supervising scientist report 141

Climate change analysis relevant to Jabiluka

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Environment Australia
Department of the Environment and Heritage

supervising scientist

Important Disclaimer

This report relates to climate simulations based on computer modelling. Models involve simplifications of real physical processes that are not fully understood. Accordingly, no responsibility will be accepted by CSIRO for the accuracy of forecasts or predictions inferred from this report or for any person's interpretations, deductions, conclusions or actions in reliance of this report.

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Foreword

At the twenty-second meeting of the World Heritage Committee, held in Paris from 22 to 27 June 1998, a decision was reached that the Chair of the Committee should lead a mission to Australia and Kakadu National Park to assess any ascertained or potential threats to the World Heritage values of Kakadu National Park that might arise from the proposal to mine uranium at Jabiluka. The visit of the Mission took place from 26 October 1998 to 1 November 1998.

The report of the Mission was submitted to the Bureau of the World Heritage Committee at its meeting held in Kyoto, Japan, on 27–28 November 1998. Following consideration of the report, the Bureau made recommendations that were considered by the World Heritage Committee at its meeting from 30 November 1998 to 5 December 1998.

The report noted 'severe ascertained and potential dangers to the cultural and natural values of Kakadu National Park posed primarily by the proposal for uranium mining and milling at Jabiluka' and recommended that the mining and milling of uranium should not proceed. In the case of threats to the natural values of the Park, the mission placed very significant weight on 'the serious concerns expressed by some of Australia's most eminent scientists as to the degree of scientific uncertainties relating to the Jabiluka mine design, tailings disposal and possible impact on catchment processes'. The concerns cited were made in a submission by Wasson, White, Mackey and Fleming (Wasson et al 1998, Appendix 2).

Because the Australian authorities had not had sufficient time to respond to the report, the World Heritage Committee made no firm decision of the future status of Kakadu at the November 1998 meeting. In its decision, the Committee requested that the Supervising Scientist conduct a full review of the areas of scientific uncertainty. The issues specified were hydrological modelling, prediction and impact of severe weather events, storage of uranium ore on the surface and the long-term storage of mine tailings.

The Supervising Scientist's response to that request has been published as a Supervising Scientist Series report:

Johnston A & Prendergast JB 1999. *Assessment of the Jabiluka Project: Report of the Supervising Scientist to the World Heritage Committee*. Supervising Scientist Report 138, Supervising Scientist, Canberra.

In preparing this report, the Supervising Scientist has drawn on the broad range of expertise available within his own organisation. In addition, given the intense interest in the World Heritage issue and the need for absolute transparency, he has sought independent expert advice from a number of scientific institutes within Australia. Scientists from the Bureau of Meteorology, the University of Melbourne, the Commonwealth Scientific and Industrial Research Organisation and the University of New South Wales prepared reports on specific topics at the request of the Supervising Scientist. These reports have been published as separate Supervising Scientist reports:

Bureau of Meteorology 1999. *Hydrometeorological analyses relevant to Jabiluka*. Supervising Scientist Report 140, Supervising Scientist, Canberra.

Jones RN, Abbs DJ & Hennessy KJ 1999. *Climate change analysis relevant to Jabiluka.* Supervising Scientist Report 141, Supervising Scientist, Canberra.

Chiew FHS & Wang QJ 1999. *Hydrological analysis relevant to surface water storage at Jabiluka*. Supervising Scientist Report 142, Supervising Scientist, Canberra.

Kalf FRP & Dudgeon CR 1999. *Analysis of long-term groundwater dispersal of contaminants from proposed Jabiluka Mine tailings repositories*. Supervising Scientist Report 143, Supervising Scientist, Canberra.

Included in the series is *Protection of the environment near the Ranger uranium mine* (Johnston & Needham 1999, Supervising Scientist Report 139), which summarises the extent to which the environment of the region has been protected throughout the period of operations at the Ranger uranium mine. This report was presented to the Mission when it visited Kakadu and subsequently to the World Heritage Committee as part of the Supervising Scientist's report.

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Acknowledgments

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Glossary

$1\times CO_2$

Describes pre-industrial (or sometimes present-day) atmospheric CO_2 concentration as used in simulations by a global climate model. Pre-industrial CO_2 is about 280 ppm, present day CO_2 is about 360 ppm. Some models use CO_2 equivalence, which is the atmospheric concentration of CO_2 equivalent to the combined forcing of all greenhouse gases. Pre-industrial equivalent CO_2 concentration in the CSIRO Mark 2 GCM is 330 ppm.

$2\times CO_2$

Describes conditions simulated by a climate model where the concentration of CO_2 in the atmosphere is doubled from the equivalent of a pre-industrial (or sometimes present-day) concentration, and the model atmosphere has been allowed to reach equilibrium after the change. The $2\times CO_2$ level in the CSIRO Mark 2 GCMs is 660 ppm.

Climate change scenario

A physically and internally consistent description of a hypothetical future climate useful for sensitivity studies.

Climate change projection

A climate change projection is a range of possible climate changes that consists of one or more sets of scenarios. Alternatively, a single climate change scenario can be selected from a climate change projection.

Climate sensitivity

The long-term change in global average surface air temperature following a doubling of CO_2, used as a benchmark to compare models. Current climate sensitivity as defined by the IPCC (1996), and estimated from GCM projections, is 1.5 to 4.5ºC for a doubling of equivalent CO_2 (see $1\times CO_2$ for definition of this term).

Climate variability

In this project, climate variability is dealt with on three scales:

1. Decadal-scale variability, where significant fluctuations in climate occur over a decade or more.
2. Interannual variability, where there are large year-to-year changes in climate. The El Niño Southern Oscillation (ENSO) is a major cause of interannual variability in Australia.
3. Daily variability, describing daily patterns of rainfall.

Control climate

A model simulation run at $1\times CO_2$ is known as the control climate. In a transient simulation where real years are simulated, the historical climate is simulated from the start of the run to 1990. In this case, the control climate, where model output is compared with historical climate for purposes of model validation, is the historical reference period of the World Meteorological Organisation of 1961–1990.

El Niño-Southern Oscillation (ENSO)

An ocean-atmosphere interaction that is centred in the Pacific, and results in three states, El Niño, La Niña and normal conditions. It is linked to increased interannual variability through El Niño which is associated with a drier than usual Australian monsoon, and La Niña, which is associated with a wetter than usual Australian monsoon. ENSO also affects tropical cyclone climatology.

Emission scenarios

A description of future greenhouse gas emissions based on considerations such as population growth, economic activity, fuel use and land-use change. The IPCC IS92a–f scenarios contain the major greenhouse gases, including CO_2, CH_4, N_2O and halogenated compounds, and sulphate aerosols (IPCC 1996). They provide a reference set of scenarios for climate modelling and impact studies that explain a broad range of possible futures (Alcamo et al 1994). Of these, the IS92a mid case scenario is the most commonly applied as the forcing for GCM simulations, either as a CO_2-only or CO_2 greenhouse gas equivalent scenario.

FCCC

United Nations Framework Convention for Climate Change

Global climate model (GCM)

A numerical, computer-based model containing simplified representations of the whole climate system – the atmosphere, the oceans, the biosphere and cryosphere (snow and ice) – that is used to simulate the behaviour of the atmosphere and the climate of the earth.

Limited-area model (LAM) or regional climate model (RCM)

A limited-area, or regional climate, model driven at its boundary by observed data or simulated data from a global climate model in a process called ‘nesting’. The technique is used to gain more detail over a region of specific interest. This works on considerably smaller scales than a GCM. The CSIRO currently has a LAM (called DARLAM) operating on 125 km^2 and finer grids.

Model resolution

Refers to the horizontal grid spacing within a GCM or RCM. Higher resolution, or smaller grid spacing, is an advantage as simulations are more realistic. Resolution is chosen as a compromise between computing power and efficiency, and is increasing as computing power increases. This is why RCM output is preferable to GCM output for many purposes, especially for analysing possible changes to climate variability.

Non-stationarity

Time series of historical climate are generally assumed to have a stationary average unless they contain a statistically significant change in trend. All variations in mean over shorter timescales are assumed to be due to natural variability. However, non-stationarity where the mean is changing but is below statistical significance may be important in systems where impacts are sensitive to small changes, or where the change is indicative of a longer-term trend that is likely to become statistically significant. This is especially important for Australian rainfall, which has a high interannual variability, so requires large changes in mean before significance can be established.

Sulphate aerosol

Sulphate aerosol is a type of small airborne particle that mainly originates from the burning of fossil fuel. Sulphate aerosol acts directly through the scatter and absorption of radiation. This has a net cooling effect both at the local scale, close to its emission source, and globally. It can also act indirectly, through modifying the optical properties, amount and lifetime of clouds. The uncertainties surrounding the effects of sulphate aerosol are large.

1 Introduction

The historical increase in atmospheric concentrations of greenhouse gases can be attributed mostly to human activities such as fossil fuel use, land-use change and agriculture (IPCC 1996). Climate change resulting from this increase is known as the enhanced greenhouse effect. Both natural and human-induced climate change is being investigated by the Intergovernmental Panel for Climate Change (IPCC) who, in their Second Assessment Report, stated that 'The balance of evidence suggests a discernible human influence on global climate' and 'Climate is expected to change in the future' (IPCC 1996).

The aim of the work presented here is to quantify the effects of climate change on rainfall and temperature, and its implications for parameters used in the design of water storage facilities to be used for the next 30 years at the Jabiluka Project, Northern Territory. Changes to average rainfall and temperature, and rainfall variability on decadal to scales of less than one day are investigated. Climate change scenarios have been constructed where projections of climate change can be quantified.

Earlier climate change studies for northern Australia include Suppiah et al (1998a & 1998b). In a final summary, Suppiah et al (1998a), concluded that some significant degree of climate change across northern Australia now seems inevitable, is likely to become apparent over the next 30–100 years, and that it had strong implications for the development of planned infrastructure.

A major issue for planners facing projected climate change over the coming decades is that of non-stationarity of historical climate series, particularly rainfall (eg Matalas 1997, see glossary). Some submissions to the Draft Jabiluka Environmental Impact Statement (EIS) raised concerns about the impact of climate change on the design of hydrologic structures for the Jabiluka project (eg Supplement to the Draft EIS, Kinhill & ERAES 1997, p5–27; Wasson et al 1998).

Six General Circulation Model (GCM) simulations were analysed to determine possible temperature and rainfall changes over the region surrounding the Jabiluka mine site: two simulations of the CSIRO GCM, one from the CSIRO limited area model, DARLAM, and single GCM simulations from the Deutsches Klimarechenzentrum (DKRZ), UK Meteorological Office (Hadley Centre) and Canadian Centre for Climate Modelling and Analysis. Due to uncertainties resulting from differing emission scenarios and climate sensitivities these climate models will give different answers (see glossary). However, they can be used to produce a range of projected climate change as explained in the next section.

Under climate change, the hydrological cycle is expected to become more intense (IPCC 1996) through higher evaporation, an increase in the water-holding capacity of the atmosphere and heavier rainfall. GCM output is required to show how this may change on the regional scale, so CSIRO has investigated the models listed above to create scenarios for seasonal rainfall. This involves deriving patterns of local change calculated from the models. The methods used are described in section 2.2.

In addition to the enhanced greenhouse effect, natural climatic variability can also have implications for the design of water retention structures. Decadal-scale rainfall variability in the historical rainfall record is examined to determine how this may affect hydrological persistence, or drought- and flood-dominated periodicity. Hulme et al (1999) show that on a regional scale, this effect may dominate possible future changes in average rainfall out to 2050. Regional warming from the same six models is also examined for its possible effect on evaporation (Chiew & Wang 1999) and Probable Maximum Precipitation.

Possible changes to the return periods of individual rainfall events have been investigated through the use of DARLAM which, with a grid spacing of 125 km, is run at a much finer resolution than a GCM (see glossary). Changes to daily variability expressed as return periods for extreme rainfall in 2030 are also presented. Modelling approaches developed by CSIRO to investigate extreme rainfall events provide the basis for the discussion of changes in Probable Maximum Precipitation.

Finally, a number of uncertainties surrounding the results are discussed. Several recommendations to allow for the uncertainty of future climate change are made.

2 Models and data analysis methods

2.1 Model descriptions

Estimates of future climate can be made by representing the earth's climatic system through global climate models (GCMs). These models are as physically representative as possible within the limitations of scientific knowledge, the ability to represent physically phenomena on an appropriate scale, and computer capacity. They link the atmosphere, ocean and biosphere both vertically and horizontally. The models are divided into three-dimensional grid boxes, the scale and number of those boxes being limited by the computer power available to carry out the necessary computations.

The current generation of GCM is the *coupled*, or ocean-atmosphere GCM which contains three-dimensional representations of both the ocean and atmosphere. With these models, the enhanced greenhouse effect is simulated by gradually increasing the atmospheric loading of greenhouse gases in a so-called transient run. Where finer resolution over a region is desired, a regional climate model (RCM) can be nested within a GCM, being forced by boundary conditions taken from that GCM (see glossary).

CSIRO Atmospheric Research currently simulates climate change using the CSIRO Mark 2 coupled GCM and the DARLAM RCM. In two experiments, the CSIRO coupled ocean-atmosphere model has been integrated from 1881 to 2100 with a gradually increasing CO_2 concentration equivalent to the forcing produced by all greenhouse gases in the mid-case IS92a emission scenario (IPCC 1996, see glossary). One simulation also incorporates the direct effects of atmospheric sulphate aerosol (the indirect effects, or atmospheric feedbacks, are omitted) which has a cooling effect. The regional climate model, DARLAM, with a finer spatial resolution of 125 km, was nested in the CSIRO Mark 2 greenhouse-gas-only simulation in order to provide higher resolution data (see glossary). Results from three GCMs from other modelling groups obtained from the IPCC Data Distribution Centre have also been used in the analysis. The models are summarised in table 1.

The grid space resolution of the GCMs range from a size of 5.625×3.2° for the CSIRO Mark 2 model to 2.8×2.8° for the DKRZ Model, with the regional model, DARLAM, at 125 km having a resolution close to 1×1°. The resolution of these models limits the spatial detail of climate output due to the simplified representation of the many sub-grid scale processes that occur in the real world. For example, rainfall occurs simultaneously across a whole grid box rather than being limited to a much more local scale. Therefore, although rainfall totals are expected to resemble those of the real world, the daily variability is greatly reduced, as high point falls cannot be simulated in the model. This is why DARLAM is preferred for the analysis of daily rainfall in section 5.1.

Table 1 Model runs used to produce the regional scenarios presented in this report. Historical emissions are used to 1990, after which the listed emission scenarios have been applied.

Research Centre	Model	Emission Scenario	Features	Years
CSIRO, Australia[1]	Mk2	IS92a equivalent CO_2	No sulphates, GM ocean*	1881–2100
CSIRO, Australia	Mk2 with sulphates	IS92a equivalent CO_2	Sulphates, GM ocean*	1881–2100
CSIRO, Australia[2]	DARLAM 125 km	IS92a equivalent CO_2	Nested in CSIRO Mk2	1961–2100
DKRZ, Germany[3]	ECHAM4/OPYC3	IS92a	No sulphates	1860–2099
Hadley Centre, UK[4]	HADCM2	1% CO_2 pa	No sulphates	1861–2100
Canadian CCMA[5]	CGCM1	1% CO_2 pa	No sulphates	1900–2100

1 Gordon & O'Farrell (1997)

2 McGregor & Katzfey (1998)

3 DKRZ-Model User Support Group (1992), Oberhuber (1992)

4 Cullen (1993)

5 Flato et al (submitted)

* The GM ocean refers to the Gent-McWilliams scheme, which offers a more realistic representation of oceanic processes than earlier schemes (Hirst et al 1996).

Before climate models can be used in the construction of scenarios, they must be validated. This is achieved by comparing model output for the years 1961–1990 with observed climate for the same period. This is an informal process, where charts of the magnitude and patterns of temperature and rainfall are inspected visually. All six models produce satisfactory representations of both variables over the larger Australasian region with the CCMA model being the poorest (Jones et al, in press). The results are shown for a much more restricted region covering the domain 5–20ºS and 120–145ºE (figs 1 to 3), centred over Jabiluka at 12.5ºS and 133ºE. Figures 1 to 3 show annual temperature, May to October rainfall and November to April rainfall respectively. The CSIRO Mark 2 sulphate run is not shown here, as it is spatially similar to the CSIRO Mark 2 greenhouse-gas-only run. Many of the differences observed in figures 1 to 3 are due to the resolution of grid boxes that do not allow the representation of the finer features of regional climate. As explained in the next section, these shortcomings are not carried over into the scenario construction process.

2.2 Scenario construction

Two levels of scenario construction are carried out in this report: climate change scenarios and climate change projections. A climate change scenario can be defined as a physically and internally consistent description of a hypothetical future climate useful for sensitivity studies. The output of a single GCM is an example of a climate scenario. A climate change projection is a range of possible climate change that consists of one or more sets of scenarios. When estimating the likely changes in climate or climate impacts, the aim is to create climate change projections that, where possible, encompass the whole range of quantifiable uncertainties (eg Pittock 1993). In this case, regional projections are constructed from two component ranges:

- global warming in 2030;
- the range of regional climate change per degree of global warming produced by the six climate models in table 1.

This is achieved by a method known as scaling, where local patterns of change from each climate model are multiplied by a factor of global warming.

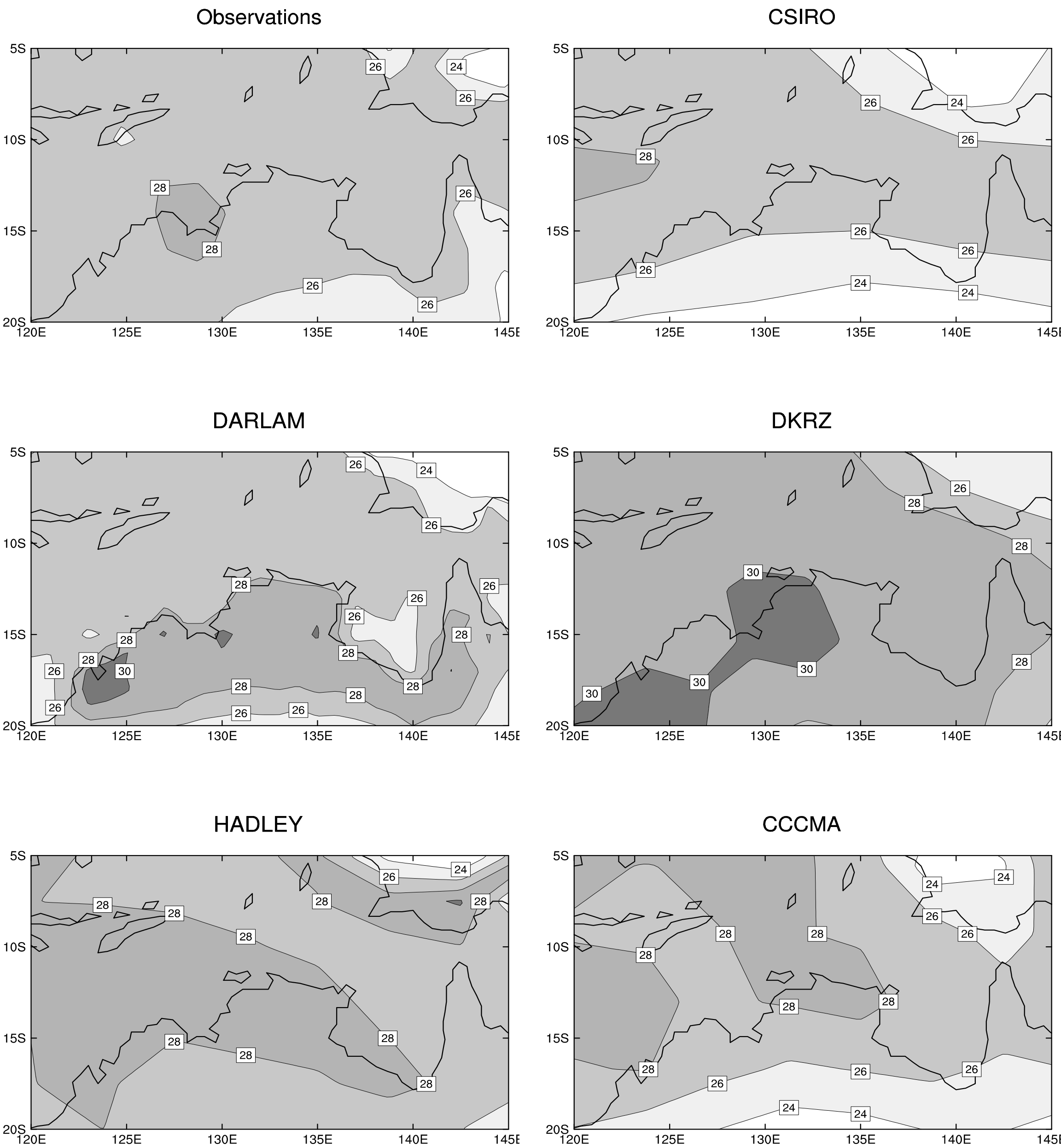


Figure 1 Observed temperature and simulated annual average temperature in °C from five climate models centred over Jabiluka for the period 1961–1990

Global warming projections from the IPCC (1996) incorporate uncertainties in greenhouse gas emission rates and climate sensitivity. The contributing emission rates are applied through the IS92a–f emission scenarios. These scenarios incorporate the major greenhouse gases, including CO_2, CH_4, N_2O and halogenated compounds, and sulphate aerosols, which lead to cooling. Global warming projections also incorporate uncertainties due to climate sensitivity, ranging from 1.5–4.5ºC at 2×CO_2. The resulting range of projected global warming for 2030 is 0.4–0.8ºC (IPCC 1996).

Local patterns of change for both temperature and rainfall are calculated by the following method. Forced by gradually increasing greenhouse gas emissions, coupled GCMs produce a gradually increasing global temperature over time (eg fig 4a), the magnitude of which is influenced largely by the climate sensitivity of the model and the emission scenario used (usually IS92a or a 1% increase in CO_2 per annum; table 1). Local warming and rainfall change in each grid box generally shows a linear relationship with global warming, even though the rate of global warming is non-linear (fig 4).

Figures 4a to c show the global warming curve from the CSIRO Mark 2 greenhouse-gas-only run, and local temperature and rainfall curves from the grid box closest to Jabiluka from DARLAM (which is nested in the Mark 2 GHG-only run). However, figures 4d and e show that the relationship between local change in rainfall and temperature, and global warming is linear. Due to this linear relationship, patterns of change can be calculated by regressing local climate against global warming on a monthly basis for each grid box, as per the trendlines in figures 4d and e (see also Hennessy et al 1998). For temperature, this local change is measured in degrees Celsius per degree of global warming. Rainfall is presented as a percentage change per degree of global warming.

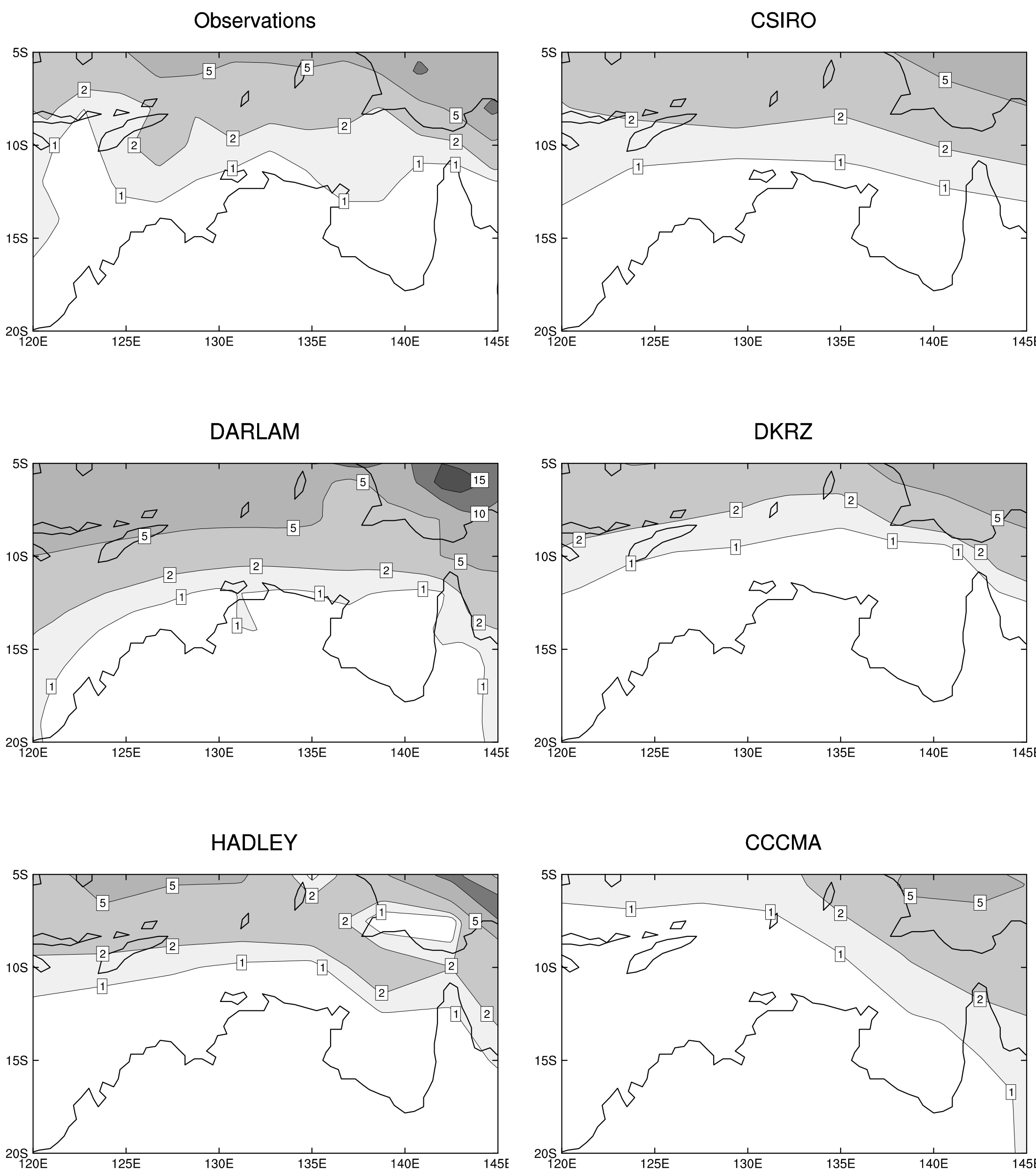


Figure 2 Observed rainfall (Legates & Willmott 1990) and simulated total rainfall in mm day^{-1} for the period May to October from five climate models centred over Jabiluka for the period 1961–1990

For instance, average global warming in the CSIRO Mark 2 greenhouse-gas-only run in 2060 is about 2.5ºC (fig 4a) with some areas warming faster and some warming slower. Standardisation reduces global average warming to 1. Areas that warm faster are >1ºC per degree of global warming and areas that warm slower than the global average are <1ºC per degree of global warming (eg fig 4b). This technique allows the results to be rescaled for different levels of global warming.

Combining the average regional pattern of change from each climate model to determine the upper and lower bounds will produce a range of local change per degree of global change for that region. When this range is multiplied by the upper and lower extremes of global warming for a particular date, regional climate change projections are produced. This is carried out for temperature in section 3.1 and rainfall in section 3.2.

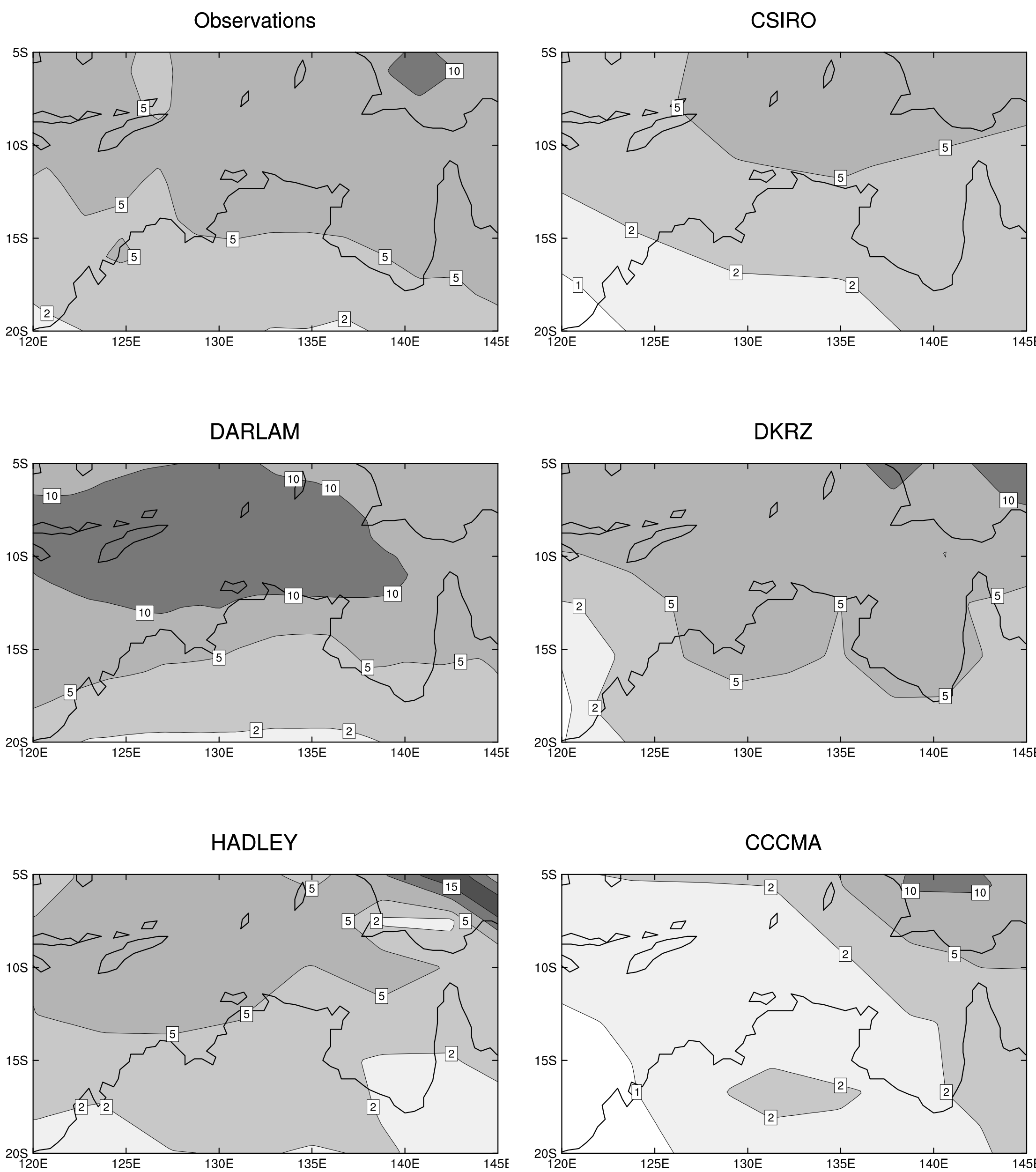


Figure 3 Observed rainfall (Legates & Willmott 1990) and simulated total rainfall in mm day^{-1} for the period November to April from five climate models centred over Jabiluka for the period 1961–1990

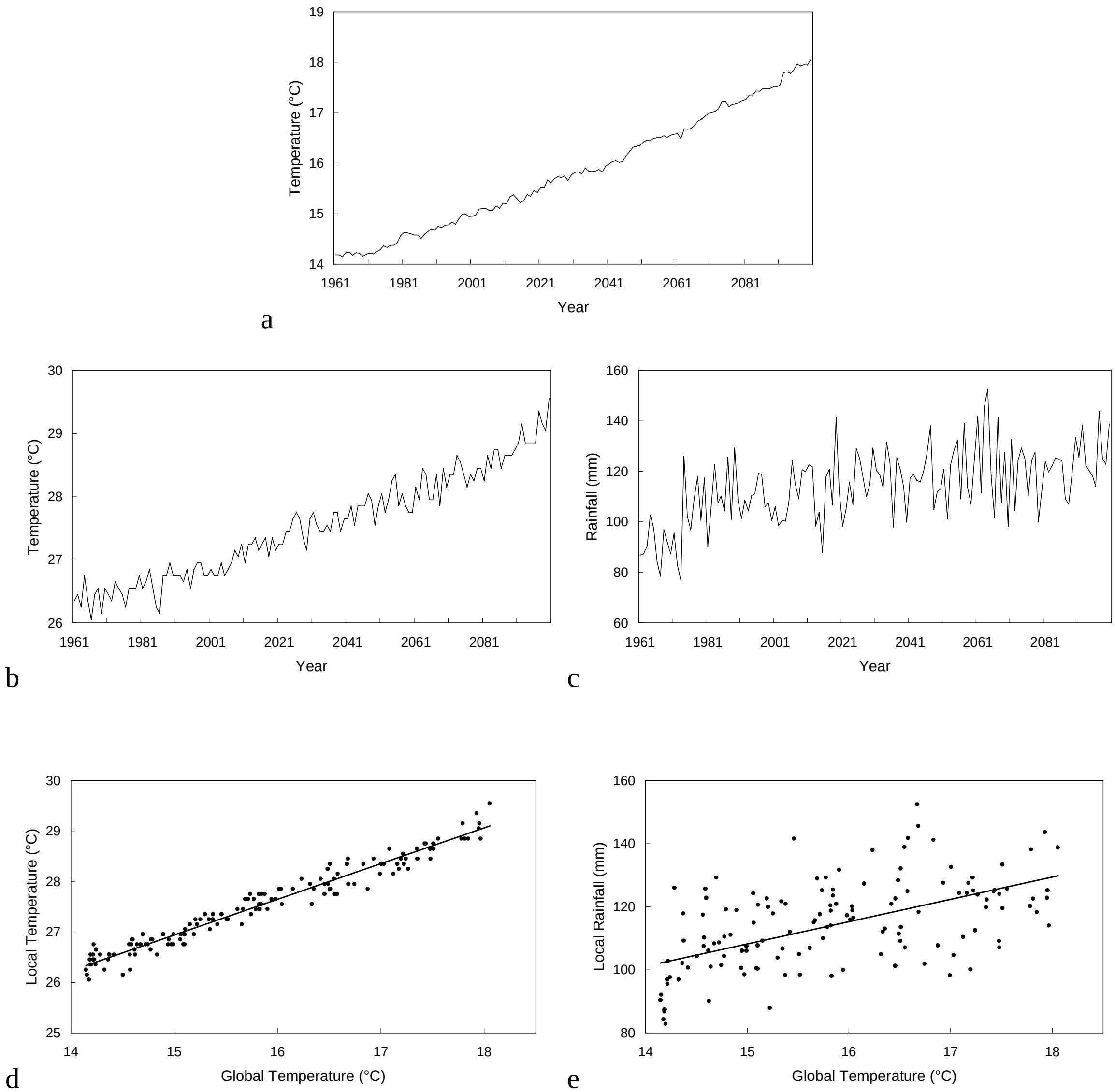


Figure 4 (a) Global warming from the CSIRO Mark 2 greenhouse-gas-only run (in which DARLAM is nested). (b) Local warming for January from the grid box closest to Jabiluka as simulated by DARLAM. (c) Local rainfall for January from the grid box closest to Jabiluka as simulated by DARLAM. (d) Scatterplot of the relationship between global warming and local warming in January from (a) and (b) respectively. (e) Scatterplot of the relationship between global warming and local rainfall in January from (a) and (c) respectively.

The regression process standardises the regional response as a function of average global warming, removing the individual climate sensitivity of that particular model. It also removes most of the errors associated with the simulation of historical climate (as shown in figs 1 to 3), as the change relative to current climate is estimated, rather than the climate simulation itself.

The major advantages of this method are that:

- The entire period of simulation contributes to the construction of climate change patterns;
- Errors in the simulation of regional climate are not a part of the analysis; and
- Transitory and non-linear influences such as decadal-scale variability are removed from the climate change signal.

However, the removal of decadal-scale variability from GCM patterns means that it may need to be added at another stage of the analysis. This is investigated further in section 3.2.

3 Climate change in the Jabiluka region

3.1 Average regional warming

The models reproduce patterns of regional temperature reasonably well when grid box resolution is taken into account. Figure 1 shows the local detail where some models may be up to 2ºC too warm in the Jabiluka region. These errors do not factor in the calculation of warming patterns under climate change. The pattern of warming in each model shows greater changes inland than on the coast because the land heats faster than the ocean. This creates a gradient of warming from the ocean, which usually warms at <1ºC per degree of global warming to inland, which warms at >1ºC per degree of global warming.

To create a standard comparison for each model, temperature change per degree of global warming was regridded from the original model grid network and averaged over a 2×2º box, with the coordinates of 11.5–13.5ºS and 132–134ºE, centred over Jabiluka. These results reflect the buffering effect of the Arafura Sea on projected temperature in the Jabiluka region, limiting local warming at, or just below, the level of global warming. They are presented in table 2.

Table 2 Values from 11.5–13.5°S and 132–134°E of temperature change per degree of global warming from six climate models

Change per degree of global warming	DARLAM 125	CSIRO Mark2 (GHG only)	CSIRO Mark2 (sulphates)	DKRZ	Hadley Centre	Canadian CCMA
Annual average	0.86	0.89	0.92	1.01	0.93	1.00

When the regional temperature increase is calculated by multiplying the projected range in global temperature (0.4–0.8ºC) by the extremes of regional temperature change per degree of global warming given in table 2, a range of 0.35–0.8ºC results (rounded to the nearest 0.05ºC). This range is calculated from a baseline of 1990. The observed warming trend for northern Australia since 1910 is 1.04ºC per century, or 0.1ºC per decade (Bureau of Meteorology, unpublished data). The low end of the projected range for 2030 is comparable with the historical rate of increase if it persisted unchanged from 1990 until 2030.

The historical increase in temperature is part of a global phenomenon that is consistent with projections of global warming. Based on the statement from the IPCC (1996) that *climate is expected to change in the future*, this rate of change may continue to a greater or lesser degree, consistent with the regional warming projections presented above. However, it is still premature to conclusively attribute the observed historical warming trend to the enhanced greenhouse effect (Suppiah et al 1998).

3.2 Seasonal rainfall change

GCM output has been used to create regional projections of seasonal rainfall over the next 30 years as described in section 2.2. The Dry season is taken as the May to October half year and the Wet season is the November to April half-year. An 87-year record of historical rainfall from the Oenpelli station, 25 km from Jabiluka, has also been analysed to determine the relative influence of decadal-scale climate variability. Both have been used to create scenarios for rainfall over the next 30 years for the Jabiluka region.

Given the coarse resolution of climate change models in table 1, they broadly reproduce patterns of rainfall over northern Australia (figs 2 & 3), although the Wet season is not so well simulated (fig 3). Simulated rainfall change per degree of global warming for each model was regridded and averaged over a 4×5º box from 11–15ºS and 130.5–135.5ºE over Arnhem Land. The results are presented in table 3.

As shown in table 3, the largest increase in Wet season rainfall is 1% per degree of global warming, with decreases of up to 8%. The Dry season produces much more variable results, ranging from an increase of 8% to a decrease of over 60%. The Dry season changes are less important for annual rainfall than those for the Wet season, due to the Dry's relatively low average rainfall.

Multiplying the projected global temperature change from 1990 to 2030 of 0.4–0.8ºC (IPCC 1996) with the range of Wet season rainfall change per degree of +1% to -8% for the Wet season (table 3), produces a range of change by 2030 of +1% to -6%. For the Dry season, a similar procedure produces a range of change in seasonal rainfall of +6% to -50% change in 2030. While more dramatic, these projected changes are less important, due to the low total rainfall during the Dry season.

Table 3 Rainfall change per degree global warming in percent from six climate models averaged over 11–15°S and 130.5–135.5°E for each month and the half-yearly periods, May to October and November to April

Month	DARLAM 125	CSIRO Mark 2 (GHG only)	CSIRO Mark 2 (sulphates)	DKRZ	Hadley Centre	Canadian CCMA
January	4	4	-3	1	-7	4
February	-6	2	6	2	1	2
March	7	9	5	-5	-15	1
April	14	1	5	-18	-12	0
May	11	12	5	-45	-18	-1
June	5	4	4	-62	-19	-2
July	6	-2	-11	-63	-17	-1
August	5	0	5	-65	4	-3
September	17	7	10	-71	-4	-5
October	5	1	5	-62	-22	-3
November	0	-8	0	-14	-22	-1
December	-4	-8	-3	2	-14	0
May to Oct	8	5	4	-63	-15	-4
Nov to Apr	1	1	1	-3	-8	0

The confidence in the projection of Wet season rainfall largely depends on the assessed ability of GCMs to simulate changes in the Australian monsoon. All the models in table 3 produce little change or decreases, a result consistent with that from Suppiah et al (1998b), who state that no coupled GCM they looked at had produced an increase in Wet season rainfall. Despite the models in figure 3 mostly being able to simulate the broad pattern of the Australian monsoon there may be many important influences being lost, especially those caused by sub grid-scale processes and northern hemisphere influences (eg Suppiah et al 1996). The Australian monsoon is smaller than most similar systems and appears to be more difficult to capture in dynamic models. Therefore, the confidence invested in the outcome is low. It is possible that the Australian monsoon may become wetter under climate change, despite not being predicted by any of the climate models used.

3.3 Historical rainfall trends and variability

The Oenpelli rainfall record was inspected to show historical rainfall trends and rainfall variability. The Oenpelli rainfall station is a member of the historical rainfall data set for Australia, one of a number of stations that have passed a series of exhaustive screening tests for data quality (Lavery et al 1997). As such, it is largely free of systematic errors. Annual average rainfall for Oenpelli from 1911–1997 is shown in figure 5. It shows significant decadal-scale variability as shown by the 10-year moving average and a positive trend of 1.7 mm pa that is not statistically significant. The average annual rainfall over the full period is 1390 mm. Decadal-scale variability as measured by the 10-year moving average which reaches extremes of ±15% of the long-term average.

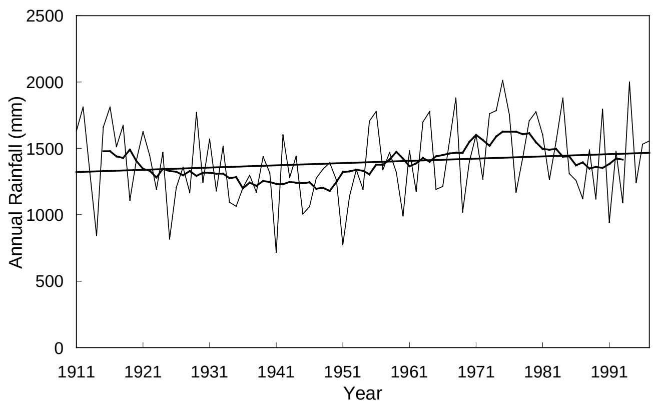


Figure 5 Average annual rainfall from Oenpelli 1911–1997, showing a 10-year moving average and linear trend of 1.7 mm pa

The non-stationarity of climate records, eg that the mean is not fixed over the life of a time series, is a major issue when dealing with climate change, particularly hydrological change (Matalas 1997). The global temperature record may already show non-stationarity, although it is still being debated as to whether the recorded increase has exceeded the rate of natural variability. Figure 5 shows that global warming can force the direction of rainfall change, so the positive rainfall trend at Oenpelli may be due to the historical increase in temperature. However, this trend is statistically non-significant and lies well within the range of historical variability. Despite this, it is possible there is an element of forcing within the historical rainfall record operating below the level of statistical significance.

If the historical trend of 1.7 mm pa indicated in the Oenpelli record were to continue until 2030, this would result in a 4% increase over the historical average. As the persistence of historical trends is possible (with or without a component of climate change), an increase of 4% for both seasons by 2030 is assumed to be a plausible scenario. As such, it is a valid addition to the data in table 3, and is used in creating regional projections for rainfall.

As the record from Oenpelli shows, both decadal-scale variability and trend influence the incidence of high annual rainfall. The wettest years occur when the 10-year running average is greater than the long-term average and vice versa for the driest years (fig 5). Both processes, long-term trend and decadal-scale variability, can increase the risk of high rainfall. The interactions of both processes are assumed to be independent, but where both increase together, the risk of extreme rainfall will be highest.

Figure 6 also depicts the broad envelope of interannual or year-to-year rainfall variability over the historical record. If this changes, annual extremes will also change. In Australia, such extremes are associated with the El Niño-Southern Oscillation (ENSO) phenomenon, where the La Niña phase results in high annual rainfall in the study area, and the El Niño phase, low rainfall. As modelling studies are indicating the continuation of the ENSO oscillations under greenhouse (Timmerman et al 1998, Wilson & Hunt 1997), it is assumed that current interannual variability continues unchanged in the scenarios presented here. Further work is needed to determine how ENSO under climate change is likely to affect future interannual variability.

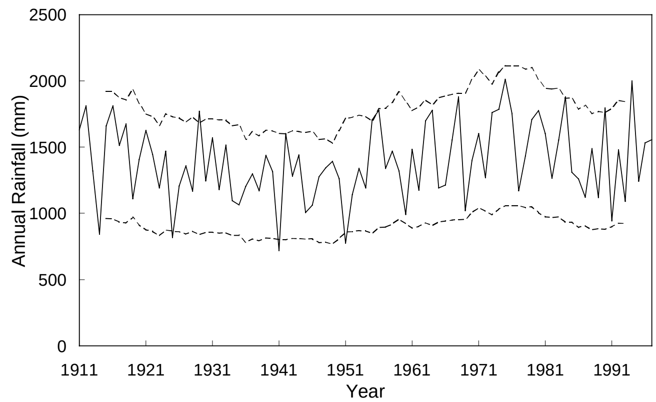


Figure 6 Average annual rainfall from Oenpelli 1911–1997 showing the envelope of interannual (year-to-year) variability

3.4 Decadal-scale rainfall variability

As mentioned in the Introduction, and illustrated by figure 4c, decadal-scale rainfall variability is an important factor within climate change and needs to be addressed during scenario construction (Hulme et al 1999). Accordingly, a 1000-year sample of the artificial rainfall data generated and used by Chiew and Wang (1999) in assessing surface water storage at the proposed Jabiluka mine site, was analysed to determine whether the decadal-scale variability observed in the historical record was reproduced. If so, climate scenarios produced for the Jabiluka region do not require a component of such variability.

Chiew and Wang (1999) generated a long sequence (1.5 Ma) of artificial daily rainfall data based on daily and monthly statistics for the Oenpelli record. They report good correspondence between the historical and artificial record on the daily to annual timescale. A 1000-year sample from that sequence was analysed to determine how well decadal scale variability was reproduced.

An 87-year sample of the artificial record (the same length as the historical series) is shown in figure 7. This sample shows decadal-scale variability of a similar magnitude to that of the historical series (fig 5) but without the same regularity. The coefficient of variability of the 10-year moving average for the 1000-year sample is 6.0±4.2% while for the historical series it is 6.5±4.1%. The long-term average of the sample shown in figure 6 is trending upwards at 1 mm pa, similar to the historical series at 1.7 mm pa, but the record contains three simulated rainfall totals that exceed the historical maximum of 2012 mm in 1976. This may be due to the positively skewed distribution of annual rainfall in the sample of the artificial series generated and analysed by Chiew and Wang (1999).

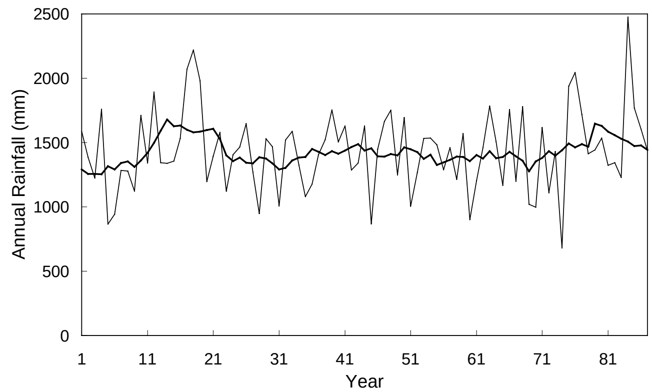


Figure 7 87-year sample of artificially generated annual average rainfall based on daily and monthly historical rainfall statistics for Oenpelli (Chiew & Wang 1999)

The rainfall data artificially generated for the hydrological design of water storage facilities at Jabiluka (Chiew & Wang 1999) includes realistic decadal-scale variability. Therefore, while decadal-scale variability is important, its inclusion into climate change scenarios for 2030 is not required if they are to be used to scale the artificially generated rainfall data of Chiew and Wang (1999) for further hydrological modelling. The methodology used in scenario construction is described in the next section.

4 Scenario construction for the Jabiluka region

Dry and Wet season climate change scenarios for 2030 have been created. These are probability matrices of temperature and rainfall, taken from the ranges in tables 2 and 3, and the 4% historical trend for rainfall from Oenpelli, summarised in table 4.

Table 4 Ranges of temperature and rainfall used in scenario construction for Jabiluka at 2030

Global temperature (°C)	Local temperature (°C)	Wet season rainfall (%)	Dry season rainfall (%)
0.4 to 0.8	0.85 to 1.0	-6 to +4	-50 to +6

A scenario probability matrix can be constructed by assuming that the ranges of uncertainty for variables contributing to a projected change in climate are either statistically independent, or that a relationship of dependence is known. Under the IPCC, it is generally assumed that a range of uncertainty constructed using two or more component ranges of uncertainty has a uniform probability distribution, ie extremes are as likely to occur as the median value (eg IPCC 1996). However, as demonstrated in Jones (1998), if these component ranges are independent, then the range of distribution is not uniform but is peaked around an average value. When this procedure is carried out for two variables, the resulting scenario probability matrix has the most likely outcomes close to the centre and the least likely at the extremes (Jones 1998).

Monte Carlo (ie random) sampling across the range of global warming of 0.4–0.8ºC for the year 2030 was multiplied by similarly sampled ranges of local change per degree global warming for both temperature and seasonal rainfall (table 4). Probability matrices for both the Dry and Wet seasons were created. The resultant matrices for both November to April and May to October are shown in figures 8a and b. The line of the outermost contour is the 95% level, so that 95% of all projected future climates lie within that contour.

The construction of probability matrices for climate scenarios raises two major issues:

1. What is the probability of occurrence over the entire range of possible climate change given that not all the uncertainties could be included here (eg rapid climate change)?
2. What level of probability represents the most appropriate use of the precautionary principle?

The precautionary principle recommends the hedging of risks in circumstances where full scientific certainty cannot be established. The FCCC states that: *Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing the mitigation of the adverse effects of climate change*. In this study, the precautionary principle is applied where a climate change scenario can be quantified, although it is recognised that not all possible climate changes can be quantified using current knowledge. This point is expanded upon in the Discussion (section 6).

The precautionary principle has a bearing on the choice of scenario for hydrological modelling. Because of the large range of possible rainfall change it might be tempting to nominate the mid-point of that range (which is negative in both the Dry and Wet season). However, figures 8a and b show that climate changes by 2030 include the possibility of both rainfall increases and decreases.

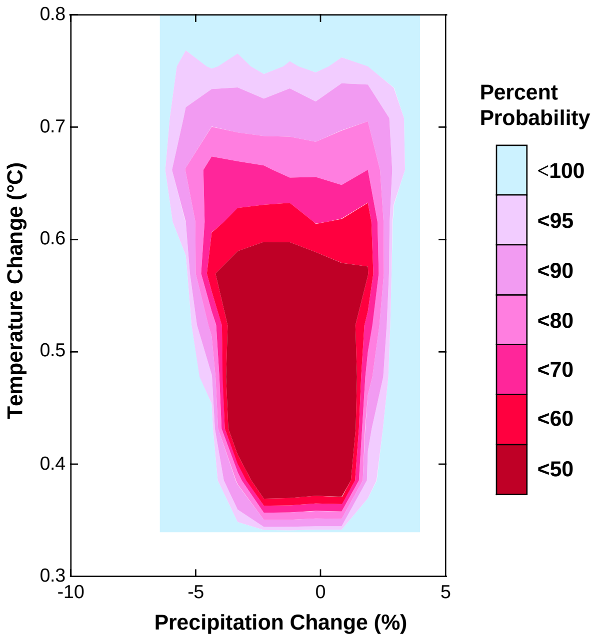
For the containment and evaporation of surface runoff, the greatest risks are associated with a scenario that has low temperature (hence low evaporation) and high rainfall. This covers the area in the lower right hand of figures 8a and b. Due to the relatively small changes in global warming by 2030 (<1ºC), the forcing of rainfall change is small in terms of percentage change per degree of global warming, except for possible decreases during the Dry season.

A scenario for 2030, based on a conservative interpretation of sections 3.1 and 3.2, and figures 8a and b, indicates that the minimum local warming in 2030 is likely to be between 0.35–0.4ºC projected from a base year of 1990. Average local rainfall change from 1990 to 2030, due to global warming, is +4%. The probability of climate being warmer and drier than this scenario,

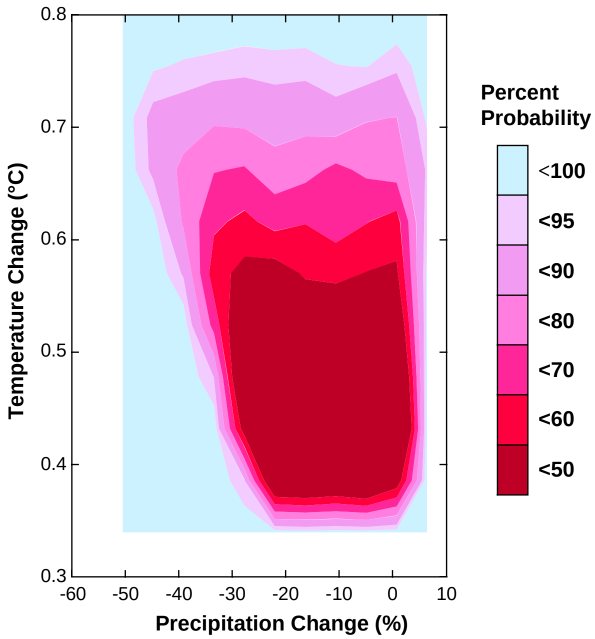
which was calculated during the construction of the probability matrices in figures 8a and b, is 98%. The wettest rainfall was chosen, as the confidence expressed in the range of regional rainfall change is low and, although not indicated by the climate models here, a larger increase in annual rainfall cannot be ruled out.

This scenario has not been incorporated into the hydrological modelling by Chiew and Wang (1999). Inspection of the 1000-year sample of artificial rainfall data generated by Chiew and Wang (1999) shows that in addition to realistic decadal-scale variability, it contains trends that are comparable to the historical trend over an 87-year timescale. Therefore, a 3% increase in average rainfall over the next 30 years is likely to be contained within the trends already sampled and applied in the hydrological modelling of Chiew and Wang (1999). Further hydrological modelling would only be justified if evidence from new climate simulations showed that greater rainfall increases than those quantified here were likely.

Despite this, due to the low confidence in the sign of rainfall change, it would be prudent to monitor rainfall trends in order to obtain an early warning of possible increases in mean rainfall. This could cover either of two cases: a positive change in the mean, where the local increase per degree of global warming exceeds the historical increase, or an unpredicted rapid climate change. Either of these changes may require the revision of the 0.01% probability rainfall calculated by Chiew and Wang (1999). Recommendations along these lines are presented in the conclusions.



a



b

Figure 8 Scenario probability matrices for temperature and rainfall in the Jabiluka region for the (a) November to April and (b) May to October half years. Results are change from a base year of 1990. Global warming is from IPCC (1996) and regional warming and rainfall data are from table 4. (NB: the jagged appearance is an artifact of the sampling process and does not affect the results.)

5 Extreme rainfall events

5.1 Daily rainfall intensity

Output from CSIRO's regional climate model (DARLAM) has been analysed to provide estimates of changes in extreme rainfall events. DARLAM has the highest spatial resolution of all the models available, therefore is likely to produce the most realistic simulations of daily rainfall variability. Daily total rainfall in grid boxes 125 km in size covering the Indo-Australia-Pacific region is available for the years 1961–2100. The model is nested in the CSIRO Mark 2 greenhouse-gas-only coupled GCM forced by the IS92a emission scenario (table 1).

To estimate possible changes in extreme daily rainfall near Jabiluka by the year 2030, the magnitude and frequency of extreme events has been compared for two 40-year periods: 1961–2000 (current climate) and 2011–2050 (centred on 2030). Results for the area of 11–15ºS and 130.5–135.5ºE, centred on Jabiluka, are used to give regional averages, which is the same domain used for calculating rainfall changes in table 3.

Figure 9 shows return periods for simulated extreme daily rainfall events, assessed on an annual and seasonal basis. The return period is defined as the average time between events of the same magnitude. For example, in the annual plot, an event of 126 mm day^{-1} is equalled or exceeded four times in the 40 years from 1961–2000, so it has a nominal return period of 10 years. During 2011–2050, an event of 134 mm day^{-1} has a 10-year return period. Therefore, the intensity of the 1-in-10 year event increased by 6%. Increases of 5–12% occur for other return periods (table 5). Alternatively, the present 1-in-10 year event (126 mm day^{-1}) becomes a 1-in-7 year event by around 2030 (a 43% increase in frequency). These increases in extreme rainfall occur despite a slight decrease in annual average rainfall. Such behaviour has been found in other modelling studies (Hennessy et al 1997, 1998).

In summer, the wettest season, average rainfall decreases by 4.5% but the intensity and frequency of extreme rainfall increases (table 5). For example, the intensity of the 1-in-10 year event increases by 4%, or the present 10-year event becomes a 9-year event by 2030. The decrease in average rainfall accompanied by increases in extreme rainfall events means that the frequency of small to moderate events must decrease. This is implied in table 5 where the shorter return period events increase in intensity by less than the larger events, suggesting probable decreases in the strength of events with return periods of less than 1 year. Hence the heaviest summer storms become stronger, and small to moderate rain events become weaker.

Autumn average rainfall increases by over 30%. This is associated with a 24% increase in the intensity of the 1-in-5 year and 1-in-10 year events, and a 13% increase in the 1-in-20 year event. The frequency of extreme events of a given magnitude is approximately doubled by the year 2030 (fig 9). Despite a 16% increase in total rainfall, increases in extreme winter rainfall of 0–8% are generally weaker than those simulated in the other seasons. The present 10-year event becomes an 8-year event by 2030 (fig 9). In spring, increases of 4–11% in extreme rainfall intensity contribute to an 11% rise in average rainfall. The present 10-year event becomes a 7-year event by 2030 (fig 9).

On an annual basis, DARLAM simulates little change in average rainfall over Jabiluka by the year 2030, but extreme rainfall becomes about 10% stronger and the present 1-in-10 year event becomes a 1-in-7 year event. Even in summer, when average rainfall decreases by 5%, extreme rainfall still increases by about 5% and the 10-year event becomes a 9-year event. The largest changes occur in autumn when it becomes about 30% wetter on average, extreme rainfall intensities rise by up to 24% and extreme events double in frequency. In winter and spring, average conditions become about 15% wetter, extreme events strengthen by about 5%, and the 10-year event becomes a 7–8-year event. These changes point to a tendency for enhanced storm activity over Jabiluka by 2030, leading to increased risk of flooding. Storm intensity is only likely to decrease if there are large decreases in average rainfall.

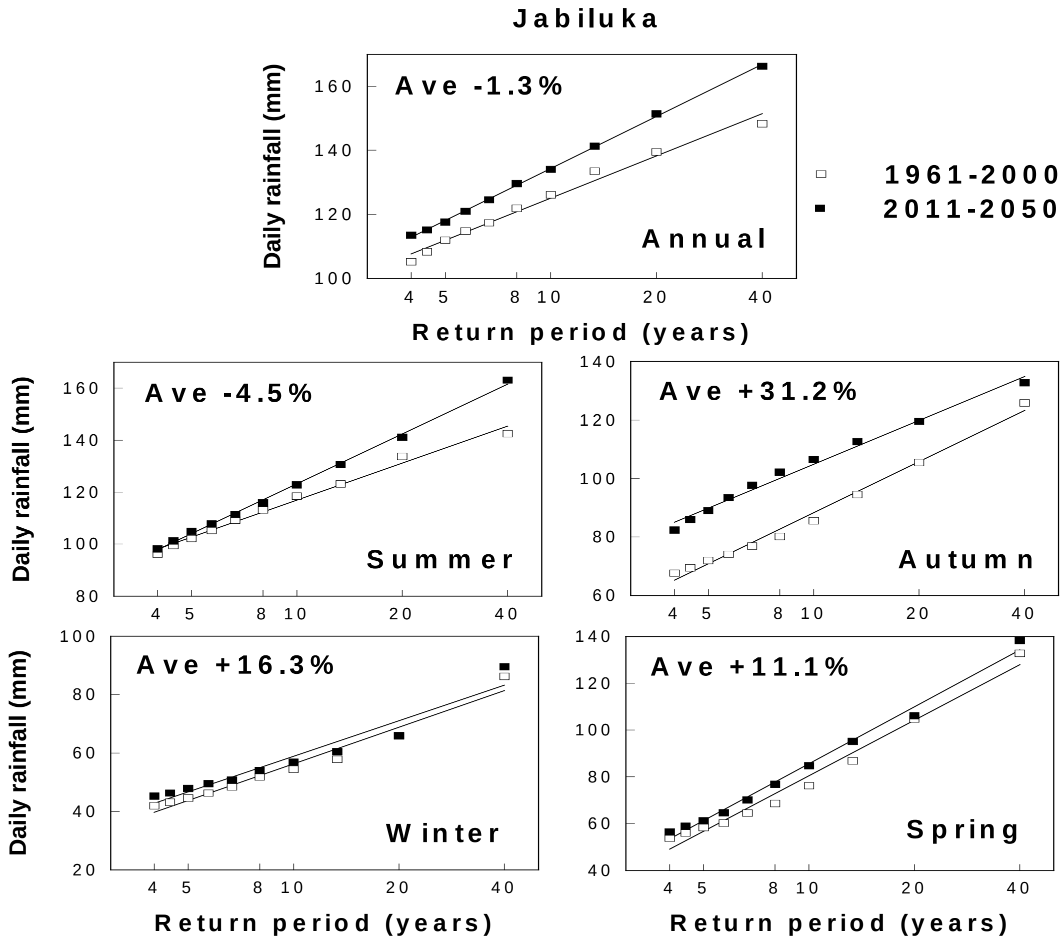


Figure 9 Annual and seasonal extreme rainfall return periods simulated by DARLAM over Jabiluka. Open squares are for the present climate (1961–2000) and solid squares are for 40 years centred on the year 2030. Percentage changes in average rainfall (Ave) are also shown.

Table 5 Percentage changes in annual and seasonal average rainfall simulated by DARLAM for the years 2011–2050 relative to 1961–2000. Percentage changes are also shown for the intensity of extreme daily rainfall events with return periods of 5 to 40 years.

Event	Annual	Summer	Autumn	Winter	Spring
Average	-1.3	-4.5	+31.2	+16.3	+11.1
1-in-5 year	+5.1	+2.7	+23.7	+7.5	+5.0
1-in-10 year	+6.3	+3.7	+24.4	+4.4	+11.2
1-in-20 year	+8.5	+5.5	+13.3	0	+1.4
1-in-40 year	+12.1	+14.5	+5.4	+3.8	+4.2

These changes are typical under enhanced greenhouse conditions where there is little change or an increase in rainfall. Similar changes have also been observed over the historical period (Suppiah & Hennessy 1998). They show an increase in intensity in the 90^{th} and 95^{th} percentiles of daily rainfall during the Dry and Wet season at Oenpelli (Gunbalunya) and Katherine, east and southeast of Jabiluka, although these are not statistically significant. This shows that current trends and model-based projections of increases in daily rainfall extremes are consistent.

Due to large uncertainties associated with rainfall simulation, the above results should be interpreted as indicating that increases in daily rainfall intensity are likely, rather than being quantitative projections. Such increases, however, will not have a large effect on the design of the retention pond at the Jabiluka mine site due to the high runoff coefficients on the site (Chiew & Wang 1999). These high coefficients result in most of the runoff simulated under current climate being diverted into the retention pond, making annual total rainfall change a much more important factor in pond design than daily rainfall intensity.

5.2 Probable Maximum Precipitation (PMP)

Introduction

Probable Maximum Precipitation (PMP) is the upper bound for rainfall at a site that is a single, deterministic number governed by physical principles that would never be exceeded (Abbs & Ryan 1997a). This section examines current methods for estimating PMP and the relationship between increased levels of atmospheric moisture expected under climate change and the estimation of future PMP. The discussion is based on the results of a numerical modelling study of extreme rainfall events published by Abbs and Ryan (1997a) in a report for the Urban Water Research Association of Australia (UWRAA).

In that study, Depth-Duration and Area (DDA) curves were calculated for periods of 2, 24, 48 and 60 hours and for a minimum area of 50 km^2 for four storms. In contrast, the Bureau of Meteorology (1999) provides a series of estimates of PMP at Jabiluka ranging from 6 minutes to 72 hours for an area of <0.2 km^2. The conclusions from Abbs and Ryan (1997a), as outlined below, have implications for the methods used by the Bureau of Meteorology (1999) and for the estimation of PMP under climate change. However, they do not provide an operational replacement for current methods (Abbs & Ryan 1997a).

Model simulations

The extreme rainfall events investigated by Abbs and Ryan (1997b) comprised two southeastern Australian storms representative of the Generalised Southern Australia Method (GSAM), and two tropical cyclones representative of the Generalised Tropical Storm Method (GTSM). For each case study, control and increased moisture simulations were performed. The increased moisture simulations were used to investigate the effects of increasing atmospheric moisture availability on the precipitation produced by a particular storm. Moisture values in the model were increased by uniformly raising atmospheric temperatures while maintaining constant relative humidities. The system under investigation remains in dynamic balance, but the specific humidity, and hence the surface dewpoint temperature and precipitable water, are increased.

This method is comparable with the technique used to maximise storms in the current PMP approach used by the Australian Bureau of Meteorology that provides the basis for the GTSM approach used by the Bureau of Meteorology (1999). However, there is an important difference: the initial atmosphere in the Abbs and Ryan (1997a) model is not necessarily saturated while that used by the Bureau is assumed to be saturated through the depth of the atmosphere.

Outcomes

Five conclusions, with implications for the estimation of PMP, may be drawn from Abbs and Ryan (1997a).

1. As the moisture availability is increased, the precipitation efficiency (the ability of the storm to convert moisture into rainfall) of the storms does not change significantly. For each case study presented, the production of heavy rainfall (rainfall rates greater than 25 mm hr^{-1}) is between 80% and 100% efficient. This supports the simple model that assumes implicitly that extreme precipitation storms have the highest efficiency.

2. As the moisture availability is increased, the duration of the heavy rainfall increases, begins earlier and is more continuous. Storm life cycles are not considered in the simple model. However, the results presented in Abbs and Ryan (1997a) and the recent paper of Zhao et al (1997) suggest that the duration of the storm increases with moisture availability. An increase in the duration of heavy rainfall will result in higher total rainfall.

3. As the moisture availability changes, the area over which more than 50% of the total rainfall falls as heavy rainfall also changes. Zhao et al (1997) also found that the areal coverage of rainfall varies nonlinearly with the precipitable water.

4. If the depth-area curve for the increased moisture simulation lies above that of the control simulation then the maximisation relationship of the current PMP technique under-estimates the precipitation, compared with that simulated by the model. The simulations reported in Abbs and Ryan (1997a) indicate that this may occur and hence the precipitation is not linearly related to the precipitable water. For the case studies presented in that report, the model may produce between 15% and 35% more precipitation than the current storm maximisation technique for areas of 50 to 70 km^2. For areas of 500 km^2, the model may produce between 5% and 15% more precipitation than the current storm maximisation technique. It should be noted that in some instances the model produced less precipitation than the current storm maximisation technique.

5. The topography affects the distribution of the precipitation due to feedback effects to the dynamics of the storm system.

Implications for PMP estimates for Jabiluka

Before proceeding, it is important to note that the above outcomes are based on the conclusions of a study (Abbs & Ryan 1997a) that has modelled storms over areas much larger than covered by the Jabiluka Mine site, are for a minimum duration of two hours, and where two of the storms modelled are not representative of the Jabiluka area. However, based on the conclusions summarised above, it is possible that PMP estimates for Jabiluka (Bureau of Meteorology 1999) may be underestimated.

High-resolution modelling studies show that the precipitation may increase as the temperature and dewpoint temperature increase (Abbs & Ryan 1997b). Section 3.1 indicates that the Jabiluka region is likely to experience an average warming of between 0.35 and 0.8ºC by the year 2030. It is difficult to assess how these temperature changes may affect the PMP of the region without also knowing how maximum 24-hour persisting dewpoint temperatures change. These data can be extracted from climate models but this has not yet been attempted. If it is assumed that the maximum 24-hour persisting dewpoint temperatures do indeed increase, then the estimated PMP for the region will also increase. This revised PMP may also be underestimated by up to 35% for durations greater than 2 hours and for areas of 50 to 70 km^2, as discussed above.

High resolution modelling studies of extreme rainfall also show that as the atmospheric temperature increases, the duration of the heavy rainfall (rainfall rates greater than 25 mm/hr) increases, begins earlier and is more continuous (Abbs & Ryan 1997b). This has obvious implications for the PMP as it means that the longer duration PMPs will become more important in the future. This is consistent with the findings for extreme daily rainfall shown in the last section. Further numerical modelling of extreme weather events, analysis of dewpoint temperatures from GCMs and high resolution modelling studies under climate change would be required before quantification of the impact of climate change on PMP could be attempted. Accordingly, no recommendations to change the estimates proposed by Bureau of Meteorology (1999) are made.

6 Discussion

This study presents regional projections of average temperature and rainfall for the Jabiluka region for 2030 and discusses possible changes to extreme daily rainfall and PMP values under climate change. To construct projections that are to be used in a planning sense, it is necessary to incorporate as many quantifiable uncertainties as possible. In this discussion, these uncertainties are outlined and accompanied by a measure of confidence, divided into three equal proportions of low, moderate and high confidence.

Global warming

The projections of global warming from IPCC (1996) incorporate ranges of uncertainty for greenhouse gas emissions and climate sensitivity. The IS92a–f emission scenarios cover a broad range of possible outcomes for CO_2 but are less comprehensive for CH_4 and sulphate aerosols (Alcamo et al 1994). Futures incorporating changes to CH_4 (decreases) and sulphate aerosols (decreases) not included under the IS92a–f scenarios are likely, but these effects will tend to cancel each other out. As the atmospheric forcing of CO_2 provides the majority of the climate forcing under climate change, this aspect is important, but not critical, and is currently being addressed by the construction of new scenarios for the IPCC. The IPCC (1996) estimate of climate sensitivity of 1.5–4.5ºC at CO_2 doubling is unlikely to be exceeded at the upper or lower limit. This range of global warming is given with high confidence.

Local warming

Six climate models, a suite of three CSIRO models and three other GCMs, were analysed to produce projections of regional warming. The model outputs ranged from 0.85–1.0ºC per degree of global warming over the Jabiluka region. Given that the variance between models is not large and the regional patterns produced by all models are similar, this group of models is thought to provide an adequate sample. The projected range of regional warming of 0.35–0.8ºC in 2030 from a baseline of 1990 is given with high confidence.

Local average rainfall

The same six models were analysed for regional changes to rainfall. The resultant patterns of rainfall were not consistent from model to model, so it is concluded that this group of models does not conclusively assess rainfall change. Two or three more models could have been added if extra time was available, but this may not have reduced the uncertainty. Rather, model improvements that provide more realistic simulations of the Australian monsoon are more likely to solve this problem. The ranges produced by the climate models and historical trends were -6 to +4% in the Wet season, and -50 to +6% in the Dry season. There is low confidence in the sign of rainfall change in the Jabiluka region as GCM simulations of possible changes to the Australian monsoon do not yet produce any robust outcomes.

Decadal-scale variability

Analysis presented in section 3.4 shows that decadal-scale variability is well represented in the artificial rainfall data generated by Chiew and Wang (1999). Therefore, the hydrologic modelling of current climate at the Jabiluka Mine site already undertaken by Chiew and Wang (1999) incorporates the changes to decadal-scale variability likely to occur to 2030.

Daily rainfall intensity

In a warmer climate, model outputs of daily rainfall from section 4.1 and other studies (eg Hennessy 1998) show that for a particular event, return periods tend to decrease where there is little change or an increase in average rainfall. These decreases will also be reflected in increased storm intensity. As yet, these results cannot be related to changes in average rainfall from different GCMs, so are difficult to quantify. Therefore, changes in daily rainfall that may alter the distribution of heavy rainfall events and the intensity of seasonal rainfall cannot presently be incorporated into data generation methods such as those used by Chiew and Wang (1999). There is a strong possibility that daily rainfall will become increasingly intense where average rainfall increases or remains constant, as this result is produced by a wide range of climate models.

Storm intensity

Storms may be expected to change in a similar manner to daily rainfall intensity due to increasing convective activity. However, this may not occur where there is a marked decrease in rainfall and also in some instances of no rainfall change. Section 4.2 concludes that the intensity of extreme events can increase if dewpoint temperatures increase with local warming, although this process is difficult to quantify. Increases in the duration of heavy rainfall with climate change will increase the importance of longer duration PMPs.

Rapid climate change

The possibility of rapid climate change occurring due to the enhanced greenhouse effect has been raised but cannot be quantified (IPCC 1996). As climate results from the interaction of a complex physical and dynamical system, the dynamics of complexity imply that non-linear changes are possible in response to a regular forcing, such as that provided by the enhanced greenhouse effect. Such responses are not predicted by the current generation of models and may be inherently unpredictable.

Rapid climate change has rarely been identified in the Australian region, a study by Jones et al (1997) being an exception, where a number of rapid changes in precipitation/evaporation ratio affecting lake levels have been noted in western Victoria over the Holocene period (past 10 000 years). At least some of these changes occurred within the space of a few decades. As the climate of northern Australia is strongly influenced by the surrounding ocean (Suppiah et al 1998a), rapid climate change if it occurs may be expressed through a reconfiguration of the ocean currents surrounding Australia, or altered patterns of sea surface temperature. Rapid climate change can be considered as a low probability/high impact outcome that cannot currently be quantified.

7 Conclusions

For the Jabiluka project area:

- Local warming in 2030 is likely to be between 0.35–0.8ºC as projected from a base year of 1990.
- Average local rainfall change due to global warming by 2030 is -6 to +4% in the Wet season, and -50 to +6% in the Dry season as projected from a base year of 1990. These changes are likely to be accommodated within the long sequences of artificial rainfall data already generated by Chiew and Wang (1999), and used in hydrological modelling.
- Decadal-scale rainfall variability, that can outweigh changes due to the enhanced greenhouse effect over the short term, is adequately simulated by the method of Chiew and Wang (1999).

Recommendations

- Where an activity is vulnerable to climate and climate change, its planning horizon extends several decades into the future, and historical climate averages are used in simulations aiming to reduce that vulnerability, non-stationary climate data incorporating a range of projected climate change should be used in planning.
- Methods for incorporating non-stationarity into climate series, including those adopted here, should be further researched and improved upon to better address the previous point.
- If, during the life of the Jabiluka project, the 10-year moving average exceeds 1600 mm (+15% above the mean), or annual rainfall exceeds previous records >2 years in 10, then hydrological modelling should be repeated to assess the new conditions. This should be based on a higher, more appropriate average rainfall (eg 1960 onwards) than that provided by the historical record.
- If a rapid climate change occurs due to events such as a reconfiguration of the ocean currents surrounding Australia, or altered patterns of sea surface temperature, then a dynamic climate model using the new conditions should be used to generate new rainfall data to drive adaptation assessments. If such an event occurred adaptations would be required, not just at Jabiluka, but right across the region affected. Such an event must be considered highly unlikely but possible.

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