9.1 RUNNING A CLIMATE MODEL IN FORECAST MODE TO IDENTIFY THE SOURCE OF TROPICAL CLIMATE ERRORS: WITH SPECIFIC REFERENCE TO THE DRY BIAS OVER THE MARITIME CONTINENT IN AN ATMOSPHERE ONLY GCM

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1. INTRODUCTION

Climate model errors are usually addressed through the analysis of model climatology fields. However, it is questionable whether this is the most logical approach. In order to identify the source of model errors, a 'Spin-up' technique is employed, using an analysis approach traditionally associated with Numerical Weather Prediction (NWP), where the first few days of integrations of a climate model ensemble are analysed alongside long-term climatological means. Analysis of the initial period lets us observe how and why the model errors develop, making the source of the errors much easier to pin-point. This has proved to be a useful tool, as it allows a much clearer analysis of the model atmosphere response, without the complications of feedback mechanisms, reactions that occur over much longer timescales.

This study is motivated by the occurrence of systematic errors across the tropics in HadGAM1 and several other General Circulation Models (GCMs), and the need to identify the source of these model errors in order to correctly represent the global atmospheric circulation. These errors are focussed over the Maritime Continent region, where precipitation is systematically underestimated.

2. SPIN-UP TECHNIQUE

a. Description of model set-up

The model set-up is a 52 member 'Spin-up' ensemble experiment run on HadGAM1, the atmosphere component of the Hadley Centre's coupled climate model. The ensemble members have been initiated from 4 years of ECMWF[1] analyses, using DJF integrations 1 week apart. Each of these 52 members has been run for 5 days on HadGAM1. The output data has then been averaged over the 52 members for each day of the 5 day run.

b. Theory behind spin-up technique

Concentrating on the first few days of a the model spin-up allows us to address the source of the model error rather than the error product, a much more logical approach if we want to successfully reduce model errors. The climatological error shows an integrated response from initial errors, remote errors and feedback responses occurring over longer time-scales. These secondary responses obscure our understanding of why the error exists in the first place. Additionally, systematic errors observed early in the model runs are expected to be more easily related to local model issues, as the influence radius is expected to be much smaller (Klinker and Sardeshmukh (1992)). Therefore the spin-up technique allows a much clearer picture to be constructed of model error development to the mature model error patterns seen in climatological means.

3. CASE STUDY: The Maritime Continent dry bias

The Maritime Continent has been identified as a region of major climatic importance on both local and global scales (Neale and Slingo (2003)). It is essential that the region is sufficiently represented in GCMs in order to correctly reproduce observed regional climatology and ultimately global circulation. However the region represents a major modelling challenge. The systematic underestimation of precipitation over the Maritime Continent region is a problem experienced in HadGAM1, along with

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several other global models. The rainfall deficit in DJF over the region compared to CMAP[2] precipitation data (figure 1 (c)), is as much as 12mm/day. The discrepancy in rainfall leads to errors not only in the Maritime Continent region, but to systematic errors seen elsewhere, both in the tropics and extra-tropics (Neale and Slingo (2003)).

4. RESULTS

The following results concentrate on the assessment of the model error development across the Indo-Pacific region, focussing on the systematic dry bias observed across the Maritime Continent region. The fields described are the anomalous fields with respect to day 1 of the spin-up ensemble.

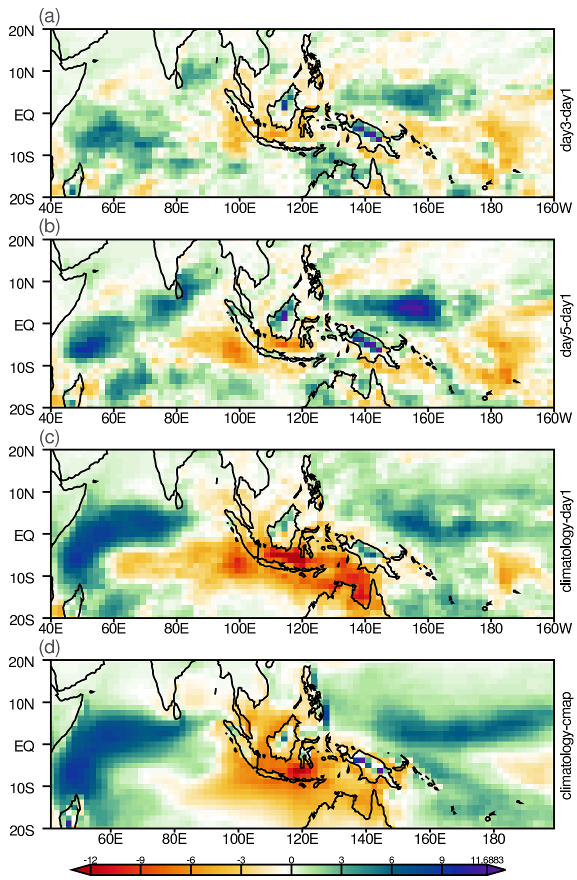

FIGURE 1: HadGAM1 spin-up ensemble precipitation anomaly (mm/day) (day(i)-day1). (a) Day 3 minus day 1 precipitation. (b) Day 5 minus day 1. (c) Model climatology DJF precipitation from a 3 year run minus day 1. Model climatology DJF precipitation minus CMAP DJF precipitation (1979-2002).

[2]CPC (Climate Prediction Centre) Merged Analysis of Precipitation

Precipitation

During the first 5 days of model spin-up there is a decrease in precipitation (figure 1 (a) and (b)):

(i) within the shallow seas of the Maritime Continent
(ii) in the east Indian Ocean off the west coast of Sumatra
(iii) off the south-east of Papua New Guinea
(iv) around the SPCZ region

By day 2 there is already a marked decrease in precipitation in these areas. However, the major drying over the Maritime Continent is not an immediate response. The climatological anomaly (figure 1 (d)) shows much stronger and extensive drying across the shallow seas of the Maritime Continent, most notably to the south of the region around Java, in the Arafura and Timor Seas to the north of Australia and in the Indian Ocean to the south-west of the Maritime Continent.

Initial increases in precipitation occur:

(i) in the west Pacific Ocean to the north-east of the Maritime Continent
(ii) in the west Indian Ocean
(iii) south-east of the Indian Peninsula

During the spin-up period, the largest increase in precipitation occurs over the west Pacific Ocean. A precipitation decrease to the south of this wet bias, causes a northward shift in the main area of precipitation from the SPCZ[3] to the ITCZ[4]. The west Pacific wet bias is not amplified in the mature pattern, and actually reduces in amplitude. However, the Indian Ocean wet bias spreads over a much larger area in the long-term, extending from Madagascar, round the East African coast and across to the peninsula of India, therefore becoming the dominant wet bias.

A hypothesis is that convective activity over the Maritime Continent is suppressed as a response to enhanced convective activity over surrounding oceanic regions. Anomalous ascent over the west Indian Ocean and west Pacific Ocean leads to anomalous descent and hence drying over the Maritime Continent. Positive feedback strengthens the anomalous circulation between these adjacent regions, resulting in an increase in amplitude and extent of the dry bias over the Maritime Continent in the long-term.

[3]South Pacific Convergence Zone
[4]Inter Tropical Convergence Zone

Low-level 950hPa winds

Assessment of the low-level winds during the first days of model spin-up reveals an anomalous strengthening of low-level easterly trade-winds across the west Pacific Ocean and into the east of the Maritime Continent (figure 2). The overall anomaly pattern is already established by day two, with the low level easterly wind anomaly being as much as 20% of the actual wind. There is also an increase in northerly winds along the East African coast from the Arabian Sea.

The climatological DJF wind anomaly pattern (not shown) looks significantly different to the spin-up anomaly, especially in the Indian Ocean, with anomalous easterly winds blowing from the Arafura Sea north of Australia to approximately 70 °E. There has been an eastward propagation of the wind error with time. This change effectively turns the winds around in the Indian Ocean from being predominantly westerly across the central Indian Ocean, flowing into the Maritime Continent, to being predominantly easterly, flowing out of the region. To the east of the Maritime Continent there is an anomalous increase of north-westerly winds from the islands along the SPCZ. The overall pattern of low-level winds therefore shows increased divergence from the Maritime Continent; this corresponds to the long-term extensive drying across the region that we do not really see within the first five days of the spin-up.

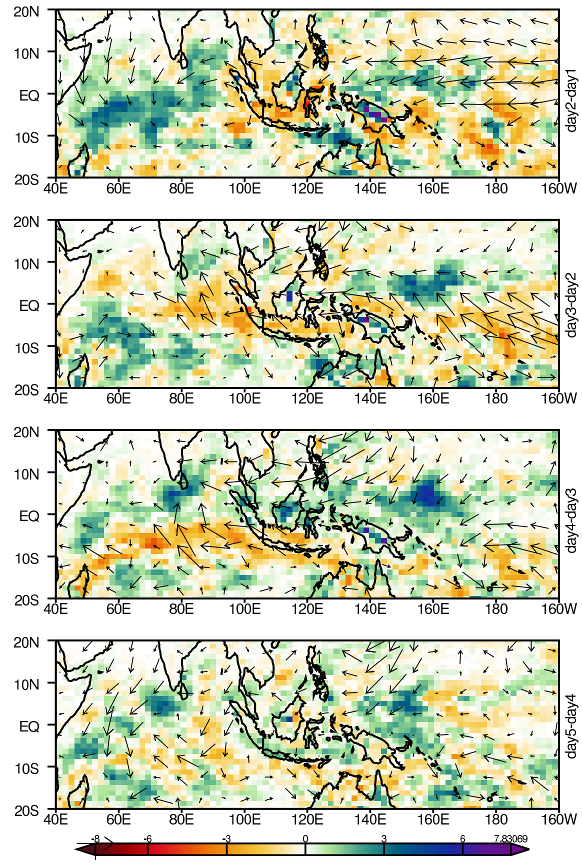

FIGURE 2: Linear anomaly of precipitation (mm/day) and 950hPa wind (m/s) (day(i)-day(i-1)) to show the linear error growth during the spin-up period

Winds versus precipitation

One of the major questions to arise from this investigation is whether the precipitation anomaly growth is a result of the wind anomaly over the region, or whether it is the winds which spin-up as a result of the precipitation anomaly. The linear anomaly plot for precipitation and low-level winds (figure 2) attempts to address this question. The wet bias over the west Pacific grows throughout the 5 day spin-up, with the main growth occurring from day 2-4. However, the anomalous low-level winds across the west Pacific spin-up within days 1-3, with very little growth on subsequent days. This timing, with the anomalous low-level winds spinning-up prior to the anomalous precipitation, suggests that the wind errors lead to the precipitation errors, rather than vice-versa. The overly strong easterly trade winds across the Pacific drive the west Pacific wet bias and the anomalous low level northerly winds from the Arabian Sea drive the west Indian Ocean wet bias.

Vertical circulation

The mean zonal circulation, constructed using vertical velocity and divergent wind fields, has been meridionally averaged over the islands 10 °N-10 °S (figure 3). During the first days of spin-up, an anomalous upper-level shallow circulation (200-400hPa) develops. This anomalous upper-level circulation may occur as a result of inaccuracies in the vertical heating profile at upper-levels. During the 5 days of spin-up and in the long-term, this anomalous circulation deepens through the atmosphere towards the surface. The patterns seen in the first 5 days reveals that anomalous ascent over the west Pacific is mainly linked to anomalous descent around the date-line, and that anomalous ascent over the west Indian Ocean is mainly linked to anomalous descent over the east Indian Ocean and west Maritime Continent. The climatological pattern reveals a strengthening in the deep circulation between the west and east Indian Ocean. The main region of anomalous descent linked to the anomalous ascent over west Pacific shifts in the

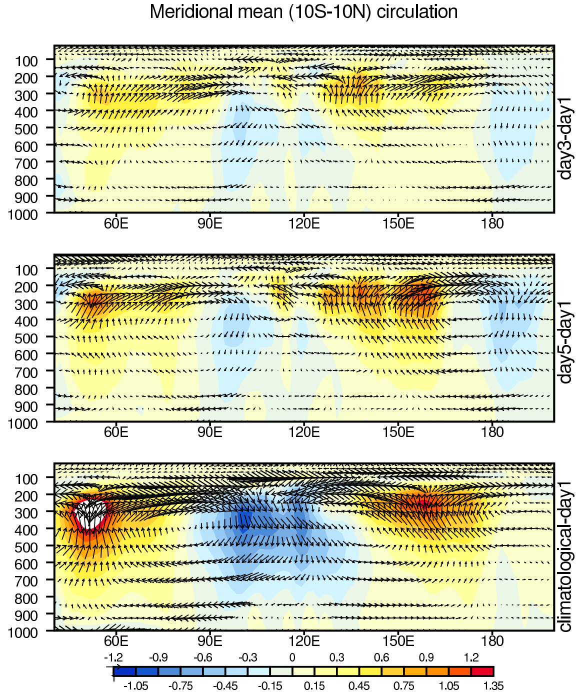

FIGURE 3: HadGAM1 spin-up ensemble zonal circulation cross-section mean (10 °N-10 °S) day(i)-day1. The first two plots show the anomalous circulation on days 5 and 3 of the spin-up run (compared to day 1). This final plot shows the anomalous circulation in the model climatological DJF mean (again compared to day 1). The Maritime Continent extends from 95 °E to 150 °E

long-term, from being over the date-line to being over the Maritime Continent. This mature pattern reveals how the Maritime Continent is subject to anomalous descent as a result of anomalous convective activity over both the Pacific and Indian Ocean regions. This additional descent accentuates the Maritime Continent dry bias.

Analysis of the evolution of vertical velocity profiles over wet and dry bias areas for the spin-up period are used to show that anomalous precipitation is initiated first, leading to anomalous drying. This shift in precipitation distribution is driven by the anomalous circulation patterns seen in the vertical circulation cross-sections. Anomalous ascent occurs where there is anomalous precipitation and accompanying anomalous descent over adjacent regions leads to reduction in precipitation.

Increment to the temperature from the convection scheme

Vertical profiles of the increment to temperature (figure 4) from the convection scheme reveal the development of the convection during the spin-up period. Anomalous convection confined to the upper-levels during the first 2 days rapidly deepens through the mid-levels. The first two anomaly plots clearly show the freezing level inversion and trade-wind inversion at 4000m and 1000m respectively. During days 4 and 5 the anomalous deep convection extends to the surface, with a decay of the freezing level inversion, revealing a further model error. During the spin-up period, this convective development is mainly seen over the west Pacific wet bas region. The west Indian Ocean wet bias region appears to have a more subtle change in convection during the spin-up period. The anomaly in this region develops in the long-term.

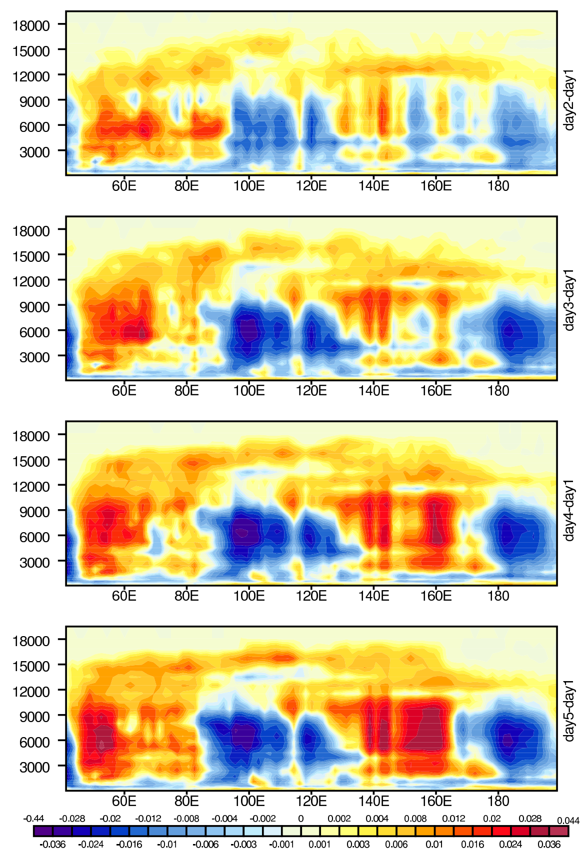

FIGURE 4: HadGAM1 spin-up ensemble mean vertical profiles (10 °N-10 °S) of increment to temperature (K) from the model convection scheme. Days 2 to 4 compared to day 1. The vertical axis shows height (m) from the surface. The Maritime Continent extends from 95 °E to 150 °E

5. SUMMARY

The 'spin-up' method of analysis is a useful technique for investigating the source of model errors and can be used to gain an understanding of how the errors seen in the first few days develop to what we see in the long-term climatological picture. This provides a logical starting point for making adjustments to the model in order to reduce the observed model errors. The technique has been applied to this particular case study, but it is a method that has universal application to modelling studies.

Spin-up ensemble runs show that model errors over the Indo-Pacific region spin-up within the first 4 days. The climatological anomalies show a maturing of the initial error patterns which may include feedback responses occurring over longer timescales. Using information gained from the daily means of the first 5 days of spin-up, the hypothesised error development is as follows:

1. A spin-up of low-level easterly trade winds across the west Pacific and northerly winds from the Arabian Sea.
2. Anomalous evaporation over the west Pacific and west Indian Ocean due to the anomalous low-level winds triggering surface heat fluxes.
3. Increased convection, and hence increased convective precipitation over these regions.
4. Anomalous circulation initiated, with ascent over wet bias regions and accompanying descent occurring over the adjacent Maritime Continent.
5. Descent over the Maritime Continent suppresses convection leading to anomalous drying.
6. Long-term growth and extension of the anomalous dry bias over the Maritime Continent due to feedback as the anomalous circulation deepens with increased descent over the region.

There appears to be three time-scales operating when considering the development of the model errors:
(a) The first 24 hours of spin-up includes an initial model response to the ECMWF initialisation data and initial growth of model errors.
(b) A slightly longer reaction of the model atmosphere within the 5 days of the spin-up run, as initial model errors develop further and secondary errors spin-up as a response to initial errors.
(c) Long-term spin-up leading to the model climatology. This is a result of the model atmosphere relaxing, with error development resulting from feedback mechanisms.

The above analysis summarises results from the daily means of the spin-up ensemble. This is not the entire picture. The analysis of the spin-up daily means suggests that anomalous low-level winds lead to the anomalous precipitation, but it is not yet clear what causes the winds to spin-up in the first place. Analysis of data from the time-steps within the first 24 hours of the spin-up ensemble will help to isolate the errors in the model physics that lead to this error growth.

It is important to note that the first few days of model spin-up may be contaminated with errors 'imported' from the initialisation data. We may be seeing errors and/or adjustment from the ECMWF analyses. The degree to which this may be affecting the spin-up results must be identified, so that we do not diagnose an incorrect model error development pattern. Initial assessment of data from the first time-steps suggests a reaction of the model to moisture profiles, with a large amount of water being precipitated out on the second time-step. However, it appears that the model responds to this anomalous moisture output very rapidly. Additionally, error patterns observed in the first days of spin-up are very similar to the mature error patterns but with reduced amplitude, suggesting that the impact of the initial data is minimal. If there was a large reaction to the initial data we would expect to see a very different initial error pattern.

References

Klinker, E. and Sardeshmukh, P. D. (1992). The diagnosis ofmechanical dissipation in the atmosphere from large-scale balance requirements. *J. Atmos. Sci.*, **49**(7), 608–627.

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