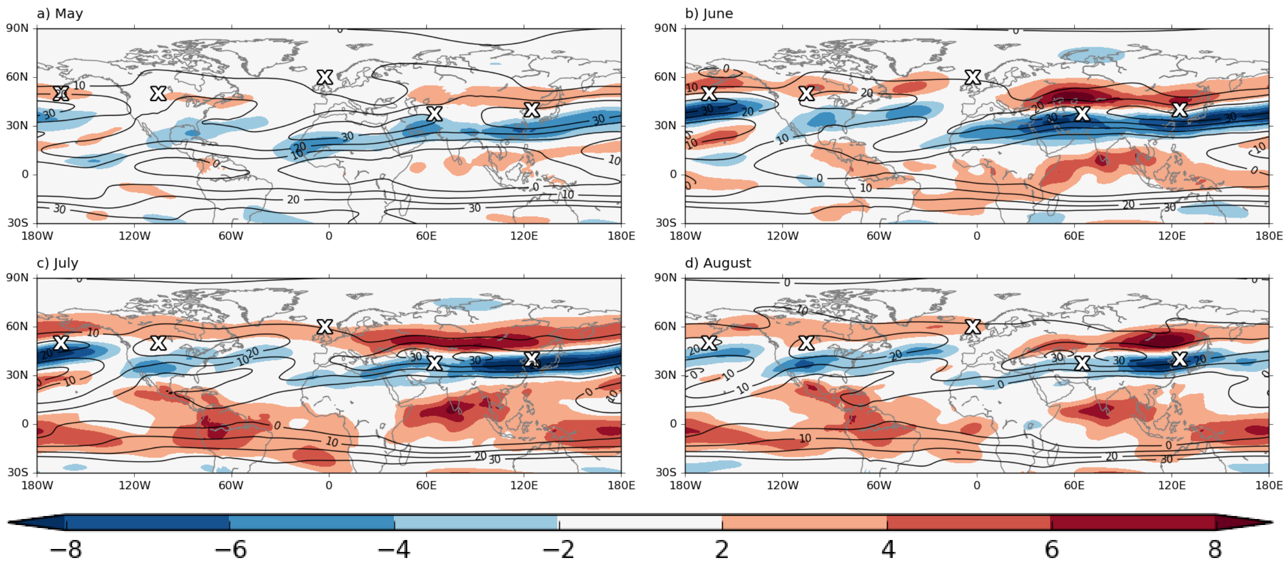

Figure 6: *Model 200 hPa zonal wind bias (filled contours, ms^{-1}), defined as the model ensemble mean minus ERA-Interim zonal wind, and ERA-I 200 hPa zonal wind (black contours) for (a) May, (b) June, (c) July and (d) August. To show the position of the observed jet, only the 0, 10, 20 and 30 ms^{-1} isotachs have been plotted. For orientation, the location of the centres of action of the CGT are marked with white crosses.*

2.2 What is the role of the Indian summer monsoon in driving the CGT?

Ding and Wang (2005) hypothesised that the ISM plays an important role in the forcing or maintenance of the CGT, either by exciting Rossby waves which then propagate downstream and influence the midlatitude circulation, or through the interaction of a Rossby wave train which propagates from Europe to west-central Asia, before being reinforced by precipitation associated with the ISM. Subsequently, Ding and Wang (2007) suggested that the second mechanism is likely to be the more dominant of the two and that Rossby waves which propagate from Europe can initially trigger precipitation in the north ISM region, but also that this convection then re-energises the downstream propagation of the wave train. Other studies have also identified the possible role of the ISM in exciting eastward propagating Rossby waves. Wang et al. (2001) and Wu and Wang (2002) both found that ISM precipitation modulates the west-central Asia anomalous anticyclone, and that this is also responsible for the formation of an anomalous anticyclone over east Asia.

Table 2: *Relaxation regions*

Experiment name	Region	Domain
DW_RELAX	Ding and Wang	35°–45°N, 55°–75°E
NWEUR_RELAX	Northwest Europe	45°–65°N, 25°W–5°E
ISM_RELAX	Indian monsoon	0°–30°N, 60°–100°E

To examine the role of the ISM in forcing or maintaining the CGT, and also to investigate the above hypothesis from Ding and Wang (2007), three relaxation experiments were carried out. In these, the circulation was relaxed towards ERA-Interim in specific regions of interest, detailed in Table 2, following the method of e.g. Jung et al. (2008). It was found that there is weak model variability in the D&W region and a weak relationship between the D&W Index and the ISM. To examine whether the weak representation of the CGT in the model is a result of weak forcing from the D&W region, the first experiment relaxed the circulation near this region. Analysis from this experiment showed that the representation of the CGT in this experiment is poorer than in the control, with a median pattern correlation of 0.35 compared to 0.59 for the control. Figure 7 shows the difference in ensemble mean 200 hPa geopotential height skill (defined as the correlation between the model ensemble mean and ERA-Interim) between the new control experiment and DW_RELAX. This is defined such that a positive value indicates that the skill in the model experiment is higher than in the control, and vice versa. It can be seen that the 200 hPa geopotential height skill is not much improved outside Asia, with the skill over Europe largely unchanged. This may suggest that the CGT is not being forced from west-central Asia, and also that the skill over Europe is not reliant on errors in the D&W region. However, the northward jet biases seen in the control experiment are still present in much of the northern hemisphere (not shown), which means that there are still likely to be errors in Rossby wave propagation. Also, a consequence of the relaxation, the variance in the D&W region will have been increased. If the model teleconnection pathway is incorrect, then this may mean that a stronger version of the incorrect response is being forced, which could explain the reduced CGT pattern correlation in this experiment.

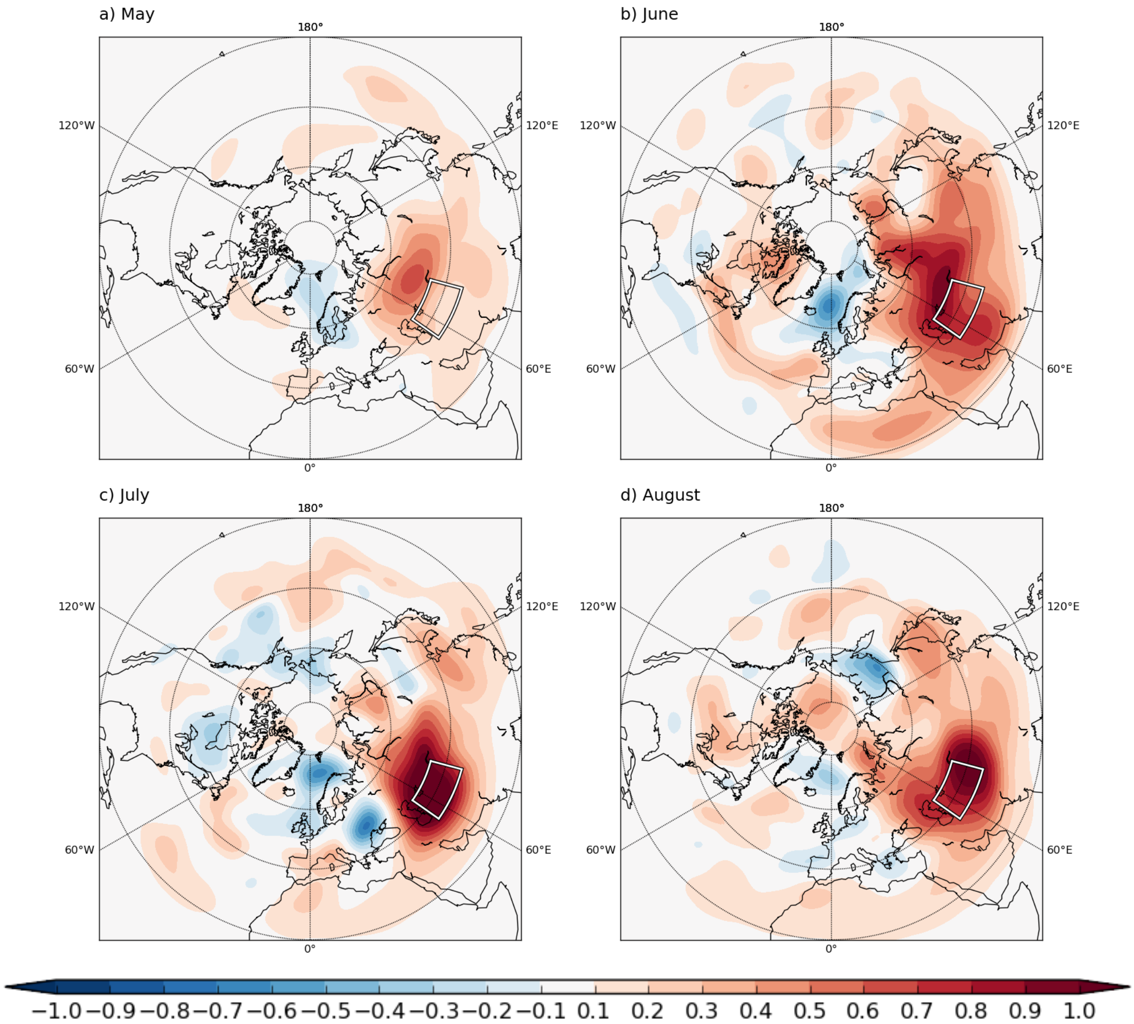

Figure 7: *DW_RELAX 200 hPa correlation skill minus control 200 hPa geopotential height skill for (a) May (b) June (c) July and (d) August. A positive value indicates that the 200 hPa geopotential height skill is increased in the relaxation experiment compared to the control. The box indicates the relaxation region used.*

The second experiment relaxed a region over northwest Europe. This experiment was performed to investigate the Ding and Wang (2007) hypothesis that the midlatitude wave train originates over northwest Europe and subsequently propagates to west-central Asia. Also, an area of reduced skill in the control appears over northwest Europe in June, before the development of areas of reduced skill over Asia in July and August, so this experiment was also designed to reveal if the errors over west-central Asia arise as a result of errors propagating from northwest Europe. Results from this experiment show that a greater area of the northern hemisphere show improvements in geopotential height skill compared to the west-central Asia relaxation (Figure 8). The CGT pattern correlations in this experiment are also improved slightly compared to the control, with a median pattern correlation of 0.67 compared to 0.59 in the control. These results strongly suggest that northwest Europe has a much more influencial role in the forcing of the CGT than west-central Asia. This in turn suggests that the ISM has a limited role in the initial forcing of the CGT, but could still play an important role in the subsequent downstream propagation of the Rossby wave train.

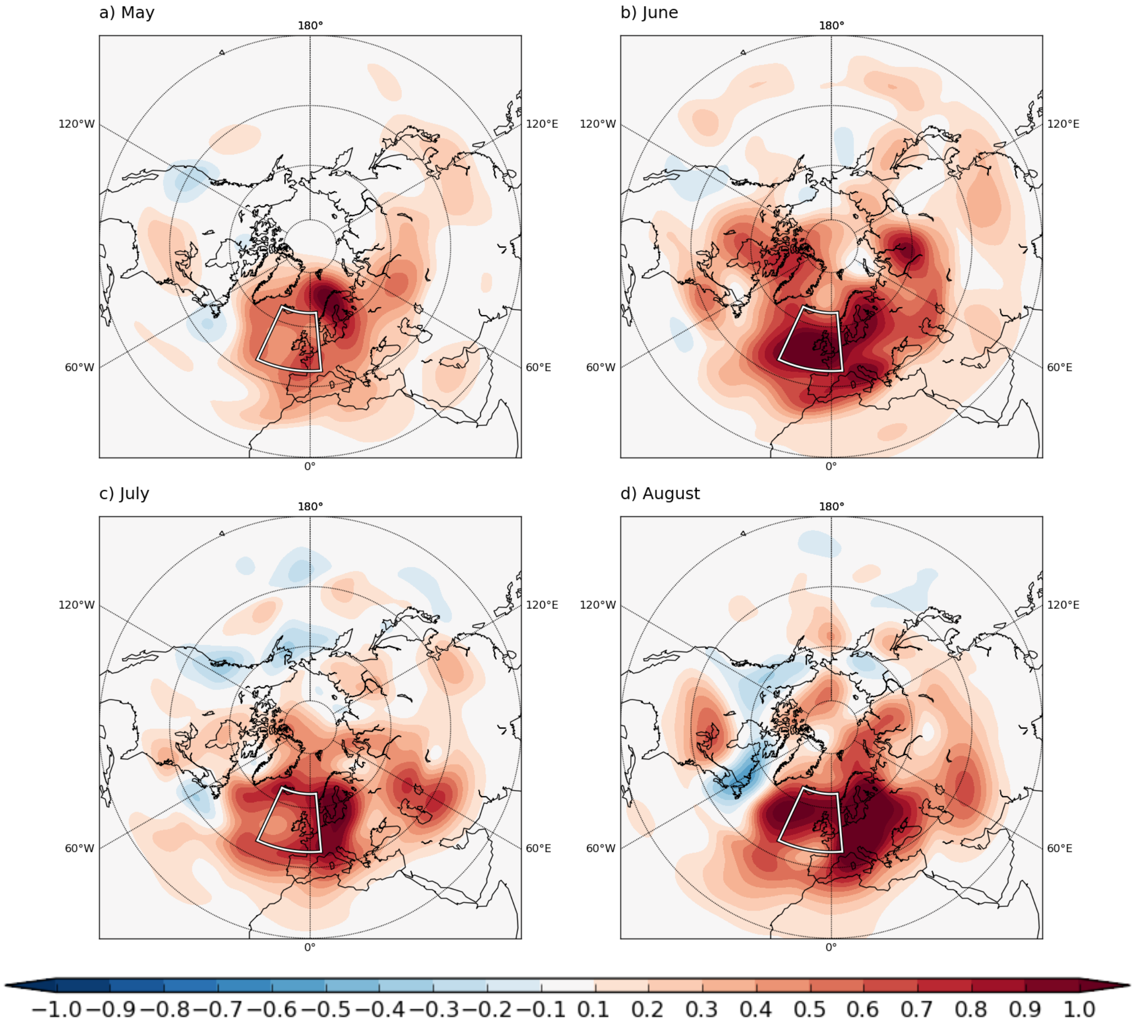

Figure 8: *DW_RELAX 200 hPa correlation skill minus control 200 hPa geopotential height skill for (a) May (b) June (c) July and (d) August. A positive value indicates that the 200 hPa geopotential height skill is increased in the relaxation experiment compared to the control. The box indicates the relaxation region used.*

The third experiment involved relaxing a larger region which encompassed most of the ISM region. As the relationship between ISM precipitation and the D&W Index is too weak in both previous relaxation experiments and in the control, and given the modest skill for the model representation of the ISM, this experiment was designed investigate the impact of correcting the monsoon circulation on extratropical skill and on the representation of the CGT. It was found that the extratropical skill is not particularly dependent on errors in the ISM circulation. In particular, the skill over Europe in June and July was largely unaffected, although some improvements were seen in August (not shown). The CGT pattern correlations were also very similar to the control, with a slight reduction in the median value. This suggests that the ISM is not the main driver of the CGT. However, the jet biases that were also present in previous experiments still remain, which could limit any improvements in the representation of the CGT.

Two thermal forcing experiments were also carried out in the ECMWF model to further investigate the

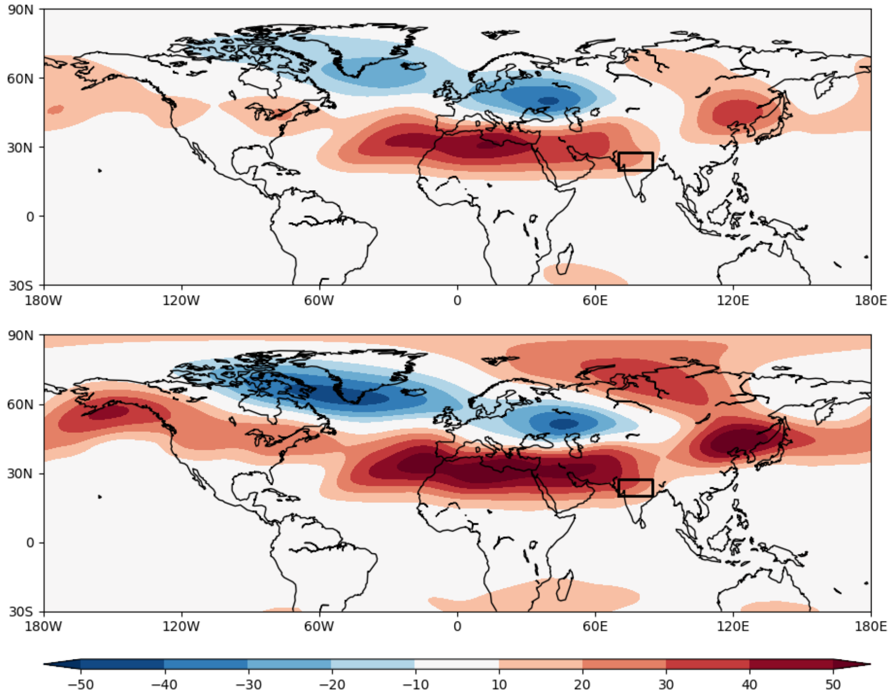

Figure 9: *Ensemble mean 200 hPa geopotential height difference (m) for the positive minus negative heating experiment for (a) July and (b) August, averaged over all years.*

role of the ISM in driving the CGT and in influencing the extratropical circulation. The two experiments consisted of applying a positive and negative heating over northwest India from the start of July onwards with a maximum equivalent to $\pm$4 mm day^{-1} of precipitation. Results from these experiments indicated that heating in the ISM region does drive an extratropical response. Figure 9 shows the difference in 200 hPa geopotential height between the positive and negative heating experiments. The response in east Asia, the North Pacific and North America is broadly consistent with a CGT-like response, with increased geopotential height in these regions in the positive thermal forcing experiment. There is also a strong monsoon-desert mechanism response, with positive anomalies extending across North Africa and the Mediterranean. However, the response over northern Europe is not similar to the CGT, with negative anomalies across much of the region associated with a northwestward propagating signal from the forcing region. This suggests that, while the ISM does excite a CGT-like response in much of the northern hemisphere, the circulation over Europe is not forced by the ISM via the CGT.

Overall, it seems that the ISM can drive the extratropical northern hemisphere circulation through a CGT-like mechanism, with the exception of Europe, which is influenced more by northwestward propagating signals associated with the monsoon-desert mechanism. While the relaxation experiments suggested that northwest Europe is a more important region for the excitation of the CGT, the thermal forcing and barotropic model experiments suggested that the ISM does influence the circulation over east Asia, the North Pacific and North America via the CGT mechanism. It does also affect the circulation over Europe but not by the same mechanism - here, the response is related more to a monsoon-desert type mechanism than the CGT.

2.3 How does the Indian summer monsoon influence circulation variability over Europe?

As described earlier, analysis of thermal forcing experiments carried out in the ECWMF model, along with barotropic model results, suggested that the circulation over Europe is not affected as part of a CGT wave train that is forced by the ISM. However, the European circulation is influenced by heating associated with the ISM in other ways. This appears to be primarily through a northwestward propagating signal from the forcing region, as part of a Rodwell and Hoskins (1996) monsoon-desert mechanism response. The thermal forcing experiments show that ISM heating is associated with a strong anticyclonic anomaly which extends across the Mediterranean and North Africa, which is consistent with the results of Rodwell and Hoskins (1996). To the north of this, over much of northern Europe, are anomalies of the opposite sign. Analysis of the heating experiments showed that these anomalies develop soon after the heating is applied, and that the European response is almost fully developed 10 days after the heating has been turned on. These anomalies also appear before the eastward travelling Rossby waves have propagated around the hemisphere, indicating that they are not associated with this Rossby wave train.

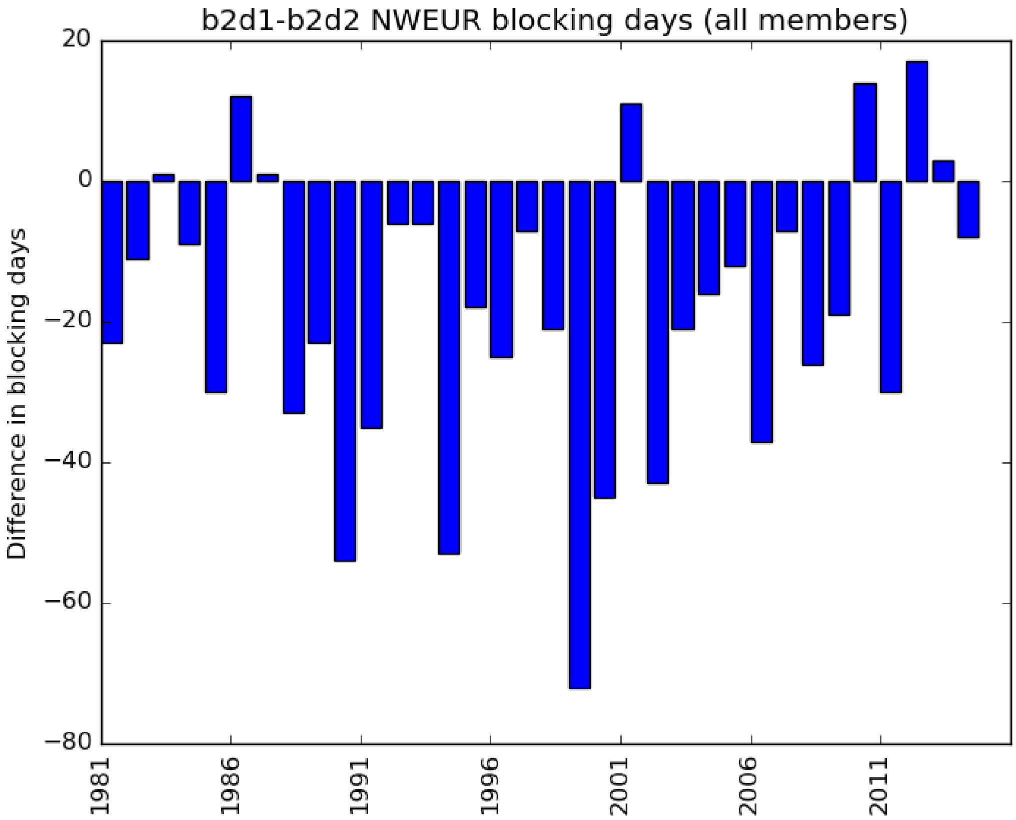

Figure 10: *Difference in the total number of blocked days in the NWEUR region between the positive and negative heating experiments. The total is over all members for each year in July and August (315 days each year in total).*

One measure of the impact of heating associated with the ISM is through analysis of the total number of blocked days in both the positive and negative heating experiments. Blocking can have severe socio-economic impacts so understanding the impact of ISM heating on European blocking is likely to be important for European summer seasonal forecast skill. Figure 10 shows the difference in the number of blocked days between the two heating experiments each year. This is calculated over all five ensemble members, as using the ensemble mean smoothes the geopotential height field so that no blocking can be detected. The values in Figure 10 are for the difference between the totals calculated from all members. The blocking index is calculated for all days in July and August (62 days in total) and the five members means that there is a total of 310 days in each experiment each year. There is a larger number of blocked days in northwest Europe in the negative heating experiment than the positive heating experiment. On average, across the 34 year period, there is around 20% more blocked days in the negative heating experiment. This is likely to be partially related to the strength of the jet stream in the two experiments, with a stronger jet stream in much of the northern hemisphere in the positive heating experiment, including over the North Atlantic. A stronger jet stream means that blocking is less likely to occur so this may partly explain the difference between the two experiments. The positive heating also leads to cyclonic anomalies over northern Europe as a result of the northwestward propagating signal, which are less conducive to the development of blocking. There are also differences in the basic state in years with the greatest difference in total blocked days between the two heating experiments, whereby the North Pacific jet is located further north. This may affect the propagation of Rossby waves away from east Asia, so that there are larger differences in the downstream circulation in the two experiments. A combination of these factors may explain the differences in the amount of blocking over Europe in the thermal forcing experiments.

Overall, while the ISM does not appear to influence the circulation over Europe through the CGT mechanism, it can cause changes in the circulation in other ways. In particular, the northwestward propagating signal from the ISM region leads to anticyclonic anomalies over northern Europe in the negative heating experiment, which increases the amount of blocking, and vice versa. Whether this mechanism occurs in observations as well as in the model is unclear and requires further investigation.

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