Coupling Spatial Models at Varying Space and Time Scales - Global Information for Regional Benefit

L. Lau, Advanced Computational Modelling Centre (ACMC), University of Queensland (UQ)
J. A. Belward, Advanced Computational Modelling Centre (ACMC), University of Queensland (UQ)
K. Brook, Climate Impacts and Applications, Queensland Department of Natural Resources (DNR)
G. McKeon, Climate Impacts and Applications, Queensland Department of Natural Resources (DNR)
R. A. Young, Climate Impacts and Applications, Queensland Department of Natural Resources (DNR)

Abstract Every Natural Resource Management (NRM) activity is dependent on climate to a large extent as the natural processes are intrinsically linked with the waxing and waning of the seasons. This paper describes an on-going project that brings together universities, state and federal research organisations to focus decades of climate research into practical outcomes. The goal is to integrate global seasonal climate forecasts with local environmental decision support systems for the explicit social and economic benefit of regional communities. Some of the complexities, both technical and human, in coupling spatial simulations operating at varying spatial and temporal resolutions will be discussed. The experience will illustrate the value of multidisciplinary collaboration and globalisation of research.

1. INTRODUCTION

Concern for the long-term sustainability of Australia and its natural resources is widely shared by both the government and the community. The challenge for scientists modelling the Australian environment is to integrate the "best" knowledge from computer models, geographical information systems (GIS), satellite imagery, economics, and scientific research, to deliver relevant information for managers and, ultimately, local benefits. Recognising the increasing interaction between local communities, state organisations and federal departments, the Prime Minister's Science and Engineering Council (1995) noted:

> ... good science in sustaining the agricultural resource base is crucial. But the science needs to be applicable at the local level ...

Faced with the monumental task of managing assets such as fresh-water supply, soil viability, native vegetation, and biodiversity on a continental scale, state organisations such as the Queensland Department of Natural Resources (DNR) are developing multi-disciplinary collaborative research programs, coupled with educational and delivery mechanisms, to support interagency initiatives such as the National Drought Alert Strategic Information Project (Brook et al. 1996). Climate is a global phenomena with impacts ranging across international boundaries, as illustrated by the El Niño-Southern Oscillation (ENSO) events which can, for example, simultaneously cause droughts in Australia and floods in California. International cooperation is crucial to address issues of this scope and complexity.

2. MANAGING CLIMATE VARIABILITY

Unfortunately Australia experiences one of the highest levels of climate variability in the world, leading to severe socio-economic fluctuations. For example, it is estimated that so far this decade, drought has adversely affected the economy of Queensland in *excess of $6.2 billion* through loss in agricultural revenue and the resulting flow-on effects (DPI 1996). Advanced warning would allow the implementation of preventive strategies to mitigate the impact of climatic extremes.

Current risk-management techniques are based on a statistical approach with the Southern Oscillation Index (SOI) phase relationship (Stone and Auliciems 1992) used to pick analog years from interpolated historical weather information (Stone et al. 1996). While highly successful, the SOI is a single number representing the air pressure gradient between two points (Darwin and Tahiti) which ignores the significant effect of the Indian Ocean and potential future climate changes.

The aim is to extend the current system by simulating the physical attributes of the atmosphere/ocean with a regular mesh of multi-layered cells enveloping the whole planet. Improving seasonal forecasting has been described as "Science's Gift to the 21st Century" (Glantz 1994) as advanced climate models can now predict seasonal climate anomalies in the tropical Pacific region with significant skill (Bengtsson et al. 1993). Currently, an Australian-US research initiative is underway to develop a three-tiered approach to integrate advanced seasonal-to-interannual climate forecasts with spatial environmental models consisting of biological/ecological point models replicated across the landscape in regular grids (Young et al. 1997).

3. LINKING MULTIPLE MODELS

General Circulation Models (GCMs) are the codified equations representing the physical processes of the atmosphere. The interaction between the different components of ocean layers, land masses, temperature gradients, solar radiation, clouds, ocean currents, trade winds, etc represent a complex system which requires significant computing resources to produce meaningful forecasts. GCMs operate at medium-coarse resolutions (~300 km) to capture the large scale circulation flows. Multiple replicates, with slightly different initial conditions, are necessary to provide adequate representation of the event space.

Regional Climate Models (RCMs) or limited area GCMs, perform essentially the same function as global GCMs but over a restricted domain. The reduced area allows higher grid resolutions (~75 km), achieving more detailed results by incorporating additional small-scale physical phenomena and local knowledge of the topology/vegetation (Barron and Sorooshian 1997). The RCM is then driven at its boundaries by periodic updates from the coarse GCM.

Spatial-Temporal Downscaling techniques infer spatial patterns of land-air fluxes across an entire heterogenous landscape, bridging the gap between climate and environmental models (~5 km). As most biological models are sensitive to precipitation events which are clumped, zero-truncated, and discontinuous, interpolation algorithms need to reflect the statistical properties of historical rainfall patterns. Other climatic variables, such as temperature, are also significantly influenced by the topography (Hutchinson 1995).

Spatial Environmental Models (SEMs) arise from the replication of point models across a regular grid superimposed on the landscape. Dynamic spatial simulations are discretisation of continuous systems in a 2D/3D domain with an explicit time-varying component, such as the daily weather pattern, altering state variables with known attributes (soil/vegetation properties). These models aid the understanding of biological, ecological, geological, hydrological, and anthropological processes within the ecosystem and are key to accurate prediction and long-term sustainability.

Socio-economic Models and decision support systems (DSS) are crucial for addressing the human dimension. Unlike the physical "hard" sciences, this area is more complex and difficult to quantify. Unfortunately, it is often difficult to translate the experimental nature of scientific research based on assumptions, imprecise/ missing data, and constrained accuracy of algorithms, with demanding requirements for definitive answers by the executive arm of government.

Not only does a frame-work need to be developed for evaluating policy based on scientific principles, but also an extension program for disseminating results and advising the potential end-users (government/ managers/community) must exist. State organisations such as DNR provide a crucial conduit between the modelling research programs and end applications.

4. INDUSTRIAL APPLICATION

DNR needs to find answers to the problems of (a) effectively managing the interactions between climatic variation, native grassland sustainability, and grazier profitability / viability, and (b) finding quantitative ways of monitoring and assessing the drought status, resource pressure and condition over space and time. The department is firmly committed to a systems approach and the vision of a comprehensive National Drought Alert Strategic Information System consisting of the best combinations of rainfall analyses, seasonal climate forecasts, satellite and terrestrial monitoring, and simulation of meaningful biological processes.

Products being deployed in such a system will lead to better assessment of seasonal condition, controlling prospects for overgrazing, timing burning regimes to maximise effectiveness, limiting land degradation and adjusting stocking rate. Currently such information is provided through glossy news letters, faxes and web pages (http://www.dnr.qld.gov.au/longpdk/).

One example is the pasture growth calculated using the GRASP model based on rainfall and other climate information. The following diagrams illustrate the projected pasture growth for the Austral-spring season based on September conditions and rainfall forecasts.

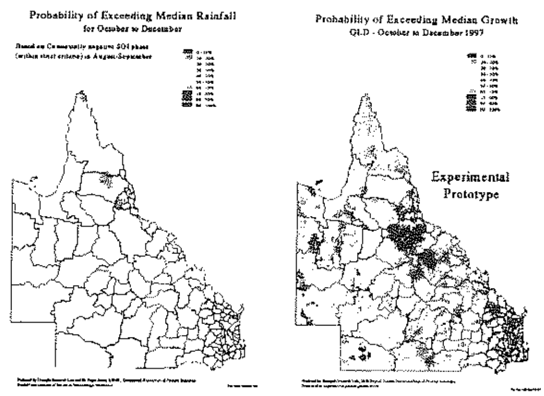

Figure 1 : Queensland experimental pasture forecast.

Currently these forecasts are based on the SOI index and near "real-time" ground stations, augmented with satellite imagery and local drought declarations. This provides an important community service to rural industries, Landcare groups, and resource managers.

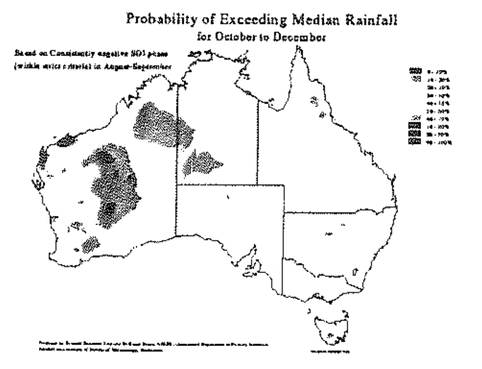

Figure 2 : Australian seasonal rainfall probability.

5. INTEGRATED SYSTEMS APPROACH

Given the complexity and magnitude of applying seasonal forecasts for Australian natural resource management (Goddard et al. 1997), a consortium of research groups has been assembled to tackle the problem. An integrated systems approach includes developing the conceptual framework, implementing then tuning the various models, interfacing the components, validating and verifying the system, and disseminating the results to users or decision-makers.

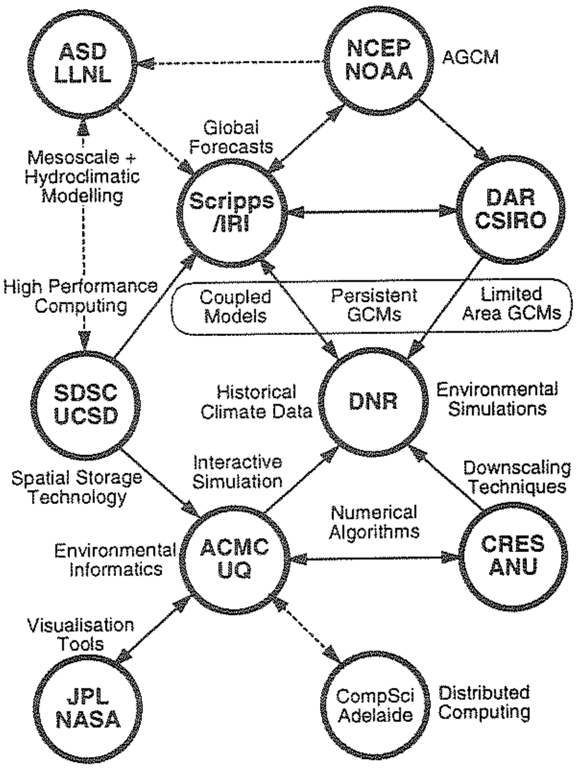

Figure 3 : Current and evolving (dashed) linkages.

In essence, this is a virtual team where each group concentrates on their area of expertise with research results being focused directly into sustainable practices (Fenwick et al. 1998). Creating, resourcing and coordinating an international multi-disciplinary, multi-institutional project is difficult and time-consuming (Lau 1998) but the benefits of combining the latest science with leading edge technology will significantly shorten the lag-time between research innovation and its implementation, as well as reducing technical risks.

While solitary models may address individual issues, a loosely coupled hierarchy, spanning multiple spatial-temporal resolutions, is considered necessary to translate coarse resolution seasonal climate forecasts to regional and local benefits as espoused by the US Global Change Research Program (1997):

> ... to be of greatest use for work on the ecological, economic, and social consequences of climate change ... models must ... simulate accurately primary processes governing the Earth on scales of tens, ... rather than hundreds of kilometres.

6. TECHNICAL ISSUES

6.1. Spatial Temporal Downscaling

Coupling models that operate at different resolutions poses additional complexity when integrating the sub-components. For example, differing grid alignments (edge or cell centred) may require geodetic corrections as in the case where the GCM produces spherical coordinates while the RCM is based on a Lambert-Conformal grid. Also state variables passed between models must match, not only in definition and units, but whether they are instantaneous or aggregate values.

Approximation techniques arise when transferring spatial or temporal information across different spatial and temporal scales. Current techniques, based on thin-plate smoothing splines (Hutchinson 1991), interpolate surfaces in the presence of noise and data uncertainty. While eminently suitable for continuous data, such as temperature, precipitation fields require redistribution tempered with historical patterns (Young et al. 1997).

6.2. Computational Expense

Interactive simulation is essential to the development cycle as well speeding up the management decision-making process. Technology such as high performance computing is therefore crucial for producing results in a realistic time-frame (Burrage et al. 1993). While climate and spatial models can be adapted for existing parallel architectures, downscaling algorithms based on minimising a global error function require a more sophisticated approach. Several numerical techniques have been developed to improve efficiency by an order of magnitude (Sidje and Williams 1996) but the $O(n^3)$ complexity of the underlying algorithm and the overheads for global array operations will eventually swamp any benefits.

Local methods based on the triangulation of scattered data are being trialed. These offer advantages of speed and retain features of the underlying data which might otherwise be smoothed out. Obtaining a surface with continuously varying gradients may be done by using the data to make estimates of derivatives. Such techniques have been analysed in the 1-dimensional situation (Hegland and Anderssen 1996). A surface approximant may also be obtained by transferring the data to a regular grid (Belward 1997) and using tensor products of functions with continuously varying slopes. This transforms the problem into a set of intrinsically parallel 1-D problems allowing efficient reconstruction of the approximants. The resolution of the grid may be dynamically or statically adapted to cater for varying densities of data points.

The end system needs to provide levels of feedback (batch→interactive) on machines ranging from work-stations to supercomputers. Software environments are being investigated that support both (near) real-time feedback and interaction, as well as scenario/sensitivity analysis on a high-performance platform within a heterogeneous parallel computing environment.

6.3. I/O Bandwidth

Linking models requires the exchange of data to synchronise operations. However, the nature of spatial models is such that data requirements scale linearly with the total area, consequently leading to I/O bottlenecks. A cost-effective solution has required the development of customised compression algorithms tuned for a Cray parallel-vector architecture which subsequently improved throughput by a order of magnitude (Davis et al. 1998).

The advantages of compressed data are a substantial reduction in storage capacity (on average only 3.5% of the original size), increased simulation throughput and faster analysis/management/interrogation of extremely large datasets. In addition, comparison of compression sizes within months is a rapid means of assessing the changing frequencies of zero rainfall events which is in turn a very good indicator of desertification as well as climate change (Young et al. 1998).

6.4. Analysis of Underlying Structure

The compressed information from the simulation runs can be easily accessed and analysed to refine and tune the individual models. Terrestrial and temporal (seasonal, etc.) influences may be readily identified and taken into account, however other less apparent features may not be recognised. The presence or otherwise of such features may be facilitated by fractal dimension identification (Breslin and Belward 1997). Image analysis techniques such as wavelet transformation and image registration are currently under examination. Data attributes, such as the fractal dimension, are a current research area which will assist the validation of model outputs against observed values of the phenomena.

6.5. Modularity

While closer integration of models will result in increased accuracy, this leads to greater complications when developing modular software. For example, the current incarnation of GRASP, DNR's spatial environmental model (McKeon and Littleboy 1997), has diversified into 11 versions, each addressing the interests of the current developer (drought, sheep grazing, cropping, etc). While this demonstrates the versatility of the basic soil-water/pasture model, the independent development means that improvement in one area (such as recoding in Fortran 90 for high performance platforms) cannot be readily assimilated into other versions without centralised coordination. Unlike normal software development, models cannot be easily separated into independent components due to the complex interactions between the water, soil, vegetation and livestock processes. One possible solution currently being investigated uses the University of Maryland's Spatial Modelling Environmental (SME) which represents the model as a system dynamics diagram and generates code for a variety of platforms whenever a new equation is added (Maxwell and Costanza 1996).

6.6. Feedback between Models

One-way coupling is currently implemented where the GCM imposes boundary/internal forcing conditions on the RCM and RCMs in turn provide the climate fluxes for the spatial environmental model. In reality, there are numerous feedback mechanisms as fine resolution environmental models possess dynamic ground cover which in turn influences the local energy-water model.

Seasonal effects of dynamic ground cover would increase bare ground cover leading to greater water loss through evaporation. Given a wide enough area of applicability, this leads to noticeable regional effects which should be reflected in higher spatial hierarchies. This can be addressed by investigating the coupling and increasing feedback mechanisms. Fundamental research needs to be undertaken into complex systems to create a framework for integrating multiple models.

6.7. Calibration

The current methodology for applying seasonal forecasts to spatial biological models is to select analog years based on SOI phases and its strong relationship with precipitation (Fenwick et al. 1997). A more advanced approach is to use the full contingent of climate information from the GCM/RCM to drive the spatial model in daily time steps. The advantage of using RCM output fields is that they have been parameterised for short-term weather, reflecting the daily spatial-temporal distribution in contrast to traditional use of GCMs for global seasonal averages. This however does not preclude the possibility of using climate generators to redistribute monthly totals from the GCM/RCM as an alternative method or developing a more refined set of criteria for selecting analog years.

The integration of downscaled GCM/RCM forecasts is being developed and validated in terms of 30 year hindcasts and by building on the existing methodology of using historic analog years to drive the spatial model. This approach is especially attractive as the spatial model has been empirically parameterised using observed climate information and their measured environmental effects.

6.8. Hierarchical Modelling Framework

The vertical coordination/integration of models within a hierarchical framework requires the standardisation of data at each interface level. Currently this is being developed as a working prototype for this project. As each group refines their individual models, results are progressively incorporated into the overall framework in parallel to an existing operational system.

In this way direct benefit of local advances can be incorporated at each stage, leading to improved overall results. For example, CSIRO have an extensive climate research program which in turn enhances the regional model for Australian conditions. The conceptual framework is designed for future expansion to include additional environmental and economic models.

7. COORDINATION OF ACTIVITIES

7.1. Hyperclustering

With the globalisation of research, collaboration is increasingly being undertaken at an international level. Rather than the traditional one-to-one twinning with another individual in the same field of research, the focus is tending towards multi-disciplinary multi-institutional "virtual teams". A cluster consists of a core of principal investigators supplemented by experts at secondary institutions. This allows additional resources and expertise to be drawn upon, with scope for expansion of project, rapid dissemination of results and early adoption of new technology. The concept of "hyperclustering" (Lau 1998) is then based on "active networking" with other clusters leading to a cohesive matrix of collaborative linkages. This has many characteristics of a "learning organisation" such as a "shared vision" and "team learning" (Senge 1993).

Similar organisational structures are evolving overseas such as NASA's Federation of Earth Science Information Partnerships (NRC 1995), NOAA's concept of International Research Institutes (IRI) and Applications Centres (NOAA 1995) and NSF National Partnership for Advanced Computational Infrastructure (NPACI). Hyperclustering is a bottom-up approach, demonstrating the "vertical coordination" (integration) of diverse research groups through to the human dimension in sustainable management practices.

7.2. Resources

Each group is essentially self-sustaining with cost savings achieved through the sharing of resources and scale of economy in accessing complementary core research programs. While more preparation is required, the team has the added bonus of collective access to bilateral and international resources. In addition, each group accesses different sources of funds, eliminating the sense of competition and resulting in greater flexibility and increased windows of opportunities, as well as tangential benefits. For example, Universities support technology refresh programs through staff exchanges across a diverse range of disciplines, leading to new avenues of research and providing a rich source of ideas which industry can draw upon.

7.3. On-going Facilitation and Coordination

The key to maintaining the group's cohesiveness is active facilitation by addressing the expectations and aspirations of the individuals as well as their respective organisations. This establishes trust and promotes understanding. While group dynamics and interactions are a topic in their own right, adroit coordination, constant promotion of the group's interests, organisation of workshop meetings, joint authorship of publications, maintenance of "corporate memory", encouragement of early career researchers and solicitation of constructive criticism from peers, are all critical to the growth and success of the overall team.

8. MANAGEMENT CONCERNS

8.1. Acceptance by managers

The following attributes are seen as *critical for acceptance* of the environmental models within the policy making process:

1. embrace enterprise activities to solve key issues;
2. builds and enhances downstream services;
3. credibility in track record and/or validation;
4. visual products or summaries accessible to users;
5. globalisation of research to access "best" models;
6. innovative combination but eminently practical.

Integrated systems that address corporate themes such as the impact of climate variability, act as a catalyst in promoting the decision support systems that involve a range of issues influencing sustainability. In addition, they *must be relevant* and *address management issues* in the corporate charter as is in this case where the results will flow into the National Drought Alert Strategic Information Project (Brook et al. 1996).

Empirical models, based on extensive observations and field trials that relate observed phenomena to measured inputs, readily achieve acceptance. In this particular project, the generation and testing of 30 year hindcasts addresses the most important aspect of any earth system simulation which is validation and verification.

8.2. Acceptance by the wider community

This research is being developing in parallel with an existing delivery mechanism that services community benefits and needs. These systems emphasise the responsible and judicious use of climate value added products. The obvious advantage of this approach is that new innovations are viewed as natural extensions or progression of existing services. Acceptance will be further enhanced by the creation of the Queensland Centre for Climate Applications (QCCA) which will establish a wider depth of community understanding as well as reducing the social barriers to use of advanced climate risk-management tools.

8.3. Peer Review

The globalisation of research combines the latest science with leading edge technology to shorten the lag-time between research innovations and its implementation. The "vertical coordination and integration" of multi-disciplinary/organisation research groups undergoes international peer review within each discipline, with the additional benefit of close scrutiny by direct collaborators. This focuses the development of research, ensuring scientific rigour and adherence to high quality research at each stage as well as in the overall integrated system. This is a critical mechanism in allowing the resulting technology to be accepted and diffused globally, especially given the innovative combination of research and applications.

9. CONCLUSIONS

Climate is a global phenomena that knows no boundaries, requiring international cooperation to foster the creation of an end-to-end system that translates the profits of climate research into the human dimension. The approach has revolved around the concept of "virtual teams" and hyperclustering to build long-term linkages. The goal has been to achieve the vertical coordination (integration) of relevant research groups to focus on sustainable management practices. Globalisation of research is seen by management as building collaborative arrangement which leverages core activities with external research groups to achieve enterprise objectives for mutual benefit.

The on-going project described in this paper brings together universities, state and federal research organisations, both local and international, in a global partnership for planet stewardship.

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