From planetary scenarios to planetary sensing: models, observations, and political legibility

Abstract: This paper explores the political uses of images generated by Earth System science. It argues that images of possible climate futures, maps of potential worlds of heatwaves and wildfires, are made legible to policymakers via an alliance with a class of climate-economy models that associate scientific estimates of climate impacts with a prescribed international policy and technology mix. While environmental models have successfully mobilized policymakers in the past by providing images of "planetary scenarios" accompanying different emissions pathways, addressing climate change requires a political actor outside the administrative state to overcome the entrenchment of fossil capital. The paper suggests such actors are empowered not by the rhetoric of scenario modeling but by the emerging practice of "planetary sensing," where activists and stakeholders directly mobilize the planetary images generated by Earth System science as they work to evacuate prisons, track pollutants, and repair pipelines.

Key words: Earth System Science, Earth System Models, scenario modeling, Integrated Assessment Models, operational image, methane

Introduction

In the fight against climate change, something isn't working. Despite many toothless pledges, as of 2023, concerned governments "plan to produce more than double the amount of fossil fuels in 2030 than would be consistent with limiting warming to 1.5°C" (SEI et al., 2023: 2). Perhaps the problem is communication. Maybe the science is good, but it needs translation into a form more likely to convince the public or policymakers to act. AI imagery of climate impacts are an extravagant but typical example of the assumed evidence-action mechanism. Recent cutting-edge work in Earth System Science (ESS) uses neural networks — algorithms for complex tasks trained on large datasets— to generate photorealistic images of flooding under climate change, showing viewers what their house or neighborhood would look like after inundation by future storms (Schmidt et al., 2019; Lütjens et al., 2021). The point of such visualizations, as one group of researchers writes, is to generate "a more visceral understanding of the effects of climate change, while maintaining scientific credibility" (Schmidt et al., 2019: 1) The authors aim to "channel the emotional response into behavioural change" by giving users affective imagery alongside interventionist "knobs" representing individual or policy actions, which they can adjust and watch the floodwaters recede. (Schmidt et al., 2019: 2)

In this essay, I argue that this AI interface closely mirrors the actual political mobilization of Earth System Models (ESMs) — miniature worlds in silicon assembled from mathematical representations of the biosphere, atmosphere, oceans, cryosphere, and more. Since the 1990s, practitioners have forged an interdisciplinary alliance across a privileged subset of the physical and social sciences, creating a modeling ecosystem that produces scientific estimates of climate impacts which might accompany a prescribed international policy and technology mix. I argue that this established ESM workflow encodes a theory of change that is indistinguishable from the flood imagery software: Policymakers, terrified by ESM simulations of the bad future, will turn the technology and policy dials corresponding with the good future. This approach, I argue, represents a strategic misreading of the present. Perhaps it is better to go back to foundations, and ask, as Sheila Jasanoff has, if ESS is producing the right kind of knowledge, not whether it is communicating its findings with the right kind of rhetoric (Jasanoff, 2021). In this essay, I discuss how Earth system scientists develop future climate scenarios by allying their ESMs with a narrow class of climate-economy models, and in the process encode a top-down, elite-focused theory of change. If only a mass movement can bring about the social transformation necessary to avert the climate crisis, as I will argue, we must re-examine this workflow and ask if it is fit for purpose. As an alternative, I discuss cases where the equipment of ESS is mobilized by more radical alliances between scientists and social movements.

Persuasive science

Like the cloud chamber of early particle physics, the ESM is the signature instrument of the young discipline of Earth System Science. Although scientists have known since the nineteenth century that greenhouse gas emissions will increase the surface temperature of the Earth (Arrhenius 1896), more accurate calculations require models representing other aspects of the Earth which "feed back" on an initial perturbation. One such complication: perhaps unexpectedly, water vapor is a potent greenhouse gas, and its concentrations increase as the planet warms. One of the first papers discussing computer-modeled climate change, led in 1967 by eventual Nobel Laureate Syukuro Manabe, showed that including the water vapor feedback in the model doubles the atmosphere's sensitivity to rising carbon dioxide levels (Manabe and Wetherald, 1967). ESMs evolved in the decades after Manabe's insight, with the goal of representing the most significant physical feedbacks in the Earth system — human activity excluded — such as changing forests, soils, albedo, and clouds. ESMs are encyclopedic in approach, an interdisciplinary literature review in executable code. Within the ESM framework, findings of soil scientists, hydrologists, and others are translated into lines of code, which are allowed to combine and interact in complex simulations. By design, ESMs offer an expansive representation of the Earth system physics which are determinate on the timescale of decades or centuries, the same temporality considered in IPCC assessment reports and assumed to be the most relevant to human policymakers (Flato, 2011). Such models serve as the "lab mice or fruit flies" of Earth System Science, as fundamental to scientific practice as the model organisms of biology because, of course, there is no way to "undertake scientific experiments on the real Earth System" (Flato, 2011: 785). Only a sufficiently realistic computer simulation can substitute. Within this disciplinary view, deliberate geoengineering or the "rather unscientific" experiment of anthropogenic climate change are not alternatives for ESMs because they do not allow for scientific practices like repeatable controlled experiments (Flato, 2011: 785).

Alongside the computation of possible futures, the political potential of planetary models like ESMs have long been apparent to practitioners. Consider the case of "nuclear winter," the theory that even a small exchange of atomic weapons would thrust dust and smoke high into the atmosphere, where it would spread around the Earth as a shroud, blocking out sunlight for months and killing millions (Rindzevičiūtė, 2016: 151). During the Cold War, disarmament activists and some scientists were concerned about discourses of local nuclear conflict, which suggested that an exchange of bombs would lead to mere local devastation; only a global computer model, serving as a lab mouse, could provide evidence that the damage might reach beyond the immediate blast radius (Rindzevičiūtė, 2016: 166). Atmospheric chemist Paul

Crutzen, who would go on to coin the "Anthropocene" term, led a 1982 paper simulating complex dynamics and chemistry after a nuclear conflict and argued that "agricultural production in the Northern Hemisphere would be almost totally eliminated" as a result (Crutzen and Birks, 2016: 146). Crutzen's work was expanded on by a team of global modelers from across Europe, the US, and the USSR in a joint 1983 nuclear winter report, featuring ESM-generated maps of global devastation (Rindzevičiūtė, 2016: 151). The findings were taken up by disarmament activists in both the US and the USSR, and, although the political impact of nuclear winter discourse is disputed, the image of the entire planet brought low by atomic weapons did much to discredit the utility of a limited nuclear war (Rubinson, 2014). The images of nuclear winter taken up as icons by the disarmament movement are similar to those generated by ESMs today. ESMs are implemented as a set of coupled differential equations discretized on a spatial and temporal grid, spread over the face of the digital Earth, generating petabytes of data — moisture desiccating from soils, bursts of wildfire, forests transitioning to savannahs, wobbling ocean currents, plumes of pollution — all of which can be readily displayed as maps. Rather than a particle track, the signature image of the ESM might be a map of the world, colored in varying shades red, showing the temperature change after a hundred years of carbon emissions.

Scholars in science and technology studies have long puzzled over the special persuasive power of scientific images. Bruno Latour argues that what separates a scientific from a prescientific culture does not necessarily come from mental perceptions of the world, but from the visual practice of inscription. He uses the example of cartography — the European colonist and the native islander are both able to think geographically and communicate with maps drawn in the sand. However, only the European needs to inscribe the map on paper so he can return the knowledge to his king; the native "does not have to keep track, since he can generate many maps at will, being born on this island and fated to die on it" (Latour, 1990: 25). Latour calls these scientific inscriptions "immutable mobiles," because they can be reproduced and transported across contexts and forms, all while maintaining some static representation of an object of scientific interest.

Unlike other depictions of catastrophe, ESM output can claim the special epistemic status of the immutable mobile. The persuasive power of this status is what motivates the political use of ESM imagery. However, an act of translation is necessary for the knowledge produced by ESMs to be operationalized by a nonscientific audience. Early models, like Manabe's, estimated climate dynamics through contrived experiments like doubling atmospheric carbon dioxide levels, a practice still common in the discipline and which defines the measure of "climate sensitivity" (Knutti et al., 2017). However, such experiments lack *political legibility*. A scientific inscription has political legibility if an actor who has or seeks political power, such as a politician, regulator, or activist, can understand its relevance to their goals and mobilize it as part of a broader strategy. Climate sensitivity simulations leave humans out by definition; they are a narrow disciplinary exercise designed to characterize a model's biophysical feedbacks. What does it mean to double carbon dioxide levels, in terms of infrastructure or economic development? By contrast, the nuclear winter images had direct political legibility to both the defense establishment and to activists: the scenarios explored in a seminal 1983 paper, publicized by its celebrity-astronomer coauthor Carl Sagan, were divided into vivid scenarios like the effects of an exchange of 10,000 megatons of explosives or a 100 megaton bomb dropped on a city (Turco et al., 1983). However, political legibility is generally not universalist. What makes a scientific image useful to a negotiator at a climate summit will be different from an environmental justice community fighting to stop the construction of a refinery. The kind of political legibility a group of technical experts seek to add to their images therefore encodes a theory of change — by choosing who they seek to inform, they implicitly choose who they believe can bring about change in the world.

The political legibility of planetary scenarios

In the most recent IPCC assessment report, scientists have granted political legibility to their ESMs by supplementing climate sensitivity experiments with detailed future scenarios called the shared socioeconomic pathways (SSPs). There are five SSPs, each consisting of a set of quantitative variables (e.g. population trends) paired with a narrative description, designed to be easily understood by a policymaking audience (Riahi et al., 2017). For example, the SSP3 scenario is characterized by strong challenges to both climate adaptation and mitigation, marked by regional rivalry (e.g. protectionism) and limited technological development. To turn the SSPs into the sort of data that can drive an ESM, practitioners enlist a separate genre of planetary model called Integrated Assessment Models (IAM). IAMs couple representations of the economy with the environment, tracing how human activity and the changing ecosystem interact with one another under a variety of policy scenarios. IAMs trace their origins to early global social models like the 1972 *Limits to Growth* report, but most IAMs "appeared in the early 1990s and their development largely co-evolved with the UN climate negotiations" (van Beek et al., 2020: 3). An influential early IAM is William Nordhaus's Dynamic Integrated Climate-Economy (DICE) model, still used today, and it is representative insofar as it prioritizes representations of the economy over the environment: the amount of acceptable warming in DICE is highly sensitive to the "discount rate," a percentage representing the value of the future relative to the present which Nordhaus determined by looking at long-term interest rates (Mann 2022). There are many kinds of IAM, including others in the cost-benefit analysis tradition of Nordhaus, but the ones most relevant to ESMs include complex representations of the economy, particularly sectors with great environmental impact such as energy and agriculture, that are able to produce time-resolved estimates of human-driven changes to greenhouse gas emissions, land use, and air pollution precursors (Nikas et al., 2019). To model a world under SSP3, IAMs assume high preferences for fossil-fuel power plants, strong demand for livestock, large tariffs, and low rates of energy efficiency improvement, among other social factors — all of which have direct policy relevance — and these assumptions are used to drive a computable general equilibrium model of the economy. Computable general equilibrium models assume that supply and demand are balanced by consumers maximizing utility and producers maximizing profit, often with model parameters calibrated using empirical data so that model results match the real world for a given year (Nikas et al., 2019: 23). National laboratories around the world then use the standardized IAM output to run their own independent ESM simulations. Practioners call this system the "parallel process" of scenario development (Moss et al., 2010: 747). IAMs and ESMs, each with their own intellectual histories and disciplinary norms, are developed independently. At the end of the scenario process, ESM output is collected as part of the Coupled Model Intercomparison Project (CMIP), an international effort designed to inform IPCC report authors in their assessment of future climate change (Gidden et al., 2019).

Call the ESM-IAM alliance the *planetary scenario* mode of political legibility in Earth System science. The SSP narratives and policy prescriptions are directly interpretable in the real world of institutional politics. Policymakers can understand the IAM scenarios without any knowledge of climate or ecology. Scientists use ESMs to produce images illustrating these scenarios with maps of possible futures and encourage the policymakers to choose the least damaging policy and technology mix as represented by the IAMs. The elite-focused planetary scenario mode of legibility has not stopped climate change, but the approach has had successes in past abatement of acid rain. Acid rain is a phenomenon where pollutants like nitrogen oxides and sulfur dioxide, both emitted by fossil fuel burning, are oxidized in the atmosphere to form nitric and sulfuric acid, which dissolve in water and are deposited by precipitation into the ecosystem (Jacob, 1999: 251-252). In the 1980s, a team at the International Institute for Applied Systems Analysis (IIASA) — which today produces the IAMs operationalizing many of the SSPs — produced the Regional Acidification Information and Simulation (RAINS) model to calculate the most cost-effective strategies to mitigate acid rain (van Beek et al., 2020: 5). Beginning in 1993, RAINS became an integral part of the production of transboundary air pollution regulation in Europe, where policymakers used its output to determine optimal abatement strategy; modelers were able to capitalize on feelings that flat emissions cuts, as prescribed in earlier negotiations, were arbitrary and unfair and offered their model as a politically legible alternative rooted in "objective" science as practiced by an intergovernmental institution seen as politically neutral (Sundqvist et al., 2002). "What then were political and economic disputes are now science," said Anna Lindh, the former Swedish environmental minister, at a 1995 acid rain conference (quoted in Sundqvist et al., 2002: 153).

The objective, neutral posture of RAINS suggests that political legibility is closely related to *legitimacy*. Sheila Jasanoff argues that legitimation of various modes of seeing can come from one of three perspectival positions: the view from nowhere, which reflects the typical moves towards "objectivity" in much of science; the view from everywhere, as practiced by institutions like review panels claiming to represent all positions; and the view from somewhere, or the eyewitness, who relies on authenticity (Jasanoff, 2017: 3). The view from nowhere position, adopted in all of the planetary modelling cases discussed so far, can be highly effective in producing scientific images that are both legible and legitimate to elite policymakers. In the case of acid rain, modeling supported the prescription of relatively affordable emissions reductions and technical interventions like the catalytic converter, and was eventually recognized by a variety of national actors as a fair, neutral means to regulate precursor emissions (Sundqvist et al., 2002: 153). In short, the problems of acid rain could be solved by technologies and modest regulations that were back-compatible with existing social infrastructure; cars, for example, could continue to burn gasoline. Power was necessary, yes, but the ordinary power of the administrative state was sufficient. Because regulatory bodies speak a language of objective, neutral science, even as their needs diverge from those of the peer review system of normal science (Jasanoff, 2003: 228-229), a strategy of producing scientific discourse, legitimized with an air of neutrality, and made legible to policymakers via clear scenarios, offered a plausible path towards political action.

Climate change is a far harder problem because carbon emissions are intricately woven into the social fabric, with fossil fuels used as key instruments in labor relations, statecraft, and population management even before considering the economics: the profitability of fossil fuels and costs sunk into existing infrastructure.[1] The neutral, objective road to political legitimacy is impossible to follow because, as Sheila Jasanoff notes, "the more radical the prescriptions for reordering lives, the less likely it is that people will unquestioningly follow the advice of science" — climate skepticism and science denial are a predictable response to an objective pose that, when made legible to policymakers, proposes to euthanize entire industries (Jasanoff 2021: 7). Because climate change is a far deeper challenge to the existing economic and social order than acid rain or the ozone hole, IAMs offer a skewed kind of political legibility to ESMs.

IAMs are built for an elite audience of climate negotiators and politicians, who may have the power to mandate catalytic converters but not abolish fossil capital.[2] If only a mass movement has the power to counter deep economic and political vested interests, it raises a question: does the planetary scenario model of political legibility meet the needs of such a subject? Here we should separate two critiques of IAMs in our analysis. The first is the common critique that IAMs are unrealistic or ideological models (e.g. Asefi-Najafabady et al., 2021). IAMs tend to be techno-optimistic, prescribing speculative negative-emissions technologies like continent-scale plantations of trees, burned for energy and with the emitted carbon captured and injected underground (Anderson and Peters, 2016; Low and Schäfer, 2020). So-called bioenergy with carbon capture and storage (BECCS) is a prominent feature of the climate scenarios used to grant legibility to ESMs, despite its questionable feasibility — no movement or politician would pay the political capital required for such a project because of its enormous hunger for land and water, which is on a scale rivaling that already used for croplands (Malm and Carton, 2021: 6). However, I argue a second point: IAMs have deeper problems than the kind of policies and technologies they prescribe, as this would imply that building a better IAM is sufficient to grant the right political legibility to ESMs. An IAM that prescribes degrowth policies or deep social transformation, although an admirable imaginative exercise (Kikstra et al., 2024), would remain politically impotent because the legibility IAMs grant ESMs, aimed at policymaking circles, is not the kind of legibility that builds movements.

Planetary sensing, targeted action

The question, then, is how planetary models can be appropriated by a more diverse cast of actors to make change in the world. Here, political legibility might not take the form of global scenarios, as this implies an actor invested with some power over planetary governance, but instead seeks to answer targeted questions of immediate practicality. In September 2022, Hurricane Ivan was due to make landfall in Tampa, Florida. People incarcerated in Hillsborough County Jail were in the path of the storm. Prison abolitionist organizers, organized through Fight Toxic Prisons, worked with MIT aeronautics PhD student Ufuoma Ovienmhada and collaborators to produce maps using satellite data showing that the jail was in a mandatory evacuation zone. The organizers spread the image on social media and led a "phone zap" public pressure campaign, where large numbers of people called to demand evacuation. Although staff originally laughed when contacted by organizers, eventually they evacuated the facility (Ovienmhada et al., 2023: 10).

Call Ovienmhada's approach *planetary sensing*. Prison abolitionists recognized that a certain form of scientific knowledge offered leverage at a certain stage in their campaign: by classifying a facility as part of an evacuation zone, they could use one part of the state against another. Here I use the term "planetary sensing" to suggest that something like cybernetics-from-below, where systems of planetary modeling and observation developed by Earth System science are directly operationalized by actors to "feed back" on the world and change it. Research agency Forensic Architecture exploits visual spectrum satellite imagery and other Earth-observational data sources to investigate specific cases of war crimes and state violence, producing the kind of evidence that might move institutions like the International Court of Justice while also feeding in to social movements (Bois et al., 2016). Air quality sensors can be used for similar efforts, as they can be operated by citizen scientists or activist-scientist coalitions to make local pollution problems legible to regulatory bodies. Efforts led by Priyanka DeSouza at the University of Colorado Denver seek to calibrate networks of low-cost sensors for airborne fine particulate matter ($PM_{2.5}$), which typically use optical retrieval methods that may be biased under certain conditions; by developing portable algorithms that correct for common issues, citizen-scientists can make stronger epistemic claims as they seek to counter-propagandize or enlist the powers of the administrative state to enforce air quality rules (DeSouza et al., 2022). The Citizen Sense lab at the University of Cambridge, led by Jennifer Gabrys, have designed a comprehensive low-cost air quality monitoring sensor and data software suite called AirKit with the explicit aim to "create trust across communities, scientists and regulatory bodies," and thus produce immutable mobiles with the kind of political legibility that might move powerful institutions (Mahajan et al., 2021). The planetary sensing approach need not be aimed at mobilizing parts of the state. The incarcerated activists Ovienmhada interviewed understood that scientific claims offered a means to build a broader base for prison abolition; one said that while "[w]e have general cred with other abolitionists and organizers," collecting data "would help us build trust with the public, with officials, and to change policy" (Ovienmhada et al., 2023: 9).

While increasingly accessible observation data — such as the low-cost particle counters championed by DeSouza and Gabrys, and the satellite data used by Ovienmhada and Forensic Architecture — show the potential of producing immutable mobiles from below, it is the confluence of observations with computer models that most fully takes advantage of the existing infrastructure for planetary sensing. As historian Paul Edwards points out, Earth system science has produced "global knowledge based on global infrastructures for monitoring, modeling, and memory," and it is this global knowledge infrastructure that "hold[s] the key to transforming these information resources" like sensor data "into knowledge" (Edwards, 2010: xix-xx). A new tool called Air Tracker, for instance, appropriates the existing infrastructure of Earth System science to ends far more useful than observation alone. Developed in collaboration with community members by Environmental Defense Fund scientist Tammy Thompson and University of Utah professor John Lin, Air Tracker allows users in some US cities to track polluted parcels of air backwards in time (Thompson, 2022). Users are presented a map of their city populated with official EPA air quality sensors, used for the enforcement of national ambient air quality standards (NAAQS), along with low-cost sensors including PurpleAir monitors. When users click on a sensor, they are presented a time series of recent pollution observed at the site. For a particular observation in space and time, the map displays a cloud indicating where that pollution likely originated. The tool runs in real time, so users could consult Air Tracker for source attribution if they "smell or see something suggesting environmental harm" (Air Tracker, 8). On the display, users can toggle on and off industrial sites; if a site lies in the cloud, it may be the culprit behind an acute air quality episode. Behind the scenes, Air Tracker uses a sophisticated atmospheric model called Stochastic Time-Inverted Lagrangian Transport (STILT), first developed by Lin and colleagues in 2003. STILT has since become a standard tool in Earth System science, used to attribute observed concentrations of air pollutants at a given point in space, such as an air quality monitor, to emissions sources upwind (Lin et al., 2003); however, STILT can normally only be run by sophisticated users with knowledge of programming and geospatial software libraries. What is innovative about Air Tracker is not the methodology, but its real-time automation and easy-to-use interface. It is aimed explicitly at civic action: the Air Tracker developers plan to release a tool that will automatically generate city-specific nuisance reports, complete with model output, in response to user requests.

With Air Tracker in mind, we might distinguish different forms of planetary sensing by the data and models they bring together in a single frame. Air quality has long attracted interventions from citizen scientists, mostly in two forms: analysis of observations and of emissions inventories. Because synthesizing models like STILT are typically inaccessible, activists tend to deploy only one dataset or methodology at a time. For example, from the 1990s until 2002, activists living in “Cancer Alley” in Louisiana used inexpensive “bucket monitors” to collect polluted air as part of their campaign against the Shell Chemical plant in their community (Ottinger 2010). Air from the buckets was sent to labs for testing, which activists used as evidence for poor air quality. Expert regulators expressed skepticism at the use of bucket data as evidence for air quality violations, as NAAQS and other standards are for time-averaged data from pre-approved surface monitors curated by the EPA, while buckets were both unofficial and designed to capture pollution for short periods (EPA 2023; Ottinger 2010: 258-259). However, regulators were willing to investigate acute episodes captured by the buckets, and in one case discovered a pile of contaminated rags at the plant which had not been properly contained (Ottinger 2010: 263). While observations were critical in capturing the attention of regulators, who ignored complaints based on smell alone, ultimately the activists were dependent on the EPA’s methodology to track pollution back to its source (Ottinger 2010: 259). With emissions inventory data, activists can start at the other end of the problem. Inventories list the amounts of pollutants emitted from a given facility, as reported in required disclosure forms, and are relatively easy for non-experts to interpret. The EPA’s Toxics Release Inventory quantifies emissions of certain compounds from industrial facilities, like the cancerous volatile organic compounds measured by the bucket monitors; it too has long been used by activists and journalists, including the Louisiana Environmental Action Network (LEAN), to make the case that unfair health burdens fall on Black communities (Hamilton 2005: 4, 234-235). However, both inventories and surface observations are spatially isolated — points of pollution emitted or detected. What makes a tool like Air Tracker remarkable is that it combines both information types into a single mechanistically-coherent image, connected by varying meteorological fields. As I clicked through the Air Tracker interface, I found myself getting angry when I saw the same few petrochemical facilities in Houston appearing over and over in back-trajectory clouds on polluted days. Air Tracker allows users to study both acute pollution episodes, which like the bucket monitors could help detect illegal chemical releases or unintentional leaks, as well as to make long-term averages of source regions using data from expensive monitors, the sort of measurement legible to agencies like the EPA. Perhaps most crucially, because it leverages existing knowledge infrastructure already deployed in the service of Earth System science, Air Tracker costs nothing for activists to use. It embodies the potential of appropriating the synthesizing tools of Earth System science in new ways that directly feed back on the world.

Others have also suggested that the planetary knowledge produced by Earth System science has something like cybernetic potential. Paul Edwards (2017) has noted that Earth System science systems have the potential to serve as the "knowledge infrastructures of the Anthropocene" and inform sustainability strategies like emissions reductions in the logistics sector, while designer Benjamin Bratton suggested that the "planetary computer" of ESMs and Earth observing sensors have the potential to become more than a "diagnostic image" and instead might serve as "a tool for *geo*-politics in formation" (Bratton, 2015: 300-301). Although the language of "planetary computer" has been appropriated at present by Microsoft, in a world free from capital's chokehold tools like ESMs could be used to aid democratic economic planning within planetary boundaries (Vettese and Pendergrass, 2022: 127-130). Rather than relying on the planetary scenario mode of political legibility to transform ESMs into a rhetorical tool aimed at high policy, the planetary sensing mode enables actors to take targeted action now — offering, to borrow Erik Olin Wright's term, a "real utopia" prefiguring the simultaneously participatory and planetary mode of environmental governance that could be constructed by a radical movement (Wright, 2010). Prison abolitionists in Tampa may be leading a local campaign, but in their actions they operationalize global infrastructure.

In the case of the potent greenhouse gas methane, scientists are already building a unique planetary sensing apparatus directly connected to stakeholders around the world, all positioned to act on the knowledge it produces. Methane is a greenhouse gas, responsible for almost a third of the observed rise in surface temperatures since the industrial revolution (Naik et al., 2021). Methane has natural sources (wetlands, termites, geological seeps) which are overshadowed by anthropogenic sources including livestock (primarily cattle), oil and gas, coal mines, landfills, and rice (Saunois et al., 2020). Methane only stays in the atmosphere for about a decade before it is oxidized to carbon dioxide by the hydroxyl radical, but during its lifetime is far more potent than carbon dioxide on a molecule-by-molecule basis because it traps infrared light in a different part of the spectrum (Prather et al., 2012). For this reason, a rapid reduction in methane emissions will lead to a rapid response in the Earth's temperature, "bending the curve" on climate change by reducing near-term warming and buying time for deep carbon dioxide reductions.

The unique political economy of methane has made it a focus of recent UN negotiations and national policy. Much methane is emitted by a small number of "super-emitters" upstream in the production process, rather than from downstream consumers. For example, in Turkmenistan, an enormous crater has been burning continuously since 1971 after a Soviet drilling accident. The so-called "gateway to hell" is fueled by methane gushing from an underground chamber and is a dramatic example of the leaks that plague gas production (Agence France-Presse, 2022). One study in California found that emissions from single-facility point sources including manure managements sites, landfills, and oil and gas infrastructure accounted for 40% of the state's inventory, with only 10% of facilities contributing 60% of point source emissions (Duren et al., 2019). When oil and gas companies in particular leak methane to the atmosphere, they are losing saleable product; many super-emitters can be abated at no net cost even without accounting for environmental benefits (Lauvaux et al., 2022). Even the gateway to hell, now a tourist attraction, will be extinguished and exploited for its remaining fossil fuel reserves (Agence France-Presse, 2022). For this reason, even the all-carrot no-stick Inflation Reduction Act in the US will punish methane emissions with a $900/tonne tax beginning in 2024, while a tax on carbon dioxide remains beyond the pale. However, the Biden administration's tax is limited to the oil and gas sector, where industry has an existing financial incentive to catch leaks in order to burn the gas at a later date (EPA, 2024).

Methane can be measured from space. Polar orbiting satellite instruments like the TROPOspheric Monitoring Instrument (TROPOMI), developed by the European Space Agency, measure the absorption of infrared light with a spectrometer and back out the amount of methane that must be present in a column of air stretching from the surface to the instrument (Lorente et al., 2021). Such observational instruments cover the globe, offering data about places without detailed surface monitoring. However, observations of methane columns on their own do not offer the sort of political legibility necessary for climate action — they don't answer questions about where the methane came from, for example. Observations need to be linked back to emission sources, something that ESMs and their components excel at in a process called *inverse modeling*. In inverse modeling, computer models can use observed methane concentrations in the atmosphere to update emissions inventories, discovering missing or underreported sources even if the methane is detected downwind; the approach serves as a more systematic version of the back-trajectories calculated by Lin for Air Tracker (Jacob et al., 2022). Recent work uses simpler models to directly quantify emissions from a single point source, and in the case of Turkmenistan has discovered extraordinarily large emissions from oil and gas infrastructure that were not flared, which would reduce climate impacts by burning methane into less potent carbon dioxide (Varon et al., 2019).

At COP27 in 2022, the International Methane Emissions Observatory, a part of the UN Environmental Program, launched the Methane Alert and Response System (MARS), which will initially focus on detection of large point sources of methane in the oil and gas sector (UNEP, 2022). The aim of MARS is not to just detect methane leaks from space, but to notify operators who can then send out a team to repair broken equipment. MARS does not have radical politics, but it does offer a mode of political legibility that directly connects the images it produces to actors who can make changes in the world on a short timescale. It connects planetary consciousness produced by the abstracting equipment of Earth System science to the embodied and local experience of actors positioned to make change in the world. One can imagine more radical possibilities. Similar assemblages of models and sensors could be used by environmental justice groups to build a grander suite of Air Trackers, which could be used, among other purposes, to identify targets for direct action campaigns — a different kind of emergency response. The global distribution and ready availability of satellite data makes possible the construction of cheap planetary sensing workflows, built for action anywhere on Earth.

Planetary sensing mode thus not only has unique political potential to make the immediate changes necessary to avert crisis, but also to expand the epistemic community that participates in knowledge production. ESS by construction smooths out difference and obliterates history in its spectroscopic measurements and differential equations, particularly in the dominant planetary scenarios approach. IAMs especially are rooted in abstract modes of economics most suitable to mathematical modeling, such as general equilibrium analysis, and are structurally hostile to historical studies and the particularities they surface. Historians Deborah Coen and Fredrik Albritton Jonsson suggest that ESS is undergirded by a particular "geo-epistemology" based on homogenous global data and models, which assumes implicitly that environmental problems can only be addressed through international governance (Coen and Jonsson 2022: 408). This dominant geo-epistemology treats human beings as external to the Earth system, mirroring the structure of ESMs. However, the planetary sensing approach suggests that other geo-epistemologies are possible. IAMs, for example, are not designed to make tactical recommendations about targeted, local actions and are therefore useless to planetary sensing. Tools like Air Tracker or MARS are made legible not by abstract economics but by user knowledge of specific geographies and local histories, views from somewhere which are necessary for constructing a winnable campaign. Detection of pollution is only the first step in the feedback system of planetary sensing, and must be followed by a series of social-political questions: Who owns a chemical plant? Who do they answer to? Who regulates their activity? Who works in the plant and who represents them? Can they be enlisted as allies in the struggle for environmental justice?

Rather than uncritically adopting the dominant geo-epistemology encoded ESS concepts like "the Anthropocene," or, at the opposite extreme, dismissing the infrastructure of global measurement and modeling as ideologically compromised, historians and critical social scientists might find a useful path forward in the forms of appropriation suggested by planetary sensing. Coen and Jonsson cite the meaning of coal in their argument about history's place in Earth

System science. They take issue with Paul Crutzen and Eugene Stoermer's suggestion, in the 2000 paper that coined the "Anthropocene," that a golden spike marking the beginning of a new geological epoch should be placed in 1784, the year of James Watt's patent for the steam engine. Coen and Jonsson rightly point out that the emergence of a fossil economy in Britain was the product of many factors, including class struggle, and not an inevitable consequence of mechanical invention (Coen and Jonsson 2022: 415-416). The affirmation of political context they feel is currently ignored in dominant modes of ESS, including the early recognition by trade union leaders of the structural importance of coal, is indispensable to the forms of planetary sensing proposed in this essay.

If the images produced by ESMs in planetary sensing mode are primarily used for action and not for persuasion, as in planetary scenario mode, then we need a new aesthetic theory to replace Latour's immutable mobiles. The "operational image" seems appropriate. Coined by artist Harun Farocki in the early 2000s, operational images are inscriptions produced "in order to monitor a process that, as a rule, cannot be observed by the human eye," and that appear "so inconsequential that they are not stored" except in the exceptional case (Farocki, 2004: 18). Integral to the operational image is the operator, who uses the imagery to guide their actions — such as fly a plane or direct logistics networks. While the term originated in discussions of military power, media theorist Jussi Parikka suggests that it would be a mistake to always view operational images as a "kind of Enlightenment gone awry," and instead build on their "logistical capacities and systemic technological potentials of power primed for the contemporary planetary situation" of environmental crisis (Parikka, 2023: 15-16). Already ESMs and Earth observing satellites produce petabytes of maps and measurements of invisible gases. In planetary sensing mode, the "operator" of the operational image is cast — the images produced by Earth System science now might deploy technicians and repair workers to leaking pipelines, or could be queried by activists as they deliberate on a strategy to advance environmental justice.

My use of the terms "operational image" and "cybernetics" to describe the embryonic planetary sensing apparatus suggests a latent danger, as both terms emerge out of military systems and top-down hierarchies. Even the word "apparatus" echoes the term Michel Foucault uses in his analysis of power-knowledge systems (Agamben 2009, 1-3). The authoritarian hazard must be contained by prioritizing the kinds of pluralistic and anti-technocratic alliances modeled so ably by scientists like Ovienmhada. However, as a practitioner of Earth System science, in my view the greatest danger is that nothing happens at all — that AI software impotently generates millions of images of floods. To make change, we need more than just open data and transparency, which fortunately are becoming common practices in the discipline. Planetary sensing remains at best unfriendly to users and at worst requires specialized equipment, like supercomputers, to use effectively. Moreover, the observation systems which could be appropriated reflect the priorities of certain governments, which may not share the priorities of social movements; a new constellation of air quality monitoring satellites, for example, excludes Africa and South America (Kim et al., 2019). Political legibility will remain a deep problem when any technical apparatus, designed for disciplinary purposes, is used for other ends. Scientist-activist coalitions are required for the planetary sensing approach to succeed, just as ESM-IAM alliances are needed for planetary scenarios.

Conclusion

Both because of disciplinary research questions and the political economy of science funding, scientists have developed an extensive apparatus for planetary observation and modeling.[3] For decades, practitioners have felt that this apparatus has political potential and have mobilized simulations like ESMs as rhetorical tools, illustrating possible policy or technology mixes with vivid images of climate or ecological consequences. The goal of this "planetary scenario" mode of political legibility is primarily to persuade elite policymakers to introduce laws matching that of the least bad scenario for them and those they represent, and to that end practitioners position their science as an objective and neutral way to transform political questions into technical ones. While this strategy has had successes with some problems like acid rain, which can be remedied cheaply and without social transformation, in the case of climate change fossil capital is too deeply entrenched to be displaced by regulatory bodies alone — admitted obliquely by the fossil-fueled growth baked into many IAMs (Mann 2022).

An alternative strategy is for non-elite actors to mobilize tools of planetary knowledge like satellites and ESMs as they design and carry out campaigns to transform the world. Prison abolitionists have used satellite imagery to evacuate the incarcerated, environmental justice communities have deployed air quality monitors to make their invisible pollution problems legible to regulators, and a new UN initiative can detect methane leaks from space and deploy technicians in real time to repair broken equipment. The data and models which can be mobilized are global, if uneven, and offer the potential to grow geographically beyond the European and North American context, so commonly the limited geographic contexts producing ESS. A radical "planetary sensing" approach, discovered independently by a diverse cast of actors, prefigures a potential future which fuses planetary consciousness with participatory decisions and action — a future which, despite its dangers, offers a way for humanity to know and govern itself and its interchange with complex ecological systems. Such a future will be built by an assemblage of unusual coalitions, each specific at first to the needs of an individual campaign, but which have the potential to grow and merge as larger political targets enter the crosshairs. The planetary modelers have only interpreted the world, in various ways; the point is to change it.

Notes

1. There is a vast literature on the entrenched political economy of fossil fuels, but for two representative books see Mitchell (2011) and Malm (2016).
2. The term fossil capital, popularized by Andreas Malm, is originally from Elmar Altvater (2007).
3. For more on the role of funding in the construction of Earth System Science, see Jenifer Barton (2023).

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