Tracking Earth's energy: From El Niño to global warming

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Science **Perspective**

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One sentence Summary:

Tracking the flow of energy through the climate system is important but remains a challenge.

If we can measure the net radiative incoming or outgoing energy at the top-of-atmosphere (TOA), then because energy is conserved, we should account for where it has gone. The main energy reservoir is the ocean, and the exchange of energy between the atmosphere and ocean is ubiquitous, so that heat once sequestered can resurface at a later time to affect weather and climate on a global scale. Thus a change in the energy balance has consequences, sooner or later, for the climate. Moreover, we have observing systems in place that nominally can measure all we need, but it remains a challenge to obtain closure.

A climate event, such as the drop in surface temperatures over North America in 2008 (1), is often stated to be due to natural variability, as if this magically accounts for what has happened. Aside from weather events that primarily arise from instabilities in the atmosphere, natural climate variability has a cause. Its origins may be external to the climate system: a change in the sun, a volcanic eruption, or Earth's orbital changes that ring in the major glacial to interglacial swings. Or its origins may be internal and arise from interactions among the atmosphere, oceans, cryosphere and land surface, which depend on the very different thermal inertia of these components.

As an example of natural variability, the biggest El Niño in the modern record by many measures occurred in 1997-98. Successful warnings were issued a few months in advance regarding the unusual and disruptive weather across North America and around the world, and were possible in part because the energy that sustains El Niño was tracked in the ocean by a new moored buoy observing system in the Tropical Pacific. Typically prior to an El Niño, the cold ocean in the central and eastern tropical Pacific creates high atmospheric pressure and clear skies, with plentiful sunshine heating the surface waters. The ocean currents redistribute this heat which then builds up in the tropical western Pacific Warm Pool until an El Niño provides relief (2). The spread of warm waters across the Pacific in collaboration with changing winds in turn promotes evaporative cooling of the ocean, moistening the atmosphere and fueling tropical storms and convection over and around the anomalously warm waters. The changed atmospheric heating alters the jet streams and storm tracks, and controls weather patterns for the duration of the event (3).

In 2007-08 a strong La Niña event, that spilled over to the 2008-09 northern winter, had direct repercussions for cooler weather across North America and elsewhere (1). But by June 2009, the situation had reversed as the next El Niño emerged and this has grown to be a moderate event, with temperatures in the top 150 m of the ocean above normal by as much as 5°C across the equatorial Pacific in December 2009. Multiple storms barreling into Southern California in January 2010 are consistent with expectations from the El Niño.

Currently we can recognize these changes once they have occurred and they permit some level of climate forecast skill. But a major challenge is to be able to track the energy more thoroughly: where did the heat for the 2009-2010 El Niño actually come from?

A human influence on climate arising mostly from the changing composition of the atmosphere (4) also affects energy flows. Increasing concentrations of carbon dioxide and other greenhouse gases have led to a post-2000 imbalance at the top-of–atmosphere (TOA) of 0.9±0.5 W m^{-2} (5) that produces "global warming". Tracking how much extra energy has gone back to space (6) and where this energy has accumulated is possible, with reasonable agreement between model and observational results for 1993 to 2003 (7). Over the past 50 years, the oceans have absorbed about 90% of the total heat added to the climate system while the rest goes to melting sea and land ice, and heating the land surface and atmosphere (4). Because carbon dioxide concentrations have further increased since 2003 the amount of heat subsequently being accumulated should be even greater.

While the planetary imbalance at TOA is too small to measure directly from satellites, instruments are far more stable than they are absolutely accurate with calibration stability < 0.3 Wm^{-2} per decade (95% confidence) (8). Tracking relative changes in Earth's energy by measuring incoming solar radiation and outgoing infrared radiation, and thus changes in the net radiation, seems to be at hand (8, 9). This includes tracking the slight decrease in solar insolation since 2000 with the ebbing 11-year sunspot cycle; enough to offset 10 to 15% of the estimated net human induced warming (7).

In 2008 for the tropical Pacific during La Niña conditions, extra TOA energy absorption was observed as expected (9). But ocean temperature measurements from 2004 to 2008 suggested a substantial slowing of the increase in global ocean heat content (10). By 2004 the ocean observing system had reached new capabilities, as some 3000 Argo floats populated the ocean for the first time to provide regular temperature soundings of the upper 2000 m, giving new confidence in the ocean heat content assessment.

Since 1992 sea level observations from satellite altimeters at millimeter accuracy reveal a global increase of ~3.2 mm yr^{-1} as a fairly linear trend, although with two main blips corresponding to an enhanced rate of rise during the 1997-98 El Niño and a brief slowdown in the 2007-08 La Niña. Since 2003, the detailed gravity measurements from Gravity Recovery and Climate Experiment (GRACE) of the change in glacial land ice and water show an increase in mass of the ocean. This so-called eustatic component of sea level rise may have compensated for the decrease in the thermosteric (heat related expansion) component (11, 12). However, for a given amount of heat, sea level rise can be achieved much more efficiently – by a factor of 40 to 70 typically – by melting land ice rather than expanding the ocean (7). So although some heat has gone into the record breaking loss of Arctic sea ice, and some has undoubtedly contributed to unprecedented melting of Greenland (13) and Antarctica (14), it does not add up to be anywhere near enough to account for the measured TOA energy. Closure of the energy budget over the past 5 years is elusive (7). Thus state-of-the-art observations are unable to fully account for recent energy variability implying error bars too large to make the products useful. Is the latest El Niño a manifestation of the missing energy reappearing?

Proposals for addressing global warming now include geo-engineering whereby tiny particles are injected into the stratosphere to emulate the cooling effects of stratospheric aerosol of a volcanic eruption (15). Implicitly such proposals assume understanding and control of this process which requires detailed tracking of energy within the climate system. How can we understand whether the strong cold outbreaks of December 2009 are simply a natural weather phenomenon, as they seem to be, or are part of some mysterious change in clouds or pollution, if we do not have adequate measurements? Tracking Earth's global energy and how it is partitioned is essential for understanding what is happening in the climate system and thus for attributing causes and predicting what comes next. It is vital information for planning adaptation to and coping with climate change.

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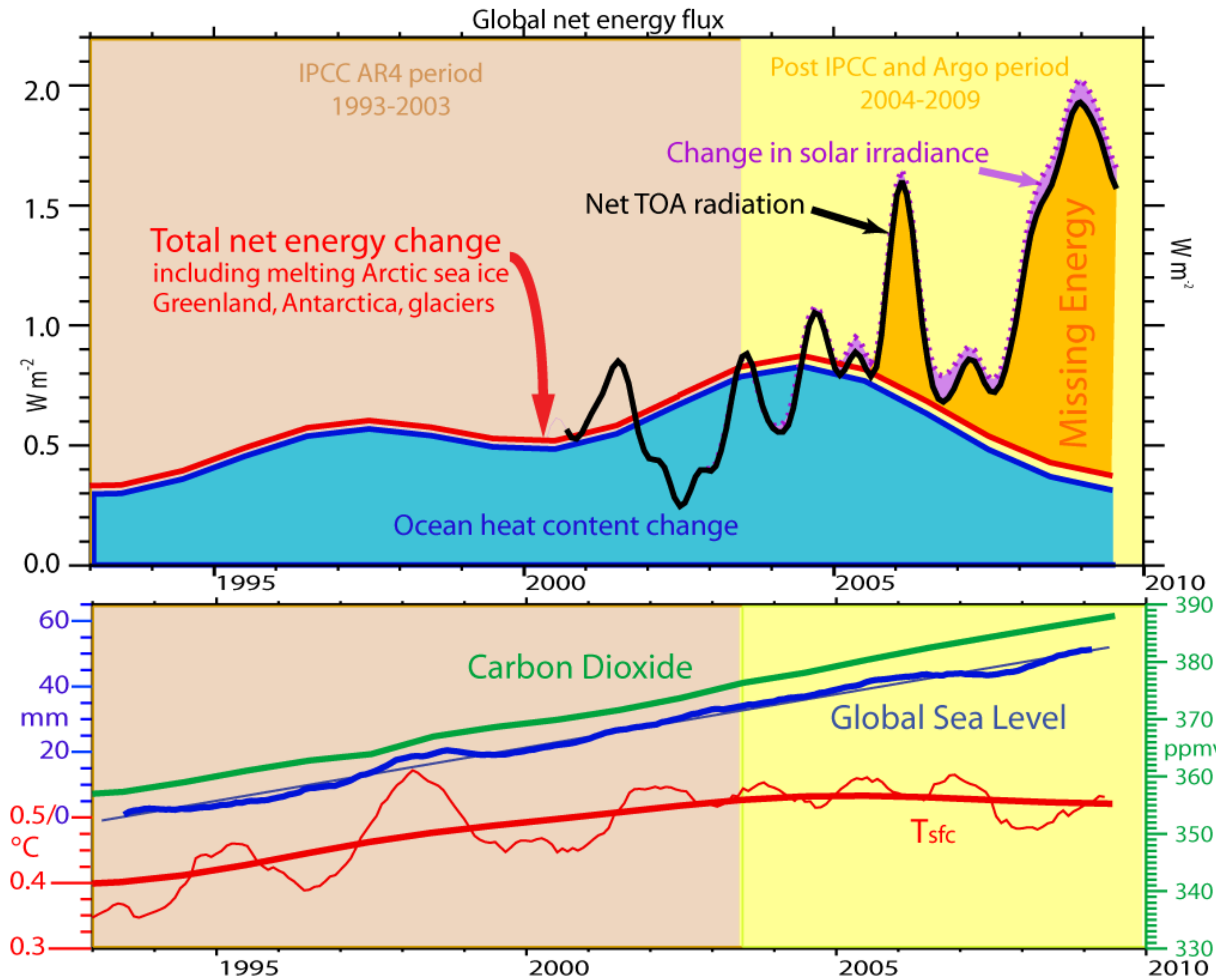

Figure 1. The disposition of energy entering the climate system is estimated. The observed changes (lower panel) show the 12-month running means of global mean surface temperature anomalies relative to 1901-2000 from NOAA (red (thin) and decadal (thick)) in °C (scale lower left), carbon dioxide concentrations (green) in ppmv from NOAA (scale right), and global sea level adjusted for Isostatic rebound from AVISO (blue, along with linear trend of 3.2 mm/yr) relative to 1993, scale at left in millimeters). Rates of change of global energy in W m^{-2} (top panel) are contrasted between the AR4-IPCC era 1993-2003 and the post-2003 Argo era. From 1992 to 2003 the decadal ocean heat content changes (10) (blue) along with the contributions from melting glaciers, ice caps, Greenland, Antarctica and Arctic sea ice plus small contributions from land and atmosphere warming (7) (red) suggest a total warming for the planet of 0.6±0.2 W m^{-2} (95% error bars) (10). After 2000, observations from TOA (9) (black) referenced to the 2000 values, show an increasing discrepancy (gold) relative to the total warming observed (red). The quiet sun changes in total solar irradiance reduce the net heating slightly (purple) but a large energy component is missing (gold). The decadal filter is from (4).

Supplementary material

The decadal low pass filter is a 13 term filter used in IPCC (2007; see p 336). This was also used for the TOA CERES monthly data, making it similar to a 12-month running mean.

The surface temperature record is presented as a 12 month running mean of anomalies relative to a 1901-2000 climatology. Monthly global surface temperature data are from NCDC, NOAA: http://www.ncdc.noaa.gov/oa/climate/research/anomalies/index.html

Global mean sea level data are from AVISO satellite altimetry data: http://www.aviso.oceanobs.com/en/news/ocean-indicators/mean-sea-level/

Carbon dioxide at Mauna Loa data are from NOAA http://www.esrl.noaa.gov/gmd/ccgg/trends/