**Observing Earth’s Energy and Water Cycles**

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**1.0 Introduction**

It is widely recognized that climate change is a defining issue of this century. Accordingly, a key objective of NASA’s Science Plan for the Science Mission Directorate is to improve the understanding and prediction of climate. Fundamentally, climate change involves a perturbation to Earth’s energy budget, which in turn impacts Earth’s water cycle. Changes in the composition of the atmosphere either through natural or anthropogenic sources alter how energy is distributed within the Earth’s system and can lead to irreversible changes in regional climate. Because climate is a global problem, satellites play a key role in climate research.

At the TOA the energy budget involves a balance between how much solar energy Earth absorbs and how much terrestrial thermal infrared radiation is emitted to space. NASA’s long history in observing the TOA ERB is acknowledged in the 2007 and 2013 reports of the IPCC (IPCC 2007, 2013), the 2007 NRC Decadal Survey (NRC 2007), and the GCOS implementation plan of the WMO (GCOS 2004). A key reason for NASA’s success in this area is due to its support of the CERES Project and its predecessor, ERBE. These projects have provided vital data for climate model evaluation and improvement over the past 3 decades.

At the surface, the energy budget involves a balance between net radiation, sensible and latent heat, and heat storage, primarily in the ocean. On average, the radiation heats the surface and cools the atmosphere, which is balanced by the hydrological cycle and sensible heating. Regional variations in the energy budget such as the equator-to-pole gradient give rise to the general circulation of the atmosphere and oceans.

Here we briefly discuss some of the key challenges and questions related to Earth’s energy and water cycles with a focus on the observations needed to support research in these areas.

**2. Earth’s Energy Imbalance (EEI)**

Approximately 30% of the incident solar radiation reaching Earth is scattered back to space by clouds, the Earth’s surface, and aerosols. The remaining 70% is absorbed by the surface-atmosphere system, providing the energy necessary to sustain life on Earth. The ASR is converted into different forms of energy (e.g., potential, internal, latent, and kinetic energy), and transported and stored throughout the system. In order to maintain a relatively stable temperature, the Earth also emits thermal infrared radiation to space as OLR. In an equilibrium climate, there is a global balance between ASR and OLR. When the climate system is forced by natural or anthropogenic factors, an imbalance in the TOA ERB results. Climate forcings that impact EEI include changes in the solar output, large volcanic eruptions, and human activities. Combined CERES and oceanic measurements indicate that there is a positive energy imbalance in which ASR exceeds OLR by 0.6 Wm-2 during the first decade of the 21st century (Loeb et al., 2012). Approximately 93% of the excess energy is stored in the ocean. A positive EEI is associated with global temperature rise, sea-level rise and an acceleration of the hydrological cycle. EEI is thus a fundamental metric of global climate change that is in many ways a more useful quantity than global surface temperature as it provides a measure of the net climate forcing acting on Earth (Hansen et al., 2005).

Monitoring how EEI changes with time and understanding what is driving the changes are critically important climate problems. Owing to internal variations in the climate system, EEI needs to be observed over a wide range of time and space scales as internal variations can mask a longer-term climate signal. Currently, the best strategy to observe EEI involves synergistic use of satellite TOA radiation observations and recently improved ocean heat content measurements. In-situ ocean measurements provide the magnitude of EEI, but require 5 or more years to reduce uncertainties to a few tenths of 1 Wm-2 due to sampling uncertainties. Conversely, satellite measurements provide global coverage daily and are highly stable radiometrically, but cannot provide an absolute measure of the EEI to the required accuracy level, as the observed ASR and OLR are well over two orders of magnitude larger than the EEI. The solution is to anchor the satellite-based EEI to that obtained from in-situ ocean heating rate measurements acquired over at least a 5-year period of well-sampled in-situ measurements, accounting also for smaller contributions from ocean heat storage in the deep ocean, ice warming and melt, and atmospheric and lithospheric warming. Loeb et al. (2012) use this approach with CERES observations and in-situ Argo measurements acquired after 2005 to track monthly changes in EEI during the CERES period.

A key challenge is to maintain the measurement systems to accurately monitor EEI over multiple decades. The CERES observations began in 2000 with the Terra launch, which was followed by Aqua and S-NPP launches in 2002 and 2011, respectively. There is also a CERES instrument that will launch on JPSS-1 in 2016, and a follow-on ERB instrument called RBI to be launched on JPSS-2 in 2021. In order to ensure the EEI record extends to the late 2020s and beyond requires that multiple copies of RBI be built and preferably flown on satellites that also carry an imager instrument with capabilities comparable to or better than those of MODIS or VIIRS. The CERES processing system combines CERES with imager data to improve the accuracy of the TOA fluxes, to enable improved attribution of what causes changes in the TOA ERB, and to estimate radiative fluxes at the surface.

**3. Closing the Surface Energy Budget with Observations**

Using the best observational estimates of surface radiation and sensible and latent heat fluxes, there remains a 15 Wm-2 bias in the global surface energy budget. This represents approximately 20% of the global mean precipitation rate when converted into latent heating. Regionally, the imbalance is most pronounced in the tropics over regions of convection (e.g., west tropical Pacific Ocean, ITCZ, SPCZ) (Loeb et al., 2014). The bias falls outside of the envelope of observational uncertainty when the stated errors in the individual datasets are combined (Kato et al., 2015). The observations include satellite precipitation (GPCP, TRMM, GPM), satellite-derived surface radiative fluxes, including a combination of many different instruments (CERES, MODIS/VIIRS, geostationary VIS/IR imagers, CALIPSO/Cloudsat), satellite and/or reanalysis-based surface latent heat fluxes, reanalysis-based sensible heat fluxes, and satellite TOA fluxes (CERES) to constrain atmosphere heating/cooling and SW surface fluxes. Some of the limitations in the observations include: precipitation algorithm dependence on rainfall drop size distribution; precipitation accuracy for drizzle, snowfall and heavy precipitation; a lack of reliable ground truth precipitation data over ocean; uncertainties in the input data stream used to compute surface radiative fluxes (reanalysis-based temperature/humidity profiles and skin temperatures, imager-based cloud and aerosol retrievals; surface albedo); and a lack of high-accuracy surface radiation measurements over open ocean and polar regions for quantifying errors in satellite surface fluxes.

In the near-term, there is a need for studies of the observational requirements to verify GPM drop size distribution assumptions to achieve stable probability distributions as a function of precipitation type/meteorological state. Studies are also needed to assess the utility and sampling requirements of long duration polar flights of ER-2 with multifrequency Doppler radar observations to estimate polar precipitation, drizzle, and snow. These studies might be accomplished with large domain Cloud Resolving Model runs with multi-moment cloud and rainfall size distributions. Studies of the long-term average (monthly and annual) accuracies of BSRN and ocean buoy surface radiative fluxes are also needed.

**4. Changes over the Arctic**

While the marked decline in sea ice and increased warming over the Arctic in recent decades are well documented, the underlying processes are poorly understood owing to a lack of reliable observations. There remains substantial uncertainty about whether clouds are reducing or increasing the rapid warming in the Arctic, especially during autumn and winter. The surface energy budget is poorly constrained, particularly in the thermal infrared owing to unreliable near-surface temperature/humidity data. The region is also challenging because it is influenced by pronounced internal variability, which means a long observational record is needed in order to provide robust conclusions from the data. This poses a major remote sensing challenge, as the longest available satellite records providing cloud information are from visible/infrared imagers, which are less reliable at high latitudes. Furthermore, due to the lack of reliable measurements and poor model representation, there is substantial uncertainty in temperature/humidity profiles from reanalyses. Nevertheless, the rapid reduction of sea ice extent is changing the radiation environment so rapidly that CERES TOA SW and LW flux trends are statistically significant after only 12 years of observations (Hartmann and Ceppi, 2014).

In the near-term, there is a need to further exploit current observations from the A-train and prepare for the upcoming EarthCARE mission, which will provide new active satellite measurements. Field experiments are essential for providing focused cloud, surface, and temperature/humidity and radiative flux measurements to help improve satellite-derived surface fluxes and cloud retrievals. Longer term, there is a critical need to plan for continued active sensors beyond the EarthCARE mission.

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**List of Acronyms**

ASR Absorbed Solar Radiation

BSRN Baseline Surface Radiation Network

CALIPSO Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations

CERES Clouds and the Earth’s Radiant Energy System

EEI Earth’s Energy Imbalance

ERB Earth Radiation Budget

ERBE Earth Radiation Budget Experiment

GCOS Global Climate Observing System

GPCP Global Precipitation Climatology Project

GPM Global Precipitation Measurement

IPCC Intergovernmental Panel on Climate Change

ITCZ Intertropical Convergence Zone

JPSS Joint Polar Satellite System

MODIS Moderate-Resolution Imaging Spectroradiometer

NRC National Research Council

OLR Outgoing Longwave Radiation

RBI Radiation Budget Instrument

S-NPP Suomi National Polar-orbiting Partnership

SPCZ South Pacific Convergence Zone

TOA Top-of-Atmosphere

TRMM Tropical Rainfall Measuring Mission

VIIRS Visible Infrared Imaging Radiometer Suite

WMO World Meteorological Organization