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Exploratory Modelling of Socio-Economic Impacts of Climatic Change

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ABSTRACT

Socio-economic systems may be influenced by climatic change in ways ranging from minor or very local to drastic and nation-wide. Any such changes will be superimposed on trends already present in these evolving systems. Therefore, it is vital to anticipate dangers, as well as new opportunities, as soon as possible. To allow governments and policy-makers to play an active role in managing these socio-economic systems effectively, they should be provided with tools that will permit them to explore impacts in their full holistic, spatial and temporal contexts. Decision-support systems are designed to assist in such tasks. The most essential part of such systems is a set of tools, mostly quantitative models and methods, which at relatively low cost, allow the user to analyse and evaluate a range of possible futures resulting from different scenarios and hypotheses.

In this chapter we propose, as part of a larger decision environment, a two-level mathematical modelling framework, geared to study the effects of climatic change on the level of the individual island or mainland state. The long-range mechanisms of change are modelled in a classic, non-equilibrium spatial interaction model. This model then feeds regional growth coefficients into a low-level cellular model that deals with the short-range location and interaction mechanisms. This technique of linked models is necessary in order to capture successfully the effects resulting from climatic change on the appropriate scales. The prototype presented is a first, mostly conceptual, step towards a system for use in real-world applications.

1 INTRODUCTION

This closing chapter of the book is an indication of the increased interest by UNEP and the IOC in climatic change: with the understanding gained from the multi-disciplinary study of the physical and biological impact of climatic change, emphasis will be put on studying the impact on human societies and their responses to the challenges raised. The ultimate aim is to provide the threatened peoples, their policy analysts and governments,

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with the necessary tools to anticipate the obstacles well in advance in order to minimize the effects on their well-being and to secure their future.

This chapter is a first (and mostly conceptual) step towards the design of a model-based decision-support system, capable of integrating the knowledge gathered by different specialists. It describes the development of a modelling framework, integrating physical, ecological, economic and social characteristics of nations in the region, within which the complex multiple consequences of public policies and actions can be examined as completely as possible. The development of such a system is the subject of a long term and possibly ambitious project. However, the rapid evolution of the information technology in the past few years, together with evolving scientific paradigms and derived modelling frameworks, offer new perspectives for the management of socio-economic systems, which make us confident that such projects can lead to successful outcomes.

Practically, the chapter will propose, as part of a decision-support system for public-policy exploration, a simple version of a complex dynamic model of a purely hypothetical island with characteristics typical of those in the region. This model ultimately will evolve into a more generic tool to study important effects of climatic change on individual islands and mainland nations. As such it may serve as a discussion piece to concert further research by the task team.

2 POSING THE PROBLEM: CLIMATIC CHANGE IN THE REGION.

If the link between greenhouse-gases emission and climate change continues to be confirmed, then the 'consensus view' on the future of the planet could come at great cost (Davis, 1990). This cost might be tolerable for the rich industrial countries, having the technology and financial resources to cope with the immediate effects of a changing climate (Ausubel, 1991). For the developing world, however, the cost might lie beyond the bearable (Ominde and Juma, 1991). The 'sustainable growth' world view, which emphasizes adaptability and voluntarily reduced exploitation of resources and strives to match the need for economic growth with a viable, environmentally sound planet for the generations to come, is certainly more adequate in this respect. Technology will propel society toward sustainability most quickly if policy-makers can agree on the appropriate global and local guide-lines (Reddy and Goldemberg, 1990). In order to attain such agreement, a good understanding of the mechanisms linking human activity and greenhouse-gases production, and of the subsequent effect of greenhouse gases on the ecological and socio-economic systems, is an essential first step.

2.1 An Evolutionary Context

Tourism and agriculture, both major sources of income in the region, rely on natural systems. Any effects of climatic change on these sectors may have a long term, large scale and irreversible impact on the physical and socio-economic environment, thereby undermining the sustainability of the economic development. Thus, climatic changes will alter the evolutionary path of the socio-economic systems. Socio-economic systems are highly dynamic, but at the same time laden with inertia. *Dynamic*, because no such system has been found to be in equilibrium; rather it is perpetually in a transition phase between an old and a new form of organization. *Inertia*, because of the long time it takes for all effects of actions and disturbances to propagate through the system and to run out in a fully reorganized system. Hence, the dynamics driving the system today may have been set in motion, deliberately or not, a long time ago, and may continue to do so for many years to come.

2.2 A Global Context: Changing World Markets

Much along the lines of the approach of meteorologists, exemplified by Wigley and Santer (Chapter 2), effects of climatic change on the social and economic system need to be studied in their full spatial extent. Meteorologists are not able to separate the Intra-Americas Sea from the global weather and climatic system. The region fits like a single piece in a world-wide jigsaw and is only one of the many interacting points in the General Circulation Models. Likewise, the region is firmly embedded in the world's demographic, social and economic systems. If we really are interested in the effects of global warming in the region, some of our attention will need to be on the way the region interacts with the rest of the world. Indeed, the worst socio-economic problems in the region could well find their origin far outside the area, because a substantial part of its income is generated externally. Tourists are being attracted for reasons strongly related to its climate: year-round sunny weather, warm seas, coral reefs, exotic fruits, beaches; they typically come from regions lacking such properties: the northern USA, Canada, northern and western Europe. If climatic change affects more drastically higher latitude regions (Vincente *et al.*, Chapter 11), possibly with temperature increases as high as 4.5°C by 2025, the drive of the traditional tourist to leave his home could weaken considerably, thus depriving the region of substantial income. Other places could acquire advantages similar to the ones now unique to the area and could start acting as intervening opportunities, thus diverting important streams of tourists. Although slightly out of the scope of this book, we imagine that further depletion of stratospheric ozone with its attendant effects on human health, may completely alter peoples' attitude to sunny beaches, causing even further stress on the economic system.

In the course of history the region has become an important, specialized exporter of agricultural staple products (coffee, fruits, sugar cane). If climatic bands start shifting, bringing more precipitation to dry areas and higher temperatures to cold ones, this specialization might become questionable. Transport costs make products sold at distant markets very sensitive to competition because the distance between origin and destination allows for intervening opportunities to pop-up. By making reasonable assumptions about the likely competition for agricultural or other products, however, early detection of vanishing comparative advantages as well as the appearance of new openings on local or world markets might give the system sufficient time to transmute smoothly from the old production base to a new one. Hence, important questions regarding investments in the region need to be addressed to prevent capital from leaving and actions will have to be taken accordingly.

2.3 A Local Context: Areas and Activities at Risk

Countries whose economic activity is strongly concentrated in the coastal areas, on lowlands, deltas, etc., doubtlessly will be strongly affected by climatic change (Alm *et al.*, Chapter 15; and Vicente *et al.*, Chapter 11). Without adequate policy interventions, activities with low value added per unit area, such as subsistence agriculture, will suffer most from changing climate or rising sea level. Firstly, on a cost-benefit basis, it will be considered non-economical to build sea-defence structures to protect this land against intrusion. Secondly, if land used by activities with higher value added, such as commerce or industry, is endangered, these activities will preferentially relocate in the immediate neighbourhood, in order to enjoy similar location advantages irrespective of the land's value for its initial use. This has to be viewed in its historical context. If, for example, commercial activities would invade subsistence agricultural land, it has to be assumed that farmers have cultivated the land they work today because of its high productivity value within the constraints of the technology at hand. Losing it to any other usage will automatically force them to farm less adequate fields, with a reduction of productivity per unit area and labour as a consequence. To the immediate clearing and building costs resulting from such relocation will be added the cost of reduced productivity. Furthermore, social tensions are likely to be amplified as the socially weak are pushed out and often have to settle for second best. They also will face the inconvenience of travelling longer distances to services and to work. Hence, deteriorating working and living conditions will worsen an already difficult financial situation. Therefore, timely anticipation and active intervention on behalf of governments will be necessary in order to keep social peace in the system.

The above points are certainly not an exhaustive enumeration of conceivable effects of global warming on the socio-economic structure of the region. They are merely meant to widen the discussion of the possible impacts on the intensity and resilience of the socio-economic linkages between the region and the external world. Even if we are only interested in what happens in the region itself, narrowing down the study to the region as a self-contained unit, thus pretending that climatic change does not exist beyond its frontiers, in a system culturally as diverse and with an economy as export oriented, runs the risk of missing the problem at hand and excluding the driving forces of the system from the study. As explained later, successfully exploring future challenges in the area calls for modelling it as an open system.

3 Towards an Integrated Framework for Policy Evaluation

The Intra-Americas Sea has a unique variety of peoples, cultures and political systems, representing countries with different types and stages of economic development. Its physical, geomorphological and ecological diversity is remarkable as well (*cf.* Chapters 5–12). Hence, defining the effects of climatic change on the socio-economic systems should take into account both the diversity among countries and the reliance of their economies on more or less distant and intercontinental markets. We therefore propose an integrated multi-disciplinary approach on the level of the individual member states.

Decision-making in social systems is a formidable task because of the dynamic character, the multi-dimensionality, the spatial character and the complex interactions that typify them. Processes in these systems are strongly interrelated and indivisible. Consequently, situations which at first glance seem well defined and limited in scope turn out to have deeper dimensions and repercussions, ones that can not be untangled or comprehended easily, if at all. Decision-makers therefore need tools that *accumulate* intelligently the historical knowledge about the system, tools to *explore* the behaviour of the systems when stressed, and tools to assist in *selecting* the best policy alternatives given the objectives and constraints. Typically, such tools are made available in decision-support systems.

3.1 Decision-Support Systems

Spatial Information Systems have evolved in the past to cover a number of rather different computer-based systems, despite their common purpose of integrating data from different sources to provide the necessary base for decision-support in a spatial context. They include systems varying from data-centred systems such as DBMS (Database Management Systems), information-centred systems such as GIS (Geographical Information Systems) and intelligence-centred systems such as Decision Support Systems (DSS). The intelligence and knowledge content increases gradually from DBMS to DSS, and the type of decision-support changes from passive support (enabling the formulation of the decision alternatives) to active support (helping to choose and implement the 'best' decision). If we define intelligence as 'the ability to catch the essential factors from complex information and data' (Catanese, 1979), we should try to provide the planner with intelligence rather than data or information. Thus, we should focus our attention on DSS rather than on DBMS or GIS. Both DBMS and GIS perform essential sub-tasks in the decision process, but separately they fall short of dealing adequately with temporal and spatial dynamics (Marble and Amundson, 1988) or in providing the decision-maker with the required active support.

Decision Support Systems (Fig. 16.1) are principally made up of three components (Han and Kim, 1990): (1) *a user interface* enabling easy interaction between the user and the system; (2) *a data base* containing the raw and processed data of the domain and area at study; and (3) *a model base* with relevant models, methods and techniques.

3.1.1 The user-computer interface

Decision-support systems are intended for use by high-level decision-makers to solve ill-structured problems. Although often specialized in their domain, these decision- and policy-makers may be unfamiliar with information science and technology. The user interface, the vehicle of interaction between the user and the computer, takes into account differences in the cognitive styles and relative knowledge of the users. It is designed to hide the complexities of the internal computer system without hampering its flexibility and provides insight into the structure of the mathematical models, methods, variables, parameters and mechanisms, the

underlying theoretical assumptions, the boundary conditions and other constraints. It allows the user to address the different components of the DSS (tools, models, data, etc.), translates the user input into appropriate computer instructions, and reports back the results of the computations. To provide maximal user-friendliness, state-of-the-art interactive graphic techniques are being applied extensively (Cleal and Heaton, 1988).

3.1.2 The data base

A thorough data base serves as an input for the models used, and is appropriate to the management or policy issues dealt with in the DSS. There is a growing trend to store spatial, social and ecological data in GIS data bases. Consequently, a good interface linking GIS and DSS is of utmost importance for policy-making and planning.

3.1.3 The model base

The convenience, richness and scope of a DSS is primarily determined by the spectrum of tools available in its model base. Typically decision models, statistical and operations research methods, as well as tools to describe, portray, compare and evaluate different policy strategies, are part of it. Even more essential in the model base are the domain-specific (simulation) models capable of grasping the complexities of the system and the problems at hand. The elements in the model base are of a formal nature, and exclude decision-making solely based on common sense or intuition. Good formal decision-support methods will assume that the decision-maker desires to make decisions on the basis of a consistent line of reasoning (Holtzman, 1989) and will suggest solutions that make intuitive sense. Elaborate model bases will contain both mathematical and rule-based techniques, often playing complementary roles in decision-making processes.

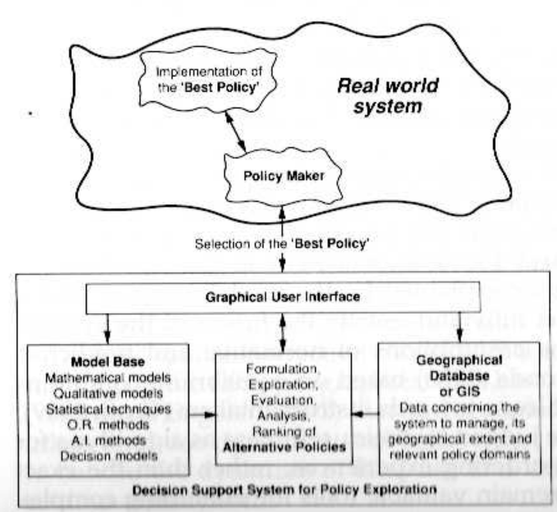

Fig. 16.1 A decision-support system for public-policy exploration consists of three essential components: a model base, a data base and a user interface, and assists the policy analyst in the evaluation of different alternatives.

Rule-based tools are often expensive to develop and to maintain, as they require a number of experts and domain specialists to build or to update them when knowledge is outdated or becomes erroneous. Mathematical models usually will be more generic in nature. Their creation will oblige the precise, detailed and explicit formulation of assumptions and relations. Hence logical contradictions will be avoided and, contrary to qualitative models, solutions will not change imperceptibly with different instances of the same problem. Mathematical models will run comparatively fast and cheaply on the computer, thus allowing the analyst to discover and fill gaps in their formulation, to test the consequences of hypotheses, and to evaluate efficiently the impacts of a number of scenarios and strategies. In the past, large models of socio-economic systems have had a chequered record, partly because of naive expectations about their ability to make detailed and precise predictions, and partly because of inapt modelling paradigms.

The highly interconnected and intertwined social systems, the human creativity and intelligence that they embody, their holistic nature, their explicit temporal and spatial dynamics, and their irreversible evolution towards greater complexity, indicate that studying partial questions is at best debatable. Rather, an integrated approach is required, as represented in the concept of holistic management, referring to the notion that 'one must seek to understand the greater whole in order to understand its parts, not vice versa' (Savory, 1988). This same view is also important in systems analysis generally and is most essential in the 'Systems Dynamics' paradigm (Forrester, 1961). It further postulates that the understanding of the relations, causalities and feedbacks in the system is more essentially an aim of the modelling exercise than the exact description of the system.

These observations are also at the roots of chaos, fractals and self-organization. Prigogine (1981) proved that thermodynamically 'open systems', far from equilibrium conditions, obey different laws of thermodynamics in the sense that they can order themselves. They are said to self-organize; they become unstable and change their macroscopic structure due to microscopic fluctuations. Hence, the great strength of the paradigm resides in the explanation of the macroscopic structure of a system as the result of its internal microscopic characteristics. When applied to social systems, which by definition are open systems, this is a clear recognition of the role of the individual in structuring the greater system of which he or she is part.

The constant exposure of a socio-economic system to fluctuations, the uncertainty as to the moment when these will hit the system and the limited knowledge about their impact, the lack of knowledge of future values and norms, and the lack of insight in the evolution of the meta-system, not treated or explained by the model, suggest that it is nearly impossible to predict fully and exactly the future of the system. This belief contrasts with the assumptions of normative and predictive modelling techniques (Simmonds, 1986) based on equilibrium conditions and deterministic relations. It leans towards instrumentalism (Casti, 1989), a view that 'models should be judged by their usefulness as algorithms for correlating observations and ordering experiences, rather than the exact description of reality'. They remain valuable tools for examining complex systems as holistic units to clarify the important elements and linkages, to point to how the system may be most critically bounded, and to examine the relative merits of various scenarios and strategies. They can at best be used as tools to explore the different possible futures of the system, in order to take the necessary actions to pilot the system past the worst outcomes and to set a more desirable course. In such a way an interactive session between the decision-maker and the modelled system can avoid catastrophes and expensive experimentation with the real system. In principle, models consisting of a set of interconnected dynamic equations with non-linear positive feedback loops have the characteristics of chaos and self-organization, and a number of schools have developed regional dynamic models based on these paradigms (for examples see among others: White, 1977; Allen and Sanglier, 1979; Wilson, 1981; Engelen and Allen, 1986; Allen and McGlade, 1987; IERC and RIKS, 1992).

4 Modelling the Impact of Climatic Change on Socio-Economic Systems in the Region

In line with the assumptions accepted in 1985 at the International Conference in Villach (*cf.* Preface), we set out to construct a model that would predict the effects of increases of 1.5°C temperature and 20 cm sea-level by 2025. As mentioned before, the model should (1) take into account larger temperature increases at higher latitudes, and (2) it should capture the main social and economic characteristics and relations of nations in the region. Further, it should look at effects that (3) happen on a time horizon of at least 35 years (1985–2025), and are (4) influenced by world-scale external factors, both climatological and economical. It should deal with (5) the macro-economic effects of climatic change that directly affect the entire economic and social system, but (6) also with the direct effects (flooding, devastation, etc.) on a fairly narrow band of land adjacent to the sea as well as (7) the 'ripple' effects inland. The geographical resolution at which we should study the effects therefore must be sufficiently fine to see all these various influences. As part of a spatial decision-support system, the model also should allow the planner to change the characteristics of spatial zones, such as change of local topography, extract building material from the land or coral reefs, develop land for a specific purpose, etc. Moreover, the model should show the human-induced effects on the ecological system, to understand better how this will change with climatic change.

From the above we conclude that to model both long- and short-range interaction in a spatial system, as well as the associated dynamics, there should be a symbiosis of techniques such that the growth due to long-range mechanisms of interaction can be allocated in a spatially detailed way on the basis of short-range interaction. That is why we propose the coupling of a dynamic spatial interaction model with a cellular automaton model, both running on the same geographical data base, ideally a GIS. We have shown (White and Engelen, 1992) that such coupled models successfully simulate urban land-use dynamics, and believe that the technique can be extended to handle the dynamics of land use and land coverage in Gulf/Caribbean settings equally well.

In this approach, the system operates on two levels. Each level takes into account the interactions and dynamics that typify it, and thus requires specific spatial information. A substantial amount of this information is obtained from or passed on to the other level in a continual interchange as the system dynamics unfold. In general this sort of two-level model operates as follows (Fig. 16.2). At each time step:

1) The basic geographical data needed by the high-level, long-range model is retrieved from the data base. This is aggregated for the regions used in the high-level model and then passed to that model.
2) The high-level model calculates the derivatives (changes) for each variable in each region modelled and passes them to the cellular model.
3) The low-level cellular model receives the derivatives for each variable in each region as external input and allocates them on the basis of short-range interaction mechanisms. To do so, it may call up additional information from the data base.
4) The results of step [3] are used to update the data base, and they thus serve as an input at the next time step (return to step [1]).

While in general these models should be fully regionalized on both levels, in our prototype model only has a single region at the high-level, meaning that we assume no long-range spatial interaction. To test the framework presented so far, we have chosen to model a theoretical island having the general characteristics of several nations. The choice of a purely theoretical case allows us to concentrate on some general mechanisms before adding specific details. The size of the island is small (about 35 by 30 km), allowing us to assume that the spatial interactions on the short-range dominate the island dynamics. For larger islands or regions, this assumption will no longer hold, and the prototype model will have to be regionalized in its more generic versions.

The state variables, the set of variables describing the fundamental properties of the island at each particular point in time of the simulated period, have a one-to-one mapping in the high-level and the low-level model. In the high-level model, they refer to activities, residential or economic, while in the cellular model they are expressed in terms of the amount of land taken in by each function. The relation between the two is simple: each person requires a fixed amount of residential space, and to be productive each type of job requires a minimum amount of space. The state variables are:

	High-level model	*Low-level model*
1)	Total population	Residential land use
2)	Jobs in the local agriculture sector	Local agriculture land use
3)	Jobs in the export agriculture sector	Export agriculture land use
4)	Jobs in the tourist sector	Tourist land use
5)	Jobs in expatriate population sector	Expatriate land use
6)	Jobs in the construction sector	Quarries and gravel pits
7)	'Other' sector (retail, wholesale and manufacturing)	'Other' land use

Additional land uses in the low-level model include: coral reefs, beach area, mangrove area, fallow land and sea. 'Sea' is the no-land state,

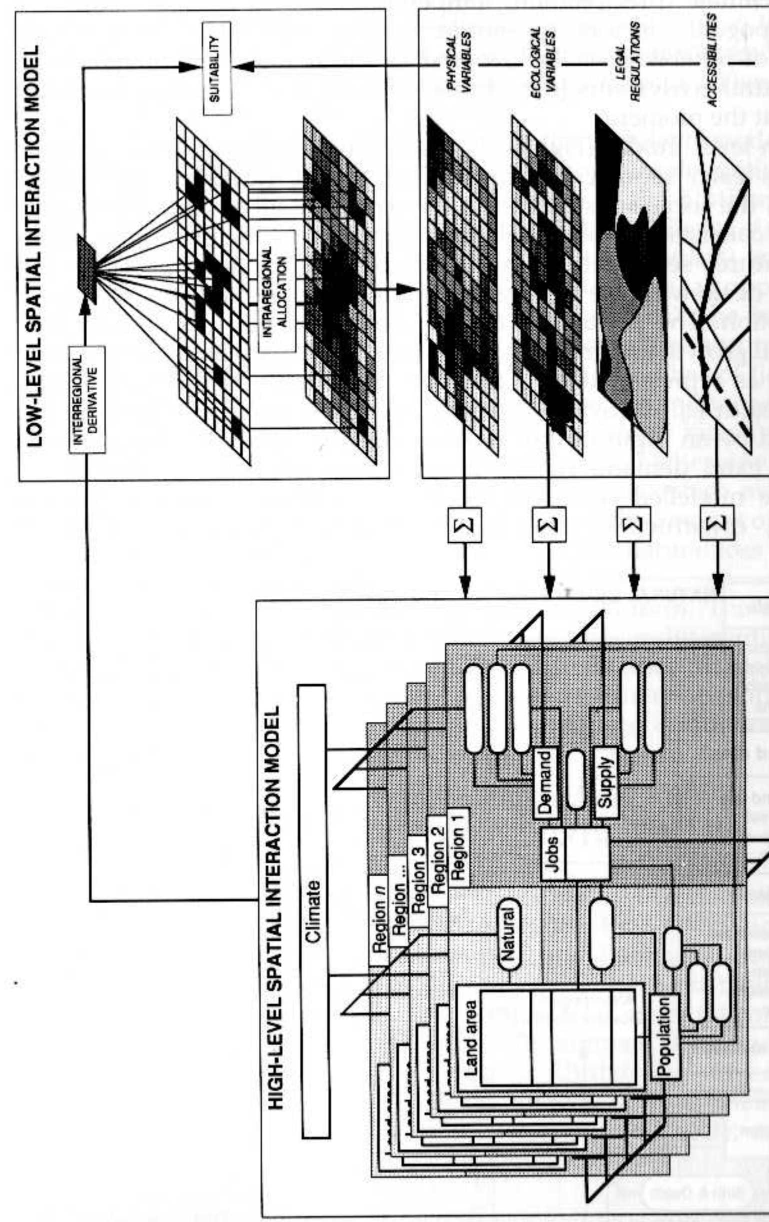

Fig. 16.2 A two-level model. On the high-level, long-range interactions are modelled by means of a dynamic spatial interaction model. The regional growth coefficients are fed into a low-level cellular model to perform the allocation on a detailed scale based on short-range interaction mechanisms. Both models will store and retrieve information from the same geographical data base.

determined by the absolute height of the sea level. The extent of 'coral reefs', 'beaches' and 'mangroves' is strongly influenced by natural factors related to climate (precipitation, temperature, storms and sea level) and by anthropogenic factors (economic activity and social welfare and behaviour of inhabitants). 'Fallow land' is the no-use state; it represents (other) natural ecosystems (e.g., tropical forest) as well as land not being cultivated at the moment.

The high-level model (Fig. 16.3) essentially consists of three coupled subsystems each represented by sets of linked variables: the natural subsystem, the social subsystem and the economic subsystem. The natural subsystem consists of a set of relations that express the evolution in time of temperature, sea level, precipitation, and storm activity. The social subsystem deals with the demographics of the island and the welfare of the population. The population of the island grows in a non-linear way; both natural growth and migrations depend on the well-being of the island population as represented by a function of the employment rate and by physical health (*cf.* de Sylva, Chapter 14). The economy of the island is represented by an input-output model, which is evaluated iteratively. At each step, extra demand (which might be negative) for products from each of the modelled economic sectors (subsistence agriculture, export agriculture, construction, tourism, services to expatriates, and 'other' sector), whether exogenous (external demand), endogenous (intersectoral demand) or due to population growth or consumer behaviour (final demand), is translated into new job opportunities. New jobs require suitable land for the associated production activities, and so the demand for new jobs in each sector is translated into sectoral demands for land, using current levels of land productivity for each sector. These demands are then passed onto the low-level model.

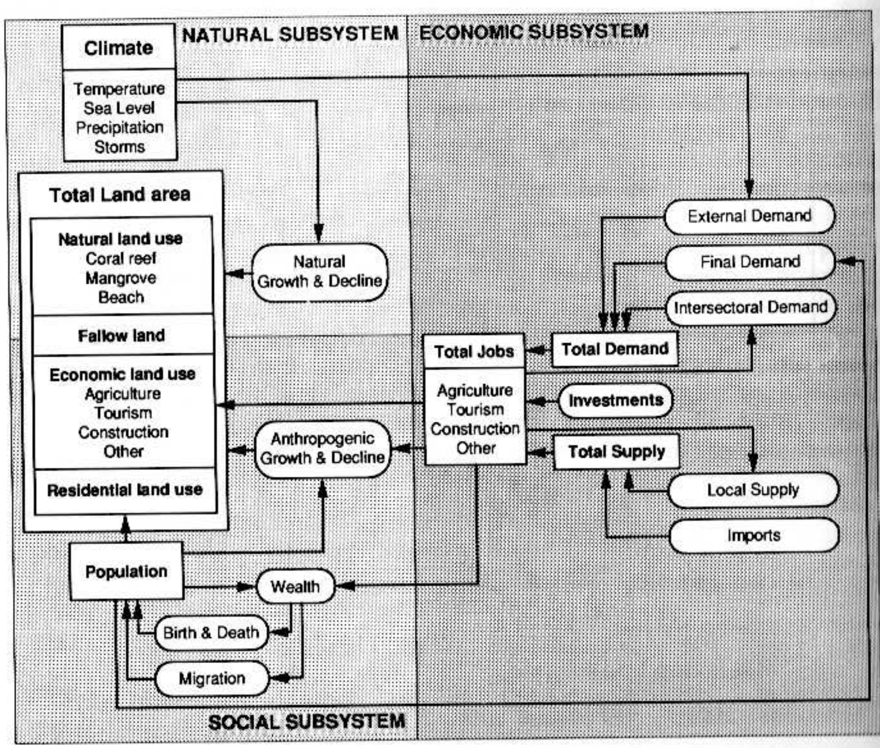

Fig. 16.3 Schematic representation of the high-level interaction model showing the loops linking the natural, the social and economic subsystem.

A number of feedback loops are built into the high-level model, the most essential of which are shown in Fig. 16.3. As an example, notice the influence of 'climate' (e.g., increase in temperature in the northern USA and Canada of 3°C and sea-level rise of 10 cm by 2025; *cf.* Gallegos *et al.*, Chapter 3) on the 'external demand' (a drop in number of tourists) and its effect on the 'total demand,' (for hotel facilities and services), as opposed to the existing 'supply' (existing hotel facilities and services), the imbalance of which will influence 'investments' (e.g., in construction and maintenance of hotels, and creation of new services) and the number of 'jobs' (in the tourism and construction sector). Notice further the influence of jobs on 'wealth,' influencing 'birth and death' and'migration' rates (e.g., a drop in the number of jobs in the tourist sector leads to higher unemployment rates, which influence people's decision to emigrate which may lead to a decreasing total population that in turn decreases the amount of residential land required). Notice also the loop indicating the natural loss of available land due to the rising sea level.

These relations are written out in mathematical form. The evolution of each of the state variables is governed by a non-linear differential equation. Due to the non-linear character of the equations and the high degree of linkage among the variables, the sets of equations can not be solved numerically; rather their simultaneous solution is simulated on the computer as a time trajectory for the state of the system.

5 Cellular Automata for Short-Range Spatial Interaction

The representation of spatial interaction common in models similar to our high-level model has the great merit of dealing with the intrinsic complexity of the systems modelled in the most explicit and direct way. Unfortunately, these models have a number of drawbacks, which limit their applicability in decision-making at a detailed geographical scale: (1) computational requirements make them impractical if the number of interacting spatial actors and geographical units is increased; (2) they are subject to the so-called 'scale problem' (Huggett, 1980), thereby limiting their validity to the spatial interactions at one specific geographical scale; and (3) they are incapable of dealing with the morphological aspects of growth on the inter- and intra-regional scale (Batty, 1991).

In contrast with the conventional dynamic interaction models in which the number of interacting regions must be severely limited, in the cellular automaton approach it is natural and feasible to use a very large number of cells or regions and thus to achieve great spatial detail. A cellular automaton consists of (Langton, 1986): (1) a Euclidean space, normally two-dimensional, divided up into an array of unit squares called cells;

(2) each cell is surrounded by a neighbourhood of the same size and geometrical shape; (3) each cell is in one of *n* discrete possible states (land-uses in our application); (4) transition rule(s) describe the new state of a cell as a function of its own state and the states of the cells in its neighbourhood; and (5) time progresses uniformly, and at each discrete time step, all cells simultaneously change state as defined in the transition rule(s).

Cellular automata are best known as games (Couclelis, 1985). One of the simplest but most widely studied models is certainly Conway's 'Game of Life' (Gardner, 1970). Although Tobler (1979) called cellular automata geographical models *par excellence*, they have hardly been used for modelling socio-economic phenomena, but have been applied more extensively to model spatial flow processes: surface and subsurface water flows (Maidman, 1991) or lava flows (Young and Wadge, 1990).

The approach has several advantages in the study of spatial phenomena. In the context of this chapter we mention:

1) Cellular automata allow extreme spatial detail. For many applications, such detail is crucial.
2) They tend to produce complex (Wolfram, 1986; Langton, 1986) and frequently fractal patterns.
3) They show, at least at the functional level, apparent similarities with the cartographic modelling known in GIS (Tomlin and Berry, 1979), and their linkage with GIS seems feasible.
4) Expanding on the previous point, the approach permits a straightforward integration of physical and environmental qualities in economic and social modelling; in contrast, virtually all regional models currently postulate uniform background conditions. This integration of socio-economic and environmental variables is certainly of major importance in the actual planning context.
5) Building a cellular automaton model and calibrating it are done in one and the same process. They are both accomplished with the definition of the correct rules for the transition functions. This type of direct manipulation makes the cellular automaton model into an excellent decision-support and learning tool, such as referred to in terms of Modelling by Example (MbE; Angehrn, 1991) or Visual Interactive Modelling (VIM; Bell *et al.*, 1984).

Since the model is designed primarily to investigate basic principles of regional spatial form, it is kept very simple. Nevertheless, since it must give a reasonable representation of diverse, competing land uses on an island, it is more complicated and more specific than the highly generic models like 'Forest Fire' or 'Game of Life'. It is specified as follows:

The island grows and evolves, in a non-isotropic space, as cells are converted from one state (type of land use) to another. Each cell is in one of 12 states (y), each representing a land use: sea, coral reef, beach, mangrove, fallow land, subsistence agriculture, export agriculture, tourism, expatriate housing, residential housing, construction, other (retail, wholesale, industry, office, etc.). The net number of cells (N_z) required by each non-vacant state (z) at each time step is determined by the high-level model. The fate of a cell at each iteration depends on the state

of the cell itself and the cells in its neighbourhood. For the island model, the neighbourhood consists of 113 cells, each of which falls within one of 19 discrete distance categories. The transition potentials for a cell are calculated as weighted sums:

$$P_z = f(s_z) * \sum_{d} \sum_{i} w_{z,y,d} * I_{d,i} + \epsilon_z \qquad (1)$$

where P_z is the transition potential to state z, $f(s_z)$ is a function expressing the suitability of cell for function z ($0 \le f(s_z) \le 1$), $w_{z,y,d}$ is the weighting parameter applied to cells with state y in distance zone d ($0 \le d \le 19$), i is the index of cells within a given distance zone d, $I_{d,i} = 1$ if the state of cell i in distance zone $d = y$, $I_{d,i} = 0$ if the state of cell i in distance zone $d \neq y$, and ϵ_z is a stochastic disturbance term.

Thus, cells within the neighbourhood are weighted differently depending on their state y and also depending on their distance d from the cell for which the neighbourhood is defined. Since different parameters can be specified for different distance zones, it is possible to build-in weighting functions that have distance-decay properties similar to those of traditional spatial-interaction equations. The function $f(s_z)$ is a measure of the physical suitability of the cell to receive the function z. Hence the cellular model retrieves from the data base (GIS) data on factors such as slope, elevation, soil conditions, legal constraints on use and access to transport, all of which affect the suitability of the cell for use by each function. To reflect the unknown factors in locational decisions, the deterministic transition potentials are subjected to a stochastic perturbation (ϵ_z). To select the N_z cells to receive the function z at each iteration, the potentials calculated for each cell for transition to a particular state are ranked. The N_z cells with the highest potentials are identified and the transformations executed.

The suitability factors for all cells actually occupied by a particular activity are monitored, and changes in average suitability for the activity are passed back to the high level which results in further changes in productivity parameters. In other words, the detailed land suitabilities and land-use patterns in the lower level of the model are reflected in changes in the specification of the high level. The micro-scale geography thus affects the global dynamics directly and continuously.

The model currently is being verified, and a sensitivity analysis is being performed to investigate the behaviour of the model under various combinations of parameter values. Thus, for example, the effects of different proportions of the 11 functions, of different growth rates, and of different levels of stochastic disturbance are being examined. Most of these results are unexceptional and will not be described here. No calibration as such has been performed since no particular island is being modelled, rather, general principles of spatial reorganization induced by climatological changes are being explored. Nevertheless, some sets of parameter values give more reasonable results than others, while some yield patterns that bear no conceivable resemblance to any actual island. It is therefore encouraging that patterns of parameter values which represent known locational preferences are also the ones which generate the most realistic looking islands. This does not guarantee, however, that the prototype model can be applied directly to a real Caribbean-region island or mainland state. To prove its applicability to any particular case, an exhaustive validation and calibration process will be required. Fig. 16.4 shows four stages in the growth of one cellular island.

6 Implementation of the Decision-Support Environment

As stated earlier, our long-term aim is to develop a spatial decision-support system allowing policy analysts to anticipate, explore and counter the risks associated with climate change for island and coastal nations in the region. As part of the model base of such a system, the prototype island model should evolve into a more generic tool. It should be clear, however, that one model does not constitute a full decision-support system. Indeed, we mentioned that additional tools must be incorporated to ease the job of the user. A number of additional models could be added into the model base. These should perform tasks complementary or supplementary to the ones done by the (enhanced) island model; for example, calculation of storm damage, soil-erosion sedimentation in deltas, which could include climatological or hydrological models and an age-cohort model for detailed demographic evolution. Typical decision models, allowing us to formulate, compare, evaluate, rank and select solutions among a set of alternatives and graphical interface tools supporting the input of data, the retrieval and presentation of output data and model results, should also be added. Already in the prototype, effort has gone into the implementation of such tools.

The system is currently being developed in MS-Windows 3 on top-range IBM-PC compatible computers, equipped with 80386 or 80486 processor and 8 Mb of RAM, and has a fully graphical interface (Fig. 16.5). This platform has the great advantage of being widely available and is sufficiently powerful to perform the calculations required within reasonable time limits. The system will allow the user to specify interactively his or her own applications. This will include decisions on the number of functions to be modelled as well as the resolution and size of the grid (currently a grid of 80 by 80 cells is being used). To start a new application, the user will import a land-use matrix from an existing application (e.g., GIS), or will enter it by means of the built-in 'land-use editor' through mouse-clicking. Similarly, data will be entered to calculate the suitabilities. The transition functions are introduced in a graphical way as well. The user disposes of a tool, mainly consisting of an X-Y graph, in which he can draw, by mouse-clicking, the distance-decay function defining the probability of transition of one type of land use into any other type, or he can select a specific distance-decay function from a library-list previously stored. The DSS environment is being enhanced with a number of dedicated tools for easy and interactive definition of policy strategies (e.g., changing land uses deliberately, influencing the suitabilities or constituent factors, etc.), and to compare and evaluate the outcomes of different scenarios.

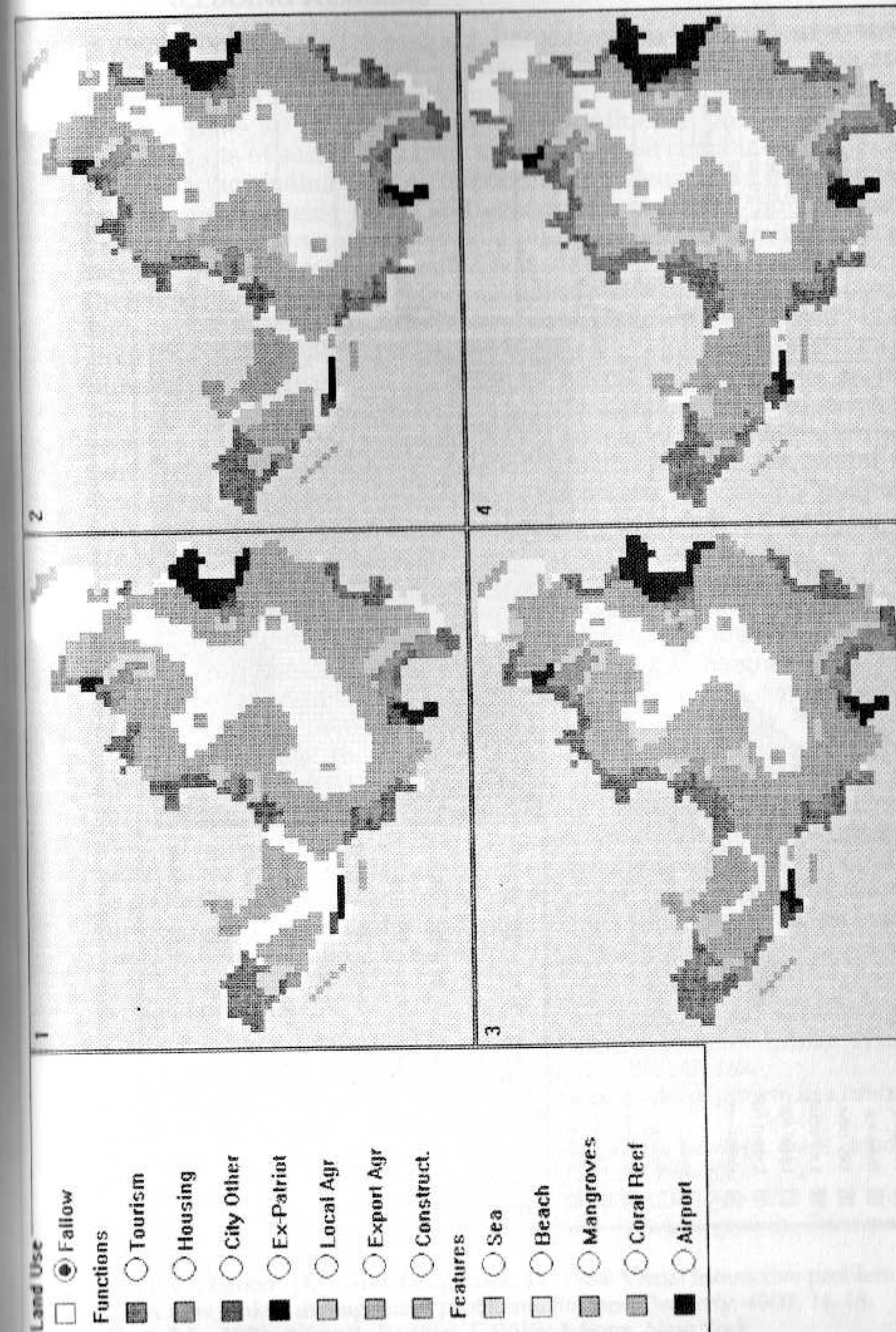

Fig. 16.4 Four stages in the evolution of a hypothetical island. See colour plates between pages 210 and 211.

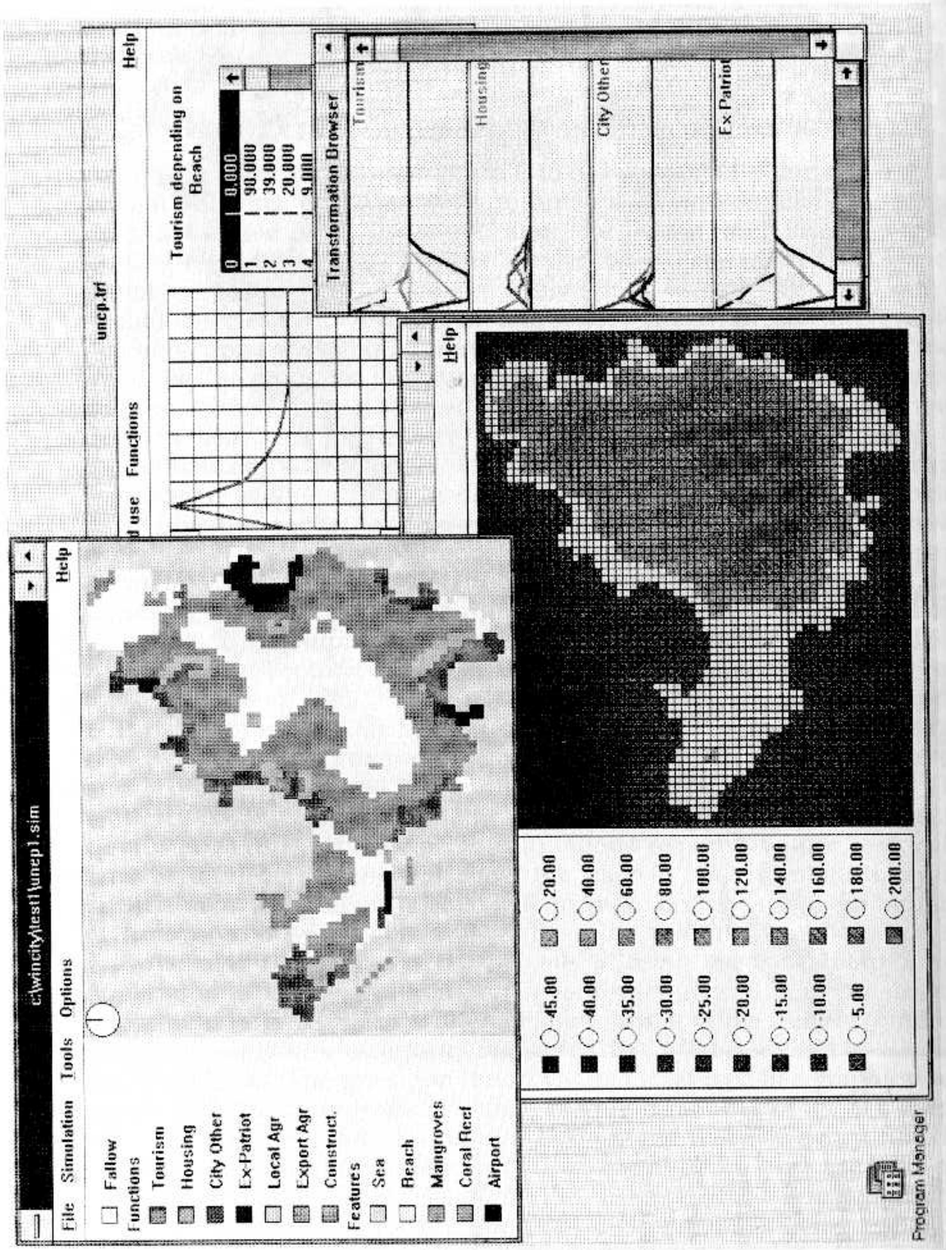

Fig. 16.5 The graphical user interface of the prototype decision-support environment. See colour plates between pages 210 and 211.

7 Concluding Remarks

A model-based decision-support framework should lead to a strategic policy tool that allows decision-makers to explore and to evaluate the possible effects of a changing climate, thereby helping them to formulate policy actions for countering any baleful influence. Among the essential requirements of such a framework it should treat climatic change as a new problem exacerbating existing or potential problems. As a world-wide phenomenon influencing social and economic behaviour, climatic change is likely to have economic effects on a macro- as well as a micro-scale in the mostly small and export oriented societies of the region. These societies, therefore, should be modelled as holistic systems, with their working and organization being subject to perturbations from abroad, but also from within the system. The time horizon of the problem at hand, the different geographical scales at which effects will be visible, as well as the importance of rather detailed physical features and ecosystems of the societies studied, lead us to propose a two-level modelling approach, in which at the high level a classical, regionalized spatial-interaction model deals with the long-range social and economic interaction mechanisms and exchanges in a cyclic process information with a low-level, short-range cellular model. The cellular model reads data such as physical and environmental characteristics from a geographical data base, ideally an existing GIS. Based on local interaction mechanisms, these serve to translate the growth coefficients received from the high-level model into detailed land-use changes. When two models are integrated in this way, their joint behaviour typically will be more realistic and complex than that of either component in isolation.

We have set out to develop a prototype model of a purely theoretical island, but have tried to incorporate in it as much as possible the typical characteristics of island nations. Initially this allows us to concentrate most of our attention on the variables, mechanisms and causalities to incorporate in the model at the most generic level. It also should allow us to test our hypotheses and to come to define better data requirements, further scientific analysis, and the desired functionality of the decision environment we set out to develop.

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17

Glossary of Scientific Terms

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Abstract

Scientists use terms that can make a treatise such as *Climatic Change in the Intra-Americas Sea* inaccessible to non-specialists, and in particular to management and policy makers not trained in the natural sciences. To overcome this difficulty, this glossary of terms covering some aspects of oceanography, geodesy, meteorology, ecology, and climatology has been included. The terms and abbreviations selected for inclusion are mostly those that have appeared in the text; the meanings are meant to be scientific rather than legal. We have freely paraphrased many of the definitions from more recent sources (Baker et al., 1966; Bates and Jackson, 1980; NOAA, 1988) without explicit acknowledgement in order to minimize text, and we have also cross-referenced some of the older texts (Sverdrup et al., 1942; Mitchell, 1948; Huschke, 1959). The reader is referred to the several sources listed below for more information, but is cautioned that terms and meanings change with time (Maul, 1988). For the future, it is urged that a multi-lingual glossary be created for the region, one that includes more information on socio-economic and public health terms.

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