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Aspects of science and technology in support of legal and policy frameworks associated with a global carbon emissions-control regime

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The delegates to COP21 in Paris, in conjunction with nationally formulated commitments and pledges, resolved that countries should take actions to "hold the increase in global temperature to well below 2 °C above pre-industrial levels" and to achieve "a balance between anthropogenic emissions by sources and removal by sinks of greenhouse gases in the second half of this century". This resolution for action suggests a step towards a global carbon emissions-control regime which, due to regional variabilities and remaining uncertainties as to the exact effects of atmospheric CO_2 concentrations, must be considered within the purview of risk management. In this Opinion, four topics are discussed that intertwine science, technology, legal, and policy issues critical to the implementation of any global carbon emissions-control regime: (i) What to regulate and at what levels; (ii) Regulating short-term *versus* long-term emissions; (iii) Validation of compliance in a regulated global emissions regime; and, (iv) Legal aspects of geoengineering.

Broader context

Recent global diplomatic conventions have focused on limiting global temperature increases, in conjunction with a goal for mid/late 21st century carbon-emissions levels. In addition to the deployment of low-carbon energy technologies, mitigation of climate change will require numerous technically based legal and policy instruments to assess compliance with a carbon-control regime on national, regional, and global levels. This Opinion evaluates some of the policy and long-term risk factors involved with controlling global temperature changes, as well as some policy and technology aspects of monitoring national and regional compliance with a carbon-emissions control regime. Some technical, legal, policy, and risk aspects of monitoring long-term carbon emissions from carbon capture and storage reservoirs, as well some legal and policy aspects involved with geoengineering, are also presented for discussion.

The mixing ratio of carbon dioxide in the atmosphere, CO_{2atm}, now has a seasonable peak slightly over 400 parts per million by volume (ppmv). This value is currently higher than at any time in the past 670 000 years, and probably higher than at any time in the past 20 million years.[2] The increase in atmospheric CO_2 concentration is primarily the result of anthropogenic activities, predominantly from fossil-fuel consumption.[2] Moreover, the rate of increase in anthropogenic CO_2 emissions more than doubled in the period 2000–2014, to 2.5–2.7% per annum, relative to the 1.1% per annum increase in the 1990–1999 period.[3,4] At the current rate of emissions increase, within 40 years, CO_{2atm} will be over double its pre-industrial, if not pre-human levels.

From ice core data that extend back for over 670 000 years, changes in CO_{2atm} have been correlated with changes in average global temperatures.[2] Prior changes in average global temperatures preceded the average global changes in CO_{2atm} over this same period, indicating that the initial changes in CO_{2atm} observed historically are the result of temperature changes, as opposed to being their cause. These periodic changes, which have repeatedly prompted glaciation/deglaciaton cycles, are reasonably ascribed to the dynamics of the Earth's orbit with respect to the sun (the so-called Milankovitch cycles).[2] The resulting change in insolation is not however sufficient to account quantitatively for the magnitude of the observed temperature changes. Hence the resulting change in CO_{2atm} is hypothesized to amplify the temperature-increasing effect of the changes in orbital-related radiative forcing.[2]

Carbon dioxide is the most oxidized form of carbon in the naturally oxidizing (rich in oxygen) atmosphere of the earth. Hence, no natural chemical destruction mechanism exists for atmospheric CO_2. After a relatively rapid equilibration of atmospheric CO_2 with the biosphere, which accounts for why only approximately 60% of the total amount of CO_2 emitted by fossil-fuel burning persistently appears in the atmosphere, the remainder of the atmospheric CO_2 will persist until it is removed by transport and mixing of CO_2 between the near-surface ocean and the deep oceans, along with sequestration in long-lived trees and weathering.[2] Assuming a complete cessation of anthropogenic CO_2 emissions once CO_{2atm} = 550 ppmv

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were reached, approximately $\frac{3}{4}$ of the CO_{2atm} would decay in 400–500 years, and $\frac{1}{4}$ would persist for 10 000 years or more.[1,5–7] If unmitigated and unabated, 21st century anthropogenic CO_2 emissions will thus persist in the atmosphere for a timescale comparable to recorded human history.

The exact effects, both negative and positive as well as variable regionally, that such atmospheric CO_2 concentrations will produce will remain uncertain, to varying degrees, until those levels are reached and observations are made on the state of the planet. An improved scientific understanding of the chemical and physical fate and transport processes in the atmosphere, biosphere and oceans, and some degree of understanding of associated feedbacks and nonlinearities such as water vapor feedback, ice melting, cloud type and distribution, and the effects of salinity changes on transport and sequestration in the ocean, as well as robust methods for data validation and assimilation, are needed to confidently formulate an assessment of current conditions. Such methods are also needed to enable confident projection of observed trends for decades and perhaps centuries into the future.

In response to an increase in the atmospheric CO_2 concentration, climate models generally indicate warming globally, with varying global and regional impacts.[2] The sign of the effect is physically reasonable, because based on optical absorption measurements, a doubling of CO_{2atm} to 550 ppm will produce an additional 4 W m^{-2} of radiative forcing relative to preanthropogenic levels, as compared to the spatially and temporally averaged value for the solar constant of 340 W m^{-2} at the top of the atmosphere. Although CO_2 emissions constitute the major and most long-lived anthropogenically produced greenhouse gas, other species, including methane, aerosols, nitrous oxide, and hydrofluorocarbons are also important. Moreover, the temporal and geospatial variation of atmospheric CO_2 is also an important indicator of regional or national actions in a global carbon-emissions control regime. Some of the major uncertainties in climate modeling lie in understanding the linear and nonlinear responses of the various sections of the planet, including the atmosphere, land, oceans, ice, *etc.*, to such an increase in radiative forcing. Feedbacks can be both positive and negative in sign, and chemical and physical couplings between these components occur on timescales ranging from seconds to centuries. To estimate the projected system response and its variance, individual climate models are run for many different initial conditions of cloud formations, global temperatures, *etc.* Of course, the Earth is a chaotic system that is not on an average path, but on a particular path, and nobody knows what distinguishes that path from other possible ones. Regulation of CO_2 emissions therefore falls under the purview of risk management.

Technical means, economic costs, and policy measures involved with reducing anthropogenic CO_2 emissions have been discussed widely, especially in Energy and Environmental Science at the research and development level. Instead, this Opinion focuses onto four topics that intertwine science, technology, legal, and policy issues. These topics must be considered in any global carbon emissions control regime, even though they may have received relatively little attention to date. They are also timely in view of the recent outcome of COP21 in Paris, in which the delegates, in conjunction with nationally intended commitments and pledges, resolved that countries should take actions (per Article 2) to "hold the increase in global temperature to well below 2 °C above pre-industrial levels" with an additional goal (per Article 4) of "achieving a balance between anthropogenic emissions by sources and removal by sinks of greenhouse gases in the second half of this century"… "in order to achieve the long-term temperature goal".[1]

A. What to regulate and at what levels?

An explicitly stated goal of the COP21 Paris agreement is to prevent globally averaged temperature increases of greater than 2 °C relative to preanthropogenic levels, with no specific baseline temperature precisely specified. This amount of temperature increase is often (but not always) associated with mixing ratios of CO_{2atm} in the range of 450 ppmv. However, while we know enough to correlate increases in CO_2 concentration with rises in temperature, we do not know for certain what levels of CO_2 will lead to what temperature changes. Additionally, any specific total CO_2 emissions budget can be produced by an infinite number of time-dependent emissions pathways, with further emissions trajectories allowed mathematically if negative emissions technologies are deployed. Other greenhouse gases, as well as aerosols, can also have substantial effects on atmospheric temperatures.

- If CO_2 emissions are controlled with the intent to produce an atmospheric CO_2 mixing ratio of – say, 450 ppmv – are further immediate, mandated cut-backs in CO_2 emissions required to comply with COP21 and/or other global accords if temperatures change by more than 2 °C?
- If some, or all, of the temperature changes are eventually ascribed to either some degree of natural variability or to other, non CO_2-emitting activities such as urbanization or land-use changes, would increased CO_2 emissions be allowed?
- What if some regions suffer climate-derived damage even at a 2 °C global average temperature increase, because an average 2 °C global temperature change could produce temperature changes at least twice as large in the polar regions, melt ice, disrupt communities, and possibly effect major economic and social changes in large regions of countries and/or continents?
- What actions would be taken if temperatures were held in check, but the coral reefs continued to be bleached, due to changes in ocean chemistry from increases in the concentration of CO_2 dissolved in sea water?
- What if 450 ppmv CO_2 levels keep the global average temperature change to 2 °C, but produce an amplification of the hydrological cycle that is predicted by most climate models, leading to an increased frequency of Category 5 hurricanes that cause extensive damage to major cities?
- How does one determine that a particular hurricane was at least in part caused by an anthropogenically derived increase in the CO_2 concentration in the atmosphere, to establish a legal basis for seeking relief for damages? Who, if anyone, is liable for such impacts? From what source would be such damages awarded? How would attribution be established?

A further limitation is that the relationship between anthropogenic emissions of CO_2 and the CO_{2atm} mixing ratio can be established with some degree of accuracy within the framework of the current earth climate system, in which ~60% of the emitted carbon stays in the atmosphere, with the remainder, in approximately equal parts, partitioning into the biosphere and the oceans.[2] If non-linearities in the global carbon cycle start to become important, then a predetermined rate of anthropogenic emissions, hypothesized to produce a given concentration of anthropogenic CO_2 in the current atmosphere, could produce much higher, or lower, actual CO_2 concentrations in a future atmosphere. Further CO_2 emissions may for example lead to warming that melts the permafrost, which then releases more CO_2 and CH_4, that in turn leads to more warming, which in turn leads to more melting of the permafrost.

• Are emitters in violation of the global accord if they are following a prescribed emissions profile hypothesized to produce CO_{2atm} = 450 ppmv, but the atmospheric CO_2 mixing ratio nevertheless increases beyond initial expectations, due to carbon cycle feedbacks?

• Can emitters be sanctioned retroactively if their emissions caused higher than initially anticipated CO_2 concentrations or temperature changes?

It seems that the only choice from a regulatory perspective is to define a CO_2 emissions budget either globally or by country, as opposed to attempting to regulate, control, target, or define the consequences of, a specified global average temperature change, or even a total atmospheric CO_2 concentration. All CO_2 levels above the preanthropogenic value of 280 ppmv will necessarily entail unknown, and imprecisely definable, risks. The risk of "dangerous" CO_2 levels likely increases with increased atmospheric CO_2 concentrations, but the exact risk vs CO_2 concentration profile is not well defined, or probably well definable.

At present, aerosols provide a net radiative forcing of -0.9 ($\pm$0.9) W m^{-2} relative to preanthropogenic levels.[2] Hence a reduction in aerosols that would accompany a cessation of coal combustion would, by itself, produce an increase in radiative forcing and thus result in an increase in the temperature of the atmosphere.

• Are nations encouraged to use more coal, so as to produce more aerosols and thereby cool the planet, if such avoids the stated maximum temperature change even transiently?

Regional concerns are also important to consider.

• If climate changes produced a northern movement in the corn belt and dust-bowl conditions in the midwestern U.S., would Canada be encouraged to engage in enhanced corn production to sustain global food supplies, and additionally benefit from associated land-use changes that would reduce Canada's net carbon emissions? Or would Canada be subject to sanctions and/or economic damages to compensate the U.S. for a loss of agricultural productivity and food export revenue?

Most low-carbon energy technologies, including batteries, wind turbines, solar panels, fuel cells, *etc.*, entail a significant capital expense, and thus energy invested, so that upon deployment, the energy returned bears relatively small ongoing "fuel costs".

• If a country emits CO_2 to manufacture solar panels or batteries for export, and another country installs said panels or grid-storage batteries and consequently lowers their CO_2 emissions, should the manufacturing country receive a portion of the emissions-reduction credit?

• If not, why would a country bear the fossil-energy burden of manufacturing low-carbon technologies for export, when another country would solely realize the carbon-control-regime compliance benefits?

• Which country bears the burden of fossil-fuel emissions associated with transcontinental shipment of solar panels from manufacture to installation?

Rigorous life-cycle assessments of the energy returned on energy invested, including labor associated with installation and operation of the resulting infrastructure, would provide a beneficial and foundational input for assessing the situation in detail.

B. Regulating short-term *vs.* long-term emissions

One of the most complex issues involved in devising a framework to regulate CO_2 and other greenhouse-gas emissions is that the impacts can be manifested on timescales from years to millennia. Some carbon, for various time periods, can be stored in terrestrial biomass, as indicated in Article 5 of the COP 21 agreement. Another proposed technology to mitigate CO_2 emissions involves capturing the CO_2 emitted from a coal-fired power plant and burying the CO_2 underground in a geologic reservoir. This approach is often called carbon sequestration, or carbon capture and storage (CCS). A related technology is bioenergy with carbon capture and storage (BECCS), in which electricity is produced by the combustion of biomass, and the resulting CO_2 is captured and sequestered.[8] BECCS can thus contribute to reductions in atmospheric CO_2 concentrations.

The above-ground engineering and technology costs associated with capturing CO_2 are reasonably well-estimated, but the fate and transport of the sequestered underground CO_2 is much less established. Natural gas has remained trapped in geologic reservoirs for millennia, but the global geologic gas reservoir inventory can only hold 30–50 years of current CO_2 emissions. At current global CO_2 emissions rates, underground aquifers could provide a larger estimated capacity, of between 50–150 years of global carbon emissions.[9]

A key metric for the technical success of CCS/BECCS is that the reservoirs must not appreciably leak over long periods of time. If, for example, CCS is practiced for 50 years, and 2% of what is put into the reservoirs leaks per year, then after 50 years the emissions would be the same as not having sequestered at all, and emissions are merely temporarily delayed. If the goal is to stabilize atmospheric CO_2 concentrations using this approach, then the globally averaged leak rate of the CCS reservoirs needs to be 0.1% or less per annum for >1000 years. Every reservoir formation and site is geologically different, and hence requires its own technical risk assessment.

• Given that we might, at best, have 10–20 years of data on the rate of CO_2 movement underground, at a few sites, between now and when CCS would have to be practiced at global scale, how could one technically and legally establish, with reasonable certainty, the leak rate of such sites for centuries to millennia into the future?

• If a reservoir has a 90% chance of holding 95% of the carbon buried therein for 100 years, is that an acceptable site for CCS?

• Who would assume the liability for personal or property damage if a CO_2 leak occurred at a CCS site, and how would leaks be mitigated?

• How would one prove that the leak came from the site and was not caused by other sources, natural or otherwise?

Technologies and operational systems that can monitor the fate and transport of subsurface CO_2 would clearly be helpful to establish a firmer basis for a technical risk assessment of CCS sites.

Enormous quantities of CO_2 would need to be involved in CCS to mitigate a significant amount of fossil-fuel-derived CO_2 emissions. A liquid volume of CO_2 the size of Lake Superior would need to be sequestered underground every year to mitigate current U.S. CO_2 emissions. If distributed uniformly over the lower 48 states, after 100 years of such CCS processing, such an amount of CO_2 material would be equivalent to a rise in elevation of the entire continental U.S. by over 5 cm. Proposals have been made to store massive amounts of CO_2 off shore, below the sea floor, where the CO_2 is calculated to be thermodynamically stable to migration.

• Should on-shore CCS be prohibited in favor of the more remote and more expensive (and also not yet proven) off-shore storage concept, pending proof in the affirmative that on-shore storage can be achieved with the needed technical requirements over both short and long time scales?

• How would one establish a legal and technological framework to ensure that adequate CCS success is validated in the long run as well as in the short run?

C. Validation of compliance in a regulated global emissions regime

Inventories of CO_2 emissions emanating from various countries are currently based on self-reported data. The COP21 accord specifies that a global "stocktaking" based on such inventories will be updated every 5 years.[1] In cooperative nations, monitoring mechanisms such as the U.S. EPA's "polluter pays" approach for CO_2 emissions monitoring have been proposed. In a global CO_2 emissions regulatory regime, some nations might be economically motivated to inaccurately report their fossil fuel consumption and resultant CO_2 emissions. Such patterns of non-treaty-compliant nation-state behavior are routinely seen or suspected with respect to treaty obligations for military purposes, such as the nuclear non-proliferation treaty, the chemical weapons convention, and other arms-control export regimes.

• If a country deliberately underreported its fossil-fuel production and consumption, how would one know?

There is ample precedent for the use of technological means to ensure compliance with international treaties, such as for the (not ratified but observed) comprehensive nuclear test ban treaty. In that instance, the putative signatories have agreed to cooperate in the installation, monitoring, and operation of a global network of sensors of various types (infrasound sensors, seismic arrays, atmospheric particle monitors, *etc.*), to monitor compliance with the treaty obligations preventing testing of nuclear devices above a certain specified yield.[10] The International Monitoring System is an operational system that monitors compliance.

Globally averaged values of CO_{2atm} can be measured at fixed sites such as Mauna Loa, Hawaii. Large-scale regionally averaged CO_{2atm} levels can be measured by satellites, with km-scale resolution.[11] However, CO_2 is a well-mixed gas in the atmosphere, hence, tracing it back to its source regionally on a relatively rapid timescale is not yet well-established technically. Additionally, the annual changes of CO_{2atm} are relatively small. In many cases, it would be challenging to confidently detect, at yearly intervals, deviations by a specific country or region from a prescribed emissions budget.

• What technologies would be employed for ensuring compliance in a globally regulated carbon-emissions regime?

• Would every industry and power plant be required to install a point-source continuous CO_2 emissions monitor?

• Would approaches such as the U.S. EPA's "polluter pays" tailpipe and stack monitoring technology and policy be robust, transparent, and enforceable in openly or covertly non-compliant nations?

• Would the existing Open Skies Treaty[12] be broadened to include CO_2 and other greenhouse gas sampling, and according to what protocol? Who would operate and pay for satellites and/or airborne platforms that performed remote CO_2 monitoring and who would have access to the data?

• How would one know how much electricity, for example, a given nation-state actually consumed in a given year, and how much of that came from fossil-fuel consumption, and from what fossil-fuel source?

• What monitoring technologies would be acceptable to, for example, U.S. industries, while still protecting them from being vulnerable to some form of industrial espionage? What group would be delegated to review the data and mandate enforcement actions, and with whose backing?

• What penalty would be levied for noncompliance?

D. Legal aspects of geoengineering

Several methods of geoengineering have been proposed to counter anthropogenically the effects of an increased CO_2-induced global warming. Geoengineering is not of course a direct carbon-emissions control technique, but is generally reserved for consideration in the eventuality of a "climate emergency".[13] Geoengineering has a unique set of very complex technical and legal aspects that warrant consideration, because geoengineering could prove to provide a tool for maintaining average temperatures to well below 2 °C above pre-industrial levels if a carbon-control regime fails to accomplish this goal. Geoengineering legal and policy issues are substantially more notional than those associated with a carbon-emissions control regime.

Some proposals involve deployment of "space parasols" that would shade a fraction of the sunlight from hitting the earth. Other proposals involve continuously, in perpetuity, injecting aerosols into the stratosphere, where they would scatter incident sunlight and thereby cool the planet (while also turning blue skies instead into a grey color, due to the light scattering from the injected aerosols). None of the geoengineering approaches proposed to date deal with the non-radiative impacts of increases in CO_{2atm}, such as the chemical impacts of acidification of the oceans and thereby increasing the bleaching of coral, or other chemical and ecological impacts (either adverse or beneficial) that would be derived from increases in CO_{2atm}. Even the developers of geoengineering concepts admit that such measures are inherently risky and ought to be considered only as measures of last resort, in the eventuality that emissions are not curtailed and in the event that the impacts produced by such unstabilized atmospheric CO_2 concentrations are deemed so unacceptably serious that they require decisive attempts towards mitigation.[13]

Because we admittedly do not fully understand the impacts of changing CO_{2atm} (ppmv) on the factors that control weather and climate, such as cloud formations, cloud distributions, *etc.*, it stands to reason that we have at least an equally incomplete understanding of the effects of man-made perturbations of the system away from its normal state. Furthermore, the timescales of monitoring the impact of such changes would range from months to centuries.

• If the U.S. launched a space parasol and restored temperatures over North America, but left alone (or even warmed further) Africa, is that acceptable?

• If three Category 5 hurricanes hit Mexico shortly after a European space parasol were deployed, would Mexico be entitled to damages, and from whom?

• If temperatures were restored but CO_{2atm} continued to rise, and the oceans thus continued to acidify, could Belize and Australia seek remediation for loss of tourism, and for loss of their natural resources, associated with coral reef bleaching?

• Would such countries have an implicit self-defense right to launch their own satellites or attack previously deployed space parasols to re-tune the climate and environment of their own regions?

Clearly, Earth systems measurement and monitoring technologies are needed to establish a scientific basis to assess such changes, and even to form an actionable basis for a case to support remediation or penalties.

None of the questions raised in this Opinion likely has an easy answer. Most are moot only in two limiting scenarios: (a) the world chooses the (default) path involved with allowing anthropogenic CO_2 emissions to continue unabated into the 21st century, and bears the risks (as well as the historical and current benefits) associated therewith; or (b) the world acts quickly, voluntarily, decisively, transparently, and globally, to dramatically curtail CO_2 emissions to levels needed to produce stabilized CO_2 concentrations near preanthropogenic levels. More likely, the future will lie in between these limiting cases, in which case the issues raised in this piece will become of critical importance in the establishment, and success, of a global carbon emissions-control regime. The present rate of accumulation of atmospheric CO_2 is rapid and its lifetime in the atmosphere is long. Long times are furthermore historically associated with effecting significant changes in energy infrastructure. Hence, the decision on which path to take, within a framework supported by the appropriate laws of state and laws of economics, needs to be made imminently. Otherwise, by default, the path will be chosen for us, supported instead by the unrepealable laws of the physics and chemistry of our planet.

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