Kevin E Trenberth

Sun and Earth's Climate
Here comes the sun...

So where does all that solar radiation go?

If the sun keeps shining why don’t we continue to get warmer?

Aaagh! But it gets dark at night...

Why can’t it be summer all the time?

Li’l darlin’

It’s all right...
Energy on Earth

The main external influence on planet Earth is from radiation.

Incoming solar shortwave radiation is unevenly distributed owing to the geometry of the Earth-sun system, and the rotation of the Earth.

Outgoing longwave radiation is more uniform.

What is the net radiation?

Where does the energy go?

How does it get from where it comes in to where it goes out?

How much is stored, where?

: annual cycle, longer term?

How does it get out?
Energy on Earth

The incoming radiant energy is transformed into various forms (internal heat, potential energy, latent energy, and kinetic energy) moved around in various ways primarily by the atmosphere and oceans, stored and sequestered in the ocean, land, and ice components of the climate system, and ultimately radiated back to space as infrared radiation.

An equilibrium climate mandates a balance between the incoming and outgoing radiation and that the flows of energy are systematic. These drive the weather systems in the atmosphere, currents in the ocean, and fundamentally determine the climate. And they can be perturbed, with climate change.
The Greenhouse Effect

Solar radiation passes through the clear atmosphere

Some solar radiation is reflected by the Earth and the atmosphere.

Most radiation is absorbed by the Earth's surface and warms it.

Infrared radiation is emitted from the Earth's surface.

Some of the infrared radiation passes through the atmosphere, and some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.
Global warming:

Under no climate change, the net flow of energy in from the sun is balanced by the net radiation out to space.  
\[ \text{ASR} = \text{OLR} \]

With global warming there is a net energy imbalance as heat trapping gases lower OLR:  
\[ \text{Net} = \text{ASR} - \text{OLR} \]
Energy on Earth

The climate is changing from increased GHGs. We expect an energy imbalance from heat-trapping GHG. The planet warms until OLR increases to match the ASR. But there are many feedbacks and complexities.

The most fundamental measure that the climate is changing is the energy imbalance.
Trenberth et al (2009)

Global Energy Flows W m$^{-2}$

- Reflected Solar Radiation: 101.9 W m$^{-2}$
- Reflected by Clouds and Atmosphere: 79 W m$^{-2}$
- Reflected by Surface: 23 W m$^{-2}$
- Absorbed by Surface: 161 W m$^{-2}$
- Absorbed by Atmosphere: 78 W m$^{-2}$
- Net absorbed: 0.9 W m$^{-2}$
- Incoming Solar Radiation: 341.3 W m$^{-2}$
- Outgoing Longwave Radiation: 238.5 W m$^{-2}$
- Atmospheric Window: 40 W m$^{-2}$
- Greenhouse Gases: 333 W m$^{-2}$
- Evapotranspiration: 85 W m$^{-2}$
Quite strong structure due to clouds in ASR and OLR that mostly cancels in the net; some other albedo effects (e.g., Sahara) and land-sea differences, but sun-Earth geometry explains most of pattern.

Trenberth et al, JGR. 2015
The role of the climate system

Atmosphere: Volatile turbulent fluid, strong winds,
Chaotic weather, clouds, water vapor feedback
Transports heat, moisture, materials etc.
Heat capacity equivalent to 3.5 m of ocean

Ocean: 70% of Earth, wet, fluid, high heat capacity
Stores, moves heat, fresh water, gases, chemicals
Adds delay of 10 to 100 years to response time

Land: Small heat capacity, small mass involved (conduction)
Water storage varies: affects sensible vs latent fluxes
Wide variety of features, slopes, vegetation, soils
Mixture of natural and managed
Vital in carbon and water cycles, ecosystems

Ice: Heat capacity large only on long time scales (conduction)
High albedo: ice-albedo feedback
Fresh water, changes sea level
Antarctica 65 m (WAIS 4-6m), Greenland 7m, other glaciers 0.35m
George Hadley (1685-1768), English lawyer and scientist. “I think the cause of the general Trade-winds have not been explained by any of those who have wrote on that subject” (1735)

The overturning Hadley cells are the main way the atmosphere transports energy polewards in low latitudes.
Cyclones and anticyclones are the main way of transporting energy polewards in extratropics. Winds converging into the low, pull cold air from the poles toward the equator, and warm air from the equator to the poles. Where they meet is where we find fronts, bringing widespread precipitation and significant weather, like thunderstorms.

Source: USA TODAY research by Chad Palmer, Graphic by Chuck Rose
\[ Q_1 = R_T + F_s + L(P-E) \]
\[ Q_2 = L(P-E) \]
\[ \nabla \cdot F_A = Q_1 - Q_2 = R_T + F_s \]
\[ F_s = H_s + LE - R_s \]
\[ \frac{d(OHC)}{dt} = -\nabla \cdot F_o - F_s \]
Diabatic heating atmosphere $Q_1$

Column latent heating $Q_2$

Total heating $Q_1 - Q_2$

Dominated by latent heating: Precipitation $L(P-E)$

Includes moistening: LE

Trenberth & Stepaniak, 2003
Net Radiation TOA $R_T$

Total heating $Q_1 - Q_2 = R_T + F_s$

Difference due to ocean transports (net surface flux)

Trenberth & Stepaniak, 2003
Annual mean surface flux

Trenberth and Fasullo (2008)
Global warming means more heat:
Where does the heat go?

1. Warms land and atmosphere
2. Heat storage in the ocean (raises sea level)
3. Melts land ice (raises sea level)
4. Melts sea ice and warms melted water
5. Evaporates moisture ⇒ rain storms, cloud
   ⇒ possibly reflection to space

>90%
Global Ocean Heat Content

ORAS4 OHC $10^{22}$ J

Upper 300m
Upper 700m
Total Depth

Amount of heat


Agung
El Chichón
Pinatubo
1997-98 El Niño

Balmaseda, Trenberth and Källén 2013
OHC from ORAS4 and rates of change

Trenberth et al. 2014 J Cl
OHC from ORAS4 and rates of change

ORAS4 OHC $10^{22}$ J

Global Ocean Heat Content Tendency

Upper 700m
Total Depth

12-mo running means

Diff: 0.21 W m$^{-2}$
2000s
Deep Doo Doo

There's a clearer analysis forming
Of the increase in powerful storming;
But it's not just hot air
About which we should care,
For the cold ocean depths have been warming.

Lynne Page

http://limericksbylin.com/