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Global climate modelling within CSIRO: 1981 to 2006

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An overview is given of the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) global climate modelling effort that has been underway, almost uninterrupted, since 1981. It reflects on the achievements over this time and also provides a comprehensive list of papers published by members of the climate modelling teams.

Introduction

At the time of writing (early 2007), Australia is about to embark on a very different direction with respect to climate modelling, that will be described later. It therefore seems appropriate to review progress in this area and, while it is acknowledged that other organisations have made substantial contributions, the focus here is mainly on the work of the climate modelling teams within CSIRO and also on global climate models. The aim of this article is to provide a relatively brief overview which attempts to convey some of the important model developments that took place and the large range of model applications. Another point that is not often recognised, and which I hope is appreciated by the reader, is that any achievements in this area are just as much a function of the successful implementation of the various physics and dynamical packages as the packages themselves. This is only possible with dedication and attention to detail over the long term.

Some of the information presented here has been gleaned from the CSIRO technical report by Gordon et al. (2002), but it has been substantially supplemented, with the aid of colleagues, using both earlier and more recent data. The reference list which accompanies this paper refers only to the non-CSIRO authored publications. A comprehensive list of publications involving CSIRO scientists as authors and co-authors is provided in an Appendix.

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Climate model development

The origins of Australia's climate modelling capacity can be dated as far back as 1969 with the setting up of the Commonwealth Meteorology Research Centre (CMRC), a joint CSIRO/Bureau of Meteorology venture with the focus on research to support Australian numerical weather prediction (NWP). This changed name to the Australian Numerical Meteorology Research Centre (ANMRC) in 1975 and, while NWP remained the focus, there were considerable developments in the area of global climate modelling (e.g. Hunt 1974; McAvaney et al. 1978). (A history of NWP in Australia written by W. Bourke can be found at: http://www.bom.gov.au/bmrc/basic/wksp16/papers/Bourke.pdf.) However, the origins of the CSIRO-only global climate modelling effort can be dated as far back as 1981, when the CSIRO2 atmospheric general circulation model (AGCM) was developed by Gordon (1981), the impetus best summarised in the abstract of that paper: 'Previously, spectral modelling has been limited to prognostic equations of the advective type. An alternative approach in which the equations have been recast in flux form is presented here. The latter type is more appropriate to model vertical boundary conditions and also guarantees mass conservation – an important consideration in extended climatic integrations.' CSIRO2 was the precursor to the models that are used today.

Table 1 provides a brief summary of the major developments (and acronyms) since that time. Although CSIRO2 comprised just two vertical levels in the atmosphere, it was eventually superseded by a four-level model (Gordon and Hunt 1991; Hunt and Gordon 1991), developed exclusively at CSIRO fol-

Table 1. A summary of CSIRO climate model progress.

Atmospheric component	*Acronym*	*First published reference*	*Oceanic component*
2 levels (56x64 grid-points)	CSIRO2	Gordon (1981)	Nil
4 levels (56x64 grid-points)	CSIRO4	Gordon and Hunt (1987) Hunt and Gordon (1987)	Slab Ocean
4 levels (56x64 grid-points)	CSIRO4 coupled	Moore (1995)	Dynamic Ocean 12 levels
9 levels (56x64 grid-points)	CSIRO Mark 1	Barton et al. (1992)	Slab ocean
9 levels (56x64 grid-points)	CSIRO Mark 1 coupled	Moore and Gordon (1994)	Dynamic ocean 12 levels
9 levels (56x64 grid-points)	CSIRO Mark 2	Watterson et al. (1997)	Slab ocean
	Coupled Mark 2	Gordon and O'Farrell (1997)	Dynamic ocean, 21 levels, flux adjusted
18 levels (96x192 grid-points)	CSIRO Mark 3	Gordon et al. (2002) Watterson and Dix (2005)	Dynamic ocean 31 levels, fully coupled, no flux adjustments
	CSIRO Mark 3.5	Hirst (2007)	As above
Conformal cubic atmospheric model	CCAM	McGregor (1996)	

lowing the disbanding of the ANMRC in 1984 (Seaman 2004). This model was used in a number of studies including a simulation of the climate from 1950-1988 using prescribed sea-surface temperatures (SSTs) (Smith 1994, 1995) but was also used in conjunction with a slab ocean model (which allows the SSTs to vary in response to the surface energy balance, but contains no advective terms). This latter model, although having a relatively coarse horizontal resolution of 5.6° longitude by 3.2° latitude, proved very useful in studies of climate change and climate variability (Davies and Hunt 1994; Gordon and Hunt 1994; Syktus and Gordon 1994; Whetton et al. 1994; Hunt et al. 1995; Hunt and Davies 1997; Hunt 1998; and Hunt 2000) and was also used in an early study of seasonal forecasting (Hunt et al. 1994). Following the Gulf War of 1990-91 and the subsequent extensive burning of oil wells, a unique study was carried out by Gordon et al. (1992) who used the model to investigate the trajectory of air parcels from the region.

The use of a dynamic ocean general circulation model (OGCM), destined for use in coupled simulations, is first described by Moore and Reason (1993). A subsequent version of the OGCM was used in studies examining the stability of the ocean's thermohaline circulation (Power and Kleeman 1993, 1994; Power et al. 1994) and decadal climate variability (Power et al. 1995a), and as the ocean component of the Bureau's first CGCM (Power et al. 1993). The first fully coupled model study in Australia, based on the Moore and Reason OGCM and the four-level AGCM, is described by Moore (1995) in a study of tropical interannual variability.

A nine-level version of the AGCM (referred to as Mark 1) was eventually developed and is described in some detail by McGregor et al. (1993). Barton et al. (1992) describe a study using this model to study the transport of volcanic clouds while Suppiah (1994, 1995) and Watterson et al. (1995a) describe climate change simulations. Watterson et al. (1995b) used it to investigate tropical cyclogenesis while experiments dealing with seasonal predictability include Dix and Hunt (1995) and the first multi-seasonal prediction with a GCM, Hunt et al. (1994). Moore and Gordon (1994) describe the first results of coupling this with the OGCM of Moore and Reason (1993). It was also used in experiments with prescribed SSTs (and sea-ice) in order to estimate the possible effect of warmer temperatures on the impacts of El Niño–Southern Oscillation (ENSO) events (Smith et al. 1997).

The Mark 1 model was eventually enhanced in a number of ways, leading to the Mark 2 version (Watterson et al. 1997). Some of these enhancements included the adoption of a semi-Lagrangian water vapour transport scheme and modifications to the convective cloud parametrisations. Conservation of energy was improved by accounting (via diabatic heating) kinetic energy dissipated by horizontal diffusion, surface drag and gravity wave drag, while conservation of global water vapour was improved by minor adjustments to the tendencies. The characteristics of land surfaces within the model allowed for bare soil and vegetative canopies. It was also run with prescribed SSTs (and sea-ice) which allowed climatic aspects of the Antarctic and Greenland Ice sheets to be estimated (Smith et al. 1998; Smith 1999). The results of experiments aimed at estimating the potential for improving seasonal forecasting are described in Hunt (1997, 2000) and Rautenbach and Smith (2001). Another major change was the adoption of a dynamic sea-ice model which allowed sea-ice to vary in response to the influence of winds and ocean currents.

Up to this point, climate change simulations relied on calculations of SSTs with slab ocean models since these experiments were relatively inexpensive to conduct. It was always recognised that more realistic climate change and climate variability studies would require coupling of the atmospheric model to a fully dynamical ocean model in which changes to the SSTs would include advective terms. To this end, the Geophysical Fluid Dynamics Laboratory (Manabe et al. 1991) ocean model was obtained and implemented, leading to the Mark 2 coupled model (Gordon and O'Farrell 1997).

One of the problems associated with coupling together two complex systems such as an atmospheric and an ocean model is the phenomenon of climate drift (see Power (1995)). In stand-alone mode, the atmospheric model typically provides a realistic simulation of the present day climate when realistic SSTs (and sea-ice extents) are prescribed. Similarly, the oceanic model typically simulates realistic SSTs (and sea-ice extents) given realistic estimates for the surface energy balance and momentum fluxes. However, the simulated surface fluxes produced by the atmospheric model differ from those required to by the ocean model to maintain a stable current climate. As a consequence, on coupling, the oceanic model tends to drift as it responds to these differences. While it is doing this, the atmospheric model also begins to drift in response to the new SSTs. This brings about a change in the fluxes and the process continues. The model climate may be far removed from the real world system, a problem common to most coupled climate models at the time. A (interim) solution was to employ the method of flux adjustments which involved adding a 'flux adjustment' term to the calculated surface energy budget in order to remove as a cause of drift the inherent imbalances between the fluxes supplied by the atmospheric model and required by the oceanic model. This term, calculated at each ocean grid-point as the difference between the surface fluxes produced by the stand-alone atmosphere and those required by the stand-alone ocean, is then kept fixed for all coupled model simulations of that particular model version, including those of perturbed climates. The methodology used for the Mark 2 model is described in Gordon and O'Farrell (1997), and allowed these authors to perform a control (constant atmospheric CO_2) simulation of several centuries duration with only modest drift (see also Cai and Gordon 1999; Cai et al. 1999). The climate drift was further reduced (to order 0.2°C per millennium or less in SST) by improvements to the Mark 2 model described in Hirst et al. (2000) which included a new oceanic mixing scheme (the 'Gent McWilliams' scheme) and an increased number (21) of levels in the ocean. The achievement of long-term stability enabled both 1000-year-long (Hirst et al. 2000; Hunt 2001; Walland et al. 2000; Vimont et al. 2002) and 10 000-year-long simulations to be performed (Hunt and Elliott 2002).

The resultant model was successfully used in transient climate change experiments where atmospheric carbon dioxide was prescribed to increase over time (see Gordon and O'Farrell 1997; Hirst et al. 1996; Dix and Hunt 1998; Cai and Gordon 1998; and Yonetani and Gordon 2001a, b). Among the topics on global warming examined in detail are the response of: the Antarctic climate and ice-sheet mass balance (O'Farrell et al. 1997; Connolley and O'Farrell 1998; O'Farrell and Connolley 1998); the Southern Ocean circulation (e.g. Hirst 1999a; Bi et al. 2001, 2002); oceanic biogeochemistry (e.g. Matear and Hirst 1999; Matear et al. 2000) and oceanic circulation patterns and their linkage to Australian climate change (Cai and Whetton 2000, 2001; Cai et al. 2003). Other topics studied included global ocean currents based on coupled model output (Watterson 2001), variability of precipitation (Watterson 2005), the southern annular mode (Watterson 2007) and the Madden-Julian Oscillation (Watterson and Syktus 2007). Recognising the importance of clouds and radiation and the role that they play in climatic change, a number of investigations were conducted into their representation within the CSIRO climate models and how they compare with other international models and observations (see, for example, Garratt 2001).

The millennia-long runs performed using the Mark 2 coupled model clearly proved very useful. However, the climate modelling community understood that the approach of flux adjustment, while useful in the short term, was not physically realistic and that a more desirable situation was one in which flux adjustments could be minimised. This was the main aim in the development of the Mark 3 coupled model and included an improved parametrisation of clouds (Rotstayn 1997). The Rotstayn cloud scheme achieved recognition as a state-of-the-art microphysical parametrisation, via its incorporation in the GFDL model (e.g. Anderson et al. 2004) and the BMRC climate model (Colman et al. 2001). Other major improvements included an increase in the number of vertical levels (from 9 to 18) and the use of a finer horizontal resolution (from R21 to T63) (Gordon et al. 2002; Kawamura et al. 2004). Work also took place to improve the oceanic component of the coupled model – an important feature requiring attention being the representation of the equatorial Pacific thermocline and its role in supporting El Niño/La Niña variability (Wilson 2000, 2002). The end result of several years of development work was a successful coupled run without flux adjustments and with only a modest amount of climate drift (Gordon et al. 2002; Watterson and Dix 2005). In parallel with this work, the low-resolution version of the model was improved by inclusion of interactive aerosol treatments and an updated radiation scheme (Rotstayn and Lohmann 2002a; Rotstayn et al. 2007). The version with interactive aerosols and prognostic clouds was used to explore uncertainties related to the indirect aerosol effects (Rotstayn and Liu 2003, 2005) and was also used in pioneering investigations of the impacts of the indirect effects of aerosols on climate, including the hypothesised contribution of aerosol forcing to the Sahelian droughts of late 20th Century (Rotstayn and Lohmann 2002b).

Recent studies with this model have dealt with topics such as pan evaporation (Rotstayn et. al. 2006), the Indian Ocean Dipole (Cai et al. 2005a), the Southern Annular Mode and oceanic circulation patterns (Cai et al. 2005b), southwest Western Australia rainfall fluctuations (Cai et al. 2005c) and the effect of Asian anthropogenic aerosols on Australian rainfall (Rotstayn et al. 2007). A low resolution version of the model suitable for millennial-scale climate simulations has also been developed and is described in detail by Phipps (2006).

Recent developments have led to the Mark 3.5 version which includes the following enhancements: the introduction of a scheme into the ocean component which controls the strength of eddy-induced transport by implicitly parametrising the strength of mesoscale eddy activity as a function of large-scale density gradients; an upgrade of the sea-ice numerics; an improved river routing scheme including time delay due to flow; and the inclusion of ocean surface current speed in wind stress calculations. Several multi-century simulations have now been completed with this model including a 1000 year ‘control’ (constant CO_2) simulation and climate change experiments conforming to the model simulation protocol of the IPCC AR4. The model output data from the simulations have been processed and are accessible from the international Program for Climate Model Diagnosis and Intercomparison (PCMDI) for inclusion in international model intercomparison and climate change impacts projects (Suppiah et al. 2007).

Over the past decade another AGCM known as the conformal-cubic atmospheric model (CCAM) was developed. Although mainly used in variable-resolution mode for dynamical downscaling from the coupled model (Mark 2 and Mark 3) simulations, CCAM was also used in stand-alone atmospheric simulations. Development of the numerics started in 1996 with a demonstration of the suitability of the conformal-cubic grid for semi-Lagrangian time integration (McGregor 1996, 1997), proceeding to a full three-dimensional atmospheric model (McGregor and Dix 2001). The model employs modern numerics (McGregor 2005b) with two-time-level, semi-implicit semi-Lagrangian time differencing. The grid is unstaggered, but the winds are transformed reversibly to/from C-staggered locations before/after the gravity wave calculations, providing very good dispersion characteristics (McGregor 2005a). A description of the latest dynamics and the incorporation of a message-passing interface are provided by McGregor and Dix (2007). A comprehensive set of physics packages was incorporated, similar to those of Mark 3. CCAM has also been used for specialised weather forecasting since around 1999, and was used to provide forecasts for the successful Alinghi team during the 2003 America's Cup. An interesting application of the model was in a sensitivity study investigating the effect of permanently flooding Lakes Eyre and Torrens (Hope et al. 2004).

Finally, it should also be noted that studies with a global focus were undertaken by CSIRO scientists with other models where these were found to be more convenient. For example, a number of studies focused on the potential impacts of nuclear war in the northern hemisphere and involved the use of a one-dimensional coupled atmospheric-oceanic model (Walsh and Pittock 1990), mesoscale models (Pittock 1989) and a version of an early climate model developed at ANMRC (Pittock et al. 1989). In addition, much of the early work in model development led to fruitful collaboration with colleagues at the Bureau of Meteorology. For example, an eddy parametrisation scheme for ocean modelling implemented by Hirst et al. (1996) was utilised in the Bureau model used by Power and Hirst (1997) to investigate the role of ocean dynamics in global warming. A penetrative radiation scheme developed at CSIRO was implemented in an ocean model (Power et al. 1995b). This model became known as the Australian Community Ocean Model, and formed the oceanic component of the Bureau’s second CGCM (Power et al. 1998). In contributing to the Bureau’s first two CGCMs, CSIRO collaboration also contributed to Australia’s first transient global warming experiment (Colman et al. 1995), one of the world’s first multivariable continental-scale detection and attribution studies (Power et al. 1998), and one of the world’s first CGCM-based seasonal prediction systems (Wang et al. 2002).

International intercomparison projects

Over time, the CSIRO climate models have participated in numerous international intercomparison projects. These include the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (for a full list of related publications see http://www-pcmdi.llnl.gov), the Atmospheric Model Intercomparison Project (AMIP) (Gleckler et al. 1995; Slingo et al. 1996; and Zhang et al. 1997), the Coupled Model Intercomparison Project (CMIP) (Barnett 1999; Covey et al. 2000b; Lambert and Boer 2001; Collier et al. 2004), the Feedback Analysis for GCM Intercomparison and Observations (FANGIO) project (Cess et al. 1996, 1997), the Project for Intercomparison of Land-Surface Parameterization Schemes (PILPS) (Chen et al. 1997; Qu et al. 1998; Pitman et al. 1999; Slater et al. 2001; Luo et al. 2003), the Global Land-Atmosphere Coupling Experiment (GLACE) (Guo et al. 2006; Koster et al. 2006) and the Paleoclimate Modelling Intercomparison Project (PMIP) (Joussaume et al. 1999).

Results have been used in a number of other intercomparison studies including those dealing with cloud feedback effects (Cess et al. 1996) cloud radiative forcing (Cess et al. 1997), the seasonal cycle (Covey et al. 2000b), northern hemisphere blocking (D'Andrea et al. 1998), sea-level change (Gregory et al. 2001) and CO_2 inversions (Gurney et al. 2003). Notably, the results of climate change simulations have been provided to all, except the first, Intergovernmental Panel on Climate Change (IPCC) assessments (IPCC 1992, 1995, 2001 and 2007).

CCAM has also participated in several international intercomparison experiments with specific foci including modelling typhoons (COMPARE3, Nagata et al. 2000) and modelling both Asian (Regional Model Intercomparison Project (RMIP), Fu et al. 2005) and USA (Stretched Grid Model Intercomparison Project (SGMIP), Fox-Rabinovitz et al. 2006) climates. CCAM is also participating in the ongoing Aqua-Planet Experiment (APE), being run with specified SSTs as described by Neale and Hoskins (2001).

How do the CSIRO climate models rank? This cannot be answered in simple terms because there are so many features of the climate that can be evaluated and there is no accepted framework for obtaining an overall ranking. For example, in an intercomparison of 29 global climate models submitted to AMIP, Lau et al. (1996) performed a ranking of their performance in terms of how well each was able to simulate various aspects of regional and hydrological processes in response to observed sea-surface temperatures and sea-ice boundary forcings. The CSIRO Mark 1 model was ranked within the top four models with respect to capturing the spatial variability of precipitation between 35°N and 70°N but, overall, was ranked within the top ten to twelve models with respect to twelve such benchmark tests. Another informative indicator is provided by a 'Taylor diagram' prepared by Covey et al. (2000a) in an intercomparison of 18 coupled models submitted to CMIP and which was published in the IPCC Third Assessment Report (IPCC 2001, Fig. 8.4). Reproduced here as Fig. 1, it provides measures of how well each model performed at simulating, globally, present day values for surface air temperature, sea-level pressure and precipitation. In simple terms, a good performance corresponds to a measure falling close to the dotted line and also lying on a radial line close to the bottom axis. For example, a perfect simulation would place the measure near the point identified as 'OBSERVED'. The three measures for the Mark 2 coupled model (identified by the number '4') are indicated by the arrows. Note that the three groupings indicate that surface air temperature is best simulated by the models as a whole, followed by sea-level pressure and then precipitation (the most difficult). It is fair to say that the CSIRO Mark 2 model ranked within the top four models at simulating each variable.

A more recent (but preliminary) assessment of coupled climate models is provided by the Taylor diagram shown in Fig. 2 (M. Collier, personal communication). In this case it is based on 25 sets of model results including those used in the IPCC Fourth Assessment Report and an observed data-set based on

Fig. 1 **Performance statistics for surface air temperature (red), sea-level pressure (green) and precipitation (blue) from CMIP2 model control runs. The radial coordinate gives the magnitude of total standard deviation, normalised by the observed value, and the angular coordinate gives the correlation with observations. From Covey et al. (2000a) and IPCC (2001, Fig. 8.4). The three arrows indicate where the CSIRO Mk2 coupled model results lie with respect to other models.**

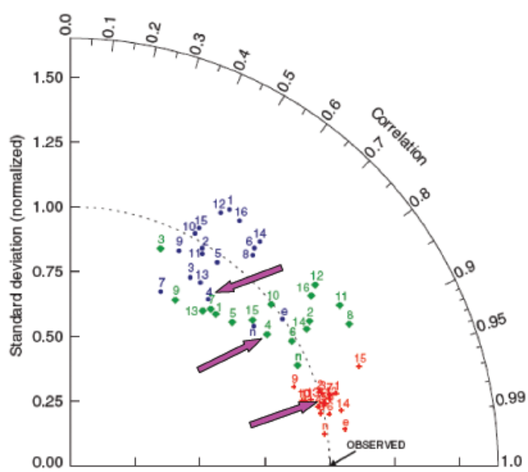
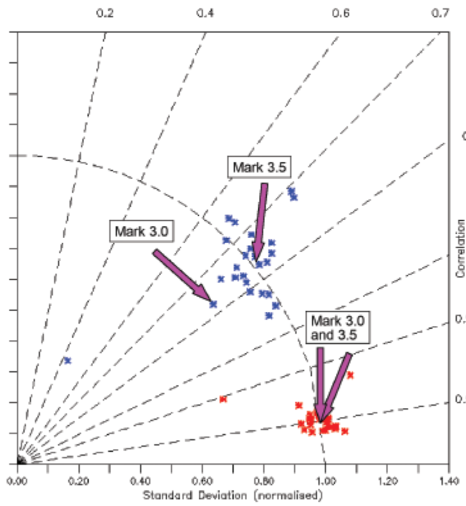


Fig. 2 **As for Fig. 1 except the statistics refer only to surface air temperature (red) and precipitation (blue) from more recent model control runs. The arrows indicate where the CSIRO Mark 3 and Mark 3.5 coupled model results lie with respect to other models (M. Collier, personal communication).**



NCEP reanalysis data (Kalnay et al. 1996). The results from Mark 3.0 and Mark 3.5 models are indicated by the arrows. In this case, both models appear to be ranked closer to the middle of the set. Reasons for this shift in the relative rankings include the fact that the Mark 2 model results were based on flux adjustments whereas the later models do not have this advantage. Secondly, there has not been the same amount of time and effort spent on improving the performance of the Mark 3 models compared to that which has undoubtedly taken place by the much larger overseas modelling groups. However, Fig. 2 indicates that the Mark 3 is comparable with most international models.

Published work

The net result of the work carried out by CSIRO scientists in developing, testing and experimenting with various climate models is partly indicated by the fact that over 200 papers and book chapters have been published (either as lead or co-authors) in the international literature. This number equates to an overall average rate of publication of about six articles per year since 1981, or about one article every two months. As can be seen from Fig. 3, this number peaked at 17 in 1999, an average rate of one article every three weeks.

The total number of articles that have relied on CSIRO model results, including those published by CSIRO scientists, can be estimated by performing a search (with Google Scholar) for references to the specific words 'CSIRO GCM'. After some filtering, this yielded (at one point in time) a total of 370, representing studies from a wide range of international institutions. Figure 4 shows the number of articles published each year. Note that the actual number is still increasing since there are articles still to appear in print. The relative paucity of articles over the first decade represents the fact that most of the effort, by only a handful of scientists, went into code development and testing. The eventual success and adoption of the models can be seen by the rapid increase in published articles over the past 15 years, culminating in a maximum of over 50 in 2005 (equivalent to, on average, about one a week).

Fig. 3 **The number of articles published each year by CSIRO authors or co-authors dealing with climate model related studies.**

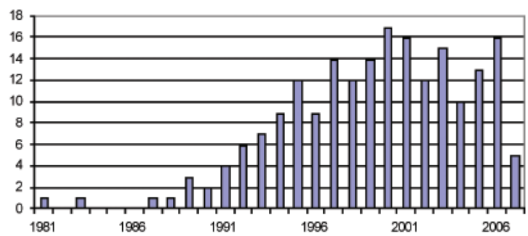
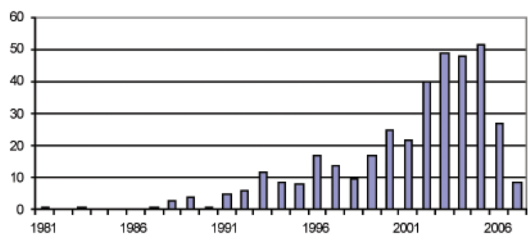


Fig. 4 **Estimates of the number of articles published each year by all authors referring to 'CSIRO GCM'.**



A further index of impact is the number of hits from a simple Google search for the exact words 'CSIRO climate model'. This returned over 16 500 hits and represents references to articles, chapters, research reports, client reports, abstracts, presentations, press releases etc. Again, this number is conservative and, although substantial, is probably typical of other international climate modelling centres. These indicators demonstrate a substantial and sustained record of achievement by a focused, relatively small group of scientists.

What of the future?

The future of climate modelling in Australia is in the process of taking a very different direction to that of the past. This has been brought about by a range of factors including substantial organisational and personnel changes that have occurred over time, the fact that increased awareness of climate change issues and its impacts has led to a greater focus on stakeholder requirements and the fact that the effort required to make further progress and maintain a world-class modelling effort has become more and more challenging. This latter point has led to the conclusion that future progress will require the pooling of resources at a national level. Some of the stakeholder demands include the need to provide more detailed and less uncertain projections of future climate change at regional scales and the need to better understand some of the 'earth system' components including carbon-cycle feedbacks, dynamic vegetation, atmospheric chemistry and oceanic oxygen content.

Consequently, a high-level decision was made in 2004 to progress the development of the Australian Community Coupled Earth System Simulator (ACCESS). ACCESS aims to address the above demands while at the same time fulfilling various operational requirements by combining the research efforts of both CSIRO and the Bureau of Meteorology in conjunction with the UK Meteorological Office. The major feature of ACCESS is that it will take a so-called 'unified model' approach in which the core model will be designed for adaptation to weather forecasting, seasonal forecasting and climate variability and climate change simulations. While the CSIRO model, as it has evolved to date, will not be part of this development, it is likely that the decision to commit substantial resources to ACCESS is partly due to the demonstrated successes achieved by the CSIRO modelling program over the past quarter of a century. Coincidentally, 2007 marks the formation of a new joint research facility between the two research organisations to be known as the Centre for Australian Weather and Climate Research (CAWCR). CAWCR comes into being 23 years after the disbanding of the ANMRC.

Finally

There currently exists a view that the quality of science can be judged by the extent to which it can drive policy and affect societal change. In one sense this idea is entirely impractical since the impacts of research can be subtle, any judgements are likely to be subjective and, as history often demonstrates, the value of science is not fully realised until well after the practitioners (and their critics) have departed. That being said, the CSIRO climate modelling program, although being primarily driven by the scientists, was also supported by a range of stakeholders eager for information to assist a range of decisions, be they policy or otherwise. From another perspective, the quality of the science can be measured by the contributions to the international climate modelling effort and consequent knowledge base and the respect afforded by peers. On this basis, the program has demonstrated prolonged and substantial success. This success comes despite the relatively small size of the modelling team in comparison to major international groups and can be attributed to the sustained effort and dedication of many team members. Two colleagues (now retired) deserve special mention. Barrie Hunt provided leadership from the beginning up until 2001 (when Tony Hirst took over) while Hal Gordon, who was solely responsible for model development during the early years, continued to play a central role up until 2006.

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