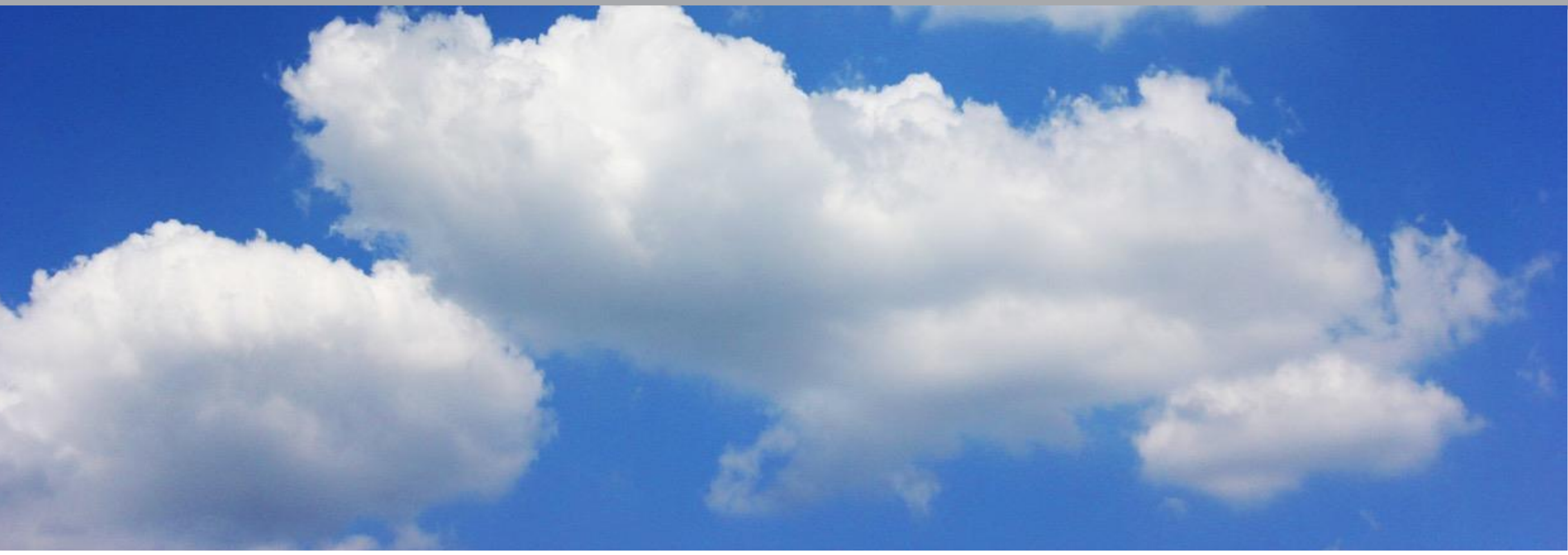
Earth Systems and Climate Change Hub

National Environmental Science Programme



Initial documentation of key systematic errors in a high-resolution (60-km grid) version of the current ACCESS atmospheric model

Harun Rashid, Hongyan Zhu and Zhian Sun

May 2018

Earth Systems and Climate Change Hub Report No. 1

Australian Government

National Environmental Science Programme

The Earth Systems and Climate Change Hub is supported by funding through the Australian Government's National Environmental Science Program. The Hub is hosted by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), and is a partnership CSIRO, Bureau of Meteorology, Australian National University, Monash University, University of Melbourne, University of New South Wales and University of Tasmania. The role of the Hub is to ensure that Australia's policies and management decisions are effectively informed by Earth systems and climate change science, now and into the future. For more information visit www.nespclimate.com.au.

Citation

Rashid H, Zhu H and Sun Z (2018) *Initial documentation of key systematic errors in a high resolution (60 km grid) version of the current ACCESS atmospheric model*. Earth Systems and Climate Change Hub Report No. 1, NESP Earth Systems and Climate Change Hub, Australia.

Contact

Enquiries regarding this report should be addressed to:

Dr Harun Rashid
CSIRO
harun.rashid@csiro.au

May 2018. First published June 2017 as Report No. 1 in the Earth Systems and Climate Change Hub Technical Report series.

This report is available for download from the Earth Systems and Climate Change Hub website at www.nespclimate.com.au.

Contents

Figures

REPORT SUMMARY

Systematic errors in a high-resolution version of the ACCESS atmospheric model

Preliminary evaluation results from an analysis of the ACCESS atmospheric model show that, overall, the model does a good job in realistically simulating the major features of the surface climate and atmospheric circulation. However, temperature, rainfall, radiation and circulation biases have been identified. The next step is to identify the cause of these biases so they can be addressed in the model. This will improve ACCESS's ability to realistically simulate our climate, resulting in better climate projections to inform decisions and policy.

The ACCESS model

The Australian Community Climate and Earth System Simulator (ACCESS) is a state-of-the-science comprehensive climate model. Just as the climate system is the result of interactions between the atmosphere, oceans, land and sea ice (among others), ACCESS comprises atmosphere, ocean, land surface and sea-ice models that are 'coupled' to communicate the relevant information between them. In this way, it can more realistically simulate the climate system.

Climate models represent the world in a series of three-dimensional grid cells. The smaller the grid cell, the higher the model resolution. Ideally, the higher the model resolution the better the model simulation should be. However, in practice, models cannot always be run at high resolutions due to the high computational costs (modelling a complex system like the climate in fine detail takes a lot of computer time). Also, while we expect that higher resolution will improve simulation for all variables and regions, this may not turn out to be the case. To assess which aspects are improved by higher resolution modelling, different model components are assessed at different resolutions (independently of the other components).

While ACCESS is among the top performing climate models internationally, like all models it has different biases (also referred to as model systematic errors) in its simulation of the climate. To improve the performance of the model, these biases in key climate variables need to be documented and the processes causing them need to be identified. We can then improve how the processes are represented in the model, so simulations better match the observed climate.

Assessing the ACCESS atmospheric model

Earth Systems and Climate Change Hub researchers examined a high-resolution (60-km grid) configuration of the latest version of the atmospheric component model (UK Met Office UM GA7) of ACCESS. To identify the biases, researchers compared model output with observational and reanalysis (a dataset obtained by combining models with observations) datasets.

Biases in the atmospheric model

Preliminary results show that, overall, the high-resolution atmospheric model does a better job realistically simulating the major surface and atmospheric climate features than the low-resolution version. However, there are still significant biases that need to be investigated further to understand their causes. Some of these biases are:

- Surface temperatures are colder than observed over the continents during winter.
- Air pressure at sea level is higher than observed over the high-latitude Southern Ocean.
- Downward shortwave radiation (visible sunlight) is greater than observed over the Southern Ocean (which causes a major warm bias there).
- Rainfall is wetter than observed over the tropical western Pacific and Indian Oceans and drier than observed over the Maritime Continent (the region between the Indian and Pacific Oceans).
- Atmospheric convection (that is, upward motion) over the Maritime Continent is weaker than observed (leading to lower than observed rainfall).
- Southern Hemisphere storm tracks are located farther south than observed.
- The dominant Hadley Cell is slightly displaced upward (affecting the position of the jet stream, which in turn affects the paths of weather systems).

Increasing the horizontal resolution of the model (from 135 km to 60 km) significantly reduces the dry rainfall bias over the Maritime Continent. Earlier studies (using GA6, the previous version of the atmospheric model) showed that this is largely due to the more realistic representation of mountains in the region in the high-resolution model. However, while increasing the resolution improves simulation of the amount of rainfall, it does not improve the simulation of the timing (day/night) of the rainfall.

Next steps

Having identified the biases, the next step is to understand the causes of some of these errors. This will require additional research. When the causes have been identified, representations of these processes can be updated accordingly in subsequent versions of the model.

Hub researchers will also collect and archive the software tools used for model evaluation so they can be made available to other potential users of the model.

Other modelling work will include conducting a coupled simulation with the high-resolution atmospheric model as part of the full ACCESS coupled model, which will then be used as a platform for further model development.

Ongoing development of ACCESS, underpinned by research to better understand the components of the climate system will ensure that Australia's climate modelling capability remains world-class. More importantly, it will ensure that governments, businesses and communities across the country have access to the best possible information about Australia's climate with which to make decisions about the future.

1 Introduction

The Australian Community Climate and Earth System Simulator (ACCESS) is a state-of-the-science comprehensive climate model. It comprises the individual models for the climate system components, namely, the atmosphere, oceans, land surface and sea-ice. The component models are dynamically coupled to communicate the relevant information between them, as the earth's mean climate and its variability are largely determined by interactions between the climate system components. Comprehensive climate models, such as the ACCESS, enable seamless predictions/projections of weather and climate at multiple time scales, from days through to centuries. Indeed, earlier versions of the ACCESS were used to do multiple scenario simulations, including the historical and RCP (Representative Concentration Pathway) simulations, to contribute to the CMIP5 (Coupled Model Intercomparison Project phase 5) archive. Also, the atmosphere-land surface components of the ACCESS, combined with a data assimilation system, form the basis of the numerical weather prediction at the Australian Bureau of Meteorology.

Thanks to the decades of development efforts by modelling groups, climate models collectively can now simulate and predict state of the climate system with remarkable skills (although individual model performance can vary widely). Comprehensive evaluations of ACCESS simulations, contributed to the CMIP5 archive, by international researchers placed the ACCESS model among the top performing models (e.g., Watterson et al. 2014). However, as for other climate models, the ACCESS model still shows considerable systematic errors in key climate variables, and continual improvement of the physical and dynamical processes is needed to better the model performance. To achieve this, the major systematic errors experienced by the model must first be documented, the processes causing the errors be identified, and then appropriate improvements to the physics or tuning of existing parameterizations be made in order to improve the model performance.

Here, we report the preliminary results of model evaluation studies using a latest version of a (relatively) high-resolution (N216, with 60 km grid spacing) ACCESS atmospheric model (the UK Met Office Unified Model (UM) with GA7 climate configuration). We concentrate on the systematic errors in the tropical region and in the Southern Hemisphere (SH), which are more relevant for Australian weather and climate. Comprehensive evaluations of Northern Hemisphere (NH) systematic errors are done at the UK Met Office, hence are not repeated in our work.

2 Models and data

Data from various AMIP (Atmospheric Model Intercomparison Project)-style simulations of the GA7 atmosphere model (hereafter, AGCM), with the N96 and N216 horizontal resolutions (~135 and 60 km grid spacing, respectively), are used in this study. AMIP experiments over a 27-year period (1982-2008) have been conducted at the UK Met Office; experiments of shorter lengths have been performed at the Bureau of Meteorology to analyse extra variables not available from the Met Office simulations. The model has 85 levels in the vertical, extending from surface to a height of about 85 km. The model incorporates a comprehensive set of sophisticated physical parameterization schemes, including the radiation, convection, cloud, atmospheric boundary layer, gravity wave drag, atmospheric aerosols and chemistry, and land surface and hydrology schemes. A detailed description of these processes may be found in recent publications (e.g. Walters et al. 2014; Rashid and Hirst 2016).

To identify the model systematic errors, we use observational and reanalysis datasets: the Global Precipitation Climatology Project (GPCP) version 2.2 (Adler et al. 2003) and the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) (Xie and Arkin 1997) datasets for rainfall and the NCEP2 and ERA-Interim (Dee et al. 2011) reanalyses for atmospheric circulations. We also use Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) data for surface radiation fields (Wielicki et al. 1996). The model errors are presented as the AGCM minus observation/reanalysis; no attempt is made in this report to estimate the statistical significance of the differences.

3 Systematic errors in surface climate

It is important to minimise the model errors or biases in the simulation of time-mean climate variables, such as, precipitation, surface temperatures and sea-level pressures. Time-mean states of these variables have important influence over the development and maintenance of both day-to-day weather systems and slowly varying climate anomalies.

Figure 1 shows the geographical distributions of seasonal mean surface temperatures for the December-January-February (DJF) and June-July-August (JJA) seasons. In general, there are warm temperature biases (~ 2 °C) over the tropical and mid-latitude oceans and cold biases over both polar regions. This results in a steeper meridional gradients of temperatures near the poles in both hemispheres, which may have implications for the locations/strength of the atmospheric jet streams and storm tracks. In addition, there are considerable warm biases near the prominent western boundary currents in DJF and near the edge of the Antarctic continent in JJA. Large biases are also seen over the NH continents, with cold and warm biases in DJF and JJA seasons, respectively.

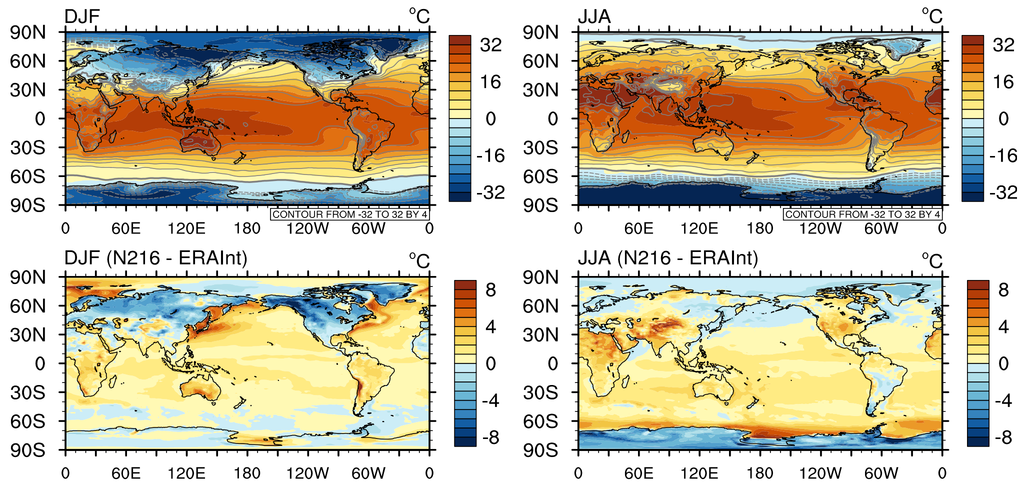


Figure 1. Seasonal mean surface temperatures for DJF (left column) and JJA (right column) seasons. The top panels show the full time-mean variables for the model simulation (shades) and for ERA-Interim reanalysis (contours). The bottom panels show the difference (i.e. error) between the simulation and reanalysis.

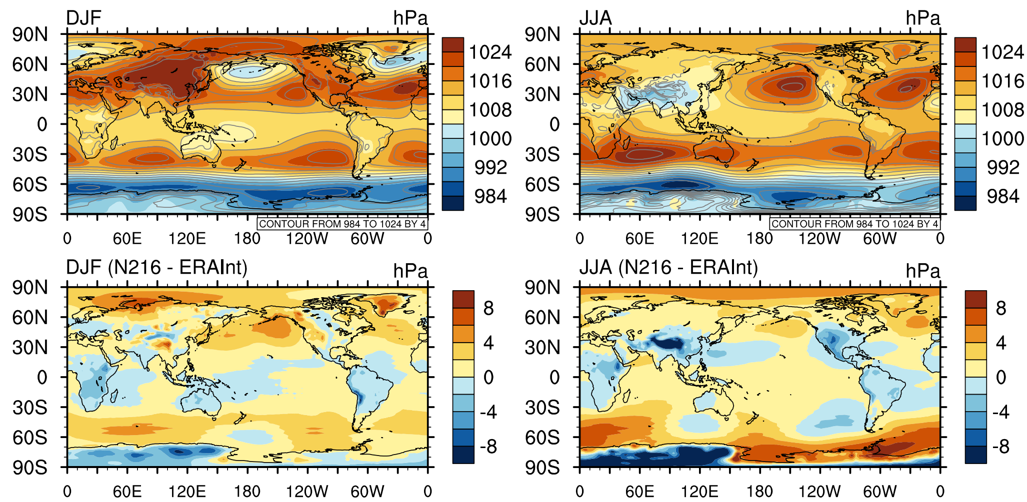


Figure 2. As in Figure 1, but for sea-level pressure.

Seasonal mean distributions of sea-level pressure are shown in Figure 2. There are areas of high pressure biases over the NH polar region and the high-latitude Southern Ocean in both seasons. The Southern Ocean high-pressure biases are particularly large in JJA. Areas with significant low pressure biases are seen mostly over the SH continents and, to a lesser extent, over the south-western United States and the Himalayan ranges during JJA.

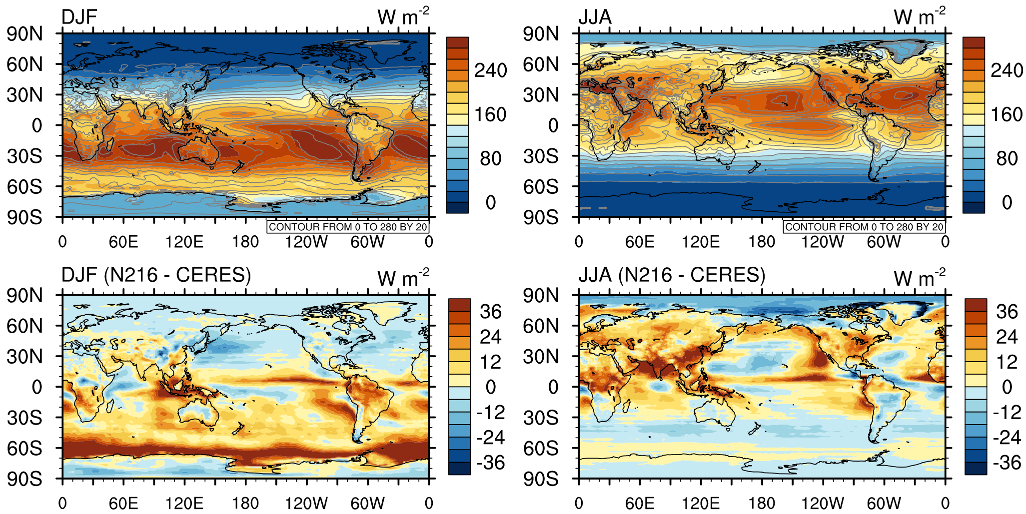


Figure 3. As in Figure 1, but for net downward shortwave (SW) radiation at the surface. Biases are calculated with respect to CERES satellite observations.

3.1 Surface radiation

Net downward shortwave (SW) radiation at the surface from two AGCM simulations and observation is shown in Figure 3. In DJF, areas of excessive downward SW are seen over the Southern Ocean, the Maritime Continent, and the eastern part of subtropical oceans in the SH (positive values in the bottom-left panel). In JJA, excessive radiations are mostly seen over the NH continents and the adjacent oceanic areas (bottom-right panel). These biases are most likely linked to an inadequate simulation of the cloud in those regions; the Southern Ocean bias, in particular, results in a pronounced warm bias in DJF sea surface temperatures (SSTs) there (Bodas-Salcedo et al. 2014), which is seen in many climate models.

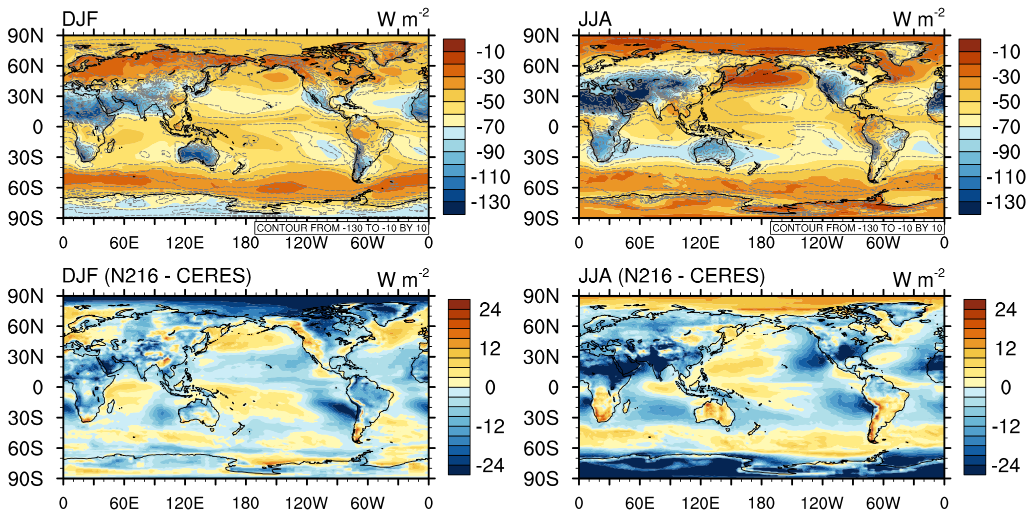


Figure 4. As in Figure 3, but for net downward longwave (LW) radiation at the surface.

The net downward longwave (LW) radiation also shows biases, with the largest negative (i.e. upward) biases seen over the Arabian Peninsula and the Antarctic Continent in JJA (bottom-right panel, Figure 4). Positive biases (i.e. downward) are seen over the SH continental subtropics and, with smaller magnitudes, over the north-western Pacific and the Southern Ocean. The latter reinforces the Southern Ocean warm bias discussed above. In DJF, the largest negative biases occur over the Arctic, with patches of smaller negative biases also seen over the continents (bottom-left panel).

3.2 Upper-level circulations

The biases in the upper-tropospheric circulation field are studied using the 200-hPa zonal and meridional winds. However, rather than directly plotting the winds, it is more instructive to illustrate the circulation biases using the streamfunction and velocity potential fields. The latter are obtained by decomposing the zonal and meridional winds into the non-divergent and irrotational components, respectively.

Figure 5 shows the seasonal mean eddy streamfunction field at the 200 hPa level; the zonal means were subtracted to emphasise the stationary wave field. The positive values indicate a clockwise circulation and the negative values a counter clockwise circulation. The AGCM does a reasonable job in simulating the upper-level stationary wave field, as can be seen from a good correspondence between the shades and contours in the top panels. However, there are some biases in this field as shown by the bottom panels. The biases are particularly large during the JJA season in the SH (bottom-right figure), perhaps because the full stationary waves have largest amplitudes during this season (top-right figure). The streamfunction biases during JJA are arranged as pairs of cyclonic anomalies over the African continent (extending over to the adjacent Atlantic and Indian Oceans) and anticyclonic anomalies over the western Pacific straddling the equator. This particular arrangement of two pairs of cyclones and anticyclones is reminiscent of a Gill-type response of the atmospheric circulation to a weaker convective heating. The implied weaker convective heating may be associated with a deficient rainfall simulation over the Maritime Continent by the AGCM, which will be discussed in more detail later in this report.

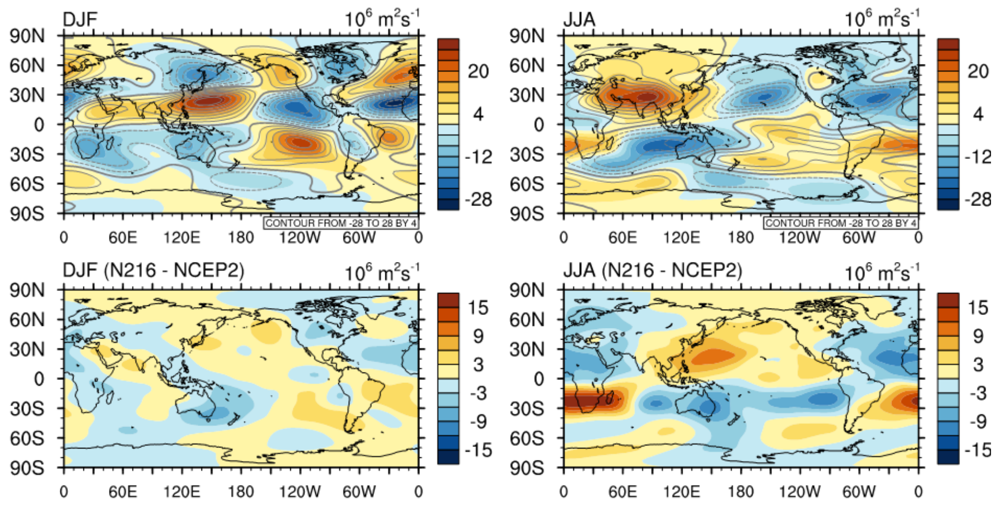


Figure 5. As in Figure 1, but for eddy streamfunction at 200 hPa (representing the non-divergent winds). Biases are calculated with respect to the NCEP2 reanalysis.

The irrotational component of the upper-level horizontal wind fields is depicted in Figure 6 using the 200-hPa velocity potential. This variable illustrates the large-scale divergence (positive values) and convergence (negative values) and is intimately related to the prominent mid-tropospheric convective heating and cooling areas, respectively. As before, the full velocity potential field has a reasonable agreement between the AGCM simulation and the reanalysis (top panels). The biases show an east-west dipole pattern, with a divergence bias in the eastern hemisphere and a convergence bias in the western hemisphere.

The maximum divergence bias occurs in JJA over the northern Indian Ocean and adjacent continental areas (bottom-right panel). This also appears to be related to the dry and wet rainfall biases over the Maritime Continent and the western equatorial Indian Ocean seen in the AGCM simulation (to be discussed later).

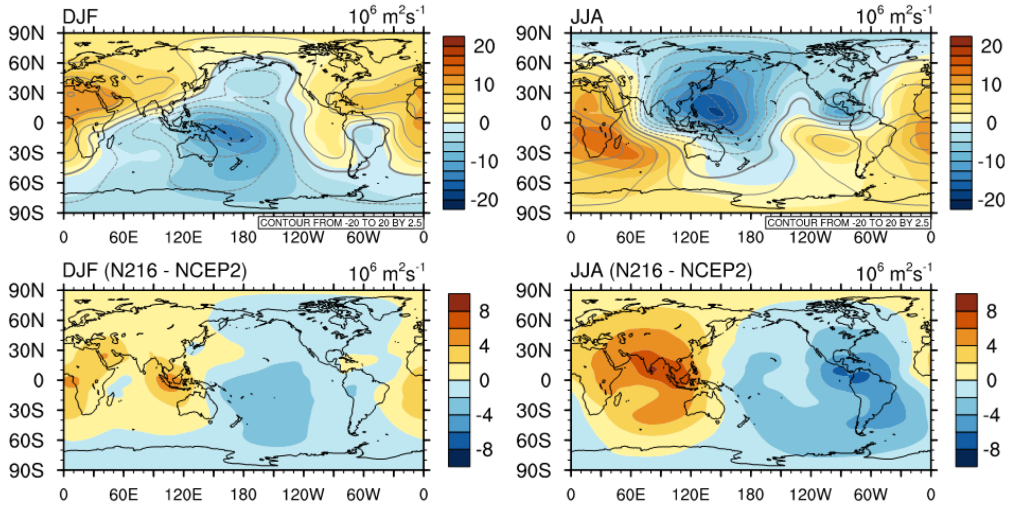


Figure 6. As in Figure 5, but for velocity potential at 200 hPa (representing the irrotational winds).

The streamfunction and velocity potential fields emphasise the tropical-subtropical circulation systems. However, the extratropical circulation systems are also important, the most prominent of which is the synoptic-scale cyclones or storms. These cyclones statistically follow preferred paths, known as the storm tracks, in middle and high latitudes in both hemispheres.

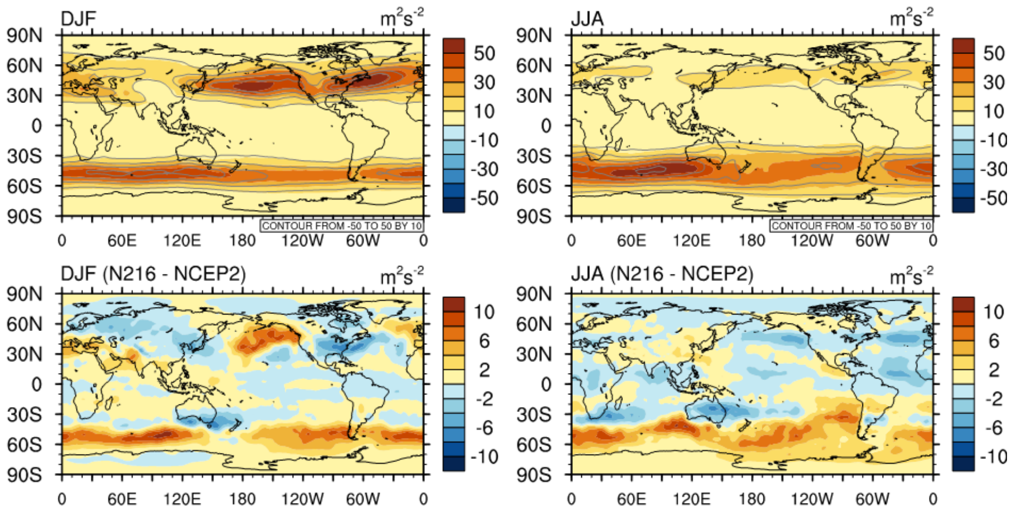


Figure 7. As in Figure 5, but for the storm tracks (preferred paths of the extratropical cyclones).

These cyclones (and the anticyclones in between) largely determine the day-to-day weather in the extratropical regions. They also play a vital role in the maintenance of the atmospheric general circulation by accomplishing the meridional transports of heat and momentum. Figure 7 shows the seasonal mean storm tracks, computed as the variance of the eddy component of the daily meridional wind anomalies. The 'eddy' component was obtained by removing the zonal means of the field and the 'anomalies' were computed by first removing from the daily winds the climatological annual cycle and then passing through a 2–8 day band pass filter. The main SH storm tracks extend zonally over the mid-latitude Southern Ocean, with the maximum intensity located over the Indian Ocean sector. As in the reanalysis, the storms are most energetic during JJA (i.e. the SH winter). There are, however, substantial biases in their time-mean meridional locations; the simulated storm tracks are located farther south than those in the reanalysis (bottom panels). The strong cold surface temperature bias over the Antarctic continent (Figure 1) may play a role in positioning the climatological storm tracks closer to the Antarctic than in the reanalysis.

3.3 The Hadley and Walker Cells

The Hadley Cell (HC) is a major component of the tropical circulation system, and is defined as the zonally averaged meridional overturning circulation at low latitudes. It is usually found in both hemispheres, although only the one in the winter hemisphere is well pronounced. This cell has rising motion at or near the equator and sinking motion at the subtropical latitudes. The HC also plays a central role in the general circulation of the atmosphere; for example, the location of the jet stream and the mid-latitude storm tracks are closely linked to the strength and width of the HC. The simulated (shades) and reanalysed (contours) HCs are depicted in Figure 8 (top panels) using the meridional overturning streamfunction.

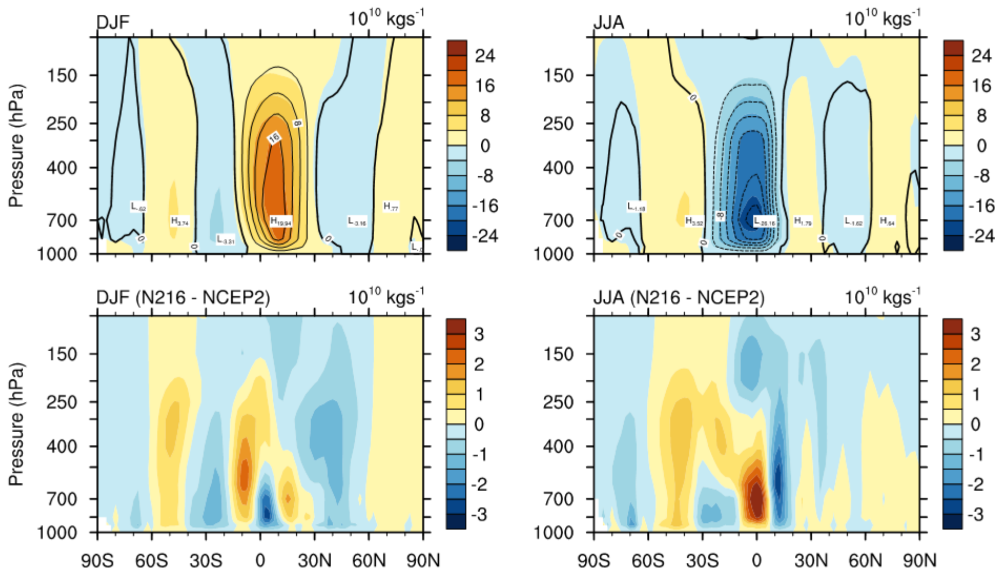


Figure 8. Seasonal mean Hadley Cells, as represented by the zonally-averaged meridional overturning streamfunction. The plotting conventions are as in Figure 1.

The large-scale features of the reanalysed HC are well captured by the AGCM. There are, however, biases near the equator and also in the SH mid-latitudes (which is related to the Ferrel Cell). The largest biases occur in JJA, as before; the most prominent of these biases is seen over the equator, with opposite signs in the lower and upper troposphere (bottom-right panel). This means that the simulated HC is slightly displaced upward.

The Walker Cell (WC) defines the zonal overturning circulations in the equatorial-vertical plane (Figure 9). It comprises several east-west overturning cells, the most prominent of which is in the Pacific sector. The positive values indicate clockwise circulations and the negative values counter clockwise circulations. The rising and sinking motions, in general, coincide with deep convective heating and broad radiative cooling, respectively. Again, the large-scale features of the WC are simulated well by the model (top panels), although significant biases are also seen (bottom panels). In DJF, there are erroneous rising (sinking) motions over the western (central) equatorial

Indian Ocean. Also, over South America, the simulated rising motion is stronger than that in the reanalysis. In JJA, a large bias appears over the Maritime Continent and the adjacent western Pacific, indicating a weaker simulated rising motion there. These systematic errors in the vertical motion over the equator are intimately related to the errors in the deep tropical convection and associated rainfall. Next, we will discuss these tropical rainfall biases in more detail and attempt to understand the causes of some of these biases.

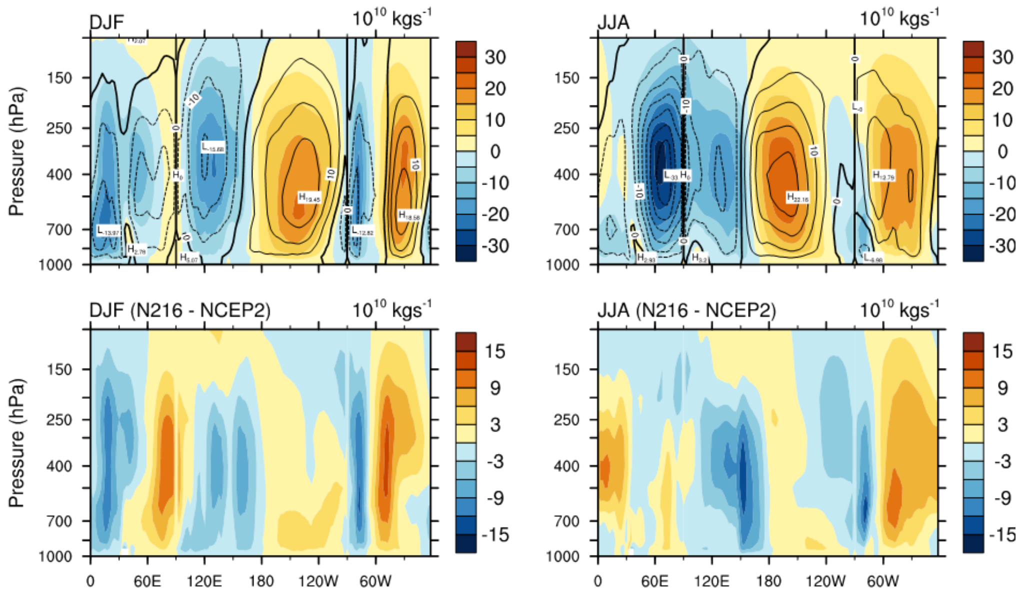


Figure 9. Seasonal mean Walker Cells, as represented by the zonal overturning streamfunction near the equator (averaged over 5°S–5°N). The plotting conventions are as in Figure 1.

3.4 Tropical rainfall biases

Rainfall is an important climate variable and climate models face a significant challenge in its realistic simulations. Figure 10 shows the 6-year averaged rainfall bias in the low-resolution version (N96) of the AGCM compared with GPCP observations (top panel).

A tri-polar pattern of the rainfall bias is seen. The rainfall bias is characterized by positive (or wet) biases in the west and central Indian Ocean and western Pacific Ocean. In between the positive biases, a negative (or dry) rainfall bias exists over the Maritime Continent (hereafter, MC) and northern Australia. A dry bias also exists in the Indian monsoon region. These model rainfall biases had also been seen in the earlier versions of the AGCM (e.g. from GA2 to GA6).

The bottom panel of Figure 10 shows the rainfall rate difference between the N216 and N96 model simulations (two-year averaged). With increased resolution (N216), the modelled rainfall increases mainly over the land and coastal areas. Due to teleconnections through the Walker circulation, the wet biases over the Indian Ocean and Western Pacific regions have been reduced. Increased resolution also helps to reduce the model dry bias for the Indian Monsoon region.

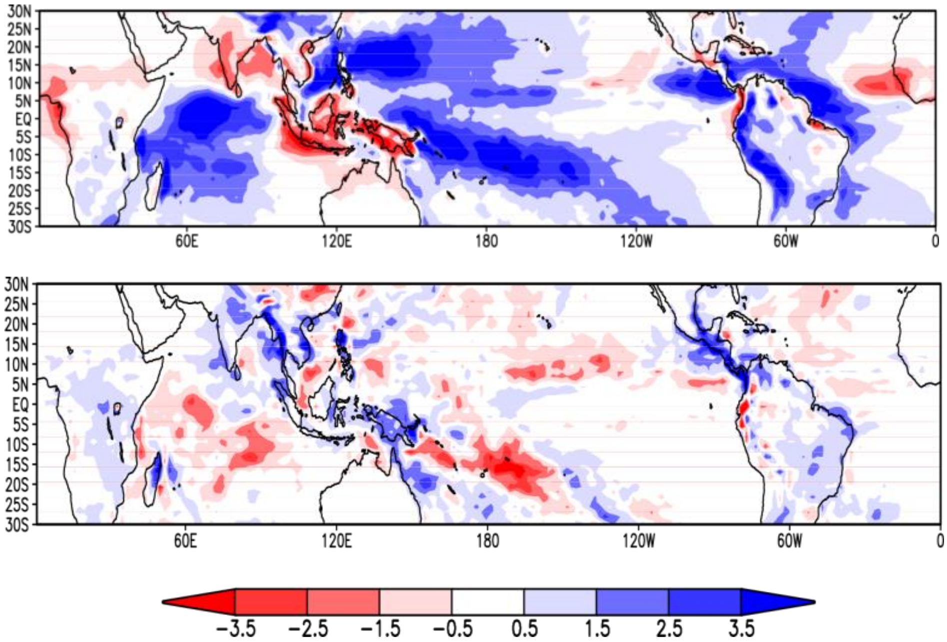


Figure 10. Tropical rainfall bias (mm/day) with respect to the GPCP rainfall observations in a low-resolution version (N96) of the AGCM (top panel). The bottom panel shows the difference between the high- and low-resolution versions (N216 and N96, respectively) of the model, illustrating an improved rainfall simulation in the N216 version.

The dominance of island contributions to the dry rainfall bias is clearly demonstrated in plots of rainfall rate distributions (Figure 11). The three plots show the distributions of rainfall rates in successive rainfall bins for *all* grid points (left) in the MC domain (defined as the region: 95°–155°E, 10°S–10°N), and separately for the *ocean* (middle) and *land* grid points only (right). The modelled results (red and blue curves) are compared with results from two observational datasets (black curves). The dry rainfall biases in two models are found to be due to deficient rainfalls at the middle rates (~3–12 mm/ day) (left panel). Similar distributions of rainfall biases are seen in both AGCMs over the oceans (middle panel). However, over the islands, the N216 AGCM (blue curve) shows a considerable improvement of the dry bias, leading to the overall improved rainfalls in this model (right panel).

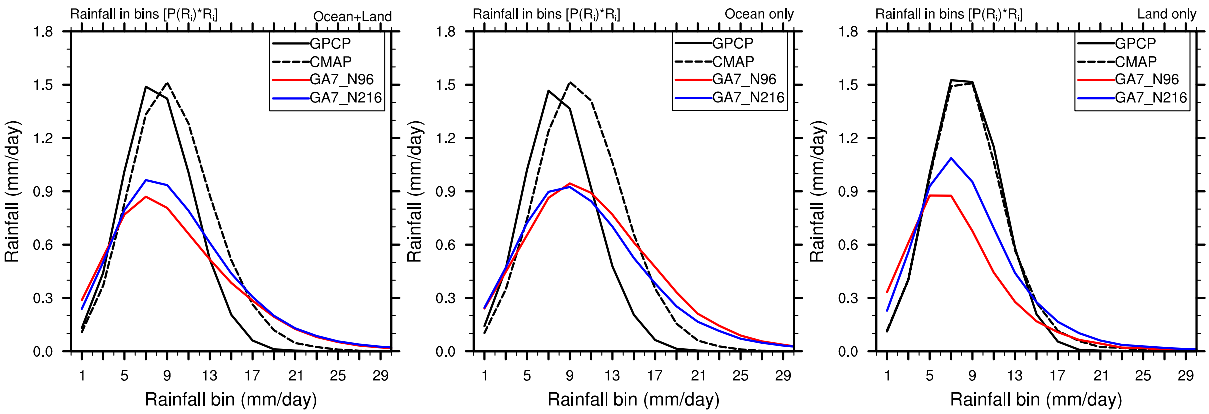


Figure 11. Distributions of monthly mean rainfall rates (mm/day) as a function of successive rainfall bins: all grid points (left), ocean grid points only (middle), and land grid points only (right). Results from two observational datasets (GPCP and CMAP) and two AGCM simulations, with high (N216) and low (N96) resolutions, are shown.

Climate models also face difficulty in realistically simulating the phase of the diurnal cycle of rainfall rates. Figure 12 shows the latter for the AGCM experiments with N96 and N216 resolutions for the

MC region (defined as 113°–127°E, 5°S–2°N for this plot only). The diurnal cycles are further separated into contributions from the ocean (left panel) and land grid points (right panel) only. For the land region, the peak rainfall occurs about 12:30 pm in both N216 and N96 models. For the ocean region, the diurnal cycle has similar pattern to the one in N96 model with rainfall peaking between 3:30am and 6:30am.

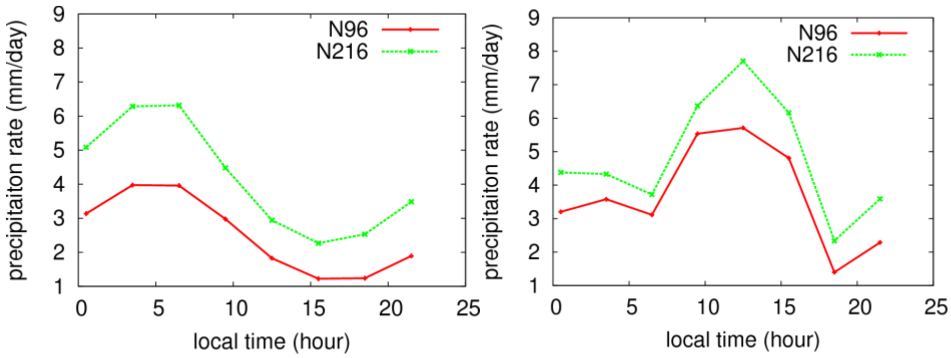


Figure 12. Diurnal cycles of the rainfall rate (mm/day) over the Maritime Continent for the AGCMs with N96 and N216 resolutions: Ocean grid points only (left) and land grid points only (right).

The overall rainfall amplitudes have increased with increasing model resolution in the N216 model. These results show that the modelled peak rainfall tends to happen much earlier than the observation (not shown here). This is due to the CAPE closure setting in the convection scheme, which is designed to release the convective instability whenever the instability is available. Observed convection tends to accumulate the instability and rains in the afternoon when the convective instability reaches the maximum. There is no obvious improvement of the diurnal cycle phase with increasing model resolution from N96 to N216 if the convection settings are kept the same in the two models.

One of main differences between the N216 and N96 simulations is a larger amplitude of the rainfall rate in the former (due to the increased horizontal resolution), which is an improvement. An important contributor to this improvement is likely to be a more realistic representation of the orography in the N216 than in the N96 model. Indeed, about half of the rainfall increase in the N216 simulation was attributed to the better resolved terrain heights in a similar study using the GA6 model (the preceding version of the GA7 AGCM used here) by Rashid and Hirst (2016).

4 Conclusions

We report the preliminary results of our analysis of the systematic errors found in a latest version of the ACCESS AGCM (with the GA7 climate configuration). AMIP-style simulations from two versions of the AGCM, with the N216 and N96 horizontal resolutions, are used. We have presented time (seasonal) mean statistics of important climate variables (e.g. surface temperature, sea-level pressure and rainfall) and atmospheric circulation systems (e.g. the upper-tropospheric stationary waves and divergent winds, extratropical storm tracks, and the tropical convective circulations: the Hadley and Walker circulations) from model simulations, and compared them with corresponding statistics from observations. The main focus here is to document the major systematic errors experienced by the AGCM; the systematic errors in tropical rainfall simulations have been discussed in more detail.

Overall, the model does a good job in realistically simulating the major features of the surface climate and tropospheric circulations. Indeed, earlier versions of the AGCM, as part of two ACCESS coupled models participated in CMIP5, were ranked among the top performing models. However, as for other climate models, the present AGCM also shows systematic errors or biases that need to be improved through continuing investigations of causes of the biases. The major biases identified and documented in this report are:

- cold temperature biases over the continents during winter
- high-pressure biases over the high-latitude Southern Ocean
- excessive downward shortwave radiation bias over the Southern Ocean, causing a major warm bias there
- large wet rainfall biases over the tropical western Pacific and Indian Oceans and a dry bias over the Maritime Continent
- a Gill-type (quad-pole) streamfunction anomalies over the tropical Indo-Pacific, linked to weaker convections in the MC region
- Southern Hemisphere storm tracks being located farther south than observed
- the dominant Hadley Cell being slightly displaced upward, and into the summer hemisphere.

In addition, a detailed study of the MC rainfall bias reveals that the dry bias is mostly contributed by deficient rainfalls over the islands in the middle range (~3–12 mm/day) of rainfall rates. This deficiency is significantly reduced by increasing the horizontal resolution of the model from 135 km (N96) to 60 km (N216). Experiments with the GA6 version of the model indicated that about half of the rainfall increase in the MC region was due a more realistic representation of the orography in the high-resolution model. Increasing the resolution, however, does not improve the phase of the diurnal cycle, although it improves the amplitude. Understanding the causes of other systematic errors documented in this report will need further research.

5 Future outlook

As mentioned before, the ACCESS AGCM is based on a model (UM) developed at the UK Met Office. There is an annual release cycle for the model, with significant refinements to dynamical and/or physical processes being incorporated in successive versions. During the analysis stage of the GA7 simulations for this report, an out-of-cycle version of the UM (called GA7.1) has been released, which incorporates important ‘fixes’ for an overly strong aerosol radiative effect in the GA7 model. It is likely that GA7.1 version will be used for the CMIP6 version of ACCESS-CM, and our future evaluation work will focus on this version of the ACCESS AGCM. We expect to see some improvements in the radiation fields (e.g. those presented in Figures 3 and 4) in this version of the model.

In addition, our future work this year will include collecting and archiving the software tools used for model evaluation. The purpose is to make the tools available to other potential users of the model (the ‘next users’). Other modelling work will include conducting a coupled simulation with the high-resolution (N216) AGCM as part of the ACCESS-CM, which will then be used as a platform for further model development.

References

Adler RF and coauthors. 2003. The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979–Present). *Journal of Hydrometeorology*, 4, 1147–1167, doi:10.1175/1525-7541(2003)004<1147:TVGPCP>2.0.CO;2. http://dx.doi.org/10.1175/1525-7541(2003)004%3C1147:TVGPCP%3E2.0.CO%5Cn2.

Bodas-Salcedo A and coauthors. 2014. Origins of the solar radiation biases over the Southern Ocean in CFMIP2 models. *Journal of Climate*, 27, 41–56, doi:10.1175/JCLI-D-13-00169.1.

Dee DP and coauthors, 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137, 553–597, doi:10.1002/qj.828.

Rashid HA and Hirst AC. 2016. Mechanisms of improved rainfall simulation over the Maritime Continent due to increased horizontal resolution in an AGCM. *Climate Dynamics*, doi:10.1007/s00382-016-3413-z.

Walters DN, Williams KD, Boutle IA, Bushell AC, Edwards JM, Field PR and Lock AP. 2014. The Met Office Unified Model Global Atmosphere 4 . 0 and JULES Global Land 4.0 configurations. 361–386, doi:10.5194/gmd-7-361-2014.

Watterson IG, Bathols J and Heady C. 2014. What influences the skill of climate models over the continents? *Bulletin of the American Meteorological Society*, 95, 689–700, doi:10.1175/BAMS-D-12-00136.1.

Wielicki BA, Barkstrom BR, Harrison EF, Lee RB, Smith GL and CooperJE. 1996. Clouds and the Earth's Radiant Energy System (CERES): An Earth Observing System Experiment. *Bulletin of the American Meteorological Society*, 77, 853–868, doi:10.1175/1520-0477(1996)077<0853:CATERE>2.0.CO;2.

Xie P and Arkin PA. 1997. Global Precipitation: A 17-Year Monthly Analysis Based on Gauge Observations, Satellite Estimates, and Numerical Model Outputs. *Bulletin of the American Meteorological Society*, 78, 2539–2558, doi:10.1175/1520-0477(1997)078<2539:GPAYMA>2.0.CO;2.

Earth Systems and Climate Change Hub

National Environmental Science Programme

www.nespclimate.com.au