Integrating Disaster Risk Reduction and Climate Change Adaptation into National Development Planning – A System Dynamics Modeling Approach

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Small islands developing States (SIDS) are recognized as a special case in the United Nations system as a special case because of their inherent vulnerabilities, including, among others, external shocks. These shocks can take different forms such as volatility in energy prices, global financial and economic crisis, natural disasters, and climate change. It is also recognized today that while SIDS are vulnerable because of their inherent characteristics, policies can be tailored to enhance their resilience in the face of these shocks. These policies should also have sustainable development dividends or social, environmental and economic co-benefits. In this paper, we deal primarily with the integration of disaster risk reduction (DRR), climate change adaptation (CCA), and 'loss and damage' into national development planning. A framework for carrying out this integration is proposed. Using the island of Mauritius as a case study, system dynamics modelling is applied to operationalize the framework. The impacts and policy responses corresponding to the reduction in precipitation from climate change, and extreme precipitation events arising from climate variability are simulated for the agriculture sector. By adopting a more conceptual approach, the cross-sectoral impacts of cyclones are simulated stochastically. All simulations have been carried out over the 2050 time horizon.

Keywords: integrated policy planning; disaster risk reduction; climate change adaptation; system dynamics modeling; SIDS; resilience; loss and damage

Background

Small Island Developing States (SIDS) were recognized as a special case for both environment and development in Chapter 17(G) of Agenda 21 as early as 1992 (UN, 1992). SIDS are vulnerable because of a number of inherent characteristics, including their small size, limited and narrow resource bases, geographic dispersion, isolation from markets, susceptibility to climate change and natural disasters, and exposure to external shocks such as energy, and financial and economic crises. While they are exposed to numerous vulnerabilities, SIDS also exhibit low levels of coping capacity due mainly to lack of financial resources, and human and institutional capacity limitations that make it even more difficult for them to address sustainable development (UN, 2012). The combination of exposure and low coping capacity places SIDS at relatively high risk to the vulnerabilities. The outcome of the inter-regional preparatory meeting for the Third International Conference on SIDS reaffirmed that SIDS remain a special case for sustainable development in acknowledgement of their unique characteristics, challenges and vulnerabilities and the ongoing impact of these on their ability to achieve sustainable development and build sustained resilience (UNDESA, 2013).

If SIDS have intrinsic vulnerabilities which for the most part cannot be changed, then how are they to deal with them? In 2005, the Mauritius Strategy made specific mention that promoting sustainable development, eradicating poverty and improving the livelihoods of peoples in SIDS would be achieved through the implementation of country-specific strategies that build resilience and capacity to address their unique and particular vulnerabilities (UN, 2005). The strong emphasis on building resilience through appropriate context-based strategies to achieve sustainable development and the green economy is drawn out clearly in the outcome document of Rio+20 (UN, 2012). The focus on building resilience to shocks was recently reaffirmed through the necessity of SIDS to promote, enhance and support more sustainable agriculture, including crops, livestock, forestry, fisheries and aquaculture, that improves food security, eradicates hunger, and is economically viable, while conserving land, water, plant and animal genetic resources, biodiversity and ecosystems, and enhancing resilience to climate change and natural disasters (UNDESA, 2013).

The focus of this paper is on resilience related to climate change and natural disasters for two reasons, namely: (1) the post-Hyogo Framework for Action will actively seek to integrate the management of natural disasters and climate change adaptation in sustainable development planning; and (2) loss and damage is an agenda that is being actively pursued by SIDS (and Least Developed Countries). We now turn our attention to these two issues.

Dealing with disasters and climate change adaptation in development planning

Different views about how to deal with disaster risk management and climate change adaptation have been identified in the literature (Mercer, 2010). There are generally two strands of thinking about how to deal with disasters and climate change adaptation. However, before discussing these two views, it has been remarked that, until recently, disaster scholars and practitioners had hardly engaged in climate change debates (Helmer and Hilhorst, 2006). This has created a situation where the cross-fertilization of approaches to deal with disasters and climate change adaptation has been late to emerge. Nevertheless, there has been the slow congruence of views that the impacts of both disasters and climate change are complex in character and that both need to be mainstreamed into national policy planning, and more specifically policy planning for sustainable development.

The initial point of divergence between disaster risk reduction (DRR) and climate change adaptation (CCA) has been that disasters are comparatively broader in scope because they can be either non-climate (e.g. earthquakes and volcanoes) or climate (e.g. amplification of certain extreme weather events like droughts, floods and cyclones) related. Mainly because of this difference, the case has been made that CCA should be integrated into DRR (Kelman and Gaillard, 2008; Kelman *et al.*, 2009). The differences and commonalities between DRR and CCA have been discussed in the literature with the view to achieving a higher level of congruence and cross-fertilization between them (Thomalla et al., 2006; Tearfund, 2008; Mercer, 2010). The difference between the scope of DRR and CCA becomes less consequential when DRR and CCA are conceptualized at the level of the vulnerability-resilience nexus, and when the two are treated as complex issues.

Deenapanray and Bassi (2014) have recently discussed the historical evolution of situating SIDS in the debate on vulnerability and resilience, and showing, as discussed earlier, the increasing emphasis on policy-induced building resilience in the face of shocks. Both DRR and CCA deal with the impacts of hazards, where a hazard can be defined as "a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage" (UNISDR, 2009). O'Brien et al. (2006) has categorized hazards into three categories, namely: natural; technological; and complex emergencies. The linkages between DRR and CCA are more immediate when dealing with natural and technological hazards. For instance, the hazards of concern under the Hyogo Framework are of natural origin and related environmental and technological hazards (UNISDR, 2005). Such hazards arise from a variety of geological, meteorological, hydrological, oceanic, biological, and technological sources, sometimes acting in combination (UNISDR, 2009). Further, the impacts of climate change on the risk of natural disasters in the form of extreme weather events like heat waves, droughts, floods, and tropical cyclones have been discussed explicitly by van Aalst (2006). In these cases, the distinction between DRR and CCA become blurred, and as recommended by van Aalst (2006), the bigger imperative is to develop more robust development planning to deal with the associated risks.

When dealing with these hazards, there is consensus that the associated risks have to be managed by a combination of reducing the vulnerability - i.e. the susceptibility to be harmed when exposed to a hazard - of the system (e.g. community or society) and increasing its resilience – i.e. the ability of the system exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions (Thomalla et al., 2006; Füssel, 2007; Joseph, 2013; UNDESA, 2013; UNISDR, 2013). It is particularly important to note that the ongoing discussions about a post-2015 framework for DRR have observed that (UNISDR, 2013):

- While all countries are vulnerable, SIDS and Least Developing Countries are disproportionately affected by disasters;
- Unsustainable development practices, ecosystem degradation, poverty as well as climate variability and extremes have led to an increase in both natural and man-made disaster at a rate that poses a threat to lives and development efforts;
- The several practical links between DRR, CCA and sustainable development have not been fully internalized in the ways in which national government institutions, international development agencies and the United Nations system itself approaches disaster risk management;
- Reducing disaster risk and re-enforcing resilience is increasingly seen as part of a new development paradigm where well-being and equity are core values and human and natural assets central to planning;
- There is a need to develop unified tools to support greater coherence between DRR, CCA and sustainable development planning.

The latter observation is central to the systems approach proposed in this paper to integrate DRR and CCA into the national planning process. The risks associated with a hazard are multi-dimensional involving the socio-economic state of a system, and compounded by the physical environment in which the system is embedded, as well as the risk perceptions of the individuals constituting the system (Thomalla et al., 2006; Reser and Swim, 2011). The impacts of hazards are likewise multi-dimensional across society, economy and environment (Thomalla et al., 2013; UNISDR, 2013). Further, Doherty and Clayton (2011) have discussed the psychological impacts of climate change (and this can be extended to hazards) within the broader complexity and multiple meanings associated with it. Another important point that has been raised by Thomalla et al. (2006) is the complex interactions of social, economic and environmental factors operate at different spatial and temporal scales. This discussion shows that the unified tools to integrated DRR, CCA and sustainable development planning should have the capacity to deal with the complexities of DRR and CCA within the broader development planning framework, as well as being able to deal with the dynamics of change at different geographical scales.

Before discussing these issues in more details in the rest of this paper, we now turn our attention to the related theme of ‘loss and damage’ that is now a pillar of the SIDS agenda on climate negotiations.

Loss and damage

Low-lying islands and countries, mostly in the developing world, whose existence is threatened by rising sea levels and storm surges, have been lobbying for the creation of a loss and damage mechanism, separate from adaptation, under the Conference of Parties in the United Nations Framework Convention on Climate Change (UNFCCC). With climate projections of up to 4^0C increases in global average temperature expected by the end of the 21st century relative to the end of the 20th century under current global emission trends (IPCC, 2013), it has become clear that there are likely to be limits the capacity of social and ecological systems to adapt (Dow et al., 2013). The Bali Action Plan called for “…[r]isk management and risk reduction strategies…and for consideration of…strategies and means to address *loss and damage* associated with climate change impacts” (UNFCCC 2007). In this context, islands states (and Least Developing Countries) have been lobbying and advocating for an international mechanism for addressing ‘loss and damage’ to the impacts of climate change, including extreme events and slow onset events.

The Warsaw Climate Change Conference (COP19) in 2013 created an international mechanism on ‘loss and damage’. This mechanism encompasses many functions, including: (a) enhancing knowledge and understanding of comprehensive risk management approaches to address loss and damage associated with the adverse effects of climate change, including slow onset impacts; (b) strengthening dialogue, coordination, coherence and synergies among relevant stakeholders; and (c) enhancing action and support, including finance, technology and capacity-building, to address loss and damage associated with the adverse effects of climate change (UNFCCC, 2014). While there are serious unresolved issues related to ‘loss and damage’ such as whether: (i) to focus attention on vulnerable countries *versus* vulnerable groups and regions; and (ii) the ‘loss and damage’ agenda should be pursued primarily with a liability-compensation reasoning *versus* be used to frame actions in terms of support and assistance of groups most at risk of losses as a result of climate change, enhancing the capacity of vulnerable countries (because the onus is on governments to represent the voice of their vulnerable groups under the UN system, and also it is the role and responsibility of government – central or local – to implement policy decisions and related instruments to deal with 'loss and damage') to grapple with the three functions of the Warsaw International Mechanism for Loss and Damage. Importantly, countries will need to develop the capacity for quantifying the impacts of loss and damage at all levels (local, national depending on the geographical size of the country and type of events leading to 'loss and damage'), and to better understand the complexity of economic, social and environmental dimensions of 'loss and damage' by making use of multi-stakeholder processes. Dow and Berkhout (2014) have called for a more actor-centered and sustainable development framing of the problem of 'loss and damage'.

This cursory introduction leads us to a discussion of a framework for integrating DRR and CCA, and also 'loss and damage' into national sustainable developing planning in order to build the resilience of SIDS in the face of these external shocks.

Framework for integrating DRR, CCA and 'loss and damage' into national development planning

The challenges related to dealing with the losses attributed to disasters and climate changes in SIDS have been summarized concisely at the Inter-regional SIDS meeting that took place in Barbados in August 2013:

> "*We call for support to be provided to SIDS in their efforts to build resilience and reduce risks associated with natural disasters in areas and sectors vulnerable to climate change threats and for support to assist SIDS in effectively addressing the multiple effects of their vulnerabilities through the adoption of sustainable development strategies. We call, further, for special consideration to be given to financing for early warning systems to reduce economic and social losses, as well as the loss of human lives. Support is also required to mitigate the negative impacts of natural disasters, particularly as it regards recovery, reconstruction and rehabilitation*" (UNDESA, 2013).

It is timely here to justify the focus of this paper on island states. The work presented here is being carried out in the context of a regional project called ISLANDS. ISLANDS is implemented by the Indian Ocean Commission (IOC) in collaboration with the United Nations Department of Economic and Social Affairs (UNDESA), and with financing from the European Union. The overall objective of the project is to contribute to an increased level of social, economic and environmental development and deeper regional integration in the East and South Africa and Indian Ocean region through the sustainable development of SIDS, and more specifically, through the accelerated implementation of the Mauritius Strategy (UN, 2005). The beneficiary countries of ISLANDS are Comoros, Madagascar, Mauritius, Seychelles and Zanzibar of Tanzania.

The approach proposed by ISLANDS is to nest capacity development through learning-by-doing, multi-stakeholder processes, knowledge management and a solid communication strategy within a systems approach that allows dynamic and integrated cross-sectoral policy planning to build the resilience of beneficiary countries. The ecosystem framework for dealing with the complexity of sustainable development planning has been recently reported by Deenapanray and Bassi (2014).

The ecosystems approach underpins the cross-sectoral, evidence-based policy and strategy formulation that will be necessary to plan coherent policies across sectors to move towards sustainable futures. Importantly, the systems approach allows the sustainable development process to be contextualized at the national or regional level, meaning that no prescribed approach (or 'one size fits all') is imposed on beneficiary countries. Instead, the process of model building and analysis is participatory and modular by nature allowing stakeholders to frame the issues and, thereafter, create appropriate models based on their specific needs (or issues to be analyzed) and actively select desired scenarios and policy interventions to be tested using a "what if" framework. In fact, the cross-sectoral model to be created will not necessarily optimize the system (which, when analyzing social, economic and environmental indicators becomes a subjective evaluation), rather it will provide insights on whether selected interventions will lead to desired outcomes (e.g. reduced vulnerability or increased resilience to shocks) at the sectoral and cross-sectoral level in the short, medium, and longer term. The identification of synergies and potential side effects (or bottlenecks) within and across sectors is a key goal of the systemic analysis. Further, the ecosystems approach to long-term policy scenario planning can accommodate a multitude of cross-cutting and complex issues such as DRR, CCA and 'loss and damage' that are now discussed.

The framework that ISLANDS has adopted to integrate DRR, CCA and 'loss and damage' in national development planning is shown in Figure 1. The framework is characterized by five key components that lead to preparedness to climate change impacts (slow onset, extreme weather events) and disasters, including deciding on an optimum set of context-specific policies and strategies to build resilience in the face of these shocks. The scenario analyses also quantify 'loss and damage' associated with the shocks. Two important inter-related characteristics of preparedness are that it provides: (1) an evidence-based approach to justify the need for external financial and technical support. SIDS are especially vulnerable because they lack the human and institutional capacities and financial means to deal with external shocks (UN, 2005; UN, 2012; UNDESA, 2013); and (2) a methodological approach based on evidence to prioritize interventions at the national and sub-national levels so that limited resources are deployed more productively – i.e. efficiently and effectively. When this framework is used within the broader ecosystems approach (Deenapanray and Bassi, 2014), the issues of DRR, CCA and 'loss and damage' are more effectively framed by and for stakeholders under the sustainable development umbrella (Dow and Berkhout, 2014).

The five components of the framework are:

1. <u>Climate modeling</u>: All policies implemented today have impacts into the future. Therefore, dealing with climate change and natural disasters that are modulated by climate variability requires that future climate change and variability be known (within uncertainties) at a geographical scale relevant for policy decisions to be made. Given the smallness of SIDS, these projections have to be made at scales less than 25 km X 25 km for meaningful results. The climate models will typically provide information about changes in temperature, precipitation, sea level rise, and extreme events that have the potential to cause 'loss and damage'. Also, the usefulness of medium-to-long range climate forecasts in disaster management to deal with climate-related events due to climate change and variability has been demonstrated (Braman et al., 2013);

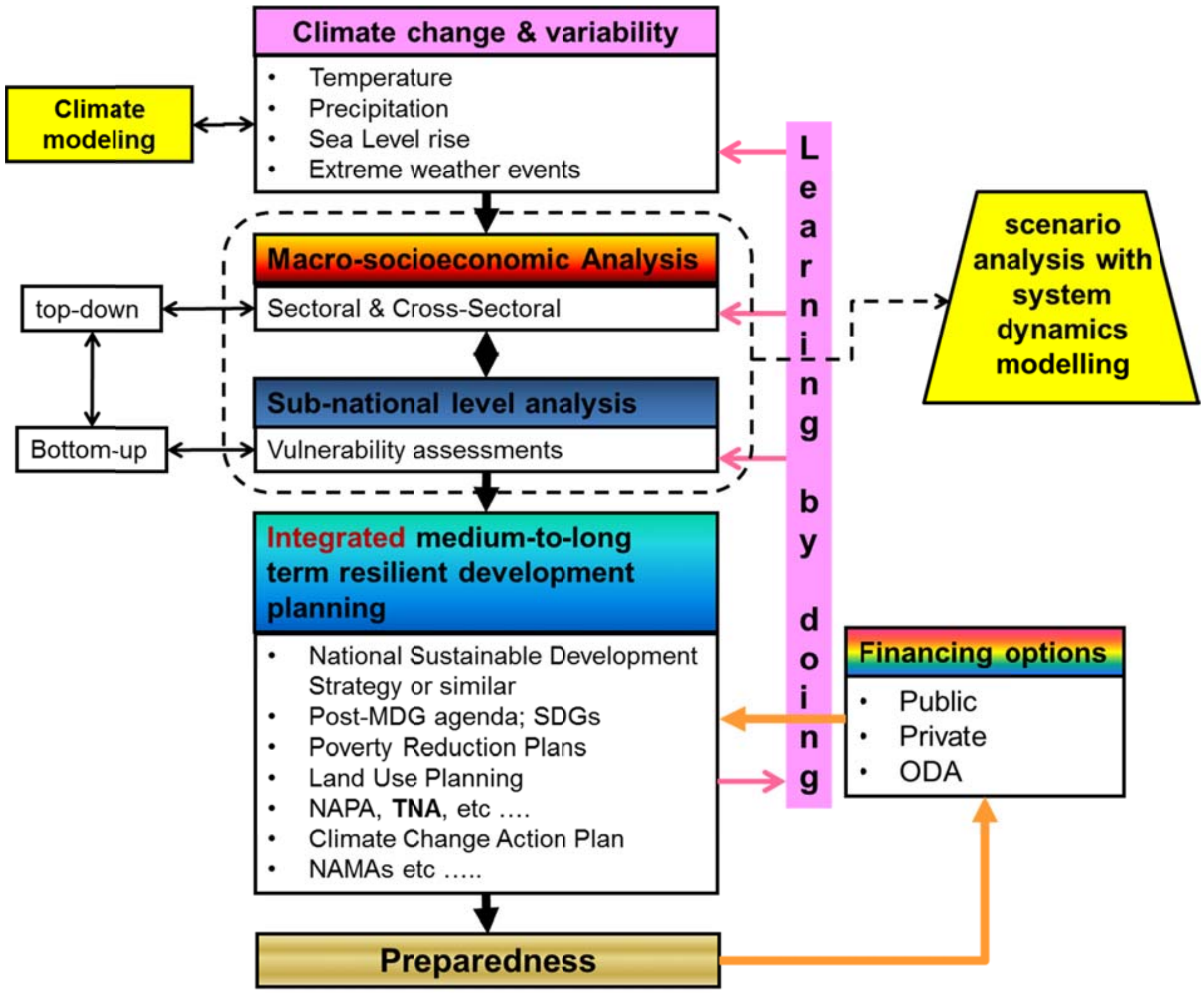

Fig. 1. Framework for integrating DRR, CCA and 'loss and damage' in national development planning.

2. Macro level socio-economic analysis: The sectoral and cross-sectoral impacts of shocks in the form of climate change and variability, and disasters are analyzed. The ecosystems approach to carrying out these integrated analyses using system dynamics modeling has been articulated for ISLANDS (Deenapanray and Bassi, 2014). This is also important for linking policy interventions to deal with DRR, CCA and 'loss and damage' to the budgetary process that is normally centralized in SIDS (UN, 2005; UN, 2012);
3. Sub-national (or local) level analyses: The impacts of shocks are rarely uniform across a country. This is because there are variations in the socio-economic conditions (including access to resources, knowledge about impacts, knowledge about reducing expose to shocks etc…) of individuals and also the physical environment in which communities are embedded (Füssel, 2007). So, in line with the Hyogo Framework for Action (UNISDR, 2005), vulnerability assessments are also carried out at the local/community level. The systems approach to climate and disaster impact assessments can also be adopted at the local level. However, there may be limitations regarding the use of system dynamics modeling because of the lack of data to validate these models;

The impact assessments carried out in 2 and 3 are informed by the climate modeling that has been carried out in 1.

4. Development and implementation of policies, strategies and action plans: Policies, strategies and action plans are developed to reduce the vulnerability and to increase the resilience against these shocks. These policies, strategies and action plans are informed by the analyses that have been carried out in 2 and 3. This component is nested in a policy cycle that is made up of five iterative steps: (1) agenda setting; (2) policy formulation; (3) decision making; (4) policy implementation; and (5) policy evaluation (UNEP, 2009). As discussed by Deenapanray and Bassi (2014), context specific indicators can be selected to carry out the monitoring and evaluation of integrated policies. Typically, the policies will be linked to the budgetary process since the macro-economic framework of system dynamics models are linked to the Social Accounting Matrix of the beneficiary country (Deenapanray and Bassi, 2014). Further, the combination of top-down and bottom-up approaches have revealed their effectiveness in dealing with climate change in SIDS (Kelman and West, 2009); and

5. Learning-by-doing: In the framework shown in Figure 1, learning-by-doing serves two purposes, namely: (1) it provides the lever for increasing human and institutional capacities in beneficiary countries to adopt tools, methodologies and processes to carry out climate modeling, vulnerability and impact assessments, and policy analysis. ISLANDS is using the learning-by-doing approach to trigger a virtuous circle between technical assistance, human and institutional capacity development and resilience building for sustainable development (Deenapanray and Bassi, 2014); and (2) it serves as the feedback loop that underpins the policy cycle mentioned in 4.

Operationalizing the framework

By making use of the case of the island of Mauritius, this section discusses how the above framework can be applied. All the analyses have been carried out at the national level – i.e. results related to component 4 are not shown here. This is not a shortcoming of the framework but rather that sub-national level vulnerability assessments are still in progress in Mauritius.

The scale of Mauritius

The Republic of Mauritius is a group of small islands in the South West Indian Ocean. The total land area of the country is 2040 km^2. The Republic of Mauritius also incorporates the island of Rodrigues, situated some 560 kilometers to the east and is 104 km^2 in area, the Agalega islands situated some 1,000 km to the north of the island of Mauritius and Saint Brandon situated some 430 km to the north-east of the island of Mauritius, both with total land area of 71.2 km^2. It also consists of the Chagos Archipelago (Diego Garcia). The island of Mauritius is the most populated part of the Republic of Mauritius followed by the island of Rodrigues and the Agalega islands. The geographical location of the Republic of Mauritius is shown in Figure 2. As an approximation to guide the reader, the island of Mauritius would fit into a rectangle of dimensions 40 km (East-West) X 60 km (North-South). In Figure 2, the island of Mauritius is labelled as ‘MAURITIUS’.

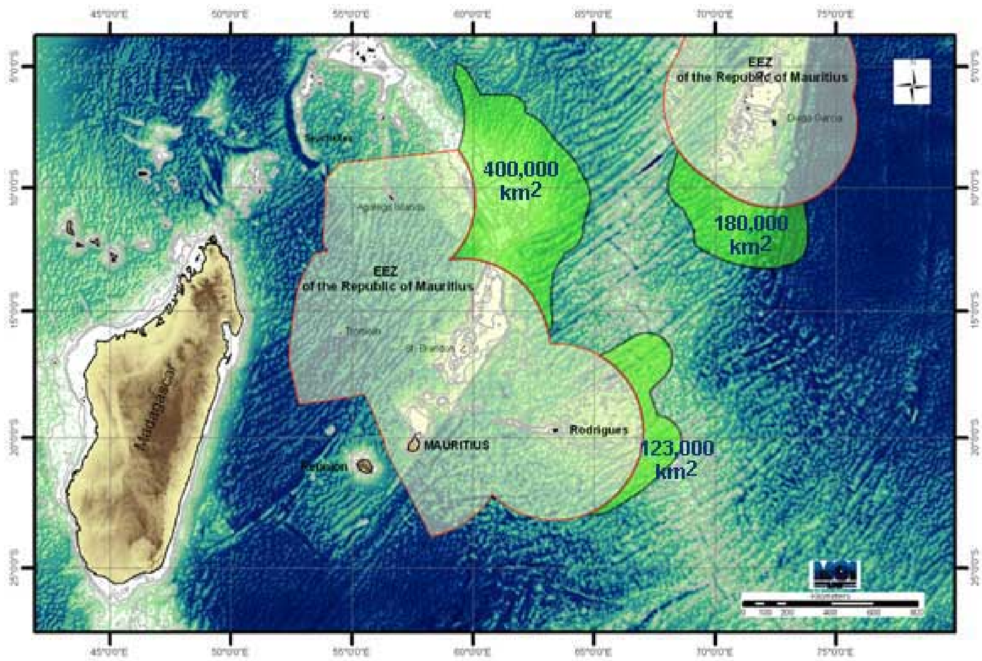

Fig. 2. Location Map of Mauritius.

Downscaling of climate models

Given the small size of Mauritius, statistical downscaling that can provide a resolution of 100 m X 100 m was carried out for climate change and variability projections. Global Climate Models (GCMs) were downscaled from the global sets available through the CMIP5 (climate models inter-comparison project) website, through statistical downscaling.

Statistical or empirical downscaling is an approach for obtaining regional-scale climate information (Kattenberg et al., 1996; Hewitson and Crane, 1996; Giorgi et al., 2001; Wilby et al., 2004)). It uses statistical relationships to link resolved behaviour in GCMs with the climate in a targeted area. The targeted area’s size can be as small as a single point. This approach encompasses a range of statistical techniques from simple linear regression (e.g., Wilby et al., 2000) to more-complex applications such as those based on weather generators (Wilks and Wilby, 1999), canonical correlation analysis (e.g., von Storch et al., 1993), or artificial neural networks (e.g. Crane and Hewitson, 1998).

Empirical downscaling can be very inexpensive compared to numerical simulations when applied to just a few locations or when simple techniques are used. Lower costs, together with flexibility in targeted variables, have led to a wide variety of applications for assessing impacts of climate change. Some methods have been compared side by side (Wilby and Wigley, 1997; Zorita and von Storch, 1999; Widman et al., 2003). These studies have tended to show fairly good performance of relatively simple vs. more-complex techniques and to highlight the importance of including moisture and circulation variables when assessing climate change. Statistical downscaling and regional climate simulation also have been compared (Kidson and Thompson, 1998; Mearns et al., 1999; Wilby et al., 2000; Hellstrom et al., 2001; Wood et al., 2004; Haylock et al., 2006), with no approach distinctly better or worse than any other. Statistical methods, though computationally efficient, are highly dependent on the accuracy of regional temperature, humidity, and circulation patterns produced by their parent global models. In contrast, regional climate simulations, though computationally more demanding, can improve the physical realism of simulated regional climate through higher resolution and better representation of important regional processes.

The probability distribution for precipitation was analysed through the generalized extreme event analysis (Jenkinson, 1955) which widely used for modelling extremes of natural phenomena. Extreme events are defined in terms of unusual values of a sequence of observations of certain meteorological elements. The term "extreme events" is used in a broad sense, encompassing both the occurrence of extraordinary values (i.e., a record- breaking maximum or minimum) and the exceedence of (or falling below) a particular threshold level. Typically, the problem is to estimate the probability that an extreme value of a sequence of observations of a meteorological variable will be higher or lower than some constant threshold level, or alternatively, to estimate that threshold value which will be exceeded with a specified fixed, small probability. These extreme values and associated probabilities are then used in the solution of related design problems or cost-risk calculations. Historical observations of the appropriate meteorological variables are used for the identification and fitting of the extreme probability distributions. The utility of the estimators depends to a great extent on the length and the homogeneity of the observational record, especially in cases when the return period of the required design value is significantly longer than the observational record.

The mathematical basis for extreme value analysis started in the 1920's (Fisher and Tippett, 1928) and has rapidly developed since then (Gumbal, 1942, 1958; Jenkinson, 1955, 1969; Galambos, 1978; Leadbetter et al., 1983). The theory of extreme values has established that, for sufficiently large parent sample size m, the probability distribution of the standardized (or "reduced") maximum value Y(m) = (X(m) - Um)/Am, Am > 0, can be approximated by one of three possible forms of the extreme distribution function:

Gumbal asymptote $\mathbf{G1 = exp(-e^{-y})}$
Frechet asymptote $\mathbf{G2 = exp(-y^{1/K})\ Y>0,\ K>0}$
Weibull asymptote $\mathbf{G3 = exp[-(-y)^{1/K}]\ Y<0,\ K>0}$

The asymptotic extreme distributions involve three parameters: **K** - the shape parameter; **Um** - the location parameter; **Am** - the scale parameter. Their determination depends upon the particular form of distribution F of the individual observations. The latter two parameters are also called the attraction coefficients.

Several methods can be used to estimate the parameters of the generalized extreme value distribution. Here the probability weighted moments (PWM) method was used. The PWMs are essentially the expectations of order statistics, and can be interpreted as moments of the quintile function (i.e., inverse of the cumulative distribution function) of any non-negative random variable. In contrast with ordinary statistical moments, the main advantage of using PWMs is that their higher order values can be accurately estimated from small samples.

System dynamics model

The system dynamics model that is used here was developed to investigate the social (e.g. job creation, food security), economic (e.g. contribution to economic growth, avoided energy bill) and environmental (e.g. emission of greenhouse gases, land use, water use) impacts of green investment scenario analyses in Mauritius (Bassi and Deenapanray, 2012). The model has also been used to carry out energy policy analysis for Mauritius (Bassi et al., 2013). The model for Mauritius was developed using the following five steps: (1) identification of key issues and opportunities; (2) data collection and consistency check; (3) causal mapping and identification of feedback loops; (4) creation of customized mathematical models; and (5) validation and analysis (Deenapanray and Bassi, 2014 and references therein). These steps are aligned with the best practices in system dynamics modeling (Martinez-Moyano and Richardson, 2013).

The Causal Loop Diagram (CLD) that represents the effects of climate change and variability and natural disasters is shown in Figure 3. Since we are concerned with the 'loss and damage' related to climate and disaster impacts, Figure 3 shows these impacts on the gross domestic product (GDP). The macroeconomic model uses a Cobb-Douglas production function that is augmented by a productivity factor. In the examples that will be discussed below, it is mainly the impacts of climate change and variability on agriculture production that have been investigated, as well as the impacts of cyclones (i.e. climate-related natural disaster) on built-up capital. In Figure 3, therefore, the climate parameters that have been derived from statistical downscaling are shown in red (temperature, rainfall and rainfall variability) and have effects on productivity and built-up capital. In turn, both parameters have direct impacts on the GDP. In the case of agriculture production, resilience can be built through policy interventions like climate resilience crops. In the case study, the effect of rising temperature due to climate change on crop pest diseases and energy consumption has also been investigated. The energy efficiency improvements relate to policy interventions to mitigate this effect. In the rest of this paper, the energy-related aspects of a changing climate will not be discussed. When 'loss and damage' take place, like in the case of a cyclone disaster, the government may intervene by increasing its relief expenditure. Where there is 'loss and damage' to built-up capital, the relief expenditure in capital (and infrastructure) expenditure seeks to balance this loss so that recovery of GDP is assured. The CLD also shows that any negative impacts of climate change and variability, and cyclones will have negative impacts on disposable income, household investment and on capital expenditure. In the presence of 'loss and damage' arising from climate change and variability, and cyclones, the negative impact of this self-reinforcing loop on GDP is attenuated by the relief expenditure intervention.

It is worth noting that this CLD is a simplification of reality (and also of the model developed) and represents primarily the reinforcing loops affecting GDP. Other factors, including those creating balancing loops, not directly related to the analysis of climate change are not included in the CLD but are captured in the model (e.g. energy consumption and prices, as well as imports and trade deficit, negatively affecting productivity).

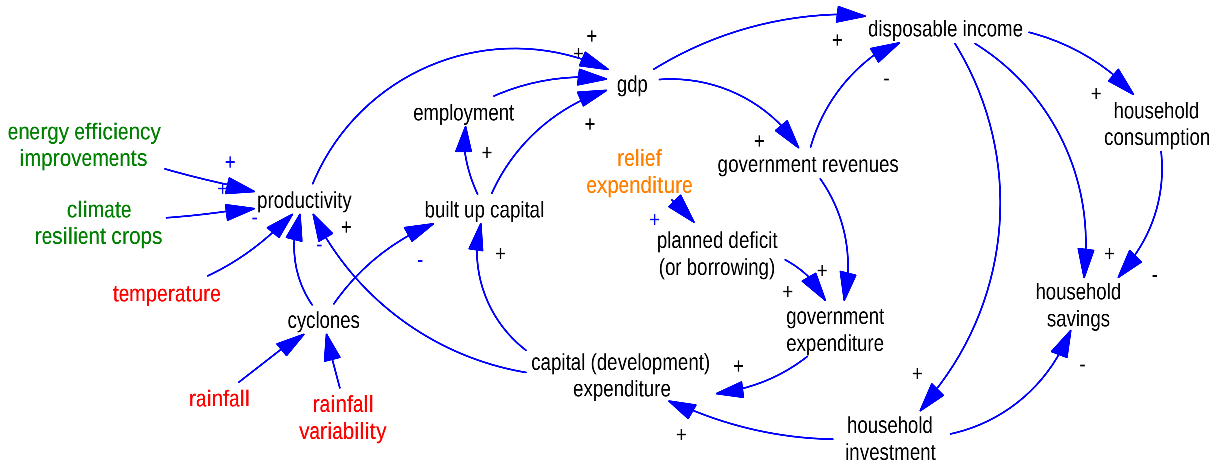

Fig. 3. Causal loop diagram showing the detrimental impacts of climate change, climate variability and cyclones on gross domestic product.

In the framework shown in Figure 1, the macro-level impact analyses using system dynamics modeling use projected climate parameters as exogenous variables. This is illustrated in Figure 4. The rainfall (or *precipitation*) images shown in Figure 4 were constructed from the downscaled models. Image 1 shows the baseline (average of 1981 to 2010, coinciding with the 1995 baseline year) of the annual precipitation (in mm/year) for Mauritius. The rainfall varies from up to 1600 mm on the West coast, to over 2000 mm East of the Central Plateau. The source of this data is the WorldClim dataset. Image 2 shows the absolute change in annual rainfall (in mm/year) by 2050, under the RCP8.5 (Representative Concentration Pathway) emission scenario, with high climate sensitivity, using the 50-percentile (the median) from an ensemble of 40-GCMs. Rainfall decreases everywhere, and is highest in the east (over 100 mm/year), and lowest on the west coast (less the 70 mm/year).

The inter-annual *variability of precipitation* for Mauritius was determined for an ensemble of 26 GCMs as follows:

1) For each of the GCM's with daily rainfall results (26), the total annual precipitation was determined for each year between 2006 and 2100 for the grid cell of each GCM that contains Mauritius under the RCP8.5 (Representative Concentration Pathway with a radiative forcing of 8.5 W/m^2) scenario. The 8.5 pathway arises from little effort to reduce emissions and represents a failure to curb warming by 2100. It is similar to the highest-emission scenario (A1FI) in the IPCC Fourth Assessment Report (AR4). This gives 95 annual values per GCM;
2) With a sliding window of 20 years the standard deviation (SD) of the annual precipitation was determined (first window: 2005-2025, last window: 2081-2100). This gives a time series of SD with 76 points;
3) The linear trend was determined for each time series, giving the constant (the SD for 2006-2025), the slope (the change in mm per year for SD) as well as goodness of fit parameters (r and r^2).

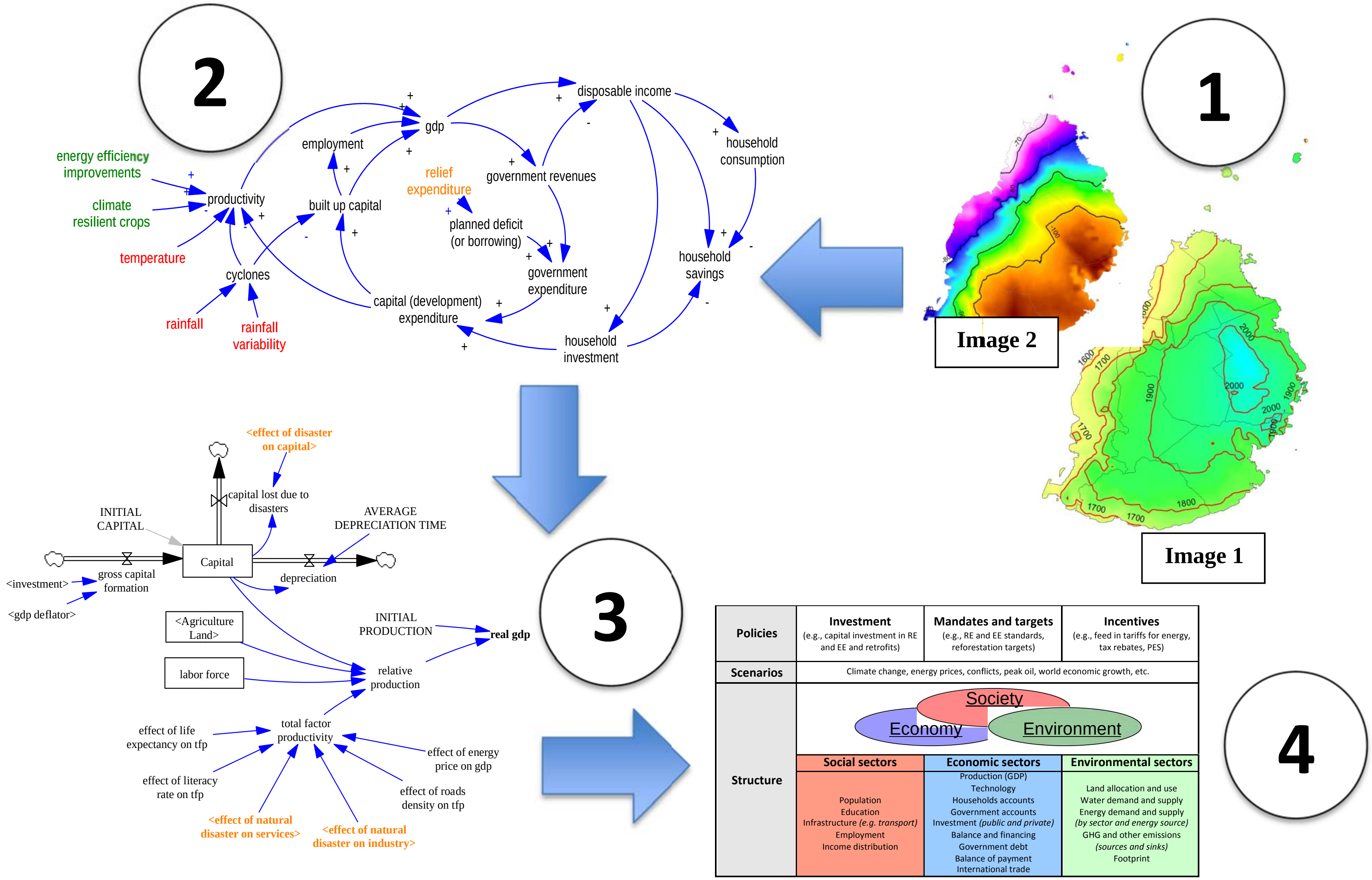

Fig. 4. Illustration of stock-and-flow diagram (3) associated with CLD (2). Climate parameters (1) are exogenous. All these tools lead to policy analysis (4), carried out with the stock-and-flow model.

Figure 4 shows a representative stock-and-flow diagram from the Mauritius model (the model has a total of 37 modules, and this is only a simplified representation of the economic production module, please see Annex 1 for the presentation of a few equations). In this case, the impacts of a natural disaster (cyclones) on loss of capital and on total factor productivity (via the effects of natural disaster on service and industry) are shown. The relevance of the impacts depends on the projected change in precipitation and its variability. The occurrence and strength of the cyclone are driven by these assumptions. It is in fact assumed that heavy rainfall events will only impact society and the economy if rainfall is above the annual average by more than 200 mm.

Indirect impacts examined with the model, which is built on causal relations reflecting the functioning mechanism of the social, economic and environmental context of Mauritius, include the repercussions of lowered GDP on employment and income, as well as on government expenditures, which will have to be lowered to contain deficit and debt increase. Further, a lowered amount of tourism, as well as a decline in the GDP growth rate might reduce water and energy demand, with the latter also being impacted by higher temperatures. In the statistical downscaling, it is assumed that the average increase in global temperature will be 2°C above pre-industrial period.

Figure 4 also shows the last step of the methodology employed: policy analysis. This is done using the System Dynamics model as a "what if" tool, that can be simulated to project and evaluate policy-driven impact for the mitigation of climate change and adaptation to climate variability and natural disasters.

Simulations were carried out to 2050 for the following four scenarios.

- ***BAU:*** *baseline precipitation (downscaling) with no increase in variability and no disasters*. This simulation considers a baseline projection for precipitation, no temperature increase, and no modifications in policies or other scenario drivers.
- ***CC1:*** *low precipitation + low variability (downscaling)*. This scenario assumes a decline in the trend of precipitation, as described above, with no increase in variability and an increase in temperature.
- ***CC2:*** *low precipitation + higher variability (downscaling)*. This scenario considers a lower precipitation trend, a higher (and growing) variability and an increase in temperature. It is worth noting that the projected increase in variability is very small compared to the absolute value of precipitation (25 mm of additional variability, over a total of approximately 1,900 mm of precipitation).
- ***CC+ND:*** *natural disasters (cyclones) driven by high precipitation events*. This scenario includes CC2, and an explicit link between high rainfall events and the occurrence of natural disasters.

Climate change, precipitation trend and variability

Annual precipitation is modeled so as to follow the longer-term trend projected using downscaled climate models. Variability is added on top of this trend. The analysis of historical data indicates that the current interannual variation in precipitation (450mm for Vacoas, 550mm for Plaisance) is likely to increase with 25mm by 2050. The average of 500 mm per year is used in the model, and the extra variability is set up so as to amplify the BAU oscillations.

The impact of increase precipitation and variability are visible for several variables, such as agriculture yield and production, also having impact on food security. On the other hand, these are generally very small impacts (below 1%), except for a few instances, where large variations in precipitatin (especially droughts) lead to a reduction of 4 to 6% in agricultural production (e.g. 2041-2042).

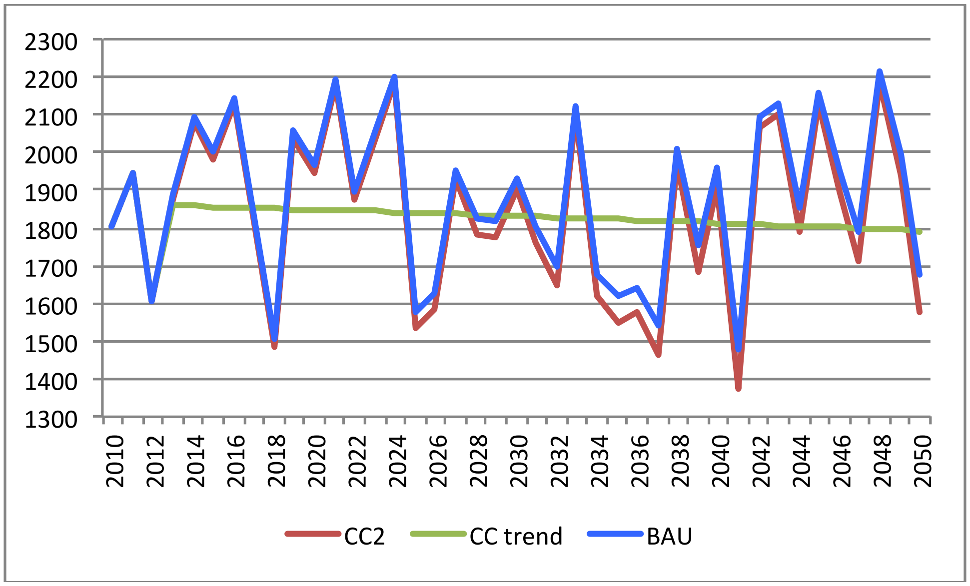

Fig. 5. Precipitation trend and projections, BAU and CC2 scenarios.

Natural disasters – the example of cyclones

This example is developed conceptually to demonstrate the ability of framework and modeling to investigate the cross-sectoral impacts of a disaster as an external perturbation to the coupled social, economic and environmental systems. Based on ongoing field work, this conceptual model will be further developed into a practical case study of policy interventions that can be implemented to build resilience to natural disasters (or any other external shock). For instance, capacity building is being carried out by ISLANDS to develop risk transfer mechanisms that will allow beneficiary countries to withstand and/or to recover from the impacts of natural disasters.

The cyclone events that are driven by high precipitation events are shown in Figure 6 (left). They have been modeled as stochastic events. The intensity of these events is given in relative terms. These cyclones do not take place in the BAU scenario. As mentioned earlier, the cyclone events are coupled with above average precipitation for socio-economic impacts are felt. In this case, the threshold has been set at 200 mm above the long-term annual mean rainfall. The equations used to estimate cyclone events and their strength are presented in Annex 1, and the impacts of these cyclone events on agriculture yield and real GDP (growth rate and absolute value) are shown in Figure 6 (right) and Figure 7, respectively.

In particular, Figure 7 shows that short-term impacts of natural disasters are visible for GDP growth rate (in correspondence with cyclone events), and are also reflected on total GDP. In addition, the impacts on GDP growth rate indicate that growth is higher relative to BAU after the natural disaster occurs. This is due to a combination of public relief expenditure (compensating for at least part of the cost of reconstruction, and avoided consumption) and for the higher efficiency (or productivity) of the newly purchased capital. These results indicate that preventive actions, aimed at increasing resilience to natural disaster, could increase GDP growth above the level of a “no action” scenario.

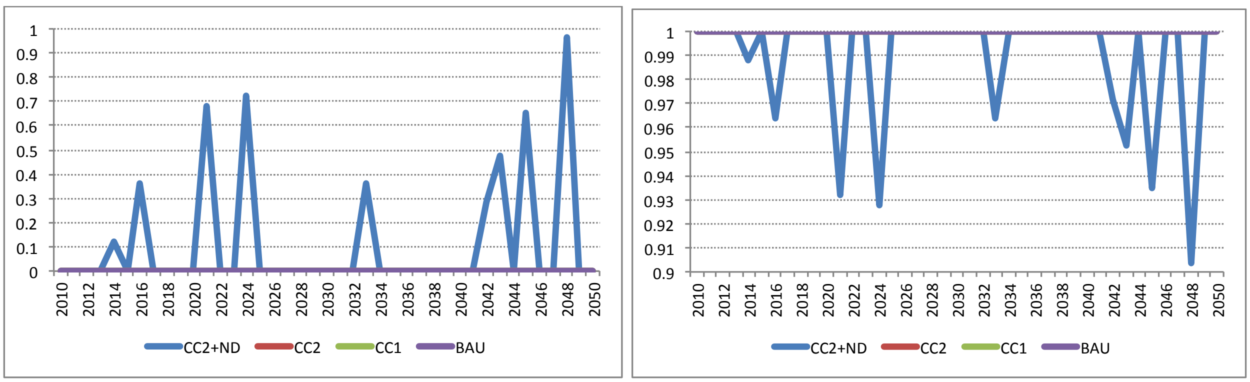

Fig. 6. Cyclone events linked with precipitation events that are above the annual mean by more than 200 mm (left), and impact of cyclone events on agriculture yield (right).

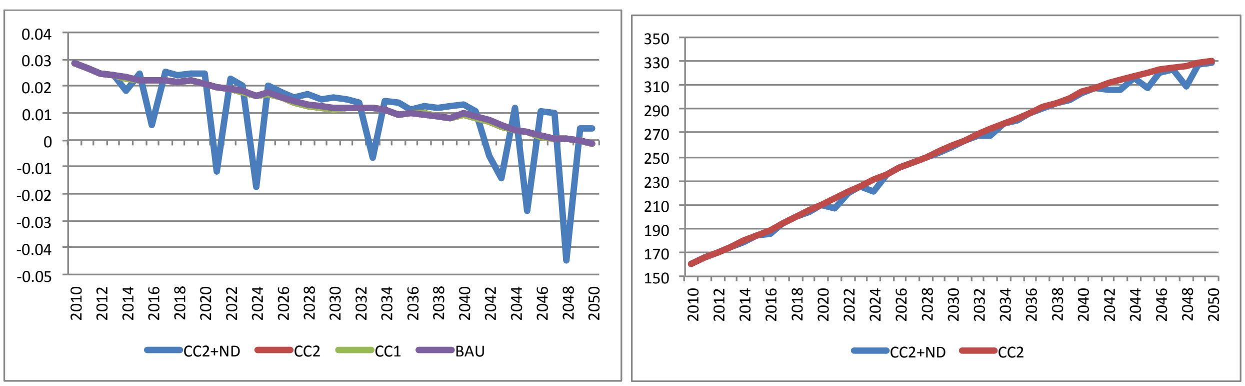

Fig. 8. The impact of cyclone events on real GDP.

Policy analysis was carried out with the model to assess the interventions required to offset the projected impacts of climate change on socio-economic development. Green economy interventions were assessed, to create win-win strategies that would support resilient growth while reducing pressures on the environment. These investments were also tested in Bassi & Deenapanray (2012), where the model and its results are explained in more detail.

In particular, since the impacts created by projected climate change are relatively small (e.g. an expansion of agriculture land of 100 to 200 ha would be sufficient to offset the negative impacts of climate variability), policy effectiveness is not discussed in this paper. On the other hand, it is worth noting that the following types of interventions were tested:

- Energy efficiency improvements in the power sector, for the domestic, commercial, industrial, irrigation sectors and other uses. This is useful to offset the increased energy demand resulting from higher temperatures.
- Increased water efficiency use, with investments primarily allocated to the residential sector and residential buildings.
- Increasing the area cultivated for food crops. In this respect, it is worth noting that food crop production is a high-risk activity in Mauritius. Foreign competition is very strong on the production of basic crops and land availability is limited, therefore reaching meaningful economies of scale is highly challenging.

Conclusions

A framework has been proposed to integrate disaster risk reduction (DRR) and climate change adaptation (CCA) into national sustainable development planning in order to build the resilience of island states in the face of external shocks (climate impacts and natural disasters). Using the island of Mauritius as a case, the application of the framework has been demonstrated. Statistical downscaling has been used to obtain projections for changes and variability in precipitation up to 2050, and the cross-sectoral impacts have been analyzed using system dynamics modeling. In particular, the impacts on agriculture yield have been demonstrated since rain-fed agriculture is practices in Mauritius for food crop production. The analysis has shown that the changes and variability in precipitation (at the mean national level) can be compensated by marginally increasing the crop land area under cultivation. The cross-sectoral impacts have also been investigated for cyclone events modelled stochastically. In this case, damage is created from extreme precipitation events that are at least 200 mm above the long-term average. There are short-term impacts on total GDP and GDP growth rate. A pertinent observation is that GDP growth is higher relative to BAU after the natural disaster occurs. This is due to a combination of public relief expenditure (compensating for at least part of the cost of reconstruction, and avoided consumption) and for the higher efficiency (or productivity) of the newly purchased capital. These results indicate that preventive actions, aimed at increasing resilience to natural disaster, could increase GDP growth above the level of a “no action” scenario.

The proposed framework and its application are also useful to provide an evidence based approach to inform the ‘loss and damage’ agenda in island states.

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Annex 1

Disaster Shock *= Disaster Size*Year Of Natural Disaster*

Disaster Size *= Max(0, Random Factor CC-200)/200*

Year Of Natural Disaster *= Disaster Event Year*

Disaster Event Year *= If Then Else((Max(200, Random Factor Cc)-200)>0, 1, 0)*

Random Factor CC *= Random Factor*(1+Rainfall Variability Climsystems)*

Actual Annual Rainfall *= If Then Else(Climate Change Switch=0, Prec 1 BAU, Prec 2 CC)*

Prec 1 BAU *= Prec 1 BAU Table+Random Factor*

Prec 2 CC *= Prec 2 CC Table+Random Factor Cc*

Random Factor *= If Then Else(Time<2013, 0, Random Normal(-400, 400 , 0, 200 , 1))*

Random Factor Cc *= Random Factor*(1+Rainfall Variability CC)*

Rainfall Variability CC *= With Lookup (Time, ([(1980,-25)-(2050,25)],(1980,-0.15),(2015,0),(2050,0.15)))*

Agricultural TFP *=Total Factor Productivity*Effect Of Water Stress Index On Agricultural Tfp Table(Water Stress Index)*Effect Of Climate Impacts On Productivity*Effect Of Natural Disaster On Yield*

Effect Of Natural Disaster On Yield *= 1 - Disaster Shock * Disaster Yield Effect Baseline*

Effect Of Climate Impacts On Productivity *= Effect Of Precipitation On Agriculture Productivity*Effects Of Crop Pests And Diseases On Productivity *Effects Of Drought On Productivity*Effects Of Floods On Productivity*

Effect Of Precipitation On Agriculture Productivity *= "Effect Of Relative Rainfall On Agr. Tfp Table"(Perceived Relative Annual Rainfall)*

Effects Of Crop Pests And Diseases On Productivity *= Effects Of Temperature On Crop Pests And Diseases Table(Relative Annual Temperature)*

Effects Of Drought On Productivity *= Rainfall Shortage Relative To Reference ^ Elasticity Of Yield To Droughts*

Effects Of Floods On Productivity *= Floods Relative To Reference ^ Elasticity Of Yield To Floods*

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