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New Metrics for Environmental Economics: Gridded Economic Data

William D. Nordhaus
Yale University [*]

Abstract

The last two decades have witnessed a dramatic growth in interest in the interaction between economic activity and geophysical variables. A major hurdle for current research is the complete disjunction of socioeconomic and geophysical data. The present study describes the results of the GEcon project, which has developed a geophysically based data set on economic activity. The G-Econ data presented here estimate gross output at a 1-degree longitude by 1-degree latitude resolution at a global scale for virtually all terrestrial grid cells. We provide applications to the impacts of global warming and to the question of the impact of geography on the economic condition of tropical Africa.

Keywords: gridded output, economic growth, spatial rescaling

1 Alternative Metrics for Economics and Geography

The last two decades have witnessed a dramatic growth in interest, at both national and international levels, in the interaction between economic activity and geophysical variables. A major hurdle for current research is the complete disjunction of socioeconomic and geophysical data. In part, the lack of intersection of the research programs has been due to the disparate interests of the different disciplines working in these two areas. The present study describes the results of a project, called the GEcon project, to develop a geophysically based data set on economic activity. The G-Econ data presented here estimate gross output at a 1-degree longitude by 1-degree latitude resolution at a global scale for virtually all terrestrial grid cells. At present, these data are available for total economic activity for a single year, 1990. Data and methodology are available on the project website at `http://gecon.yale.edu`.

Examining economic relationships on a gridded scale has many advantages. One important advantage is that it can easily link economic data to readily

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[*] Corresponding Author. E-mail: william.nordhaus@yale.edu

available geophysical data (such as on climate, soils, ecology, and the like). A second advantage is that the database for studying global processes is much more detailed than the standard ones. By disaggregating to grid cells, the number of useful observations increases from around 100 countries to over 27,000 terrestrial cells. By emphasizing gridded data rather than national data, this data set allows a much richer set of geophysical data to be used in the analysis. Most of the important geographical data (climate, location, distance from markets or seacoasts, soils, and so forth) are generally collated on a geophysical basis rather than based on political boundaries. Finally, there is also an important interaction between the finer resolution of the economic data and the use of geophysical data because, for many countries, averages of many variables (such as temperature or distance from seacoast) cover such a huge area that they are virtually meaningless, whereas for most grid cells the averages cover a reasonably small area.

2 Methodology for Estimating Gross Cell Product

2.1 The concept of gross cell product

The major statistical contribution of the present research program has been the development of "gridded output" data, which are called *gross cell product* or GCP. The conceptual basis of GCP is the same as gross domestic product (GDP) as developed in the national income and product accounts of major countries. The basic measure of output is gross value added in a specific geographical region; gross value added is defined as total production of market goods and services less purchases from other businesses. GCP will aggregate up across all cells within a country to gross domestic product.

The globe contains 64,800 such grid cells; we provide output estimates for 27,079 terrestrial cells. Of these, 20,934 cells are outside Antarctica; 18,819 have complete and minimum-quality data; and 16,219 have complete, minimum-quality data with non-zero population and output.

We measure output in purchasing-power-corrected 1995 U.S. dollars using national aggregates estimated by the World Bank. We do not generally adjust for purchasing-power differences within individual countries. The exception to this rule is that we make purchasing-power adjustments for oil and mineral production in countries with a high proportion of output coming from these sources.

The general methodology for calculating GCP is the following:

$$\text{GCP by grid cell} = (\text{population by grid cell}) \times (\text{per capita GCP by grid cell}) \tag{1}$$

The approach in Equation 1 is particularly attractive because a team of geographers and demographers has recently constructed a detailed set of population estimates by grid cell, the first term on the right-hand side of Equation 1.[1] Estimates of gross cell product primarily require new estimates of per capita output by grid cell. Measuring disaggregated per capita income has proven a major task.

2.2 Methodologies for estimating per capita gross cell product

The detail and accuracy of economic and demographic data vary widely among countries, and we have developed alternative methodologies depending upon the data availability and quality. The methodologies and underlying data are described in a companion paper, and detailed results and data for each country are also available (Nordhaus et al., 2006).

In developing the data and methods for the project, two different attributes are central: the level of spatial disaggregation and the source data used to construct the estimates of gross cell output. In terms of spatial disaggregation, there are usually three political subdivisions: (A) national data, (B) "state data" from the first political subdivision, and (C) "county data" from the second political subdivision. We use the lowest political subdivision for which data are available, although different levels are sometimes combined.

There are four major sources of the economic data: (i) gross regional product (such as gross state product for the United States); (ii) regional income by industry (such as labor income by industry and counties for the United States and Canada); (iii) regional employment by industry (such as detailed employment by industry and region for Egypt); and (iv) regional urban and rural population or employment along with aggregate sectoral data on agricultural and non- agricultural incomes (used for African countries such as Niger). For each country, we combine one or more of the four data sets at one or more regional levels.

2.3 Spatial rescaling

The data on output and per capita output are estimated by political boundaries. To create gridded data, we need to transform the data to geographic boundaries. I call this process "spatial rescaling," although it goes by many names in quantitative geography such as "the modifiable areal unit problem," "cross-area aggregation," or "areal interpolation." (See Tobler, 1979; Flowerdew & Green, 1989; Gotway & Young, 2002) Spatial rescaling arises in a number of different contexts and requires inferring the distribution of the data in one set of spatial aggregates based on the distribution in another set of spatial aggregates, where neither is a subset of the other. The scaling problem arises here because all economic data are published using political boundaries, and these need to be converted to geophysical (gridded) boundaries.

Having reviewed alternative approaches and done some simulations with economic data, we settled on the "proportional allocation" rule (details are

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[1] The gridded population data are available online at `http://sedac.ciesin.columbia.edu/plue/gpw`, with full documentation in Tobler et al. (1995), updated in Deichmann et al. (2001)

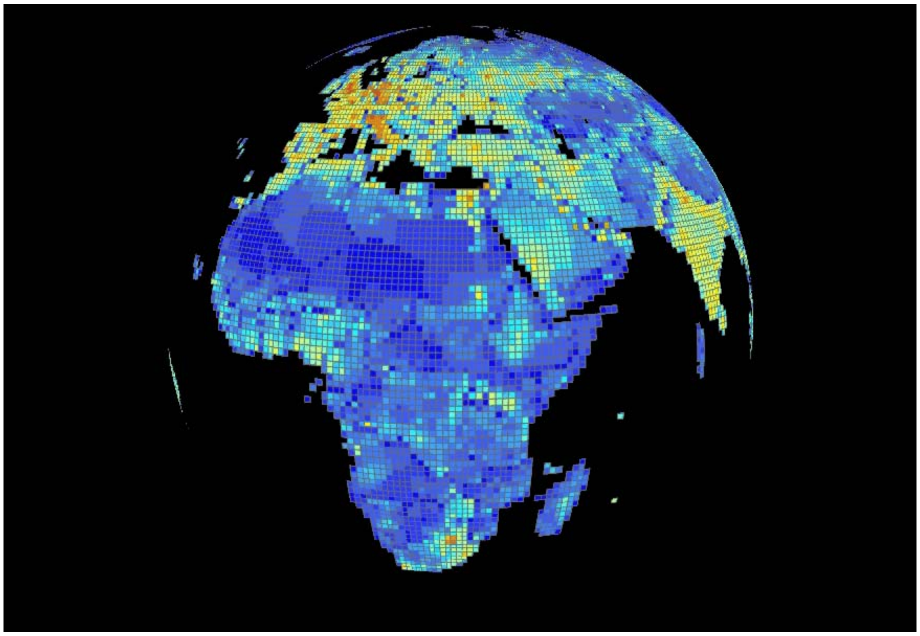

Figure 1: Output density for Eurasian hemisphere:This picture shows the output density for the Eurasian hemisphere, with colors indicating the output density from lowest density or coolest (blue) to highest output density or hottest (red).

available in papers on the project website). The first step is to divide each grid cell into "sub-grid cells," each of which belongs uniquely to the smallest available political unit (the "counties") in a country. The next step is to collect or estimate per capita output for each province. Third, the proportional allocation rule assumes that per capita output is uniformly distributed in each province and that population is uniformly distributed in each grid cell. Based on these assumptions, we can calculate a tentative estimate of output for each sub-grid cell as the product of the sub-grid cell area times the population density of the grid cell times the per capita output of the province. We next calculate the gross cell product as the sum of the outputs of each sub-grid cell. The final step is to adjust the gross cell products to conform to the totals for the province and the country. Figure 1 provides a picture of the output density for the Eurasian hemisphere.

3 Impact of geography, climate, and other geographic activities on economic activity

There are many potential applications of gridded data. I will discuss in this paper one only in detail—examining the impact of global warming. Additionally, I mention at the end of this section some other important related applications.

3.1 Impact of climate change on output

Most studies of the economic impacts of global warming have analyzed the impacts upon specific sectors (such as agriculture) and focus on individual countries or regions (Fankhauser, 1995; Mendelsohn & Neumann, 1999; Nordhaus & Boyer, 2000). Using the G-Econ database, we can estimate the impact of different warming scenarios on output using our gridded global database. The assumptions underlying this estimation are similar to those using the "Ricardian" technique for estimating economic impacts of climate change in agriculture (Mendelsohn & Nordhaus, 1994). More specifically, this approach assumes that economies are in long-run equilibrium with respect to climatic and other geographic variables. Because climatic variables in recent years have changed slowly relative to the turnover time of most capital stocks and other underlying economic variables, the assumption of climate- economy equilibrium is reasonable except for those areas where the capital or natural stocks change extremely slowly.

To estimate the impact of climate change, I compare the economic productivity of the existing climate with that of two climate-change scenarios that reflect an equilibrium impact of doubling of CO_2-equivalent atmospheric concentrations. The scenarios are:

CC1: The first scenario is one in which only temperature is assumed to change. We take a standard scenario that corresponds to a doubling of atmospheric concentrations of CO_2-equilvalent greenhouse gases. This scenario assumes a mean surface temperature change of 3.0°C averaged over all terrestrial grid cells in the sample, and the temperature change is latitude-dependent to capture estimates from general-circulation models. The first scenario assumes no change in precipitation.

CC2: The second scenario is one in which there is mid-continental drying as well as the temperature change assumed in CC1. To model the mid-continental drying, it is assumed that precipitation declines by 15 percent in areas at least 500 km from the coast in mid-latitude regions (between latitudes 20 and 50 north or south), while precipitation rises 7 percent in other areas.

The scenarios are drawn from the multi-model assessments in the IPCC Third Assessment Report, Chapter 9, Figures 9.10 and 9.11 (Houghton et al., 2001). They have been rescaled to correspond to a 3°C global average equilibrium increase. CC1 has been widely used in the impacts literature. While oversimplified, it captures the results of general-circulation models reasonably well. The assumptions underlying the second scenario are less well established because the extent and location of the mid-continental drying differ significantly across models.

Table 1: Estimated impact of global warming on world output: This table shows estimated impact of a standard 3-degree warming scenario. Scenario CC1 is warming only, while scenario CC2 also includes mid- continental drying, as explained in text. Different weights take average output change by grid cell weighted by the fraction of global output, population, or area in grid cell. Estimates omit cells with zero output. Bootstrap standard error is for 200 samples.

	Impact on Global output	
	Estimated impact	Bootstrap estimated standard error
Scenario CC1		
Output weights	-0.34%	0.03%
Population weights	-1.44%	0.13%
Area weights	-0.51%	0.05%
Scenario CC2		
Output weights	-0.30%	0.04%
Population weights	-2.44%	0.14%
Area weights	-1.17%	0.05%

The projection of the impact of climate change relies upon an equation with the natural logarithm of gross cell output density as a dependent variable and geophysical variables as independent variables. Additionally, I have added variables that are country-specific linear temperature effects. The purpose of this specification is to reduce the possibility of spurious correlations and to ensure that low-quality country data do not contaminate the estimates[2].

To estimate the impact of the two scenarios involves the following steps: (a) First, estimate a regression of cell output using the historical climate and other variables. (b) Next, change temperature and precipitation by grid cell according to scenarios CC1 or CC2. (c) Then, estimate the change in output as the difference between the projections for scenarios in (a) and (b). (d) Next, aggregate the changes using as weights cell area, output, and population. (e) Because the equations and transformations are highly non-linear, estimate the statistical variability of the estimates and projections using “bootstrap” techniques with 200 replications.

The basic results are shown in Table 1, where we combine the two scenarios and the bootstraps with different aggregation approaches. The population weights measure the change in average incomes; the output weights estimate the impact on global output; the area weights ask what happens to the average terrestrial location (These estimates are slightly different from those presented in Nordhaus, 2006*b*, the current estimates have added several smaller countries, corrected data errors in the earlier publication, and aused an updated coastal distance variable).

The basic message is that the CC1 scenario (warming with no precipitation

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[2] The equation used for the global warming equation is the natural logarithm of output density as dependent variable. Independent variables are mean and squared temperature, mean and squared precipitation, elevation, roughness, roughness squared, distance from coast (linear and quadratic), country effects, and temperature effects by country.

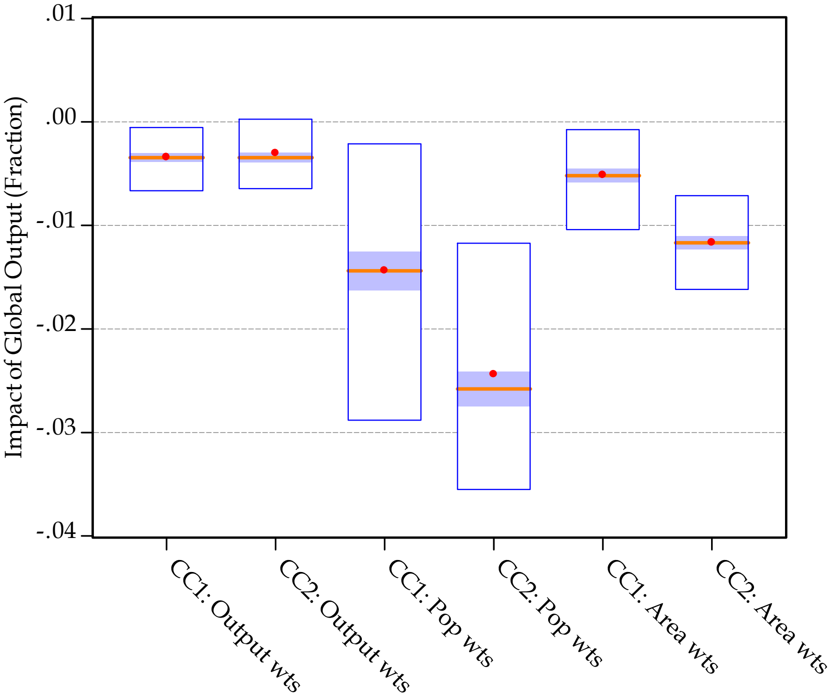

Figure 2: Bootstrap estimate of impact of climate change on global output: This figure shows the distribution of estimates from bootstrap calculations of the impact of global warming. In boxplots, the means are the red circles, the medians are the heavy orange horizontal line, the one-sigma ranges of the median are the blue shaded regions, and the interquartile ranges are the boxes. For estimates, see text and discussion of Table 1.

change) shows a negative impact on output by any of the three weighting systems. The projected output change is -0.3 percent using cell output weights and -1.4 percent using cell population weights. Figure 2 shows a set of box plots that indicate the results of the bootstrap estimation.

The CC2 scenario (warming with mid-continental drying) shows more adverse effects than the CC1 scenario. The differences between the two scenarios are progressively greater as the weights move from output to area to population. The intuition here is that the largest adverse impacts occur where population densities are highest. Perhaps the most relevant result is the population-weighted CC2 scenario, which indicates an average impact of -2.4 percent of average output from the doubling scenario.

The estimated impacts described here are larger than most existing estimates of market damages. Nordhaus and Boyer estimated impacts of a 2.5°C warming to be -0.2 percent and -0.4 percent of global output for output and population weights, respectively (Nordhaus & Boyer, 2000). Tol's benchmark estimate for a 1°C warming is + 2.3 percent for output weighted-impacts (Tol, 2002). Mendelsohn, Dinar, and Williams use an approach similar to the present one, focusing on countries, and find a neutral effect of climate change (+ 0.1 percent globally using output weights) in 2100, although low-latitude countries are expected to experience serious negative economic impacts (Mendelsohn et al., forthcoming).

At the same time, three reservations should be emphasized. First, the estimates of the impact of geographic variables on output leave a significant fraction of output unexplained. Second, these estimates include only market output and do not incorporate any non-market impacts or abrupt climate changes. Hence, impacts on ecosystems or amenities need to be included in a full impacts analysis (National Research Council, 2002; Alley et al., 2003). Finally, the model underlying the estimates here, particularly the assumption of climate-economy equilibrium, is highly simplified. Pursuing each of these issues requires further data and methodological developments.

3.2 Other applications

This paper has described a new approach to measuring economic activity that is particularly well-suited to environmental economics and to integrating geophysical and economic factors. There are many potential applications; I conclude with three:

3.2.1 Africa

What are the sources of poverty in tropical Africa? This topic has engaged scholars for at least two centuries. In their major statistical analysis of Africa, Bloom and Sachs and their colleagues argue that much of the economic backwardness of Africa is due to geography (Among several studies, see Sachs et al., 2004; Kiszewski et al., 2004). In an earlier article, I applied the GEcon data set to examining the impact of geography on economic activity in tropical Africa. The conclusion was as follows:

> Geography explains 20 percent of the difference in per capita output between tropical Africa and the two industrial regions (the U.S. and industrial Europe); and it explains about 12 percent of the difference in per capita output between tropical Africa and other low-latitude regions. Hence, geography contributes substantially to Africa's poor economic performance, but other factors appear to contribute more. (Nordhaus, 2006*b*)

3.2.2 Hurricanes

Another application of this approach is to examine the economic impact of hurricanes. Because the impact of hurricanes is so localized, current economic measures cannot adequately capture their impacts. By integrating gridded economic data with geophysical data, it is possible to determine the vulnerability of different regions to hurricanes, and to examine the interaction of sea-level rise, the projected increase in hurricane intensity, and economic activity. In a preliminary paper, I have used this approach, downscaling the GEcon data set to a $\frac{1}{6}$ degree × $\frac{1}{6}$ degree resolution. The preliminary conclusions of that paper were as follows:

> 1. There are substantial vulnerabilities to sea-level rise and coastal inundation in the southern coast of the United States. The major concentrations of economic activity and capital (with capital stock greater than $50 billion [per $\frac{1}{6}^\circ$ by $\frac{1}{6}^\circ$ grid cell]) are in the Miami coast and in New Orleans, both of which have been hit by major storms in the last fifteen years.
>
> 2. Greenhouse warming is likely to lead to greater intensity but not necessarily to greater frequency of intense hurricanes. Using the historical frequency of hurricane power as a guide, a rough estimate is that the annual frequency of very active seasons (similar to that in 1886, 2004, and 2005) will increase from about 3 in 150 years to 5 in 150 years. This assessment is based on an increase in tropical Atlantic temperatures of $2\frac{1}{2}^\circ$C, which is approximately the prediction of an equilibrium doubling of atmospheric concentrations of CO_2-equivalent greenhouse gases.
>
> 3. The experience of 2005 appears to have been a quadruple outlier of nature. The number of North Atlantic storms is at the top of a long-term cycle; the fraction of intense storms in 2005 was above average; the fraction of the intense storms making landfall in the United States was unusually high; and one of the intense storms hit what is the most vulnerable high-value region in the country. New Orleans is to the gods of natural destruction what the World Trade Towers were to the gods of human destruction. (Nordhaus, 2006*a*)

3.2.3 The North Atlantic Thermohaline Circulation

One of the important potential impacts of climate change is a slowing or reversal of the North Atlantic Thermohaline Circulation (NATC). Calculations of the geophysical impacts of NATC changes have been made by several modeling groups. However, the socio-economic impacts are to date incomplete because of the need to connect a spatially heterogeneous climatic impact of NATC changes with the relevant socio- economic data. National economic data will be virtually useless for this question because of the large scale of many affected countries (particularly Canada, the United States, the United Kingdom, and large European countries). By contrast, the G-Econ data set can estimate impacts because of the much finer resolution of the data. For example, Canada has 717 grid-cell observations and the U.K. has 62 observations, so the impacts of regionally differing NATC change can be investigated using this finer resolution. Integration of the GEcon data with climate models can provide the first order-of-magnitude estimates of the economic impact of changes in the NATC.

3.3 Conclusion

This concludes the description of the G-Econ database for gridded output along with a discussion of applications. It must be emphasized that the current results are the first word and not the last. If this approach to measuring economic activity proves fruitful, then other researchers, particularly those in the countries involved, and especially national statistical agencies, will be able to provide much more detailed and accurate assessments of regional and gridded data, as well as time series. The history of innovative data systems usually involves small-scale efforts by private researchers to show how a particular data system might be constructed or used. After the initial experience, if in fact the data set appears valuable, more extensive and regular collection can be routinized and institutionalized within government statistical agencies. The production of gridded global and national economic data by statistics agencies of governments is entirely feasible, and it should form part of the regular data collection and processing activities of governments. With additional time-series and industrial data, this approach would help advance our understanding of the interaction of economic and geophysical activity.

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