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Socio-Economic Analysis of Climate Services in Disaster Risk Reduction: A Perspective on Pacific SIDS

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This paper explores methods and the key factors influencing socio-economic analysis of the role of climate services in disaster risk reduction, with a regional emphasis on Small Island Developing States in the western tropical Pacific. We analyse the role of traditional benefit-cost analysis especially in the context of evaluating the importance of science-based climate change services (i.e., relevant to current and future climate change over multi-decadal timescales) in disaster risk reduction at a national economy level. Our analysis is premised on a range of relevant social and economic metrics at a national economy scale, including surrogate indicators for specific disaster risk reduction sensitive sectors in context of both mitigation (transitional risk) and adaptation (physical risk) to climate change. Relative importance of different methodologies of socio-economic analysis (i.e., partial/sectoral vs economy-wide modelling), gaps in relevant data and information, and the role of the public and private sectors in mobilising resources and capability for facilitating such analysis are explored. Our paper also discusses the issues relating to investing in, producing and undertaking on-ground applications associated with disaster risk reduction using climate change services for both public good and private (-for-profit) benefit outcomes, and provides suggestions for further research to improve socio-economic analysis of Climate Information Services impacts.

Keywords: climate impacts, economic analysis, climate service, public private partnerhips, pacific island nations

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INTRODUCTION

Numerous studies have provided strong evidence of the social, economic and environmental benefits of weather and climate services (Zillman, 1999; Freebairn and Zillman, 2002; Gunasekera, 2004; World Meteorological Organisation, 2015), hereafter referred to collectively as Climate Information Services (CIS). In this context, reference to CIS in this paper broadly aligns with the definition of CIS described by the EU Roadmap for Climate Services (European Commission 2015).

CIS transform climate and weather data into tailored information and knowledge that help users. They enable users to make informed decisions across different sectors and activities. Given the increasing impacts of climate-related natural disasters around the world (e.g., Coronese et al., 2019), and in the Pacific specifically (e.g., Kumar 2020), provision of relevant climate services is regarded as an important activity that can help Pacific Small Island Developing States (SIDS) in climate and weather-related disaster risk reduction (DRR) (SPREP 2016; Cheng et al., 2020). We explore different methods (i.e., partial/sectoral vs economy-wide modelling) and key factors influencing socio-economic analysis of the role of climate services in DRR here.

By contrast, there is also a body of opinion questioning the efficacy of CIS to inform adaptation planning and associated decision-making more generally, including at a sectoral level in the Pacific (Webber 2017, 2019; Webber and Donner, 2017).

Given this background, the key objective of this paper is (by using a case study) to estimate the socio-economic effects of CIS-based improved decision-making around investment and protection of coastal assets and infrastructure in Pacific SIDS. Our analysis will provide a useful illustration of a rigorous and systematic framework for evaluating the net socio-economic benefits of CIS to decision-makers, including donors, national governments and CIS user groups, funding agencies, internal stakeholders, user groups and local communities. Furthermore, we anticipate that our research will build increased understanding and awareness of the role and value of so-called "'next generation"' CIS (Jacobs and Street 2020) among climate scientists, national meteorological and hydrological services, the DRR sector and associated CIS user communities, with learnings for both developing countries/SIDs and developed countries where appropriate.

The remainder of this paper is organised as follows. In the next section, we present the methodological framework used in this study. Following on from this we provide a brief discussion of our analysis. In *Methodological Framework*, the main results of our analysis are presented. The final section provides a policy discussion associated with our key findings.

MATERIALS AND METHODS

Role and Value of CIS

Assessing the role and value of CIS presents several challenges. The analysis presented in this paper is necessarily therefore predicated on explicit assumptions. Firstly, majority of CIS are produced and delivered as a public good. More specifically, they are a service provided without intended explicit commercial profit to all members of a society, either by the government or by a private firm or an organization and funded by the government. Secondly, CIS are both non-excludable and non-rivalrous. This implies that individuals cannot be effectively excluded from their use and use by one individual does not diminish their availability or value to others. Thirdly, the value of CIS improves with the investment in skill, resolution and capability of the basic meteorological and climatological data and information generated by relevant observations and models on the further assumption that 1) such data and information is tailored to the specific needs of users, and 2) the cost of which is generally borne by government or those providing the public good. Finally, the downstream benefits that accrue to end-users include for both public good and in many cases private-for-profit; the latter of which occurs when core CIS products and services are utilised as the primary input for development of more differentiated products and services, typically by and/or for the private sector.

CIS are an intermediate good and an enabling technology that adds value to other goods and services. To understand their value, we need to explore the benefits that users draw from CIS. Estimating the consumer surplus through willingness to pay for CIS (using a partial equilibrium framework) is one approach to assessing their value. Consumer surplus is the difference between the price a consumer is prepared to pay for a good or service and the price that the consumer has to pay. This approach has been used in a number of studies attempting to value CIS (see Ouédraogo et al., 2018; Tesfaye et al., 2020).

An alternative approach is to examine the impact of CIS as an enabling technology on productivity of downstream users/sectors of the services (see Newth et al., 2017; Naab et al., 2019). The productivity impacts are then translated into an increase in value added in a sector. In this paper we adopt the productivity approach (using a general equilibrium framework) to assessing the value of CIS. This approach was chosen, as within an economy wide framework, the full implications of changes in productivity can be accounted, giving a wider prospective on the benefits and value of CIS, without having to explicitly model the CIS sector.

METHODOLOGICAL FRAMEWORK

General equilibrium theory attempts to explain the behavior of supply, demand, and prices in a whole economy with several or many interacting markets, by assuming that a set of prices exist that will result in an overall equilibrium, where supply equals demand (See **Appendix A1** for more details). General equilibrium theory is distinguished from partial equilibrium theory by the fact that it attempts to look at several markets simultaneously rather than a single market or sector of a market in isolation. As an example, in the agricultural sector, if producers use seasonal forecasting (as a CIS) to improve the productivity (both in terms of quantity and quality) of the production of agricultural commodities, then producers will have a competitive advantage over competitors. This allows them to maintain or increase supply. Our methodological framework is an economy-wide modelling framework or a computable general equilibrium (CGE) modelling framework.

The major advantage of general equilibrium modelling is that it tracks all the relationships between supply side factors (such as availability of labour, infrastructure, other inputs and technology) and demand side factors (prices, change in quantity demanded). A number of studies have used CGE models to assess the implications of a changing climate on agricultural productivity (Cai et al., 2015), labour productivity (Newth et al., 2015), changes in patterns of crop production (Porfirio et al., 2017), and the impact of ENSO on agricultural productivity (Araújo et al., 2015).

The CGE model that we have used here is the Global Trade and Analysis Project (GTAP) model, a widely used general equilibrium model (see Hertel, 1997). GTAP Model has been used by over 400 government and international research and donor organizations and a host of academic and private sector organizations across the world for many decades. The standard

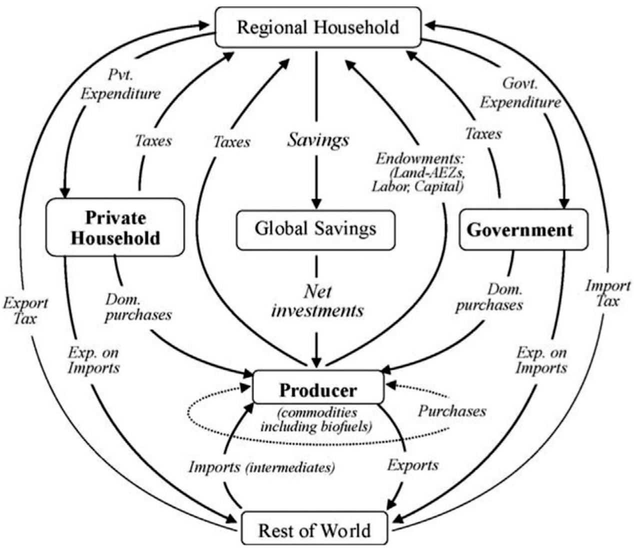

FIGURE 1 | A schematic illustration of the standard GTAP Model (*Source:* Hertel et al. (2010) after Brockmeier (2001).

Global Trade Analysis Project (GTAP) model used in this study is a multi-region, multi-sector, computable general equilibrium model. For a full account of the key GTAP model assumptions and equations, the reader is directed to Hertel (1997) and Valenzuela et al. (2008).

For understanding the whole of economy implications of CIS and the flow of effects of productivity changes, the GTAP model is a logical choice. The GTAP model gives users are wide range of options for understanding economy effects such as unemployment, tax revenue, trade obstacles, and productivity, which map naturally to understanding the benefits of CIS. GTAP also allows for partial equilibrium closures, which facilitate the comparison of results to studies between partial equilibrium assumptions, so sector specific modelling results around the use of CIS can be included within the GTAP framework to provide more detailed analysis.

In more detail, the GTAP model assumes constant returns to scale and perfect competition in all the markets with Walrasian adjustment to ensure a general equilibrium. As illustrated in **Figure 1** (based on Brockmeier, 2001; Hertel et al., 2010), each region has a representative household that collects all the income in its region and spends it over three expenditure types: private household (consumer), government and savings, in accordance with a Cobb-Douglas utility function.

Each sector is modelled by a representative firm that maximizes profits subject to a nested Constant Elasticity of Substitution (CES) production function. The CES production function combines primary factors and intermediate inputs to produce the sector's final good.

Firms pay wages/rental rates to the regional household in return for the employment of land, labour, capital and natural resources. Firms sell their output to other firms (intermediate inputs), to private households, government and investment. Firms also export tradable commodities and import tradable goods and intermediate inputs from other regions. These goods are assumed to be differentiated by region, following the Armington assumption, and hence the model can track bilateral trade flows.

The GTAP database version of the model used in this paper comprises 140 regions, and 57 sectors of the global trade analysis project database, version 9 (Aguiar et al., 2016). The model was run with the standard comparative static model closure, allowing for the analysis of policy changes relative to what would otherwise be.

There were three main steps in conducting the study:

- Developing the GTAP model aggregation that represented the key sectoral and regional economic activities;
- Establishing a reference case or a baseline, against which the counterfactuals will be evaluated; and
- Establishing the counterfactual scenarios.

We undertook ground-truthing of this approach, along with relevant assumptions and applicability of the analysis described here, in part using a stakeholder engagement process involving various in-country stakeholder meetings held in Vanuatu as part of the Green Climate Fund project entitled "Climate Information Services for Resilient Development Planning in Vanuatu" (https://www.greenclimate.fund/project/fp035). This project is designed to develop and deliver CIS to inform climate action and associated decision making at a sectoral and local community level.

Regional and Sectoral Aggregation

The GTAP model is based on the GTAP database, with economy-wide information for 140 regions across the world and 57 sectors of each economy/region. To make the analysis more tractable, it is necessary to aggregate the sectors and regions into larger regions. As we are interested in the impacts of protection of coastal assets and infrastructure from sea level rise on Pacific SIDS, we have created 1) an aggregation that has Pacific SIDS as a separate region (named as Rest of Oceania or XOC), although this is itself an aggregate region, 2) its main trading and foreign aid partners, and 3) similar collection of island nations (for comparison) and 4) other major geographical and economic regions. The aggregation is described in **Table 1**. We have aggregated the industry sectors of each economy/region into 14 sectors and they are listed in **Table 2**. We note that alternative aggregations are possible, and aggregations should be determined by the question under investigation.

The reference case has been defined as the prevailing situation with existing CIS data and information from meteorological and climatological service providers, including from existing, basic infrastructure. The reference case scenario represents as closely as possible the likely changes expected to occur in the global economy consisting of the countries/regions covered in the GTAP model database. These changes in the global economy are grouped into two areas: the first deals with the macro economic forecasts of each country/region and the second deals with expected policy changes. The key macroeconomic variables covered include gross domestic product (GDP), gross

TABLE 1 | Regional Aggregation for the GTAP model.

Region name	Code	Countries composing region
Rest of Oceania	XOC	American Samoa, Cook Islands, Fiji, French Polynesia, Guam, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, New Caledonia, Niue, Northern Mariana Islands, Palau, Papua New Guinea, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, United States Minor Outlying Islands, Vanuatu, Wallis and Futuna
Australia	AUS	
New Zealand	NZL	
Asia and the Subcontinent	ASC	China, Hong Kong, Japan, Mongolia, Taiwan, Democratic People's Republic of Korea, Macao, Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Myanmar, Timor Leste, Bangladesh, India, Nepal, Pakistan, Sri Lanka, Bhutan, Maldives
Caribbean	CAR	Jamaica, Puerto Rico, Trinidad and Tobago, Anguilla, Antigua and Barbuda, Aruba, Bahamas, Barbados, Cayman Islands, Cuba, Dominica, Grenada, Haiti, Montserrat, Netherlands Antilles, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Turks and Caicos Islands, British Virgin Islands, US Virgin Islands
United States	United States	
Canada	CAN	
Korea	KOR	
Russia	RUS	Russia, Tajikistan, Turkmenistan, and Uzbekistan
Developed and Emerging Nations	DEN	Mexico, *Argentina*, Brazil, Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungry, Ireland, Italy, Latvia, Lithuania, Luxemburg, Malta, Netherlands, Poland, Portugal, Slovakia Slovenia, Spain, Sweden, United Kingdom, Saudi Arabia, South Africa
Rest of the World	ROW	Rest of the world not elsewhere classified

TABLE 2 | Sectoral Aggregation for the GTAP model.

Sector name	Code	Composition
Crops	CRP	Paddy rice, Wheat, Cereal grains nec, Vegetables, fruit, nuts, Oil seeds, Sugar cane, sugar beet, Crops nec
Livestock	LIVSTK	Cattle, sheep, goats, horses, animal products nec
Agricultural products	AGPRD	Plant-based fibres, Raw milk, Wool, silk-worm cocoons
Forestry	FOR	
Fisheries	FISH	
Manufacturing	MFG	Meat products nec, Vegetable oils and fats, Dairy products, Processed rice, Sugar, Food products nec, Beverages and tobacco products, Textiles, Wearing apparel, Leather products, Wood products, Paper products, publishing, Petroleum, coal products, Chemical, rubber, plastic prods, Mineral products nec, Ferrous metals, Metals nec, Metal products, Motor vehicles and parts, Transport equipment nec, Electronic equipment, Machinery and equipment nec, Manufactures nec
Transport	TRNS	Transport nec
Sea Transport	STRNS	Sea transport
Air Transport	ATRNS	
Natural Resources	NRES	Coal, Oil, Gas, Minerals nec
Water Services	H_2O	
Trade	TRADE	
Energy Sector	ELY	Electricity
Services	SER	Construction; Communication; Financial services nec; Insurance; Business services nec; Recreation, Tourism and other services; Public Administration, Defence, Health, Education, Dwellings

domestic investment and population and labour force projections. The reference case assumes that there is no impact of climate change on the underlying economic parameters and settings. The key policy changes relate to trade policy changes at multilateral, regional and bilateral levels converting major sectors/industries across the world with a particular focus on major trading partners. The major purpose here is to develop a realistic base case scenario for the global economy.

Counterfactual Scenario

To illustrate the economic implications of global sea level rise from climate change and the potential avoidable socio-economic damages, we made use of two counterfactual scenarios. The first counterfactual assumed that the current level of investment in basic CIS is maintained, and that based on this information decision makers are able to make decisions about future infrastructure, economic investments and coastal adaptation measures. These decisions are far from optimal. We will refer to this case as the "sea level rise scenario".

The second additional government investment in CIS, which is invested into the existing CIS sector, and additional payments to the construction sector to implement the required mitigation steps. In this scenario, an additional investment in tailored CIS is provided to support sectoral decision-making around coastal adaptation and infrastructure investments. These decisions are assumed to be more effective than those made under the "sea level rise scenario", but there are still unavoidable affects from sea level rise. We will refer to this as the '"mitigated sea level rise scenario"'.

TABLE 3 | Policy shocks used in modelling.

Economic shock or policy setting	Sea level rise scenario	Mitigated sea level rise scenario (%)
Reduction in infrastructure due to storm surges damage, flooding and loss of infrastructure	7%	4
Reduction in sea transport efficacy, due to lost infrastructure and reduced operating conditions of harbours	6%	4
Reduction in air transport efficiency, due to flooding and storm surge damage to infrastructure	3%	2
Reduction in transport efficiency due to storm surge and flooding damage to roads, bridges and infrastructure	2.5%	1.5
Reduction in the productivity of fisheries due to reduced operating capacity of harbour and ports	5%	3
Reduction in crop output due to inundation and flooding	4%	2
Reduction in forestry output due to inundation and flooding	3%	2
Reduction in shipping efficiency, to Oceania from other regions, due to change harbour productivity	8%	6
Increase in government funding to climate services	—	1
Increase in government funding to mitigate sea level rise	—	3

Table 3 lists the assumed key economic shocks and policy changes associated with these two counterfactual scenarios used in this study using the GTAP model. In each case the productivity of the sector was targeted by the shock. It should be realized that the chosen values of the economic shocks and policy changes are illustrative and indicative only from the consultation process. The impact of climate change is governed by a 2°C of warming above pre-industrial levels. As the GTAP model is comparative static, we are concerned that the level of warming has occurred rather than when it will occur. The selection of values was done via stakeholder engagement and the availability of background information.

RESULTS

The key results of our analysis are presented in **Figures 2–4**. As illustrated in **Figure 2**, the gross domestic product (GDP) of the Pacific SIDS represented by the Rest of Oceania (XOC) region in the GTAP model is estimated to fall by 8 percent under the sea level rise scenario and 3.5% under the mitigated sea level rise scenario relative to the baseline or reference case. They equate to US$ 3.5 b and US$ 1.5 b, respectively. This is in comparison to the reference case GDP level of US$ 44 b for the Rest of Oceania region. Our analysis indicates that at the aggregate regional level, mitigation of sea level rise is estimated to save US$2 b (in terms of potential losses) relative to what would otherwise be. It is important to recognize that the sea level rise mitigation impacts will vary across the individual Pacific SIDS depending on their level of vulnerability with some countries receiving disproportionately higher impacts than others. Hence, from an empirical point of view, it will be an important step in future GTAP data base development to disaggregate the region into individual countries of the Pacific SIDS.

The GTAP model tracks the changes in output of each sector of the economy resulting from specific policy shocks. These estimated sectoral output changes relative to the baseline are shown **Figure 3**. Under both the sea level rise scenario and the mitigated sea level rise scenarios, outputs of most of the sectors are estimated to decline relative to the baseline levels. Fall in outputs are driven by the loss in sectoral productivity and increased transport costs associated with effects of sea level rises in general. However, it is important to note that loss in sectoral outputs is smaller under mitigated sea level rise scenario relative to the sea level rise scenario.

Figure 4 illustrates the changes in household incomes for the sea level rise scenario and the mitigated sea level rise scenario. Under the sea level rise scenario, household income is estimated to fall by an average of US$612 per household, while under the mitigation of sea level rise scenario the reduction is estimated to be US$276 per household. This in turn is expected to have a significant impact on household income in individual Pacific SIDS. To put this in context, for example, the Vanuatu household income expenditure survey lists the average household income to

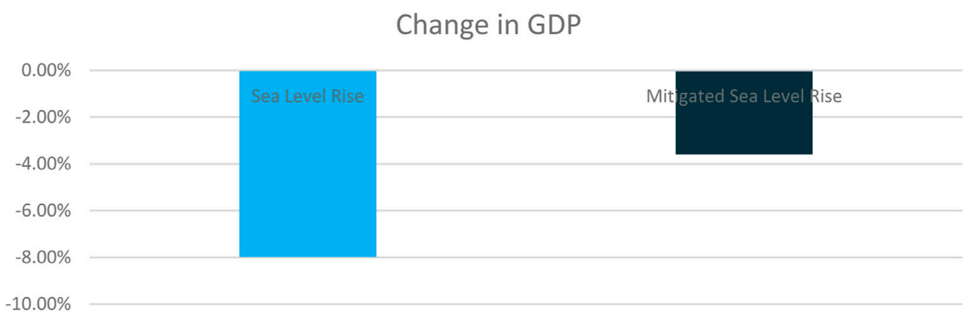

FIGURE 2 | Comparison of the GDP outcomes for the two counterfactual scenarios.

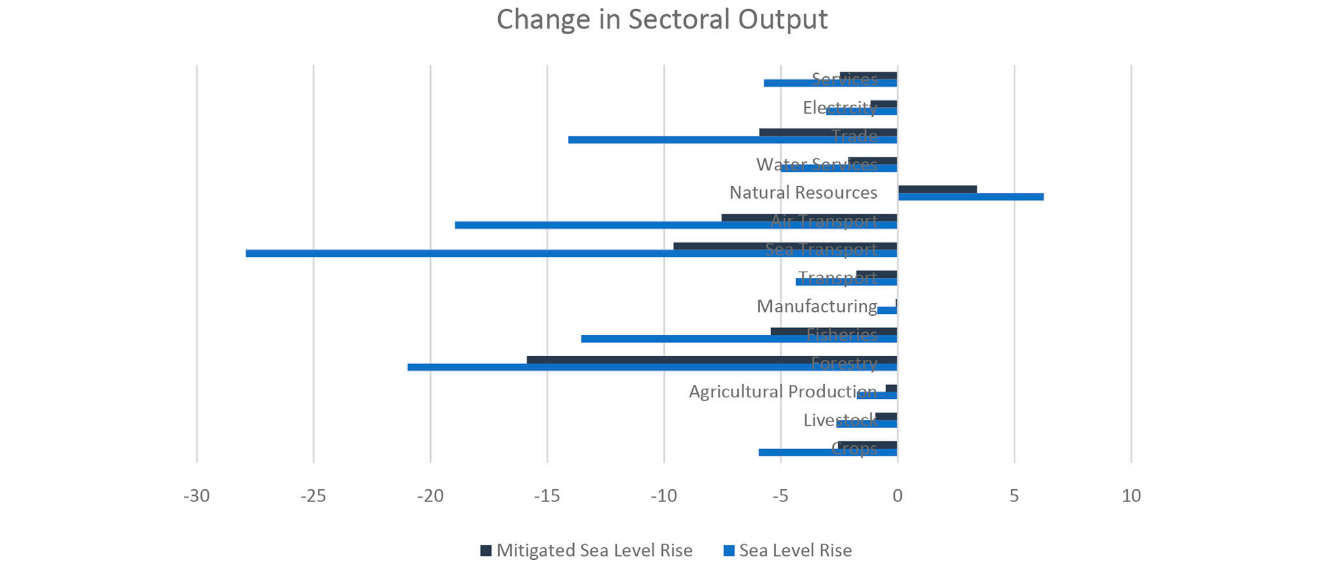

FIGURE 3 | Changes in sectoral output relative to the baseline.

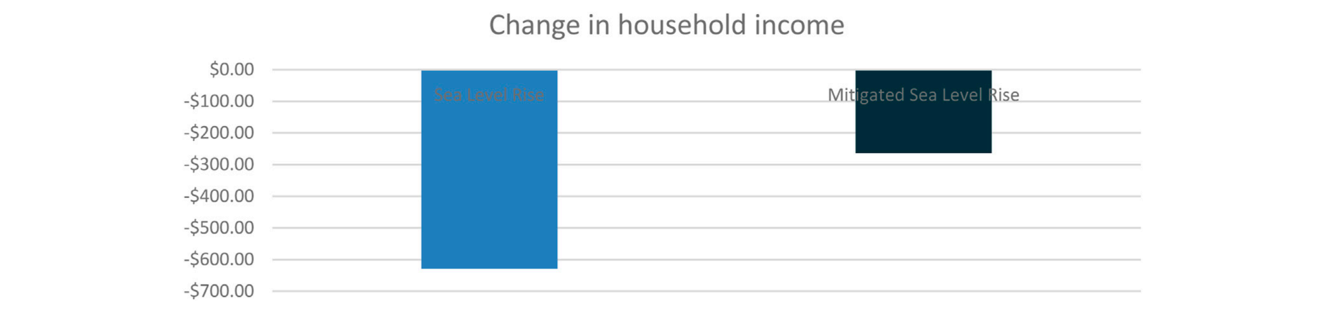

FIGURE 4 | Change in household incomes.

be between $US8,511 and US$10,585. Again, it is important to recognize that the reduction in household income estimated here is at the aggregate region level. The specific impacts will vary across individual countries, with some countries receiving disproportionately higher impacts than others.

DISCUSSION

Virtually every economy and every industry are directly or indirectly affected by climatic and weather conditions, and these impacts are increasing due to climate change (e.g., Coronese et al., 2019). Climate and weather data and information in the form of CIS acquires economic value by influencing the behaviour of users whose activities are sensitive to climatic and weather conditions. Hence, it logically follows that CIS can be used to mitigate the risks and impacts of climate change. Such information provides the evidence-base for improved policy development, planning and associated decision-making underpinning national, regional, and household-level adaptation to events such as sea level rise and various climate-related natural disasters. Developing economies such as those in the Pacific SIDS can be disproportionately affected by the effects of climate and weather. These effects include impacts on economic activity, household income and well-being of local communities etc.

The analysis presented in this paper illustrates that the use of CIS-based improvements to DRR decision making could potentially help lower the adverse impacts of sea level rise in the Pacific SIDS. This can be in relation to investment and protection of coastal assets and infrastructure in Pacific SIDS. Our analysis has shown that even modest reductions in the impact of such events have considerable socio-economic and welfare implications for the regions affected. For example, under the "mitigation of sea level rise" scenario the estimated reduction in GDP and average household income in Pacific SIDS are much lower (3.5% and US $276) than under the "sea level rise" scenario (8% and US$ 612), respectively.

This highlights the importance of allocating adequate resources for supporting the development and delivery of CIS on a sustained basis concurrently with strategic climate finance investment in adaptation and disaster risk reduction. It is also the case that the public-good/private-for-public nexus in relation to CIS in developing countries such as Pacific SIDS is entirely compatible on the assumption that 1) core CIS products and services benefitting all of society should be publicly funded to address relevant market failure on a needs basis, and 2) that the additional investment required for differentiated CIS products and services can/should be funded by the private sector where there are clear private-for-profit imperatives at play; noting in particular that so-called "commercialisation" of climate science (e.g., as referred by Webber and Donner 2017) in and of itself is not problematic as long as the associated science-based CIS delivery is appropriately balanced, accessible and the funding burden equitably distributed across the CIS value chain.

The limitations of CIS in providing tangible benefits to ultimate on-ground beneficiaries such as in the Pacific are well recognized (Webber 2017; 2019), and this paper makes no attempt to further elucidate the additional requirements for ensuring CIS are appropriately tailored to meet the priority needs of users. Rather it is assumed that best practice delivery of CIS is followed by providers, including compliance with contemporary principles of co-design and co-production of CIS with users as mainstream service delivery process. Likewise this study makes no attempt to expand on the broader evidence and associated data/information sources required to ensure a multi-disciplinary approach to effective and efficient CIS delivery. It is however assumed that such outcomes require multiple lines of evidence of which CIS is but one, albeit we believe a critical component. It follows that to achieve the types of societal outcomes described in this paper, the CIS process more broadly needs to be optimized, including along lines suggested by Webber (2017; 2019) and more recently by Jacobs and Street (2020) in relation to so-called "next generation" climate services.

Furthermore, the analysis of the socio-economic costs and benefits of the use of CIS needs to be recognized as an ongoing process. Such analysis will have several policy implications in terms of providing valuable evidenced based information to help 1) frame the planning and policymaking dialogue with government and other stakeholders at sectoral and community level, 2) demonstrate the net socio-economic and environmental return on investment, 3) provide a quantifiable decision-making framework through which investment in climate services can be made, and 4) provide a monitoring and evaluation capability for demonstrating the long-term net socio-economic impact of CIS.

In the context of the analysis undertaken in this paper there are several areas where further modelling improvements can be made. These are areas for future research. The first area of improvement relates to the explicit treatment of CIS in our modelling work. Currently our modelling would assume that all changes to CIS are exogenously driven, that is, the basic costs and benefits are calculated off the model and then used to form the reference case and the counterfactual scenarios. An alternative approach is to create a CIS sector within our model, and then further activate that sector directly with changes in policy through increased funding, new infrastructure and investment, etc. The model would then endogenously calculate the associated productivity changes. This approach would still require exogenous calculations of the impacts of climate phenomena such as the impact of sea level rise on infrastructure. This expansion would allow us to explore issues such as the implication of reduced/increased government funding for CIS on the mitigation of sea level rise.

The second area of improvement relates to **the disaggregation of Pacific SIDS in our model.** The GTAP database linked to the GTAP model has 147 countries and regions. These regions can be aggregated and disaggregated in appropriate ways to answer key policy and economic questions. In this paper, the Pacific Islands were aggregated together to form the "Rest of Oceania" or XOC. Disaggregation of XOC into smaller economies is possible and it would allow a more robust analysis of the beneficiaries of different types of CIS. This can be done in one of two ways. First via creating regional households within the modelling framework, where we could see the household-level effects. This is plausible as the required information such as the Vanuatu Household Expenditure Survey (see https://vnso.gov.vu/index.php/census-and-surveys/surveys/household-income-expenditure-survey-hies) is available. Second way is to split Pacific Island Countries out so they have a distinct country and sectoral representation. This may be difficult, as the detailed data required may not be available, but it should be possible to construct a good representation of any island nation economy based on reliable proxy data.

Here, we have used scenario analysis of the impact of sea level rise in the Pacific, we illustrate the use of socio-economic analysis as one means of quantifying societal value and benefits of CIS. Such analysis is a legitimate line of evidence (amongst others) to enhance DRR policy development, planning and decision making in the Pacific. The CGE modelling framework presented here is highly flexible, meaning that with methodological improvements in socio-economic, such as more detailed partial sectoral analysis or improved impact analysis, outputs can be easily incorporated into decision-making, thereby leading to more robust analysis and policy making into the future.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

DN, GG and DG, Wrote the paper, DN, DG conducted research, DN GG and DG designed research, DG and DN performed analysis.

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APPENDIX 1 BRIEF DESCRIPTION OF THE GTAP MODELLING APPROACH

The standard GTAP model used in this study is a multi-region, multi-sector, computable general equilibrium model. For a full account of the key assumptions and equations, the reader is directed to Hertel (1997) and Valenzuela et al. (2008).

The model assumes constant returns to scale and perfect competition in all the markets with Walrasian adjustment to ensure a general equilibrium.

As illustrated in **Figure 1** (based on Brockmeier, 2001; Hertel et al., 2010), each region (e.g., Indonesia) has a representative household that collects all the income in its region and spends it over three expenditure types: private household (consumer), government and savings, in accordance with a Cobb-Douglas utility function.

Each sector is modelled by a representative firm that maximizes profits subject to a nested Constant Elasticity of Substitution (CES) production function. The CES production function combines primary factors and intermediate inputs to produce the sector's final good.

Firms pay wages/rental rates to the regional household in return for the employment of land, labour, capital and natural resources. Firms sell their output to other firms (intermediate inputs), to private households, government and investment. Firms also export tradable commodities and import intermediate inputs from other regions. These goods are assumed to be differentiated by region, following the Armington assumption, and hence the model can track bilateral trade flows.

The GTAP database version of the model used in this paper comprises (140 regions aggregated to) 84 regions (with each of the 10 ASEAN countries as separate regions), and 57 sectors of the global trade analysis project database, version 9 (Aguiar et al., 2016). The model was run with the standard comparative static model closure, allowing for the analysis of policy changes relative to what would otherwise be.