Earth Systems and Climate Change Hub

National Environmental Science Programme

Australia's national climate model, ACCESS

Enabling national and international research and input into climate assessments

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1 Introduction

Australia's climate has already changed and is expected to continue to change over the coming century. As a result, decision-makers from across Australian sectors, industries, businesses and communities need the best available scientific information on climate change to better understand their current and future climate risks.

Climate science, like all science, is built on theory, observations and experiments. These are used to construct an understanding of how the world works. But we only have one Earth, and the climate system works on space and time scales on which we can't carry out traditional laboratory experiments. So, climate change 'experiments' are carried out on a virtual twin Earth – constructed with a climate model.

Climate models, sometimes referred to as general circulation models or 'GCMs', are computer programs which simulate the Earth's climate system under past, current and future conditions. Climate models draw upon vast observations of the climate (through satellite images, ocean float data, air composition, measurements of temperature etc), knowledge of how the climate system works and interacts and are underpinned by the laws of nature (physics, chemistry, biology). These data and understandings are used to develop representations or 'simulations' of past, current and future climates. Climate models draw upon much of the same physics and computer algorithms which support weather forecasts. In fact, the atmospheric component of Australia's climate model shares its base code with the weather model the Bureau of Meteorology uses for the weather forecasts we use daily.

Climate models are the best tools currently available for understanding our future climate. They are vital for understanding how the components of the climate system – the oceans, atmosphere, snow and ice and land – interact and change due to both natural variability and human-influences. They are also invaluable tools for understanding climate processes, such as coupled ocean-atmosphere climate modes, including El Niño-Southern Oscillation.

2 Why an Australian national climate model?

Around the world there are over 100 global climate models available and used by international research teams to better understand our historical and future climate. Each climate model has different strengths and biases. Most climate models are developed by research groups in the Northern Hemisphere. As a result, these models may not always focus on the climate drivers and phenomena most important or relevant to Australia.

Australia has therefore developed our own national weather, climate and Earth system model - the Australian Community Climate and Earth System Simulator (ACCESS). ACCESS has been developed over the past 15 years by researchers across leading Australian climate research agencies, such as the Commonwealth Scientific and Industrial Research Organisation (CSIRO), the Bureau of Meteorology (BoM), the Australian Research Council (ARC) Centres of Excellence for Climate System Science and then for Climate Extremes and multiple Australian universities in collaboration with international research institutes. The development of ACCESS has been supported through programs such as the Australian Climate Change Science Program, the National Environmental Science Program (NESP) and the National Collaborative Research Infrastructure Scheme (NCRIS).

ACCESS equips Australia with the ability to focus on global climate as well as the weather and climate of the Australasian region and the Southern Hemisphere. The development of ACCESS has also built the capability and capacity of Australian researchers and technicians in climate science, observations and high-performance computational modelling. This means that Australia has the modelling capability to be able to conduct its own global and regional climate experiments using ACCESS and can critically assess the results of climate experiments done by others internationally.

Researchers under the Earth Systems and Climate Change (ESCC) Hub have been instrumental in the development and improvement of ACCESS and in contributing, through ACCESS, to global climate science initiatives. This includes the submission of ACCESS simulations to the international Coupled Model Intercomparison Project (CMIP) Phase 6. CMIP coordinates experiments using global climate models and makes simulations from climate models publicly available for use by researchers around the world. CMIP projections of future climates are key inputs into the Intergovernmental Panel on Climate Change (IPCC) assessment reports. The IPCC provides governments around the world with credible and relevant information on the science of climate change, climate mitigation and adaptation.

3 Understanding ACCESS

3.1 ACCESS model components

ACCESS is made up of multiple sub-component models representing the oceans, atmosphere, cryosphere and land. The 'CABLE' land-surface model, which simulates energy, water and carbon flows, has been developed by Australian researchers in the Hub and across the national climate science community. Most other model components have originated from international research groups with whom the Hub maintains strong connections. These include the UK Met Office (UM atmospheric model), the US Geophysical Fluid Dynamics Laboratory (for an ocean model component), the US Los Alamos National Laboratory (for a sea ice model component), and the French Institute 'CERFACS' (for an atmosphere-ocean coupler). These component models are coupled through another program that enables the synchronous exchange of information between the components (shown in Figure 1 as the 'coupler').

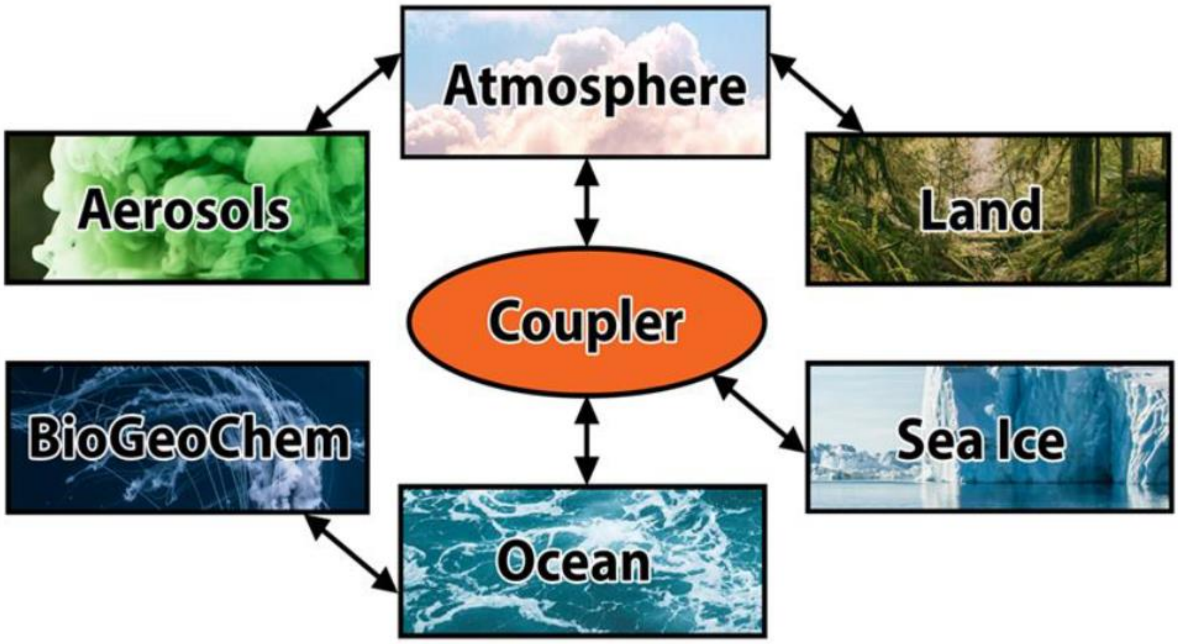

Figure 1: Schematic representation of the sub-component models which make up the versions of ACCESS.

3.2 ACCESS model versions

ACCESS also comes in two distinct model versions: the **Earth System Model version 1.5 (ESM1.5)**, which simulates the carbon and other bio-chemical cycles alongside climate; and the **Coupled Model version 2 (CM2)**, which has up-to-date atmosphere and sea-ice components and produces physical climate simulations. CM2 features improved fluid dynamics and atmospheric chemistry modelling, including an interactive aerosol scheme.

One or more components of ACCESS, configured with different atmosphere or ocean models and with an added data assimilation system, are also used in dynamical seasonal (ACCESS-S) and decadal (ACCESS-D) forecasting applications. The seasonal and decadal forecasting systems have been developed and used outside of the ESCC Hub by the Bureau of Meteorology and the CSIRO Decadal Forecasting Project, respectively.

The ACCESS simulations from each of the ESM1.5 and CM2 model versions provide extensive datasets encompassing a wide range of variables that characterise the climate, such as temperature, rainfall, cloud cover, sea-ice extent and ocean circulation. Both models allow climate scientists to simulate climate to 2100 (and beyond) for a range of future socioeconomic pathways.

For the most recent Coupled Model Intercomparison Project, CMIP6, Hub researchers have, for the first time, delivered experiments from *both* of these distinct ACCESS climate models.

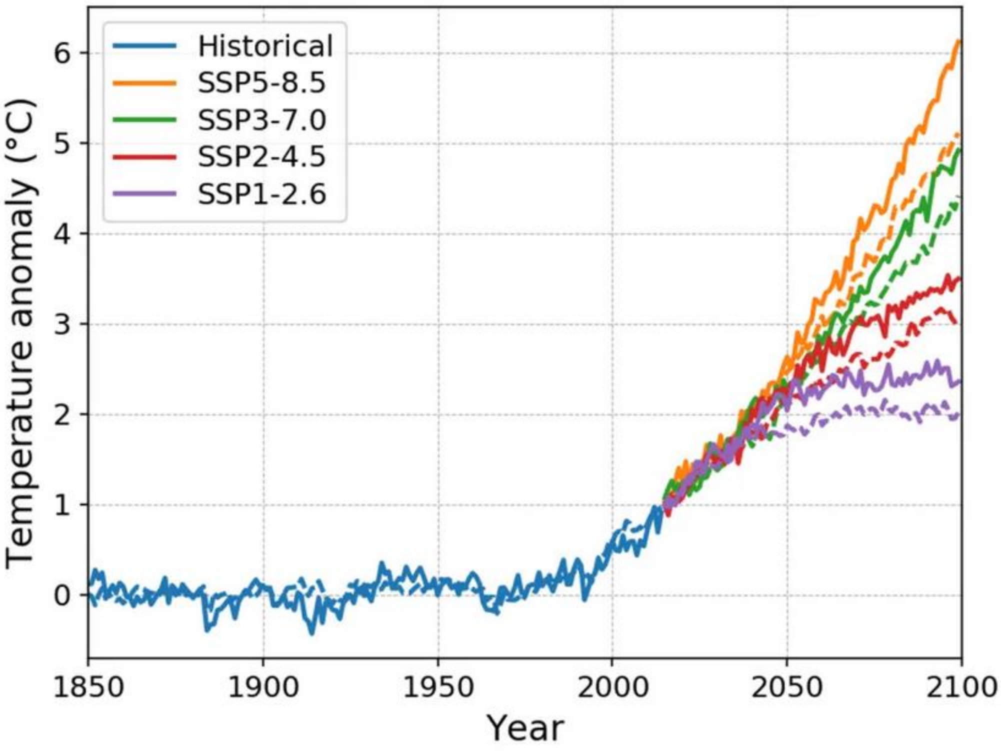

Figure 2: ACCESS model simulations used in CMIP6 to project global temperatures across various emission scenarios. Global surface temperature anomalies (departures from the baseline 1850-1900 period) for the CMIP6 historical period and future scenarios, as simulated by ACCESS-CM2 (solid lines) and ACCESS-ESM1.5 (dashed lines).

3.3 Developing ACCESS

The development of ACCESS is beyond the capability and capacity of any one organisation alone, and so a collaborative approach has been essential. The research collaboration between CSIRO, the Bureau of Meteorology and Australian universities, together with the UK Met Office, has provided access to a vast range of expertise and knowledge to build the best model possible for Australia. Through national and international partnerships, Hub researchers have helped to build and evaluate ACCESS, as well as optimise the model performance.

Successive versions of ACCESS have been developed over the lifetime of the ESCC Hub, each demonstrating world-class performance in climate simulations. This progress has been made possible through the ACCESS model developers' deep knowledge of climate processes, physical and computational aspects of climate system modelling, code development, high-performance computing, data processing and management and evaluation of climate model outputs. For example, using this deep expertise ESCC Hub and CSIRO researchers developed a state-of-the-art land-surface model component, the Community Atmosphere Biosphere Land Exchange (CABLE) model. CABLE is a crucial component of ACCESS as it simulates water, energy, momentum and carbon exchanges between land and atmosphere.

3.4 Improving ACCESS

The more accurately ACCESS (or any climate model) can replicate past and current climates, the more confidence we have that its projections of future climates are plausible. While ACCESS is a state-of-the-science climate model, like other climate models it experiences systematic errors (or biases) in its simulations of the climate.

The ESCC Hub undertook research to understand the sources of some of the prominent model biases in ACCESS, with a focus on tropical rainfall and convection. Hub researchers have helped to reduce these biases through refinements of the model's existing convection scheme, as well as designing a new convection scheme. This has resulted in an improved version of ACCESS with better representation of tropical rainfall and convection processes in the model simulations. This enhances confidence in Australian rainfall simulations in current and future climates.

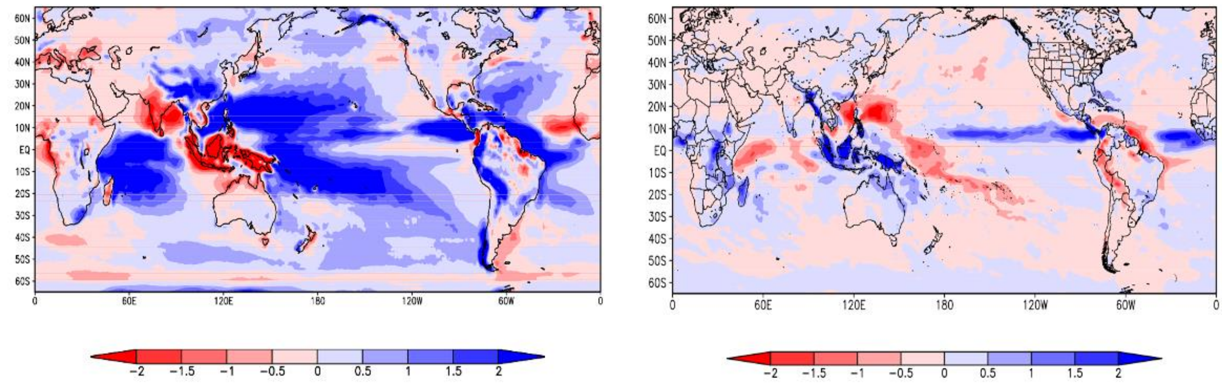

Figure 3: Improved rainfall simulations in the ACCESS atmospheric model resulting from a refined convection scheme. Left panel: Differences between the simulated and observed rainfall rates (in mm/day), with the simulation performed using the original convection scheme; blue and red colours show the regions with excessive and deficient rainfall simulations in the model, respectively. Right panel: Rainfall differences between two simulations with the original and refined convection schemes; regions with an opposite colour (to that in the left panel) have improved rainfall simulations.

4 Contributing to the Coupled Model Intercomparison Project (CMIP)

The Coupled Model Intercomparison Project (CMIP) is a World Climate Research Programme initiative which aims to foster the development and review of coupled models from around the world. It organises international model intercomparison projects which help to understand internal climate variability and the response of the climate system to natural and human-caused changes in the radiation energy balance. The Hub's flagship offering to the national and international climate modelling effort has been to contribute ACCESS climate simulations to CMIP6, which was completed in 2020.

The impact that CMIP delivers to the international climate research effort is measured in dataset downloads and publications that improve our understanding of climate processes. Under CMIP6, ACCESS has simulated over 30,000 model years and more than 350 terabytes of climate simulation data have been downloaded to date by researchers around the world.

Climate simulations from ACCESS are a crucial input into CMIPs and ACCESS has previously been ranked as among one of the top performing models for the Australian region globally (Watterson et al., 2013).

CMIP provides climate projections for a range of plausible future greenhouse gas emissions pathways. These projections are key inputs into policy-making processes and enable countries around the world to make informed climate change related decisions as part of the international community. For example, CMIP simulations have been used in high-profile international reports and climate assessments, such as those produced by the IPCC. Outputs from previous versions of ACCESS and other Australian climate models have been continually used in IPCC assessment reports since 1994. Inclusion of ACCESS into CMIP6 therefore ensures our climate modelling efforts and results continue to inform decisions on the implementation of international climate agreements, such as the 2015 Paris Agreement.

ACCESS also provides input into regional climate downscaling studies for a number of areas in the Australia-Pacific region. 'Downscaling' to produce climate simulations at higher spatial resolution than is possible using global climate models is often more useful for on-ground decision-making purposes. ACCESS has contributed to the WCRP Coordinated Regional Climate Downscaling Experiment (CORDEX) project, which is an international initiative aiming to advance and coordinate the science and application of regional climate downscaling through global partnerships.

5 ACCESS benefits

5.1 Benefits of ACCESS to decision-makers

The published model outputs of ACCESS adhere to strict best-practice CMIP protocols. This provides decision-makers in Australia with the confidence that ACCESS is following global best-practice for the production of climate change information and data to inform decision-making and management activities. ACCESS outputs have been continually used in national climate assessment reports, such as the State of the Climate reports co-produced by the BoM and CSIRO, and the CSIRO Report on Climate and Disaster Resilience. Simulations from ACCESS also featured recently in CSIRO's presentation to the Bushfire Royal Commission and are likely to be utilised as critical input to future downscaled projections through current initiatives, such as the Australian Climate Service. ACCESS is the only Australian climate modelling system to have such wide-spread national and international impacts.

5.2 Benefits of ACCESS to researchers

ACCESS benefits national and international climate researchers in their quest to better understand how the climate works and how it may change in the future. ACCESS model outputs have been used in peer-reviewed publications and across the ESCC Hub to address national climate challenges, including hydroclimate and water resources; food security, ecosystems and natural resource management; carbon cycle and future warming; changes in coastal climate; and climate extremes and risk management.

ACCESS is also used by other Australian research groups, such as the ARC Centre of Excellence for Climate Extremes, to better understand the mean change in Australia's climate (i.e. temperature and rainfall trends) and changing extremes (i.e. such as extreme heat and rainfall). In addition, the ACCESS model provides a platform for training future Australian climate scientists. Ongoing development of our national climate model develops our national capability to produce independent climate assessments by performing our own simulations and to critically assess outputs from the international community.

ACCESS benefits the international research community by providing world-class climate and Earth-system simulations to CMIP, and so contributes to the development of global climate assessments and initiatives. Improvements to the ACCESS atmospheric model have been adopted by the UK Met Office (UKMO) for inclusion in their Unified Model (Global Atmosphere version 8, released at the end of 2020). This has a wider impact beyond Australian applications, as the UKMO Unified Model is used by national agencies in at least five countries.

6 Applying ACCESS for national benefit

Developing and improving ACCESS is a large undertaking and has been a key focus of the ESCC Hub in order to build Australia's climate modelling capability. However, it's the application, or use, of ACCESS in various experiments to better understand Australia's current and future climate that shows the impact of the work to date to build ACCESS.

The below short application case studies provide just four examples of how ACCESS has been applied to solve important questions about the climate system and its response to increasing greenhouse gas emissions.

Case study 1: Insights into historical climate change from ACCESS CMIP6 simulations

Understanding the causes of past climate variability and change is interesting in itself, but it also gives us insights into the causes of possible future climate changes. Complex climate models, such as ACCESS, have played a central role in this understanding through simulation experiments of the Earth's climate.

Under CMIP6, each modelling centre across the world (including Australia with ACCESS-CM2 and ACCESS-ESM1.5 simulations) must carry out a mandatory set of climate experiments using a common forcing dataset. They are also encouraged to perform additional sets of experiments targeted at understanding specific behaviours of the climate system. One of these additional sets is the 'detection and attribution' experiments (DAMIP), which use single climate forcing agents to explore the role of these drivers in historical climate. These experiments are designed to facilitate an improved understanding of the roles of human-induced and natural forcings on changes in temperature, rainfall and other climate variables by examining how well models represent historical changes in climate ('detection') and how well they can represent climate change using known climate forcings ('attribution').

In one study, ACCESS-CM2 and ACCESS-ESM1.5 model simulations were used to investigate the effects of greenhouse gas , aerosol and natural forcings on past global-mean surface temperature (GMST) changes. As shown in Figure 5, the sum of the GMST changes from individual forcings (thick brown curve in top panels) compares well with the GMST change from all forcings applied together (dashed brown curve). The forcings include changes in anthropogenic aerosols (particles which reflect sunlight, interact with clouds and thus cool the climate), greenhouse gases (which warm the climate) and natural forcings (caused by the stratospheric aerosols from volcanic eruptions and changes in total solar irradiance). These forcings may cool or warm the climate. The combined simulation also compares well with the observed GMST changes (black curve), although the models show stronger than observed GMST cooling during the 1950-1980 period. This is a trait also seen in many other climate models. Possible reasons for this cooling bias include an overly sensitive response to aerosols by the models or sources of climate variability not accounted for in this study. If this is confirmed, then further research will be needed to understand the aerosol-climate interactions.

The ACCESS DAMIP experiments deconstruct the total GMST evolution into the contributions from human-induced greenhouse gas emissions and aerosols and from natural causes, such as volcanic eruptions and solar output changes. The different contributions from ACCESS-CM2 and ACCESS-ESM1.5 are shown in the bottom panels of Figure 5.

While both models simulate the observed warming over the historical period, there are slight differences in the magnitude of the estimated warming. In particular, ACCESS-CM2 shows somewhat larger responses to the anthropogenic forcings (i.e. greenhouse gases and aerosols) than ACCESS-ESM1.5 does. This behaviour also persists in the future climate projections. This difference stems from the fact that ACCESS-CM2, with its updated physical parametrisations, has a larger equilibrium climate sensitivity (ECS). That is, this model shows a larger global-mean surface-air temperature increase (4.7 ˚C) due to a doubling of CO_2 concentration from its pre-industrial value, in line with many other CMIP6 models. The ECS value for ACCESS-ESM1.5 somewhat lower, at 3.9 ˚C.

The true value of ECS for the real climate system is as yet unknown. The median ECS value across about 50 CMIP6 models is 3.8 ˚C. Therefore, both ACCESS ESM1.5 and CM2 have plausible ECS values and so provide two possible representations of the future climate system.

These ACCESS model experiments, individually or combined with similar experiments from other climate models, facilitate the estimation of the climate changes attributable to human and natural causes. This information enables decision-makers to formulate sensible policies regarding future emissions of human-induced greenhouse gas emissions and aerosols for societal benefit.

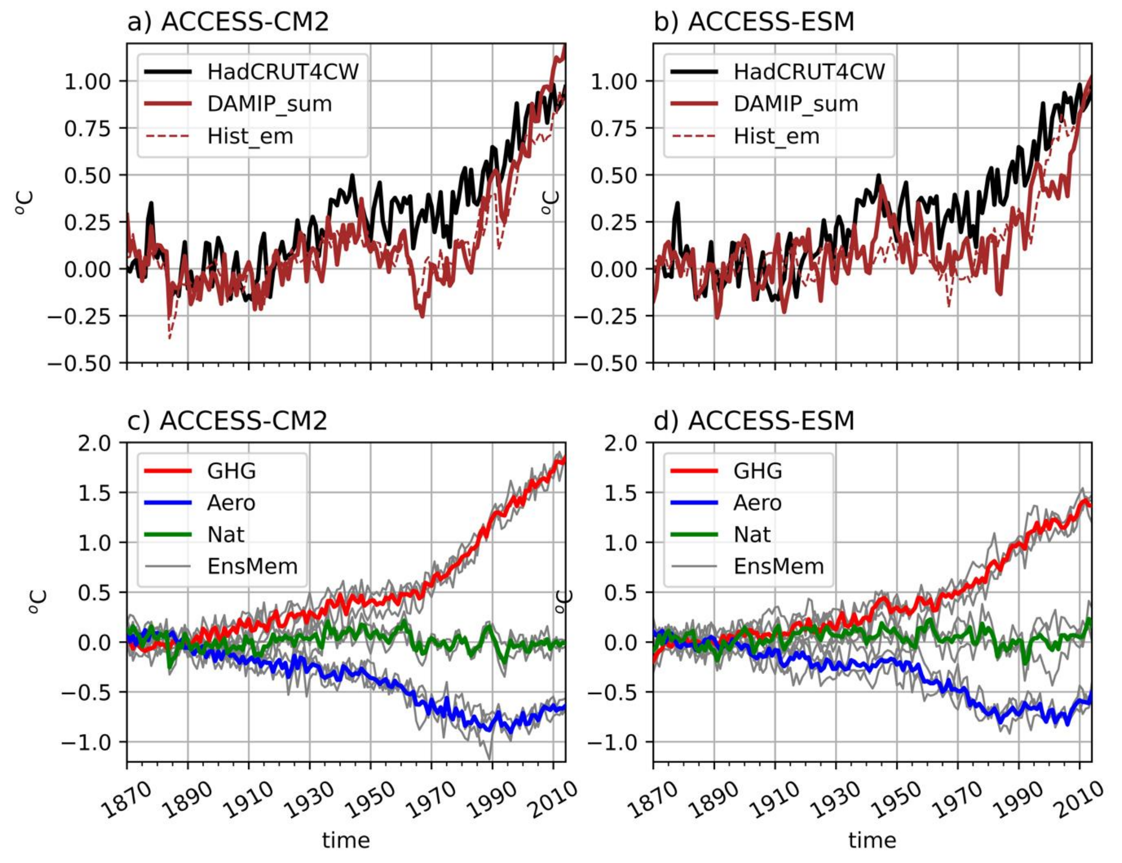

Figure 5. The contributions of anthropogenic and natural forcings to surface air temperature from ACCESS CM2 and ACCESS ESM1.5. Historical evolutions of global-mean surface-air temperatures, from: a) observations (HadCRUT4; black curve) and ACCESS-CM2 simulations (brown curves); b) observations and ACCESS-ESM1-5 (brown curves); c) ACCESS-CM2 DAMIP experiments; d) ACCESS-ESM1-5 DAMIP experiments. The coloured thick curves in c) and d) are the ensemble mean GMSTs from ACCESS DAMIP simulations with separate GHG, aerosol and natural forcings. The grey curves are individual ensemble members. The brown solid and dashed curves in a) and b) represent the sum of ensemble-mean simulations with individual forcings and the ensemble-mean simulation with all forcings, respectively.

Case study 2: Insights from CMIP6 for Australia's future climate

The CMIP6 multi-model ensemble provides researchers with a new opportunity to examine the climate system. CMIP6 is of strong interest for both assessing climate change processes and for producing updated national climate change projections for Australia.

The ACCESS models and expertise of researchers across the ESCC Hub significantly helped to inform the insights gathered from CMIP6 on Australia's future climate (see Grose et al. 2020). Hub researchers found that the projections of Australian mean and extreme climates are broadly similar in CMIP5 (the previous CMIP project which ended in 2013) and CMIP6 in terms of directions of change and spatial distributions. Both CMIP ensembles project warming temperatures and increases in hot extremes, which depend on the greenhouse gas emission trajectory input into the models (i.e. low, mid or high emissions scenario). However, warmest projections beyond 2050 from CMIP6 are higher than those from CMIP5 and include a possible change of over 6 °C mean annual temperature from the preindustrial baseline by 2100 under a high-emissions scenario.

CMIP5 and CMIP6 projections both indicated significant future drying of southwest Australia in the cool season and less significant rainfall changes in other regions. The CMIP6 ensemble so far suggests there is greater confidence (as indicated by greater model agreement) in rainfall decrease in Southern Australia in the cool season than in CMIP5. There is also a smaller inter-model range of rainfall change in Northern Australia during the austral warm season and in Southern Australia during the cold season in CMIP6 compared to CMIP5 (Figure 6). If this result is maintained as more models are added to CMIP6 evaluation efforts, these projections will be a strong line of evidence to support the need for more targeted and specific adaptation actions to adequately manage Australia's water resources into the future.

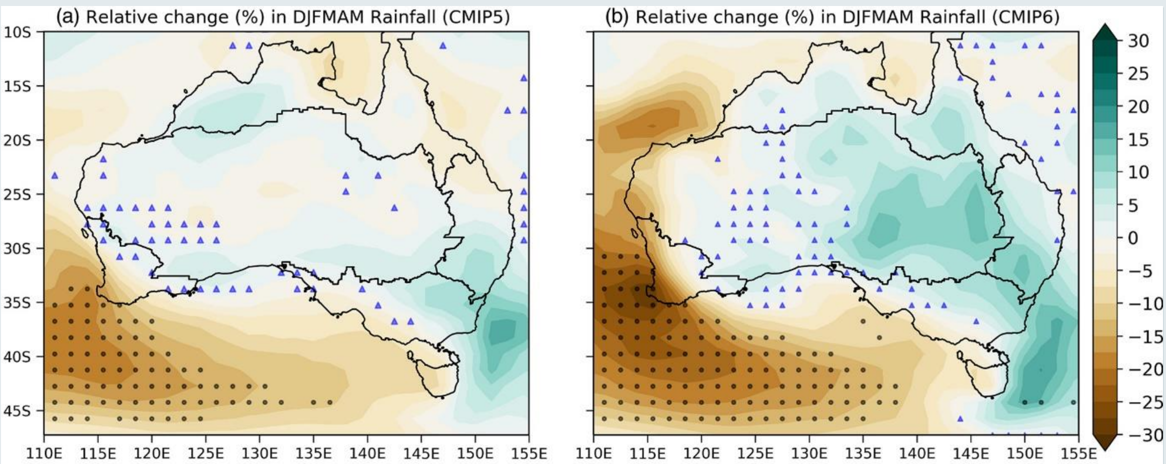

Figure 6. Australian projected rainfall change (%) for DJFMAM for 1995–2014 to 2080–2099 under high emissions (RCP8.5 and SSP5-85) from CMIP5 (left) and CMIP6 (right). More detailed results, including that for the austral cold season, may be found in Grose et al, 2020.

Case study 3: Arctic sea ice in CMIP6

The evolution of Arctic sea-ice area and volume in 40 CMIP6 models, including ACCESS-ESM1.5 and ACCESS-CM2, was analysed and compared with CMIP3 and CMIP5 model results. While the newer and older models agreed on some aspects, a larger fraction of CMIP6 models captured the observed sensitivity of Arctic sea ice to human-caused emissions and global warming.

The CMIP6 models simulate a large spread for when Arctic sea-ice area is predicted to become practically sea-ice free (below 1×10^6 km^2 sea-ice area). However, the clear majority of all models, including ACCESS, project that the Arctic will become almost sea-ice free in September by the end of the century under both a medium (SSP2-RCP4.5) and high (SSP5-RCP8.5) emissions scenario.

The Arctic sea-ice is an important modulator of global climate and its long-term changes can significantly affect the climate change in both hemispheres through teleconnections. Therefore, a realistic simulation of sea-ice in the Arctic (and the Antarctic) is an important performance indicator for climate models, including ACCESS.

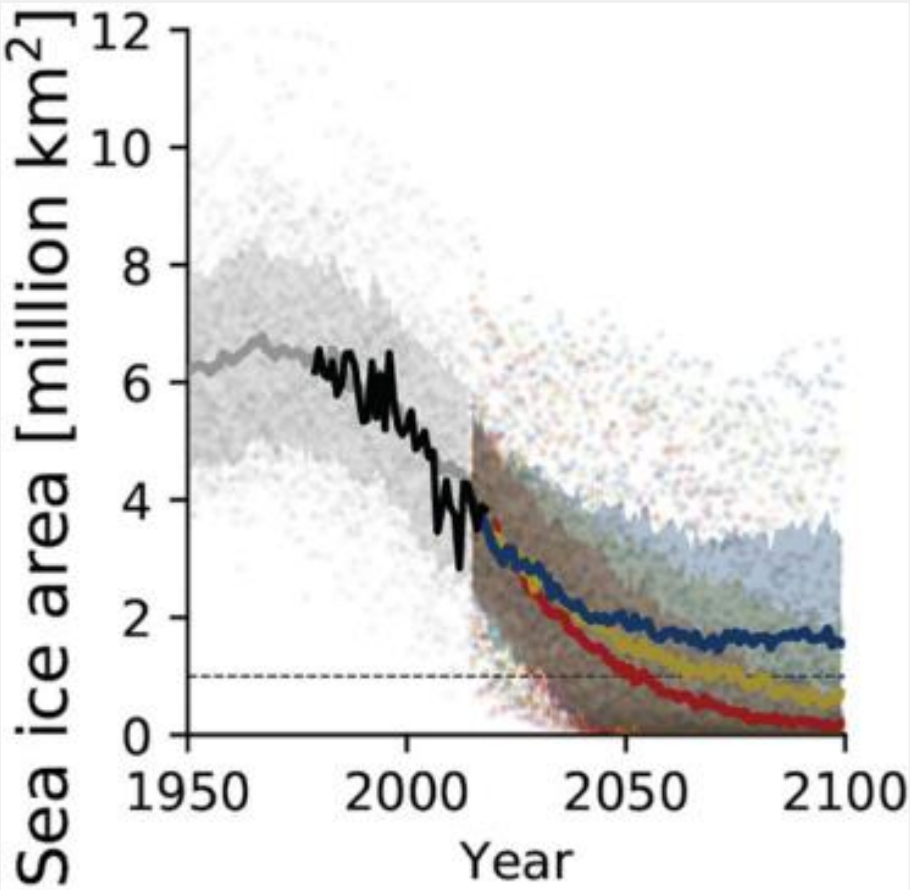

Figure 7. ACCESS and other climate models under CMIP6 show that the Arctic is likely to become almost sea-ice free in September under a high and medium emissions scenario by the end of the century. Evolution of Arctic sea-ice area over the historical period and following three scenario projections in time for available CMIP6 models. Thick lines denote the multi-model ensemble mean and the shading around the lines indicates one standard deviation around the multi-model mean. Faint dots denote the first ensemble member of each model and the thick black line denote observations. Source: SIMIP Community, 2020

Case study 4: Understanding carbon reversibility

Future levels of climate change depend not only on greenhouse gas emissions but also on carbon uptake by the land and ocean. This uptake occurs naturally but can be carried out through the application of a range of technologies aimed at carbon dioxide removal and sequestration, known as negative emissions technologies or 'NETs'. Developing technologies to help reduce carbon levels in the atmosphere is becoming an increasing priority for many nations around the world. Under the 2015 Paris Agreement, most countries resolved to limit global warming to below 2 degrees Celsius (°C). The IPCC Special Report on Global Warming of 1.5°C (IPCC, 2018) concluded that emissions reductions alone would not be enough to reach this goal, and that countries would need to employ NETs to extract carbon dioxide from the atmosphere. One of the big unknowns, however, is the extent to which land and ocean sinks can sequester carbon dioxide removed from the atmosphere.

To investigate this question, ACCESS-ESM1 was used to explore the potential and impact of removing carbon dioxide (CO_2) from the atmosphere through a modelling experiment known as the 'climate and carbon cycle reversibility experiment'. In this experiment, global atmospheric CO_2 levels were increased at 1% per year until quadruple the concentration over pre-industrial times (4xCO_2) was reached. They were then decreased at the same rate to bring the CO_2 back to pre-industrial levels. The model was then run with constant CO_2 for another 350 model years.

This experiment illustrated that, after the CO_2 is brought back to its pre-industrial level (at year 380), it would take about another 300 years for the land and ocean temperatures to return to their pre-industrial values (Figure 8). This long time lag is because a component of the carbon dioxide taken up by the ocean is re-released to the atmosphere as atmospheric CO_2 decreases by other processes.

Therefore, NETs may have to be applied for longer and at greater scales than previously estimated.

This experiment also showed that there are strong regional variations in the strength of the land response to changing CO_2. Australia shows the largest variability in biomass carbon (about 40%) and productivity, which is strongly correlated with rainfall distribution patterns. This highlights the importance of assessing regional responses to underlying climate processes and their sensitivities within each model. It also illustrates the usefulness of ACCESS-EM1 and other Earth-system model experiments as one way to evaluate proposed applications of carbon dioxide removal technologies.

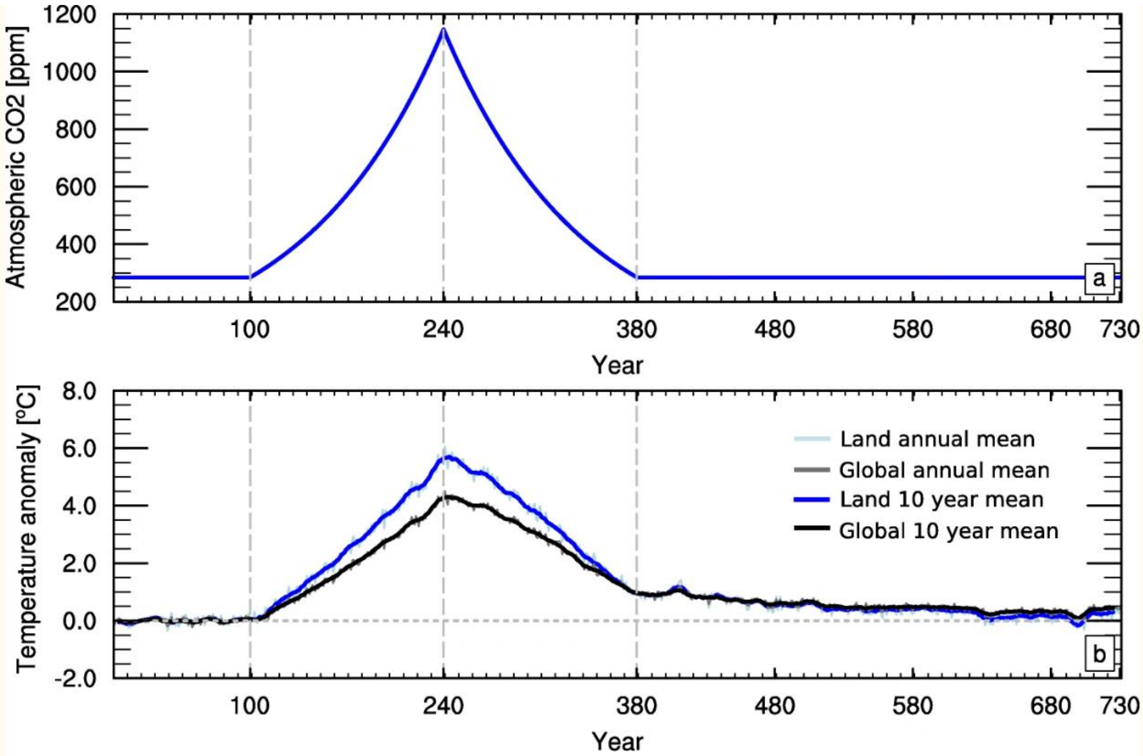

Figure 8. ACCESS EMS-1 experiments illustrate it could take about 300 years for carbon stores to recover after decreasing concentrations of atmospheric emissions. Temporal evolution of prescribed atmospheric CO_2 concentrations in parts per million (ppm) (top), global (black) and land (blue) temperature anomaly in °C (bottom). Annual and 10-year running mean values are shown. Source: Ziehn et al., 2020

7 Climate change modelling to inform decision-making

ACCESS is a critical tool for climate researchers in understanding past and current climates. In addition, climate change simulations and data produced by ACCESS provides critical information on how our climate may change into the future with increasing greenhouse gas emissions. The development of ACCESS has also transformed Australia's modelling capability and trained a generation of climate science experts.

The ESCC Hub has been instrumental in the development and improvement of ACCESS to ensure the resulting information about our climate is as accurate as possible. This information is already informing national and international climate assessments which are used by governments and decision-makers as sources of credible, robust and accurate information to inform current and future climate smart decisions. Climate information and data produced by ACCESS will continue to contribute climate change information and data to inform policy development and decision-making outcomes for Australian stakeholders.

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Additional details on the application and evaluation of ACCESS are available from the ESCC Hub website: https://nespclimate.com.au/access-evaluation-and-application-5-1/.

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