

Analyzing the Variations of the Global Ocean Energy Cycle

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The Earth's climate is an energy cycle that converts absorbed solar radiation into heat and associated terrestrial radiation and into the circulations of the atmosphere and ocean. A key exchange of energy within the system, which also couples the circulations of the atmosphere and ocean, is between the surface and the atmosphere, primarily through evaporation cooling of the surface and precipitation heating of the atmosphere, forming a water cycle intimately linked to the planetary energy cycle. Because of Earth's spherical shape, rapid rotation and elliptical orbit about the sun, the solar heating is neither uniform nor constant. Because of the turbulent nature of the atmospheric and oceanic motions that transport heat and water with very different characteristic times scales, the response of the system is neither steady nor in instantaneous balance. Although some statistics of the variations of energy and water exchanges among the several climate system components may be static, the energy-water cycle is fundamentally dynamic.

Basic questions about the climate are: how variable is the climate with a "statistically steady" forcing (natural variability) and how sensitive is the climate to systematic changes in the forcing (climate change)? The latter is determined by numerous feedback processes that operate to alter the exchanges of energy and water within the system and with the outside but, in the truly dynamic climate system, the former is also influenced by these same processes. To learn the answers to these questions, therefore, we must observe the varying relationships amongst the components of the climate system and diagnose the variations of their exchanges of energy and water to determine how they regulate and modulate the climate response to forcing. For this purpose, the observations must have a combination of high space-time resolution and global, long-term coverage that can only be provided, in practice, by systematic satellite observations. The former is required to resolve accurately the energy and water exchange variations at the weather-process-level and the latter is required to provide enough examples of the different possible configurations of the climate system to understand the range of multi-variate, non-linear relationships that are produced by the interactions of the processes.

To describe the complete energy-water cycle requires measurements of the thermodynamic state of all the climate components and the hydrodynamic state of the atmosphere and ocean, as well as all the properties of them that affect the energy and water exchanges. The state is described by the 4-dimensional distribution of temperature, humidity and winds in the atmosphere, of the temperature, salinity and currents in the ocean and the temperature and "water content" of the land and ice. To calculate the exchanges of energy requires determination of the tendencies of the state variables and their atmospheric and oceanic transports which are functions of spatial derivatives of these variables. Additional properties that are needed to calculate radiative exchanges are the gas composition of the atmosphere (including the main greenhouse gases), aerosols, clouds and surface spectral albedo/emissivity. The main additional quantities to determine the water cycle are precipitation (rain and snow), evaporation,

water storage on the land as snow/ice and in the deep aquifer, as well as water runoff from the land to the ocean.

The state of the ocean has been observed very sparsely for the past many decades but only recently have these data been compiled to provide a comprehensive description of the state and circulation of the ocean. The World Climate Research Program (WCRP) was established, in part, to coordinate activities to develop a number of datasets that were missing for describing the energy-water cycle [GARP 1975]. Among the first WCRP activities were projects to determine the thermodynamic state of the world ocean (the World Ocean Circulation Experiment, WOCE) and to study the coupling between the tropical oceans and global atmosphere (Tropical Ocean Global Atmosphere, TOGA). These studies are continuing as part of the Climate Variations (CLIVAR) project. Several other projects, now collected under the Global Energy and Water Experiment (GEWEX), have produced a collection of cloud, precipitation, aerosol and radiative flux products that can provide important information about ocean-atmosphere exchanges of energy and water (Table 1, see Rossow *et al.* [2006]). A newer initiative under GEWEX includes a project (SeaFlux) to determine the turbulent fluxes of heat and water at the ocean surface [Curry *et al.* 2004].

As one illustration of analyses that can be done with this set of data products, Figure 1 shows the decadal variations (anomaly relative to 1993) of the global mean heat content of the upper ocean, diagnosed from buoy and satellite observations (Willis *et al.* [2004], updated, private communication), compared with the heat content variation inferred from the total surface energy fluxes, based on the GEWEX Surface Radiation Budget product (SRB, Stackhouse *et al.* [2001]) and the GSSTF2 turbulent fluxes [Chou *et al.* 2003]. Such a diagnostic approach for the heat budget has been advocated by Pielke [2003]. Levitus *et al.* [2000] has compiled a longer record of ocean heat content. Given the “large” uncertainties associated with these data products, it is no wonder that these results do not yet agree but the magnitude of the differences is much smaller than expected. Moreover, the surface flux products have known sources of uncertainty that can be worked on to improve them; in particular the surface latent heat flux products based on satellite microwave measurements appear to have an excessively strong increase (cooling) over this time period associated with known problems of calibration.

Using six different combination-datasets (two different surface radiative flux products, ISCCP-FD and SRB [Stackhouse *et al.* 2001] and three different surface turbulent flux products, GSSTF2, HOAPS [Grassl *et al.* 2000] and WHOI [Yu *et al.* 2004]), we can estimate the mean meridional heat transport of the global oceans (Figure 2), where the error bars indicate the spread of estimates obtained from these different data combinations (*cf.* Zhang and Rossow [1997]). The uncertainties are particularly significant in the southern oceans and are primarily caused by differences among the turbulent flux data products (*cf.* Chou *et al.* [2004]) rather than the surface radiative flux products (*cf.* Zhang *et al.* [2006]).

Figure 3 shows the anomalies in the total (atmosphere plus ocean) meridional energy transport over the past two decades inferred from the ISCCP-FD reconstruction of top-of-atmosphere radiative fluxes, which agrees very well [Zhang *et al.* 2004] with directly inferred anomalies at lower latitudes from ERBE [Wong *et al.* 2006]. The uncertainties in the surface fluxes currently preclude a definitive separation of these features into separate atmospheric and oceanic contributions, but the association with ENSO events is clear, although variable. The higher latitude location of the transport anomalies in 1998/99, as contrasted with generally lower latitude anomalies during other events, suggests the possibility that the former event was dominated by a change in atmospheric heat transport while the earlier events were dominated by

changes in oceanic heat transport. If the quality of these products can be improved by further evaluation and systematic re-processing, then this difference could be investigated further.

To stimulate more extensive analyses of the variations of the global energy-water cycle and the processes that influence them, as well as re-processing of these products to improve their reliability, the GEWEX Radiation Panel is organizing a complete set, at least one dataset for each of the components of the energy-water cycle, in two forms. The first is a summary of the datasets in the form of monthly mean global maps, all in the same grid covering the same time period, posted on and downloadable from the GRP web site (<http://grp.giss.nasa.gov/gewexdsets.html>). The second is providing access to the original versions of these datasets (with a variety of map grids, sampling intervals and periods covered), starting with the four GRP products for radiation, precipitation, clouds and aerosols, on an active server to be hosted by NCDC. The online summary is now available and the datasets are being assembled for the server and should be available by the end of in 2007. This collection could form the core of a larger climate dataset, if datasets are added by other components of the World Climate Research Program such as CLIVAR.

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Table 1

Some available global, long-term datasets that can be used to quantify variations of the global energy-water cycle. Most of these are being produced or studied in GEWEX activities; references and relevant web site addresses for these datasets can be found on the GEWEX Radiation Panel web site at <http://grp.giss.nasa.gov/gewexdsets.html>). Additional products (not all mentioned below) are being studied in CLIVAR activities. Asterisks indicate datasets to be provided on the NCDC active server.

| E&W Cycle Element Dataset Names | Period Covered | Sampling Spatial (km) | Time (hrs) |
|--|---------------------------|--------------------------|------------|
| Atmospheric State | | | |
| *TOVS (no winds) | 1979-current | 280 | 24 |
| *NCEP/NCAR ERA-40 | 1948-current 1963-2003 | 280 280 | 6 6 |
| Clouds | | | |
| *ISCCP | 1983-2005 | 280 | 3 |
| SOBS | 1971-1996 | 280-560 | 3-24 |
| Ozone | | | |
| TOMS | 1978-2003 | 110 | 24 |
| *SBUV | 1978-2005 | 280 | 24 |
| SAGE II | 1979-2005 | 560 | month |
| Trace Gases | | | |
| CO ₂ , CH ₄ , etc. | 1958-current | global | month |
| Aerosols | | | |
| *GACP (ocean only) | 1981-2004 | 280 | month |
| *NOAA aerosol (ocean only) | 1995-2005 | 110 | 24 |
| SAGE II (strat.) | 1984-2005 | 560 | month |
| Radiation | | | |
| NIMBUS-7 (TOA) | 1978-1985 | 280 | 12 |
| ERBE (TOA) | 1984-2002 | 280 | 24 |
| CERES (TOA) | 2000-current | 110 | 3 |
| *SRB (TOA-SRF) | 1983-2004 | 110 | 3 |
| *FD (TOA-SRF) | 1983-2005 | 280 | 3 |
| Precipitation | | | |
| *GPCP | 2002-current | 280 | 3 |
| *GPCP | 1997-current | 280 | 24 |
| *GPCP | 1979-current | 280 | pentad |
| Surface Fluxes | | | |

| | | | |
|---|-----------|------------|--------|
| GSSTF2 (oceans) | 1988-2000 | 280 | day |
| HOAPS (oceans) | 1988-2002 | 50 | pentad |
| WHOI (oceans) | 1981-2002 | 110 | day |
| Oceanic State | | | |
| *Reynolds (SST) | 1982-2005 | 110 | week |
| *World Ocean Atlas (Levitus) | 1948-1998 | 110-560 | month |
| *WOCE | 1990-1997 | — | — |
| Ocean Srf Winds | | | |
| Wentz | 1987-2005 | 110 | 24 |
| Ocean Currents | | | |
| T/P-Jason | 1992-2005 | 50-110 | 5-day |
| GRACE | 2002-2005 | — | — |
| Key Supporting Datasets | | | |
| Baseline Surface Radiation Network | 1994-2005 | 35 sites | 5 min |
| Global Precipitation Climatology Center | 1951-2004 | 50 | month |
| Global Runoff Data Center | 1970-2005 | 4500 sites | daily |

Figure Captions

Figure 1: Comparison of the decadal-scale anomaly in net surface fluxes and the variations of annual upper-ocean heat content.

Figure 2: Mean meridional heat transport by the global ocean inferred from six different combinations of two radiative flux and three turbulent flux products.

Figure 3: Monthly anomalies in the implied total (atmosphere plus ocean) mean meridional heat transport from the ISCCP-FD reconstruction of top-of-atmosphere radiative flux anomalies.