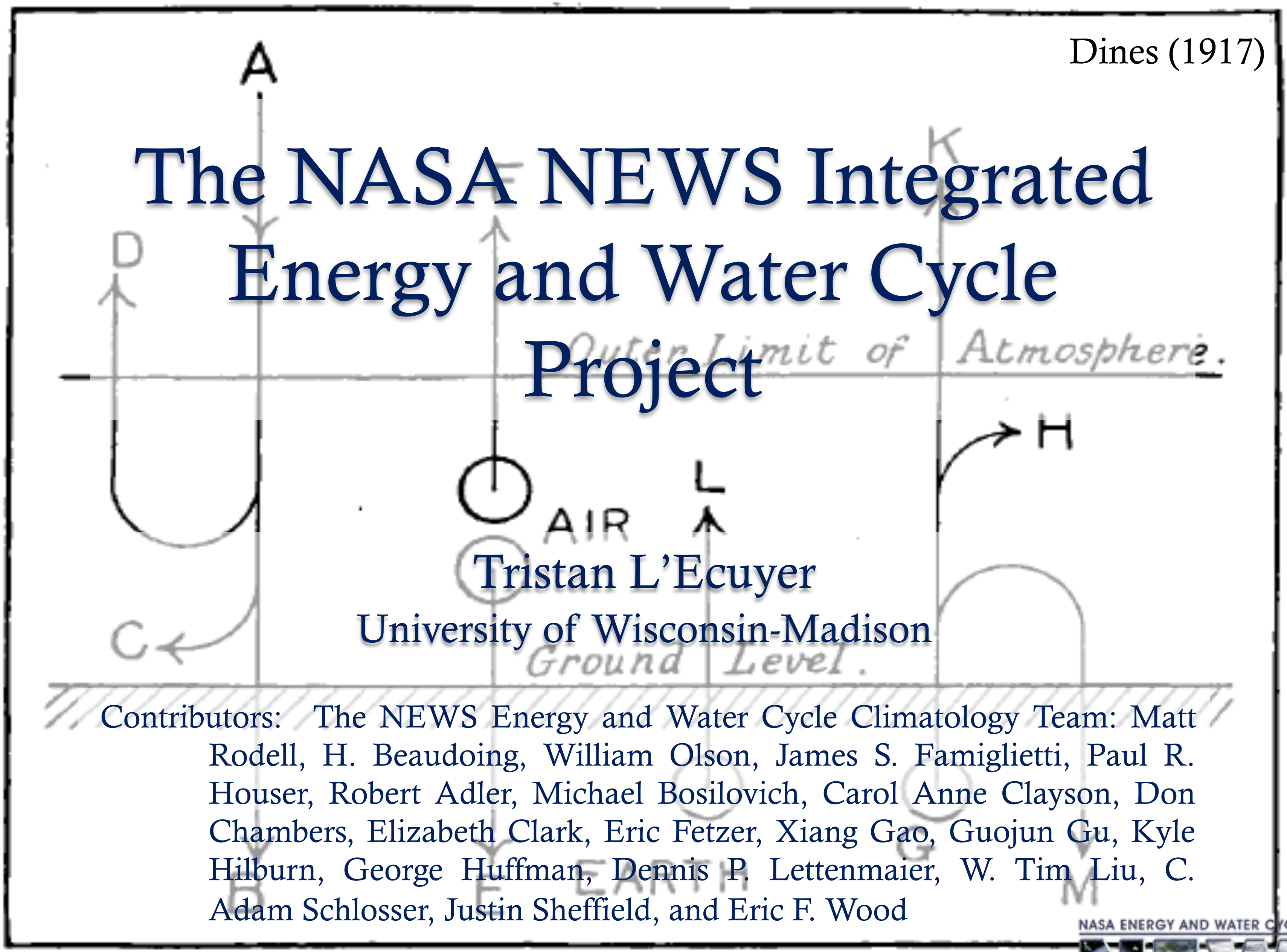

Dines (1917)

The NASA NEWS Integrated Energy and Water Cycle Project

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University of Wisconsin-Madison

Contributors: The NEWS Energy and Water Cycle Climatology Team: Matt Rodell, H. Beaudoing, William Olson, James S. Famiglietti, Paul R. Houser, Robert Adler, Michael Bosilovich, Carol Anne Clayson, Don Chambers, Elizabeth Clark, Eric Fetzer, Xiang Gao, Guojun Gu, Kyle Hilburn, George Huffman, Dennis P. Lettenmaier, W. Tim Liu, C. Adam Schlosser, Justin Sheffield, and Eric F. Wood

Objectives

Goals: (1) Provide observation-based estimates of the integrated energy and water cycles (with associated error bars) on continental scales for climate studies and model assessments; (2) Document the scales over which independently-derived flux estimates balance; (3) Identify the which observations should be targeted to realize largest near-term improvement.

Methods: Apply variational techniques to objectively re-introduce balance constraints in reconstructions of the WEC from modern observations and observation-integrating models to estimate the mean annual cycles of component WEC fluxes on continental/basin scales.

Energy Balance Datasets

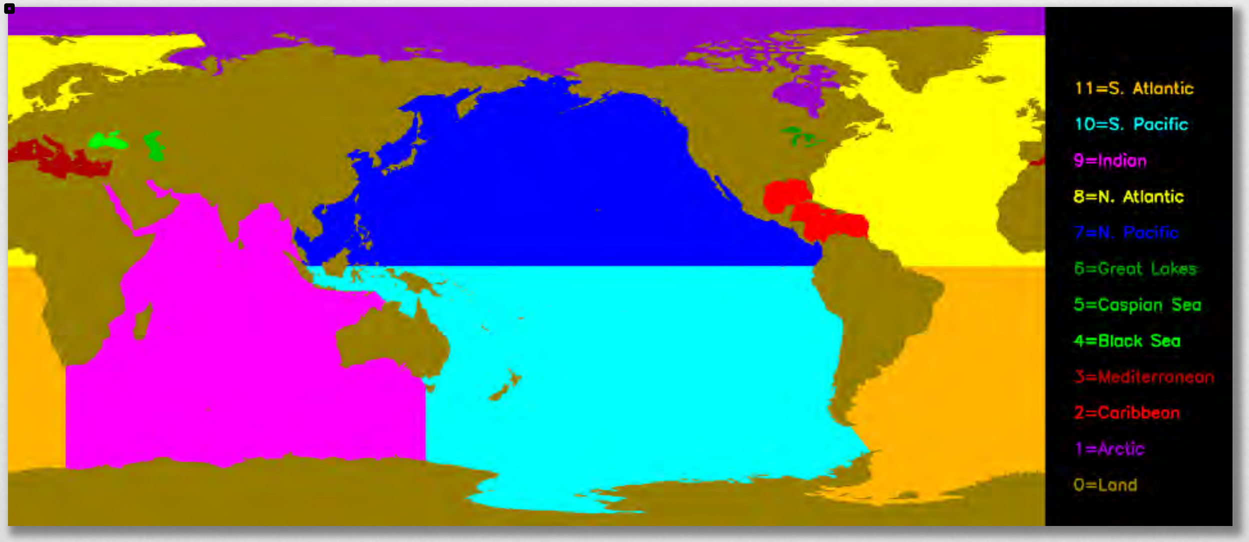
Variable	Dataset Name	Contributing Instruments
Precipitation	GPCP v. 2.2, MERRA, CMAP	SSMI, SSMIS, GOES-IR, TOVS, AIRS, TRMM
Surface Latent Heat Flux (Evaportranspiration)	Princeton, MERRA, GLDAS, SeaFlux	AIRS, CERES, MODIS, TRMM, AVHRR, MSU, HIRS, SSU, AMSU, SSMI, SSMIS, ERS1/2, QuikSCAT, GOES, TOVS
Surface Sensible Heat Flux	Princeton, MERRA, GLDAS, SeaFlux	AIRS, CERES, MODIS, TRMM, AVHRR, MSU, HIRS, SSU, AMSU, SSMI, SSMIS, ERS1/2, QuikSCAT, GOES, TOVS
Radiative Fluxes	GEWEX-SRB ISCCP-FD 2B-FLXHR-LIDAR C3M	CERES, AVHRR AVHRR CloudSat, CALIPSO, MODIS, AMSR-E CERES, CloudSat, CALIPSO, MODIS

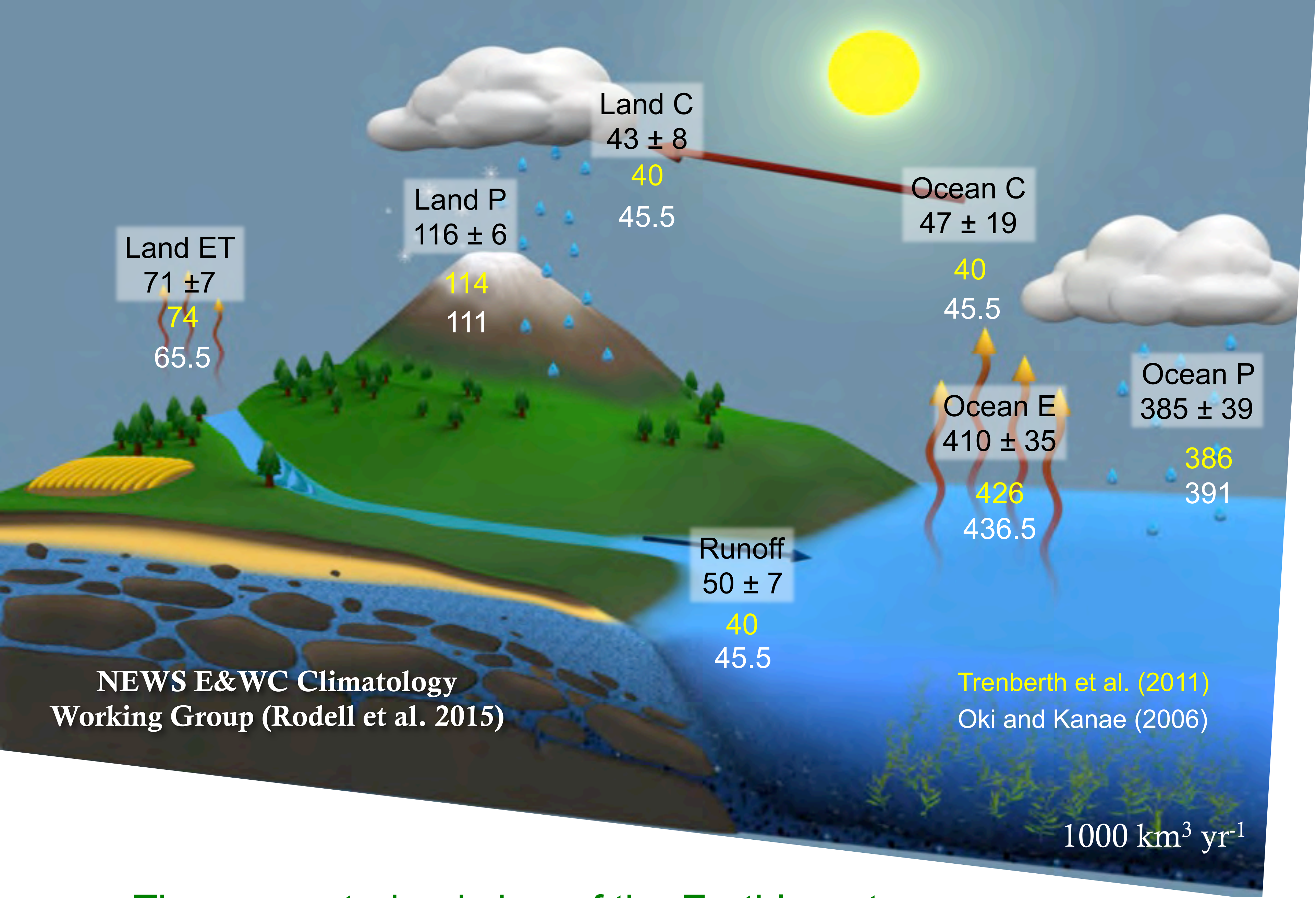
Water Cycle Datasets

Variable	Dataset Name	Contributing Instruments
Precipitation	GPCP v. 2.2, MERRA, CMAP	SSMI, SSMIS, GOES-IR, TOVS, AIRS, TRMM
Evapotranspiration	Princeton, MERRA, GLDAS	AIRS, CERES, MODIS, TRMM, AVHRR, MSU, HIRS, SSU, AMSU, SSMI, SSMIS, ERS1/2, QuikSCAT, GOES, TOVS
Runoff	U. Washington Dai and Trenberth, MERRA, GLDAS	TRMM, GOES-IR, TOVS, SSM/I, ERS, ATOVS
Water Storage Change	GRACE CSR RL05 (Chambers)	GRACE
Atmospheric Convergence	QSCAT, MERRA, PWMC	QuikSCAT, TRMM, GRACE, MSU, HIRS, SSU, AMSU, AIRS, SSMI, ERS1/2, MODIS, GOES
Atmospheric Water Storage Change	(Fetzer)	AIRS, AMSR-E
Ocean Evaporation	SeaFlux v. 1.0, Princeton, MERRA	SSMI, AVHRR, AMSR-E, TMI, WindSat

Initial Time/Space Scales

Mean annual cycle from (approx) 2000 to 2009.





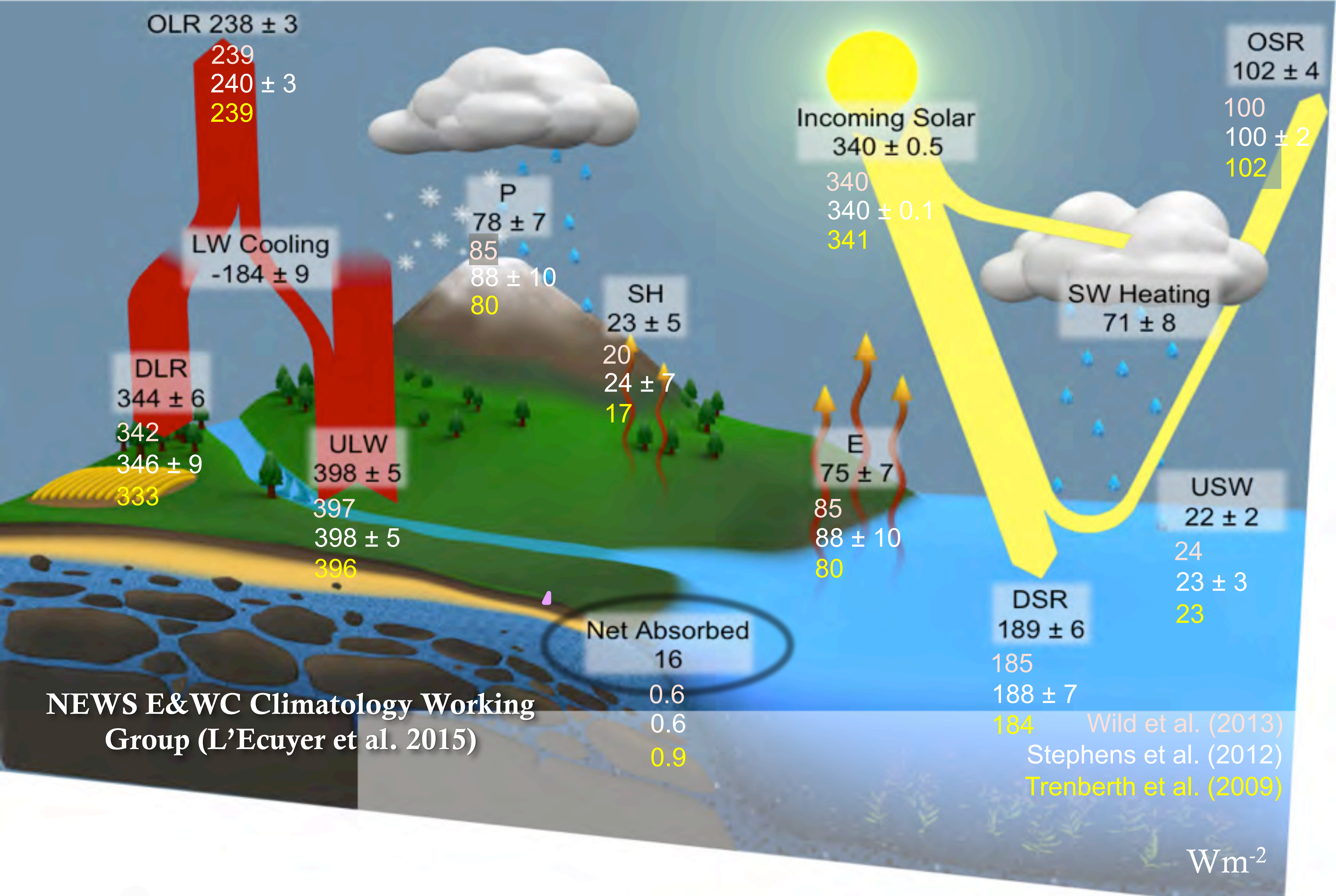
NEWS E&WC Climatology Working Group (Rodell et al. 2015)

Trenberth et al. (2011)

Oki and Kanae (2006)

1000 km^3 yr^{-1}

The unconstrained view of the Earth's water cycle in the early 21st century.



NEWS E&WC Climatology Working Group (L'Ecuyer et al. 2015)

The unconstrained view of global Earth's energy budget in the early 21st century.

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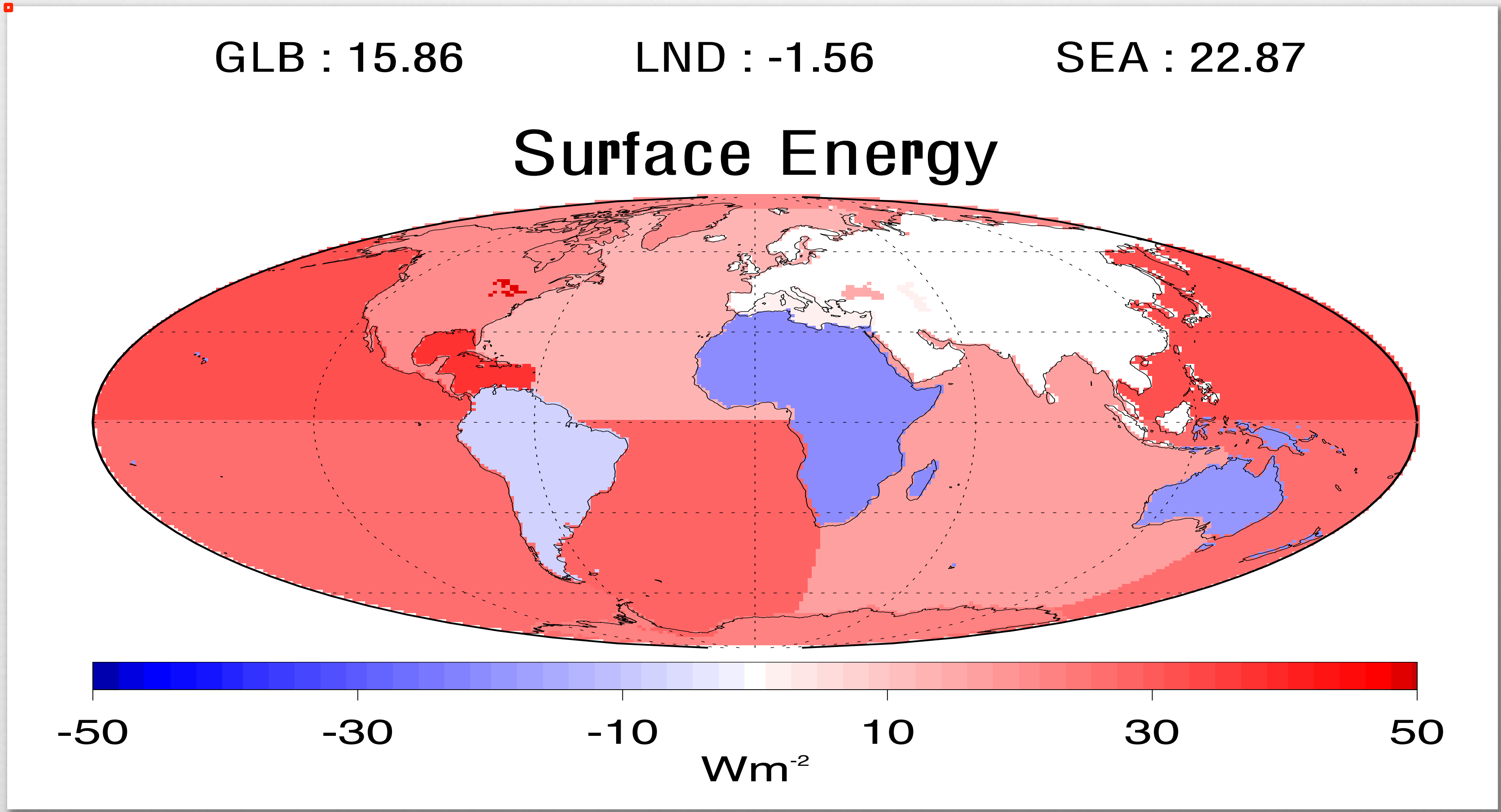
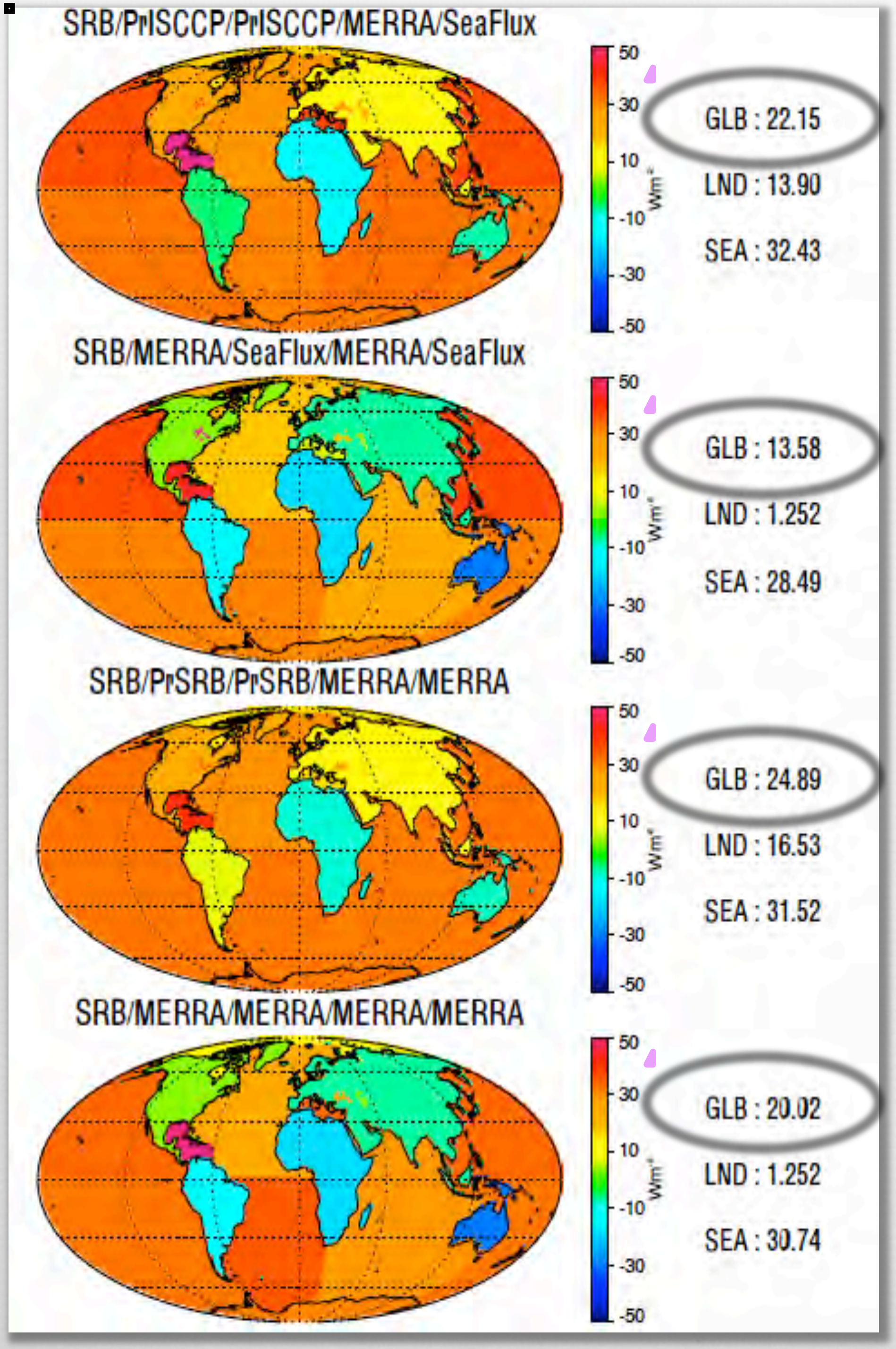
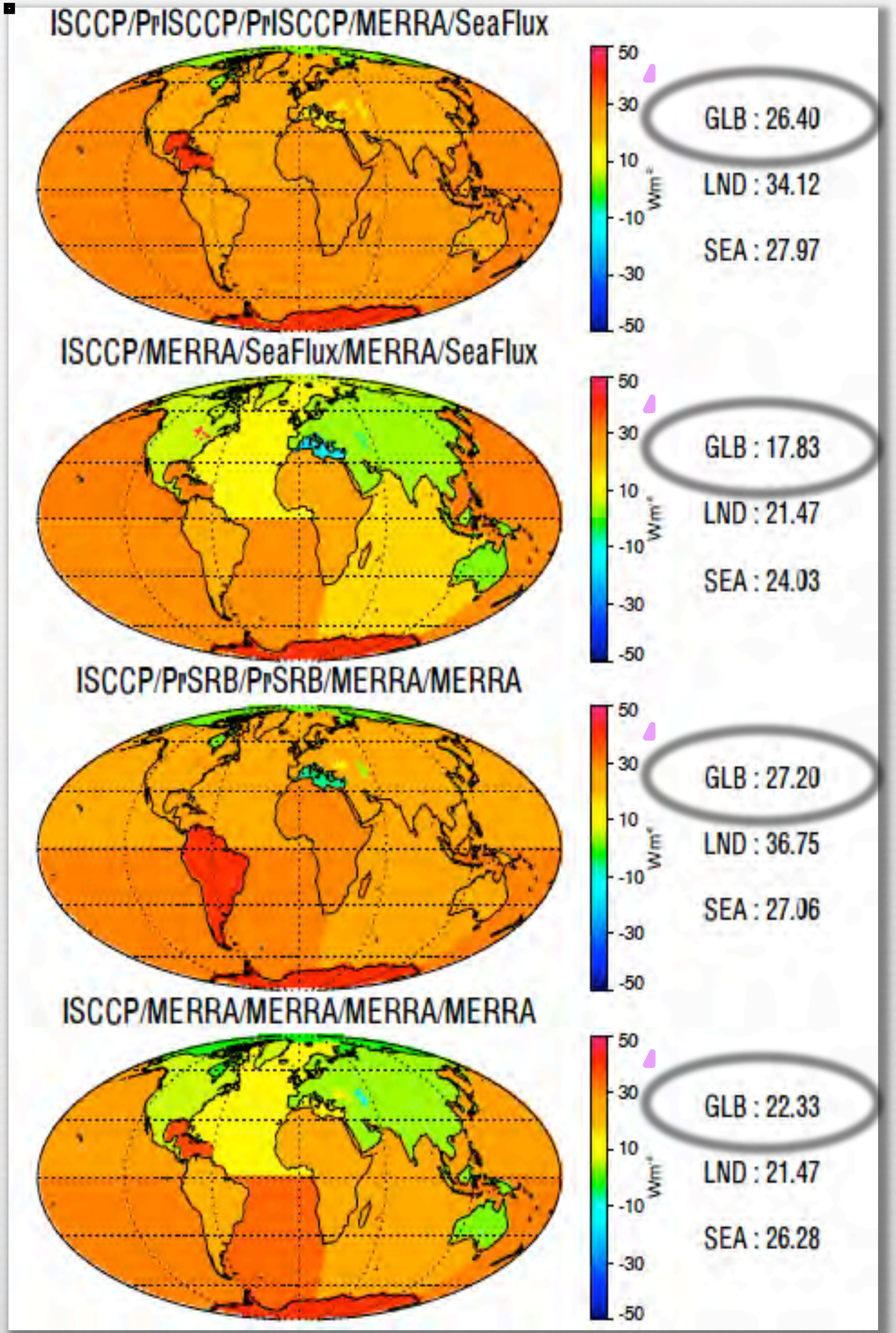
Global Distribution

(SRB, Princeton-SRB, SeaFlux, MERRA)



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


SRB/PrISCCP/PrISCCP/MERRA/SeaFlux
GLB : 22.15
LND : 13.90
SEA : 32.43
SRB/MERRA/SeaFlux/MERRA/SeaFlux
GLB : 13.58
LND : 1.252
SEA : 28.49
SRB/PrSRB/PrSRB/MERRA/MERRA
GLB : 24.89
LND : 16.53
SEA : 31.52
SRB/MERRA/MERRA/MERRA/MERRA
GLB : 20.02
LND : 1.252
SEA : 30.74
50
30
10
-10
-30
-50
Wm⁻²


ISCCP/PrISCCP/PrISCCP/MERRA/SeaFlux
GLB : 26.40
LND : 34.12
SEA : 27.97
ISCCP/MERRA/SeaFlux/MERRA/SeaFlux
GLB : 17.83
LND : 21.47
SEA : 24.03
ISCCP/PrSRB/PrSRB/MERRA/MERRA
GLB : 27.20
LND : 36.75
SEA : 27.06
ISCCP/MERRA/MERRA/MERRA/MERRA
GLB : 22.33
LND : 21.47
SEA : 26.28
50
30
10
-10
-30
-50
Wm⁻²

Questions

- Do these imbalances fall within observational uncertainties?

- Can closure information that is lost when datasets are generated in isolation be *objectively* re-introduced?

Introducing Balance Constraints

General budget equation:

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

Surface Energy Budget:

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

Surface Water Budget:

$$Q = P - LH$$

(E)

- 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 = 0.9 for world oceans based on ocean heat content measurements

$$\sum_{\text{continents}} Q_L = \sum_{\text{basins}} Q_O$$

Variational Optimization

- If errors are assumed to be Gaussian and random, balance can be objectively imposed by minimizing the cost function:

$$J = \left(\mathbf{F} - \mathbf{F}_{obs}\right)^{\mathbf{T}} \mathbf{S}_{obs}^{-1} \left(\mathbf{F} - \mathbf{F}_{obs}\right) + \left(\mathbf{R} - \mathbf{R}_{obs}\right)^{\mathbf{T}} \mathbf{S}_{R}^{-1} \left(\mathbf{R} - \mathbf{R}_{obs}\right)$$

Minimum occurs when:

$$\mathbf{F} = \mathbf{F}_{\mathbf{obs}} - \mathbf{S}_{\mathbf{F}} \mathbf{K}^{\mathbf{T}} \mathbf{S}_{\mathbf{y}}^{-1} \left(\mathbf{R}_{obs} - \mathbf{K}\mathbf{F}_{\mathbf{obs}}\right)$$

$$\mathbf{S}_{\mathbf{F}} = \left(\mathbf{K}^{\mathbf{T}} \mathbf{S}_{\mathbf{y}}^{-1} \mathbf{K} + \mathbf{S}_{\mathbf{obs}}^{-1}\right)^{-1}$$

- Energy and water cycle constraints are satisfied simultaneously (linked through ET → LH)

- "Goodness of Fit" (χ^2) helps answer 'can balance be achieved within current uncertainties?'

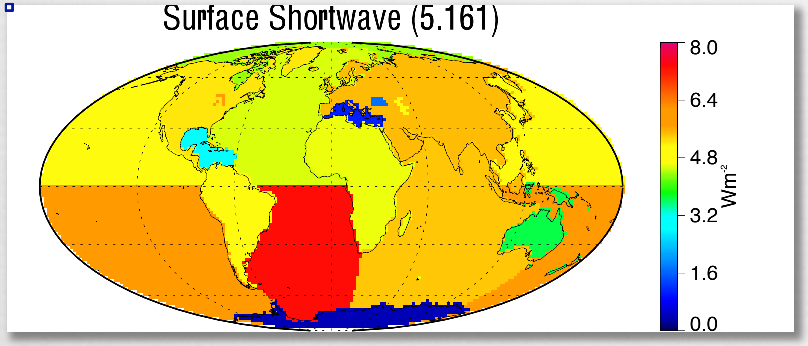
$$\chi^2 = \left(\mathbf{F} - \mathbf{F}_{obs}\right)^{\mathbf{T}} \mathbf{S}_{obs}^{-1} \left(\mathbf{F} - \mathbf{F}_{obs}\right) + \left(\mathbf{R} - \mathbf{R}_{obs}\right)^{\mathbf{T}} \mathbf{S}_{R}^{-1} \left(\mathbf{R} - \mathbf{R}_{obs}\right) = 22$$

Uncertainty Estimates

- ☐ Validation Against Ground Obs.
- ☐ Product Inter-comparisons
- ☐ Sensitivity Studies

E.g. Surface Radiative Fluxes:

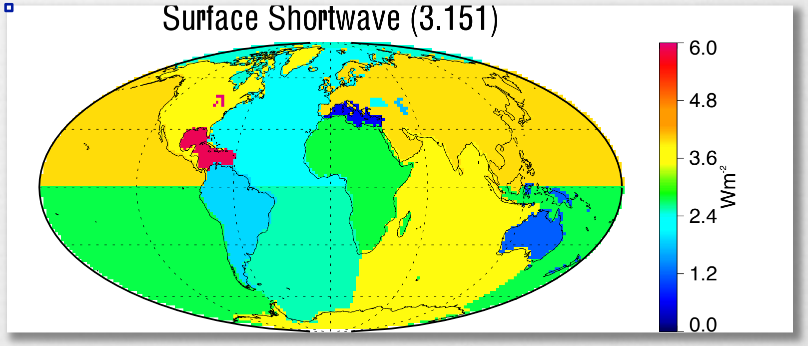
(Impact of Cloud Property Errors on DSR)



Surface Shortwave (5.161)

Effective Radius/LWP

(CloudSat Errors +
CALIOP clouds)

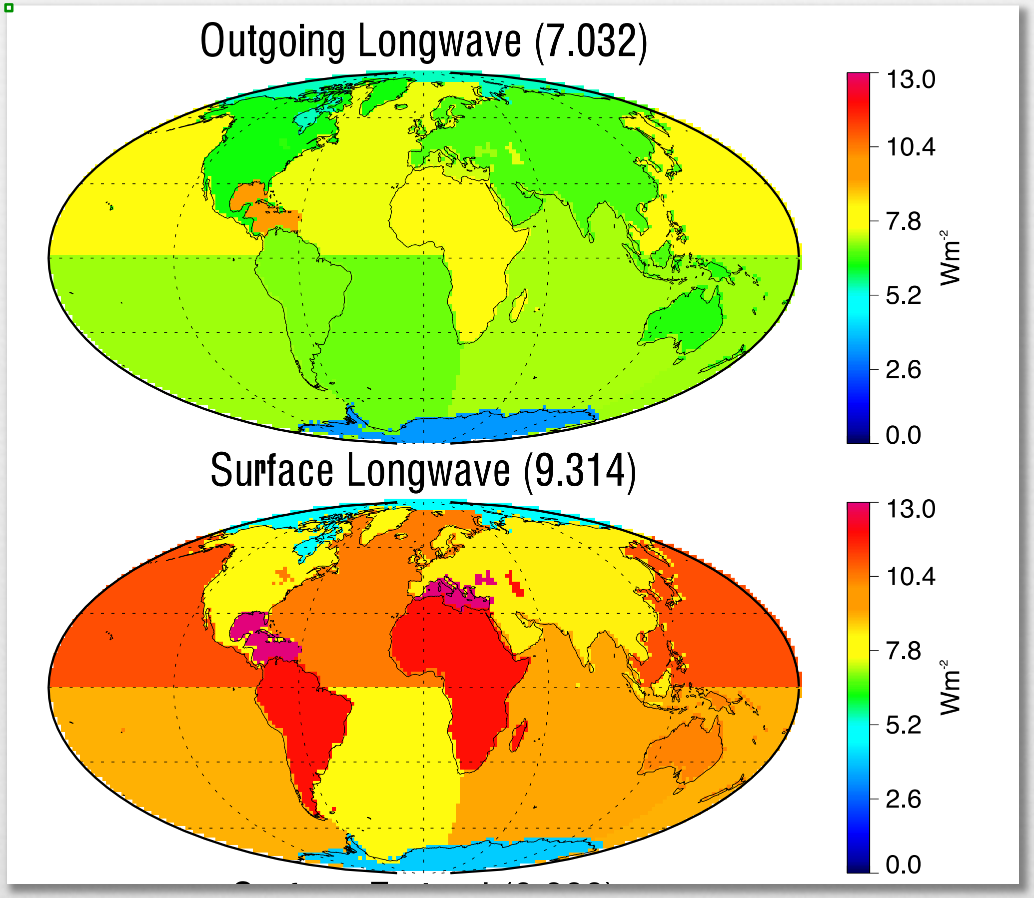


Surface Shortwave (3.151)

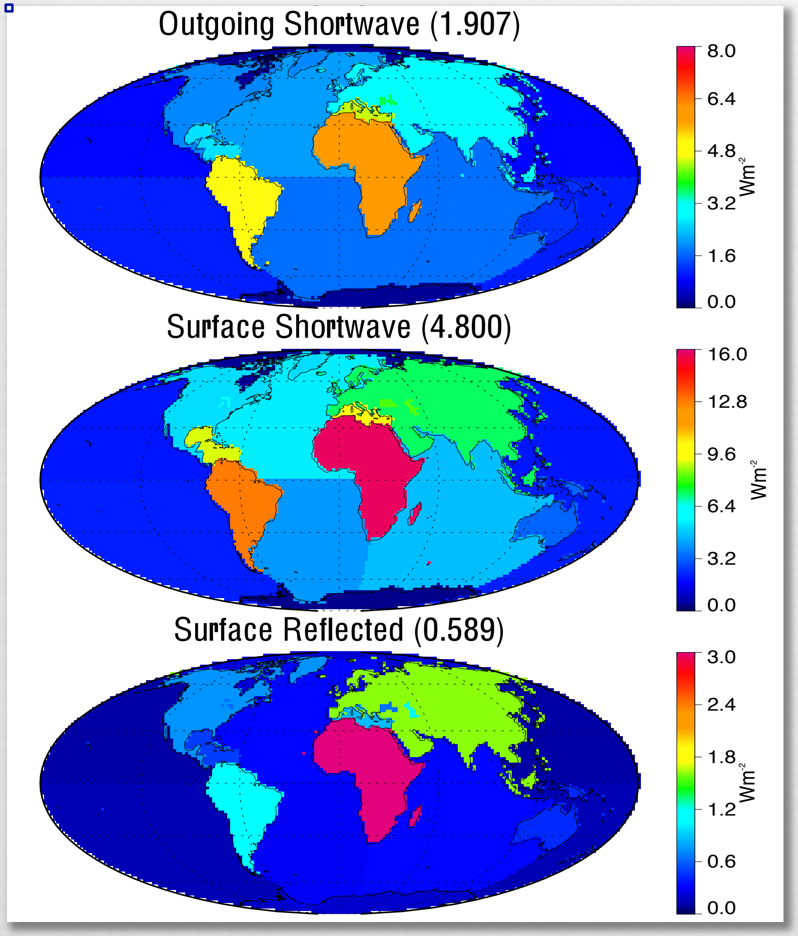
Effective Radius/IWP

(CloudSat Errors +
CALIOP clouds)

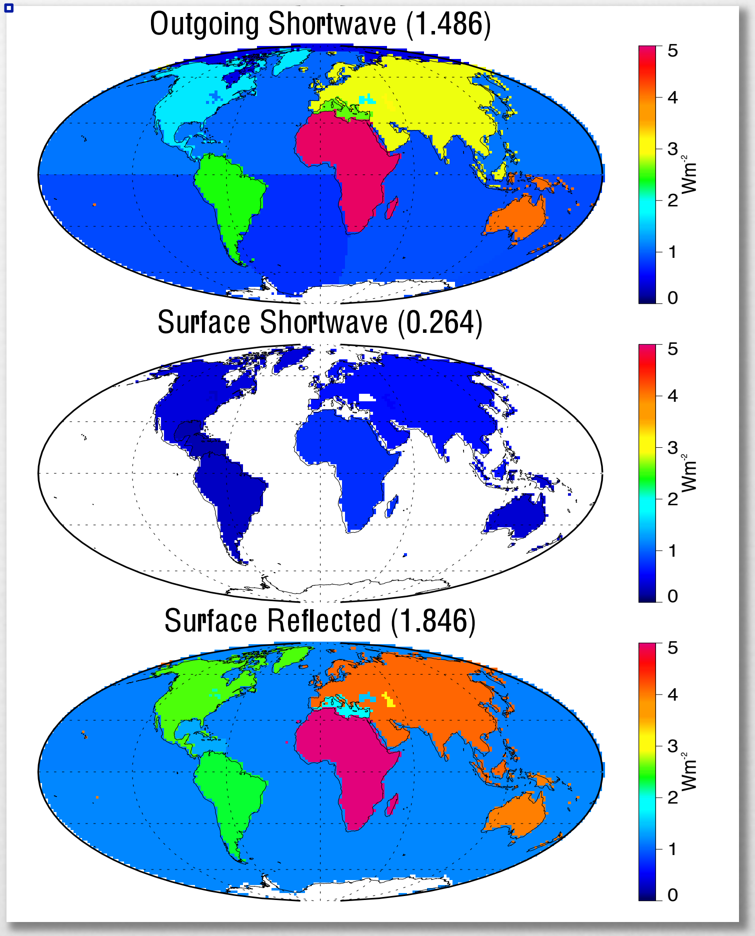
Impact of Temperature Biases on OLR and DLR



Impacts of Errors in Aerosols and Surface Albedo

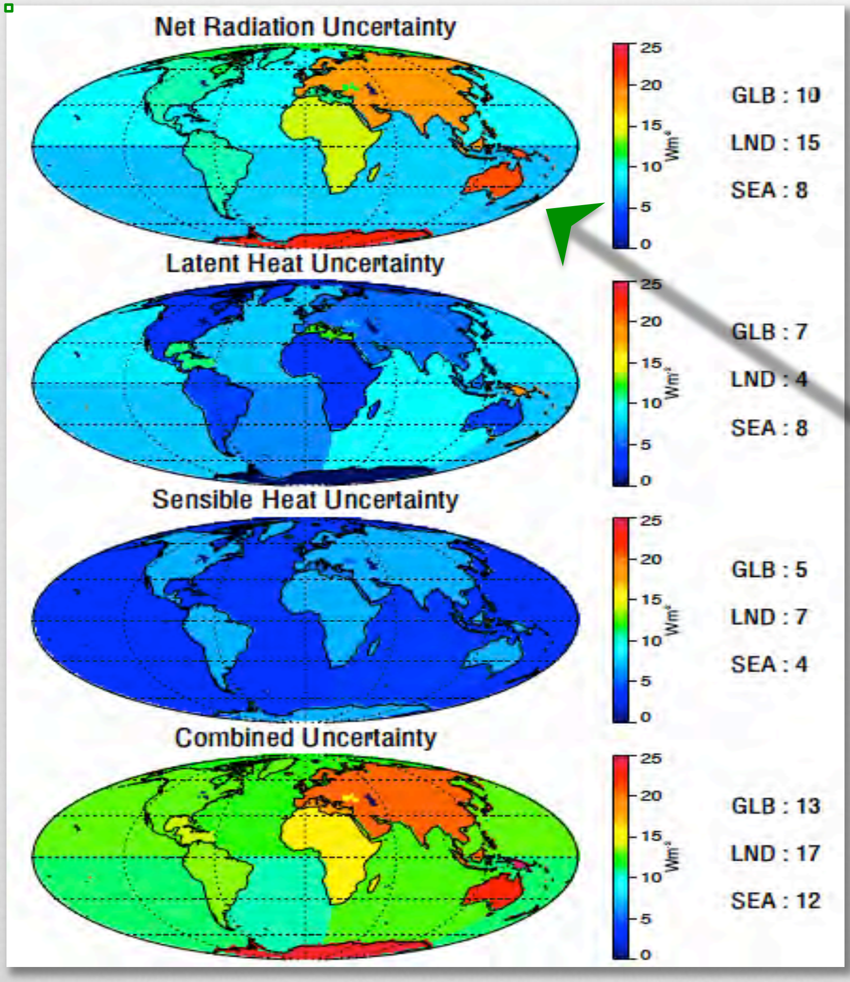


AOD/Composition



Surface Albedo

Uncertainty Estimates


Net Radiation Uncertainty

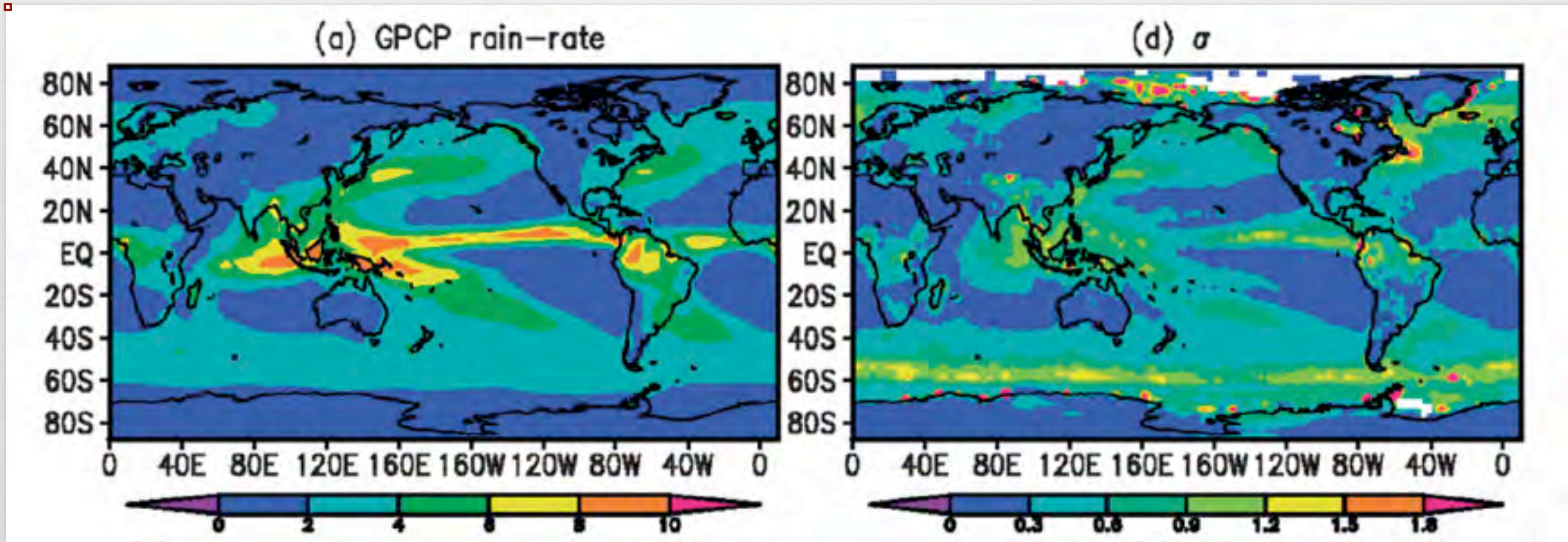
Latent Heat Uncertainty

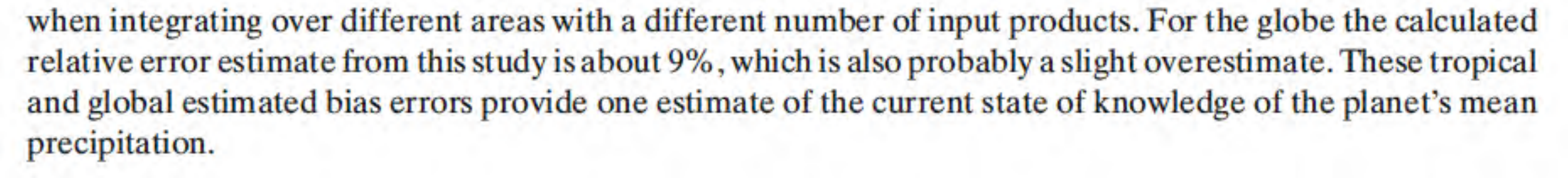
Sensible Heat Uncertainty

Combined Uncertainty

Errors by Source	DLR	DSR	OLR	OSR
Low Cloud Properties	1	**5**	1	**5.5**
High Cloud Properties	1	3	**4**	3
Cloud Thickness	2	3.5	0.5	3.5
Atmospheric Properties	**9**	2.5	**7**	1
Aerosols	0	**5**	0	2
Surface Properties	5	0.3	1	1.5

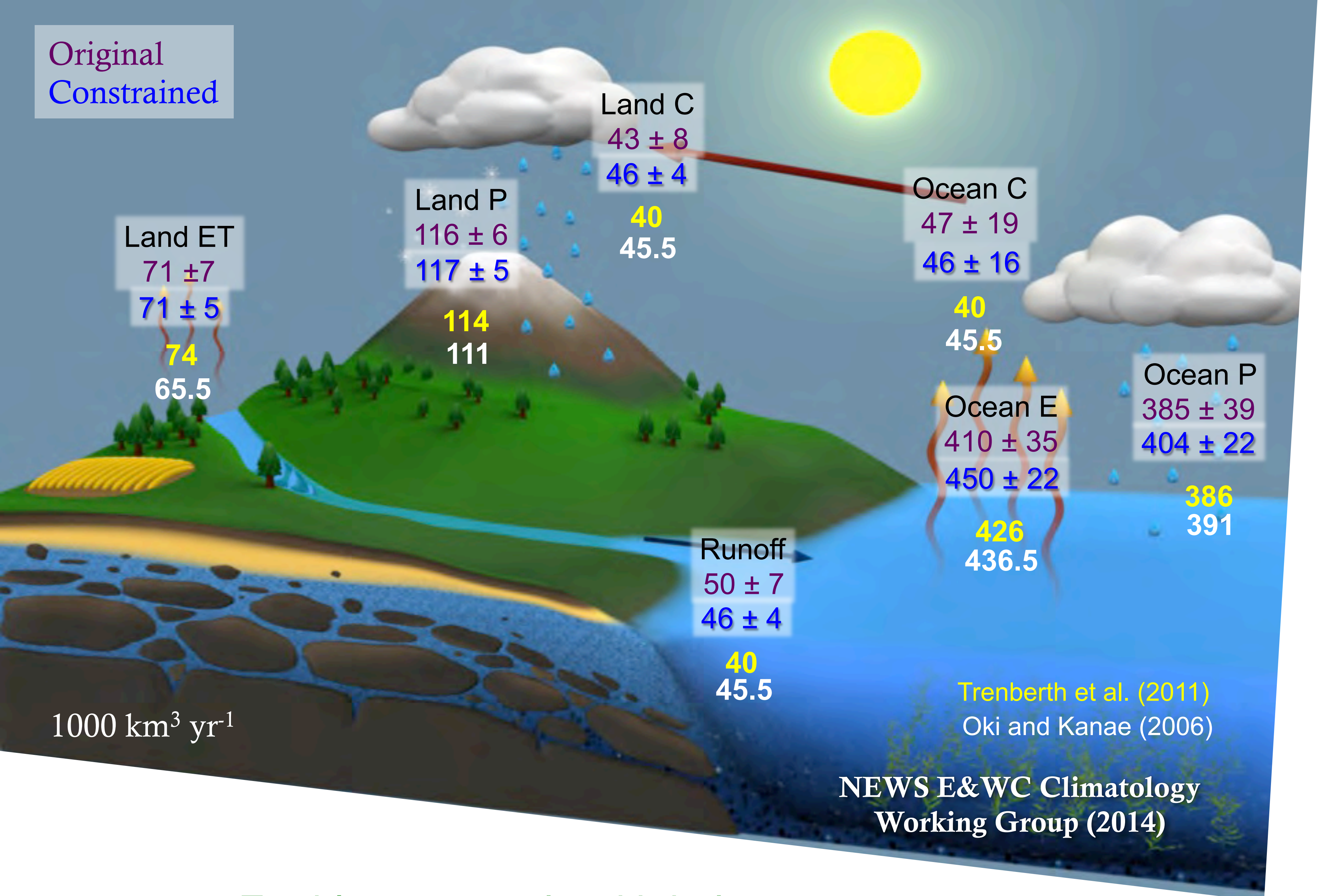
Uncertainties in Precipitation




when integrating over different areas with a different number of input products. For the globe the calculated relative error estimate from this study is about 9%, which is also probably a slight overestimate. These tropical and global estimated bias errors provide one estimate of the current state of knowledge of the planet's mean precipitation.

$9\% \approx 7\ \mathrm{Wm}^{-2}$

Adler et al (2012)



Original
Constrained

Land ET
71 ±7
71 ± 5
74
65.5

Land P
116 ± 6
117 ± 5
114
111

Land C
43 ± 8
46 ± 4
40
45.5

Ocean C
47 ± 19
46 ± 16
40
45.5

Ocean E
410 ± 35
450 ± 22
426
436.5

Ocean P
385 ± 39
404 ± 22
386
391

Runoff
50 ± 7
46 ± 4
40
45.5

1000 km^3 yr^{-1}

Trenberth et al. (2011)
Oki and Kanae (2006)

NEWS E&WC Climatology Working Group (2014)

Earth’s water cycle with balance constraints imposed.

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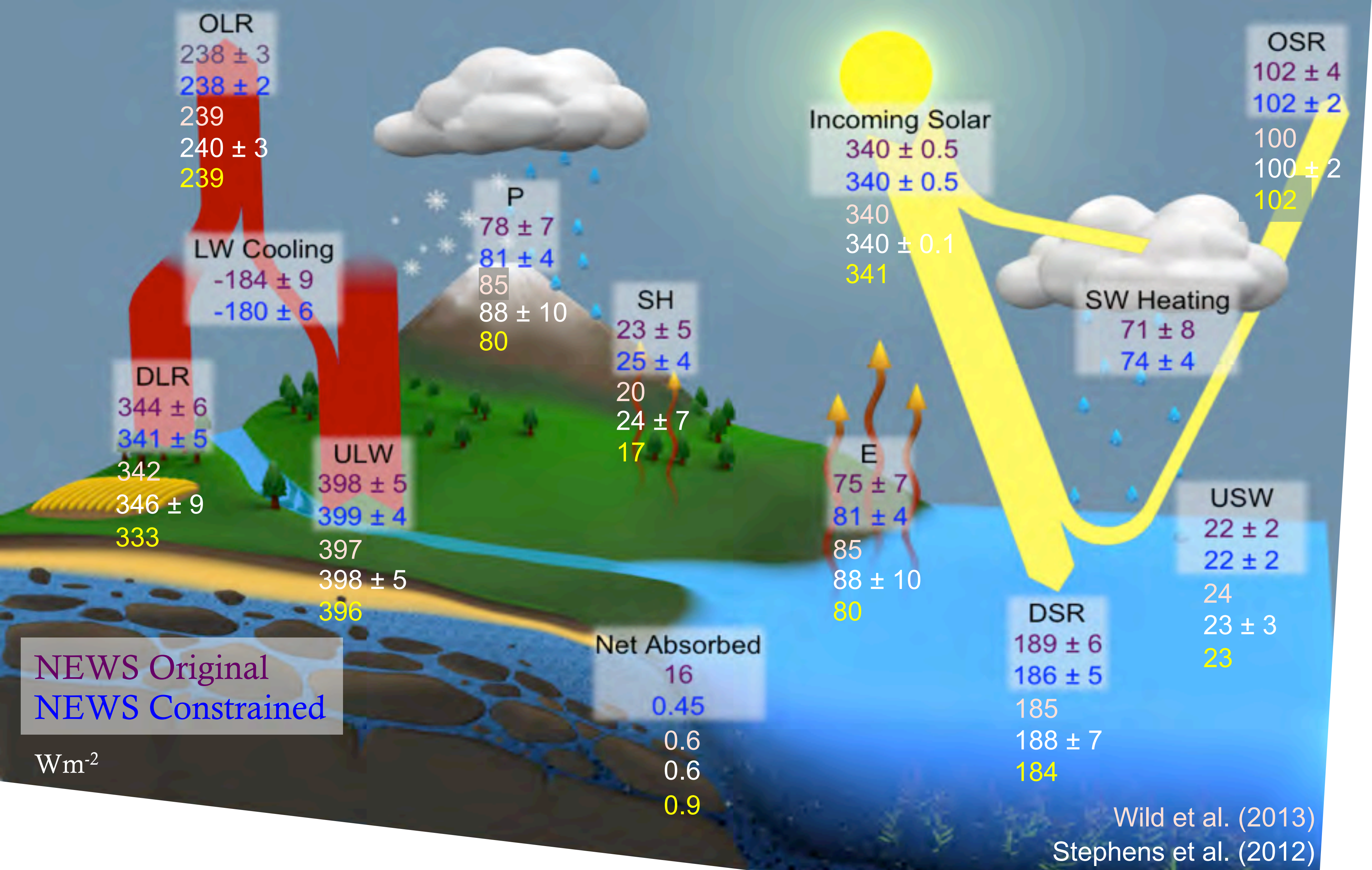
Water Cycle Adjustments

	Expected Closure Error	Best Guess Residual
North America	8.6%	11.0%
South America	8.0%	5.0%
Eurasia	12.5%	5.1%
Africa	8.1%	2.1%
Australia Mainland	15.0%	7.6%
Australasian and Indonesian Islands	19.5%	12.5%
Antarctica	32.4%	*0.0%*
World Land	10.1%	4.3%
World Ocean	13.8%	6.6%

Note the residual after optimization is ~0% in all cases.



OLR
238 ± 3
238 ± 2
239
240 ± 3
239

LW Cooling
-184 ± 9
-180 ± 6

DLR
344 ± 6
341 ± 5
342
346 ± 9
333

ULW
398 ± 5
399 ± 4
397
398 ± 5
396

P
78 ± 7
81 ± 4
85
88 ± 10
80

SH
23 ± 5
25 ± 4
20
24 ± 7
17

Net Absorbed
16
0.45
0.6
0.6
0.9

E
75 ± 7
81 ± 4
85
88 ± 10
80

Incoming Solar
340 ± 0.5
340 ± 0.5
340
340 ± 0.1
341

OSR
102 ± 4
102 ± 2
100
100 ± 2
102

SW Heating
71 ± 8
74 ± 4

DSR
189 ± 6
186 ± 5
185
188 ± 7
184

USW
22 ± 2
22 ± 2
24
23 ± 3
23

NEWS Original
NEWS Constrained

Wm^{-2}

Wild et al. (2013)
Stephens et al. (2012)
Trenberth et al. (2009)

Earth’s energy budget with balance constraints imposed.

L’Ecuyer et al. (2015); Rodell et al. (2015) under revision.

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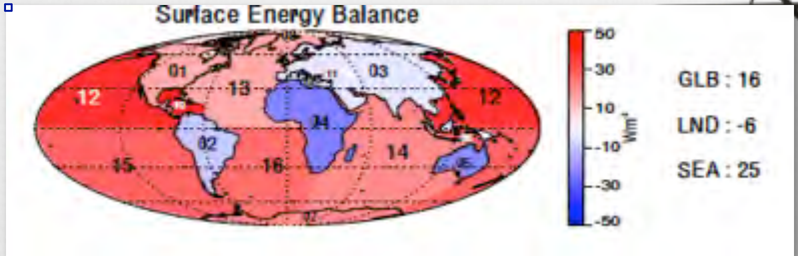
Can the surface energy budget be reconciled with observed changes in OHC?

(i.e. Are the adjustments realistic?)

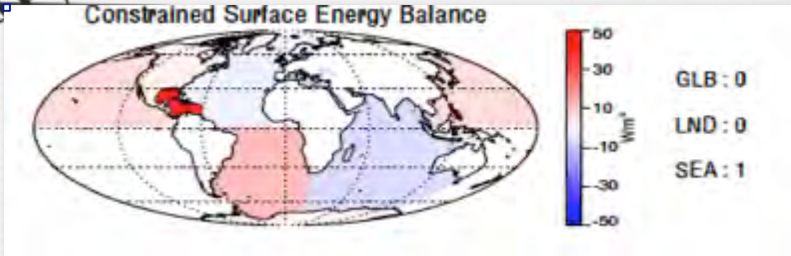
Flux	Raw	Optimized	Change	Error
OLR	238	239	1	2
OSR	100	102	2	5
DLR	344	341	3	7
DSR	190	186	4	6
E	75	81	6	7
P	77	81	4	7
SH	21	25	4	5

All in Wm^{-2}

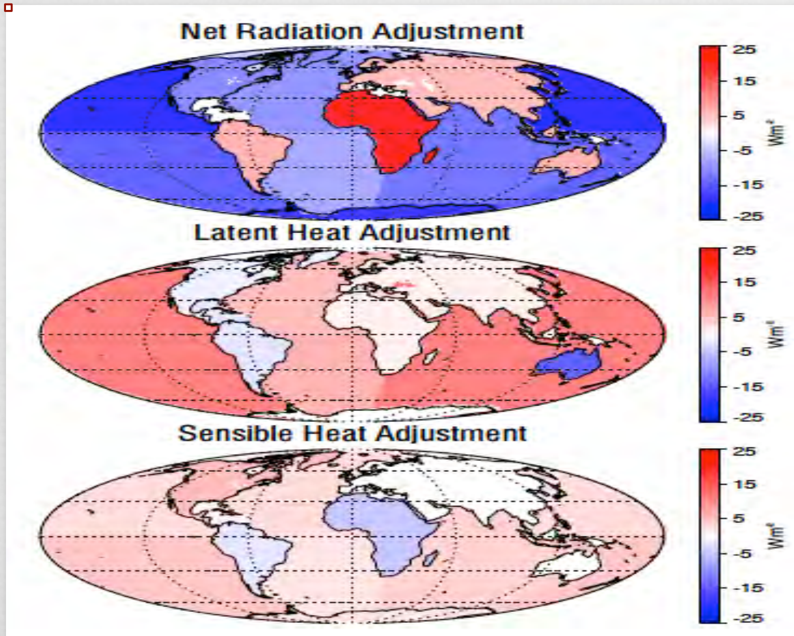
Surface Energy Balance



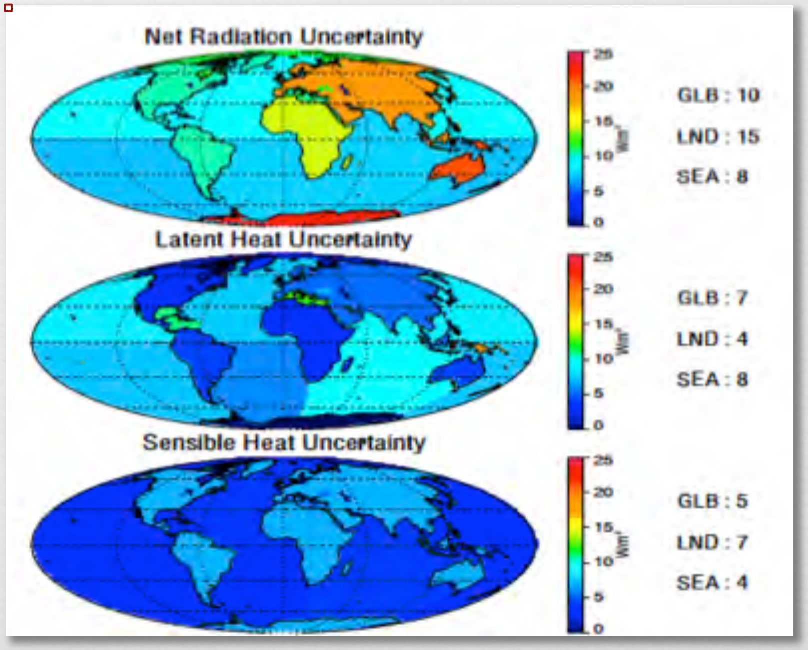
Raw Observations



Constrained



Flux Adjustments



Uncertainty Estimates

New Initiatives

Quantifying Uncertainties, Variability and Trends, Model Evaluation

New Working Groups

- NEWS Water and Energy Cycle Uncertainties Working Group (WECU)
  - Chair: Brent Roberts

- NEWS Working Group on Water and Energy Cycle Variability (WECV)
  - Chairs: Paul Houser and Tristan L'Ecuyer

Water and Energy Cycle Uncertainties

- Objective: Generate dynamic (i.e. space and time-varying) uncertainty estimates in all component fluxes and their dependence on time/space scale and regime (e.g. weather state, thermodynamic conditions, cloud state, etc.).
- Methods:
  - Systematic dataset inter-comparisons on a hierarchy of time and space scales from global/annual through monthly/gridded across different time periods.
  - Results stratified by location, season, and environmental regimes (TBD).

Water and Energy Cycle Uncertainties

- Target time period 1998-2014

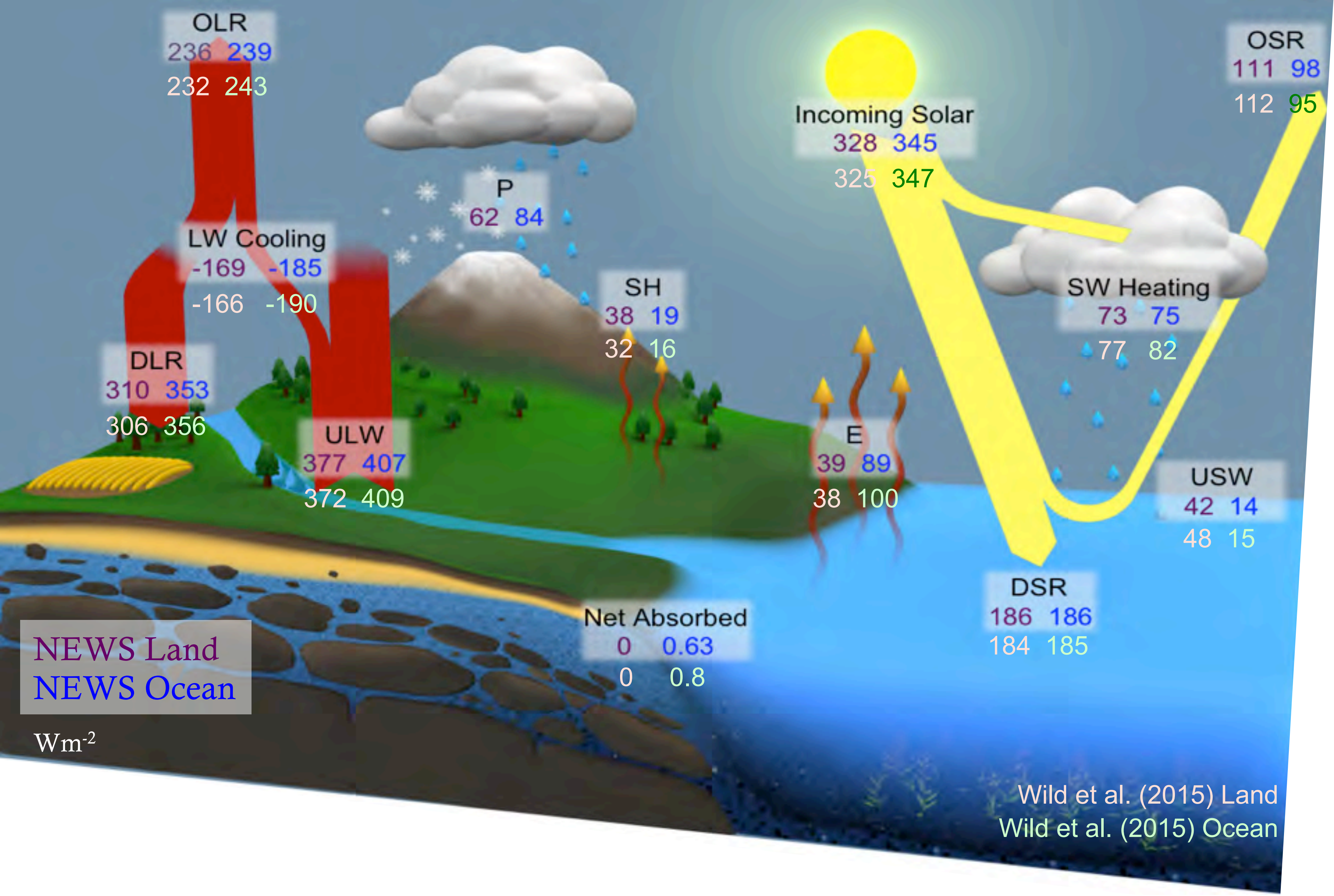
Energy and Water Cycle Budget Variables		
Incoming solar	Sensible heat flux	Surface net heat flux
Outgoing shortwave	Latent heat flux (Evap and ET)	Atmospheric net heat flux
Outgoing longwave	Precipitation (Atmos LH)	Ocean heat content
Downwelling LW @ SFC	Atmos moisture convergence	Ocean heat convergence
Downwelling SW @ SFC	Runoff	
Surface emitted	Atmos water storage	
Surface reflected	Surface water storage	

Water and Energy Cycle Variability

- Objectives: Build upon the methodology developed by NEWS Energy and Water Cycle climatology working group to document and analyze temporal and spatial variability and trends in objectively constrained integrated WECs
- Methods:
  - Apply E&WC closure methodology to monthly fluxes averaged over smaller domains (expanded from 17 to 52)
  - Expand period covered backward in time to span the modern satellite era (target: 1980's to present)
  - Incorporate new time/regime-dependent error and covariance information from WECU

Science Targets

- Document year-to-year water and energy cycle variability
- Test alternative dataset combinations and systematically diagnose sensitivity of balance results to these assumptions
- Examine seasonal variability in land-ocean water and energy exchanges
- Quantify structural correlations in WEC variability (spatial and temporal)
  - Correlations between land-ocean energy and water exchanges and ENSO
  - Inter-annual variations in hemispheric energy imbalances and their role in modulating the ITCZ
  - Inter-annual variability in basin-scale ocean heat transports
  - Trends in WEC fluxes and imbalances



OLR
236 239
232 243

Incoming Solar
328 345
325 347

OSR
111 98
112 95

P
62 84

LW Cooling
-169 -185
-166 -190

SH
38 19
32 16

SW Heating
73 75
77 82

DLR
310 353
306 356

ULW
377 407
372 409

E
39 89
38 100

USW
42 14
48 15

DSR
186 186
184 185

Net Absorbed
0 0.63
0 0.8

NEWS Land
NEWS Ocean

Wm^{-2}

Wild et al. (2015) Land
Wild et al. (2015) Ocean

Constrained land and ocean energy budgets.

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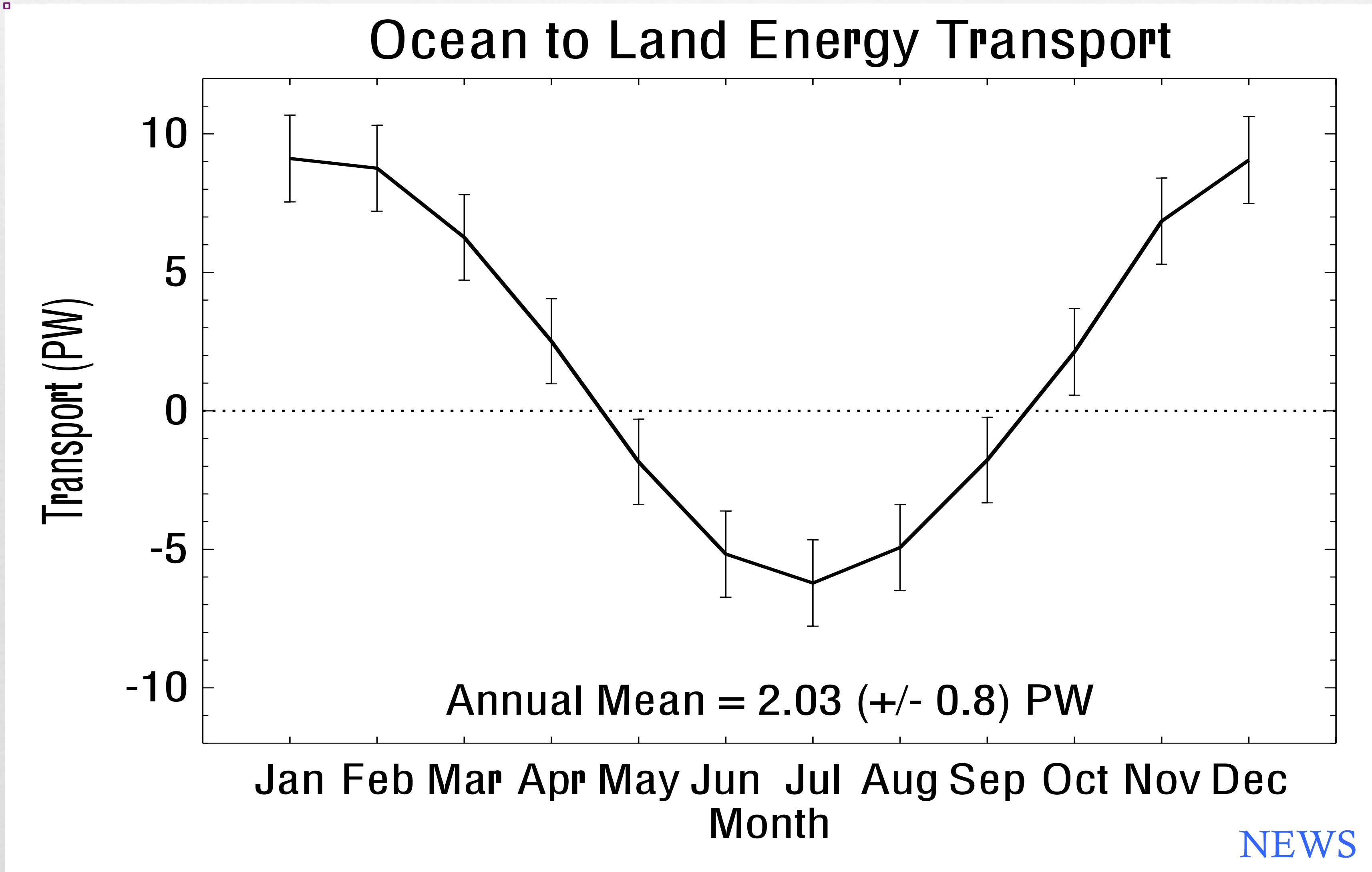
Implied Ocean – Land Heat Transport



Trenberth and Fasullo (2013) → 2.2 PW

Summary

- Integrated closure constraints provide a useful sanity check on uncertainty estimates assigned to individual fluxes and may form a useful part of future assessment strategies.
- *Global* Energy and Water Cycles can be objectively balanced within realistic error estimates
  - Results are a compromise between those presented in other recent studies
- Uncertainty estimates may be too optimistic at *continental* scales. Adjustments are indicative of biases (esp. over oceans).
- The methodology can be applied to diverse dataset combinations and adapted to include dynamic error estimates.
- Expansion to smaller regions and shorter timescales will allow variability and trends to be assessed possibly revealing physical processes through analyses of time-space correlations.