Tyndall Centre
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A country-by-country analysis of past and future warming rates

Timothy D. Mitchell and Mike Hulme

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Introduction

Most studies of climate change have concentrated on global or sub-continental scales, because of issues of spatial resolution. However, two recent developments that overlap at the University of East Anglia have made it possible to conduct a meaningful examination of climate change at the level of individual countries. The two developments are the construction of observed data sets on a half-degree grid (New *et al.*, 2000) and the fresh impetus given to inter-model comparisons by the setting up of the Data Distribution Centre (DDC, 2000).

To coincide with the official opening of the Tyndall Centre for Climate Change Research on 9 November 2000 we have released this new study. We have combined the 20th century observations with the 21st century changes from five state-of-the-art climate models, and examined both at the level of UN member states. We also present our results in the wider context of human responses to climate change, by combining them with measures of current carbon emissions and wealth. Thus we are able to provide information for each country for the following indicators (see Graphic, Table, and Figure):

- Past Warming: the climate change each country has experienced in the recent past;
- Future Warming: the climate change each country may experience in the near future;
- Consumption: the responsibility each country bears for those changes;
- Vulnerability: an index of each country's capacity to respond to those changes.

20th century temperature change

We employed an updated version (1901-1998) of an existing data set of monthly temperatures on a 0.5° grid (New *et al.*, 2000). We allocated each land grid-box to a single country, and for each country we calculated the mean of its constituent grid-boxes. We used a robust method of least squares regression (Emerson and Hoaglin, 1983) to calculate the trend in annual temperature over the 20th century for each country.[2] We expressed the trend in °C per century.

Caveat:

- 20th century climate change is reduced to a linear trend of annual temperature.

Consumption (current carbon emissions)

We employed an existing data set of carbon emissions, developed by the Carbon Dioxide Information Analysis Center (Marland *et al.*, 2000). The emission rates are mostly for 1997, and are given in metric tons of carbon per capita for each country.

Caveats:

- only an instantaneous (1997) measurement of emissions;
- values for individual countries are expected to change in the future.

21st century temperature change

We used results from five state-of-the-art global climate models from modelling centres around the world:

[2] Superior data were available for the UK, in the Central England temperature record (Jones and Hulme, 1997), which we used instead.

country	model	reference
UK	HadCM2	Johns *et al.* (1997)
UK	HadCM3	Gordon *et al.* (2000)
Germany	ECHam4	Roeckner *et al.* (1999)
Canada	CGCM1	Flato *et al.* (2000)
Japan	CCSR-NIES	Emori *et al.* (1999)

Each model has been used to simulate climate change in the 21st century using a scenario for the future in which greenhouse gas concentrations increase by approximately 1% per year. The results were interpolated onto a common grid (2.5° latitude by 3.75° longitude). Since there is some evidence that averaged model behaviour provides the best comparison with observations (Lambert and Boer, 2000) we developed a measure of 21st century climate change based on the average model behaviour.

We allocated each land grid-box to a single country, and for each country we calculated the mean of its constituent grid-boxes. For each model we calculated the annual temperature anomaly (relative to 1961-90) for a 30-year period centred on the 2080s for each country and for the globe. We eliminated any inter-model differences arising from different model climate sensitivities by expressing each country anomaly relative to the model's global anomaly of 3.9°C. This was then added to the inter-model global-mean anomaly. We express the model-related uncertainty in 21st century temperature change in terms of the inter-model mean and range for the adjusted country anomalies described above.

Caveats:

- only one emissions scenario was used; the mean warming by the 2080s of the model simulations used here was 3.9°C compared to a range of warming using the full set of IPCC emissions scenarios of between about 1.5°C and 5.5°C;
- only a selection of models was used;
- the spatial resolution is such that some UN countries are too small to be represented (e.g. San Marino), and for some small countries that are simulated there are doubts about the information that may legitimately be drawn from the models;
- temperature is only one of a number of possible climatological or impact indicators.

Vulnerability

We have developed a measure of vulnerability that combines the amount of change to which humans may have to face with their capacity to adapt; we express this measure in GDP per capita per °C. We used GDP per capita data for 1998-99 for individual countries, expressed in terms of purchasing power parities in US $ (World Fact Book, 2000). We divided each country's value by the inter-model mean temperature change (°C) in the 21st century that we calculated above.

Caveats:

- although GDP per capita has been used to measure human vulnerability to climate change in some studies (e.g. Nicholls *et al.* 1999), there are other dimensions that cannot be captured by present GDP alone;
- those described above for 21st century temperature change.

Annexes

Finally we combined all the work described above by calculating means for Annex I countries, non-Annex I countries, and the world. Annex I includes countries in the OECD, and in Central and Eastern Europe. The contrast between Annex I and the rest of the world (non-Annex I) enables us to compare rich and poor countries. We combined the statistics for individual countries into Annex I and non-Annex I, weighting them by their populations. We calculated the world statistics using global-mean temperature changes for the 20th and 21st centuries, together with global-mean emissions, population, and GDP per capita (see Graphic).

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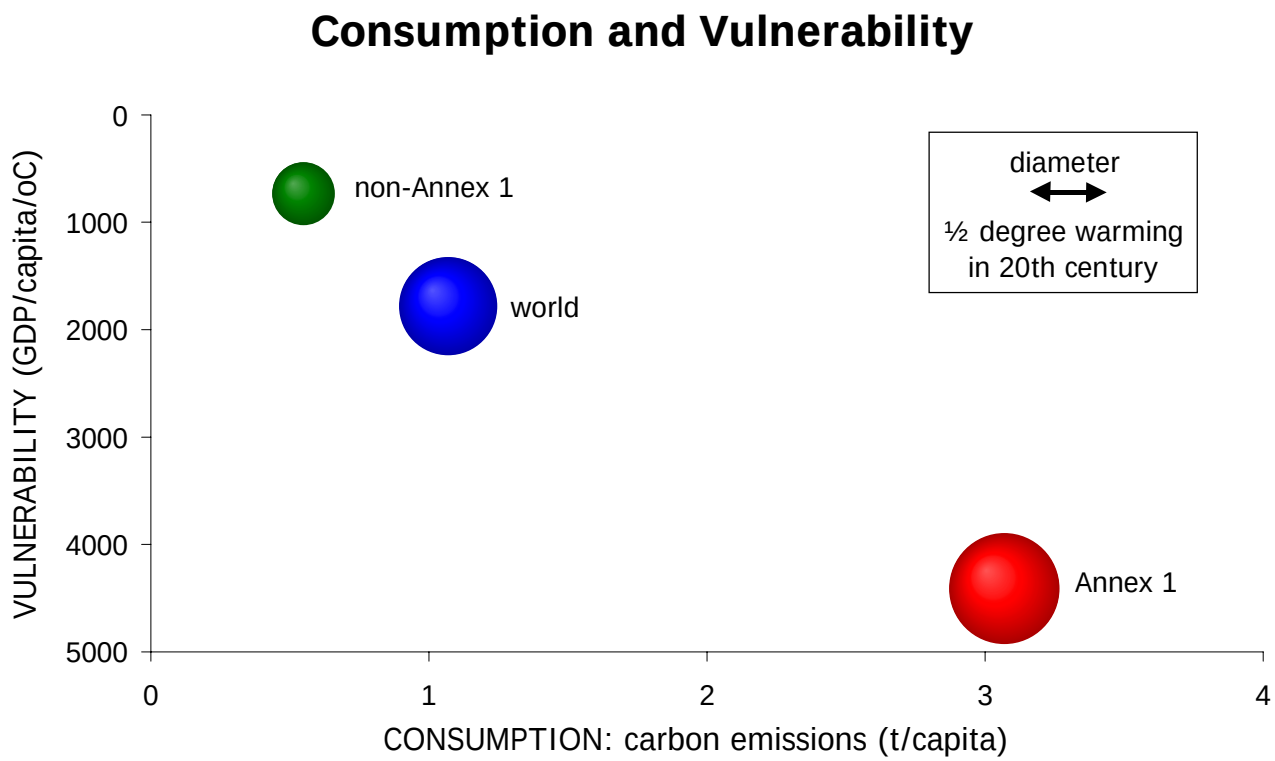
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Graphic



The graphic gives a pictorial summary of the results for 'rich' (Annex I) and 'poor' (non-Annex I) countries. The carbon emissions (tons/capita) for 1997 (Marland *et al.*, 2000) are a crude index of consumption for each country. The 20th century warming was calculated for each country by aggregating an existing data set (New *et al.*, 2000). The mean 21st century warming in each country was calculated from five fully-coupled models. The index of vulnerability was obtained for each country by dividing the current GDP per capita (World Fact Book, 2000) by the mean 21st century warming. The statistics for individual countries, weighted by population, were combined into Annex I, non-Annex I, and the world. The combined statistics are plotted as spheres in which the diameter is proportional to the 20th century warming, on a chart where the index of consumption is on the x-axis, and the index of vulnerability is on the y-axis.

Table

The table gives a quantitative summary of the results for each country. The carbon emissions (tons / capita) for 1997 (Marland *et al.*, 2000) are a crude index of consumption. The 20th century warming was calculated by aggregating an existing data set (New *et al.*, 2000). The 21st century warming was calculated from five fully-coupled models; the table contains the inter-model range and mean. The index of vulnerability was obtained by dividing the current GDP per capita (World Fact Book, 2000) by the mean 21st century warming.

Figure

The figure gives a pictorial summary of the results for each country. The carbon emissions (tons / capita) for 1997 (Marland *et al.*, 2000) are plotted as a grey bar. The 20th century warming, calculated by aggregating an existing data set (New *et al.*, 2000), is plotted as a black circle. The 21st century warming, calculated from five fully-coupled models, is plotted as a black dot (the inter-model mean) and as a black bar (the inter-model range).

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country	consumption C emissions t/capita	20th warming °C	21st century minimum °C	mean °C	warming maximum °C	vulnerability $/capita/°C
Afghanistan		1.09	4.8	5.8	8.4	$100
Albania	0.14	-0.63	2.8	4.4	5.3	$400
Algeria	0.88	1.43	4.4	5.2	5.7	$900
Andorra		1.78				
Angola	0.12	0.72	4.5	5.3	5.8	$200
Antigua + Barbuda	1.40	1.60				
Argentina	1.05	1.17	2.5	3.0	3.6	$3,300
Armenia	0.21	0.08	4.5	4.9	5.7	$600
Australia	4.71	0.65	3.0	4.1	4.8	$5,400
Austria	2.04	0.56	2.0	4.3	5.5	$5,400
Azerbaijan	1.14	1.01	4.3	4.8	5.6	$400
Bahamas	1.63	1.26				
Bahrain	6.95	0.01	3.7	5.1	6.6	$2,700
Bangladesh	0.05	0.33	2.8	4.1	5.3	$400
Barbados	0.92	1.79				
Belarus	1.62	0.77	2.5	4.9	7.6	$1,100
Belgium	2.78	0.37	1.7	3.9	5.4	$6,100
Belize	0.47	0.03	2.5	4.0	5.1	$800
Benin	0.04	0.42	3.0	4.7	6.7	$300
Bhutan	0.05	0.31	4.0	4.6	5.2	$200
Bolivia	0.38	0.67	3.5	4.8	5.9	$600
Bosnia + Herzegovina	0.34	-0.24	2.3	4.5	5.6	$400
Botswana	0.59	0.86	4.7	5.8	7.0	$700
Brazil	0.48	0.71	3.4	4.5	5.8	$1,400
Brunei Darussalam		0.30				
Bulgaria	1.60	0.82	3.0	4.4	5.2	$1,000
Burkina Faso	0.02	0.89	3.4	5.1	7.1	$200
Burundi	0.01	-0.05	3.1	4.2	5.2	$200
Cambodia	0.01	0.73	3.0	3.9	5.0	$200
Cameroon		0.08	3.0	4.3	5.7	$500
Canada	4.42	0.49	5.3	6.3	8.8	$3,700
Cape Verde	0.08	-0.94				
Central African Rep.	0.02	0.09	2.7	4.6	6.1	$400
Chad	0.00	0.22	3.2	4.8	6.5	$200
Chile	1.09	0.61	2.6	3.1	3.8	$4,000
China	0.75	-0.01	4.5	5.3	7.0	$700
Colombia	0.46	0.96	2.9	4.2	5.7	$1,500
Comoros	0.03	0.35				
Congo (DR)	0.01	0.26	3.4	4.7	5.4	$200
Congo (Rep)	0.03	0.61	3.0	4.4	5.1	$300
Costa Rica	0.36	0.21	2.8	3.8	5.5	$1,900
Côte d'Ivoire	0.25	0.87	3.1	4.5	6.0	$400
Croatia	1.16	0.29	2.3	4.5	5.6	$1,100
Cuba	0.62	0.58	2.1	3.3	4.6	$500
Cyprus	1.95	0.32				

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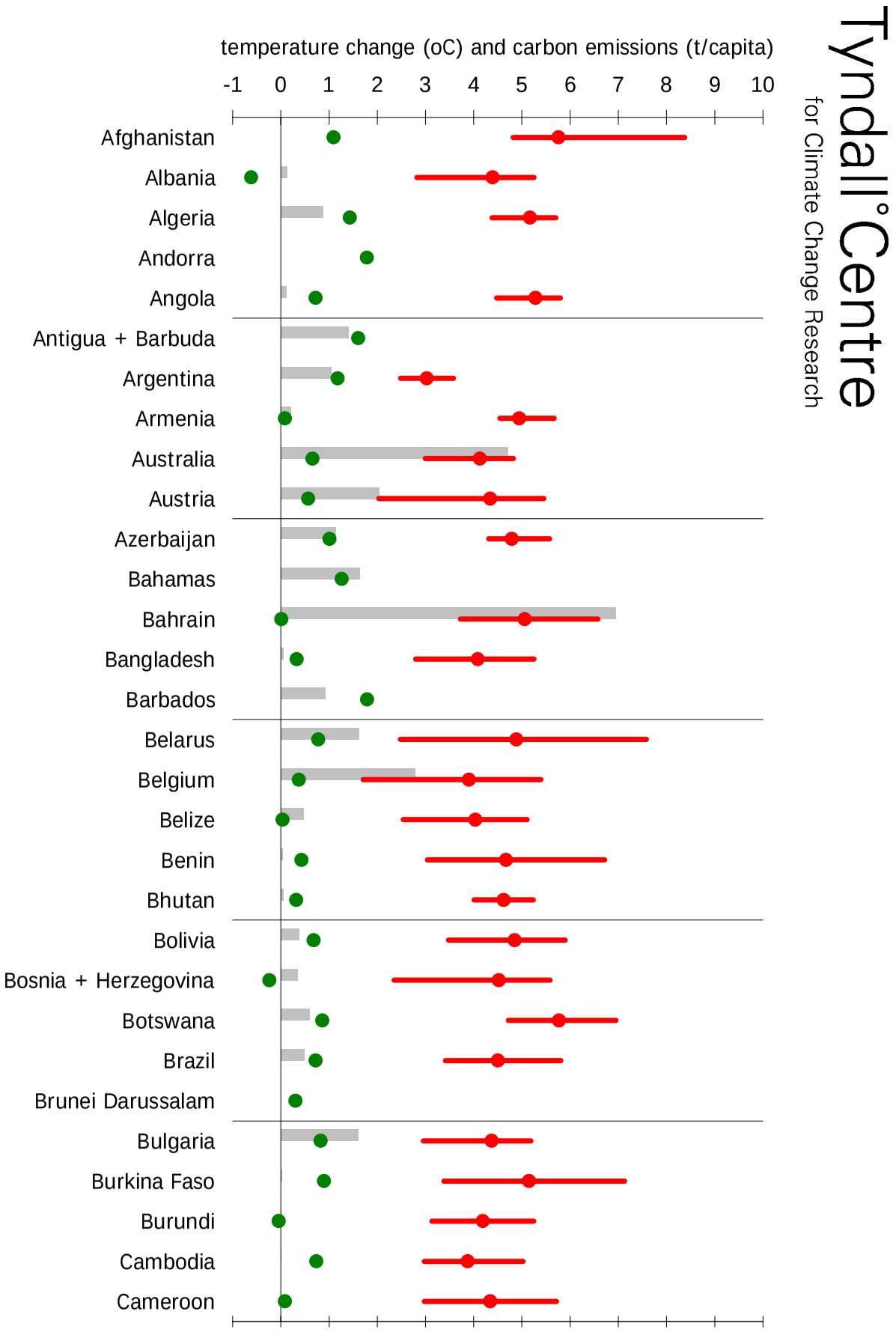
country	consumption	20th	21st min	21st mean	21st max	vulnerability
Czech Republic	3.25	-0.05	1.9	4.3	6.0	$2,700
Denmark	2.93	0.08	1.7	3.8	5.6	$6,300
Djibouti	0.16	0.02	2.6	4.2	5.5	$300
Dominica	0.31	1.79				
Dominican Republic	0.45	1.53	2.3	3.4	4.4	$1,600
Ecuador	0.46	0.63	3.0	3.8	4.6	$1,100
Egypt	0.46	0.08	4.4	4.7	4.8	$600
El Salvador	0.25	0.20	2.5	4.0	5.1	$800
Equatorial Guinea	0.40	0.38	2.9	4.0	4.5	$500
Eritrea		-0.02	2.6	4.2	5.5	$200
Estonia	3.56	0.91	2.5	4.9	8.0	$1,100
Ethiopia	0.02	-0.03	2.6	4.2	5.5	$100
Fiji	0.26	0.05				
Finland	2.98	0.53	3.0	5.2	8.1	$4,000
France	1.59	0.87	2.0	4.1	5.2	$5,700
Gabon	0.80	0.60	2.9	4.0	4.5	$1,600
Gambia	0.05	0.02	3.3	4.5	5.4	$200
Georgia	0.24	-0.89	4.0	4.7	5.6	$500
Germany	2.77	0.68	1.7	4.0	5.3	$5,600
Ghana	0.06	0.91	3.0	4.7	6.7	$400
Greece	2.08	-0.10	3.1	4.3	5.1	$3,300
Grenada	0.54	1.98				
Guatemala	0.20	0.11	2.5	4.0	5.1	$1,000
Guinea	0.04	0.52	3.5	4.9	6.2	$200
Guinea-Bissau	0.06	-0.01				
Guyana	0.33	1.52	2.8	4.5	5.7	$600
Haiti	0.05	1.26				
Honduras	0.19	0.53	2.5	3.6	5.0	$600
Hungary	1.56	0.63	2.2	4.5	6.0	$1,700
Iceland	2.09	0.69	1.1	3.2	4.7	$7,500
India	0.29	0.58	3.7	4.4	5.7	$400
Indonesia	0.32	0.50	2.3	3.3	4.3	$800
Iran (IR)	1.22	0.83	4.8	5.5	7.0	$1,000
Iraq		0.55	4.8	5.3	5.5	$500
Ireland	2.72	0.13	1.3	2.9	4.1	$7,000
Israel	2.66	0.17	4.3	4.6	4.8	$4,000
Italy	1.94	0.11	2.3	4.4	5.0	$4,900
Jamaica	1.16	0.73				
Japan	2.51	1.19	2.2	3.8	5.2	$6,100
Jordan	0.63	0.19	4.4	4.7	5.1	$700
Kazakhstan	2.04	1.03	4.8	5.8	7.2	$600
Kenya	0.06	-0.02	3.0	3.7	4.6	$400
Kiribati	0.07	0.08				
Kuwait	7.88	0.78				
Kyrgyzstan	0.38	1.75	5.0	6.2	9.3	$400
Lao (PDR)	0.02	0.48	3.1	3.9	5.0	$300
Latvia	0.90	1.51	2.5	4.9	8.0	$900

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country	consumption	20th	21st min	21st mean	21st max	vulnerability
Lebanon	1.37	0.50	4.3	4.6	4.8	$1,000
Lesotho		0.36	3.6	4.6	5.7	$500
Liberia		0.48	3.1	4.0	5.0	$200
Libya (AJ)	2.19	0.38	4.1	4.6	5.0	$1,700
Liechtenstein		1.17	2.0	4.3	5.5	$5,300
Lithuania	1.09	1.20	2.5	4.9	8.0	$1,000
Luxembourg	5.16	-0.13	1.7	3.9	5.4	$8,800
Madagascar	0.01	0.47	2.4	3.5	4.5	$200
Malawi	0.02	0.01	3.4	4.7	5.7	$200
Malaysia	1.70	-0.07	2.4	3.4	4.2	$3,100
Maldives	0.32	0.20				
Mali	0.01	0.99	3.8	5.4	7.1	$200
Malta	1.26	0.60				
Marshall Islands		0.11				
Mauritania	0.33	0.44	4.2	5.1	5.9	$400
Mauritius	0.41	0.12				
Mexico	1.06	-0.12	3.8	4.3	4.8	$2,000
Micronesia (FS)		0.19				
Moldova (Rep)	0.65	1.59	2.6	4.6	6.2	$500
Monaco		1.00				
Mongolia	0.83	0.98	4.7	5.9	7.3	$400
Morocco	0.32	0.73	4.1	5.0	5.6	$700
Mozambique	0.02	0.56	3.2	4.5	5.2	$200
Myanmar	0.05	-0.07	2.9	3.8	4.6	$300
Namibia		0.88	3.8	4.9	5.9	$900
Nauru	3.43	0.05				
Nepal	0.02	-0.11	4.2	4.8	6.3	$200
Netherlands	2.83	0.39	1.7	3.9	5.4	$5,900
New Zealand	2.26	1.24	0.5	2.1	3.1	$8,200
Nicaragua	0.18	0.32	2.8	3.9	5.2	$700
Niger	0.03	0.26	3.7	5.1	6.5	$200
Nigeria	0.22	-0.06	3.2	4.6	6.2	$200
North Korea (DPR)	2.99	1.00	4.3	5.0	5.8	$200
Norway	4.20	0.81	1.9	4.3	5.9	$5,900
Oman	2.10	0.21	3.0	4.6	5.9	$1,700
Pakistan	0.18	0.94	4.3	5.1	7.0	$400
Palau		0.19				
Panama	0.77	0.60	2.6	3.6	4.6	$2,100
Papua New Guinea	0.15	0.14	2.2	3.2	4.3	$800
Paraguay	0.20	1.59	3.6	4.2	5.2	$900
Peru	0.32	0.38	3.3	4.4	5.6	$1,000
Philippines	0.28	0.68	2.6	3.4	4.5	$1,100
Poland	2.47	0.62	2.1	4.4	6.7	$1,600
Portugal	1.37	1.19	3.2	4.4	5.2	$3,500
Qatar	18.19	0.10	3.0	4.6	5.9	$3,700
Romania	1.30	1.28	2.6	4.6	6.2	$900
Russian Federation	2.65	0.45	5.4	6.7	8.5	$600

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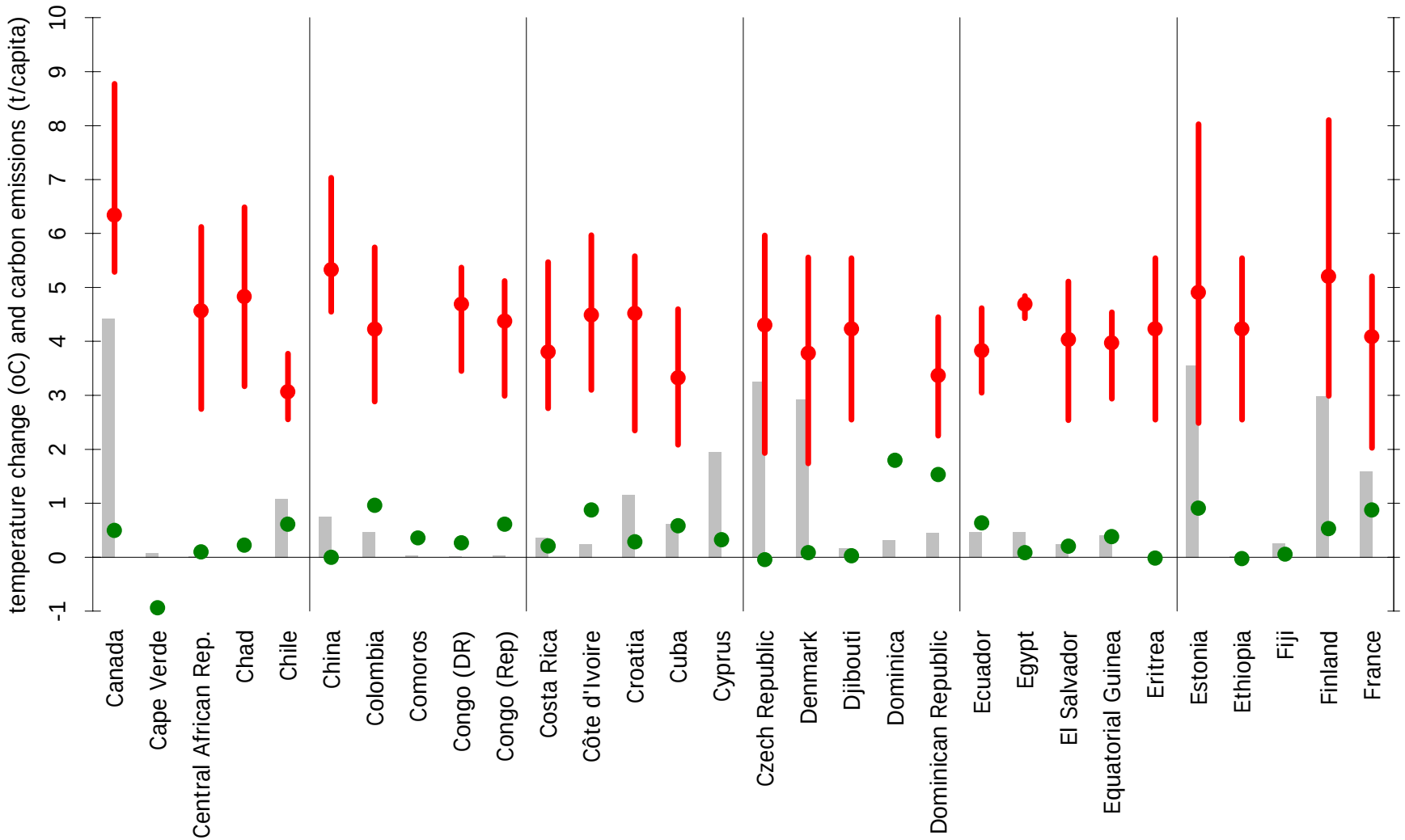
country	consumption	20th	21st min	21st mean	21st max	vulnerability
Rwanda	0.02	0.01	3.1	4.2	5.2	$200
Saint Kitts + Nevis	0.71	1.69				
Saint Lucia	0.37	1.87				
Saint Vincent + Gren.	0.32	1.79				
Samoa	0.21	0.29				
San Marino		0.04				
Sao Tome + Principe	0.15	0.63				
Saudi Arabia	3.73	0.57	4.1	5.1	6.0	$1,800
Senegal	0.10	-0.22	3.3	4.5	5.4	$400
Seychelles	0.71	0.07				
Sierra Leone	0.03	0.22	3.1	4.0	5.0	$100
Singapore	6.39	-0.20				
Slovakia	1.87	0.62	1.9	4.3	6.0	$2,000
Slovenia	2.06	0.58	2.3	4.5	5.6	$2,400
Solomon Islands	0.11	0.17				
Somalia		0.09	2.7	3.8	4.7	$200
South Africa	2.23	0.62	3.6	4.6	5.7	$1,500
South Korea (Rep)	2.55	1.32	4.0	4.6	4.9	$2,900
Spain	1.68	1.27	2.8	4.4	5.1	$3,900
Sri Lanka	0.11	0.44	3.7	4.4	5.7	$600
Sudan	0.04	0.33	2.9	4.6	6.0	$200
Suriname	1.40	1.16	3.0	4.5	5.9	$800
Swaziland	0.12	0.96	3.6	4.6	5.7	$900
Sweden	1.46	0.96	2.3	4.4	6.4	$4,700
Syria (AR)	0.87	0.42	4.3	4.6	4.8	$500
Tajikistan	0.26	0.60	4.7	5.9	8.3	$200
Tanzania (UR)	0.02	0.08	3.2	4.2	4.9	$100
Thailand	0.95	0.62	3.0	3.9	4.9	$1,700
Togo	0.05	0.81	3.0	4.7	6.7	$400
Tonga	0.33	0.13				
Trinidad and Tobago	4.69	1.96				
Tunisia	0.49	1.78	3.4	4.3	5.2	$1,300
Turkey		0.22	3.5	4.5	4.9	$1,400
Turkmenistan	1.98	1.34	4.5	5.3	7.1	$300
Tuvalu		0.09				
Uganda	0.01	0.06	3.1	4.2	5.2	$300
Ukraine	1.97	1.58	2.9	4.7	6.6	$500
United Arab Emirates	9.40	0.17	3.7	5.1	6.6	$3,500
United Kingdom	2.41	0.47	1.4	3.1	4.5	$6,900
USA	5.45	0.64	4.2	4.9	6.1	$6,900
Uruguay	0.45	-0.02	1.6	2.6	3.4	$3,300
Uzbekistan	1.20	0.49	4.4	5.4	7.3	$500
Vanuatu	0.09	0.26				
Venezuela	2.25	1.68	2.6	4.4	6.0	$1,800
Viet Nam	0.15	0.49	3.0	3.8	4.7	$500
Yemen	0.27	0.27	2.4	4.5	5.7	$200
Yugoslavia (FR)		0.10	2.5	4.6	6.0	$400
Zambia	0.08	-0.18	4.4	5.3	6.0	$200
Zimbabwe	0.44	0.01	3.9	5.3	6.2	$500



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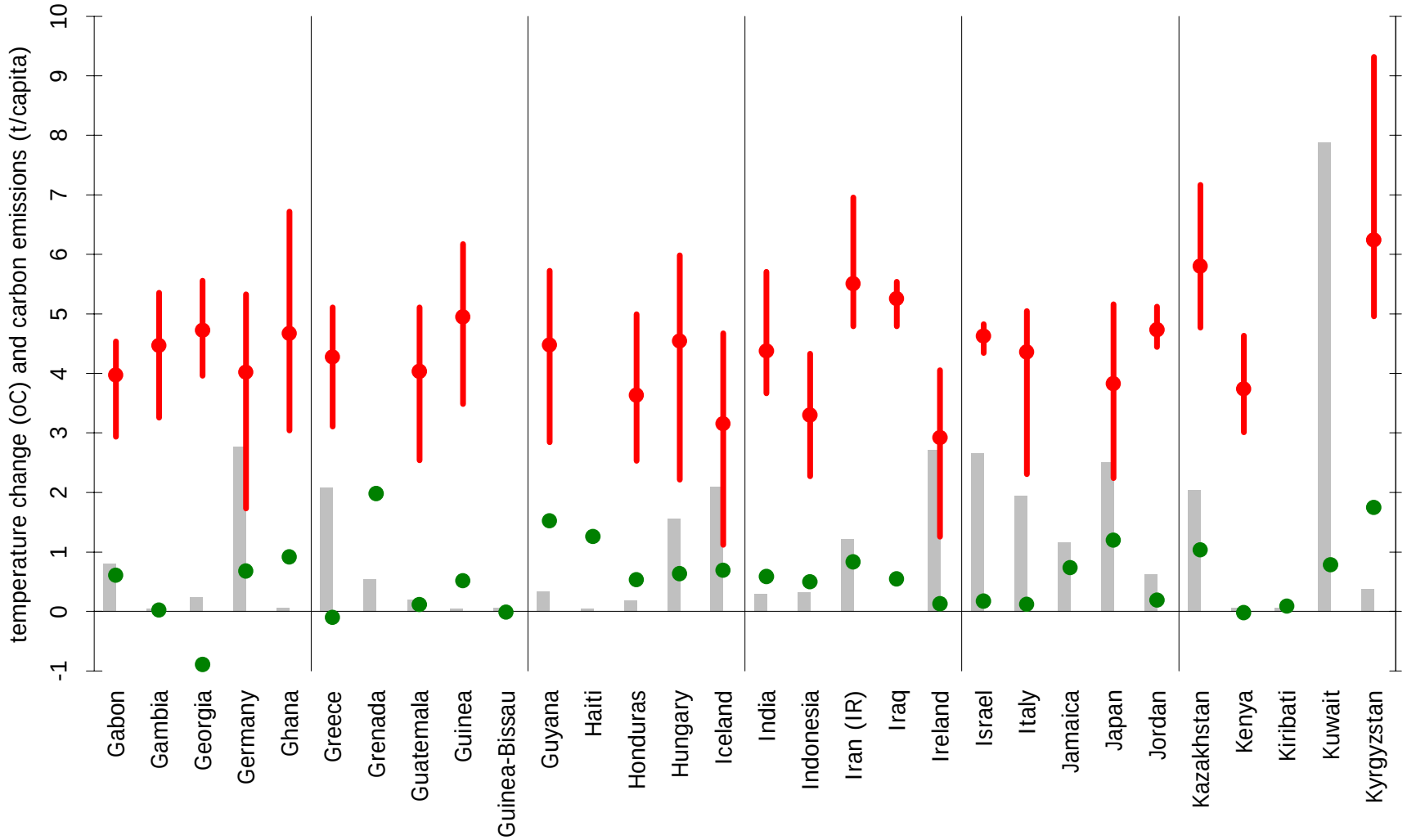
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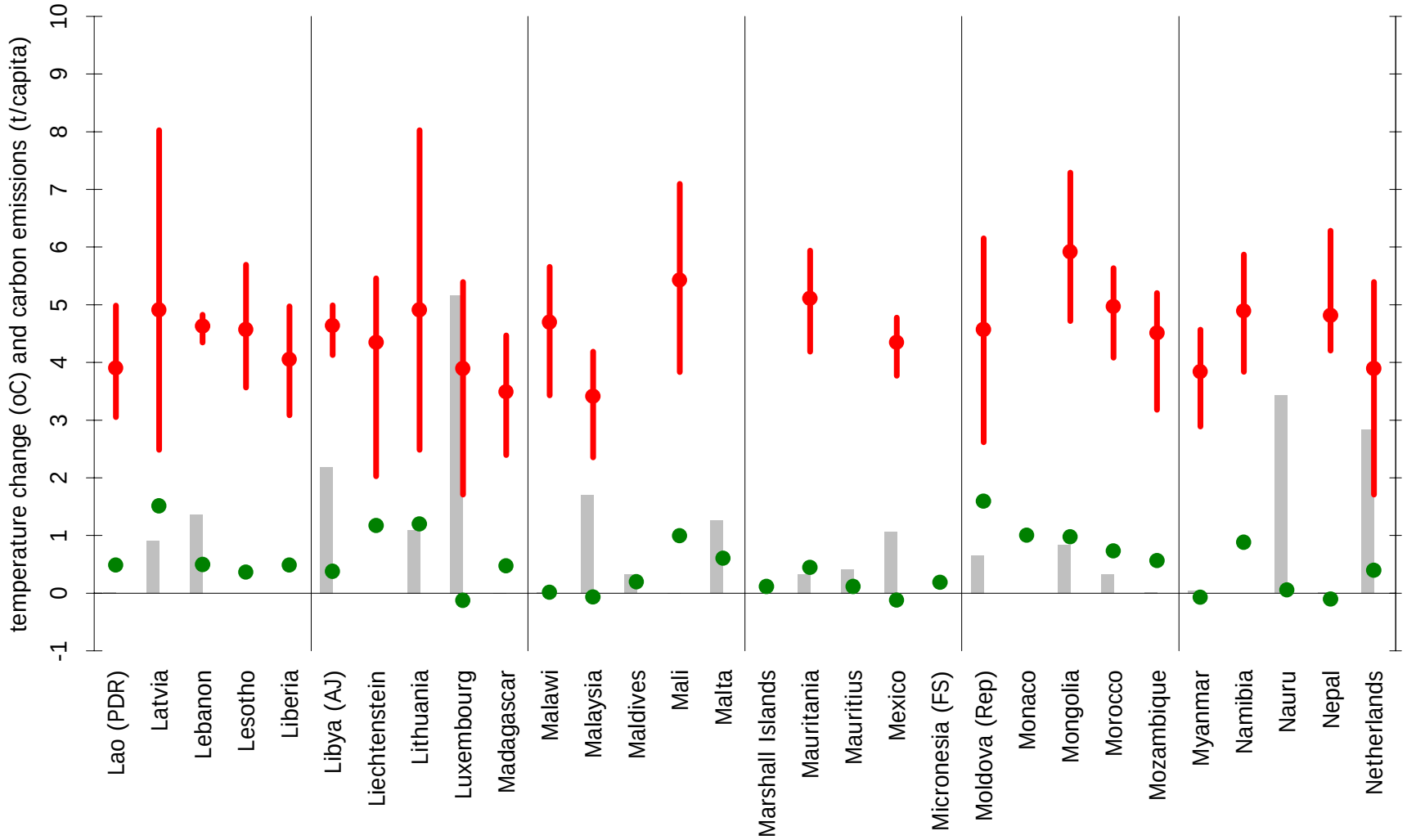
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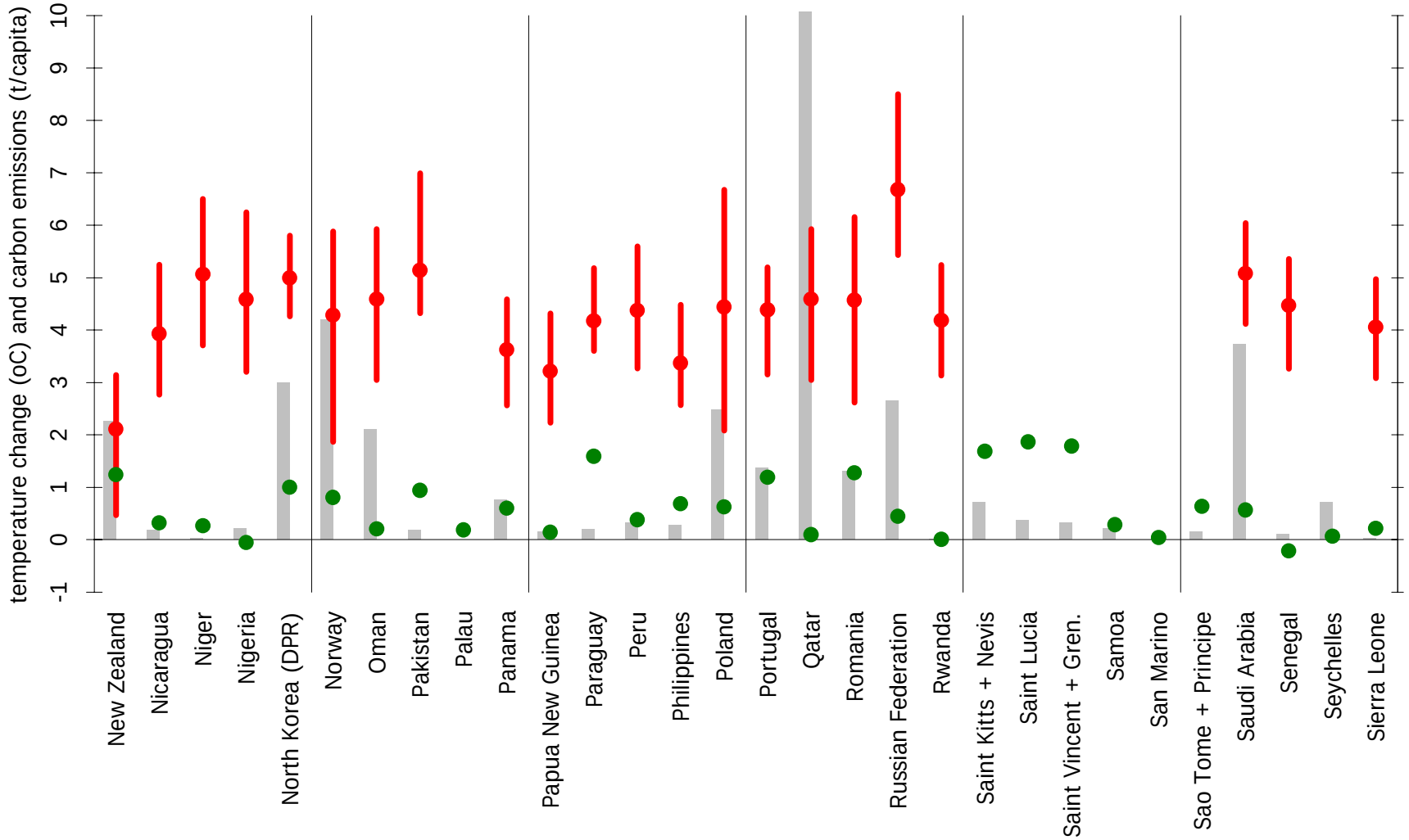
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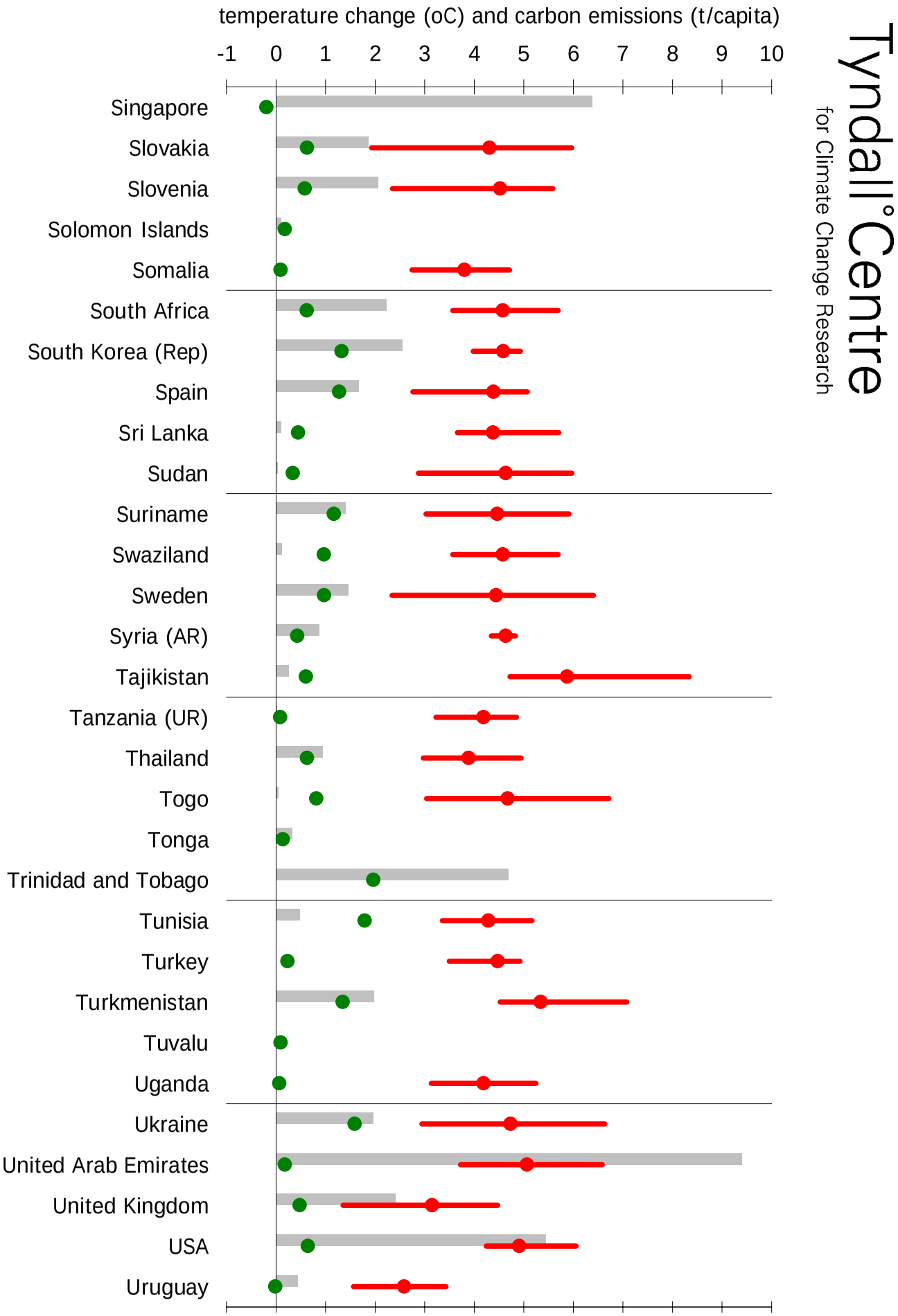
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The inter-disciplinary Tyndall Centre for Climate Change Research undertakes integrated research into the long-term consequences of climate change for society and into the development of sustainable responses that governments, business-leaders and decision-makers can evaluate and implement. Achieving these objectives brings together UK climate scientists, social scientists, engineers and economists in a unique collaborative research effort.

Research at the Tyndall Centre is organised into four research themes that collectively contribute to all aspects of the climate change issue: Integrating Frameworks; Decarbonising Modern Societies; Adapting to Climate Change; and Sustaining the Coastal Zone. All thematic fields address a clear problem posed to society by climate change, and will generate results to guide the strategic development of climate change mitigation and adaptation policies at local, national and global scales.

The Tyndall Centre is named after the 19th century UK scientist John Tyndall, who was the first to prove the Earth's natural greenhouse effect and suggested that slight changes in atmospheric composition could bring about climate variations. In addition, he was committed to improving the quality of science education and knowledge.

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