18th World IMACS / MODSIM Congress, Cairns, Australia 13-17 July 2009
http://mssanz.org.au/modsim09

Climate change impacts and adaptation in Bangladesh: An agent-based approach

Angus, S.D. [1], **Parris, B.** [2,3] **and Hassani-M., B.** [2]

[1] *Department of Economics, Monash University, Clayton, Victoria.*
[2] *Department of Econometrics & Business Statistics, Monash University, Clayton, Victoria.*
[3] *World Vision Australia, Burwood East, Victoria.*
Email: Simon.Angus@buseco.monash.edu.au

Abstract: Bangladesh exemplifies the complex challenges facing densely populated coastal regions. The pressures on the country are immense: around 145 million people live within an area of just 145,000 sq-km at the confluence of three major river systems: the Ganges, the Brahmaputra and the Meghna. While progress has been made, poverty remains widespread, with around 39% of children under five malnourished. Most of its land-mass lies below 10m above sea level with considerable areas at sea level, leading to frequent and prolonged flooding during the monsoons. Sea level rise is leading to more flooding as storm surges rise off higher sea levels, pushing further inland. Higher sea levels also result in salt-water intrusion into freshwater coastal aquifers and estuaries, contaminating drinking water and farmland. Warmer ocean waters are also expected to lead to an increase in the intensity of tropical storms.

Bangladesh depends on the South Asian summer monsoon for most of its rainfall which is expected to increase, leading to more flooding. Climate scientists are also concerned about the stability of monsoon and the potential for it to undergo a nonlinear phase shift to a drier regime. Bangladesh faces an additional hydrological challenge in that the Ganges and Brahmaputra rivers both rise in the Himalaya-Tibetan Plateau region, where glaciers are melting rapidly. The Intergovernmental Panel on Climate Change (IPCC) concluded that rapid melting is expected to increase river flows until around the late-2030s, by which time the glaciers are expected to have shrunk from their 1995 extent of 500,000 sq-km to an expected 100,000 sq-km. After the 2030s, river flows could drop dramatically, turning the great glacier-fed rivers of Asia into seasonal monsoon-fed rivers. The IPCC concluded that as a result, water shortages in Asia could affect more than a billion people by the 2050s. Over the same period, crop yields are expected to decline by up to 30% in South Asia due to a combination of drought and crop heat stress. Bangladesh is therefore likely to face substantial challenges in the coming decades.

In order to adequately understand the complex, dynamic, spatial and nonlinear challenges facing Bangladesh, an integrated model of the system is required. An agent-based model (ABM) permits the dynamic interactions of the economic, social, political, geographic, environmental and epidemiological dimensions of climate change impacts and adaptation policies to be integrated via a modular approach. Integrating these dimensions, including nonlinear threshold events such as mass migrations, or the outbreak of conflicts or epidemics, is possible to a far greater degree with an ABM than with most other approaches.

We are developing a prototype ABM, implemented in Netlogo, to examine the dynamic impacts on poverty, migration, mortality and conflict from climate change in Bangladesh from 2001 to 2100. The model employs GIS and sub-district level census and economic data and a coarse-graining methodology to allow model statistics to be generated on a national scale from local dynamic interactions. This approach allows a more realistic treatment of distributed spatial events and heterogeneity across the country. The aim is not to generate precise predictions of Bangladesh's evolution, but to develop a framework that can be used for integrated scenario exploration. This paper represents an initial report on progress on this project. So far the prototype model has demonstrated the desirability and feasibility of integrating the different dimensions of the complex adaptive system and, once completed, is intended to be used as the basis for a more detailed policy-oriented model.

Keywords: *Bangladesh, South Asia, climate change, adaptation, agent-based model*

1. INTRODUCTION

Bangladesh exemplifies the complex challenges facing densely populated coastal regions. The pressures on the country are immense: around 145 million people live within an area of just 145,000 sq-km at the confluence of three major river systems: the Ganges, the Brahmaputra and the Meghna. While progress has been made, poverty remains widespread, with around 39% of children under five malnourished (World Bank, 2008). Most of its land-mass lies below 10m above sea level with considerable areas at sea level, leading to frequent and prolonged flooding during the monsoons. Sea level rise is leading to more flooding as storm surges rise off higher sea levels, pushing further inland. Higher sea levels also result in salt-water intrusion into freshwater coastal aquifers and estuaries, contaminating drinking water and farmland. The impact of climate change on the frequency of tropical storms is uncertain, but the sea-surface temperature over the North Indian Ocean has warmed by about 0.6º C since 1960 and warmer ocean waters are expected to lead to an increase in the intensity of tropical storms (Yu & Wang, 2009; IPCC, 2007a, p. 15).

Bangladesh depends on the South Asian summer monsoon for most of its rainfall. A multi-model study for South Asia projected "a significant increase in mean monsoon of 8% and a possible extension of the monsoon period" with an intensification of both extremely heavy and extremely deficient monsoons (Kripalani *et al.* 2007). Climate scientists are also concerned about the stability of monsoon and the potential for it to undergo a nonlinear phase shift to a drier regime (Lenton *et al.* 2008, p. 1790). A recent fine-scale study noted the potential for climate change to weaken monsoon overall across the sub-continent, an average decline in summer rainfall, a delay in the onset of monsoon and more monsoon break periods, but also potentially increased rainfall in Bangladesh, which would lead to more flooding (Ashfaq *et al.* 2009).

Bangladesh faces an additional hydrological challenge in that the Ganges and Brahmaputra rivers both rise in the Himalaya-Tibetan Plateau region, where glaciers are melting rapidly. Glacial meltwater provides as much as 70% of the summer flow in the Ganges and 50-60% for other major rivers in the region (Barnett *et al.* 2005, p. 306). But temperatures on the Tibetan Plateau have risen three times faster than the global average for the last 50 years (Qiu, 2008). The Intergovernmental Panel on Climate Change (IPCC) concluded that rapid melting is expected to increase river flows until around the late-2030s, by which time the glaciers are expected to have shrunk from their 1995 extent of 500,000 sq-km to an expected 100,000 sq-km (Cruz *et al.* 2007, pp. 493). After the 2030s, river flows could drop dramatically, turning the great glacier-fed rivers of Asia into seasonal monsoon-fed rivers. The IPCC concluded that as a result, water shortages in Asia could affect more than a billion people by the 2050s. Over the same period, crop yields are expected to decline by up to 30% in South Asia due to a combination of drought and crop heat stress (IPCC, 2007b, p. 13).

It seems then that Bangladesh could experience a phase shift in future climatic conditions: An initial period of more frequent and intense flooding as the Himalayan glaciers melt and monsoon rainfall increases, followed after the 2030s by a more uncertain period when glacier meltwaters decline dramatically, monsoons become more uncertain and variable, crop losses increase from heat and drought, and humanitarian and security concerns start to dominate as the entire region experiences major water and food shortages. Bangladesh is therefore likely to face substantial challenges in the coming decades. But the country has also made significant progress on disaster preparedness, helping to reduce mortality from more than 300,000 in the 1971 cyclone to just over 4,000 in Cyclone Sidr in 2007 (Luetz, 2008, p. 106).

In order to adequately understand the complex, dynamic, spatial and nonlinear challenges facing Bangladesh, an integrated and appropriately scaled model of the system is required. An agent-based model (ABM) permits the dynamic interactions of the economic, social, political, geographic, environmental and epidemiological dimensions of climate change impacts and adaptation policies to be integrated via a modular approach. Integrating these dimensions, including threshold effects such as mass migrations or the outbreak of conflict or epidemics, is possible to a far greater degree with an ABM than with most other approaches (Boulanger & Bréchet, 2005). We are developing a prototype ABM, implemented in Netlogo (Wilensky, 1999), to examine the dynamic impacts on poverty, migration, mortality and conflict from climate change in Bangladesh from 2001 to 2100. This paper represents an initial report of progress on this project. The model employs GIS and sub-district level census and economic data and a coarse-graining methodology to allow model statistics to be generated on a national scale from local dynamic interactions. This approach allows a more realistic treatment of distributed spatial events and heterogeneity across the country. The aim is not to generate precise predictions of Bangladesh's evolution, but to develop a framework that can be developed for integrated scenario exploration, to help inform future plans similar to the official *Bangladesh Climate Change Strategy and Action Plan 2008* (MoEF, 2008). Our goal is to learn lessons from the development of this simple prototype model which can be applied to the development of a more sophisticated model, similar in scope to the EURACE ABM of Europe (Deissenberg *et al.* 2009), that will be of use to policymakers.

2. MODELLING APPROACH

2.1. Overview

Many of the traditional approaches to the economic modelling of climate change impacts and responses have been heavily criticized for their reliance on smooth, linear equilibrium approaches which presume perfect information, perfect competition, complete networks, spatial homogeneity and unique equilibria, among other things (e.g. by DeCanio, 2003 and Ackerman, 2008). Rather than using a Computable General Equilibrium (CGE) methodology then, which would provide a mean-field approximation to the phenomena under investigation, we will allow key non-linear effects to emerge from the interactions of discrete agents. For instance, threshold effects in external and internal migration, in political stability, and in food and water supplies are likely to be vital in shaping the more or less resilient development pathways for Bangladesh. To accommodate such effects, each critical component of the overall economic system is implemented in a scaled and inter-connected way. Our approach is to build an *agent-based*, *scaled* and *verifiable* model of the key components of Bangladesh's economic, social and demographic characteristics, using the results of climate model of the region as a data input. For simplicity we ignore the possible feedback from Bangladesh's development trajectory on the climate, since this is likely to be negligible compared with global forcing from the rest of the world's emissions.

The model is *agent-based* in that interactions take place within a population of discrete heterogeneous agents which include people, households, districts, the government, the rest of the world and the climate itself. In this way, through initialisation and then repeated updating of state-variables, the model represents an adaptable framework to run development response experiments over a long time horizon. We report below the main features of the approach and the rationale for their adoption.

2.2. Temporal scaling

Our aim is to produce development and climate impact pathways over a 100 year time-horizon. With such a long time-scale, the choice of model time-resolution is critical since it can have significant cumulative ramifications. The time-resolution choice is complicated further by the mixture of event time-scales expected in the model. Major harvests and weather patterns (dry, monsoon) occur approximately every six months, though not in phase, while crisis events such as epidemics, cyclones or floods can take as little as a few days to occur (and many months for their full impact to be realised).

A lower bound for the time-resolution is provided by computational considerations. For instance, a time-resolution of one day would require 36,525 model updates per run. Since we wish to produce statistical quantities of output data over several IPCC climate scenarios (not to mention further robustness tests over any free-parameter ranges) a coarser resolution is desirable. On the other hand, the time-scale on which significant events are expected to occur must provide an upper bound. Since our approach emphasises the interaction between the economy and the environment, with particular emphasis on extreme weather events such as cyclones, floods and storm surges, a time resolution of three months would be unlikely to afford the model sufficient adaptability to respond to significant shifts in either the economic or environment inputs. Balancing these considerations, we have opted for a time-scale of *one week per update*, thus reducing the count of model updates to 5,200 over the 100 year period while ensuring that most significant model events have at least a few updates in which to take effect.

2.3. Spatial, demographic and other scaling considerations

Given that Bangladesh's population numbers over 145 million, and inhabits 6 Divisions, comprised of 64 *zilas* (districts) or 493 *upazilas* (sub-districts), there are several decisions to be made for agent-scaling in the model. While it may be intuitively appealing to carry out a one *Person* agent per real person approach, one must consider the potential interactions that *n* objects can undergo. Whilst the maximal count of such interactions scales in polynomial order, even after applying a localisation criterion these interactions would be overwhelming on the scale of Bangladesh's underlying population, and so we believe the setup demands *many-to-one* scaling.

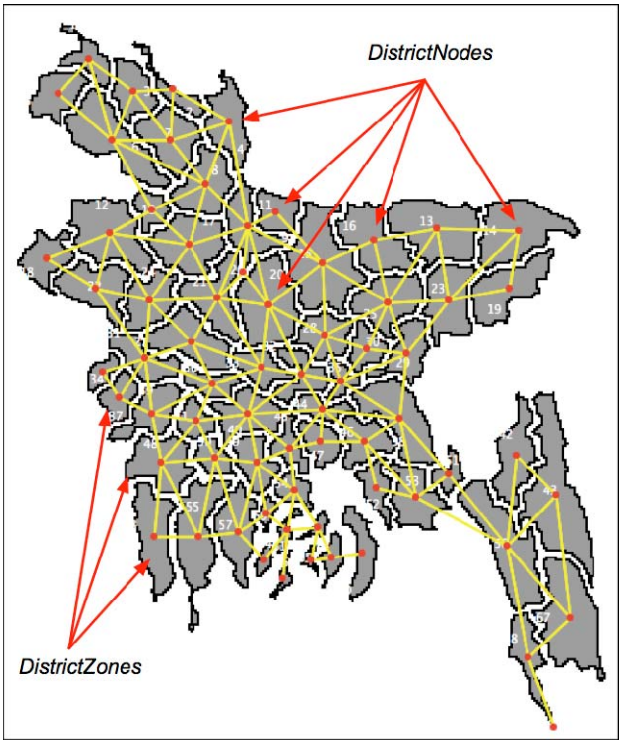
In this domain we have decided on approximately 10,000 *Person* agents as a somewhat arbitrary upper bound based on the computational capability of our software and hardware after some experimentation, and the desire to see what is possible to implement on a standard desktop machine with careful scaling and aggregation choices. This desire arises from a consideration of the equipment most likely to be available in developing country settings. In our view, if we can obtain useful results while avoiding the need for supercomputers or large clusters then so much the better. The architecture is intended to be scalable however, for when high performance facilities are available for more detailed work. This assumption means that each *Person* agent represents around 14,500 people in terms of his or her production and consumption, in the manner of super-individuals described by Schaffer *et al.* (1995) and Parry and Evans (2008). The *Person* agents are grouped together in family groups and households just as individual people would be. While not perfect, this approach, followed by Parris (2006) for a demographic ABM of Tanzania, strikes a useful balance between the need to model individuals, so that children's development, gender effects, illness, education, births and deaths can all be modelled explicitly, while reducing the computational burden imposed by the larger-scale production and consumption that would normally undertaken by that number of real individuals.

This decision to use super-individuals was guided by a parallel decision regarding the spatial resolution of the model, that is, the number and layout of the *DistrictZones*. Here, the resolution of available input data, desired output statistics and computational ability are all relevant. Since there are many data sources that pertain to Bangladesh's 64 *zilas*, they are an obvious first option. Using *zilas* results in the pleasing property that each district-zone in the model will be inhabited by over 150 *Person* agents grouped into approximately 20 *Households*. These figures provide the desired level of diversity for measures such as population demographics and economic activity and engagement. The other available computationally feasible jurisdictions, namely Divisions, would dramatically reduce the diversity of *Person* agents within a *DistrictZone*, which is undesirable.

As integrators of economic activity (both farm and non-farm) and all data pertaining to *DistrictZones* we also include 64 static *DistrictNodes* which are located at the centroids of the 64 *zilas*. We have adapted GIS data to locate our *DistrictZones* and thus *DistrictNodes*. Both components of the model can be seen in **Fig. 1**.

As can be seen in the figure, we conceive of the *DistrictNodes* as nodes in a district neighbourhood network such that decisions made at the district level by the *DistrictNodes* can operate on information from neighbouring districts. Similarly, information of a diverse nature (e.g. political, topographic etc.) can be incorporated into the *DistrictZone* layer and so feed into the *DistrictNodes'* methods. While Figure 1 demonstrates the generation of the district neighborhood network layer, it is also possible to generate other network layers such as an agent transport layer which takes as an input the time-resolution decision such that a network of feasible node-to-node journeys are generated in (say) seven days. All network connections can of course be weighted by relevant statistics pertaining to road carrying capacities and/or inter-district transport options (e.g. road, rail, air, sea).

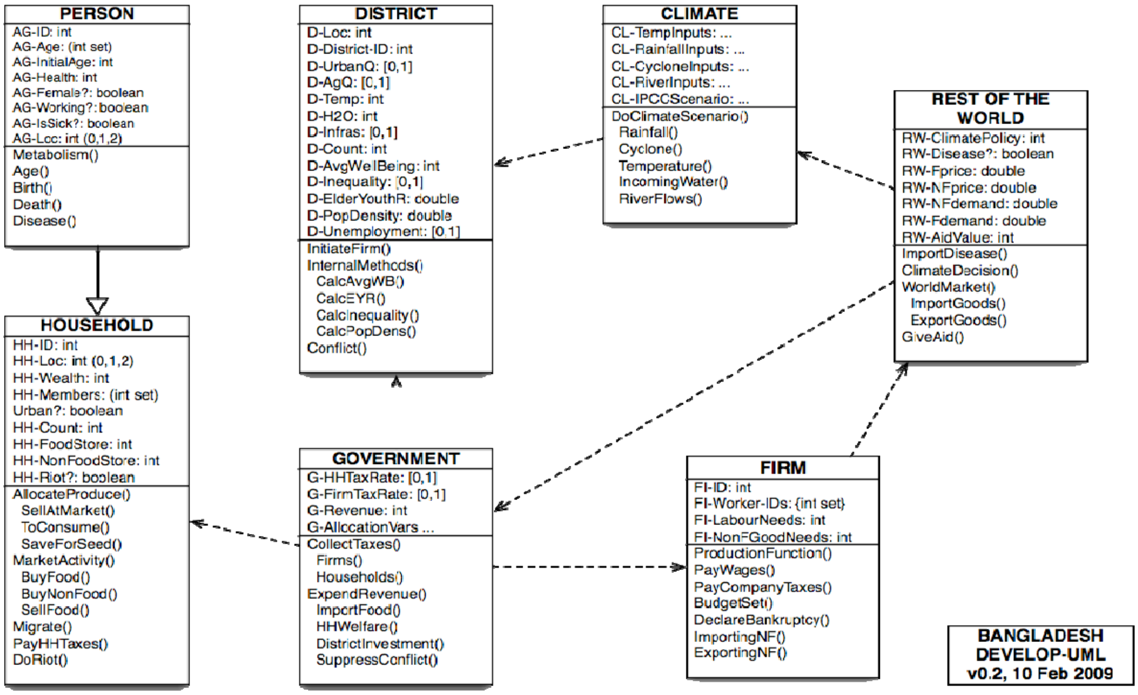
Figure 1: The resultant combined GIS layer and DistrictAgents/ModelZone network layer representation of the spatial model environment.



2.4. Other agents

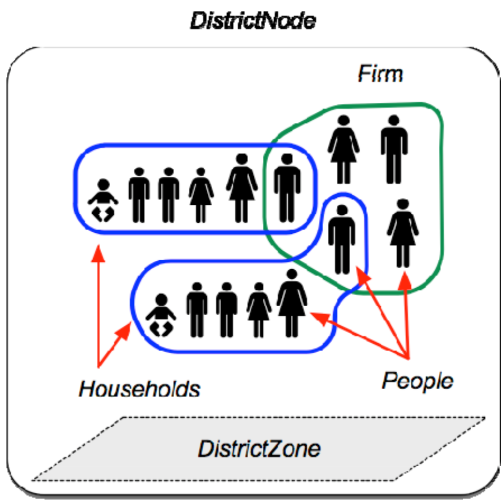
A stylised summary of the key agents in the model to be discussed is presented in the indicative Unified Modeling Language (UML) chart seen in **Fig. 2** and in the relational diagram in **Fig. 3**. In addition to the *People* and *DistrictNodes*, *Households* (comprised of a collection of *People*) facilitate actions and decisions at the household/family level such as family migration, family planning and family income/budget setting. The *Households* also importantly represent food/farm economic activity. Alternatively, urban/non-farm economic activity is represented by *Firms* who interact with buyers in the market to generate prices and transfers of food and non-food products. Next, the climatic influence is represented by the *Climate* agent which takes the particular IPCC scenario under investigation as an input and generates river-flow, rainfall, temperature and importantly extreme weather data for all districts in the model, including river flows originating outside Bangladesh.

Figure 2: Draft Unified Modeling Language (UML) class diagram for the model, showing key agents and linkages between agents.



Finally, the *RestOfTheWorld* agent is relatively simple, but is important to drive export/import and migration in the model. This agent must not only represent near-neighbour effects and actions but also trading-partner nations. It is possible that this agent will be split along direct-neighbour, far-neighbour lines in future implementations of the model. Lastly, the government, the main implementer of policy, is modelled as a single *Government* agent, responsible for taxation, price policies, import and export policy setting and migration laws. As with the *RestOfTheWorld*, the *Government* will likewise be a focus of robustness testing since large variation in government activity is very likely.

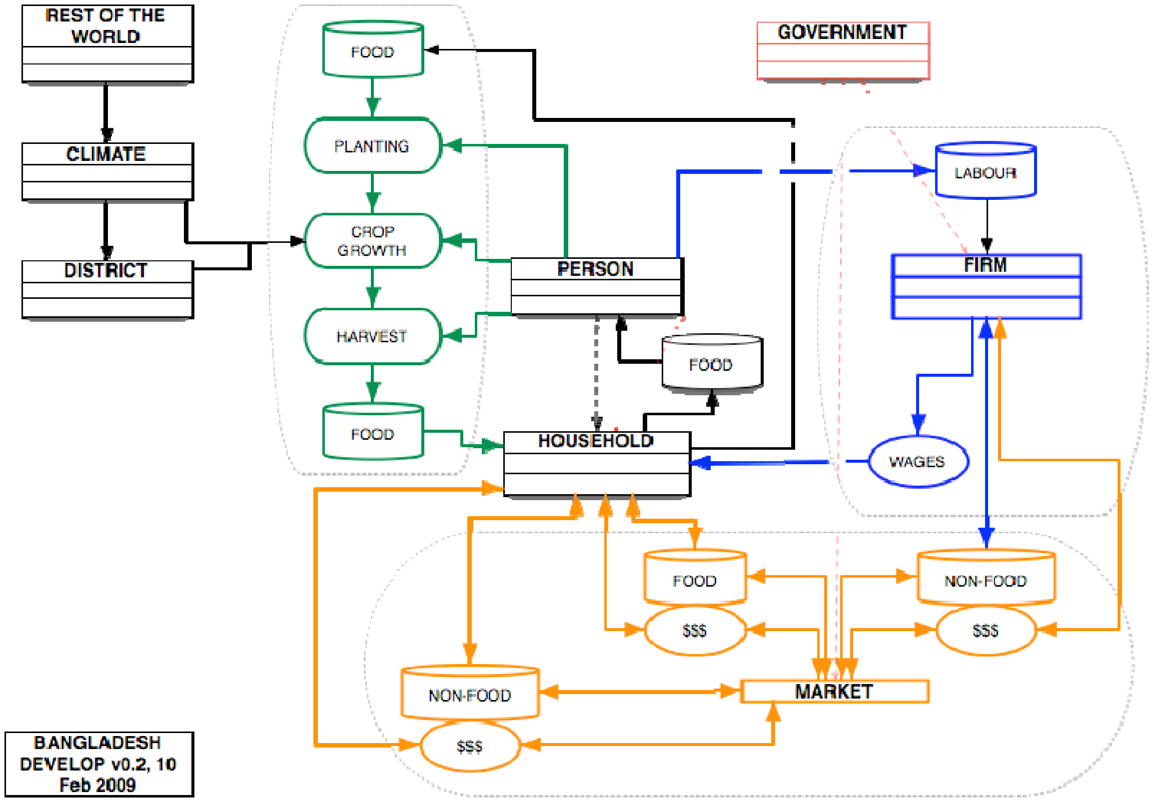
Figure 3: The relationship between People, Households, Firms, DistrictZones and DistrictNodes in the proposed approach.



2.5. Interactions

While the precise interactions of each agent in the model are the focus of our current work in this early stage of the project, an indicative relational diagram of our intentions is given in **Fig. 4** below. The proposed approach takes seriously the path-dependence of such elements as agricultural production. In Bangladesh, average monthly rainfall varies between 7 mm and over 480 mm, so planning decisions by households and subsequent rainfall activity will have major impacts on the viability of crops. This importance is reflected in the multi-stage crop cycle we propose as shown in the diagram, and the associated UML methods for households and districts. At this stage, a simple two-good market (food and non-food) is established between the urban and non-urban sectors of the districts.

Figure 4: Indicative model schematic showing major anticipated interactions and functions.



3. DISCUSSION AND CONCLUSIONS

The modelling approach, as described above and presently under development, has the potential to offer useful insights to the long-run outcomes for Bangladesh's policy options in response to climate change. It should be stressed that the above approach and associated model represents a *pilot, 'proof-of-concept' model* leading to a more elaborate design in the future. Nonetheless, the pilot offers sufficient detail and complexity to test our assumptions concerning key components and the importance of non-linear feedbacks and threshold events in this modelling domain.

Furthermore, while the model appears to have many free variables, it should be noted that since we are aiming for a scaled approach, a significant portion of the inputs will appear as constants in the model, derived from statistical and econometric analysis of the relevant source data. The long-run climate projections will come from the multi-model Program for Climate Model Diagnosis and Intercomparison (PCMDI) (see: http:www-pcmdi.llnl.gov/). Bangladesh also maintains an excellent central statistical agency (see: http://www.bbs.gov.bd/) which provides several key data series and projections at the *zila* (district) level.

ACKNOWLEDGMENTS

The authors wish to thank the Faculty of Business and Economics at Monash University for the provision of a Faculty Pilot grant that supported this work.

REFERENCES

Ackerman, F., (2008) *Can We Afford the Future? The Economics of a Warming World*, The New Economics Series; Zed Books, London & New York.

Ashfaq, M., Shi, Y., Tung, W.-w., Trapp, R.J., Gao, X., Pal, J.S. and Diffenbaugh, N.S., (2009) "Suppression of South Asian Summer Monsoon Precipitation in the 21st Century", *Geophysical Research Letters*, 36, L01704, 3 January.

Barnett, T.P., Adam, J.C. and Lettenmaier, D.P., (2005) "Potential Impacts of a Warming Climate on Water Availability in Snow-Dominated Regions", *Nature*, 438(7066), 17 November, 303-309.

Boulanger, P.-M. and Bréchet, T., (2005) "Models for Policy-Making in Sustainable Development: The State of the Art and Perspectives for Research", *Ecological Economics*, 55(3), 15 November, 337-350.

Cruz, R.V., et al., (2007) "Asia", In *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E.; Cambridge University Press, Cambridge & New York, 469-506.

DeCanio, S.J., (2003) *Economic Models of Climate Change: A Critique*, Palgrave Macmillan, New York & Houndmills, Basingstoke, UK.

Deissenberg, C., van der Hoog, S. and Dawid, H., (2008) "EURACE: A Massively Parallel Agent-Based Model of the European Economy", *Applied Mathematics and Computation*, 204(2), 15 October, 541-552.

IPCC, (2007a) "Summary for Policymakers", In *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed. Solomon, S., Qin , D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L.; Cambridge University Press, Cambridge & New York, 1-17.

IPCC, (2007b) "Summary for Policymakers", In *Climate Change 2007: Impacts, Adaptation and Vulnerability*. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed. Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J. and Hanson, C.E.; Cambridge University Press, Cambridge & New York, 7-22.

Kripalani, R.H., Oh, J.H., Kulkarni, A., Sabade, S.S. and Chaudhari, H.S., (2007) "South Asian Summer Monsoon Precipitation Variability: Coupled Climate Simulations and Projections Under IPCC AR4", *Theoretical and Applied Climatology*, 90(3-4), November, 133-159.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S. and Schellnhuber, H.J., (2008) "Tipping Elements in the Earth's Climate System", *Proceedings of the National Academy of Sciences of* the United States of America, 105(6), 12 February, 1786-1793.

Luetz, J., (2008) *Planet Prepare: Preparing Coastal Communities in Asia for Future Catastrophes*, World Vision International, Asia-Pacific Regional Office, Bangkok.

MoEF, (2008) *Bangladesh Climate Change Strategy and Action Plan 2008*, Dhaka, Ministry of Environment and Forests, Government of the People's Republic of Bangladesh, September. http://www.moef.gov.bd/moef.pdf

Parris, B.W., (2006) *Modelling Economic Development Policy: Econometric, General Equilibrium and Agent-Based Perspectives*, PhD Thesis; Monash University, Melbourne.

Parry, H.R. and Evans, A.J., (2008) "A Comparative Analysis of Parallel Processing and Super-Individual Methods for Improving the Computational Performance of a Large Individual-Based Model", *Ecological Modelling*, 214(2-4), 24 June, 141-152.

Qiu, J., (2008) "The Third Pole", *Nature*, 454(7203), 24 July, 393-396.

Scheffer, M., Baveco, J.M., DeAngelis, D.L., Rose, K.A. and van Nes, E.H., (1995) "Super-Individuals: A Simple Solution for Modelling Large Populations on an Individual Basis", *Ecological Modelling*, 80(2-3), July, 161-170.

Wilensky, U., (1999) *NetLogo*, http://ccl.northwestern.edu/netlogo/, Evanston, IL, Center for Connected Learning and Computer-Based Modeling, Northwestern University.

World Bank (2008) 'Bangladesh at a Glance' http://devdata.worldbank.org/AAG/bgd_aag.pdf

Yu, J. and Wang, Y., (2009) "Response of Tropical Cyclone Potential Intensity over the North Indian Ocean to Global Warming", *Geophysical Research Letters*, 36, L03709, 14 February, 5 pp.