OBJECTIVE CLOSURE OF SURFACE ENERGY FLUXES
Global Energy Flows W m⁻²

- Reflected Solar Radiation: 102 W m⁻² (101.9 W m⁻²)
- Outgoing Longwave Radiation: 239 W m⁻² (238.5 W m⁻²)
- Latent Heat:
  - Absorbed by Atmosphere: 169 W m⁻²
  - Emitted by Atmosphere: 30 W m⁻²
- Absorbed by Surface:
  - Thermals: 17 W m⁻²
  - Evapotranspiration: 80 W m⁻² (Net absorbed: 0.9 W m⁻²)

Trenberth et al. (BAMS 2009)
SH 7 Wm\(^{-2}\) higher; 8 Wm\(^{-2}\) higher; DLR 12 Wm\(^{-2}\) higher
Latent Heating (PrSRB + SeaFlux)

GLB : 75.99
LND : 40.44
SEA : 90.29

Latent Heating (PrSRB/SeaFlux)

ET ~ 4 Wm\(^{-2}\) less than Trenberth et al; 12 Wm\(^{-2}\) less than Stephens et al
Sensible Heating (MERRA + SeaFlux)

GLB: 22.21  LND: 33.19  SEA: 17.79

Sensible Heating (MERRA/SeaFlux)

SH 5 Wm$^{-2}$ larger than Trenberth; 2 Wm$^{-2}$ less than Stephens et al
Surface Net Radiation (SRB)

GLB : 114.0  LND : 72.07  SEA : 130.9

\[ S = F_{\text{LW}}^{\downarrow} + F_{\text{SW}}^{\downarrow} - F_{\text{LW}}^{\uparrow} - F_{\text{SW}}^{\uparrow} \]

DLR 11 Wm$^{-2}$ larger than Trenberth et al; DSR 7 Wm$^{-2}$ larger
DLR 1 Wm$^{-2}$ smaller than Stephens et al; DSR 3 Wm$^{-2}$ larger
Surface Energy Balance

\[ S = F_{LW}^{\downarrow} + F_{SW}^{\downarrow} - F_{LW}^{\uparrow} - F_{SW}^{\uparrow} - LH - SH \]

Surface energy imbalance of \(~16\,\text{Wm}^{-2}\)
Other Flux Combinations

SRB/PrISCCP/PrISCCP/MERRA/SeaFlux

SRB/MERRA/SeaFlux/MERRA/SeaFlux

SRB/PrSRB/PrSRB/MERRA/MERRA

SRB/MERRA/MERRA/MERRA/MERRA

ISCCP/PrISCCP/PrISCCP/MERRA/SeaFlux

ISCCP/MERRA/SeaFlux/MERRA/SeaFlux

ISCCP/PrSRB/PrSRB/MERRA/MERRA

ISCCP/MERRA/MERRA/MERRA/MERRA

GLB : 22.15
LND : 13.90
SEA : 32.43

GLB : 13.58
LND : 1.252
SEA : 28.49

GLB : 24.89
LND : 16.53
SEA : 31.52

GLB : 20.02
LND : 1.252
SEA : 30.74

GLB : 26.40
LND : 34.12
SEA : 27.97

GLB : 17.83
LND : 21.47
SEA : 24.03

GLB : 27.20
LND : 36.75
SEA : 27.06

GLB : 22.33
LND : 21.47
SEA : 26.28
Raw Observations

Trenberth et al. (BAMS 2009)
Objective Addition of “Soft” Balance Constraints

General budget equation:

\[ R = \sum_{i=1}^{M} F_i - \sum_{o=1}^{N} F_o \]

Surface Energy Budget:

\[ S = \sum_{i} F_{LW}^{\downarrow} + \sum_{i} F_{SW}^{\downarrow} - \sum_{i} F_{LW}^{\uparrow} - \sum_{i} F_{SW}^{\uparrow} - LH - SH \]

Surface Water Budget:

\[ Q = P - LH \]

Equations are valid for all continents on annual time-scales.

Similar equations apply to the world oceans (cannot separate basins since transports are not known).

Additional constraints:

- \( S = 0 \) for all continents
- \( S = 1 \) for world oceans based on ocean heat content measurements
Variational Minimization Procedure

If errors are assumed to be Gaussian, balance constraints can be imposed by minimizing the cost function:

$$J = (F - F_{obs})^T S_{obs}^{-1} (F - F_{obs}) + (R - R_{obs})^T S_R^{-1} (R - R_{obs})$$

Minimum occurs when:

$$F = F_{obs} - S_F K^T S_y^{-1} (R_{obs} - K F_{obs})$$

$$S_F = (K^T S_y^{-1} K + S_{obs}^{-1})^{-1}$$

Since balance constraints are linear in the various fluxes, this solution collapses to the minimum variance solution if errors are assumed to be uncorrelated.
Uncertainties

- **Key** is determining uncertainties to weight the various flux terms (represented by the error covariance $S_y$)

- Error estimates based on a combination of product inter-comparisons, comparisons with ground observations, and sensitivity studies.
Complete Monthly/Continental Scale Results
Constrained Energy Budget

Global Energy Flows W m\(^{-2}\)

- Reflected Solar Radiation: 100±2 W m\(^{-2}\)
- Incoming Solar Radiation: 341±2 W m\(^{-2}\)
- Outgoing Longwave Radiation: 240±3 W m\(^{-2}\)

Stephens et al.: Unconstrained

1 W m\(^{-2}\)
Advantages

- Objective approach based on estimated uncertainties in component fluxes
- Energy and water cycle constraints are satisfied simultaneously
- “Goodness of Fit” ($\chi^2$) helps answer ‘can balance be achieved within current uncertainties?’

$$\chi^2 = (F - F_{obs})^T S^{-1}_{obs} (F - F_{obs}) + (R - R_{obs})^T S^{-1}_R (R - R_{obs}) = 22$$

- Updated error estimates that account for additional information supplied by constraints
Are the Adjustments Realistic?

SFC Net Radiation

- LH
  - GLB: 11.37
  - LND: 15.30
  - SEA: 9.876
- SH
  - GLB: 11.64
  - LND: 6.032
  - SEA: 13.89
- Total Error
  - GLB: 6.072
  - LND: 7.000
  - SEA: 5.699

Surface Net Radiation

- LH
  - GLB: -7.20
  - LND: 2.101
  - SEA: -10.9
- SH
  - GLB: 5.276
  - LND: 0.850
  - SEA: 7.057
- Total
  - GLB: 2.509
  - LND: -0.31
  - SEA: 3.644

Original Uncertainties

Flux Changes
INSIGHTS INTO ERROR SOURCES IN A-TRAIN FLUX ESTIMATES
RADIATIVE FLUXES
2B-FLXHR Algorithm

CloudSat Radar Reflectivity (dBZ)

Precipitation

Tropical Thin Cirrus

Mixed Phase Cloud

Aerosol

CALIPSO 532 nm Backscatter

MODIS 11 µm
1. Clouds – CloudSat CPR + MODIS optical depth
2. Sub-visual Cirrus – CALIPSO (5 km Cloud Layer Product)
3. Stratus/mixed-phase – CALIPSO (identification) + MODIS (microphysical properties)
4. Aerosol – CALIPSO (5 km Aerosol Layer Product)
5. Precipitation – explicit rain DSD and CloudSat 2C-PRECIP-COLUMN (identification/LWP)
6. Temperature & Humidity – ECMWF/AIRS (in progress)
Pixel-Level Heating Rates

L’Ecuyer et al., J. Geophys. Res., 2009
Global Radiation Budget in FLXHR-Lidar

Trenberth et al. (BAMS 2009)
SENSITIVITY STUDIES
Cloud Impacts on DLR

Effective Radius/LWP
(CloudSat Errors + CALIOP clouds)

Effective Radius/IWP
(CloudSat Errors + CALIOP clouds)

Geometric Thickness (±240 m)
**Cloud Impacts on DSR**

**Effective Radius/LWP**
(CloudSat Errors + CALIOP clouds)

**Effective Radius/IWP**
(CloudSat Errors + CALIOP clouds)

**Geometric Thickness (±240 m)**
ECMWF Specific Humidity ±25 %
ECMWF Temperatures ±2 K
Surface Properties

**Outgoing Longwave (1.062)**

**Surface Longwave (5.355)**

**Surface Emitted (10.90)**

**Outgoing Shortwave (1.486)**

**Surface Shortwave (0.264)**

**Surface Reflected (1.846)**

**Surface T ±2K**

**Surface Albedo ±0.02**
Aerosols (AOD/Composition)

AOD Doubled/Halved
SSA/g Modified between Dust and Smoke Extremes
<table>
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<td>Surface Properties</td>
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<td>1</td>
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</tr>
</tbody>
</table>
Combined Errors

Outgoing Shortwave (7.526)

Surface Shortwave (7.712)

Surface Reflected (1.999)

Outgoing Longwave (8.267)

Surface Longwave (11.01)

Surface Emitted (10.90)
LATENT HEATING FROM LIGHT RAIN AND SNOW
CloudSat Rainfall Algorithm

- Path integrated attenuation calculated using a SST and wind speed-dependent clear-sky estimate of surface reflectivity, provides an indicator of rainfall and a crude intensity estimate.

Haynes et al., J. Geophys. Res., 2009
Snowfall
- R < 1 mm h\(^{-1}\): CPR accumulation is 0.47 mm/d, PR’s is 0.19
- R > 5 mm h\(^{-1}\): CPR accumulation is 1.35 mm/d, PR’s is 1.86
- Light rain accounts for ~10% of total accumulation in tropics.

Berg and L’Ecuyer, *J. Climate*, 2010
Global Distribution of Light Precipitation
Implied Latent Heating

Rain < 1 mm⁻¹ (13.64)

R < 0.5 mm⁻¹ (5.994)

Snow (0.661)

Combined (R < 0.5 mm⁻¹) (6.655)
Conclusions

- Energy and Water Cycle can be objectively balanced at annual and continental scales within realistic error estimates
  - Results like between those from recent competing studies
- The addition of active CloudSat and CALIPSO measurements appears to drive DLR further away from balance ($350 \text{ Wm}^{-2}$)
- DLR errors in FLXHR-lidar are dominated by atmospheric properties as opposed to cloud properties but could still be up to $10 \text{ Wm}^{-2}$
- LH from light rainfall observed by CloudSat ($R < 0.5 \text{ mm h}^{-1}$) is to be $\sim 6 \text{ Wm}^{-2}$
- LH release from snowfall may be $\sim 1 \text{ Wm}^{-2}$
Closure?

Surface Energy

GLB : 0.874  LND : 0.002  SEA : 1.222
- Can’t sample the diurnal cycle of clouds and precipitation but can at least model the solar cycle.
- Due to the high along-track sampling of CloudSat, we simply move the sun by 2 hours in each successive pixel.
- The complete diurnal cycle of SZA is, therefore, sampled every 12 pixels along track.
Regional Radiation Budgets
Comparisons with CERES

Outgoing Longwave Radiation [Wm$^{-2}$]

Bias: 0.008
RMSE: 4.47

Outgoing Shortwave Radiation [Wm$^{-2}$]

Bias: 5.01
RMSE: 26.31

Surface Longwave Radiation [Wm$^{-2}$]

Bias: 13.36
RMSE: 18.02

Surface Shortwave Radiation [Wm$^{-2}$]

Bias: 17.29
RMSE: 29.51