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A Critique of Mapping Carbon as Currency, and a Call for Atmospheric Realism

In this article, I argue that changes in carbon dioxide (CO_2) mapping did not mirror the trajectory of how other atmospheric gases have been mapped, in part because of the invention of national carbon inventories and the subsequent re-calibration of what CO_2 means in our minds—molecule or accounting unit. Unlike other trends of mapping natural phenomena, the growth of the choropleth[1] style [see **Fig. 1**] of mapping greenhouse gas (GHG) emissions was not due to an improvement in technology, or our ability to measure CO_2 more accurately. Why does it matter if politics was the force that brought about this mapping change? This cartographic style may have had the unintended effects of over-promoting state-level climate change solutions and clouding how CO_2 is conceived of by non-scientists especially. I trace the history of gas mapping in the past and present, reflect on the effects of major policy shifts affecting CO_2 monitoring, and make a guess about the future.

[1] A choropleth map (from Greek χῶρος "area/region" and πλῆθος "multitude") is one that shades pre-defined areas such as counties, congressional districts, or continents according to some statistical variable of interest. "Choropleth Map - Wikipedia." Accessed December 16, 2019. https://en.wikipedia.org/wiki/Choropleth_map.

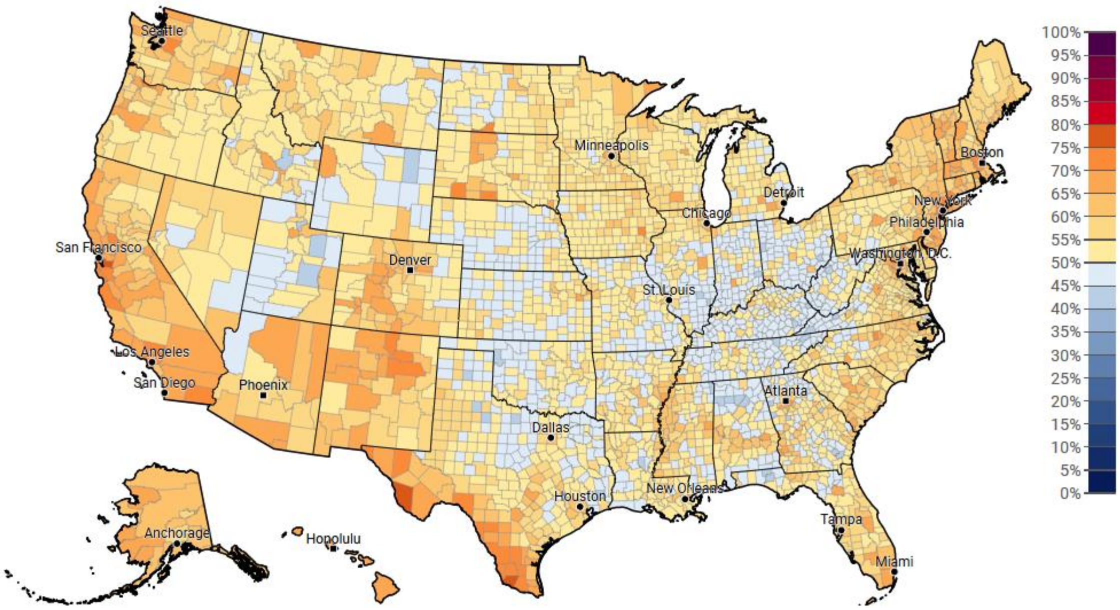

Figure 1: Example of a choropleth map. Estimated percent of adults in each county who are worried about global warming according to 2019 surveys. Source: Marlon, Jennifer, Peter Howe, Matto Mildenberger, Anthony Leiserowitz, and Xinran Wang. "Yale Climate Opinion Maps 2019." *Yale Program on Climate Change Communication* (blog), September 17, 2019. https://climatecommunication.yale.edu/visualizations-data/ycom-us/.

1) Technology historically drives the mapping of the invisible

Traditionally, the natural sciences have created "maps" of gases in geographic space by interpolating between point measurements of that gas, whether collected on the ground or in the air. Many concentrations of trace gases,[2] like carbon monoxide (CO), are quantified by capturing an air sample in a flask and reacting it with a chemical solution. Dobson spectrophotometers, a contraption about the size of a hot dog cart, are wheeled into place to measure the concentration of ozone molecules in the column of air above it. Once point measurements are acquired, the act of interpolation guesses at the values between the known points. Isopleth lines, like contours on a topographic map,

[2] A trace gas is one of many that make up the minority of the Earth's atmospheric composition, i.e., all gases other than oxygen, nitrogen, and argon.

are used to visually suggest the highs and lows of gas concentrations in the landscape.

As technology advanced and the world’s space programs progressed,[3] scientists around the globe began designing instruments specifically designed to “photograph” gases in the atmosphere. CO could be imaged from both the Measurement of Air Pollution from Satellites (MAPS) instrument aboard the *Challenger* [**Fig. 2**] and NASA’s *Terra* satellite carrying the Measurement of Pollutants in the Troposphere (MOPITT) instrument.[4] Values that used to be estimated via on-the-ground Dobson instruments could now be measured from above with the Total Ozone Mapping Spectrometer (TOMS) mounted on the Nimbus 7 [**Fig. 3**]. After the launch of TOMS, continental-scale maps of ozone were common in high-impact academic journals as well as periodicals, and these images played a major role in the visualization of (and policy response to) the Antarctic “ozone hole.”

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[3] The 1972 launch of the joint USGS-NASA satellite Landsat likely mobilized greater interest in monitoring the Earth system via photographs and Earth-observing satellites.

[4] Voiland, Adam. “Fourteen Years of Carbon Monoxide from MOPITT.” Climate Change: Vital Signs of the Planet. Accessed December 17, 2019. https://climate.nasa.gov/news/2291/fourteen-years-of-carbon-monoxide-from-mopitt.

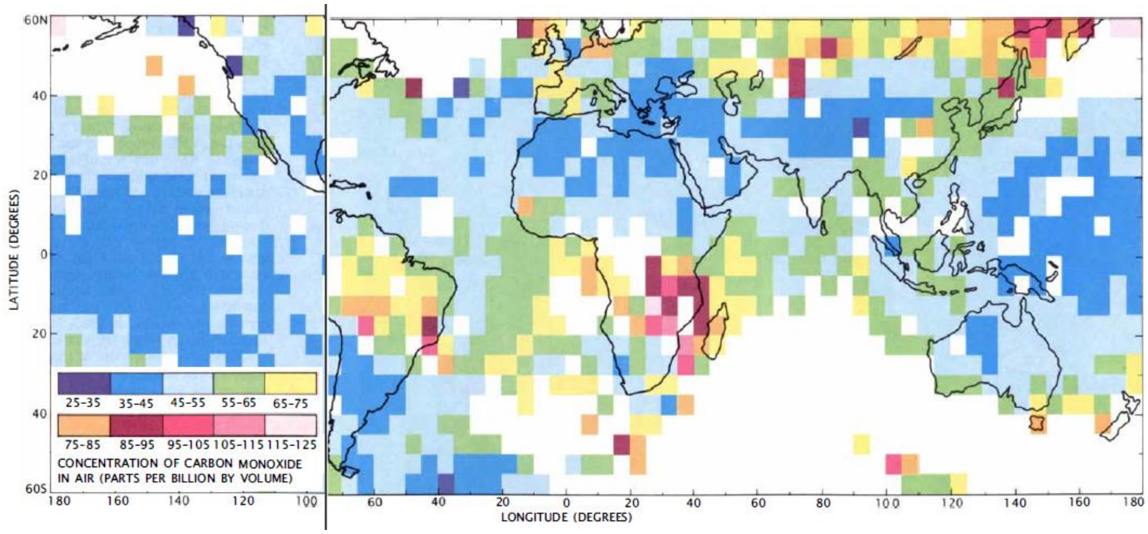

Figure 2: CO data collected from the *Challenger* satellite in October 1984. The instrument generates one CO value per "square" of 5 degrees latitude and longitude. Revised from Newell, Reginald E., Henry G. Reichle, and Wolfgang Seiler. "Carbon Monoxide and the Burning Earth." *Scientific American* 261, no. 4 (October 1989): 82–88. https://doi.org/10.1038/scientificamerican1089-82.

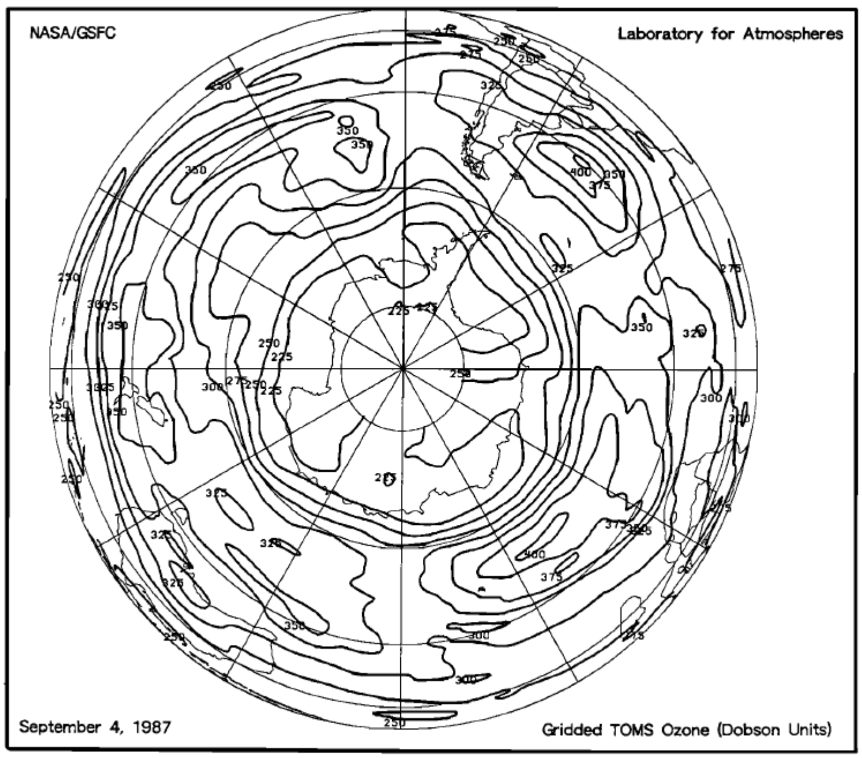

Figure 3: TOMS readings from the southern hemisphere on September 4, 1987, with isopleths drawn in thick lines. Note the Antarctic continent drawn with thin lines in the center of the map. Source: McKenna, D. S., R. L. Jones, J. Austin, E. V. Browell, M. P. McCormick, A. J. Krueger, and A. F. Tuck. "Diagnostic Studies of the Antarctic Vortex during the 1987 Airborne Antarctic Ozone Experiment: Ozone Miniholes." *Journal of Geophysical Research: Atmospheres*, August 30, 1989, 11641–68. https://doi.org/10.1029/JD094iD09p11641@10.1002/(ISSN)2169-8996.AAOE1.

CO_2 resists spatialization

But where was CO_2? A combination of suitable technology and a wave of environmentalism in the Western world in the 1970s furthered the atmospheric sciences as a fecund field of study. However, CO_2 would not become the focus of direct atmospheric observation for some time. In fact, prior to the 1990s, maps depicting CO_2 in any form are a bit elusive to find.

Most publications on CO_2 under climate-related auspices stuck with line charts. One famous example is the Keeling Curve, the long timeseries dataset of CO_2 concentrations collected by Mauna Loa Observatory in Hawai'i. The Observatory applies a near-constant suite of corrections and calibrations to ensure the *lack* of spatial bias in the instrument's data, instead aiming to represent the atmosphere covering most of North America.[5] When CO_2 was in fact depicted spatially, it was often not mapped in its gaseous form—for instance, in maps depicting CO_2 sources arising from volcanic features [**Fig. 4**]. And when atmospheric CO_2 observations were mapped, they followed the methods of isopleth lines. These figures [like **Fig. 5**] resided primarily in academic publications of the time.

[5] Monroe, Rob. "The History of the Keeling Curve." The Keeling Curve, April 3, 2013. https://scripps.ucsd.edu/programs/keelingcurve/2013/04/03/the-history-of-the-keeling-curve/.

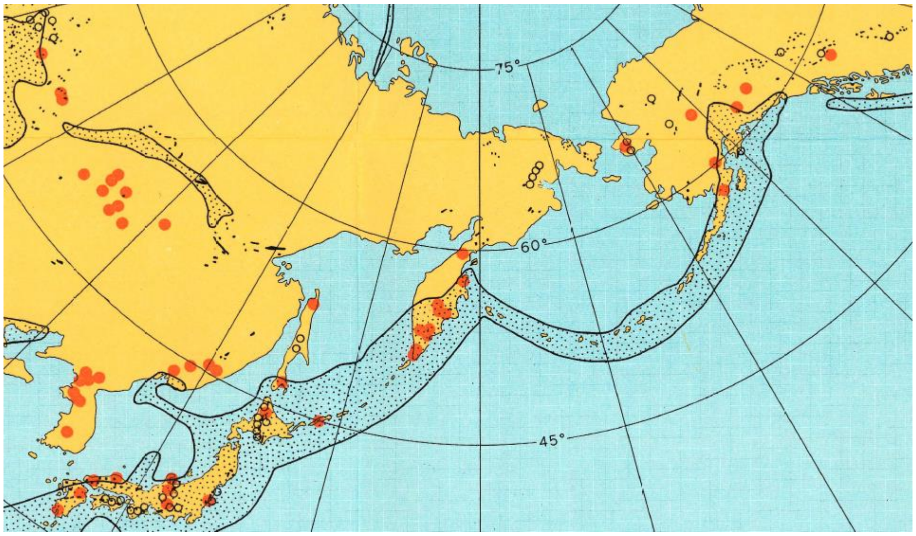

Figure 4: Detail along the northern section of the volcanic “Ring of Fire” showing point sources of CO_2 discharge (red dots) and zones of seismic activity (speckled polygons). From Barnes, Ivan, William Porter Irwin, and Donald Edward White. “Global Distribution of Carbon Dioxide Discharges, and Major Zones of Seismicity.” Water-Resources Investigations Report 78-39. US Geological Survey, Water Resources Division, 1978. https://doi.org/10.3133/wri7839.

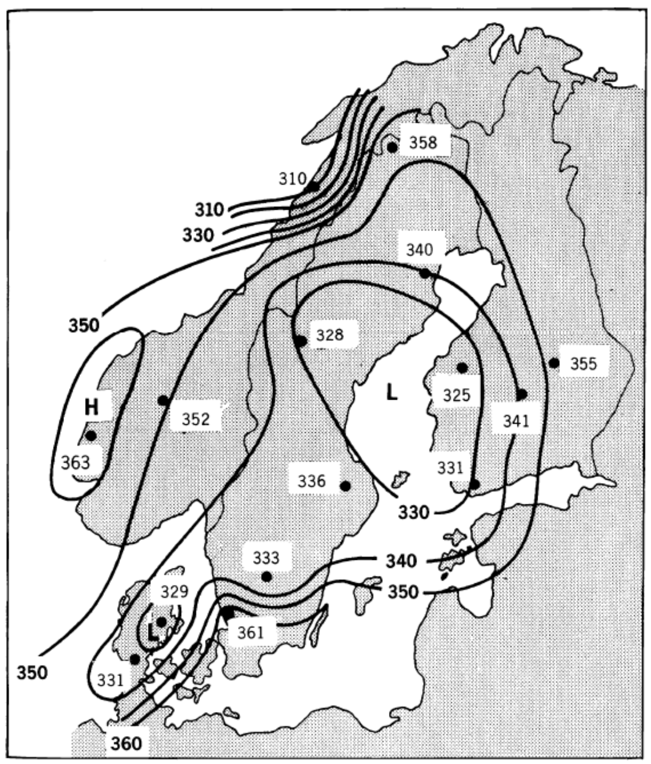

Figure 5: CO_2 concentrations (in ppm) in Scandinavia on Feb 20, 1955. Labeled points represent values from chemical flask measurements, and isopleth lines attempt to interpolate the values between the measurements. From Keeling, Charles D. “The Influence of Mauna Loa Observatory on the Development of Atmospheric CO2 Research.” *In Mauna Loa Observatory. A 20th Anniversary Report (National Oceanic and Atmospheric Administration Special Report)*, 1978, 36–54.

CO_2 mapping and visualization may not have been a top priority for scientists at this time for a few reasons. For one, other scientific questions seemed more pressing. In the 1950s and decades afterwards, the scientific workforces of nations implicated in WWII were driven in part by a fear of nuclear fallout. Both U.S. and Soviet science focused on the meteorology of upper-atmosphere gas transport and wind. During the International Geophysical Year in 1957-1958 scientists globally turned their studies to solar disturbances in the upper atmosphere, auroras in the ionosphere, and radioactivity in the air and sea.[6] Second, some greenhouse gases pose direct risks to human health, but CO_2 is not one of them per se. Ground-level ozone can cause painful breathing or aggravate lung disease, and ambient CO can reduce our blood's ability to transport oxygen and reduce organ function. CO_2 levels up to 5,000ppm can be reached in stuffy rooms and usually cause only headaches and sleepiness.[7] (Today, outdoor air CO_2 concentrations hover around 410ppm.) Lastly, when it comes to climate change, scientists were re-introducing the theory that the earth's climate system was susceptible to changes in CO_2,[8] but the dramatic magnitude of its implications had not been realized yet.

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[6] Edwards, P. N. "Making Data Global." In *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. MIT Press, 2010.

[7] US EPA, OAR. "Health Effects of Ozone in the General Population." Data and Tools. US EPA, March 21, 2016. https://www.epa.gov/ozone-pollution-and-your-patients-health/health-effects-ozone-general-population; US EPA, OAR. "Carbon Monoxide's Impact on Indoor Air Quality." Overviews and Factsheets. US EPA, July 31, 2014. https://www.epa.gov/indoor-air-quality-iaq/carbon-monoxides-impact-indoor-air-quality; Wisconsin Department of Health Services. "Carbon Dioxide," November 20, 2018. https://www.dhs.wisconsin.gov/chemical/carbondioxide.htm.

[8] In 1956 scientist Gilbert Plass brought this old theory back into the limelight, drawing on an 1861 publication by John Tyndall. See Plass, Gilbert N. "The Carbon Dioxide Theory of Climatic Change." *Tellus* 8, no. 2 (1956): 140–54; Tyndall, John. "On the Absorption and Radiation of Heat by Gases and Vapours, and on the Physical Connexion of Radiation, Absorption, and Conduction." *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 22, no. 146 (1861): 169–94.

Implicit in all of this is that the mapping of gases, including CO_2, has for most of history been a task limited to the professional scientist. Though a meteorologist or atmospheric scientist would probably call images like these "data" rather than "maps," they were the only people in possession of the highly-specialized tools and knowledge to spatialize these invisible substances and quantify their locations and amounts with reasonable certainty.

The techniques of mapping atmospheric reality

All the gas visualizations touched upon thus far present (nay, argue) a specific paradigm of what the gas being depicted *is*—what I will call an "atmospheric reality." The way that these substances were visualized supported and reinforced the notion that they were not confined by political boundaries or even by land masses.

Imagine a cartographer designing a map of a territory. They might consider some basic design questions depending on what they wanted to represent: Do I include hachure marks to indicate terrain, or hill-shading, or show no terrain at all? Do I color the landscape according to its land cover type (green vegetation, grey urban areas, etc.)? Do I add boundaries of cities or countries? All of these questions could be lumped under the larger question of: How realistic do I want (or need) to make this map to convey my message successfully? But when tasked with mapping an invisible, transient phenomenon, one must answer slightly different questions. Shall I identify the places where CO_2 rises from the Earth's surface? Shall I identify where these molecules are in a section of the atmosphere? Shall I depict the raw amount of said molecules in a snapshot of time, the average amount over a period of time, or the amount that molecule count deviates from a baseline value?

The visual techniques of isopleths and color blocking unbound by national borders are common among maps of natural phenomena, like temperature and precipitation. Air pressure (measured in millibars) has been mapped with contour lines for so long that the specific term "isobars" is synonymous with the lines demarcating it. In all these presentations, there seems to be no question that these are physical qualities present in the troposphere. And the fashion in which CO_2 was mapped from the 1950s through the 1980s followed these atmospheric reality guidelines, too. CO_2 was not only being mapped unbounded by states; it was mapped in a way that visually resembled other gases and atmospheric phenomena, asserting that CO_2 concentration values definitely belonged in the category of "based upon measurements on the physical Earth." However, this was about to change.

2) Politics re-calibrate our image of CO_2

The Intergovernmental Panel on Climate Change (IPCC) is a United Nations (UN) body responsible for reviewing the state of peer-reviewed climate science. Hundreds of participating scientists representing their home nations synthesize thousands of peer-reviewed publications to produce routine Assessment Reports that inform decision-making not only of UN officials but countless leaders around the world. The IPCC's First Assessment Report was released in 1990, in which it called for the development of international agreements and specific goals to reduce global emissions.[9] As a direct response, parties of the UN drafted the United Nations Framework Convention on Climate Change (UNFCCC), an international treaty adopted by the UN parties in 1992.

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[9] Intergovernmental Panel on Climate Change. First Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 1990.

The treaty was the first document of its kind to not only suggest that nations reduce their GHG emissions, but to present evidence-backed, non-binding emission limits. Regardless of whether nations fulfilled these idealized targets, the UNFCCC required that member states begin submitting national inventories of their emissions to the UN on an annual basis. Even if nations would not be formally penalized for surpassing a recommended emissions limit, they were now obligated to institute methods for counting their GHG emissions into their federal regulations. The UNFCCC didn't leave nations to fend for themselves in this auditing effort—authors behind the treaty devised detailed manuals instructing nations on exactly how to tally GHG sources and sinks[10] within their national boundaries.

A second treaty would hasten the shift in how countries and individuals thought about CO_2. By the time the Second IPCC Assessment Report was released in 1995, scientific literature increasingly agreed that anthropogenic carbon dioxide was contributing to global warming. In December 1997 over 150 nations[11] signed the Kyoto Protocol, another international treaty with one critical difference from UNFCCC: signatory nations were *legally committing* to reducing their GHG emissions by a specified amount before 2012, as tallied following the UNFCCC methods. In a sense, the Kyoto Protocol provides the teeth to the idealistic goals of the UNFCCC. [The Kyoto-mandated inventories are made publicly available; see **Fig. 6** for a preview of the online interface.]

Suddenly, carbon was being described as an accounting unit across international boundaries. This stands in contrast to the kind of highly localized,

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[10] In an emissions context, a sink is an entity that sequesters GHGs from the air. For example, a forest absorbs CO_2 through the process of photosynthesis.
[11] As of 2019, 192 nations are parties to the Kyoto Protocol. Many nations—mostly those that were considered "developing countries" at the time Kyoto was signed, do not officially have binding targets, though many voluntarily follow-through on reduction efforts.

location-specific CO_2 "quantifying" happening in experiments like **Fig. 5**. Nations wouldn't think to compare their levels of ambient CO_2 to another country's because the values were highly dependent on time of day, local topography and wind patterns, and an argument that this concentration was the result of any national policy would be a loose one. This shift in how CO_2 was conceived of was not a bad thing, per se; these methods for GHG emission calculation were developed by subject experts over many years, and decisions of what and how to count were not made lightly. However, the shift did carry implications for how carbon would be visually depicted, and subsequently, upon narratives of responsibility.

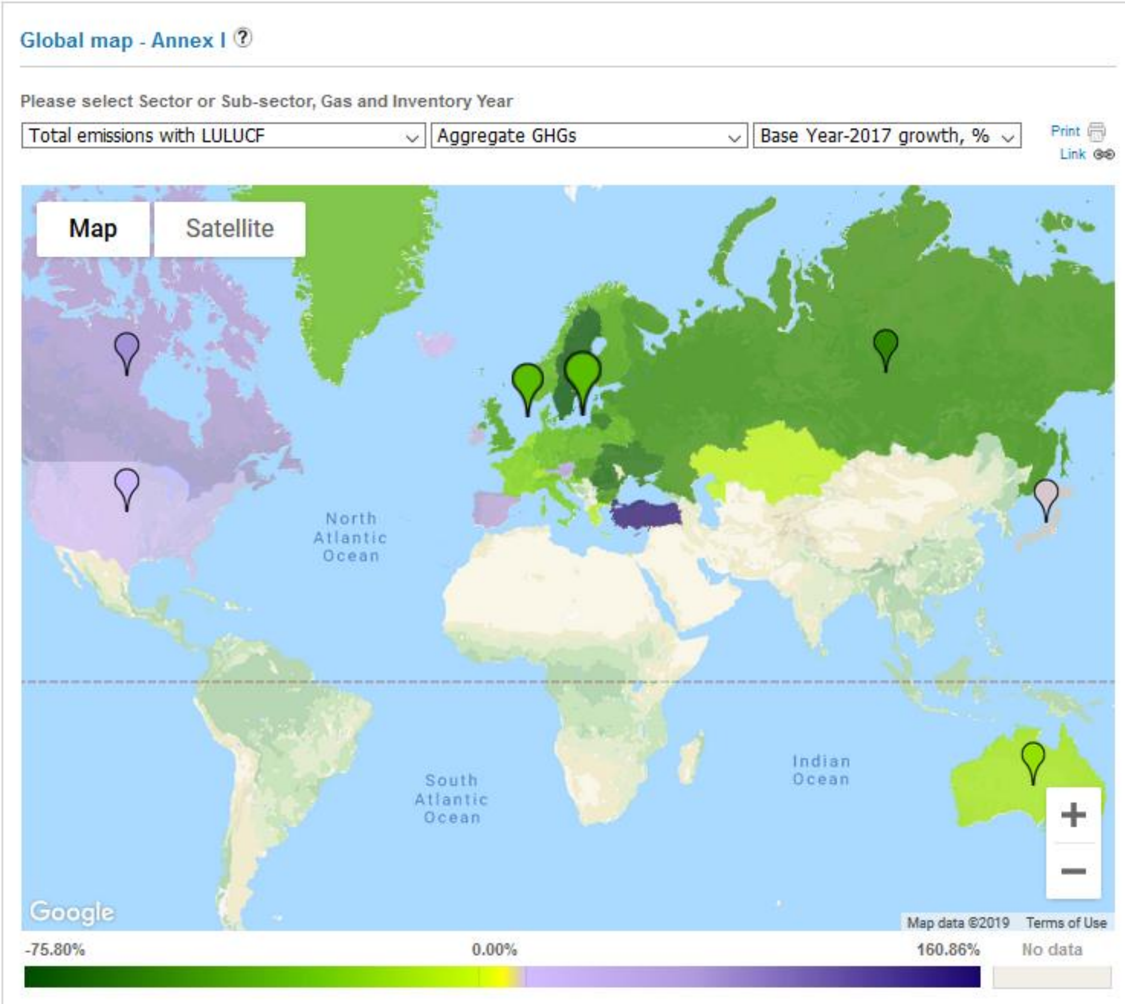

Figure 6: The UNFCCC map interface for visualizing Kyoto GHG emission inventory totals as submitted to the UN. The mapping function is only available for Annex I countries (non-Annex countries are listed in tables only) but allows the user to shade countries based on specific GHGs like methane and nitrous oxide. From "Greenhouse Gas Inventory Data - Global Map - Annex I." Accessed December 17, 2019. https://di.unfccc.int/global_map.

State solutions and the currency of CO_2

The Kyoto Protocol governs the emission and reduction of not one but six different types of GHGs, each with a different "global warming potential" or strength exerted upon the climate system. For example, one pound of methane—another GHG governed by Kyoto—causes the same amount of atmospheric warming that 25 pounds of CO_2 would; therefore, one pound of methane would be counted in an inventory as 25 pounds of "carbon dioxide equivalent," or

CO_2e. Suddenly, CO_2 molecules in the atmosphere are no longer the entity being measured. Nations no longer rely on a top-down method (literally) to measure CO_2 in the atmosphere directly. Rather, parties to Kyoto conduct a bottom-up audit of tabulating how much coal their power plants are burning, how much electricity is used for heating their buildings, and how much exhaust their cars are emitting. Akin to global maps of gross domestic product (GDP) being converted into US dollars for legibility to American audiences, GHG emissions are converted into the commensurable unit of CO_2e to compare nation-states apples-to-apples. One could argue that treating CO_2 as a currency unit wasn't a novel creation by the UNFCCC and Kyoto, for the term "CO_2 equivalent" existed prior to 1992.[12] However, the term does not appear regularly in policy documents, let alone the public discourse, until at least the release of the IPCC's First Assessment Report; then, the term's prevalence swiftly began to change.

The Kyoto Protocol outlines state-level and market-based solutions to climate change. The document specifies three "flexible mechanisms," prescribed behaviors nations can take part in to reduce their national emissions and reach targets. The fundamental basis for these mechanisms is the creation of a carbon marketplace: for example, a nation can spend money on a carbon-reduction initiative in another country and count that as a CO_2 reduction within their borders. The scheme relies on the principle that as long as emissions are reduced somewhere on Earth, the entire atmosphere benefits;[13] i.e., carbon trading is a

[12] I have tried extensively, though not exhaustively, to find the earliest mention of CO_2e in context in published literature. The earliest mention I've found comes from a textbook published in 1980, though this is likely not the origin of the term: "When comparing the CO_2 equivalents, the varying lifetimes of individual compounds in the atmosphere must be taken into account." Page 119, Anliker, Rudolf, G. C. Butler, E. A. Clarke, U. Förstner, W. Funke, C. Hyslop, G. Kaiser, et al. *Anthropogenic Compounds*. Softcover reprint of the original 1st ed. 1980 edition. Vol. 3. The Handbook of Environmental Chemistry. Berlin: Springer, 2013.

[13] "Mechanisms under the Kyoto Protocol | UNFCCC." Accessed December 16, 2019. https://unfccc.int/process/the-kyoto-protocol/mechanisms.

zero-sum game. The Protocol sets the guidelines for these markets on the national level—which makes sense, since the document is an international treaty to which nations had to agree. While it does not preclude the development of sub-national carbon markets or other solutions, it does not address them.

The public face of the choropleth

I argue that choropleth emission maps reinforce the legitimacy and authority of state-level interventions on climate change. After the ratification of UNFCCC and Kyoto, global-scale maps of CO_2 sans-borders *could* prove useful to meteorologists, but these maps were no longer the most effective aid to governments and businesses responsible for tracking their emissions. The natural phenomenon of CO_2 became a lot more important when quantified within the boundary of a state.

And indeed, these maps *should* be read as arguments about intervention. Climate scientists were not unaware of the power of visual messages. In the IPCC's Third Assessment Report section, a subsection entitled "Discourse and Symbolism" emphasizes that "governments, along with the business community and NGOs [non-governmental organizations], continue to have a substantial presence in the media and they all contribute to the shaping of the public discourse on climate change." Visual depictions of GHG emissions in the media play a large role in what "ideas, arguments, and values are transferred from the public to the private sphere" and which ones are ultimately "integrated into individuals' consciousness and identity."[14] The choropleth format wasn't the only way one could map CO_2 in the 1990s, yet it is the data visualization that

[14] Intergovernmental Panel on Climate Change Working Group III. *Climate Change 2001: Mitigation: Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, 2001, pages 369-370.

became most common in the popular media. Interestingly, IPCC's Assessment Reports—which have evolved responsively with climate science and policy concerns over time—are not where choropleth maps of CO_2 emissions appear. These visualizations find their home in news features [**Fig. 7**], public-facing accountability institutions [**Fig. 8**], and interactive blog posts [**Fig. 9**].

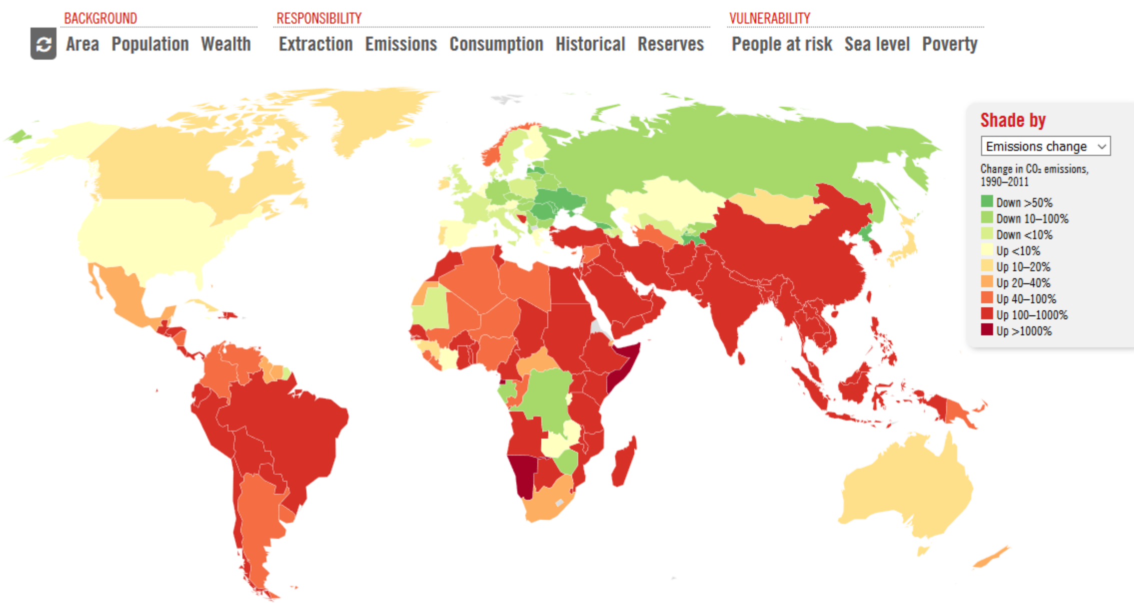

Figure 7: This interface, designed by a London digital journalism studio, allows the user to not only shade nations based on various emissions variables but also warp the shape of the countries based on the factors in the top banner (population, resource extraction, poverty level, and more). From Kiln.it. "Carbon Map – Which Countries Are Responsible for Climate Change?" *The Guardian*, September 23, 2014. Accessed December 17, 2019. https://www.theguardian.com/environment/ng-interactive/2014/sep/23/carbon-map-which-countries-are-responsible-for-climate-change.

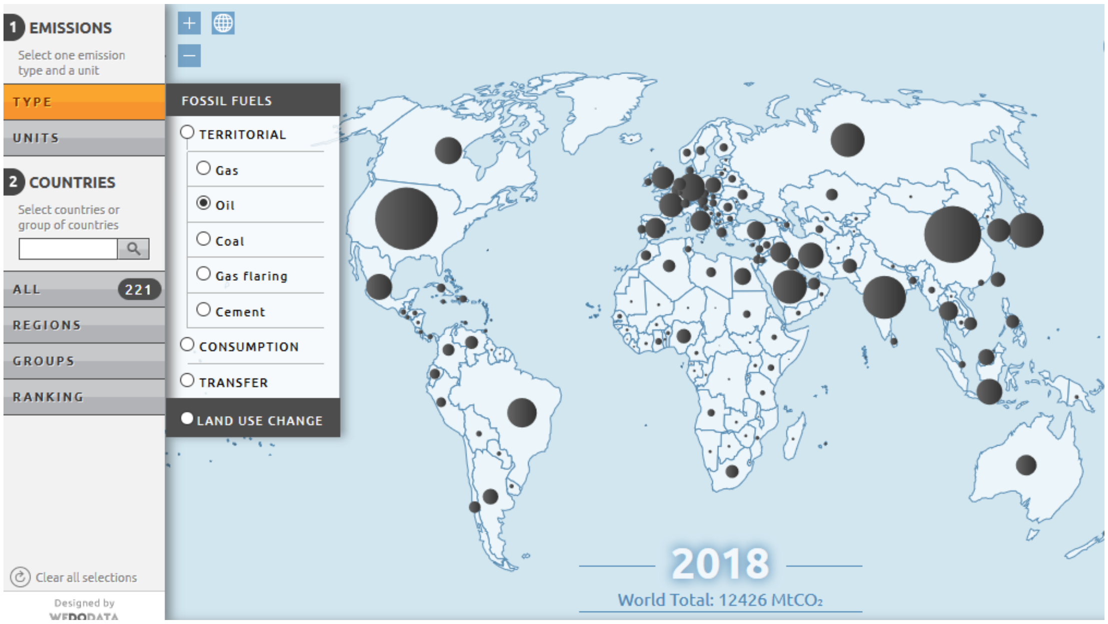

Figure 8: The Global Carbon Atlas allows the viewer to alter the type of fossil fuels depicted by the sized circles, in addition to normalizing emissions by GDP and per capita. From Global Carbon Project. "CO2 Emissions." Global Carbon Atlas. Accessed November 17, 2019. http://www.globalcarbonatlas.org/en/CO2-emissions.

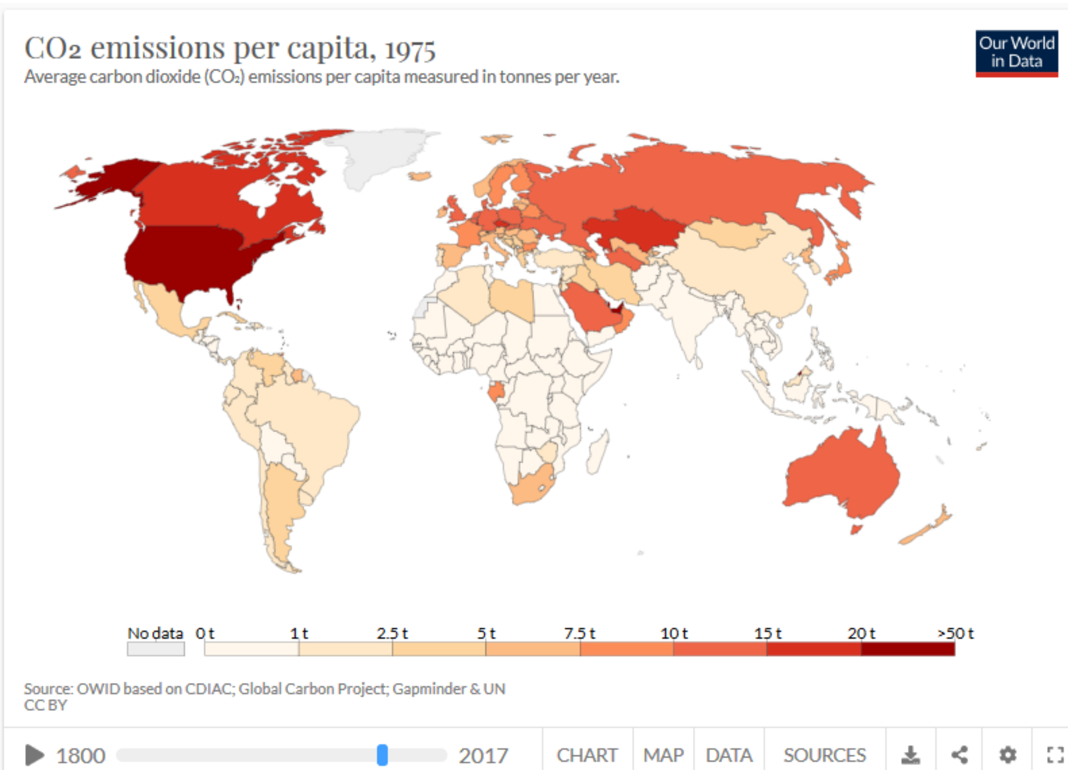

Figure 9: This interface uses not just contemporary CO_2 emissions (incidentally cited from the Global Carbon Project [see **Fig. 8**]) but historical estimates, allowing the viewer to slide the map back to year 1800. From Ritchie, Hannah, and Max Roser. "CO_2 and Greenhouse Gas Emissions." *Our World in Data*, May 11, 2017. Accessed November 4, 2019. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions.

3) Choropleth downsides & atmospheric reality

So what if the choropleth map representation of CO_2 emissions enjoys popularity in the public sphere? While we shouldn't be so critical of the choropleth as to avoid it altogether, the effects of its prevalence should be examined more closely. Clearly, a choropleth emissions map has a different goal and message in mind than one aiming to display "atmospheric reality;" each graphic is better suited for some subset of applications. However, map viewers—whether an influential decision-maker or not—must be aware of the limitations of the choropleth's representative abilities. In many mediums geared more towards non-scientists and the general public, the use of the choropleth has become prevalent enough to sometimes seem like a "default" method of representing CO_2 spatially. This default mode could lead to a misinterpretation of the science behind GHG emissions and the location of responsible parties.

Limits as data visualizations

A choropleth emissions map is essentially a visualization of a table of numbers, one for each state. And thus, when the table is converted to a graphic, some information can get lost in translation. Decisions on where to set color breaks along a number line can group together countries in ways that tell different stories and give different regional "pictures" of emissions.[15] Quantitative measures of data accuracy or the robustness of the GHG inventory method used is not immediately obvious. Digital scholars have already implored that digital map data graphics "should always be accompanied by a warning to be wary of reading the artifactual features of the graphic as if they are an unmediated

[15] Monmonier, Mark. "Data Maps: Making Nonsense of the Census." In *How to Lie with Maps*, 2nd ed. University of Chicago Press, 1996.

presentation."[16] However, too often, the viewer cannot make a quick judgment as to how much authority or quality to afford this map unless he looks at the data citations or methodologies written in the work's appendices (if there is one). In addition to the limits choropleths face as static visualizations, many of these "databases" are presented through online interfaces, which lose their explanatory, narrative power as the user is often left to aimlessly explore.[17]

Blame & responsibility: shown or obscured?

The choropleth design is naïve to the data it depicts. It can, and often does, depict values that are not caused by the political area being symbolized. Yet, the choropleth seems to assert that the nation is to blame—moreover, that the homogenous, monolithic area of the entire nation is equally to blame for that depicted value. Our current methods of carbon accounting subtly back the concept that all CO_2 is being produced and/or reduced by people. By extension, the *responsibility* for reducing those emissions must lie with people as well. In this case, I use *blame* to mean "the person culpable for the GHG emission" and *responsibility* to mean "the person whose duty it is to change their future behavior and/or amend the damage they have caused."

There are so many reasons why a country's colored value in the choropleth may differ from another country, reasons that are not due to the total amount of CO_2 molecules arising from that nation. The choropleth smooths over the complex tangle of these reasons which, to be fair, would perhaps be illegible if we tried to depict them all at once. Some countries count the release of GHGs

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[16] Drucker, Johanna. "Graphical Approaches to the Digital Humanities," in Susan Schreibman, Ray Siemens, and John Unsworth, eds., *A New Companion to Digital Humanities* (Wiley, 2016), page 239.

[17] Hayles, N. Katherine. "Narrative and Database: Digital Media as Forms." *In How We Think: Digital Media and Contemporary Technogenesis.* University of Chicago Press, 2012.

from forest fires in their annual emissions inventory; some do not.[18] When CO_2 emissions are tallied based on CO_2e units that can be bought and traded, a wealthier country could appear with smaller total CO_2 emissions because they spent money on an emission-reduction project in a country on the other side of the world.

In a choropleth emissions map, the primary unit of analysis besides the amount of CO_2e is the bounded nation-state. And because people drew the boundaries, the map rhetorically implies that the people within the boundaries are in some way involved in the emission process. In a representation where CO_2 values can quickly and easily be scaled by population count or GDP, the gas becomes inextricably bound up in economics or humans even more quickly. Choropleth emission maps carry a tendency to not only erase and fail to visualize non-human contributors to CO_2 emissions—they also allow for the glossing-over of non-human-centric climate solutions in policy or public discourse.

The paradigm shift of treating CO_2 as an accounting unit isn't inherently bad. After all, the impetus for carbon inventories has led to quantifiably decreased CO_2 emissions all over the world, plus a useful lexicon that politicians can actively engage with re: our changing climate. However, with the codifying of the UNFCCC method for tallying CO_2 emissions, we also in a sense "codified" the government's and public's way of seeing and assessing responsibility for these emissions.

[18] Jones, Ryan Patrick. "B.C. Forests Emitting Huge Amount of 'hidden' Carbon: Report." CBC, January 28, 2019. https://www.cbc.ca/news/canada/british-columbia/sierra-club-report-forest-carbon-emissions-1.4995191.

Climate change solutions concealed by national accounting

Dissecting the responsibility for emissions suggested by maps invites the question: Does placing too much visual emphasis on national actors, as in a choropleth, ignore certain insidious contributors to climate change? An emphasis on national actors as both responsible emitters and problem-solvers obscures two critical sub-national (or in some cases inter-national) actors: urban areas and private companies. According to an analysis conducted by the non-profit CDP Worldwide (formerly known as the Carbon Disclosure Project), 100 active fossil fuel producers are linked to 71% of industrial greenhouse gas emissions since 1988.[19] And it’s not just fossil fuel companies: Online shopping giant Amazon emitted 44.4 million metric tons of CO_2e in 2018, approximately the same amount emitted by the country of Norway; Walmart emitted even more.[20]

Scholars have estimated that cities are responsible for up to 80% of annual greenhouse gas emissions.[21] What’s more, some of the world’s developed areas bleed across provincial or national boundaries which people, business, or transit may move freely and frequently between.[22] If some of Earth’s largest source areas

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[19] Griffin, Paul. “The Carbon Majors Database - CDP Carbon Majors Report 2017.” CDP Worldwide and Climate Accountability Institute, July 2017. https://www.cdp.net/en/articles/media/new-report-shows-just-100-companies-are-source-of-over-70-of-emissions.

[20] “Amazon’s Emissions Bigger Than Some Rivals, Trail Walmart.” Bloomberg.Com, September 20, 2019. https://www.bloomberg.com/news/articles/2019-09-20/amazon-s-emissions-bigger-than-some-rivals-trail-walmart; Global Carbon Project. “CO2 Emissions.” Global Carbon Atlas. Accessed November 17, 2019. http://www.globalcarbonatlas.org/en/CO2-emissions.

[21] Rosenzweig, Cynthia, William Solecki, Stephen A. Hammer, and Shagun Mehrotra. “Cities Lead the Way in Climate–Change Action.” *Nature* 467, no. 7318 (October 2010): 909–11. https://doi.org/10.1038/467909a; Satterthwaite, David. “Cities’ Contribution to Global Warming: Notes on the Allocation of Greenhouse Gas Emissions.” *Environment and Urbanization* 20, no. 2 (October 1, 2008): 539–49. https://doi.org/10.1177/0956247808096127.

[22] Take, for example, the Buffalo NY-Niagara Falls ON metro area; the developed area of Luxembourg bleeding into France, Germany, and Belgium; and the contiguous stretch of development spilling from Singapore into Malaysia and Indonesia.

of GHG emissions fall under different sets of house rules, are national or even provincial-scale maps the best way of identifying areas in which policies should be changed? When "developed land" is not contiguous with a city's legal municipal boundary, novel methods must be employed to define the true "urban area of interest."[23]

4) Satellites, a shift in the carbon paradigm?

Since the Kyoto Protocol was signed, new technologies for measuring CO_2 have emerged. The clumsily-named but ground-breaking SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY (SCIAMACHY) was the first major satellite to measure concentrations and distributions of CO_2 and other GHGs from space [**Fig. 10**], collecting data from 2002 to 2012. The Orbiting Carbon Observatory 2 (OCO-2) was launched in 2014, another instrument designed to measure CO_2 directly and with greatly improved spatial resolution compared to SCIAMACHY [**Fig. 11**]. Both SCIAMACHY and OCO-2 record the concentration of CO_2 molecules in a column of atmosphere beneath the satellite as it moves in orbit, in the same way the TOMS instrument peered at ozone in the column directly beneath the satellite. When the first valid OCO-2 data sets were released as images by NASA and JPL, scientists lauded the potential of these fine-grained observations.

[23] This study created an innovative algorithm for redrawing "urban area" polygons based on satellite images to quantify urban heat anomalies: Chakraborty, T., and X. Lee. "A Simplified Urban-Extent Algorithm to Characterize Surface Urban Heat Islands on a Global Scale and Examine Vegetation Control on Their Spatiotemporal Variability." *International Journal of Applied Earth Observation and Geoinformation* 74 (February 1, 2019): 269–80. https://doi.org/10.1016/j.jag.2018.09.015.

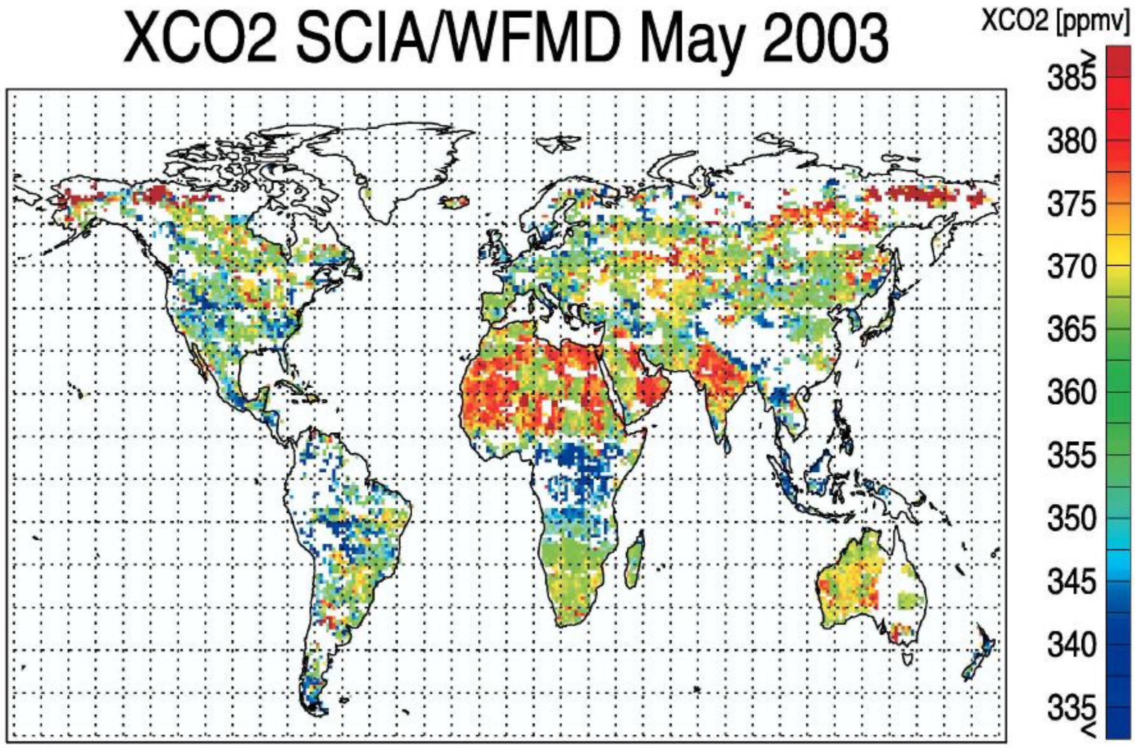

Figure 10: CO_2 concentrations acquired by SCIAMACHY in May 2003. All cloud-free measurements over land have been averaged and binned into 60 x 30 km grid squares. Source: Buchwitz, M., R. de Beek, S. Noël, J. P. Burrows, H. Bovensmann, H. Bremer, P. Bergamaschi, S. Körner, and M. Heimann. "Carbon Monoxide, Methane and Carbon Dioxide Columns Retrieved from SCIAMACHY by WFM-DOAS: Year 2003 Initial Data Set." *Atmospheric Chemistry and Physics* 5, no. 12 (2005): 3313–3329.

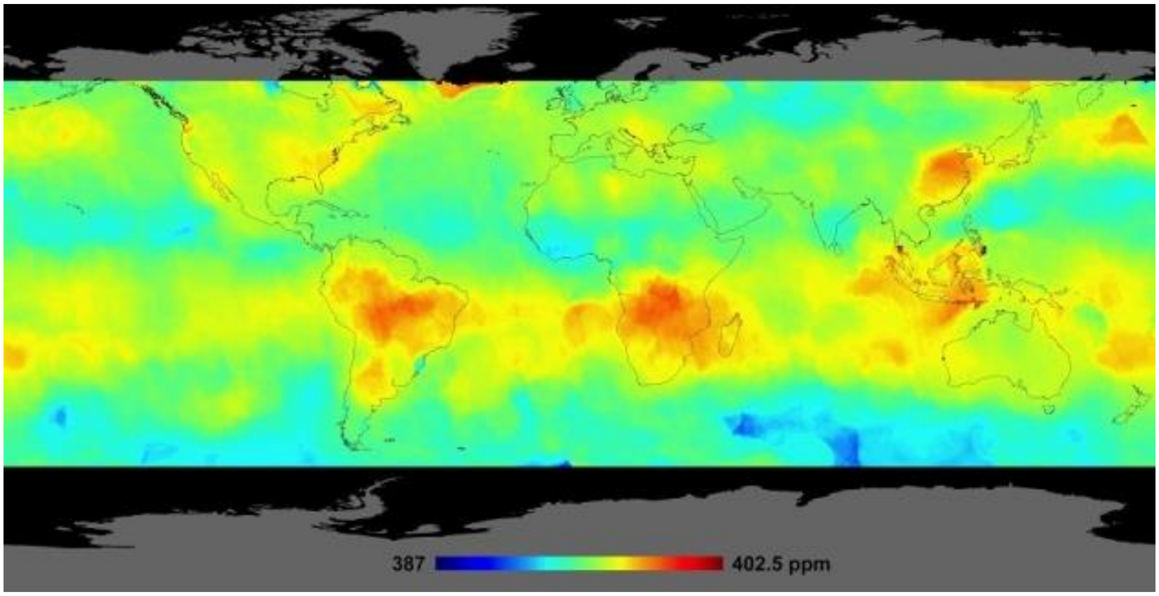

Figure 11: Averaged CO_2 concentrations from OCO-2 satellite measurements between October 1 and November 11, 2014. Image credit to NASA/JPL-Caltech, and featured in Monastersky, Richard. "Satellite Maps Global Carbon Dioxide Levels." *Nature News*, December 18, 2014. https://doi.org/10.1038/nature.2014.16615.

With their graded color zones that spread across land masses, data products from these next-generation CO_2 satellites strongly resemble the isopleth or zonal maps of methane and ozone from the 1970s and 1980s—those that conveyed an "atmospheric reality." The CO_2 hotspots lie in completely different places than those often found in standard CO_2 choropleth maps. For instance, OCO-2 captures GHG plumes above the burning biomass in South America and Africa [**Fig. 11**]. What do these satellite images suggest about responsibility? Are the people living in the red zones equally as responsible as companies or booming urban areas for GHGs? The simplicity of a red-colored hotspot equaling responsibility no longer holds true with these satellite images. How many of those fires were actually caused by humans? And to what extent should tropical nations that are primarily forest and undergo massive seasonal burning be treated differently than more developed countries?

Already, a growing number of journal articles (and NASA blog posts) feature data from OCO-2, representing CO_2 as gridded columns of atmosphere. But at present, these images remain mostly cloistered within academic publications. Perhaps it would behoove the scientific community, or even the mainstream media community, to thrust more images that resemble SCIAMACHY and OCO-2 data into the spotlight. For at the end of the day, it is the choropleth CO_2 maps with reader-friendly graphics that have the biggest hold on the popular audience's imagination. Popularizing images like these would have the benefit of disrupting and refreshing the conversation about who is responsible for CO_2 concentrations on Earth. Proliferation of these non-choropleth images of CO_2 could pivot focus away from state-driven interventions to reduce GHG emissions, if only for a moment, and re-center city-driven or forest-based initiatives for proper consideration from both politicians and the lay-public whose everyday choices play a role in their potential success.

Of course, there are downfalls to reducing simplicity and adding complexity in maps. A map must be legible in order to transfer a message and assert power. And it is important to note that these satellite "atmospheric reality" maps should not be heralded as the ultimate way of quantifying CO_2, for there are many caveats to the OCO-2 dataset and others like it. But I believe these maps achieve the goal of complicating a viewer's preconceived notions of what CO_2 is, where it comes from, and who the responsible parties are for putting it there. What *does* it mean to "map CO_2 better" today? Higher resolution satellites? GHG inventories with fewer uncertainties? The challenge lies in striking that magic balance—creating a map that is at once legible but also pushes the boundaries (pun intended) of conventional graphic representations to advance more sophisticated arguments than we thought possible before.[24]

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[24] Rankin, Bill. "Cartography and the Reality of Boundaries." *Perspecta* 42 (2010): 42–45.