CSIRO Mk3 Climate System Model and Meeting the Strict IPCC AR4 Data Requirements

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EXTENDED ABSTRACT

The Intergovernmental Panel on Climate Change (IPCC) has recently completed its Fourth Assessment Report (AR4) "Climate Change 2007". Results from comprehensive numerical models of the climate system are fundamentally important for understanding climate processes and how climate has changed in the past and may change in the future.

Some time ago the Commonwealth Scientific and Industrial Research Organisation (CSIRO) completed its submission to the IPCC AR4 Model database a set of experiments simulating past, present and future climate with the Mk3 Climate System. The Mk3 model has been in development and used for production climate runs for the best part of a decade and is the end result of a significant commitment of financial and intellectual resources from a relatively small group of developers and stakeholders.

The task of processing, deriving, validating and submitting Mk3 output provided significant computing and logistic challenges. Data requirements were substantially more demanding than ever before and the schedule for inclusion in the AR4 database was extremely tight. Particularly when several key model experiments were still underway when the call for data (from Joint Scientific Committee (JSC)/Climate Variability and Predictability (CVP) Working Group on Coupled Models (WGCM)) came. However, the importance of contributing to the IPCC AR4 with a climate model developed in the Southern Hemisphere cannot be underestimated. This effort will provide a useful "model development" yardstick for the Australian Community Climate Earth-System Simulator (ACCESS) development program that is underway in Australia. The best indicator of the Mk3 outcome is the inclusion of its performance in hundreds of peer-reviewed scientific articles and the many contractual reports completed and underway.

We briefly describe the system for managing Mk3 model output based on a modern, locally developed, scripting computer language for the efficient processing of large and complex datasets. This system takes into account different Mk3 model configurations and model output inconsistencies and is able to generate a temporally, spatially and physically consistent set of data products. An essential feature is the ability to make the model results self describing (CF-compliant netCDF files) to enable efficient uptake by researchers. Experiences with data validation and quality control checking is described, an often overlooked aspect of data delivery. Our goal was to make the Mk3 model output easily accessible to the international climate research community.

In this presentation a brief history of the development and features of the CSIRO Mk3 model will be provided. Although the Mk3.5 model was not included in AR4, the Mk3.5 version of the climate model includes many improvements over its predecessor resulting in a control climate with a relatively small drift. Mk3.5 output forms part of the new World Climate Research Programme (WCRP) Coupled Model Intercomparison Project Version 3 (CMIP3) Multimodel Dataset. This new and updated archive of model outputs will provide the local and international community with a wealth of informative and sophisticated climate model experiments for completion of important institutional studies. An indication of the regional demands for Mk3 outputs will be given. Details of how to access the CSIRO Mk3.0 and Mk3.5 data will be provided.

1. INTRODUCTION

Globally much attention has been given to the debate regarding human influence on the weather and climate of our planet. Presently the best method for understanding climate processes and how climate has changed in the past and may change in the future is through the use of sophisticated global climate models. These are based upon the best modern understanding of the physical interactions between the atmosphere, ocean, land-biosphere and cryosphere. The Intergovernmental Panel on Climate Change (IPCC) has recently completed its Fourth Assessment Report "Climate Change 2007" (AR4). This report relied heavily on the results of climate models (see http://ipcc-wg1.ucar.edu/wg1/wg1-report.html). For any reliable understanding of future climate change these models must be able to simulate past and present climates to a high level of accuracy. CSIRO has a long history of being involved in the science of climate (Smith, 2007) and weather and the CSIRO Mk3 model is the latest in a series of models to be developed for a broad range of scientific investigations and applications. The CSIRO model is one of about two dozen recognised climate models operating around the world. In preparation of the Fourth Assessment Report (AR4) of the IPCC it was recognised that a centralised data store of pertinent prognostic and diagnostic model variables should be collected so that scientists outside the major modelling centres could also actively participate in relevant analyses. It was also particularly important that scientists would be able to practically compare model behaviour and characteristics across the full range of models, and to examine how model results agree or disagree and draw some conclusions on why this might be.

The WGCM Climate Simulation Panel with the assistance of PCMDI (Program for Climate Model Diagnosis and Intercomparison) developed a plan to 1) define the required high (and low) priority parameters to be submitted 2) create a self-describing, machine portable data and metadata standard that all modelling centers must conform to and 3) provide high capacity computer hard disks, procedures and guidelines on appropriate methods of validating data once copied to the disk. This approach was extremely successful and, as of February 2007, over 32 terabytes of data were in the PCMDI archive. This has officially become known as the WCRP CMIP3 multi-model dataset (Meehl et al., 2007). Now that work for the IPCC AR4 is complete, the dataset will continue to be used extensively for other international projects quite possibly until the next round of the IPCC Assessment Reports in 2010. As an indication of the amount of interest in this data set, over 171 terabytes of data had been downloaded among the more than 1200 registered users. Over 200 journal articles based in part on the dataset have been published (Karl Taylor, personal communication).

2. METHOD

In comparison to similar previous activities, the requirements for IPCC standard output contributed to the PCMDI archive were substantially toughened. This policy proved sound in view of the large number of participating models and analysts and the vast volume of data held. The specific details of the output requirements were contained in the document:

http://www-pcmdi.llnl.gov/ipcc/IPCC_output_requirements.htm

2.1. Features of the Mk3.0 Climate system model

Output from two versions of the CSIRO Mk3 model were contributed to the CMIP3 these are the Mk3.0 and Mk3.5. The CSIRO Mk3.0 Climate System Model (hereafter CSIRO Mk3.0) is documented in Gordon et al. (2002). Additional details pertaining to the CMIP2 experiments (which in the document are described by the experiment names PIcntrl and 1%to2x, see Table 2) are provided in Collier et al. (2004). The Mk3.0 model is based on the Mk2 model as described in Gordon et al. (1997), O'Farrell (1998) and Hirst et al. (2000), with major numerical, computational and parameterisation improvements. Importantly, the Mk3.0 model is run without any flux adjustments and suffers from only a moderate amount of climate drift.

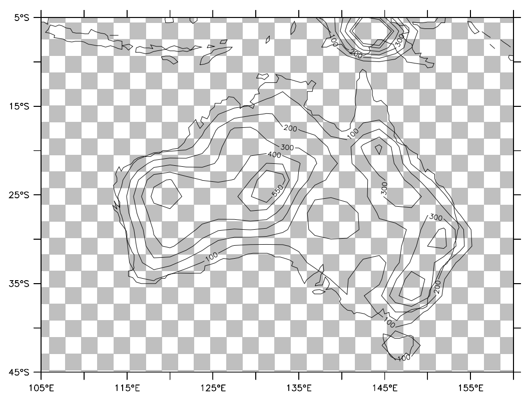

Figure 1. The Mk3 atmospheric model horizontal grid shown over the Australian region with surface altitude (m).

Briefly, the horizontal resolution of the Mk3.0 atmospheric model is spectral T63 (approximately 1.875° latitude×1.875° longitude) with 18 vertical levels (hybrid sigma-pressure vertical coordinate). The Mk3.0 grid-cell density can be visualised from Figure 1.

The atmospheric model includes a comprehensive cloud microphysical parameterisation (Rotstayn et al., 2000) and the convection parameterisation is based on that used in the Hadley Centre model (Gregory et al., 1990). This convection parameterisation has been linked to the cloud microphysics scheme via the detrainment of liquid and frozen water at the cloud top.

Atmospheric moisture advection (vapour, liquid, and frozen) is carried out by the semi-Lagrangian method (McGregor, 1993). A simple treatment of the direct radiative effect of sulphate aerosol using a perturbation of the surface albedo (Mitchell et al,. 1995) is included in the model. The land surface scheme uses six soil layers with a vegetation canopy (Kowalczyk et al., 1991, 1994) and also includes a three-layer snow model. Multiple soil (9) and vegetation (12) types are included. The model incorporates a dynamical-thermodynamic sea ice model that includes a variable fraction of leads (O'Farrell, 1998).

The Mk3.0 ocean model is based upon the Modular Ocean Model version 2.2 (MOM2.2) of the Geophysical Fluid Dynamics Laboratory (GFDL) model (Pacanowski, 1996). The oceanic component has a horizontal resolution matching that of the atmospheric model in the east-west direction and twice that in the north-south direction. This represents an approximate grid spacing of 0.9375° latitude×1.875° longitude and allows the atmospheric model and ocean model to have matching land-sea masks. There are 31 levels in the vertical, with the spacing of the levels gradually increasing with depth, from 10 m at the surface to 400 m at depth. The ocean model includes a parameterisation of mixing of tracers based on the formulation of Griffies et al. (1998) and Griffies (1998), and improved vertical mixing in the tropical Pacific (Wilson, 2000).

Readers are further referred to http://www-pcmdi.llnl.gov/ipcc/model_documentation/CSIRO-Mk3.0.pdf for a summary of Mk3.0 model specifications on a standard template for ease of comparison with the other CMIP3 participating models.

Table 1. The Mk3.0 monthly and daily periods for which model data was submitted to PCMDI for use in the IPCC AR4 activity.

Experiment Name	Ensemble	Monthly Years	Daily Years
PIcntrl	run1	1871-2250	1961-2000
PIcntrl	run2	2001-2080	2061-2080
20C3M	run1	1871-2000	1961-2000
20C3M	run2	1871-2000	1961-2000
20C3M	run3	1871-2000	1961-2000
Commit	run1	2001-2100	2031-2050 2081-2100
SRESA2	run1	2001-2100	2046-2065 2081-2100
SRESA1B	run1	2001-2200	2046-2065 2081-2100 2181-2200
SRESB1	run1	2001-2300	2046-2065 2081-2100 2181-2200 2281-2300
1pctto2x	run1	2001-2080	2061-2080
Slabcntl	run1	2041-2060	2001-2020
2xCO2	run1	2041-2060	2001-2020

Experiments conducted with the Mk3.0 model and the periods for which data have been submitted to PCMDI are shown in Table 1. The experiments most sought after (so called "high priority") were included in the set, however, a number of experiments were not performed. These are an Atmospheric Model Intercomparison Project (AMIP), present day control (PDcntrl) and the 1%/year CO2 increase from doubling to quadrupling (1%to4x) experiments. The contributed data, however, covers 1800 simulated years comprising 1.7 terabytes of data.

2.2. Improvements in the new Mk3.5 Climate System Model

A number of physical parameterisation and numerical improvements were made to the Mk3.0 model to produce the Mk3.5 version. These include a scheme to control the strength of the ocean eddy-induced transport, vertical ocean mixing due to wind-generated turbulent kinetic energy, and an improved runoff and river routing method. See http://www-pcmdi.llnl.gov/ipcc/model_documentation/CSIRO-Mk3.5.pdf for a summary of Mk3.5 model specifications. Importantly, a rebalance of the model's energetics was carefully performed after the model improvements were implemented, resulting in a markedly reduced drift in the global mean temperature ~-0.008°/century compared to ~-0.121°/century in the Mk3.0 model[1].

A similar set of experiments was performed and data subsequently submitted with the Mk3.5 model as for the Mk3.0 model. The Mk3.5 SRESA1B experiment, however, was integrated out a further 100 years and only one long (~1000 years) control experiment was performed. It is a noteworthy achievement that the flux uncorrected Mk3.5 control model experiment was able to be integrated out for over 1000 years with a negligible surface temperature drift. The experiments most sought after were included in the Mk3.5 set, however, a number of experiments were not performed. These are an Atmospheric Model

[1] This was calculated over the arbitrarily assigned calendar period of 2000-2250 for both experiments.

Intercomparison Project (AMIP), present day control (PDcntrl) and the 1%/year CO2 increase from doubling to quadrupling (1%to4x) experiments.

As of the writing of this paper, the slab ocean control experiment (Slabcntl) and 2xCO2 equilibrium experiment (2xCO2) were complete but submission of data to PCMDI is yet to occur. The contribution presently covers 2000 simulated years comprising 1.9 terabytes of data.

2.3. Processing system for generating IPCC AR4 data

The Working Group on Numerical Experimentation (WGNE)/PCMDI set up strict guidelines and provided software to write and check data contributions made to the IPCC AR4 archive. The CSIRO Mk3 model already produced netCDF, but not in the correct format, and not all the required variables were readily available.

To sort out these inadequacies with the raw Mk3 output, a comprehensive processing system was developed using the scripting language Tcl and an extension written for this language called NAP (Numerical Array Processing). This was extensively used because of its sophisticated array processing capability and data input/output facilities (Davies, 2007).

A schematic representation of the system is shown in Figure 2. The system identifies the variable being requested for a particular experiment and period etc. and the data "engine" processes through the relevant raw Mk3 data. A second set of inputs are shown by the box labelled "derived". These are parameters that must be prepared *a priori* else the data engine will not identify the required inputs. Examples of derived parameters include atmospheric geopotential height and ocean potential density and generally depend upon a number of other parameters and/or an external executable that cannot be readily obtained directly within the data engine itself. Thus this constitutes a 2-step process compared to the normal process of everything being handled through the data engine. The metadata portions of the schematic include features such as conversion of internal units, conventions used in naming the raw input files, and definitions of output dimensions, attributes and dimension bounds. In normal practice numerous processing tasks are conducted simultaneously up to a limit specified to avoid adverse effects on the overall throughput of the host computer system. This is usually identified through trial and error, if too many jobs are submitted the system will be swamped. The processing system runs in an iterative manner until all data outputs are generated. The only manual intervention includes the setting up of repeat runs where erroneous data were identified during the data validation stage or reported back through the managers of the data portal.

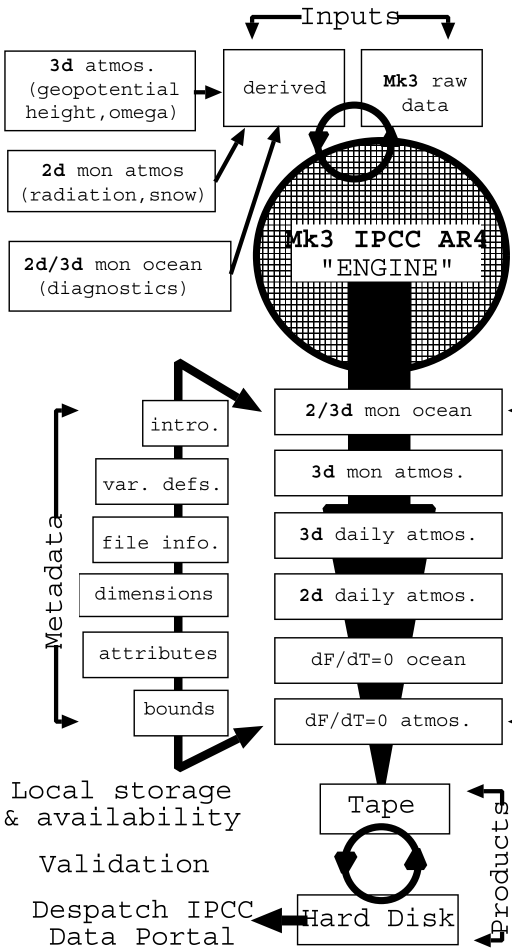

Figure 2. A schematic overview of the Mk3 processing system.

It was decided not to directly utilise the recommended Climate Model Output Rewriter (CMOR[2]) for generating Mk3 CF-Compliant[3] netCDF[4] files as at the time we were confident that we could address all of the necessary data requirements set by PCMDI. Tcl-NAP has a comprehensive ability to read and write in various data formats (including netCDF, the required format) and is able to perform a number of standard operations (e.g. vertical interpolation, temporal averaging) on multi-dimensional arrays. To ensure that we were on track to meet the official guidelines, extensive checking of selected files by the CMOR was conducted to highlight any deficiencies present or that may have crept into the system as it

[2] http://www-pcmdi.llnl.gov/software/cmor/cmor_users_guide.pdf
[3] http://www.cfconventions.org/
[4] http://www.unidata.ucar.edu/software/netcdf/

was continually built upon. Overall, this approach proved to be successful and allowed a locally developed Tcl-Nap data processing package to be tested and supported.

Table 2. The Mk3 monthly, daily and time invariant parameter tables. Superscript *a* indicates a lower-priority parameter whilst superscript *b* indicates files that were generated but never supplied. λ, φ, P, D, R and T denote latitude, longitude, pressure, depth, region and time, respectively. NoP: number of parameters. NoPS: number of parameters supplied.

Data Table	Quantity	Function of	NoP	NoPS
	Monthly-mean			
A1a	2-d atmosphere or land surface	λ φ T	44	40
A1c	3-d atmosphere data	λ φ P T	9	9
A1f	surface fields and prescribed land surface characteristics		2	2
O1a	1-d ocean data	φ R T	1	1
O1b	2-d ocean data	φ D R T	1	1
O1c	0-d or 2-d ocean or sea ice data	λ φ T	13	13
O1e	3-d ocean data	λ φ D T	6	6
	Daily-mean			
A2a	2-d atmosphere data	λ φ T	14	14
A2b	2-d atmosphere data	λ φ T	4	4
A3	2-d atmosphere data	λ φ T	9	0
A4	2-d atmosphere data	λ φ T	10	10
	Time-Independent			
A1b	2-2-d land surface data	λ φ	4	4
O1d	2-2-d d ocean data	λ φ	2	2

The major requirements and outcomes of the processing system can be summarised as follows:

1) Tcl-Nap procedures were written to convert Mk3 model data stored in various data formats and spread heterogeneously across computing accounts to IPCC netCDF form (110 atmospheric and oceanographic parameters, see Table 2).

2) Several IPCC parameters were derived from basic model parameters which required the generation of algorithms for operation in the processing system (e.g. 3D atmospheric vertical velocity from 3D velocity components and surface pressure, atmospheric geopotential height from 3D temperature, mixing ratio and mean sea-level pressure, 2D meridional overturning streamfunction from 3D ocean velocities and land-sea masks, and monthly pressure parameters from raw daily sigma-level data).

3) Almost every high priority parameter (annual, monthly, daily and time invariant) that was requested was able to be generated by the processing system and made available on time and with very few errors. See Table 2 for a summary of how complete this was for each of the parameter tables. Comprehensive data validation and quality checking were performed.

4) Built into the processing system was an ability to re-grid raw model data from various sources (each experiment and user accounts) to the required destination grids in both space and time. This was necessary as experimental design differed between Mk3 experiments (horizontal and time resolutions of many raw output fields were increased in stages as computer resources increased). Conventions used in raw Mk3 model data changed as new experiments came on-line and between different maintainers of experiments. These needed to be understood by the system. Algorithms were written and adapted to map model output on the hybrid sigma coordinate levels onto standard pressure levels.

5) The processing system was able to ensure that a complete and conforming set of metadata were supplied with each data file contributed to PCMDI containing vital parameter, dimension, experiment and contact information. The required range and detail of metadata was vital in making the model data sets transparent and as self-explaining as practically possible.

3. RESULTS

Table 3. Model sensitivity α for WGCM CMIP 3 models computed from $2xCO_2$ conditions from slab-ocean experiments.

Model name	ΔT (K)	F (Wm^{-2})	α ($KW^{-1}m^2$)
BCC-CM1			NA
BCCR-BCM2.0			NA
CGCM3.1(T47)			NA
CNRM-CM3			NA
CSIRO-Mk3.0	3.07	3.5	0.88
CSIRO-Mk3.5			NA
GFDL-CM2.0	1.6	-	-
GFDL-CM2.1	1.6	-	-
GISS-AOM	2.65	-	-
GISS-EH	2.7	-	-
GISS-ER	2.7	-	-
UKMO-HadCM3	-	-	0.89
UKMO-HadGEM1	4.4	3.83	1.15
FGOALS-g1.0			NA
INGV-SXG	2.44	2.40	1.02
INM-CM3.0	-	-	0.52
IPSL-CM4	4.4	3.48	1.26
MIROC3.2(hires)	4.3	3.1	1.39
MIROC3.2(medres)	4.0	3.1	1.29
ECHAM5/MPI-OM	3.35	4.01	0.84
MRI-CGCM2.3.2	-	-	0.86
ECHO-G	3.18	4.0	0.80
CCSM3	2.7	3.5	0.77
PCM			NA

Changes in greenhouse gases affect the climate through changing the radiation balance. The climate sensitivity α ($KW^{-1}m^2$) is a convenient parameter relating the temperature change (K) to radiative forcing (W m^{-2}). Table 3 shows the climate sensitivity α for the full range of IPCC AR4 models derived from equilibrium doubled CO_2 experiments using a simple slab-ocean. These values were obtained from the individual model documentation at (http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php). In five cases, the model sensitivity was not available (NA) from the online document. In a few cases only the temperature increase ΔT (K) were provided, which is an inadequate representation of the sensitivity as a change in climate must be reflected by the radiative forcing that brought about that change (Gregory et al 2004). In the cases where both the ΔT and the adjusted forcing at the tropopause F (KWm^{-2}) were provided α could be calculated by the simple ratio of the two. The CSIRO Mk3.0 model has a sensitivity of 0.88 $KW^{-1}m^{2}$, which is slightly less than the average value of the group of 0.97 $KW^{-1}m^{2}$, and similar to the sensitivity of 1.01 $KW^{-1}m^{2}$ calculated using HadSM3 and their new method for diagnosing climate sensitivity (Gregory et al 2004).

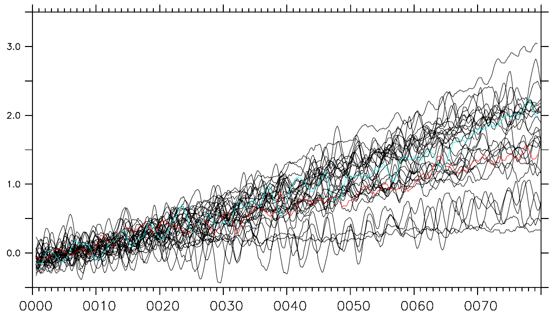

Figure 3. Globally averaged annual surface air temperature anomalies (°C, relative to average from the first 10 years) of each modelling groups (24 in total) IPCC AR4 1%/year CO_2 increase to doubling experiment. Results from each modelling group (24) and all individual ensemble members are shown (32 in total). The CSIRO Mk3.0 (Mk3.5) ensemble is shown in thick red (cyan).

The result is clearly depicted in Figure 3 where the CSIRO Mk3.0 and Mk3.5 coupled model results are shown together with all other CMIP3 models for the 1%/year CO_2 increase to doubling experiment (1pctto2x). Mk3.0 lies near the lower end of the range of warming displayed by most of the models (1.3°C – 2.2°C by year 80). Mk3.5 lies toward the upper part of this range. Work is under way to assess the mechanism for the difference in sensitivities between the Mk3.0 and Mk3.5 models

As a way of describing the relative performance of the CSIRO Mk3.0 model against other models in the IPCC AR4 archive, a Taylor diagram (Figure 4) has been generated which compares basic statistics formed from monthly model results and observational values for surface air temperature, sea level pressure and precipitation over the period 1948-2000. Note that all time information is initially removed from the monthly series and so standard deviation and correlation refer to that in space only. In this case we have used the NCEP reanalysis as the (quasi) observational set and the first ensemble for each of the IPCC AR4 models. Time constraints did not permit real observational data to be used as the reference this will be the focus of future work.

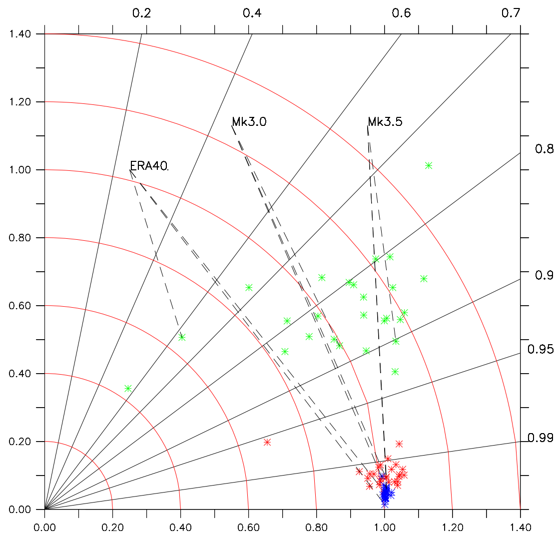

Figure 4. Taylor diagram of model surface air temperature (red), sea level pressure (blue) and precipitation (green) compared against NCEP reanalysis for the years 1948-2000. Only the first ensemble of all IPCC AR4 models are included in this diagram, and the location of the CSIRO Mk3.0 and Mk3.5 model is indicated along with the ERA40 reanalysis.

Generally, the CSIRO models perform well when compared to the other models and ERA40 reanalysis for each of the three parameters. The Mk3 precipitation correlation is somewhat low (but performs better than the ERA40 reanalysis which is known to have some problems, for example in the tropics over oceans precipitation minus evaporation is too large by 2 mm day^{-1}, I. Watterson, private communication) and its variance ratio is on the low side. The Mk3 temperature correlation is relatively high when compared to other models and the "observed" variance ratio is also simulated quite well. As the sea level pressure calculation is problematic over regions of high topography, we have restricted the calculation to terrain of less than 1000 metres (93 percent of the globe) and this eliminates spurious sea level pressure values over most of the Antarctic continent and Greenland, as well as more significant land areas found in the sub-continent, Americas and South Africa. When compared over the whole globe, the variance ratio is somewhat overestimated. When judging this performance it is important to note that there is no flux-correction in the Mk3 and most other models. We expect that there to be some discrepancy between model and observations due to the extra freedom of the coupled system.

4. DISCUSSION

The key driver of this work is the desire to make the CSIRO Mk3 datasets available to the widest possible community internationally (through the IPCC AR4 data portal) and locally via our own data store. Although the team of Mk3 developers and analysts was small, a great deal of value is gained by all through the efficient dissemination of model data to CSIRO's collaborators and partners, and the communities of people that do not have the resources to perform their own climate simulations. As with most model experiments, any one set of output generally loses some value when it is superseded by a new result and due to our small team, we rely on a larger "virtual team", that is, the outside community to scrutinise and interpret Mk3 output before too much value from the archive is lost. The IPCC AR4 was one such activity. As a consequence, an important aspect of this work has been to clearly describe methods of obtaining Mk3 data, either through email broadcasts, presentations and reports.

4.1. Obtaining the Mk3 data

There are 3 typical ways to obtain the Mk3 model data: 1) become a registered user of the official WCRP CMIP3 multi-model dataset 2) using OpenDAP or 3) directly from the CSIRO data server. For details on these approaches please refer to then read the MS word file access_mk3.doc found at the web link http://hpsc.csiro.au/cgi-bin/OpenDAP/CMAR_mk3/nph-dods/ using the login cmar_mk3 and password: ipcc4.

5. CONCLUSION

There is no doubt that the collection of model output at the PCMDI data archive represents an unprecedented effort in terms of quality and quantity of model products from the major climate modelling centres around the world. Over 60,000 years of simulated monthly-mean data has been provided to PCMDI from 25 different model versions developed in 17 climate modelling centres based in 13 nations. For CSIRO the data volume was considered about an order of magnitude greater than previous similar exercises, but perhaps more importantly much more effort was invested in ensuring the quality and clarity of archived data and explanation of model features. The high quality features of the CSIRO and other group's model data in AR4 was brought about by the strict IPCC requirements. The coordinating and participating groups were motivated by the efficiency gains that can be realised by all groups in adhering to this requirement.

In this paper we have described some technical features of the CSIRO Mk3 model, highlighted a system for processing its output and noted aspects that were particular to our meeting of the strict IPCC AR4 data requirements. The processing system described herein eliminated experimental inconsistencies and data discontinuities to produce a time, space and physically consistent and accurate set of data for both the local and international community.

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