POLICY RESPONSES TO CLIMATE CHANGE

Allocation: GLCPC/250 Knh
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EXECUTIVE SUMMARY

Cai, Brock, Xepapadeas, and Judd [1] have built a model of Dynamic Integration of Regional Economy and Spatial Climate under Uncertainty (DIRESCU), incorporating a number of important climate science elements that are missing in most integrated assessment models. These include spatial heat and moisture transport from low latitudes to high latitudes, sea level rise, permafrost thaw, and tipping points. Using this more realistic model of the world economy and climate, we study policy responses to climate change under cooperation and various degrees of competition among regions. We find that other assessment models that are missing elements of climate science lead to significant bias in important policy variables such as the social cost of carbon and adaptation.

RESEARCH CHALLENGE

Leading integrated assessment models assume that climate damages are related to the mean surface temperature of the planet. But climate science shows that when the climate cools or warms, high-latitude regions tend to exaggerate the changes seen at lower latitudes due to spatial heat and moisture transport. This effect is called polar amplification (PA). Thus, the surface temperature anomaly is differentiated across spatial zones of the globe. The low- (high-) latitude regions would be hotter (colder) if poleward heat transport were absent; hence, damages in the low-latitude regions would be higher since they are already under heat stress and transporting some of that heat poleward helps relieve this heat stress.

PA will accelerate the loss of Arctic sea ice, a potential meltdown of the Greenland and West Antarctica ice sheets, which could cause serious global sea level rise. Moreover, PA will lead to faster thawing of the permafrost, which is expected to bring about widespread changes in ecosystems and damage to infrastructure, along with the release of greenhouse gases that exist in permafrost carbon stocks. Furthermore, PA will also affect the likelihood of tipping points, such as the "nearest" three potential tipping points located in the high latitudes of the Northern Hemisphere (Arctic summer sea ice loss, Greenland ice sheet melt, and boreal forest loss).

METHODS & CODES

We developed the DIRESCU model to include spatial heat and moisture transport from low latitudes to high latitudes, sea level rise, permafrost thaw, and tipping points. To model spatial heat and moisture transport, we disaggregate the globe into two regions: Region 1 is the region north of latitude 30°N to 90°N (called the North), while Region 2 is the region from latitude 90°S (the South Pole) to 30°N (called the Tropic-South). The disaggregation also makes clear their significant economic difference, since most countries in the Tropic-South are poor and most countries in the North are rich.

To address the tipping points and solve the dynamic stochastic programming problem, we adapt the computational method in DSICE [2], developed by Cai and Judd in the past four years using GLCPC allocations on Blue Waters. The computational method is parallel backward value function iteration using the master-worker structure—the master assigns N tasks for workers to solve in parallel and then gathers the results of these tasks from workers. Our code shows high parallel efficiency, with an almost linear speed-up from 30 nodes to 5,000 nodes.

RESULTS & IMPACT

In 2017, Cai, Judd, and Steinbuks published a paper in *Quantitative Economics* [3] that develops a nonlinear certainty equivalent approximation (NLCEQ) method to solve efficiently and in parallel huge-dimensional dynamic stochastic problems without exogenous trends, by using Blue Waters resources. We also extended NLCEQ to solve high-dimensional dynamic stochastic problems with exogenous trends and applied it to analyze the effect of climate and technological uncertainty in crop yields on the optimal path of global land use in [4].

Also in 2017, Yeltekin, Cai, and Judd published a paper in *Operations Research* [5] that developed a parallel algorithm that can solve supergames with states, which models strategic interactions among multiple players, by using Blue Waters resources.

In 2018, Cai, Brock, Xepapadeas, and Judd released a National Bureau of Economic Research working paper [1] that is under review for publication in a prestigious economic journal. The paper builds the DIRESCU model, studies optimal climate policies under cooperation and various degrees of competition among regions, and finds that excluding some of the elements of climate science leads to significant bias in important policy variables such as the social cost of carbon and adaptation.

WHY BLUE WATERS

Our parallel computational package requires low-latency communications because the algorithm uses the master-worker structure and needs frequent communications between the master and workers. Our problems are large. For example, the DIRESCU model has 10 continuous state variables and one binary state variable, as well as eight continuous decision variables, and a more than 500-year horizon. It corresponds to solving a Hamilton–Jacobi–Bellman equation with 10 or 11 state variables. Using our efficient parallel algorithm, we solved it with one specification case in 3.4 wall-clock hours with 102 computer nodes on Blue Waters. Moreover, we have solved the model with many specification cases for analysis. In addition, the largest problem we solved for DSICE used 3,459 computer nodes and took 7.5 wall-clock hours on Blue Waters. Blue Waters allows us to solve these large problems efficiently as has already been shown in our previous work.

PUBLICATIONS & DATA SETS

Cai, Y., K.L. Judd, and J. Steinbuks, A nonlinear certainty equivalent approximation method for stochastic dynamic problems. *Quantitative Economics*, 8:1 (2017), pp. 117–147.

Yeltekin, S., Y. Cai, and K.L. Judd, Computing equilibria of dynamic games. Operations Research, 65:2 (2017), pp. 337–356.

Continued from page 265

partisan redistricting case, *Gill v. Whitford*. Our computational approach to redistricting reform has garnered media attention from popular outlets (Vox.com, *Chicago Inno*, *Reason*, the *Washington Post*); computing outlets (Cray Inc., TOP500, *Communications of the ACM*); and outlets aimed at the science and mathematics communities (*Quanta Magazine*, Science Node, *WIRED*, *Nature*). Most of the discussion has focused on the impact of our work on gerrymandering litigation. However, our work is also applicable to earlier stages of the redistricting process, which is now evolving and becoming clearer to practitioners and politicians as the project progresses.

WHY BLUE WATERS

The PEAR library is designed for extreme-scale redistricting applications. From the beginning, it was intended to scale to all of the processor cores on Blue Waters through nonblocking MPI communication calls. The computational approach implemented in our solution requires generating a very large number of electoral maps for quantitative study of redistricting phenomena. Identifying quality electoral maps requires significant computing in the combinatorial optimization process. Generating a large number of statistically independent maps is only feasible on a supercomputer at Blue Waters' scale.

PUBLICATIONS & DATA SETS

Cho, W.K.T., and Y.Y. Liu, Sampling from Complicated and Unknown Distributions: Monte Carlo and Markov Chain Monte Carlo Methods for Redistricting. *Physica A*, (2018), DOI:10.1016/j.physa.2018.03.096.

Cain, B., et al., A Reasonable Bias Method for Redistricting: A New Tool for an Old Problem. *William & Mary Law Review*, 59: 5 (2018).

Cho, W.K.T., and Y.Y. Liu, Massively Parallel Evolutionary Computation for Empowering Electoral Reform: Quantifying Gerrymandering via Multi-objective Optimization and Statistical Analysis. *SC17: The International Conference for High Performance Computing, Networking, Storage and Analysis* (Denver, Colo., November 12–17, 2017).

Cho, W.K.T., Measuring Partisan Fairness: How well does the Efficiency Gap Guard against Sophisticated as well as Simple-Minded Modes of Partisan Discrimination? *University of Pennsylvania Law Review Online*, 166 (2017).

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