An Old Story, but Useful Lessons

26 September 2013

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"Climate Sensitivity, Sea Level and Atmospheric Carbon Dioxide" was published last week, in the venerable Philosophical Transactions of the Royal Society, and is freely available.

I already commented on the paper (Exaggeration, Jumping the Gun, and Venus Syndrome), as has Joe Romm, so, for the sake of getting onto other matters, I make only a few comments here.

Paleoclimate, changes of climate over Earth's history, provide valuable insights about the effects of human perturbations to climate, even though there is no close paleoclimate analog of the strong, rapid forcing that humans are applying to the climate system. International discussions of human-made climate change (e.g., IPCC) rely heavily on global climate models, with less emphasis on inferences from the paleo record. A proper thing to say is that paleoclimate data and global modeling need to go hand in hand to develop best understanding -- almost everyone will agree with that. However, it seems to me that paleo is still getting short-shrifted and underutilized. In contrast, there is a tendency in the literature to treat an ensemble of model runs as if its distribution function is a distribution function for the truth, i.e., for the real world. Wow. What a terrible misunderstanding. Today's models have many assumptions and likely many flaws in common, so varying the parameters in them does not give a probability distribution for the real world, yet that is often implicitly assumed to be the case. But enough introduction.

1. "Fast-Feedback" Climate Sensitivity

Jule Charney, in discussions around the time of the 1979 NAS CO_2 study, focused on the notion of what we can call the "fast-feedback equilibrium climate sensitivity". In the real world, the transient climate response to a forcing does not allow a clean separation of processes into fast and slow, because the transient climate response is inherently slow, due to the great inertia of the system, especially the ocean -- and that allows slow feedbacks to begin to operate while the fast ones are still growing. Nevertheless, the concept is very useful, and the paleoclimate record allows us to separate the effects of fast and slow feedbacks.

Charney included water vapor, cloud and sea ice changes in response to a changing climate in the category of fast feedbacks. He would also have included aerosol changes in response to climate change as a fast feedback, but climate models then did not yet simulate aerosol changes, so the aerosol feedback was not addressed.

Climate simulations took ice sheets, greenhouse gases (other than water vapor), and the vegetation distribution as fixed boundary conditions. These were considered to be slow feedbacks, unlikely to change much on time scales of interest (decades, up to a century or so).

Aerosols warrant a comment. Human-made aerosols are a climate forcing, as is their indirect effects on clouds. However, the aerosol changes that occur in response to climate change are logically treated as a fast feedback.

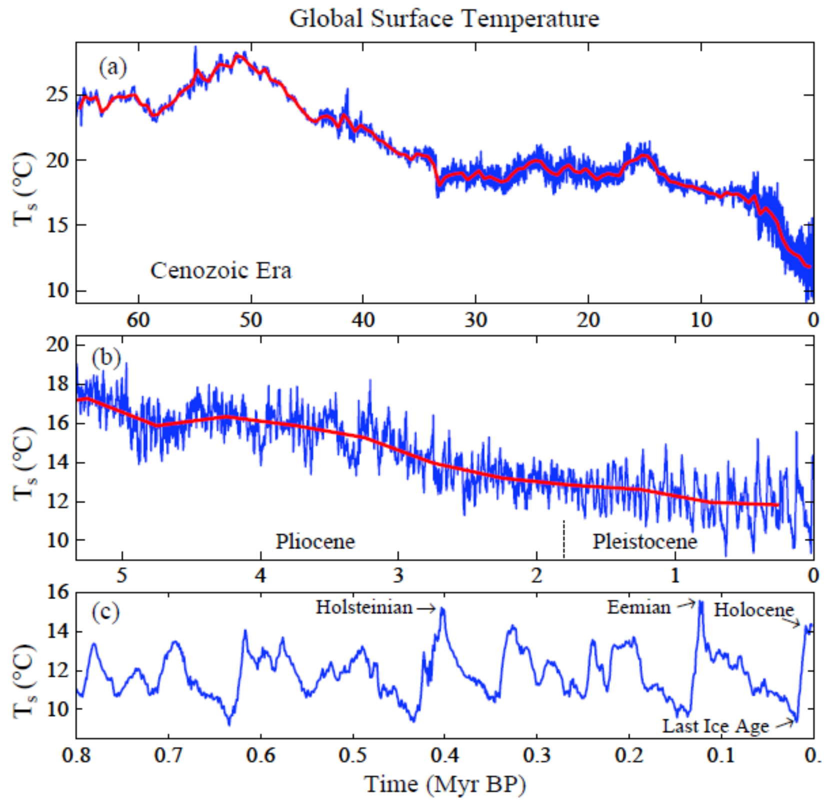

Fig. 4. Surface temperature estimate for the past 65.5 million years, including an expanded time scale for (b) the Pliocene and Pleistocene (past 5+ million years) and (c) the last 800,000 years. The red curve has 500 kyr resolution. Data for this and other figures are available in the electronic Supplementary Material.

Comparison of different climate states, e.g., neighboring glacial and interglacial periods, both of which can be assumed to be in near equilibrium with their respective boundary conditions, potentially can yield an accurate assessment of the fast-feedback climate sensitivity, because there is reasonably good knowledge of the boundary conditions in both climate states, i.e., ice sheet size, vegetation distribution, and long-lived greenhouse gas amounts (CO_2, CH_4, N_2O).

We show that a single fast-feedback sensitivity, for the most part, fits the entire 800,000 year ice core record quite well. That sensitivity is approximately 3°C for doubled CO_2. Remarkably the biggest source of uncertainty is not the change in boundary conditions between glacial and interglacial states, but rather the change of global temperature. Was global temperature during the last ice age 4.5°C colder than the Holocene? 3°C colder? 6°C colder? There is still a wide disagreement about that, leading us to conclude that the equilibrium sensitivity is 3±1°C.

We suggest that perhaps the most useful way to improve evaluation of fast-feedback climate sensitivity would be a focused program to evaluate global temperature during the last ice age. It is strange and unfortunate that the uncertainty is about the same now as it was 30 years ago.

However, we also note that there are issues about using the Holocene (current interglacial period, about 10,000 years long) as a measuring point, because of changes within the Holocene and the possibility that humans contributed to them. Climate change from the prior glacial to interglacial period, the Eemian (~125,000 years ago), would provide a clean alternative to focus on.

Despite uncertainties in the paleo data, this empirical climate sensitivity is much better than that provided by attempts to extract a value from observed climate change in the past century. We don't know the net climate forcing, because human-made aerosol changes and their effect on clouds are not known. The paleo case does not suffer that problem, because paleo aerosol and cloud changes are fast climate feedbacks, except perhaps some human effect in the Holocene.

2. Slow Feedbacks, Ice Sheet Response Time

Additional insight is provided by the longer paleoclimate record, not only glacial-to-interglacial changes, but climate change over the entire Cenozoic era, all the way back to an ice-free planet. For example, we can see effects of both amplifying and diminishing slow feedbacks.

"Hyperthermal events" such as the Paleocene-Eocene Thermal Maximum (PETM), a global warming of at least 5°C in response to sudden injection of a huge amount of carbon into the climate system, probably from thawing methane hydrates and/or Antarctic permafrost and peat, are eventually followed by a strong diminishing feedback as the excess carbon is drawn down and deposited as carbonates on the ocean floor. However, the time scale of this diminishing feedback is of the order of 100,000 years. This same slow feedback will also draw down the human-made carbon injection into the atmosphere, on the time scale of 100,000 years.

Unfortunately, slow feedbacks are *amplifying* on time scales that humans care about: decades, centuries, even millennia. As the planet warms, for example, ice sheets melt, exposing a darker surface that increases warming. Also warming causes a net release of long-lived greenhouse gases from the ocean and soil. Vegetation changes that occur as climate warms from today's situation will also have a significant amplifying effect, as forests move into tundra regions in North America and Eurasia. This feedback contributed to Pliocene warmth.

How fast will the amplifying feedbacks come into play? The paleoclimate record does not include a large positive (warming) forcing introduced at the speed of the human-made change. However, the paleo climate changes reveal little evidence of a significant lag between warming and slow feedbacks. That includes sea level change in response to warming; global temperature and sea level changes are nearly synchronous in the paleoclimate record. Our paper shows that ice sheet models are too lethargic -- they do not reproduce the rapid sea level change in the data.

Of course the ocean's thermal inertia causes a lag between the rapid human-made change of CO_2 and global temperature. Also, even though we cannot detect a lag between slowly changing paleo temperatures and sea level, in the case of human-made warming the lag associated with the ice sheet response is surely significant compared with the rapidity of the growing human forcing. However, we have neither a good paleo analog for the human forcing nor as yet adequate ice sheet models to let us determine the time scale of the response.

In my opinion, multi-meter sea level rise will occur this century, if the huge business-as-usual climate forcing actually occurs. I have described in prior papers reasons to expect non-linear rapid ice sheet response, if ocean warming melts the ice shelves now buttressing the ice sheets. I expect the new IPCC report will only begin to inch toward that answer. On the other hand, I think there is a good chance that we will come to our senses in the next several years and begin to rapidly phase down emissions -- in which case we might still avoid really large sea level rise.

3. The Venus Syndrome (repeated from 15 April post, as there was a misstatement in my book, Storms of My Grandchildren)

I get questions from the public about the Venus Syndrome: is there a danger of "runaway" greenhouse warming on Earth leading to Venus-like conditions? Related questions concern specific positive (amplifying) feedbacks such as methane hydrates: as warming thaws tundra and destabilizes methane hydrates on continental shelves, thus releasing methane, won't this cause more warming, thus more methane release, thus more warming -- a runaway warming?

Amplifying feedbacks. Let's consider a positive climate forcing (say a solar irradiance increase or CO_2 increase) that causes a unit of warming. Let's ask how this unit warming will be amplified by a very strong feedback, one that increases the initial warming by 50%. The added warming of 0.5 induces more feedback, by $0.5\times0.5 = 0.25$, and so on, the final response being $1 + 0.5 + 0.25 + 0.125 + \ldots = 2$. So this very strong feedback causes the final warming to be twice as large as it would have been without the feedback. But it is not a runaway effect.

The strongest feedback that we observe on Earth today, from water vapor, is almost as strong as this example. Other feedbacks are occurring at the same time, some amplifying and some diminishing (negative). The net effect of all fast feedbacks can be assessed by comparing different well-characterized climate states in Earth's history, as described in our paper,[4] treating slow changes such as ice sheet size as specified boundary conditions. It turns out that the net effect of fast feedbacks is to amplify the global temperature response by about a factor of 2-3.[1]

Other feedbacks become important on longer time scales. As the planet becomes warmer the ice sheet area tends to decrease, exposing a darker surface that absorbs more sunlight. And as the planet warms the ocean and land release long-lived greenhouse gases, mainly CO_2 and CH_4 (methane). Thus Earth's climate is dominated by amplifying feedbacks on time scales of 10-100,000 years and less. For this reason, Earth can be whipsawed between glacial and interglacial conditions by the small climate forcings caused by perturbations of Earth's orbit.[i]

The dominance of amplifying feedbacks and the resulting high climate sensitivity make Earth susceptible to what we can call a mini-runaway. By mini-runaway, I refer to a case with an amplifying feedback large enough that the total feedback reaches runaway (the infinite series above does not converge), but eventually that process runs out of fuel. Evidence of such behavior is provided by hyperthermal events[2] in Earth's history, sudden rapid warmings that occurred during periods of more gradual warming.

The most studied hyperthermal is the PETM (Paleocene Eocene Thermal Maximum), which occurred in the middle of a 10 million year period of gradual warming. A rapid warming spike occurred in conjunction with injection of a large amount of CO_2 into the climate system on a time scale of the order of a millennium. The source of the rapid CO_2 increase is most commonly suggested to have been the melting of methane hydrates due to a warming ocean, with an alternative suggestion being incineration of large peat deposits, especially on Antarctica.

Whatever the CO_2 source, global temperature increased about 6°C over several millennia. The continental weathering process provided a negative feedback, as a pumped-up hydrologic cycle drew down atmospheric CO_2 and deposited it as carbonate on the ocean floor. However,

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[1] Global warming in response to doubled CO_2 or a 2% increase of solar irradiance would be 1.2°C in the absence of climate feedbacks. Thus the net fast feedback factor of 2-3 yields 2.4-3.6°C warming for doubled CO_2.

[2] A brief discussion of hyperthermals on page 3 of our paper[4] includes many references to the scientific literature.

this feedback requires tens of thousands of years, so the rapid warming stopped only when the fuel source was depleted.

Are hyperthermals relevant now, as a possible amplification of fossil fuel warming? Unfortunately, they may be. Burning all fossil fuels would produce such large ocean warming, which would continue to exist for centuries, that ignition of a hyperthermal amplification of global warming is a possibility. Consequences are unclear. Carbon release in prior hyperthermals occurred over a millennium or more, at a rate up to ~ 5 GtC/year. This can be compared with the present global rate of fossil fuel burning, which is ~ 9 GtC/year.

It is instructive to consider the task of dealing with such continuing carbon release, in the event that we did set it off. Humanity could defuse a continuous release of 5 GtC/year, thus avoiding hyperthermal warming, by capturing and sequestering the carbon. The American Physical Society estimates[ii] the cost of capture and sequestration as ~ $2 trillion per GtC. Given that the United States is responsible for 26% of the fossil fuel CO_2 in the air today[iii], the U.S. cost share for removing 5 GtC/year would be ~$2.6 trillion each year. Technology development might be able to lower that cost, but fundamental energy constraints imply that cost reduction at most will be a factor of a few.[iv]

We had better be sure to avoid a mini-runaway. If we phase out fossil fuels rapidly and move to a clean energy future in accord with a scenario that my colleagues and I have described[8], we could be reasonably confident of avoiding that situation. We know that prior interglacial periods were moderately warmer than the current (Holocene) interglacial. A fossil fuel emissions scenario similar to the one we have defined is needed for other reasons, especially for the purpose of maintaining reasonably stable shorelines, i.e., avoiding sea level rise of many meters, which would destroy thousands of coastal cities all around the world.

In contrast, if we burn all the fossil fuels it is certain that sea level would eventually rise by tens of meters. The only argument is how soon the rise of several meters needed to destroy habitability of all coastal cities would occur. It is also possible that burning all fossil fuels would eventually set off a hyperthermal event, a mini-runaway. Is it conceivable that we could get a runaway leading all the way to the Venus Syndrome, Venus-like conditions on Earth?

Runaway Greenhouse. Venus today has a surface pressure of about 90 bars, compared with 1 bar on Earth. The Venus atmosphere is mostly CO_2. The huge atmospheric depth and CO_2 amount are the reason Venus has a surface temperature of nearly 500°C.

Venus and Earth probably had similar early atmospheric compositions, but on Earth the carbon is mostly in Earth's crust, not in the atmosphere. As long as Earth has an ocean most of the carbon will continue to be in the crust, because, although volcanoes inject crustal carbon into the atmosphere as CO_2, the weathering process removes CO_2 from the air and deposits it on the ocean floor as carbonates. Venus once had an ocean, but being closer to the Sun, its atmosphere became hot enough that hydrogen could escape from the upper atmosphere, as confirmed today by the extreme depletion on Venus of normal hydrogen relative to heavy hydrogen (deuterium), the lighter hydrogen being able to escape the gravitational field of Venus more readily.

Earth can "achieve" Venus-like conditions, in the sense of ~90 bar surface pressure, only after first getting rid of its ocean via escape of hydrogen to space. This is conceivable if the atmosphere warms enough that the troposphere expands into the present stratosphere, thus eliminating the tropopause (see Fig. 7 in our paper[4] in press), causing water vapor to be transported more rapidly to the upper atmosphere, where it can be dissociated and the hydrogen can then escape to space. Thus extreme warming of the lower atmosphere with elimination of the cold-trap tropopause seems to be the essential physical process required for transition from Earth-like to Venus-like conditions.

If Earth's lower atmosphere did warm enough to accelerate escape of hydrogen it would still take at least hundreds of millions of years for the ocean to be lost to space. Additional time would be needed for massive amounts of CO_2 to accumulate in the atmosphere from volcanoes associated with plate tectonics and convection in Earth's mantle. So Venus-like conditions in the sense of 90 bar surface pressure and surface temperature of several hundred degrees are only plausible on billion-year time scales.

Is it possible, with the present surface pressure of ~ 1 bar, for Earth's surface to become so hot that that the planet is practically uninhabitable by humans? That is the situation I depicted in "Storms of My Grandchildren"[v], which was presumed to be a consequence of burning all fossil fuels over a period of several centuries, with warming further amplified by ignition of PETM-like hyperthermal warming. Support for the possibility of large warming was provided by global climate model simulations indicating an upturn in climate sensitivity at climate forcings ~10 W/m^2 (Fig. 30 in "Storms"[10]). If other forcings are unchanged, a 10 W/m^2 forcing requires a CO_2 increase by a factor of 4-8 times its pre-industrial amount (~280 ppm) -- an increase that is possible if all extractable fossil fuels are burned[4,8]. Other complex global climate models also find an upturn in climate sensitivity or climate model "crash" when CO_2 amount reaches such high levels[vi], raising the question of whether such a level of climate forcing is already trending toward a runaway greenhouse effect.

The concept of a runaway greenhouse effect was introduced[vii] by considering a highly idealized situation with specified troposphere-stratosphere atmospheric structure, a simple approximation for atmospheric radiation, and no inclusion of how clouds might change as climate changes, as is appropriate for introduction of a concept. More recent studies[viii] relax some of the idealizations and are sufficient to show that Earth is not now near a runaway situation, but the idealizations are still sufficient that the studies do not provide a picture of where Earth is headed if all fossil fuels are burned.

An alternative promising approach is to employ the fundamental equations for atmospheric structure and motions, i.e., the conservation equations for energy, momentum, mass, and water, and the ideal gas law. These equations form the core of atmospheric general circulation models and global climate models. However, today's global models generally contain representations of so many additional physical processes that the models are difficult to use for investigations of extreme climatic situations, because invariably some approximations in the scores of equations become invalid in extreme climates. In contrast, my long-term colleague Gary Russell has developed a global model that solves the fundamental equations with the minimum additional physics needed to investigate climate sensitivity over the full range from snowball Earth to a hothouse uninhabitable planet. The additional physics includes accurate spectral dependence of solar and thermal radiation, convection, and clouds. Although the precision of the results depends on the representation of clouds, we suggest that the simple prescription employed is likely to correctly capture essence of cloud change in response to climate change.

We use the Russell model in our paper to show that the tropopause rises in response to the global warming that occurs with larger and larger CO_2 amounts (Fig. 7 in our paper[4]), and cloud cover decreases with increasing CO_2. In consequence climate sensitivity initially increases as CO_2 increases, consistent with the upturn of sensitivity found in more complex global climate models[11]. With the more realistic physics in the Russell model the runaway water vapor feedback that exists with idealized concepts[12] does not occur. However, the high climate sensitivity has implications for the habitability of the planet, should all fossil fuels actually be burned. Furthermore, we show that the calculated climate sensitivity is consistent with global temperature and CO_2 amounts that are estimated to have existed at earlier times in Earth's history when the planet was ice-free.

One implication is that if we should "succeed" in digging up and burning all fossil fuels, some parts of the planet would become literally uninhabitable, with some time in the year having wet bulb temperature exceeding 35°C. At such temperatures, for reasons of physiology and physics, humans cannot survive, because even under ideal conditions of rest and ventilation, it is physically impossible for the environment to carry away the 100 W of metabolic heat that a human body generates when it is at rest[ix]. Thus even a person lying quietly naked in hurricane force winds would be unable to survive. Temperatures even several degrees below this extreme limit would be sufficient to make a region practically uninhabitable for living and working.

The picture that emerges for Earth sometime in the distant future, if we should dig up and burn every fossil fuel, is thus consistent with that depicted in "Storms" -- an ice-free Antarctica and a desolate planet without human inhabitants. Although temperatures in the Himalayas may have become seductive, it is doubtful that the many would allow the wealthy few to appropriate this territory to themselves or that humans would survive with the extermination of most other species on the planet. At least one sentence in "Storms" will need to be corrected in the next edition: even with burning of all fossil fuels the tropical ocean does not "boil". But it is not an exaggeration to suggest, based on best available scientific evidence, that burning all fossil fuels could result in the planet being not only ice-free but human-free.

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[iii] Hansen, J et al., 2013: Scientific prescription to avoid dangerous climate change to protect young people, future generations, and nature (submitted for publication).

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