MATHEMATICAL MODELLING RELATED TO THE
INTERNATIONAL GEOSPHERE–BIOSPHERE PROGRAM AT
THE CENTRE FOR RESOURCE AND ENVIRONMENTAL STUDIES

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INTRODUCTION

The aim of the research in CRES is to help identify and provide balanced analyses of resource and environmental policy problems, thereby facilitating the resolution of policy options. There has recently been a shift in emphasis away from analysis of specific national problems that can be treated in a short time frame, and hence mostly with existing knowledge and data. Research is now directed towards the construction of decision support tools for long-term acquisition of fundamental information of general use to a common core of resource and environmental problems of national and global concern. At the same time flexibility has been retained to consider important topical problems as they arise on the public policy agenda; attention to these motivates the long-term research program and makes it more robust.

The basic premise in the Centre's long-term research direction is that there are large gaps in the knowledge base for treating many resource and environmental problems, including impact assessment of the greenhouse effect. Research and decision support tools are required to address these gaps and in general they are intended to be climate sensitive and their predictions robust to changes in climatic-related inputs. Examples of the tools in continual development are geographic information systems to house essential spatial and temporal information in a systematic and accessible form and generic 'models', such as
those for environmental flow and solute transport, which can interpolate, extrapolate or predict with this information those quantities of prescriptive interest.

The form of any given model is highly dependent on the type of problem for which it is intended and the nature of the knowledge and data available for its construction and use. Many are physically based mathematical models often containing a stochastic element to account for uncertainty, but the models may also be more qualitative, particularly when the problem is set in a social science context. Exercises involving the construction, calibration and validation of models is called 'system identification', while exercises involving the running of models with inputs and already calibrated parameter values is called 'system simulation'. Most of the research time is spent on system identification.

In the following sections, some specific information and references are provided which illustrate the Centre's research effort and success in developing tools for climate impact assessment.

1. STREAM HYDROGRAPH SEPARATION

The unit hydrograph is the streamflow response of a catchment to a unit of rainfall excess, excess being that rainfall not lost through evapotranspiration. It is a fundamental catchment-scale property reflected in the streamflow. Jakeman, Littlewood and Whitehead [1, 2] have developed a conceptual model and procedure for characterising the unit hydrograph and for separating the quickflow response, which includes overland flow, and the slowflow response, which includes subsurface flows, to stream. Uses of the separation include the construction of baseflow indices for water quality potential and for inferring moisture content in the catchment. The approach has several attractive features which its competitors lack. It can be used for small catchments from short time series of rainfall, temperature and streamflow records with sampling intervals as short as one hour. Base flow separation is an integral component of model identification and unlike traditional methods, is related dynamically to the rainfall. All the available rainfall–streamflow data
can be used, avoiding the need to arbitrarily select clean, single-peaked events for analysis and contributing to model parameters with better definitions.

2. PREDICTING ENVIRONMENTAL EXTREMES

Extremes such as air pollutant and water pollutant concentrations which occur for short periods in an annual series are difficult to predict. Jakeman and Taylor [3] report details of a hybrid modelling concept developed in CRES to predict pollutant extremes from process-based model predictions of annual mean concentrations and a statistical appreciation of the parametric form of the frequency distribution of pollutant concentrations. The approach has been used in several studies to predict air pollutant concentrations from vehicle emissions and industrial sources (e.g. Jakeman, Simpson and Taylor [4]; Jakeman and Taylor [5]; Jakeman and Simpson [6, 7] and Taylor, Simpson and Jakeman [8, 9]). More recently, it has been applied to the prediction of water quality extremes (Jakeman et al. [10]) and in particular stream acidity variables.

3. GROUNDWATER SYSTEM IDENTIFICATION VIA INDIRECT METHODS AND RANDOM FIELD REPRESENTATION OF UNKNOWN PARAMETERS

The problem of groundwater system identification is an inverse problem in which unknown aquifer parameters (such as hydraulic conductivity) in the groundwater flow equation are inferred from data on piezometric pressure. Because data on such groundwater systems are typically scarce and unreliable, care must be taken in inferring aquifer parameters (Dietrich et al. [11]). Work is in progress on a random field representation of hydraulic conductivity that depends only on a few parameters describing essentially the small- and large-scale features of the porous matrix through which water flows. Parameter inference from water pressure data is then obtained via non-linear optimisation to best fit
the available data. Results of this work are to be used for a paper (Dietrich [12]) at an

Work has also commenced on reducing the operation count associated with solving
the groundwater flow equation in steady and unsteady state for those cases where the
hydraulic conductivity is smooth. Finite element discretisation is used. Among others, an
application of such an algorithm is the use of Monte Carlo type procedures for parameter
identification along the lines of a Generalised Sensitivity Analysis. An example of the latter
procedure is given in Jakeman et al. [13].

Among the set of parameters that need to be measured to model climatic effects on
an aquifer, recharge is possibly the most important and the one least known. In another
CRES project, the aim is to estimate effective recharge from head measurements and prior
information through an inverse procedure based on a maximum likelihood approach
stabilised by imposing constraints on the noise structure.

4. MATHEMATICAL MODELLING OF UPCONING AND SEAWATER
INTRUSION

Management of groundwater resources in coastal areas and isolated islands, where
groundwater is the major source of water supply and the aquifers are subject to intrusion of
seawater, is a delicate problem. The extent of this intrusion depends on many factors,
including aquifer geometry and properties, abstraction rate and depth, recharge rate and
distance of pumping bores from the coastline. Some of these factors can be affected by
changes in climate. Sophisticated tools are required to quantify the effect of these factors.

In this context, the ability of a two-dimensional mathematical model named
SUTRA, developed by the US Geological Survey in 1984, has been tested to simulate a
critical case in Nauru Island in the Pacific Ocean (Ghassemi, Jakeman and Jacobson
[14]). The methodology proved to be very successful in quantifying the sensitivity of the
aquifer to the type and level of abstraction and could be applied to coastal aquifers of
Australia. Data collection is in progress to identify the most suitable coastal aquifers in
Australia for the simulation approach. In the meantime, the performance of a
three–dimensional model named HST3D, developed by the US Geological Survey in 1987,
is under investigation. If tests prove successful, new opportunities will arise for more
accurate simulation of these problems.

5. CLIMATE CHANGE AND GROUNDWATER RESOURCES OF AUSTRALIA

Recent statistics published by the Department of Primary Industry and Energy
show that the annual runoff of the continent is about 397 billion cubic metres out of which
98.1 billion are divertible. Divertible fresh and marginally fresh groundwater resources with
salinity less than 1500 mg/L comprise about 22 billion cubic metres.

The annual water use in Australia is 15 billion cubic metres of which 70 per cent is
used for irrigation, 21 per cent is used for the domestic and industrial sectors and 9 per
cent for other purposes.

As a source of water supply, surface water contributes 82 per cent and groundwater
the remaining 18 per cent. Although the contribution of groundwater to total water use
seems relatively small, many areas, especially in arid and semi–arid, and even temperate
and tropical zones, are totally or at least heavily dependent on groundwater as a source of
water supply. While the country enjoys a substantial volume of undeveloped surface and
groundwater resources per head of population, these potential sources are not evenly
distributed and in many cases they are far from the major sources of demand.

To complicate this assessment, there is some evidence from climatological studies
that the pattern of Australian rainfall changed from the period 1913–45 to the period
1946–73. Rainfall increased in many areas, an exception being the southwest of Western
Australia where rainfall decreased. There was a southward shift in the region of
summer–dominated rainfall. Predicted climatic changes due to the accrual of greenhouse
gases from fossil fuel burning and other anthropogenic sources means that these trends may continue.

Climatic change of this nature will have major effects on the groundwater resources of the continent. CRES analysis by Ghassemi, Jacobson and Jakeman [25] argues that the effects will be beneficial in the arid and semi-arid areas and in areas where aquifers are under stress due to overdevelopment, such as many of the alluvial aquifers of Queensland and New South Wales. Effects will be detrimental in some other important areas such as the Perth and Murray Basins. In addition, rises in sea-level will increase the intrusion of seawater in coastal aquifers and will reduce the sustainable yield of freshwater in aquifers such as the Swan Coastal Plain (WA), Botany Bay and Tomago Sands (NSW), Western Port (Vic), Burdekin Delta (Qld) and Seven Mile Beach (Tas).

6. CLIMATE MODELLING

The greenhouse effect and the potential for climate change have attracted considerable attention from the Australian scientific community and the Australian public over the past few years (Taylor [15]). This interest has been prompted by the concern for the substantial impacts of climate warming on Australia and the world. In order to address these concerns and to coordinate research within the Centre, a versatile, modular and well-documented climate model was obtained from the United States National Center for Atmospheric Research (NCAR). In conjunction with the ANU supercomputer facility, the Community Climate Model (CCM1) code is being converted to run on the ANU Fujitsu VP-100 supercomputer. The code conversion will be completed in 1990. The model has been developed and used successfully by the United States university research community to conduct many diverse experiments which were seen to relate to each other when performed with the same model. The CCM1 has led to much constructive dialogue and collaboration between experts in several disciplines. In view of the successful application of the CCM1 in the United States and the large body of documentation of the model and
large number of scientific studies conducted with it, it is intended that the code will be made available to the Australian scientific community through the ANU Supercomputer Facility external grants scheme and through collaboration with ANU scientists.

7. GLOBAL TRACER TRANSPORT MODELLING

A major impediment to our understanding of the biogeochemical cycles of atmospheric trace gases that cause climate change has been the lack of high resolution three-dimensional global circulation models which can be used to identify the sources and sinks, including atmospheric chemistry, of these trace gases (Taylor [16]). In the past, even low resolution three-dimensional models have placed enormous computational demands on supercomputers. This project has involved the development of a computationally efficient high-resolution simulation model for atmospheric transport and chemistry with parameterised interactions between the oceans and the biosphere (Taylor [16, 17, 18, 19]; Taylor et al. [20]).

The basic approach of the stochastic Lagrangian model is to divide the atmosphere into 100,000 air parcels of equal mass. Trajectories for these air parcels are calculated using wind speed data derived from observed wind fields obtained from the European Centre for Medium Range Weather Forecasting. While the simulated air parcels are being transported around the globe they can exchange chemical species with the oceans, the biosphere and one another and receive industrial emissions of greenhouse gases.

An important aspect of this approach is the very high computational speed achievable on modern supercomputers. One-year model integrations are now achievable in a few minutes on supercomputers where once this would have taken hours. Model results, consisting of predicted atmospheric concentrations are currently analysed and displayed as colour animations on a Sun workstation at CRES.
The determination of the fluxes associated with the sources and sinks of CO₂ remains an important problem in the study of the global carbon cycle. The difficulties associated with obtaining precise quantitative estimates of the biospheric and oceanic exchanges of CO₂ with the atmosphere by direct measurement or from theoretical considerations has led a number of researchers to attempt to infer from modelling studies, employing the best available transport data, a set of fluxes consistent with the observations of CO₂ in the atmosphere.

Using the three-dimensional stochastic Lagrangian model and incorporating available estimates of the global distribution of anthropogenic CO₂ emissions and biospheric and oceanic exchanges of CO₂, a model of the global distribution of atmospheric CO₂ concentration was constructed (Taylor [16]). Model predictions were then compared with available observations.

From the model studies it was found that a flux from the oceans of 1.6 gigatonnes of carbon and biospheric growing season net flux of 6.5 gigatonnes were consistent with available observations. However, the assumption that large amounts of CO₂ were transported from the northern hemisphere to the southern hemisphere and then absorbed by the southern oceans below 45°S could not be supported.

This observation has important climatic implications. If the oceans are not absorbing as much CO₂ as previously thought, then the biosphere must be absorbing a large amount of CO₂. It is unlikely that the biosphere will be able to continually remove increasing anthropogenic releases of CO₂. This may lead to an increase in the rate of climate change. Alternatively, a different model of the spatial distribution of the uptake of CO₂ by the oceans may also explain the observed CO₂ concentrations. It was also found that above 60°N the predicted seasonal cycle associated with the biospheric release of CO₂ was inconsistent with the observed seasonal cycle. This may mean that carbon storage is occurring at these latitudes and that the model of CO₂ respiration needs to be revised.
9. GREENHOUSE GASES: METHANE AND METHYL CHLOROFORM

The sources and sinks of methane and methyl chloroform have also been investigated by incorporating models for their sources and sinks into the global tracer transport model (Taylor et al. [20]). Results indicated that available estimates of methyl chloroform emissions for the period 1981–84 were underestimated by 10–20 per cent or that the hydroxyl radical concentration had declined by a similar amount. Results of recent assessments of the release of methyl chloroform published after the completion of this study have confirmed the predicted releases of methyl chloroform. The much larger releases of methyl chloroform predicted by the model indicate that the release of this greenhouse gas is continuing to grow at a rapid rate.

Methane is a key chemical in the chemistry of both the troposphere and the stratosphere. Two source functions for the spatial and temporal distribution of the flux of methane to the atmosphere were developed. The first model was based on the assumption that methane is emitted from the biosphere as a proportion of net primary productivity (NPP). This model generated an estimate of the methane source term of 623 Tg CH₄, giving an atmospheric lifetime for methane of 8.3 years. The excellent performance of the NPP model for generating estimates of methane fluxes indicates that anaerobic oxidation closely follows the seasonal cycle of photosynthesis. The results also indicate that if methane fluxes are proportional to NPP, then any CO₂ fertilisation effect will lead to increasing releases of methane, further accelerating climate change produced by the greenhouse effect.

The second model identified source regions for methane from rice paddies, wetlands, enteric (intestinal) fermentation, termites and burning of biomass, based on high-resolution land use data. This methane source distribution resulted in an estimate of the global total methane source of 611 Tg CH₄, giving an atmospheric lifetime for methane of about 8.5 years. The most significant difference between the two models were predictions of methane fluxes over China and Southeast Asia, the location of most of the world's rice paddies.
10. ACCOUNTING FOR AUSTRALIAN CARBON DIOXIDE EMISSIONS

If policies to abate global warming are to be adopted, a major focus will be carbon dioxide emissions arising in fuel combustion. The proper analysis of policy options in this context will require an accounting of the sources of such emissions in terms of the ultimate purpose of the combustion, rather than in terms of institutional and structural location. It is not enough to know, for example, that \( x \) per cent of emissions arise in electricity generation. It is also necessary to know what electricity is used for, and to allocate the \( x \) per cent over those uses. This section of the paper briefly describes a methodology for such an end use accounting for carbon dioxide emissions, and reports results for Australia. The analytical potential of the methodology is also indicated. A fuller treatment of each of these matters is given in Common and Salma [21].

The objective is an exhaustive allocation of total emissions across a commodity/industry disaggregation of deliveries to final demand, which consists of consumption by households and government, capital and stock accumulation, and exports. These are regarded as the end purposes of economic activity. The appropriate methodology is input–output analysis. With

\[
y \quad = \quad \text{a vector of final demand requirements by commodity},
\]

\[
x \quad = \quad \text{a vector of gross output levels by industry},
\]

\[
A \quad = \quad \text{a matrix of technological coefficients for the industrial input requirements of industries for unit activity levels, and}
\]

\[
n \quad = \quad \text{number of commodities and industries},
\]

we have

\[
x = (I-A)^{-1} y = Ly
\]

giving the relationships between gross output levels and final demand deliveries, where the former comprise the latter plus production of inputs to other industries. Then with

\[
C \quad = \quad \text{a matrix of coefficients for primary energy inputs per unit of gross output by industry},
\]
\[ F = \text{a matrix of coefficients for primary energy inputs per unit of delivery to final demand,} \]
\[ e = \text{a vector of coefficients for carbon dioxide release per energy unit of fuel burned,} \]
we have
\[ T = e (Cx + Fy) = e (CLy + Fy) = e (CL + F) y = ty \] and
\[ z = t^* y \]
where \( T \) is total emissions, \( t \) is a vector the \( n \) elements of which are emissions per unit of commodity delivery to final demand, \( z \) is a vector of the total emissions attributable to each commodity, and \( t^* \) is an \( n \times n \) matrix with \( t \) along its diagonal and zeros elsewhere.

Implementation of this methodology for Australian carbon dioxide emissions requires data for \( e \), \( C \) and \( F \), and for \( L \) (known as the Leontief inverse) and \( y \). The source for \( L \) and \( y \) is input–output data. At the time of writing the most recent available was that for 1982/3, in ABS [22], and it is to that year that the results to follow relate. For reasons discussed in Common and Salma [21] it was necessary to modify the commodity/industry classifications used in ABS [22], and to set \( n \) equal to 27. This meant calculating \( L \) from reconstructed flow data rather than using the published table for this matrix. The elements of the matrices \( C \) and \( F \) were calculated from energy data for 1982/3 given in BRE [23]. Six primary fuels – black and brown coal, wood, bagasse, natural gas and oil – were used, so that \( C \) and \( F \) are \( 6 \times 27 \) matrices. The other primary fuels are solar and hydro, which give rise to no emissions, and uranium which additionally is not used in Australia. The vector \( e \) then has six elements, values for which were taken from AIP [24].

On this basis, total fuel combustion emissions in Australia for 1982/3 were calculated as 257340 kT. The corresponding figure for 1988/9, which can be derived without using the input–output data, is 318258 million kT. Figures 1 and 2 here give results obtainable only by way of the input–output approach. In Figure 1 the elements of \( t \) as defined by (2) above are shown, i.e. the height of a column gives the amount by which total emissions would increase (decrease) for a unit ($A million) increase (decrease) in the
Figure 1: Carbon Dioxide Intensity (kilotonnes/$Am).

Figure 2: Total Carbon Dioxide (million tonnes).

1. Gas
2. Electricity
3. Petroleum and coal products
4. Basic metals
5. Non-metallic minerals
6. Agriculture, forestry and fishing
7. Other food products
8. Chemicals
9. Fabricated metal products
10. Mining
11. Meat and milk products
12. Paper and paper products
13. Wood and wood products
14. Alcohol and tobacco products
15. Miscellaneous manufacturing
16. Construction
17. Machinery
18. Water
19. Transport and communications
20. Transport equipment
21. Textiles, clothing and footwear
22. Recreational services
23. Public administrative services
24. Financial services
25. Community services
26. Wholesale and retail services
27. Ownership of dwellings
delivery to final demand of the corresponding commodity. The columns in Figure 2 refer to the elements of $z$ as defined at (3) above, ie. they give the actual emissions attributable to commodity deliveries to final demand taking account of the unit carbon dioxide intensity from Figure 1 and the size of the deliveries made. Note that electricity here refers to electricity delivered to final demand, not to the total of electricity generated. That part of generated electricity which is not delivered to final users — households, government and exports — is allocated to the industries which use it. Similar remarks apply to the other fuels. Thus, the emissions attributed, for example, to Transport Equipment include those arising in fuel combustion taking place in that industry and those arising in the production of inputs, including secondary fuels, to that industry.

These results refer to emissions taking place in Australia. The emissions attributable to Australians are not those within the nation's boundaries, due to foreign trade. Some light can be shed on the distinction and its quantitative significance using the input–output methodology and data. Of emissions arising in Australia, some part is due to production for consumption overseas. This can be figured by repeating the calculations described above with the vector $y$ modified to exclude export deliveries. Then, emissions on account of exports are found to be 53924 kT. If it is assumed that the matrices $A$, $C$ and $F$ are applicable to overseas production, the intensity results in the vector $t$ can be applied to import value quantities to get a figure of 52651 kT for emissions arising overseas on account of Australian consumption. On this basis, Australia's carbon dioxide trade is approximately in balance. However, Australia exports coal to be burned overseas, the quantity involved in 1982/3 accounting for 167434 kT of carbon dioxide emissions.

With this data and methodology it is straightforward to compute the systemwide effects of postulated changes in technology or final demand, with reference to the 1982/3 data base. For example:

1. A 10 per cent reduction in the element of $C$ for primary fuel input to electricity generation reduces $T$ by 3.9 per cent;

2. A 10 per cent reduction in all 27 coefficients in $A$ for electricity inputs reduces $T$ by 4.2 per cent;
3. A 10 per cent reduction in all 27 coefficients in $A$ for basic metal inputs reduces $T$ by 1.4 per cent;

4. A 10 per cent reduction in the final demand for electricity reduces $T$ by 1.6 per cent.

11. SPATIAL AND TEMPORAL ANALYSIS OF ENVIRONMENTAL DATA FOR GREENHOUSE SCENARIO EVALUATION

Current analyses of greenhouse gas induced climate trends are largely based on the development of general circulation models (GCMs). While this approach has undoubtedly made a major contribution to our understanding of the underlying dynamics of the earth's atmosphere, the current spatial resolution of GCMs of at best a few hundred kilometres is recognised to be a serious deficiency. Reliable simulation of ocean and atmospheric dynamics is heavily dependent on having a detailed description of ocean bathymetry and surface topography, as well as having an accurate representation of the hydrological properties of the earth's surface. Computational limitations, as well as limits on the availability of suitably detailed surface and bathymetric data, have meant that GCMs have very little to say about projected regional climate changes at spatial resolutions of a few kilometres. However, it is only at this relatively fine resolution that useful conclusions can be made, especially with regard to the development of strategies for coping with climate change.

Generic (process based) spatial and temporal analysis techniques are being developed at the Centre for Resource and Environmental Studies. These techniques impact in a number of ways on the problem of generating regional greenhouse scenarios. Principal contributions are:

(i) procedures for accurately describing the spatial distributions of both current and projected climate;

(ii) the development of process based models of the dependence on climate of both natural and human related biological activity.
Aspects of these contributions are now briefly described.

11.1 SPATIAL ANALYSIS OF CLIMATE

Thin plate smoothing splines have been applied to Australia wide, terrain dependent, interpolation of climate (Hutchinson, [26]). The basic interpolation technique has been described by Wahba and Wendelberger [27] and, in an enhanced form suitable for larger data sets, by Bates and Wahba [28], Elden [29] and Hutchinson [30]. Thin plate smoothing splines determine an optimal balance between data fidelity and surface smoothness by minimizing the generalized cross validation, a reliable measure of the true predictive error of the fitted surface. A simply calculated stochastic estimator of the trace of the influence matrix associated with thin plate smoothing splines has also been recently described by Hutchinson [45]. This estimator is particularly useful for calculating the generalized cross validation when analyzing very large data sets.

<table>
<thead>
<tr>
<th>Variable</th>
<th>No. of data points</th>
<th>Standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar radiation</td>
<td>150</td>
<td>3%</td>
</tr>
<tr>
<td>Daily maximum temperature</td>
<td>900</td>
<td>0.2–0.4°C</td>
</tr>
<tr>
<td>Daily minimum temperature</td>
<td>900</td>
<td>0.3–0.5°C</td>
</tr>
<tr>
<td>Precipitation</td>
<td>10000</td>
<td>10–15%</td>
</tr>
<tr>
<td>Pan evaporation</td>
<td>300</td>
<td>5%</td>
</tr>
</tbody>
</table>

A major factor in the accuracy of Australia wide interpolated climate surfaces has been the incorporation of significant dependencies on elevation. This dependence is well known in the case of temperature, where elevation lapse rates of the fitted surfaces approximate the usually accepted value of about 6°C per km. However, both precipitation and evaporation also exhibit significant, if less systematic, dependencies on elevation. The number of data points and approximate standard errors of surfaces fitted to monthly mean
values of solar radiation, daily maximum and minimum temperature, precipitation and pan
evaporation are shown in Table 1. These variables are the principal climatic determinants
of plant growth.

11.2 DIGITAL ELEVATION MODELLING FOR CLIMATE AND HYDROLOGIC
ANALYSIS

Terrain plays a dominant role in determining the hydrological and environmental
characteristics of a landscape. In order to make use of the dependence on elevation
exhibited by the climate surfaces described above, a procedure for calculating regular grid
digital elevation models from surface specific point elevation data, contour line data and
stream line data has recently been developed by Hutchinson [31, 32]. The procedure
incorporates three principal innovations. The first is an efficient multi-grid, finite
difference interpolation algorithm which can interpolate many thousands of data points
according to a user specified roughness penalty. The second is a drainage enforcement
algorithm which automatically removes spurious sinks or pits in the fitted elevation grid, in
recognition of the fact that sinks are normally quite rare in nature. The third is an
algorithm which automatically calculates ridge lines and stream lines from points of locally
maximum curvature on data contour lines.

The drainage enforcement algorithm in particular has been found to significantly
increase the power of the interpolation technique, especially when data are relatively
sparse. It also facilitates the use of the calculated digital elevation models in hydrological
process studies which depend in part on the calculation of contributing catchment areas
(Abbot et al., [33]; Moore et al., [34]). This is also of significance in modelling soil moisture
regimes which strongly moderate plant growth, especially in the semi-arid conditions
which prevail over much of Australia.

11.3 CONSEQUENCES FOR GREENHOUSE SCENARIO ANALYSIS

The digital elevation modelling technique has been applied to the calculation of a
digital elevation model for Australia (Hutchinson and Dowling, [35]). The resolution of this
model is 0.025 deg lat/long (about 2.5 km). When combined with the elevation dependent climate surfaces described above, this yields accurate, continent wide, descriptions of the spatial distribution of the current climate. By systematically perturbing these distributions according to zonally averaged predictions afforded by general circulation models, preliminary assessments of the effects of climate change on agriculture have been made by Pittock and Nix [36] and Hennessy and Pittock [37]. Projected spatial displacements of climate also have major implications for the conservation of plant and animal species which currently inhabit environments of limited areal extent. The BIOCLIM program described by Nix [38] can be used to match occurrences of native flora and fauna to existing climate in order to generate likely consequences on the distribution of native plant and animal species under changed climate conditions.

11.4 PROCESS BASED STOCHASTIC WEATHER MODELS

In order to address temporal variability in a more realistic fashion than that allowed by long term monthly climate means, simple process based stochastic weather models are being developed. An important aspect of this work is its attempt to incorporate in the stochastic model key physical interactions between the weather variables. Thus a model in continuous time is being developed which is based on modelling the occurrence of cloud, since cloud moderates rates of heating during the day and rates of cooling at night. Cloud occurrence is also a necessary precondition for the occurrence of precipitation. The goal of this approach is to develop a weather model with a relatively small number of physically interpretable parameters which can be robustly determined from limited climate statistics and which can be realistically perturbed in response to projected climate changes. The physical basis for the model means that its validity should be relatively unaffected by these changes.

The first step in this work has been the development of a stochastic model for precipitation occurrence based on a continuous Markov process (Hutchinson, [39]). The model appears to be superior to existing point rainfall models based on Poisson cluster processes in terms of its physical interpretability, its ability to match observed statistics
and its mathematical tractability. Moreover, the model is amenable to further enhancements such as the simulation of cloud occurrence. Related work on the development of physically based stochastic models for temperature and solar radiation is being carried out by Guenni et al. [40] and Chia [41] respectively. An important aspect of this work is model calibration. A technique for robust calibration of seasonally varying stochastic weather models using periodic polynomial splines has been described by Hutchinson [42]. Unlike methods based on Fourier series, the coefficients of polynomial splines are well conditioned in terms of the data (de Boor, [43]) which makes them well suited to spatial interpolation.

Stochastic models can be used to generate information on important aspects of the future climate such as the probabilities of extreme events (frosts, floods, droughts etc.). Calculations of these probabilities by repeated simulation of a general circulation model are limited on grounds of computational expense. Moreover, a stochastic weather model can be used to drive simple process based crop growth models, such as that described by Nix [44], in order to generate information on both the amount and variability of agricultural output. This technique is vital to the assessment of consequences for agricultural production and the development of appropriate strategies to maintain if not improve agricultural output under a changed climate.

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