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Climate and Earth's Energy Flows

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Abstract Under equilibrium conditions, climate can be viewed in simple terms as the average energy pathways that incoming solar radiation takes before exiting the system in order to maintain overall energy balance. Similarly, future climate change will ultimately be determined by how the Earth's energy balance and average energy pathways change in response to external radiative forcings, such as anthropogenic greenhouse gases, and internal redistributions. Here, we give an overview of climate research in the context of Earth's energy flows and make the case for improved observations of total energy as a more physically robust metric of climate change than the commonly used surface temperature record.

Keywords Climate · Energy · Oceans · Ocean heat content · Radiation

1 Background

Energy is the currency of Earth's climate system. The non-uniform absorption of incoming solar energy gives rise to equator-to-pole surface temperature gradients that drive the planetary large-scale circulation of both the atmosphere and ocean. For an equilibrium climate, the long-term (e.g., century timescale) net top-of-atmosphere radiation (TOA) is zero. That is, the amount of incoming shortwave solar radiation is balanced by the reflected outgoing shortwave radiation and emitted longwave radiation. In some sense, an equilibrium climate state can be defined by the "average" pathways of the incoming solar energy, before it leaves the system (e.g., Trenberth and Fasullo 2011, this volume, Fig. 1).

Multi-century climate model simulations show that, about such an equilibrium state, the system generates internal variability—transient fluctuations in TOA and other important climate variables, such as surface temperature. At timescales of days or weeks, internal variability is dominated by weather systems and the chaotic nature of the atmospheric circulation. At timescales of years to decades, internal variability is associated with large-

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scale ocean–atmosphere modes, such as the El-Nino Southern Oscillation (McPhaden et al. 2006), the North Atlantic Oscillation (Hurrell et al. 2001), the Southern Annular Mode (Connolley 1997) and the Atlantic Multi-decadal Oscillation (Knight et al. 2005). All such modes of variability redistribute energy within the ocean and among other climate system components. This internally generated "noise" of the climate system is an important concept when interpreting observed or simulated climate changes.

At its simplest, climate change arises when an equilibrium climate is perturbed by an external forcing, so that the net TOA, and therefore the net convergence/divergence of energy into the system, is no longer zero. Changes in total solar irradiance, natural or anthropogenic aerosols and concentrations of atmospheric greenhouses can all contribute to "external" forcing of the climate system. The relative importance of these various factors in shaping Earth's climate record can be assessed under the framework of detection and attribution (Hegerl et al. 2007). This framework also provides a means of quantitatively assessing global climate model performance and has potential to reduce the large range of climate projections by scaling model projections using observational constraints (e.g., Stott and Forest 2007).

A standard metric used to interpret climate change projections is climate sensitivity, which is defined as the equilibrium response of global surface temperature to an imposed change in radiative forcing (e.g., a doubling of carbon dioxide concentrations, relative to pre-industrial levels, Meehl et al. 2011). Thus, models with high climate sensitivity will predict a greater surface temperature rise for a given CO_2 emissions scenario than those with low climate sensitivity. The climate response is determined by the strength of the climate feedbacks (Stocker et al. 2001), and how these affect the global energy balance. In reality, CO_2 emissions will continue to evolve and are unlikely to remain constant for any length of time. Therefore, additional terms, such as the rate of ocean heat uptake, are important for determining the rate of surface temperature rise (Raper et al. 2002). In essence then, climate change projections are ultimately dependent on how the energy pathways change in response to increased greenhouse gas concentrations (and other external forcings, such as anthropogenic aerosols).

2 Observing Earth's Energy Budget

There are fundamentally two ways in which we can estimate Earth's energy budget. The first is to measure the net energy flux (TOA) using direct satellite measurement of the incoming and outgoing radiation. The second is to estimate the energy storage terms, which on decadal and longer timescales is dominated by accumulation of heat within the global ocean (Bindoff et al. 2007; see also Trenberth and Fasullo 2011, this volume). The two approaches are highly complementary and make use of independent observational data sets. The ability to cross-reference these estimates provides an important means to diagnose the presence of systematic errors in the global climate observing system.

The first satellite measurements targeted at measuring Earth's radiation balance date back to 1975 and the launch of NASA's Earth Radiation Budget (ERB) instrument onboard the Nimbus-6 and Nimbus-7 satellites (Jacobowitz et al. 1979). This was followed in the 1980s by NASA's Earth Radiation Budget Experiment mission (ERBE; Barkstrom 1984). More recently, several international efforts have contributed measurements and improved understanding of Earth's radiation balance. These include the Clouds and Earth's Radiant Energy System (CERES; Wielicki et al. 1996); the Scanner for Radiation Budget (ScaRaB; Kandel et al. 1998); and the Geostationary Earth Radiation Budget Project (GERB; Harries et al. 2005). The great virtue of satellite observations is the spatial coverage they provide, although temporal sampling can be problematic for non-geostationary platforms. However, absolute calibration of satellite instruments makes estimating the residual of the globally integrated radiation terms a challenge. In addition, biases between different satellite sensors can introduce spurious climate signals unless great care is taken. Loeb et al. (2011, this volume) discuss the need to inter-calibrate successive satellite missions and document the progress being made toward development of a homogeneous climate record for the CERES data sets.

The accumulation of energy in the Earth System associated with anthropogenic global warming is manifest in numerous climate variables, including rising ocean heat content, global sea level, near surface temperature, reduced sea-ice coverage, ice-cap and glacial mass loss (e.g., Kennedy et al. 2010). However, in energetic terms, by far, the single largest term is associated with increased ocean heat storage (Bindoff et al. 2007). Recent attempts to quantify the rate of heat uptake using in situ observations in the 0–700 m layer represent an energy accumulation equivalent to a radiative forcing of 0.64 ± 0.11 W m^{-2} for the period 1993–2008 (Lyman et al. 2010). The largest single contribution to the uncertainty arises from bias correction of the expendable bathythermograph (XBT) measurements, which dominate the observational database for the 1970s to 2000s. As such, it may be possible to reduce this uncertainty if better agreement can be reached among a group of researchers actively developing new XBT corrections. Lyman (2011, this volume) explores to what extent ocean heat content changes are constrained by the in situ observations on shorter timescales.

3 Observing and Modeling Earth's Energy Flows

The preceding section has focused on Earth's energy budget. Of equal importance to our understanding of the climate system is the way in which the incoming solar radiation is redistributed and how this redistribution might change in response to anthropogenic climate change.

Our most comprehensive estimates of the atmospheric circulation over the twentieth century come from atmospheric reanalyses (e.g., Kalnay et al. 1996; Uppala et al. 2005). These are essentially the same data assimilation models used for weather forecasting, but often used at a lower spatial resolution in order to facilitate a continuous run over 40 years or more (e.g., Compo et al. 2006) to estimate the historical atmospheric state. The most sophisticated systems ingest a large suite of in situ and satellite measurements, but are fundamentally poorly constrained in areas with few historical observations, such as the polar regions.

One must be cautious in the application of atmospheric reanalysis data for studying Earth's energy flows and climate, in general, for a number of reasons. Reanalyses often use prescribed SSTs as the lower boundary condition, which provide an infinite source of heat and freshwater to the simulated atmosphere. Therefore, these models do not conserve heat or freshwater, and many have unrealistic TOA imbalances (Trenberth et al. 2009, 2011). In addition, inhomogeneous input observations and biases in the underlying physical models can limit the utility of reanalyses for studying climate and climate change, as discussed by Bengtson et al. (2007).

With careful consideration of the limitations described above, reanalyses are still a useful tool for informing us about part of Earth's energy flows. Trenberth et al. (2009) have presented an updated estimate of Earth's annual mean energy budget for the period

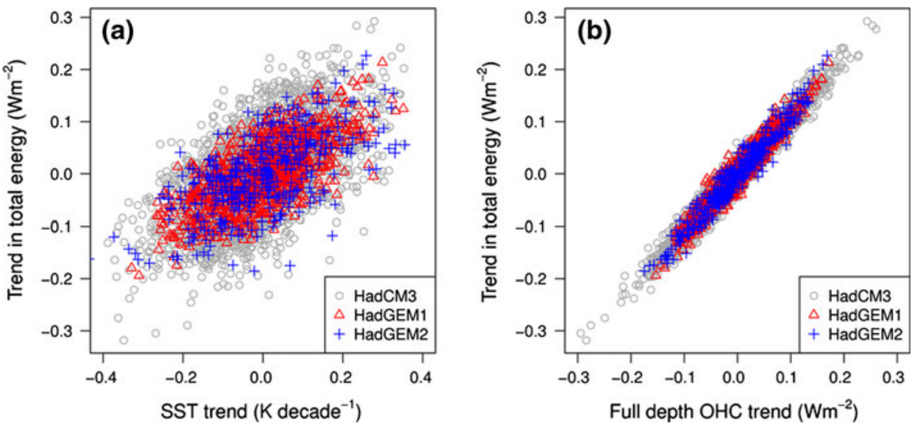

Fig. 1 Plot of linear decadal trends in total energy (W m^{-2}) regressed against: **a** decadal trends in globally averaged sea surface temperature (SST, K decade^{-1}) and **b** decadal trends in full-depth ocean heat content (OHC, W m^{-2}). Note that the trend in total energy is equivalent to the average top-of-atmosphere radiation balance (TOA) over the same period. Figure reproduced from Palmer et al. (2011)

2000–2005 based on new CERES measurements (see Trenberth and Fasullo 2011, Fig. 1, this volume) in combination with a wide range of observational and reanalysis data sources. However, there is not universal agreement among the research community on the values presented by Trenberth et al. (2009), and discussions have highlighted the need to work toward error bars for each of the energy flow terms presented by the authors (see Stevens and Schwartz 2011, this volume). In particular, Kato et al. (2011, this volume) suggest a total downwelling longwave radiation of 347 ± 7 W m^{-2} based on Cloudsat measurements (Stephens et al. 2002). This value is substantially larger than the 333 W m^{-2} put forward by Trenberth et al. (2009), but it remains unclear where the difference between these terms can be accounted for in the energy budget.

Contrary to atmospheric reanalyses, coupled climate models provide a physically consistent representation of the Earth System that conserves heat and freshwater. Since these tools are the primary means by which we make projections of future climate change, it is essential to evaluate their performance against current observations. Evaluating the top-of-atmosphere and surface energy budgets of climate models against observations provides a powerful means of diagnosing model errors. Trenberth and Fasullo (2010) have performed such an analysis using the CERES observations. The authors report that many of the models used in the AR4 show a similar systematic bias in surface downward shortwave radiation over the Southern Ocean that is also seen in atmospheric reanalyses. This bias in absorbed solar radiation arises mainly from a lack of mid-level cloud that is common feature of many state-of-the-art atmospheric models. The associated increase in sea surface temperature reduces poleward temperature gradients and leads to anomalously low southward ocean heat transport. These model deficiencies undermine projected changes in Southern Hemisphere cloud changes and migration of storm tracks.

4 Total Energy as a Metric for Climate Change

In recent years, there has been considerable controversy surrounding the reduced rate of surface temperature rise over the first decade of the twenty first century (e.g., Willet et al.

2010). A similar reduction in the rate of ocean heat uptake is also apparent in the estimate of Lyman et al. (2010), although it remains questionable whether this feature is statistically significant. The 0–700 m layer changes reported by Lyman et al. (2010) represent only the upper 15–20% of the full ocean depth, and this has motivated studies to look into the relationships between globally averaged temperature, TOA and full-depth ocean heat content in coupled climate model simulations. On decadal to multi-decadal timescales, the essential balance in the Earth System is between total ocean heat content, which is the primary energy storage term (Bindoff et al. 2007), and TOA, which is the total energy flux entering or leaving the system.

Trenberth and Fasullo (2011, this volume) and Katsman and van Oldenborgh (2011) demonstrate that in the presence of anthropogenic global warming, hiatuses in surface temperature rise are associated with increased heat export to the deeper ocean. These findings are supported by the work of Palmer et al. (2011), who find that decadal trends in surface temperature place a relatively weak constraint on TOA over the same period (Fig. 1). These studies highlight the ability of the ocean to re-arrange large quantities of heat on decadal timescales through internal variability. The implication is that the recent hiatus in surface temperature rise may not require us to invoke changes in external forcings as the primary explanation (although these may have also played a role). In addition, these studies point toward measurement of accumulated energy in the Earth System as a more robust metric of anthropogenic global warming than surface temperature.

5 Summary

A key goal of weather and climate research is to understand how internal variability and external forcings contribute to changes in TOA and the flow of energy within the Earth system on a range of timescales. This goal will ultimately be reached through a combination of improved Earth system observation and numerical model simulations. Central to these aims are the continuation of CERES-like TOA measurements (Loeb et al. 2011, this volume) and the development of a deep ocean observing array to better constrain future ocean heat content change (Palmer et al. 2010; Garzoli et al. 2010). These observations will help us to improve coupled climate models, understand their shortcomings and ultimately make better projections of changes in Earth's energy budget and how the energy redistribution pathways may change under anthropogenic climate change.

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