Australian Government
Department of Climate Change

HOT TOPICS

How reliable are climate models?

Summary

Climate models are based on the laws of physics and can reproduce many observed features of current climate and past climate changes. Confidence in model estimates is higher for some climate variables (e.g., temperature) than for others (e.g., precipitation).

Confidence in the reliability of these models for climate projections has also improved, based on tests of their ability to simulate:

- the present average climate and year-to-year variability;
- observed climate trends in the recent past;
- extreme events, such as storms and heatwaves;
- climates from thousands of years ago.

Models show significant and increasing skill in representing many important mean climate features, such as the large-scale distributions of atmospheric temperature, precipitation, radiation and wind, and of oceanic temperatures, currents and sea ice cover. Patterns of climate variability that are well simulated include the advance and retreat of the major monsoon systems, the seasonal shifts of temperatures, storm tracks and rain belts. Simulations, that include estimates of natural and human influences, can reproduce the observed large-scale changes in surface temperature over the 20th century, including the global warming that has occurred during the past 50 years.

However, there are deficiencies in the simulation of tropical rainfall and some important climate processes such as the El Niño-Southern Oscillation and the Madden-Julian Oscillation. Climate features with smaller space and time scales are also simulated with lower skill, e.g., tropical cyclones and thunderstorms. With increasing computer power and better understanding of climate processes, future models will include finer resolution and more processes, which should reduce some of these uncertainties.

Overall, climate models provide credible quantitative estimates of future climate change, particularly at continental scales and above. There will always be a range of uncertainty in climate projections. Decision-makers need to incorporate this uncertainty in risk management.

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Climate model development

Climate models are mathematical representations of the climate system, expressed as computer code and run on powerful computers. One source of confidence in models comes from the fact that they are based on established physical laws, such as conservation of mass, energy and momentum, along with a wealth of observations. They include most of the important physical, chemical and biological processes associated with climate, so they are process-models rather than empirical-statistical models. Climate models use mathematical equations that describe the behaviour of the atmosphere, ocean, sea ice, snow cover, the land surface and other elements of the Earth system. Climate variables, such as temperature and precipitation, are typically calculated in 15–30 minute time-steps across the Earth's surface and throughout the atmosphere and ocean, using a three-dimensional grid of boxes. Each box is about 150 km x 150 km, and there are typically 40 levels in the atmosphere and 50 levels in the ocean. Climate modellers are progressively reducing the size of the grid boxes as computer power increases.

Figure 1 shows the development of climate models from the 1970s. Different components are first developed separately, tested, and then coupled into comprehensive climate models. The key components are the atmosphere, ocean, sea ice, land surface, aerosols and the carbon cycle. Over the past decade, scientists have improved their understanding of important climate processes such as the role of water vapour, sea-ice dynamics and ocean heat transport. Representation of these processes in climate models has also improved. New components being included are non-sulphate aerosols, indirect aerosol effects on cloud properties, and vegetation that responds dynamically to changes in climate.

Due to their coarse resolution, global climate models only provide broad-scale projections of climate change, whereas policy-relevant projections and impact assessments often require more detail. Consequently, regional climate models have been developed. These models typically include components for the atmosphere and land surface only, using a relatively fine grid (e.g. box size about 30 km x 30 km) and covering a limited area (e.g. the Australian region). A regional model is driven at its boundaries by input from a global climate model. This technique is called 'dynamical downscaling' because it can zoom down to local scales. Regional climate models give a much better representation of coastal and mountain effects and local-scale variations in climate.

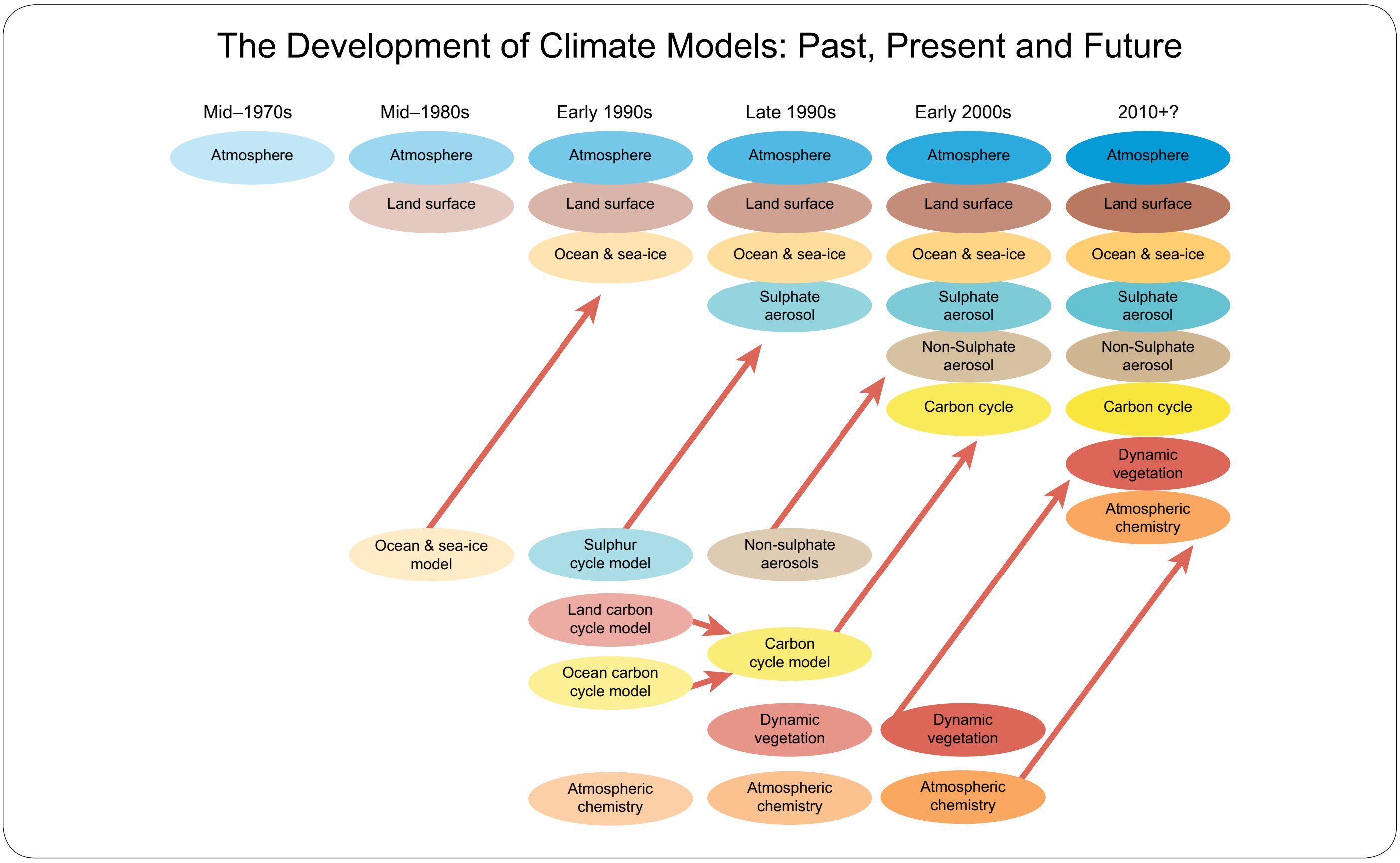

Figure 1: Different components are first developed separately, and then coupled into comprehensive climate models. (IPCC, 2001).

Model evaluation

Unprecedented levels of evaluation have taken place over the last decade in the form of organised multi-model (ensemble) ‘intercomparisons’. Such testing is central to assigning levels of confidence to model outputs (IPCC, 2007).

Present average climate and year-to-year variability

Models are routinely and extensively assessed by comparing their simulations with observations of the atmosphere, ocean, cryosphere and land surface (IPCC, 2007). Model strengths and weaknesses have been identified for different climate variables, time scales and space scales (Räisanen, 2006; IPCC, 2007; Bader *et al.*, 2008; Zhou *et al.*, 2009), as described below.

Most models show significant skill in representing average climate features, such as large-scale patterns of temperature, precipitation, solar radiation, wind, ocean currents and sea-ice. They also show skill in simulating patterns of climate variability, such as seasonal shifts in temperature and rainfall, the Asian-Australian monsoon, and north-south shifts in pressure at high latitudes.

Deficiencies remain in the simulation of the El Niño-Southern Oscillation (a see-saw of atmospheric pressure and ocean temperature in the Pacific affecting climate in many regions, including Australia) and the Madden-Julian Oscillation (an observed variation in tropical winds and rainfall with a time scale of 30 to 90 days which strongly affects the Australian summer monsoon). The ultimate source of most such errors is that many important small-scale processes cannot be represented explicitly in models (IPCC, 2007, FAQ 8.1). This is partly due to limitations in computing power, but also results from limitations in scientific understanding or in the availability of detailed observations of some physical processes.

Observed climate trends in the recent past

The presence of natural climate variability in both the model simulations and the observed record guarantees that the observed and modelled data will not be exactly alike on a year-to-year, or even decade-to-decade basis. This is why an ensemble of climate simulations is needed — each simulation starting from a slightly different set of initial conditions, leading to a different evolution of climate, thereby capturing the effect of chaotic natural variability.

Models can simulate many observed aspects of climate change over the instrumental record. One example is that the global temperature trend over the past century (Figure 2) can be modelled with high skill when both human and natural factors that influence climate are included (IPCC, 2007). Models also reproduce other observed changes, such as the faster increase in night time than in daytime temperatures, the warming of the troposphere and cooling of the lower stratosphere, the larger degree of warming in the Arctic and the small, short-term global cooling (and subsequent recovery) which has followed major volcanic eruptions, such as that of Mt. Pinatubo in 1991 (IPCC, 2007, FAQ 8.1).[1]

It is important to emphasise that simulations for the 20th and 21st centuries show year-to-year fluctuations in global average surface air temperatures, superimposed on a background long-term warming trend (Figure 2). Climate models do not predict a steady increase in global average surface air temperature year-by-year. There are periods of no trend or even cooling in the last 34 years of the observed record, and in climate model simulations of the 20th and 21st century forced with increasing greenhouse gases (Easterling and Wehner, 2009) (Figure 3). These short-term fluctuations are caused in part by exchanges of heat between the ocean and atmosphere resulting from natural processes (e.g., El Niño Southern Oscillation, North Atlantic Oscillation and Interdecadal Pacific Oscillation). There is now considerable research underway to improve our ability to start each model from the current (2005) observed state of the ocean and atmosphere, with the aim of better prediction of the character of climate change over the next decade (Smith *et al.*, 2007; Keenlyside *et al.*, 2008).

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[1] For more information see Hot Topics ‘Is there an inconsistency between observed and modelled patterns of warming in the lower atmosphere?’ and ‘Has global warming stopped?’ available online at www.climatechange.gov.au

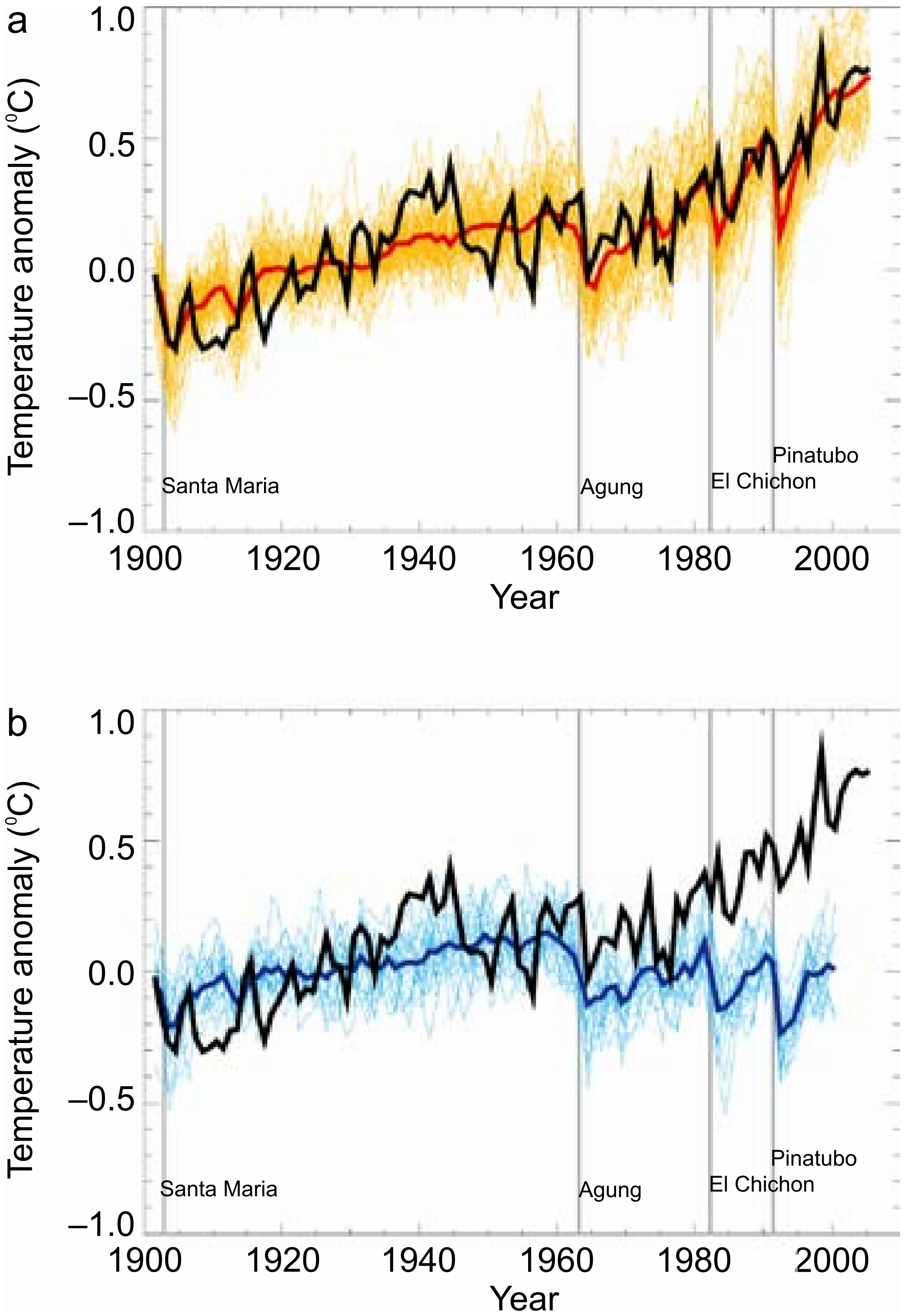

Figure 2: Comparison between global mean surface temperature anomalies (°C) from observations (black) and climate model simulations forced with (a) both anthropogenic and natural forcings and (b) natural forcings only. All data are shown as global mean temperature anomalies relative to the period 1901 to 1950, as observed (black, Hadley Centre/Climatic Research Unit gridded surface temperature dataset (HadCRUT3); Brohan *et al*., 2006) and, in (a) as obtained from 58 simulations produced by 14 models with both anthropogenic and natural forcings. The multi-model ensemble mean is shown as a thick red curve and individual simulations are shown as thin yellow curves. Vertical grey lines indicate the timing of major volcanic events. Those simulations that ended before 2005 were extended to 2005 by using the first few years of the IPCC Special Report on Emission Scenarios (SRES) A1B scenario simulations that continued from the respective 20th century simulations, where available. The simulated global mean temperature anomalies in (b) are from 19 simulations produced by five models with natural forcings only. The multi-model ensemble mean is shown as a thick blue curve and individual simulations are shown as thin blue curves. Simulations are selected that do not exhibit excessive drift in their control simulations (no more than 0.2°C per century). Each simulation was sampled so that coverage corresponds to that of the observations. (IPCC, 2007, Figure 9.5).

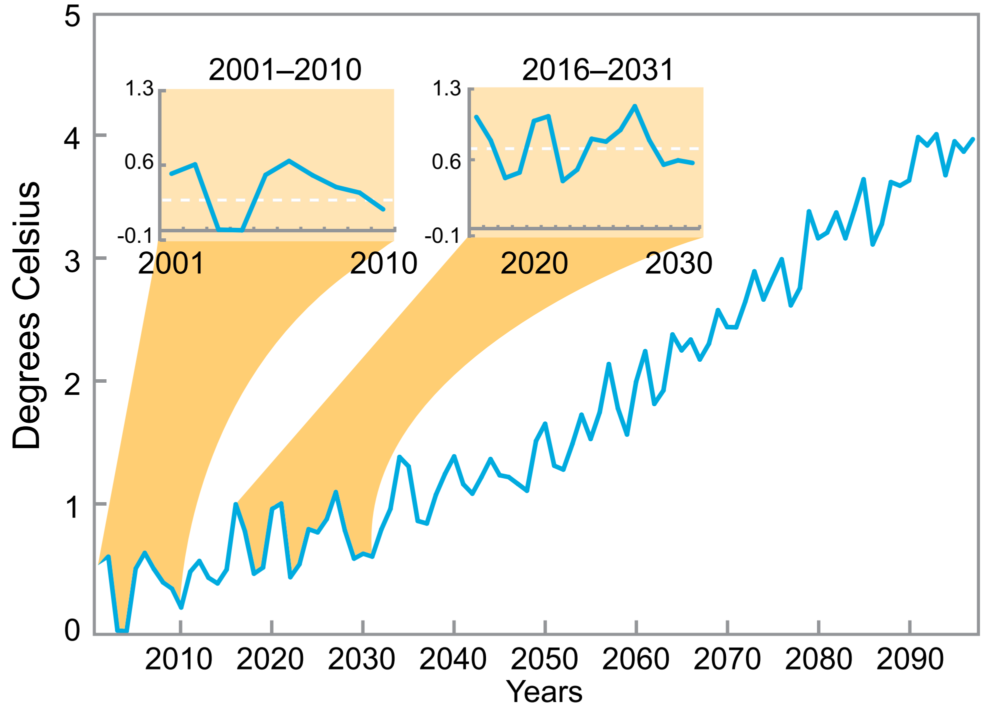

Figure 3: A simulation of globally averaged surface air temperature anomalies (°C) from the ECHAM5 climate model forced with the A2 greenhouse gas increase scenario for the 21st century. (Easterling and Wehner, 2009).

Extreme events

Modelling groups worldwide submitted a standard set of ten extremes indices to the World Climate Research Program's Coupled Model Intercomparison Project phase 3 (CMIP3). There were five temperature-based indices (e.g. heat wave duration, occurrence of frosts) and five precipitation-based indices (e.g. heavy precipitation events, consecutive dry days). Assessments show that models are more capable of reproducing temperature extremes than precipitation extremes (IPCC, 2007, Ch 8; Alexander *et al.,* 2009).

Sun *et al*., (2006) investigated the intensity of daily precipitation simulated by 18 models and found that most of the models produce too much light precipitation (below 10 mm/day), too few heavy precipitation events and too little precipitation in heavy events (over 10 mm/day). Finer-resolution simulations tend to produce more realistic daily precipitation statistics (Iorio *et al*., 2004; Kimoto *et al*., 2005).

Simulations from nine climate models were assessed by Alexander and Arblaster (2009) for their ability to reproduce observed trends in a set of indices representing temperature and precipitation extremes over Australia. Observed trends over the period 1957–1999 were compared with individual and multi-modelled trends calculated over the same period. When averaged across Australia, the magnitude of trends and interannual variability of temperature extremes were well simulated by most models, particularly for the index for warm nights. The majority of models also reproduced the correct direction of trend for precipitation extremes although there was much more variation between the individual model runs.

Perkins *et al*., (2007) assessed the ability of climate models to capture the observed daily frequency distributions for precipitation, minimum temperature, and maximum temperature in 12 Australian regions. Precipitation was simulated reasonably by most and very well by a small number of models, although excessive drizzle was apparent in most models. Averaged over Australia, 3 of the 14 climate models captured more than 80% of the observed frequency distributions for precipitation. Minimum temperature was simulated well, with 10 of the 13 climate models capturing more than 80% of the observed frequency distributions. Maximum temperature was also simulated reasonably well, with 6 of 10 climate models capturing more than 80% of the observed frequency distributions.

The spatial resolution of the global models is generally unable to resolve tropical cyclones, but tropical-cyclone-like features can be simulated with improved realism in models with finer spatial resolution (IPCC, 2007, Ch 8). Oouchi *et al*., (2006) used one of the finest-resolution (20 km) atmospheric models to simulate the frequency, distribution and intensity of tropical cyclones in the current climate. The overall simulation of geographical distribution and frequency was remarkably good, but the model could not simulate the strongest observed maximum wind speeds or lowest central pressures. This suggests that even finer resolution may be required to simulate the most intense tropical cyclones (IPCC, 2007, Ch 8).

Climates from thousands of years ago

Additional confidence comes from the ability of models to reproduce features of past climates and climate changes (IPCC, 2007, Ch 6). Models have been used to simulate ancient climates, such as the warm mid-Holocene of 6,000 years ago or the last glacial maximum of 21,000 years ago. They can reproduce many features (allowing for uncertainties in reconstructing past climates) such as the magnitude and broad-scale pattern of oceanic cooling during the last ice age.

Implications for climate projections

Based on extensive testing of global climate model performance, these models represent the best tools available for estimating future climate change, particularly at continental scales and above. Since confidence decreases at smaller scales, other techniques, such as the use of regional climate models, or statistical downscaling methods, have been developed (IPCC, 2007, FAQ 8.1 and 11.1). In parallel, the resolution of global models continues to improve, so they are becoming increasingly useful for assessing changes in extreme weather events.

Over several decades of development, models have consistently indicated significant warming in response to increasing greenhouse gases. While the warming effect of greenhouse gases is well understood, there are uncertainties associated with factors that may enhance or reduce this warming and associated sea level rise, e.g., changes in aerosol emissions, ice-cover, ice-sheet dynamics, cloud properties and the biosphere. With increasing computer power and better understanding of climate processes, future models will include finer resolution and more processes. This will lead to some potential reduction in uncertainty but not remove it altogether. Hence, there will always be a range of uncertainty in climate projections. Decision-makers need to incorporate this uncertainty in risk management.

Climate change projections for the Australian region (CSIRO and BoM, 2007) are based on the 23 CMIP3 models. Projections from each model are weighted according to their ability to simulate the present average patterns of temperature, precipitation and mean seal level pressure over Australia. Ranges of change in average temperature, precipitation, wind-speed, relative humidity, solar radiation and potential evaporation are provided for six emission scenarios for 2030, 2050 and 2070. Projections for a host of other variables, including extreme weather events, are also provided for a selection of years and emission scenarios.

References

Alexander, L.V. and Arblaster, J.M. (2009). Assessing trends in observed and modelled climate extremes over Australia in relation to future projections. *Int. J. Climatol.* **29**, 417–435 pp.

Alexander, L.V., Tapper, N., Zhang, X., Fowler, H.J., Tebaldi, C. and Lynch, A. (2009). Climate extremes: progress and future directions. *Int. J. Climatol.* **29**, 317–319 pp.

Bader, D.C., Covey, C., Gutowski, W.J., Held, I.M., Kunkel, K.E., Miller, R.L, Tokmakian, R.T., and Zhang, M.H. (2008). *Climate Models: An Assessment of Strengths and Limitations*. A Report by the U.S. Climate Change Science Program, U.S. Department of Energy, Washington, DC, USA. www.climatescience.gov/Library/sap/sap3-1/final-report/default.htm.

CSIRO and BoM (2007). *Climate Change in Australia – Technical Report*. CSIRO and Australian Bureau of Meteorology, 148 pp ISBN 9781921232930 www.climatechangeinaustralia.gov.au/.

Easterling, D.R. and Wehner, M.F. (2009). Is the climate warming or cooling? *Geophys. Res. Lett.*, **36**, L08706, doi:10.1029/2009GL037810.

Iorio, J.P., *et al.*, (2004). Effects of model resolution and subgrid scale physics on the simulation of precipitation in the continental United States. *Clim. Dyn.*, **23**, 243–258 pp, doi:10.1007/s00382-004-0440-y.

IPCC (2001). *Climate Change 2001: The Scientific Basis*. (Houghton, J., Ding, Y., Griggs, D., Noguer, M., van der Linden, P. and Xiaosu, D., Editors). Contribution of the Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. World Meteorological Organisation and United Nations Environment Programme. Cambridge University Press, 944 pp. www.ipcc.ch.

IPCC (2007). Climate models and their evaluation. Randall *et al*. (Chapter 9), in *Climate Change 2007: The Physical Scientific Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor & H.L. Miller (eds), Cambridge University Press. www.ipcc.ch.

Keenlyside, N.S., Latif, M., Jungclaus, J., Kornbleuh, L. and Roeckner, E. (2008). Advancing decadal-scale climate prediction in the North Atlantic sector. *Nature*, **453**, 84–88 pp. doi:10.1038/nature06921

Kimoto, M., Yasutomi, N., Yokoyama, C. and Emori, S. (2005). Projected changes in precipitation characteristics near Japan under the global warming. *Scientific Online Letters on the Atmosphere*, **1**, 85–88 pp, doi: 10.2151/sola.2005-023.

Oouchi, K., *et al*., (2006). Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: Frequency and wind intensity analyses. *J. Meteorol. Soc. Japan*, **84**, 259–276 pp.

Perkins, S.E., Pitman, AJ., Holbrook, N.J. and McAneney, J. (2007). Evaluation of the AR4 climate models' simulated daily maximum temperature, minimum temperature and precipitation over Australia using probability density functions, *J. Clim*., **20**, 4356– 4376 pp.

Räisanen, J. (2006). How reliable are climate models? *Tellus*, **59A**, 1–28 pp.

Smith, D. M., Cusak, S., Colman, A. W., Folland C. K., Harris, G. R. and Murphy, J. M. (2007). Improved surface temperature prediction for the coming decade from a global climate model. *Science*, **317**, 796–799 pp. 10.1126/science.1139540.

Sun, Y., Solomon, S. Dai, A. and Portmann, R. (2006). How often does it rain? *J. Clim*., **19**, 916–934 pp.

Zhou, T., Wu, B. and Wang, B. (2009). How well do atmospheric general circulation models capture the leading modes of the interannual variability of the Asian–Australian monsoon? *Journal of Climate*, **22** (5), 1159–1173 pp.

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