HEAT STORAGE WITHIN THE EARTH SYSTEM

BY ROGER A. PIELKE SR.

The assessment of heat storage and its changes over time should be a focus of international climate monitoring programs.

This commentary describes how an examination of the global heat budget allows a straightforward explanation for understanding one of the consequences of human changes in the composition of the earth's atmosphere. Data and analysis provided in Levitus et al. (2000, 2001) on increases in heat stored within the world's oceans provide a unique opportunity to explore this perspective. The use of a global heat budget to assess this consequence of human perturbations of the earth system was also introduced in Pielke (2001b).

This note expresses the Levitus et al. data in terms of long-term, globally averaged values of heat flux (W m^{-2}), and relates the fluxes to the radiative forcing of the earth's climate system. These fluxes provide a constraint on estimates of radiative forcing such as provided by the Intergovernmental Panel on Climate Change (IPCC). Such an assessment of the global heat budget was provided in Peixoto and Oort (1992), based on the study of Ellis et al. (1978).

In this contribution, it is concluded that the IPCC would more effectively depict changes over time in the climate system by using a heat balance perspective in order to diagnose the earth's radiative imbalance. The application of such a perspective will require new priorities in global climate monitoring that are outlined in the conclusions.

Radiative forcing is defined by the IPCC as "a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth–atmosphere system, and is an index of the importance of the factor as a potential climate change mechanism. It is expressed in W m^{-2}."

The IPCC presents estimates of the change in radiative forcing of the climate system between 1750 and 2000 (Houghton et al. 2001; presented in Fig. 3 of the Statement for Policymakers and reproduced in this paper as Fig. 1). A continuous rate of 1.43 W m^{-2} of radiative forcing, for example, would correspond to a transfer of 2.33×10^{23} J of energy per decade into the climate system.

The Levitus et al. data provide an opportunity to assess the portion of this radiative forcing that is actually warming the earth system. To do this, the Levitus et al. ocean data is reported in W m^{-2}. Expressing their data in this manner provides a constraint on the net radiative forcing that results from the terms listed in Fig. 1.

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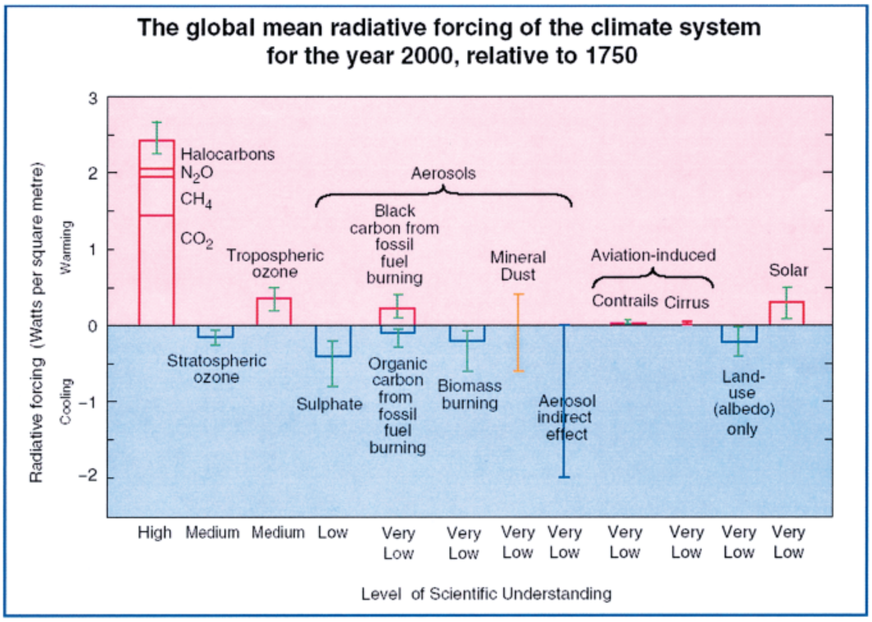

Fig. 1. Many external factors force climate change. [Figure 3 from Houghton et al. (2001).]

The heat budget for the earth system can be expressed as

$$\iint\limits_{t,A_{\mathrm{Earth}}} R_N dAdt = \iint\limits_{t,V_{\mathrm{atmos}}} QdVdt + \iint\limits_{t,V_{\mathrm{ocean}}} QdVdt + \text{other heat reservoirs}, \tag{1}$$

where R_N is the global mean nonequilibrium radiative forcing, A_{Earth} is the area of the earth, Q is the heating rate, V_{atmos} is the volume of the atmosphere, and V_{ocean} is the volume of the ocean.

Since the troposphere encompasses about 80%, of the mass of the atmosphere, Eq. (1) can also be integrated from the tropopause downward in order to relate more closely to the IPCC definition of radiative forcing of the earth system. It is important to note that R_N is not the quantity shown in Fig. 1, but is the instantaneous radiative flux divergence. Temperatures regionally within the earth system can change without a change in the left-hand side of Eq. (1). Cooling in one region can occur with warming elsewhere. However, unless the global mean nonequilibrium radiative forcing is nonzero, the earth system integrated heat will not change.

When radiative forcing changes, the earth system eventually reaches a new thermal equilibrium state (Cotton and Piekle 1995). Thus, any change in radiative forcing will involve two components: the fraction of the equilibrium response that has been achieved and the remaining radiative imbalance. The equilibrium component is reflected in changes in the earth system heat that have already occurred, and the imbalance component refers to heating or cooling of the earth system that continues.

With this interpolation, some portion of the anthropogenic greenhouse gas radiative forcing felt by the earth since 1750 has already resulted in warming of the earth. The rest of that forcing, the nonequilibrium forcing, R_N, is the relevant term for calculating changes from the present to some point in the future. This quantity is approximately equal to the additional heat stored in the ocean. The other heat reservoirs, such as sea ice and continental ice sheets, are assumed to be inconsequentially small, following Levitus et al. (2000). The radiative forcing of the system is a result of the left-hand side of (1). The first term on the right-hand side of Eq. (1) is also observed to be small (and essentially zero between the years of 1979–2001; more information is available online at www.ghcc.msfc.nasa.gov/temperature).

The use of Eq. (1) yields a different perspective of climate change than Raper et al. (2002), for example, who utilize global average surface air temperature along with a climate feedback parameter to evaluate the sensitivity of the earth system to atmospheric radiative forcing. Since Eq. (1) expresses a closed heat budget, however, feedback does not need to be estimated.

Figure 1 reproduced from Houghton et al. (2001) is missing important information because it fails to distinguish equilibrium from radiative imbalance forcing. Most of the radiative forcing portrayed has already been realized in the climate system. The labeling of the left axis with the terms “warming” and “cooling” could be misinterpreted to mean that the entire listed radiative forcing is continuing to warm or cool the earth system. A figure is needed that portrays the actual radiative forcing to the climate system that is felt at any particular time, in this instance in 2000. As this planetary energy imbalance is virtually the same as the energy stored in the top 3 km of the oceans, and other energy stores in the climate system are much smaller (Levitus et al. 2001), we can examine either the global mean nonequilibrium radiative flux or the ocean storage to evaluate this quantity. Peixoto and Oort (1992, p. 351) even concluded that such a relation exists between the radiative forcing and ocean heat storage over the annual timescale. They showed that the annual variation of net radiation at the top of the atmosphere is in good agreement, both in phase and amplitude, with the ocean heat storage.

The construction of such a figure using R_N would require, for instance, knowledge of the net flux at the top of the atmosphere, either averaged over the entire planet and averaged over a year, or instantaneously measured. In either case, direct observation of this quantity is difficult, given the required precision (0.1 W m^{-2}). An alternative approach is to use a model to calculate this quantity. However, aerosol effects, for example, are still poorly represented in the models. This lack of understanding is clearly evident in the uncertainty bars presented in Fig. 1. Thus, models also have a large uncertainty.

The Levitus et al. (2000) data given by 5-yr means and expressed in W m^{-2} are shown in Fig. 2. As evident in Fig. 2, the Levitus et al. observations have large positive and negative amplitudes over this time period. Satellite observations and models need to resolve this variability in order to improve our confidence in those tools.

One interesting consequence of displaying the data in W m^{-2} is that if a time period had zero heat storage change in the earth system, there would be no "unrealized warming," such as discussed, for example, by Wetherald et al. (2001). The concept encapsulated by the term "unrealized heating" more appropriately refers to storage of heat in a nonatmospheric reservoir (i.e., primarily the ocean), with the "realization" of the warming only occurring when heat is transferred into the atmosphere.

Short-term radiative imbalances can also be assessed. The Pinatubo volcano eruption of 1991, for instance, produced a radiative flux divergence of −4 W m^{-2} in August and September 1991, which gradually reduced to zero by March 1993 (Minnis et al. 1993). This effect resulted in a reduction of 5.64×10^{22} J of heating within the earth system [according to Eq. (1)].

When presenting observations, it is important to assess the accuracy of the observational data. S. Levitus (2001, personal communication) has concluded that the "decadal" variation in the upper 300 m is real. Below 300 m the amount of data decreases with depth, which is why the Levitus et al. (2000) paper used 5-yr running means. Thus, Fig. 2 should be interpreted as more of a challenge to modelers and observationalists than a confident diagnosis of the actual variations in heat content of the ocean on decadal timescales.

The observations for the period 1955–95 reported in Levitus et al. (2000) produce an average heating rate of about 0.3 W m^{-2}. The model values of Barnett et al. (2001) and Levitus et al. (2001) are close to the long-term value. However, the large decadal variability in the observations should raise concerns as to whether the models and observations agree over this time period for the right reasons. Moreover, from this perspective, the IPCC should present the magnitudes of planetary energy imbalance simulated by all of the models used in Houghton et al. (2001).

To be able to predict future climate change, in principle, it is necessary to be able to evaluate the actual current and future heating of the climate system from anthropogenic and natural sources as well as to evaluate where this heating is accumulating. For ex-

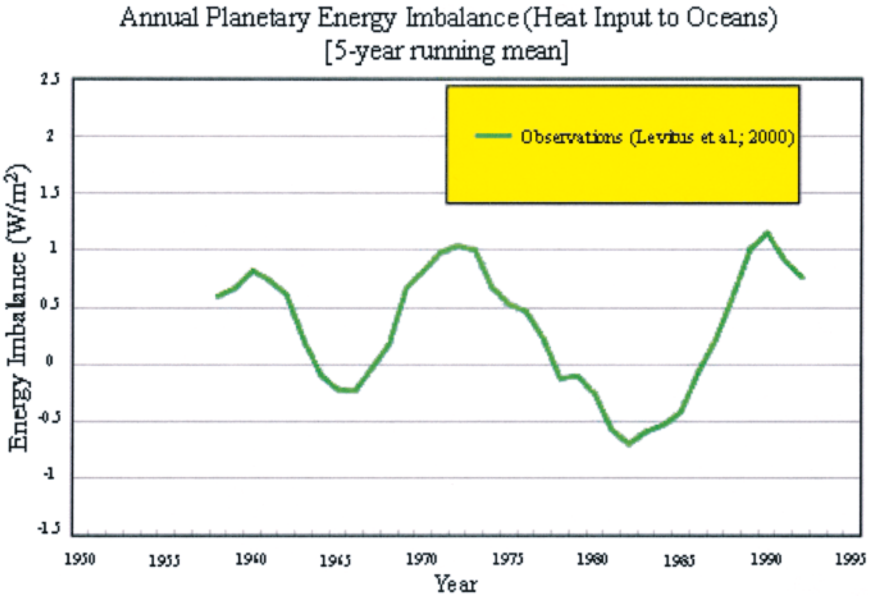

FIG. 2. Planetary energy imbalance (heat storage in the upper 3 km of the World Ocean) observations expressed in units of W m^{-2} (adapted from Levitus et al. 2001). (Figure prepared by A. Robock, Rutgers University, 2001, personal communication.)

ample, heat could be stored in the ocean at depths greater than 3 km (where observations were not reported in the Levitus et al. studies), instead of lost to space, through relatively small-scale areas of vertical turbulent mixing and three-dimensional mesoscale circulations. With coarse spatial resolution, GCMs might not be able to adequately simulate these modes of heat transfer. Moreover, the latest assessment of tropospheric heat (November 2002) shows that the atmosphere has returned to near its 1980 value, after the warm 1997–1998 ENSO event. This rapid cooling of the atmosphere, in terms of where the heat has gone, provides an example of why precise observations of the global heat content should be a scientific priority.

An assessment of the heat storage within the earth's climate system offers a unique perspective on global change. If the heat actually remains within the earth system in the deeper ocean, for example, while the heat content of the remainder of the heat reservoirs in the earth system remains unchanged, sudden transfers of the heat between components of the system (from the ocean into the atmosphere) could produce rapid, unanticipated changes in global weather. Similarly, relatively large warming and cooling radiative forcings (e.g., well-mixed greenhouse gases and the indirect effect of aerosols) could be in near balance at present, suggesting that sudden climate changes could occur if one of these forcings becomes dominant. On the other hand, a loss of space to a large portion of the increased radiative fluxes, as the atmosphere adjusts, such as through a change in cloud cover (e.g., Lindzen et al. 2001), would suggest that the climate system is relatively more resilient to continued anthropogenic heating effects than conventionally assumed.

The IPCC would present a more scientifically robust picture of the anthropogenic effect on the climate system by presenting a figure in terms of planetary energy imbalance in which observed changes in heat within the earth system would be used to constrain the global mean radiative forcing. The magnitude of heat within the earth's climate system to date also elevates the significance of anthropogenic land-use change as an influence on the global and regional climate (Chase et al. 2000; Pielke 2001a; Pielke 2002b), since this change appears to alter the long-term global atmospheric circulation even though the net average global changes in heat content may be small.

The assessment of the heat storage and its changes over time should be a focus of international climate monitoring programs. This includes extending the Levitus et al. data up to the present and achieving annual time resolution. The reduction of the uncertainties in the global mean radiative forcing is also a clear priority. This requires improved monitoring of the agents of this forcing, including aerosols and their influences on cloud microphysical processes.

In conclusion, there are several major reasons that the assessment of the earth system's heat budget is so valuable.

- The earth's heat budget observations, within the limits of their representativeness and accuracy, provide an observational constraint on the radiative forcing imposed in retrospective climate modeling.
- A snapshot at any time documents the accumulated heat content and its change since the last assessment. Unlike temperature, at some specific level of the ocean, land, or the atmosphere, in which there is a time lag in its response to radiative forcing, there are no time lags associated with heat changes.
- Since the surface temperature is a two-dimensional global field, while heat content involves volume integrals, as shown by Eq. (1), the utilization of surface temperature as a monitor of the earth system climate change is not particularly useful in evaluating the heat storage changes to the earth system. The heat storage changes, rather than surface temperatures, should be used to determine what fraction of the radiative fluxes at the top of the atmosphere are in radiative equilibrium. Of course, since surface temperature has such an important impact on human activities, its accurate monitoring should remain a focus of climate research (Pielke et al. 2002a).

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REFERENCES

Barnett, T. P., D. W. Pierce, and R. Schnur, 2001: Detection of anthropogenic climate. Change in the world's oceans. *Science,* **292,** 270–274.

Chase, T. N., R. A. Pielke Sr., T. G. F. Kittel, R. R. Nemani, and S. R. Running, 2000: Simulated impacts of historical land cover changes on global climate in northern winter. *Climate Dyn.,* **16,** 93–105.

Cotton, W. R., and R. A. Pielke Sr., 1995: *Human Impacts on Weather and Climate.* Cambridge University Press, 288 pp.

Ellis, J. S., T. H. Vonder Haar, S. Levitus, and A. H. Oort, 1978: The annual variation in the global heat balance of the earth. *J. Geophys. Res.,* **83,** 1958–1962.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, Eds., 2001: Summary for policymakers. A Report of Working Group I of the Intergovernmental Panel on Climate Change, 20 pp. [Available online at http://www.ipcc.ch.]

Levitus, S., J. I. Antonov, T. P. Boyer, and C. Stephens, 2000: Warming the world ocean. *Science,* **287,** 2225–2229.

——, ——, J. Wang, T. L. Delworth, K. W. Dixon, and A. J. Broccoli, 2001: Anthropogenic warming of Earth's climate system. *Science,* **292,** 267–270.

Lindzen, R. S., M.-D. Chou, and A. Y. Hou, 2001: Does the earth have an adaptive infrared Iris? *Bull. Amer. Meteor. Soc.,* **82,** 417–432.

Minnis, P., E. F. Harrison, L. L. Stowe, G. G. Gibson, F. M. Denn, D. R. Doelling, and W. L. Smith Jr., 1993: Radiative climate forcing by the Mount Pinatubo eruption. *Science,* **259,** 1411–1415.

Pielke, R. A., Sr., 2001a: Comments on "IPCC report cautiously warns of potentially dramatic climate change impacts." *Eos, Trans. Amer. Geophys. Union,* **82,** 394, 396.

——, 2001b: Earth system modeling—An integrated assessment tool for environmental studies. *Present and Future of Modeling Global Environmental Change: Toward Integrated Modeling,* T. Matsuno and H. Kida, Eds., Terra Scientific Publishing Company, 311–337.

——, and Coauthors, 2002a: Problems in evaluating regional and local trends in temperature: An example from eastern Colorado, USA. *Int. J. Climatol.,* **22,** 421–434.

——, G. Marland, R. A. Betts, T. N. Chase, J. L. Eastman, J. O. Niles, D. Niyogi, and S. Running, 2002b: The influence of land-use change and landscape dynamics on the climate system—relevance to climate change policy beyond the radiative effect of greenhouse gases. *Phil. Trans. A. Special Theme Issue,* **360,** 1705–1719.

Piexoto, J. P., and A. H. Oort, 1992: *Physics of Climate.* American Institute of Physics, 520 pp.

Raper, S. C. B., J. M. Gregory, and R. J. Stouffer, 2002: The role of climate sensitivity and ocean heat uptake on AOGCM transient temperature response. *J. Climate,* **15,** 124–130.

Wetherald, R. T., R. J. Stouffer, and K. W. Dixon, 2001: Committed warming and its implications for climate change. *Geophys. Res. Lett.,* **28,** 1535–1538.