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

John A. Taylor, Anthony J. Jakeman,
Michael S. Common and Michael F. Hutchinson

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 (eg. 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 international conference on groundwater modelling at The Hague in September 1990.

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.

8. GREENHOUSE GASES: CARBON DIOXIDE

The determination of the fluxes associated with the sources and sinks of CO_2 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 CO_2 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 CO_2 in the atmosphere.

Using the three–dimensional stochastic Lagrangian model and incorporating available estimates of the global distribution of anthropogenic CO_2 emissions and biospheric and oceanic exchanges of CO_2, a model of the global distribution of atmospheric CO_2 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 CO_2 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 CO_2 as previously thought, then the biosphere must be absorbing a large amount of CO_2. It is unlikely that the biosphere will be able to continually remove increasing anthropogenic releases of CO_2. This may lead to an increase in the rate of climate change. Alternatively, a different model of the spatial distribution of the uptake of CO_2 by the oceans may also explain the observed CO_2 concentrations. It was also found that above 60° N the predicted seasonal cycle associated with the biospheric release of CO_2 was inconsistent with the observed seasonal cycle. This may mean that carbon storage is occurring at these latitudes and that the model of CO_2 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 CH_4, 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 odixation closely follows the seasonal cycle of photosynthesis. The results also indicate that if methane fluxes are proportional to NPP, then any CO_2 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 CH_4, 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 = a vector of final demand requirements by commodity,

x = a vector of gross output levels by industry,

A = a matrix of technological coefficients for the industrial input requirements of industries for unit activity levels, and

n = number of commodities and industries,

we have

(1) $$x = (I-A)^{-1}\, y = Ly$$

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 = a matrix of coefficients for primary energy inputs per unit of gross output by industry,

F = a matrix of coefficients for primary energy inputs per unit of delivery to final demand,

e = a vector of coefficients for carbon dioxide release per energy unit of fuel burned,

we have

(2) $$T = e\,(Cx + Fy) = e\,(CLy + Fy) = e\,(CL + F)\,y = ty$$

and

(3) $$z = t^*y$$

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 and $n \times n$ 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 6×27 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, ie. 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).

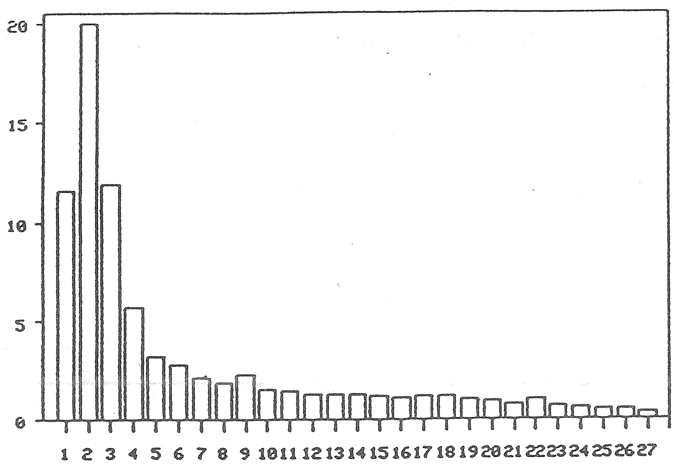
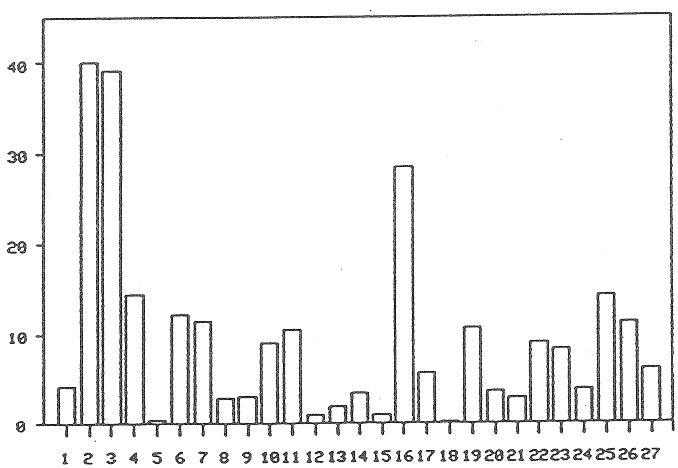


Figure 2: Total Carbon Dioxide (million tonnes).



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 1: Number of data points and approximate standard errors of Australia wide monthly mean climate surfaces.

Variable	No. of data points	Standard error
Solar radiation	150	3%
Daily maximum temperature	900	0.2–0.4° C
Daily minimum temperature	900	0.3–0.5° C
Precipitation	10000	10–15%
Pan evaporation	300	5%

A major factor in the accurracy 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 accpepted 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.

REFERENCES

[1] JAKEMAN, A.J., LITTLEWOOD, I.G. and WHITEHEAD, P.G., (1990) Computation of the instantaneous unit hydrograph and identifiable component flows with application to two small upland catchments. *J. Hydrology* (in press).

[2] JAKEMAN, A.J., LITTLEWOOD, I.G. and WHITEHEAD, P.G., (1990) Catchment–scale rainfall–runoff event modelling and dynamic hydograph separation. *Proceedings Natural Environment Research Council and Institute for Mathematics and Its Applications Conference on Computer Modelling in the Environmental Sciences*, Keyworth, UK. 10–11 April.

[3] JAKEMAN, A.J. and TAYLOR, J.A. (1989) Identification, estimation and simulation of frequency distributions of pollutant concentrations for air quality management. Chapter 4 in *Library of Environmental Control Technology*, Gulf Publishing, Houston, Cheremisinoff, P., (ed.) **2**, 135–158.

[4] JAKEMAN, A.J., SIMPSON, R.W. and TAYLOR, J.A., (1988) Modelling distributions of air pollutant concentrations. Part III: the hybrid deterministic–statistical distribution approach. *Atmospheric Environment* **22**, 163–174.

[5] JAKEMAN, A.J. and TAYLOR, J.A., (1985) A hybrid ATDL–gamma distribution model for predicting urban area source acid gas concentration. *Atmospheric Environment* **19**, 1959–1967.

[6] JAKEMAN, A.J., and SIMPSON, R.W., (1985) Assessment of air quality impacts from an elevated point source. *Journal of Environmental Management* **20**, 63–72.

[7] JAKEMAN, A.J. and SIMPSON, R.W., (1987) *Air quality and resource development: a risk assessment in the Hunter Region in Australia.* CRES Monograph, Centre for Resource and Environmental Studies, Australian National University.

[8] TAYLOR, J.A., SIMPSON, R.W. and JAKEMAN, A.J., (1985) A hybrid model for predicting the distribution of pollutants dispersed from line sources. *Science of the Total Environment* **46**, 191–213.

[9] TAYLOR, J.A., SIMPSON, R.W. and JAKEMAN, A.J., (1987) A hybrid model for predicting the distribution of sulphur dioxide concentrations observed near elevated point sources. *Ecological Modelling* **36**, 269–296.

[10] JAKEMAN, A.J., WHITEHEAD, P.G., ROBSON, A., JENKINS, A. and TAYLOR, J.A., (1990) A method for predicting the extremes of stream acidity and other water quality varibales. *J. Hydrology* (in press).

[11] DIETRICH, C.R., NEWSAM, G.N., ANDERSSEN, R.S., JAKEMAN, A.J. and GHASSEMI, F. (1990) A practical account of instabilities in identification problems in groundwater systems. *Australian Journal of Geology and Geophysics* (in press).

[12] DIETRICH, C.R., (1990) Optimum selection of basis functions for ill–posed inverse problems. *IAHS International Conference on Model Calibration and Reliability in Groundwater Systems*, The Hague, 3–6 September, 1990.

[13] JAKEMAN, A.J., GHASSEMI, F., DIETRICH, C.R., MUSGROVE, T.J. and WHITEHEAD, P.G. (1990) Calibration and reliability of an aquifer system model using generalised sensitivity analysis. *IAHS International Conference on Model Calibration and Reliability in Groundwater Systems*, The Hague, 3–6 September 1990.

[14] GHASSEMI, F., JAKEMAN, A.J. and JACOBSON, G., (1990) Mathematical modelling of sea water intrusion, Nauru Island. *Hydrological Processes* (in press).

[15] TAYLOR, J.A., (1990) *The greenhouse effect and climate change: an Australian perspective.* CRES Working Paper, Australian National University.

[16] TAYLOR, J.A., (1989) A stochastic Lagrangian atmospheric transport model to determine global CO_2 sources and sinks. A preliminary discussion. *Tellus* 41B, 272–285.

[17] TAYLOR, J.A., (1990) New approaches to modelling the global distribution of trace gases in the troposphere. *Mathematics and Computers in Simulation.*

[18] TAYLOR, J.A., (1990) A 3–dimensional global tropospheric transport and chemistry model. *Proceedings of the 10th International Conference of the Clean Air Society of Australia and New Zealand.*

[19] TAYLOR, J.A., (1990) A model of sources and sinks of trace gases important to climatic change. *Proceedings Natural Environment Research Council and Institute for Mathematics and Its Applications Conference on Computer Modelling in the Environmental Sciences*, Keyworth, UK. 10–11 April.

[20] TAYLOR, J.A., BRASSEUR, G., ZIMMERMAN, P. and CICERONE, R., (1990) A study of the sources and sinks of methane using a global 3–d Lagrangian tropospheric tracer transport model. *J. Geophys. Res.* (To appear).

[21] COMMON, M. and SALMA, U., (1990) *Accounting for Australian Carbon Dioxide Emissions*, Centre for Resource and Environmental Studies, ANU.

[22] ABS, (1988) *Australian National Accounts: Input–Output Tables 1981–2 and 1982–3*, Australian Bureau of Statistics, Canberra.

[23] BRE, (1987) *Energy Demand and Supply Australia 1960–61 to 1984–5*, Bureau of Resource Economics, Canberra.

[24] AIP, (1989) *The Greenhouse Effect: A Position Paper, Australian Institute of Petroleum*, Melbourne.

[25] GHASSEMI, F., JACOBSON, G. and JAKEMAN, A.J., (1990) Potential effects of climatic change on major aquifers of Australia. *Water International* (submitted).

[26] HUTCHINSON, M.F., (1989) A new objective method for spatial interpolation of meteorological variables from irregular networks applied to the estimation of monthly mean solar radiation, temperature, precipitation and windrun. In: Fitzpatrick, E.A. and Kalma, J.D., (eds), *Need for Climatic and Hydrologic Data in Agriculture in Southeast Asia, Proceedings of United Nations University Workshop*, Canberra, 12–15 December, 1983. CSIRO Division of Water Resources Tech. Memo. 89/5, 95–104.

[27] WAHBA, G. and WENDELBERGER, J., (1980) Some new mathematical methods for variational objective analysis using splines and cross–validation. *Mon. Weather Rev.* **108**, 1122–1143.

[28] BATES, D. and WAHBA, G., (1982) Computational methods for generalized cross validation with large data sets. In: Baker, C.T.H. and Miller, G.F., (eds) *Treatment of Integral Equations by Numerical Methods.* Academic Press: New York, 282–296.

[29] ELDEN, L., (1984) A note on the computation of the generalized cross–validation for ill–conditioned least squares problems. *BIT* 24, 467–472.

[30] HUTCHINSON, M.F., (1984) A summary of some surface fitting and contouring programs for noisy data, CSIRO Div. Math. and Stats. Consulting Report ACT 84/6, 24pp.

[31] HUTCHINSON, M.F., (1988) Calculation of hydrologically sound digital elevation models. *Proceedings Third International Symposium on Spatial Data Handling*, Sydney August 17–19, 1988. International Geographical Union: Columbus, Ohio, 117–133.

[32] HUTCHINSON, M.F., (1989b) A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. *J. Hydrol.* **106**, 211–232.

[33] ABBOTT, M.B., BATHURST, J.C., CUNGE, J.A., CONNELL,P.E. and RASMUSSEN, J., (1986) An introduction to the European Hydrological System – Systeme Hydrologique Europeen, "SHE", 1: History and philosophy of a physically–based, distributed modelling system. *J. Hydrol.* 87, 45–59.

[34] MOORE, I.D., O'LAUGHLIN, E.M. and BURCH, G.J., (1988) A contour–based topographic model for hydrological and ecological appllications. *Earth Surf. Processes Landform* 13(4), 305–320.

[35] HUTCHINSON, M.F. and DOWLING, T.I., (1990) An evaluation of a new grid–based digital elevation model of Australia for hydrological analysis. *Hydrological Processes* (submitted).

[36] PITTOCK, A.B. and NIX, H.A., (1986) The effect of changing climate on Australian biomass production – a preliminary study. *Climatic Change* 8, 243–255.

[37] HENNESSY, K.J. and PITTOCK, A.B., (1990) The sensitivity of extreme temperature effects to greenhouse warming in Victoria, Australia. *Climatic Change* (in press).

[38] NIX, H.A., (1986) A biogeographic analysis of Autralian elapid snakes. In: Longmore, R., (ed), *Atlas of Elapid Snakes of Australia*, Australian Flora and Fauna Series No.7, Bureau of Flora and Fauna: Canberra, 4–15.

[39] HUTCHINSON, M.F., (1990) A point rainfall model based on a three–state continuous Markov occurrence process. *J. Hydrol.*, 114, 125–148.

[40] GUENNI, L., CHARLES–EDWARDS, D., ROSE, C.W., BRADDOCK and HOGARTH, W., (1989) Stochastic weather modelling: a phenomenological approach. *Mathematics and Computers in Simulation,* Special Issue 32 (in press).

[41] CHIA, E., (1990) Some fundamental questions in stochastic simulation of weather sequences, with applications to ANU–CLOUD. *Mathematics and Computers in Simulation*, Special Issue 32 (in press).

[42] HUTCHINSON, M.F., (1990) Robust calibration of seasonally varying stochastic weather models using periodic smoothing splines. *Mathematics and Computers in Simulation*, Special Issue 32 (in press).

[43] DE BOOR, C., (1978) A practical guide to splines. *Applied Mathematical Sciences* 27. Springer–Verlag: New York.

[44] NIX, H.A., (1981) Simplified simulation models based on specified minimum data sets: the CROPEVAL concept. In: Berg, A., (ed), *Application of Remote Sensing to Agricultural Production Forecasting*, Commission of the European Communities: Rotterdam, 151–169.

[45] Hutchinson, M.F. (1990) A stochastic estimator of the trace of the influence matrix for Laplacian smoothing splines. *Commun. Statist. Simul.* (in press).

Centre for Resource and Environmental Studies
Australian National University
GPO Box 4
Canberra ACT 2601
Australia