

Earth's Energy Out of Balance: The Smoking Gun for Global Warming

Scientists at Columbia University, NASA, and the Department of Energy have found that the Earth is out of energy balance: the Earth is absorbing more energy from sunlight than it is emitting back to space in the form of heat radiation. This imbalance provides confirmation of global warming theory and a measure of the net forcing that humans are applying to the Earth by adding greenhouse gases and other pollutants to the Earth's atmosphere.

The Earth's energy imbalance was predicted by the authors' climate model as a consequence of growing amounts of greenhouse gases in the atmosphere, especially carbon dioxide, methane, and ozone, and black carbon (soot) particles. They report in an article to be published Thursday April 28 in Science Magazine that the imbalance has been confirmed by precise measurements of temperature within the ocean, which is the principal reservoir accumulating the excess heat.

"This energy imbalance is the 'smoking gun' that we have been looking for" according to Jim Hansen, a climatologist who directs the NASA Goddard Institute for Space Studies at the Columbia University Earth Institute and the lead author on the study. "The magnitude of the imbalance agrees with what we calculated using known climate forcing agents, which are dominated by increasing human-made greenhouse gases. There can no longer be substantial doubt that human-made gases are the cause of most observed warming."

The energy imbalance occurs because of the ocean's thermal inertia – the ocean is slow to respond to climate forcings. Ocean water's inertia is obvious to beachgoers who find that the summer sun warms the waters much more slowly than it warms the sandy beach. The imbalance will continue to exist until the Earth has warmed enough that its infrared (heat) radiation to space increases to match the absorbed solar radiation.

One consequence of the ocean's inertia and the resulting planetary energy imbalance is that there is about 1 degree Fahrenheit more global warming 'in-the-pipeline' – warming that will occur this century without any further increases of greenhouse gases. The Earth has already warmed, on average, about one degree Fahrenheit over the past century.

The magnitude of the Earth's energy imbalance and the long climate response time are of importance to policy-makers who may wish to limit the effects of undesirable human-made climate change. The authors note that the delay of the climate response "provides an opportunity to reduce the magnitude of anthropogenic climate change before it is fully realized, if appropriate action is taken. On the other hand, if we wait for more overwhelming empirical evidence of climate change before acting, the inertia implies that still greater climate change will be in store, which may be difficult or impossible to avoid."

The authors evaluated the energy imbalance using precise measurements of ocean temperature obtained by ocean floats that regularly lower an instrument package into the ocean to a depth of about half a mile. These local measurements were complemented by satellite measurements of the height of the ocean surface to centimeter scale accuracy. The ocean height reveals subsurface ocean thermal anomalies that cause the ocean water to expand or contract.

The authors find a planetary energy imbalance that averages almost 1 Watt per square meter, more precisely 0.85 plus or minus 0.15 watts per square meter. The authors note that it would be necessary to reduce greenhouse gas forcing by that amount if it were desired to stabilize climate at today's global temperature. "In principle we could do that", says Hansen, "by halting all anthropogenic methane emissions or by somehow removing half of the human-

made carbon dioxide now in the atmosphere, but that is not practicable in the foreseeable future, so the world is going to become warmer.”

“The fundamental question is: how much more global warming can we afford before we reach the level of ‘dangerous anthropogenic interference’ with climate, which all countries agreed to avoid in the United Nations Framework Convention on Climate Change” says Hansen. “Based on the history of the Earth, which reveals large sea level increases when global mean temperature was more than 1 degree Celsius (1.8 degree Fahrenheit) greater than today, I argue that we can allow at most one degree Celsius of additional global mean warming.”

“It is possible to limit additional global warming to less than one degree Celsius, but it would require slowing the growth rate of carbon dioxide (CO₂) emissions and halting the growth of non-CO₂ emissions. These are all possible, but only with concerted efforts. The most effective actions that we could take now are strong efforts to improve energy efficiency, employ renewable energies, and reduce air pollutants, especially fugitive methane, other ozone precursors, and black carbon (soot). On the long-run we will need either carbon-free power sources or we will need to capture and sequester CO₂.”

The authors note that sea level rose 3.1 cm in the past decade, twice the rate of sea level rise during the preceding century. They calculate that half of the 3.1 cm increase was from the heat entering the ocean, which caused the water to expand. The remainder of the sea level rise is assumed to be due mainly to world-wide melting of mountain glaciers and possibly fringes of the large ice sheets covering Greenland and Antarctica.

“Large sea level change is a potential “impact” of climate change that could be especially destructive, so it’s important to monitor the Greenland and Antarctic ice sheets precisely,” according to Hansen. “So far changes of the ice sheets are small, but at some point positive feedbacks could lead to a situation in which ice sheet disintegration begins to run out of our control.” The authors of the report conclude that the NASA IceSat mission, presently monitoring the ice sheets to centimeter-scale accuracy, and the related GRACE mission for precise regional gravity measurements, warrant follow-on missions.

Below are answers to typical questions about this research topic and its implications.

Responses to questions about “Earth’s Energy Imbalance”, provided by Jim Hansen.

1. Direct significance of the energy imbalance found by the authors in their study.

“This is the ‘smoking gun’ that we have been looking for (with regard to identifying the human role in causing global warming).”

“There can no longer be genuine doubt that human-made gases are the dominant cause of observed warming. The imbalance occurs at a time when natural forcings, e.g., changes of solar irradiance and volcanic aerosols, are small and while human-made greenhouse gases increased at a rate consistent with the imbalance.”

“The deduced planetary energy imbalance also helps us quantify additional climate change that is coming down the pike.”

2. Principal implication of this study for the public.

“The large energy imbalance that we have found implies that the global temperature responds slowly to forcing agents, with much of the response lagging several decades behind imposition of the forcing.” “This long response time is a problem for policy-makers, because it

means that we must identify the level of global warming that would constitute dangerous anthropogenic interference well before that level is reached.”

“The large energy imbalance makes it clear that we are dealing with a (climate) system with a multi-decadal lag time and positive feedbacks. That is an unfortunate and challenging combination for policy-makers who wish to stabilize climate.”

3. What are the primary factors that determine the energy imbalance?

“The imbalance is a function mainly of the magnitude of climate forcing agents (imposed changes of the planet’s energy budget, e.g., a change of the brightness of the sun, or addition of human-made greenhouse gases that trap heat radiation emitted by the Earth’s surface) and climate sensitivity to forcing agents. The rate of mixing between the ocean surface layer and the deeper ocean influences the effective inertia of the ocean, and thus it is also a significant factor.”

“We now know climate sensitivity quite well, mainly from looking at the history of the Earth, but also from climate models, i.e., numerical simulations of climate on large scale computers. We also know the rate of mixing in the ocean. Thus the measured planetary energy imbalance primarily tells us about the net climate forcing acting on the planet.”

4. What have we learned about climate forcings from the energy imbalance.

“The fact that the observed and simulated rates of ocean heat storage are similar in magnitude suggests that our estimated net climate forcing is reasonably accurate. The measured energy imbalance confirms that the aerosol (fine particle) forcing is substantial and opposite in sign (cooling) to greenhouse gas forcing, but it is smaller than the positive (warming) greenhouse gas forcing. The net climate forcing now clearly is positive and will lead to additional warming.”

“There are still substantial uncertainties about the values and trends of several climate forcings, especially aerosol effects. The good agreement that we find in simulated global temperature change may be partly coincidental as errors in some forcings cancel errors of the opposite sign in other forcings.”

“Nevertheless, because aerosol amounts are unlikely to increase in the future, and may decrease as nations attempt to reduce particulate pollution, we can predict with considerable confidence that the net climate forcing and global warming will continue to increase.”

5. How do you know that the increase of ocean heat content is not just a natural dynamical fluctuation in the ocean?

“Unforced fluctuations of ocean heat content can occur, but generally to increase the flux of energy into the ocean surface requires a negative (cool) ocean surface temperature anomaly. The observed period of increasing ocean heat content instead has occurred while the ocean surface temperature has been rising. We infer that the increasing heat content is a result of positive climate forcings.”

“Any doubt or suggestion that the anomaly is an unforced fluctuation should be erased over the next several years as the positive imbalance continues.”

6. Do you expect the knowledge of this planetary energy imbalance to have an effect on the policies of the United States toward CO₂ and other greenhouse gases?

“My guess is that it will lead to such reconsideration and to increased efforts to deal with global warming, not this week or next week, but in the near future, because this planetary energy imbalance is the smoking gun that we have been looking for. Part of the reluctance to do more to address climate change has been based on genuine skepticism that we understand the problem

well enough to warrant greater action. The Science Advisor and others in his office concerned with climate are exceptionally good scientists and the significance of the planetary energy imbalance will not escape their attention as the matter is chewed over and reconfirmed by others.”

7. Is it practical to slow the growth of human-made climate forcing agents and eventually stabilize atmospheric composition and climate?

“I believe that it is possible and that the needed actions make sense for other reasons. Equal emphasis is needed on CO₂ and non-CO₂ forcings. Uncaptured CO₂ emissions must be stabilized and eventually reduced, but that is practicable and has ancillary benefits. Contrary to frightening scenarios with 3-4%/year growth of CO₂ emissions, actual growth of fossil fuel CO₂ emissions in the past few decades has been 1.4%/year, even with a strong U.S. economy and rapidly growing economies in China and India. With a genuine emphasis on achieving higher energy efficiencies, increased use of renewable energies, and perhaps CO₂ sequestration and next-generation nuclear power, the growth of CO₂ emissions can be slowed while achieving many other benefits including reduced air pollution and greater energy independence.”

“Equally important, we must halt the growth of the non-CO₂ forcings, especially fugitive methane, other ozone precursors, and black carbon (soot) aerosols. All of these are practicable and make sense for multiple reasons including improved public health, but they will not happen just because they make sense – strong leadership is required to achieve concerted actions.”

“Finally, concerning ‘practicality’, it should be noted that reduced air pollution and stable climate are important to both the West and the East, so there is opportunity for mutually beneficial cooperation in achieving these objectives.”

8. How is the Earth’s energy imbalance related to melting ice and sea level?

“A few percent of the excess in incoming energy has been going into world-wide melting of ice. As a result, within a few decades Glacier National Park will contain no glaciers and the ‘Snows of Kilimanjaro’ (the ‘permanent’ ice cap on the mountain) will exist only in pictures and books.” “Also a small part of the energy imbalance is beginning to soften and melt the fringes of the Greenland and West Antarctic ice sheets. But, so far, most of the excess energy has been going into the ocean.”

“Both of these processes, melting ice (which must eventually end up in the ocean) and warming sea water (which expands) cause sea level to rise. The large recent energy imbalance undoubtedly is responsible for the 3.1 cm rise of sea level in the past decade, which is twice the rate of sea level rise in the preceding century. This rate of sea level rise cannot be explained as a ‘natural’ continuation of the glacial-interglacial transition, as it corresponds to a rate of sea level rise of 3.1 meters in 1000 years, which is much greater than long-term changes during the interglacial period.”

“The greatest danger of a positive planetary energy imbalance is its effects on the fringes of Greenland and West Antarctica. As these areas are softened by melt-water and rainfall, they begin to discharge icebergs into the ocean more rapidly. As warming continues the ice sheet area with surface snow-melt increases and the melt season becomes longer, bringing positive feedbacks into play, including reduced ice sheet albedo (wet ice is darker, absorbing more sunlight), warming coastal waters and rising sea level that remove grounded coastal ice shelves that previously had impeded movement of glacial icebergs to the ocean, and sinking of the ice sheet that increases the temperature at its surface.”

“The potential result, if this process is allowed to proceed beyond a critical point, is much more rapid discharge of ice into the ocean. If this should happen, the ice sheet melting process would be able to tap into the vast reservoir of ocean heat, leading to greatly accelerated sea level rise that would be measured in meters, rather than centimeters.”

See *Reference 1* below for further discussion of this matter in lay terms.

9. Are there sensible metrics that the interested public could keep their eye on, so they could judge for themselves the course of and prospects for climate change, rather than relying on the opposite talking heads that the media insists on presenting to the public?

“Yes, but they need to be made available in a convenient understandable format. I have discussed this concept previously (*Reference 2* below). Several of the most fundamental quantities, including both causes and effects of climate change, are being measured with high precision. I mention here a few important metrics (see also *Reference 3*).”

a. Fossil fuel CO₂ emissions. Reasonably reliable estimates of CO₂ emissions from burning of fossil fuels are available annually. This provides a better measure than atmospheric CO₂ amount of progress in slowing the growth rate of CO₂ emissions, because of the fluctuations of natural sources and sinks of CO₂ (in the ocean, soils, and plants).

b. Greenhouse gas amounts. CO₂ and CH₄, the most important greenhouse gases, are now monitored at enough sites to estimate global change on an annual basis. The annual changes of the gas amounts in the air fluctuate because of interannual variations of natural sources and sinks. The interannual fluctuations as well as changes of the underlying trends contain valuable clues that can help us understand the prospects for future gas amounts.

c. Aerosol amounts. Unfortunately, this important metric is not yet being measured to a useful accuracy. There are a variety of aerosol types that have contrary effects on climate, so we need global aerosol measurements with composition specificity (*Reference 4*).

d. Annual change of global climate forcing due to measured forcing agents. Most of the agents responsible for changing climate forcing, including well-mixed (long-lived) greenhouse gases and natural forcings such as volcanic aerosols and solar irradiance, are being measured. The resulting annual increment to global climate forcing can be computed accurately. Although aerosols cannot be included in the calculation, it is of interest that the growth rate of the measured forcings peaked about 1980 with the subsequent decline due primarily to constraints on the production of chlorofluorocarbons [*Reference 3*].

e. Planetary energy imbalance. The planetary energy imbalance, which had been predicted in earlier papers [*Reference 5*], can be measured accurately in the indirect fashion that we employed for our present paper [*Reference 6*], i.e., via measurements of internal ocean temperature supplemented by precise satellite altimetry of the ocean surface. It is desirable that the internal ocean measurements be extended to greater depths of the ocean. It also will be necessary to account for the heat used to melt ice, if ice sheet disintegration and sea level rise accelerate, but this term can be obtained accurately from the measurements described below (items h and i). Planetary radiation imbalance can in principle be measured by satellite, but in practice the needed absolute accuracy is not yet attainable. This is because the measurements must include the solar radiation reflected by the Earth in all directions, as well as the thermal radiation emitted in all directions, the measurements must be made to an absolute accuracy of $\sim 0.1 \text{ W/m}^2$, and there must be no temporal gaps in the measurements. Ocean heat storage is an ideal proxy measurement, because temperature can be measured accurately and the ocean naturally integrates the energy imbalance over time. Although satellite radiation budget measurements do not meet the accuracy requirements, they are a valuable complement to the

ocean measurements. The satellite data can be calibrated against the ocean data, and the satellite can then provide greater spatial and temporal information that is useful for many climate analyses and other purposes.

f. Global mean temperature. This is a more meaningful metric than generally realized. Global temperature responds proportionally to the net effective global climate forcing (*Reference 7*) and even some regional climate characteristics (e.g., the strength of the overturning Hadley circulation and its regional effects) seem to respond to the effective forcing (*Reference 7*). Global average temperature is affected less by the year-to-year chaotic (unforced) variations of weather and climate than is regional climate, but such chaotic ‘noise’ is still substantial even on global and annual average. One of the strongest El Ninos of the century occurred in 1998, almost precisely coinciding with the calendar year, thus causing 1998 to stand out as far warmer (by about 0.2°C, or two standard deviations) than any year in the period of instrumental temperature data. However, because of the present strong planetary energy imbalance, the climate system is now being pushed so hard that I have suggested that we can say with confidence that 2005 will have a warmth comparable to that of 1998, and the remarkable 1998 global temperature record will soon be broken, if not this year than within the next several years. [A large volcanic eruption conceivably could delay the record a few years and solar irradiance is in the declining phase of its 11-year cycle, but the amplitude of this short-term solar decrease is only a few tenths of 1 W/m², so it cannot overcome the positive climate forcing associated with the present planetary energy imbalance.]

g. Regional climate. Global warming is smaller than local or regional unforced (chaotic) variability, even when temperature is averaged over a season or a full year. However, global warming is large enough that it is beginning to affect the probability of a season being warmer than normal, as well as the trend of local temperature over the past several decades. When seasonal or annual local temperatures are reported it would be helpful if a graph of this temperature for the period of measurements were included, so that the lay person and scientist could see both the long-term trend and the year-to-year variability.

h. Ice sheet mass. Changes of the important Greenland and Antarctic ice sheets can be monitored with great precision by the combination of lidar altimetry from satellites such as IceSat and gravity satellites such as GRACE.

i. Sea level. The combination of satellite instruments that measure sea level height with remarkable accuracy and time gauge stations can yield useful annual monitoring of sea level.

References

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