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The impacts of climate change on Australia and New Zealand: a Gross Cell Product analysis by land cover*

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This paper examines the newly constructed geographically scaled economic output measure, Gross Cell Product (GCP), of Australia and New Zealand to quantify the impacts of climate change in the region. The paper discusses advantages of using the GCP instead of the Gross Domestic Product. The paper reveals that the GCP falls sharply as temperature increases in the region. A 1°C increase in temperature would decrease the productivity with an elasticity of −2.4. A 1 per cent decrease in precipitation would decrease productivity with an elasticity of −2.3. However, forest vegetation on the coasts will benefit from initial warming. We find that the changes in climate means are potentially more harmful than changes in climate variability. In the long term, a 3.4° warming coupled with 6.6 mm decrease in rainfall would decrease the GCP by 34 per cent by 2060. The damage is largely accounted for by population effects. The paper confirms that Australia is highly constrained by climate and geographic factors.

Key words: climate change, G-ECON, Gross Cell Product, Oceania.

1. Introduction

The earth has warmed by about 0.6°C since the industrial revolution due mainly to industrial activities and land-use changes [Intergovernmental Panel on Climate Change (IPCC) 2007a]. It is particularly worrisome that the concentration of carbon dioxide observed at the Mauna Loa observatory has been rising rapidly from 310 to 370 ppm since the 1960s, and it will continue to increase in the coming decades (Keeling and Whorf 2005). Researchers have studied the impacts of climate change around the globe [Intergovernmental Panel on Climate Change (IPCC) 2007b]. However, economic estimates of the potential damage on Oceania have been sparse (Nordhaus and Boyer 2000). Given that Australia and New Zealand are strongly conditioned by their climate and ecological systems and there is surging political interest in climate policy, there is a serious knowledge gap in the understanding of potential impacts of climate change on the continent (See Garnaut 2010).

* I thank Professor William Nordhaus at Yale University for more than a decade long efforts in building the G-ECON database. The views expressed in this paper are the author's alone.

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Although concentrated efforts have been made on exploring detrimental effects of warming on the Great Barrier Reef, researchers are not well aware of the impacts of global warming on natural resource intensive enterprises including, but not limited to, agricultural crops, livestock management, mining and forestry, let alone the impacts on the whole economy. Moreover, economic valuation has been extremely rare. Regional estimates of the damage from climate change have never been established up until now.

This paper proposes a novel approach to measure monetary impacts of climate change on the economy of Oceania. Building on the extensive work by Nordhaus and his colleagues to construct a geographically scaled economic output data set across the globe, the G-ECON database, we analyse the variation of Gross Cell Product (GCP) across climate zones in Australia and New Zealand (Nordhaus 2006).[1] Further, we match the GCP variation with the variation of land covers on the ground. Based on the global vegetation classification by Mathews this paper quantifies the impacts on the 17 vegetation types across Australia and New Zealand (Matthews 1983). This study examines the impacts of both changes in climate means and variances using the Climate Research Unit Average Climatology high resolution data set (New *et al.* 2002).

This study examines diverse ecosystems in Australia and New Zealand. Although population is currently concentrated on the coastal areas and economic outputs are high there, there exist vast areas suitable for other economic activities such as agriculture, forestry, mining and livestock management. For example, in the vast grasslands found across Australia and New Zealand, people raise beef cattle, dairy cattle and sheep for income [Australian Bureau of Agriculture and Resource Economics (ABARE) 2010]. Previous studies find that when crops fail due to too hot and dry conditions, African farmers move away from crops to livestock management in the savannah zones (Seo and Mendelsohn 2008; Seo 2010a). When climate becomes hotter and wetter, African families switched to forest products (Seo 2010b). This type of adaptation can account for half of the expected damage from global warming in Latin America (Seo 2010c). This paper aims to capture all income generating activities and adaptations across Oceania such as agriculture, livestock, mining, forestry, fishery, manufacturing, tourism and service industries.

The paper proceeds as follows. In the following section, I describe an analysis of the GCP to value the impacts of climate change in comparison with more traditional studies of the variation in Gross Domestic Product (GDP) (Dell *et al.* 2009). The third section describes the data set and sources, focusing on the G-ECON database which includes climate variables and a global vegetation classification. Estimation results and simulations are presented in the ensuing sections. We employ an Atmospheric-Oceanic General Circula-

[1] The analysis of the variation of an aggregate economic measure such as GDP across climate variation is well established. See, for example, the recent study and review by Dell *et al.* (2009).

tion Model (AOGCM) compiled by the Commonwealth Scientific and Industrial Research Organization (CSIRO) to predict the impacts of climate change (CSIRO 2010). The paper concludes with a summary of results and discussions of policy implications.

2. Theory

The central variable of the present analysis is GCP across Australia and New Zealand. The concept of GCP is the same as that of Gross Domestic Product and Gross Regional Product developed and widely used in the national income and product accounts of major countries. It is the gross value added in a specific region or total production of market goods and services in a region less purchases from other businesses. The main difference between GCP and GDP is that the former is defined by a geographic unit of 1° latitude by 1° longitude grid cell, whereas the latter is defined by political boundaries such as countries or provinces (Nordhaus 2006).

The major advantage of using the GCP instead of the GDP is that it can capture land productivity well across the landscape as it is measured per unit land, called a cell, instead of per capita.[2] The measure is independent of political boundaries such as states and countries. Second, the GCP is likely to provide a more accurate measure of productivity across different geographical regions as the underlying units are not bound by policy boundaries. A political boundary, such as a county or a state, is drawn with no regard to geographical variations, therefore is likely to be inclusive of all the geographical components such as deserts, savannahs, forests and mountains.

However, at least for the present moment, there exists a constraint in the database in applying the GCP measure. To be more specific, although most developed countries calculate and report the GDP at finer political units such as counties or districts and at finer time scales such as monthly, the GCP is at present not measured directly by any country. In the case of Australia, the GCP per capita is therefore spatially rescaled from the GDP per capita reported at the eight 'States' while from the 17 regions in New Zealand. Nonetheless, it is possible that the GCP be measured directly in the near future by collective efforts of concerned people given the high value of such data in studying numerous problems including global environmental issues.

The main hypothesis to be tested at later sections of this paper is that economic productivity measured as the GCP varies as the external climate varies. Therefore, climate change would lead to changes in productivity. As climate changes, people can switch to a more profitable enterprise. For example, if agriculture becomes less productive in a region, people would shift to forest products or livestock management, and vice versa. If the currently dry zones

[2] Land productivity, in this case, refers to the production across Oceania in a gridded cell of equal size which is composed of both the production per capita and the number of person in the cell.

were to receive more rainfall owing to climate change, population might move from coastal zones to dry zones. To adapt to climate change, people would also change their product portfolios of their existing enterprises. They would also change the composition of inputs to make the best use of the new climate. The major advantage of this approach is therefore the capacity to include all the adaptations that can be taken by individuals endogenously.

To formalise the idea, given the land, let each cell j maximise the profit from the different uses of the land:

$$\mathrm{Max}\pi_j = \sum_i [R_{ij}(E_j, G_j, H_j, F_j|\mathrm{land}) - C_{ij}(E_j, G_j, H_j, F_j|\mathrm{land})] \quad (1)$$

where the subscript j denotes cell, i denotes a type of land use such as manufacturing, service, mining, cropping, animal husbandry and forestry, E environmental variables such as climate, G geography such as elevation and soils, H socioeconomic factors and F country-fixed effects. Note that the baseline geographical unit is each cell, not political unit such as a country or a province. Note also that the size of land is fixed in each grid cell that controls land size in the GCP.

The maximum profit of cell j is achieved when the profits at the marginal land are equated across different land uses:

$$\pi_{ji} = \pi_{jk}, \forall i, k. \quad (2)$$

Then, the maximum profit of the each gridded cell can be written as a function of the exogenous variables:

$$\pi_j^* = f(E_j, G_j, H_j, F_j). \quad (3)$$

The optimum profit for each gridded cell reflects the optimal composition of land uses given the external climate and geographical conditions. As climate changes, this optimal composition will change, leading to the changes in the GCP. Therefore, the impacts of climate change are measured as the difference in the optimum outputs before and after climate change. If climate changes from E^b to E^a, the impacts are calculated as follows:

$$\Delta\pi_j^* = f(E_j^a|G_j, H_j, F_j) - f(E_j^b|G_j, H_j, F_j). \quad (4)$$

In the ensuing empirical sections, exact specifications of the above Equation 3 will be discussed in greater detail.

3. Data

Australia has six states—New South Wales, Queensland, South Australia, Tasmania, Victoria and Western Australia—and two major mainland territories—the Northern Territory and the Australian Capital Territory. Each state is composed of numerous counties. Separated by the Tasman Sea, New Zealand comprises 16 regions and 1 territory: Northland, Auckland, Waikato, Bay of Plenty, Gisborne, Hawke's Bay, Taranaki, Manawatu-Wanganui, Wellington, Marlborough, Nelson, Tasman, West Coast, Canterbury, Otago, Southland and Chatham Islands.

The main source of data is the G-ECON database established by more than a decade of work by William Nordhaus and his colleagues and used for his recent article (Nordhaus 2006). The G-ECON project developed a geographically scaled economic data set, which produced a global data set of economic activity for all terrestrial grid cells.[3] It includes 27,500 terrestrial grid cells with each grid of 1° longitude by 1° latitude resolution. This size is approximately 100 by 100 km, which is somewhat smaller than the size of the major subnational political entities for most large countries (e.g. states in the United States) and approximately the same size as the second level political entities in most countries (e.g. counties). In the present analysis for Australia and New Zealand, the G-ECON database has 877 gridded cells: 815 for Australia and 62 for New Zealand.

The primary variable of the G-ECON database is GCP. It is the Gross Domestic Product scaled to the geographical unit of a latitude–longitude grid cell. The general methodology for calculating GCP is the following:

$$\text{GCP by grid cell} = (\text{population by grid cell}) \times (\text{per capita GCP by grid cell}) \tag{5}$$

The population estimates by grid cell, the first term on the right-hand side, were constructed separately by a team of geographers and demographers (Deichmann *et al.* 2001). The second term, per capita GCP by grid cell, was estimated from four different economic data: (i) gross regional product (such as gross state product for the United States), (ii) regional income by industry (such as labour income by industry and counties or provinces), (iii) regional employment by industry (such as detailed employment by industry and region) and (iv) regional urban and rural population or employment along with aggregate sectoral data on agricultural and nonagricultural incomes. To create a gridded cell data, Nordhaus interpolates the economic data currently available by political units to geographic boundaries by a spatial rescaling, after testing seven different methods, using a proportional allocation rule, i.e. by assuming that per capita output is uniformly distributed in each province and that population is uniformly distributed in each grid cell (Nordhaus 2006).

The environmental data contain climate [precipitation (monthly), temperature (monthly)], terrain (elevation, roughness), vegetation types and soil types.

[3] A detailed description and major outputs of the G-ECON Project is available at http://gecon.site.yale.edu.

Climate and terrain data were derived from the Climate Research Unit Average Climatology high-resolution data sets (New *et al*. 2002). The data set includes both climate means and variabilities of temperature and precipitation.

Soil data are from the Zobler's World File for Global Climate Modeling (Zobler 1986). It classifies all grid cells into 27 great soil groups. Major soils found in Oceania are Acrisols, Cambisols, Ferralsols, Phaeozems, Lithosols, Luvisols, Nitosols, Podzols, Arenosols, Regosols, Solonetz, Andosols, Vertisols, Planosols, Xerosols, Yermosols and Solonchaks. Many cells in the sample are also dominantly water such as lakes or oceans.

Vegetation and land cover data are from the Matthews' Vegetation and Land Use Data (Matthews 1983). Vegetation types are highly diverse in Oceania from desert, grassland, shrubland, woodland, and forested zones. Forest vegetations are tropical mangrove and rainforests, tropical/subtropical evergreen broadleaved forests, subtropical rainforests, temperate rainforests, temperate broadleaved forests and evergreen sclerophyllous forests. Woodland vegetations include evergreen sclerophyllous woodlands and tropical/subtropical drought deciduous woodlands. Shrub vegetations are evergreen broadleaved shrublands, evergreen needleleaved shrublands and xeromorphic shrublands. Grassland vegetations are tall/medium/short grasslands with woody cover, tall/medium/short grasslands with shrub cover, tall grasslands with no woody cover, medium grasslands with no woody cover and meadow. Lastly, there are deserts.

In Figure 1, we map the vegetation types found in Oceania. Along the eastern coasts of Australia are mostly temperate broadleaved forests. Adjacent to the forests are sclerophyllous woodlands. Further inlands are xeromorphic shrublands. Central parts of Australia are occupied by grasslands and deserts. The South of Australia is mostly xeromorphic shrublands. Western Australia is a mixture of forests, woodlands and shrublands in the south and a combination of shrublands and meadow in the north. Northern parts are drought deciduous woodlands, sclerophyllous forests and grasslands. Major vegetations in New Zealand are temperate forests and meadows.

4. Empirical results

Descriptive statistics of the sample are shown in Table 1. Average temperature is 19.6°C. The continent is dry with average monthly rainfall of just 62 mm. For reference, average rainfall of Africa is around 80 mm/month (Seo 2010a). Standard deviation of annual temperature is about 4.5°C, while that for precipitation is 37 mm. The mean altitude of the continent is 240 m above sea level and cells on average are 192 km away from the coasts. Average cell population is 32,285. Yermosols, Vertisols, Xerosols and Luvisols are the most common soil types.

In Figure 2, we map the log GCP across the two countries. The highest GCP regions are mapped as black filled-in circles. These regions are located in the eastern coasts, in the south, in the southern parts of the Western

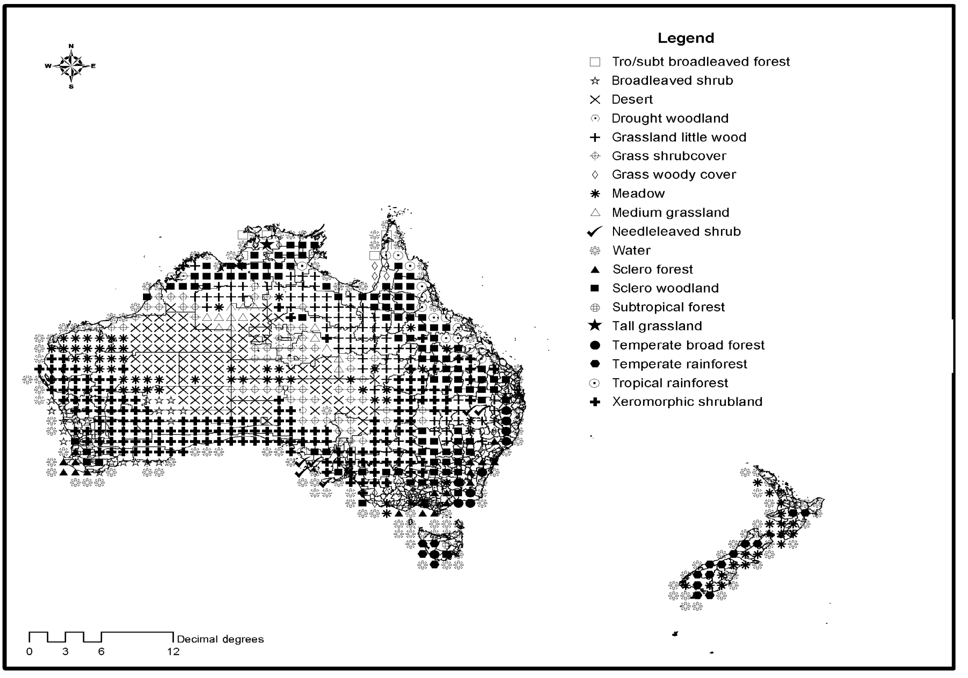

Figure 1 Natural vegetation in Oceania.

Table 1 Descriptive cell statistics (by 1 × 1 degree cell)

Variable	Mean	SD
Temperature	19.86	5.31
Precipitation	62.69	45.60
Temperature variability	4.45	1.29
Precipitation variability	37.52	38.16
Elevation	0.24	0.19
Distance	192.96	206.33
Population	32,285	151,853
Acrisols	0.03	0.17
Cambisols	0.03	0.18
Ferralsols	0.02	0.15
Phaeozems	0.00	0.06
Lithosols	0.06	0.24
Luvisols	0.09	0.29
Nitosols	0.01	0.12
Podzols	0.01	0.12
Arenosols	0.05	0.23
Regosols	0.03	0.16
Solonetz	0.04	0.19
Andosols	0.01	0.10
Vertisols	0.10	0.30
Planosols	0.07	0.25
Xerosols	0.09	0.28
Yermosols	0.13	0.34
Solonchaks	0.01	0.08

Australia and in New Zealand. The second most productive zones are mapped as black squares. They are located further inland from the highest GCP regions in the eastern coasts and in Western Australia. They are also located in New Zealand. The next most productive regions are mapped as black triangles, followed by black crosses. Unproductive regions occupy the vast land areas in the centre. The highest GCP regions are likely to be earning incomes mainly from manufacturing and service industries. The next most productive regions, black squares and triangles, are likely to be more suitable for agriculture, livestock, mining and forests [Australian Bureau of Agriculture and Resource Economics (ABARE) 2010].

To explain the variation of the GCP across climate variation in the two countries, we estimate the following reduced form of the log GCP in each cell against climate means (E) and climate variations (E_{SD}), soil variables (S), access and market variables (H), and country-fixed effects (F):

$$\begin{aligned}\text{LogGCP} = \alpha + \sum_{E=T,P} (\beta_1 \cdot E + \beta_2 \cdot E^2) + \sum_{E_{SD}=T_{SD},P_{SD}} \beta_3 \cdot E_{SD} \\ + \sum_{j=1}^{J} \gamma_j \cdot S_j + \sum_{k=1}^{K} \varphi_k \cdot H_k + \sum_{l=1}^{L} \kappa_l \cdot F_l + \varepsilon.\end{aligned} \quad (6)$$

Estimation results, parameter estimates and heteroscedasticity-consistent P values are shown in Table 2.[4] The model is highly significant with adjusted R^2 of 0.62. Individual parameter estimates are also highly significant. The White test does not reject the null hypothesis of homoscedasticity. The errors are approximately normally distributed.

We also test the hypothesis of spatial correlation. Using the spatial weight matrix with pairwise distance among locations as elements, the spatial correlation of the log GCPs is revealed to be low according to the Moran's I statistics and Geary's C statistics, both of which does not reject the null hypothesis of no correlation (Griffith 1993; Wooldridge 2002). The table also presents a regression which corrects for spatial correlation of the errors using a Gaussian distribution. As expected, the parameter estimates are not much different from those of the Ordinary Least Squares (OLS) regression.

Climate parameters are highly significant. The log GCP has a hill-shaped relationship with annual mean temperature, which indicates vulnerability of the continent's economy in high temperatures. It has also a hill shaped-relationship with annual mean precipitation. A higher variability in temperature is beneficial to the economy, while a higher precipitation variability is harmful to the economy.

Soils play important roles in the determination of productivity, i.e. most parameters are highly significant. Against the base case of mainly water body,

[4] Since vast areas in the central areas have no economic activities at all, we left the cells with zero GCP values out of the regression.

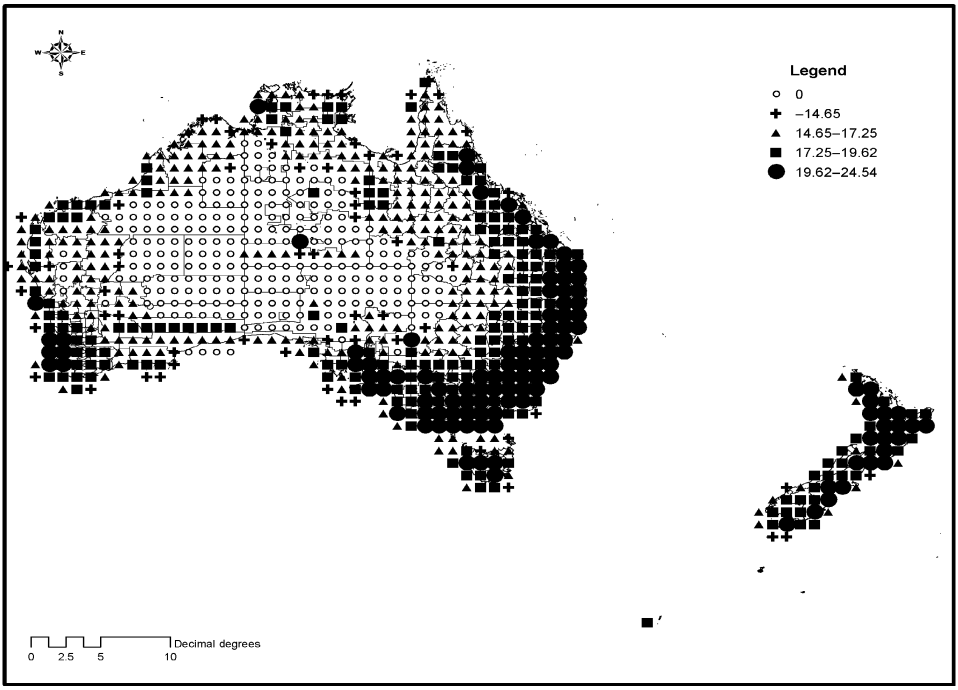

Figure 2 Log Gross Cell Product across Oceania.

productivity is higher in most soils with the exception of Phaeozems. This soil has a humus rich surface layer found in grasslands and deciduous vegetations (FAO-UNESCO 1987). Productivity is higher especially in soils Cambisols, Luvisols and Planosols. Elevation parameters, on the other hand, are not significant, unlike other continents such as North America, South America, Asia and Africa where high mountains are important resources (Seo *et al.* 2005).

Access and market variables are highly significant. The farther away a cell is from the coasts, the lower is the GCP. This is reasonable as most cities are located near the coasts especially in Australia. The GCP is higher in high population density areas as expected, but with a decreasing rate.[5] The country dummies are intended to control country-specific effects such as policy, trade, culture and language (Anderson 2009). Against the base case of Australia, New Zealand has slightly lower GCPs on average, and the estimate for New Zealand is significant.

As it is not obvious from Table 2, we calculate the effects of the changes in climate variables by small increments in Table 3. For the entire sample, a marginal increase in temperature by 1°C would decrease the GCP by 4.6 million dollars. This is equivalent to a temperature elasticity of −2.3. A marginal

[5] We ran the two models, OLS and spatial, with and without population density variables. Without them the regressions predicted slightly larger damage due to climate change.

Table 2 Regressions of Log Gross Cell Product

Parameter	OLS		Spatial error-Gaussian	
	Est.	Heteroscedasticity consistent *P*-value	Est.	Heteroscedasticity consistent *P*-value
Intercept	10.15864	< 0.0001	10.1888	< 0.0001
Temperature	0.41688	0.0041	0.4516	0.006
Temperature sq	−0.01349	0.0003	−0.01518	0.000
Precipitation	0.05918	< 0.0001	0.05437	< 0.0001
Precipitation sq	−0.00016	< 0.0001	−0.00015	< 0.0001
Temperature Variation	0.44444	0.0056	0.4564	0.020
Precipitation Variation	−0.01145	0.0865	−0.00651	0.358
Elevation	−0.89556	0.3253	0.03596	0.975
Elevation sq	−0.01515	0.9903	−0.7505	0.572
Distance to coasts	−0.00337	< 0.0001	−0.00363	< 0.0001
Population density	1.12E-05	< 0.0001	8.86E-06	< 0.0001
Population density sq	−4.55E-12	< 0.0001	−3.35E-12	< 0.0001
Acrisols	1.31349	0.0001	1.2743	0.000
Cambisols	2.12981	< 0.0001	1.4073	< 0.0001
Ferralsols	1.49386	< 0.0001	0.9113	0.003
Phaeozems	−0.42984	0.8285	−0.1581	0.848
Lithosols	1.16636	< 0.0001	0.9418	0.001
Luvisols	2.06568	< 0.0001	1.5474	< 0.0001
Nitosols	1.12237	0.0054	0.8831	0.016
Podzols	1.00836	0.0092	0.7035	0.073
Arenosols	1.13948	0.0004	1.0078	0.000
Regosols	1.27824	0.0002	1.1513	0.003
Solonetz	1.09163	0.0063	1.0808	0.000
Andosols	1.59787	< 0.0001	1.2317	0.024
Vertisols	1.59841	< 0.0001	1.4166	< 0.0001
Planosols	1.71748	< 0.0001	1.0272	< 0.0001
Xerosols	1.2096	0.0004	1.2724	< 0.0001
Yermosols	1.51351	< 0.0001	1.4132	< 0.0001
Solonchaks	0.34925	0.4847	0.7588	0.181
New Zealand	−0.96457	0.0063	−0.8823	0.048

$N = 615$. Adjusted $R^2 = 0.65$.
Tests of spatial correlation: Moran's I = 0.36 ($P = 0.32$), Geary's C = 0.66 ($P = 0.22$). Weight matrix is pairwise distance.

increase in precipitation would increase the GCP by 1.4 million, which corresponds to an elasticity of +2.4. The marginal impact estimates are striking, although commensurate with our belief, in that the marginal damage from a small temperature increase is extremely large. Although researchers tend to overlook Oceania, it seems that the impact of climate change is more severe in Oceania than even in Africa, South Asia and Latin America. The marginal impact for precipitation confirms the common observation that Australia is constrained by rainfall, and will be severely harmed by any decrease in rainfall.

At the bottom panel of Table 3, we further decompose the marginal impact estimates by vegetation types mapped in Figure 1. It reveals that not all

Table 3 Marginal effects of climate change on GCP (million $)

	Marginal Temperature Increase	Marginal Precipitation Increase	Elasticities temperature	Elasticities precipitation
Entire sample				
Oceania as a whole	−4,576,441	1,491,692	−2.35	2.42
By major vegetations				
Tropical rainforests	−18,878,320	2,726,833	−4.76	2.68
Broadleaved forests	−10,760,673	643,963	−7.15	2.17
Subtropical rainforests	89,664,614	49,512,866	0.60	2.59
Temperate rainforests	50,308,117	2,512,942	1.53	1.26
Temperate broadleaved forests	24,955,718	21,003,074	0.50	2.68
Sclero forests	36,724,518	44,062,701	0.41	2.61
Sclero woodland	−7,387,402	1,660,239	−3.81	2.41
Drought deciduous woodland	−4,625,650	406,402	−8.58	2.67
Broadleaved shrubland	−8,104,921	5,035,860	−1.38	1.76
Needleleaved shrubland	−4,304,586	3,657,398	−0.94	1.89
Water	−1,963,547	690,102	−1.39	2.65
Xeromorphic shrubland	−2,424,607	1,157,732	−2.05	1.35
Grassland with woody cover	−11,424,043	3,478,974	−2.29	2.58
Grassland with shrub cover	−2,600,507	620,652	−4.76	1.50
Tall grassland	−7,384,570	467,687	−8.93	2.43
Meadow	−6,204,195	3,324,466	−1.33	2.39
Deserts	−972,058	220,712	−5.29	1.33

GCP, Gross Cell Product.

vegetation types are expected to suffer from climate change. In particular, forest vegetations will likely gain from an initial warming, albeit slightly. Temperature elasticities are positive in subtropical rainforests, temperate rainforests, temperate broadleaved forests and evergreen sclerophyllous forests. As shown in Figure 1 and Table 1, forest vegetations are located close to the coasts. They are not vulnerable to, at least, initial warming owing to forest shading or higher adaptive capacity in urban areas. However, most other vegetations will suffer seriously from even a minor warming. Especially vulnerable are tall grasslands, grasslands with shrub cover, deserts, drought deciduous woodlands and broadleaved forests.

The rainfall effects are all positive across all vegetations. However, rainfall increase is most beneficial in forested zones such as tropical rainforests, tropical/subtropical evergreen broadleaved forests, temperate rainforests and temperate broadleaved forests. The positive effects of rainfall increase are smaller in grasslands, shrublands and deserts. An alternative perspective would be that all the land cover will be severely harmed by any decrease in rainfall, but that the grasslands are less vulnerable to drying than forests (Seo 2010a).

Another line of literature questions whether climate variability changes would overwhelm the impacts from changes in climate means [Intergovernmental Panel on Climate Change (IPCC) 2007b, Schlenker and Roberts 2009]. In Figure 3, we plot the log GCPs, both observed and predicted, against annual mean temperature in the top figure and against annual

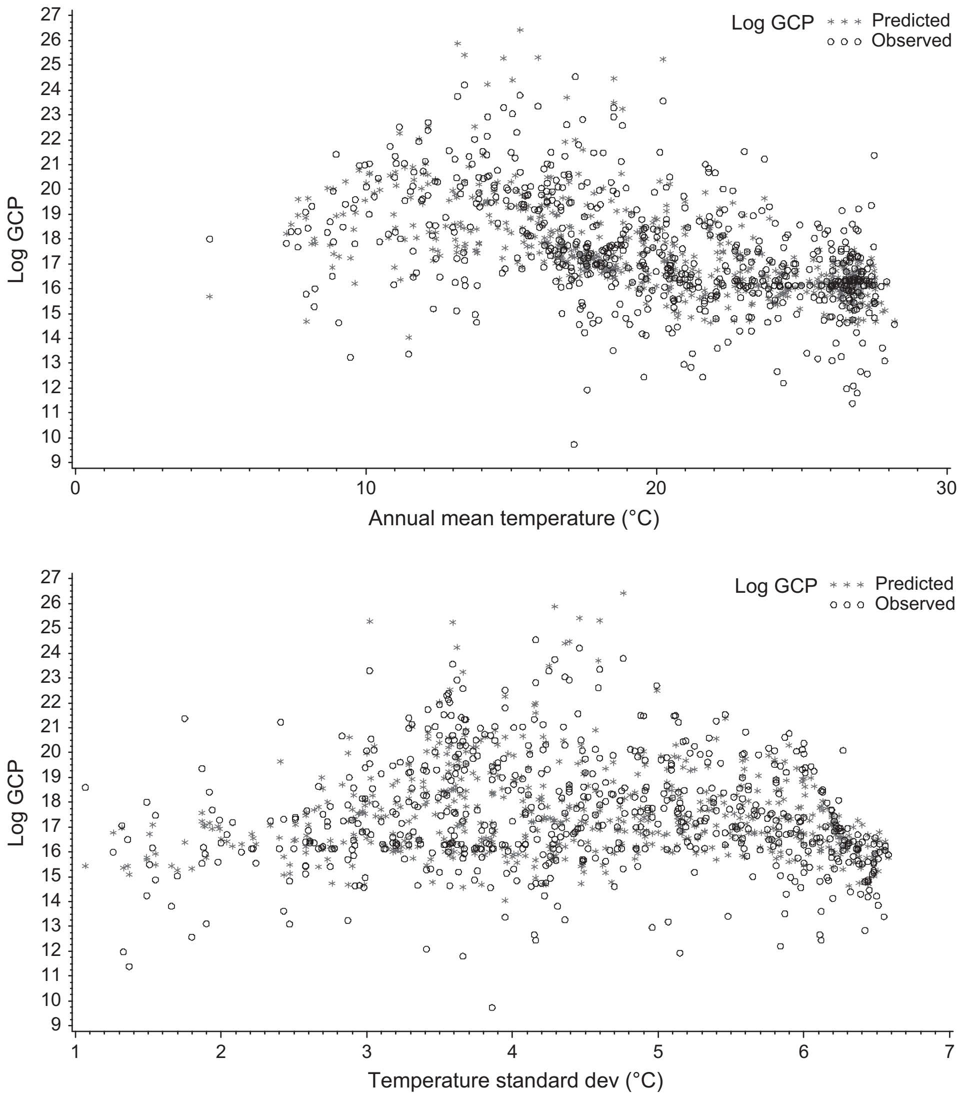

Figure 3 Log GCPs across temperature means and variabilities.

temperature variability in the bottom figure. There are several interesting observations in these figures. First, productivity falls rather sharply when average temperature passes beyond around 15°C. Second, productivity is relatively stable against the increases in climate variability. It even increases until temperature standard deviation reaches 5°C annually. Therefore, the results are against the claims that climate variability is more important than climate means.

The estimated and actual log GCP values against the rainfall variation in the continent are plotted in Figure 4. The top figure shows that as rainfall increases, productivity increases sharply until 110 mm of rainfall per month.

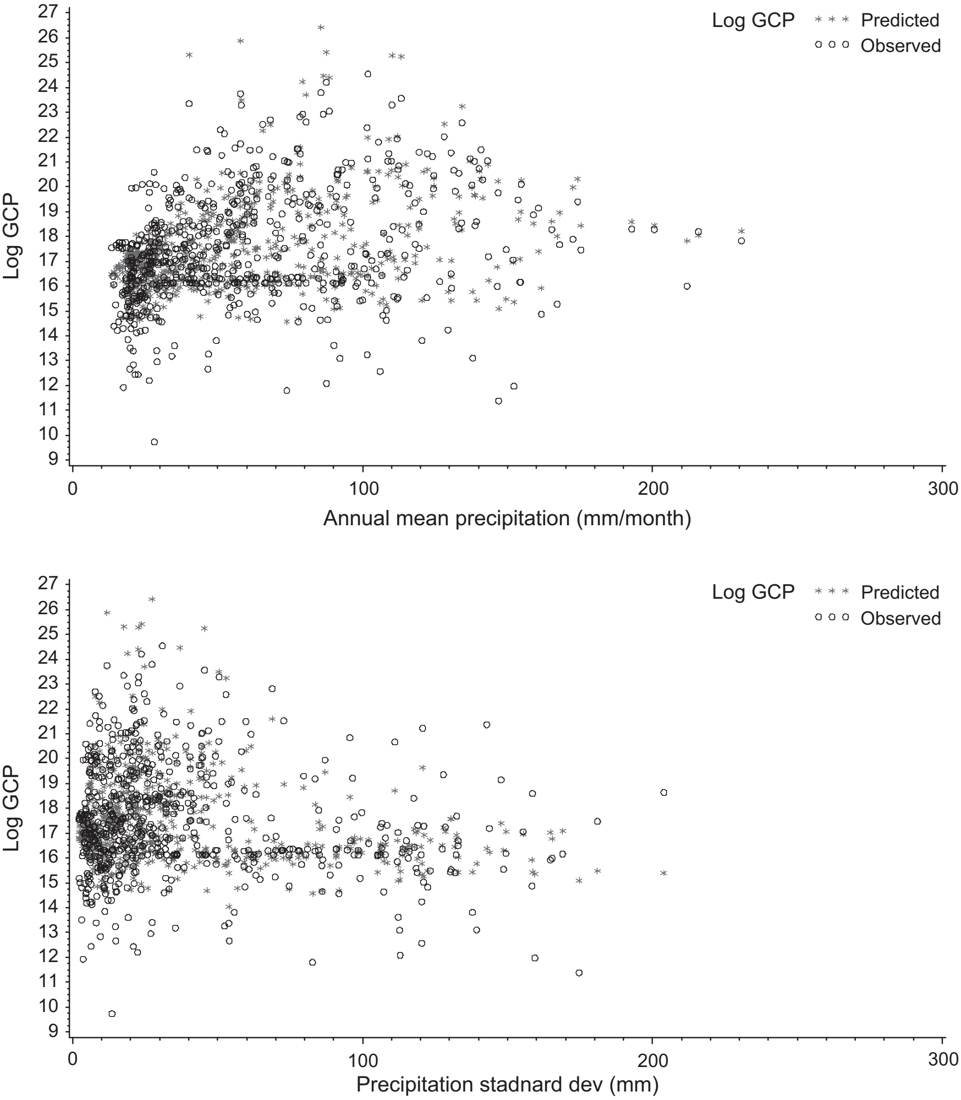

Figure 4 Log GCPs across precipitation means and variabilities.

Reversely, productivity sharply declines with less rainfall on this range. The bottom figure shows that productivity is sustained quite stably across a broad range of rainfall variability in the continent. However, high productivity regions are concentrated on low variability zones.

5. Climate simulations

What may happen in the long term? Based on the estimated parameters, we predict the impacts of climate change on the Oceania economy using an AOGCM scenario compiled by the CSIRO. For the purpose of comparison

Table 4 Impacts of AOGCM scenario on Oceania in 2060

	Current temperature (°C)	Temperature increase	Current precipitation (mm per month)	Precipitation increase
Entire sample				
Oceania as a whole	20.8	3.4	54.6	−6.3
By major vegetations				
Broadleaved forests	25.7	3.3	130.32	−6.04
Broadleaved shrublands	18.3	2.6	37.58	−11.65
Deserts	23.7	4.3	26.23	−3.64
Drought deciduous woodland	27.2	3.7	96.22	−1.45
Grassland with shrub cover	23.1	3.9	30.51	−2.82
Grassland with wood cover	19.7	3.1	73.20	−5.73
Meadow	22.3	4.1	33.77	−6.17
Needleleaved shrublands	17.4	2.6	41.46	−8.37
Water	20.4	2.8	83.13	−8.82
Sclera forests	14.4	2.8	76.20	−16.28
Sclera woodland	21.9	3.8	61.58	−5.04
Subtropical rainforests	13.8	2.8	107.45	−8.62
Tall grasslands	27.5	3.6	118.24	−2.18
Temperate broadleaved forests	14.2	3.3	90.99	−10.22
Temperate rainforests	10.1	1.6	136.15	−13.98
Tropical rainforests	23.1	3.5	90.07	−6.75
Xeromorphic shrublands	19.4	3.2	26.75	−5.02

AOGCM, Atmospheric-Oceanic General Circulation Model.

with other studies, we take a scenario which predicts a high rate of global warming[6] (CSIRO 2010). We take the time frame of half a century later, 2060. The results are displayed in Table 4. The scenario predicts 3.4°C increase in temperature and 6.4 mm decrease in monthly rainfall. However, the scenario predicts different degrees of climate change across major vegetations. Temperature increase is larger in deserts, meadow, drought deciduous woodlands and grasslands with shrub cover. On the other hand, rainfall reductions are expected to be larger in forest vegetations and smaller in dry vegetations.

Based on this scenario, we calculate the changes in the GCP by 2060, the results of which are again displayed by major land covers in Table 5. From the current productivity of 1.8 billion USD per cell, global warming would decrease it by 622 million USD per cell, 34 per cent of the current productivity. This magnitude is extremely large against the commonly used estimates of the impacts (Nordhaus and Boyer 2000). However, it is not unreasonable given that Australia is highly constrained by climate and geographic conditions.

Across the land covers, damage estimate is more than 70 per cent in tall grasslands, deserts and drought deciduous woodlands where current productivities are also low. Among the most productive regions, sclerophyllous

[6] It goes without saying that we do not intend this scenario to be most likely or representative of what the future climate would look like in the region. However, this scenario reflects one of the severe climate change scenarios.

Table 5 Effects of climate scenarios on the GCP by vegetation (US$) for 2060

	Current GCP	Absolute impacts	Percentage changes
Oceania	1,803,839, 508	−622,021,949 (−1,115,212,853, −128,831,045)	−34.5
By vegetations			
Tropical rainforests	140,874,361	−95,060,229	−67.5
Broadleaved forests	151,207,309	−86,832,355	−57.4
Subtropical rainforests	4,759,922,350	−1,986,769,870	−41.7
Temperate rainforests	764,481,715	−72,389,213	−9.5
Temperate broadleaved forests	4,666,450,667	−1,411,967,449	−30.3
Sclero forests	24,280,885,113	−7,975,180,973	−32.8
Sclero woodland	1,416,927,512	−512,848,568	−36.2
Drought deciduous woodland	14,650,046	−10,930,137	−74.6
Broadleaved shrubland	1,228,937,634	−829,772,729	−67.5
Needleleaved shrubland	93,995,874	−48,225,963	−51.3
Water	1,171,098,841	−656,130,860	−56.0
Xeromorphic shrubland	32,581,576	−16,161,085	−49.6
Grassland with woody cover	1,155,862,660	−554,491,312	−48.0
Grassland with shrub cover	15,580,806	−9,147,823	−58.7
Tall grassland	22,743,407	−16,954,375	−74.5
Meadow	5,483,604,907	−1,069,235,134	−19.5
Deserts	5,280,147	−3,793,398	−71.8

Note: Numbers inside the parenthesis are 95% confidence intervals. GCP, Gross Cell Product.

forests are expected to lose 8 billion dollars annually or 32 per cent of the current income. Temperate rainforests, temperate broadleaved forests and meadow zones are the least vulnerable areas of the continent. Shrublands and grasslands are overall highly vulnerable.

6. Conclusion

We explore the newly constructed geographically rescaled economic data set, G-ECON database, to examine the impacts of climate change on Australia and New Zealand. The database provides a detailed description of economic output cell by cell, called GCP, along with environmental, climate, access and population data. Using the novel productivity measure, GCP, this paper examines the variation of the GCP across climate zones. This approach has several advantages over conventional methods: it provides a productivity measure independent of political units, it controls land size, and it is matched with variation in vegetations.

Across the region, we find that major vegetations vary a great deal, and so does productivity measured by the GCP. Along the eastern coasts of Australia are mostly temperate broadleaved forests, which are adjoined by woodlands. Cells further inlands are occupied by shrublands, grasslands and deserts. The most productive regions are found in the eastern coasts, in the south, in the southern parts of the Western Australia and in New Zealand. The second most productive zones are located further inland in the eastern coasts and in the western coasts. A large chunk of land in the centre of Australia records no economic outputs.

An analysis of the log GCP across the region reveals that climate parameters are highly significant determinants of productivity. The log GCP has a hill-shaped relationship with annual mean temperature and also with annual mean precipitation. A higher variability in temperature is beneficial, while a higher rainfall variability is harmful to the economy. Distance to coasts is a significant variable, but elevation is not for GCP. Soils play important roles. Population and country-fixed effects are significant.

The regression indicates large damage from climate change, both from temperature increase and from precipitation reduction. A marginal increase in temperature by 1°C would decrease the GCP by 4.6 million dollars, equivalent to a temperature elasticity of −2.3. A marginal decrease in precipitation would decrease the GCP by 1.4 million, with an elasticity of + 2.4. However, forest vegetations will likely gain from an initial warming, albeit slightly. Temperature effects are positive in subtropical rainforests, temperate rainforests, temperate broadleaved forests and evergreen sclerophyllous forests. A decrease in rainfall, on the other hand, is harmful across all vegetations.

We find that changes in climate means are potentially more harmful than changes in climate variability. Although productivity falls rather sharply when average temperature passes beyond around 15°C, productivity is relatively stable against the increases in climate variability. The GCP is also sustained quite well across a broad range of rainfall variability in the continent.

Assuming an AOGCM climate scenario which predicts a high rate of global warming, we simulate the impacts of climate change on the Oceania economy. When temperature increases by 3.4°C and precipitation decreases by 6.4 mm per month, the GCP would decline on average by 622 million USD per cell, 34 per cent of the current output. Across the land covers, damage estimate is more than 70 per cent in tall grasslands, deserts and drought deciduous woodlands where current productivities are also low. Most productive regions, i.e. sclerophyllous forests, are expected to lose 8 billion dollars annually or 32 per cent of the current income.

Why is the damage from global warming so high in the region? This is because of the presently unfavourable climate conditions in the region. As evident in Figure 3, as temperature passes beyond about 15°C, the GCP falls drastically. Similarly, in Figure 4, the GCP declines rapidly as rainfall decreases. As shown in Table 4, temperature elasticity of the GCP is −2.3 and precipitation elasticity is + 2.4. Therefore, changes in both factors would turn out to be extremely harmful to the regional economy. When climate becomes hot and dry, people do not, or cannot, live in such unfavourable climate

Table 6 A further analysis of log gross cell population

	Parameter estimates	Heteroscedasticity consistent *P*-value	Marginal effects	Elasticities
Intercept	−1.754	0.300		
Temperature	0.575	0.001	−293.49	−2.81
Temperature sq	−0.018	< 0.0001		
Precipitation	0.076	< 0.0001	+103.19	+3.12
Precipitation sq	0.000	< 0.0001		
Temperature variation	0.602	0.001		
Precipitation variation	−0.016	0.036		
Elevation	−1.118	0.290		
Elevation sq	−0.739	0.615		
Distance to coasts	−0.004	< 0.0001		
Acrisols	2.347	< 0.0001		
Cambisols	2.757	< 0.0001		
Ferralsols	1.652	< 0.0001		
Phaeozems	−0.452	0.820		
Lithosols	1.274	< 0.0001		
Luvisols	2.109	< 0.0001		
Nitosols	2.019	0.000		
Podzols	1.306	0.041		
Arenosols	1.222	0.001		
Regosols	1.370	0.000		
Solonetz	1.070	0.018		
Andosols	2.313	< 0.0001		
Vertisols	1.645	< 0.0001		
Planosols	2.031	< 0.0001		
Xerosols	1.099	0.004		
Yermosols	1.537	< 0.0001		
Solonchaks	0.357	0.470		
New Zealand	−1.096	0.015		

$N = 615$. Adjusted $R^2 = 0.55$.

conditions, and move out lowering the GCP. We present an additional regression in Table 6 of cell population density against the same set of explanatory variables. As shown in the estimates of marginal effects and elasticities in the table, large damage from climate change is largely accounted for by population effects. The temperature elasticity of population is −2.8, while the precipitation elasticity of population is + 3.1.

Some factors, however, may offset some of the expected damage. This paper does not assume any technological advances over time such as development of new crop or livestock species, development of alternative energy sources or other advances in technology which may make it possible to supply air-conditioning or irrigation water at cheaper prices, comparable to the Green Revolution (Evenson and Gollin 2003). In addition, the paper assumes no population changes in the simulation, although they are controlled in the estimation. If population increases substantially in the coming decades owing to an external influx, suburban areas where there is currently no or low economic productivities may become substantially utilised by overcoming climate and geographic factors. As shown in Table 2, population increase will increase the regional GCP.

As the first major article on the impacts of climate change using the GCP measure, this paper brings about intriguing results. The recent analysis of the municipal per capita GDP across the Americas by Dell and her co-authors finds that within-country variation of per capita income is weaker than cross-country variation. Further, they find that a 1° increase in temperature would lead to a 1.2–1.9 per cent decline in municipal per capita income (Dell *et al*. 2009). This paper, on the other hand, finds that even the within-country variation can be quite large. Furthermore, this paper points out that the GCP measure is capable of capturing both productivity effects and population effects after controlling land size which is fixed to the humanity in practice. However, the results presented in this paper may arise because Australia and New Zealand are countries in which full potential of the land resources have not yet been reached. Therefore, a cross-sectional analysis presented in this paper may not accurately reflect a 'climate-economy equilibrium' assumed in the analysis (Nordhaus 2006). On top of the innovations and insights this paper brings about, this paper calls for the need to build a more geographically explicit and detailed system of national accounting of both GDP and GCP in the region.

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