The LandFLUX initiative

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on belhalf of the LandFLUX community

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• Several global data analysis activities are conducted in the frame of **GEWEX** to complete the description of the energy and water cycle.

• Most products are now being worked on (clouds, aerosols, radiative fluxes, precipitation, ocean surface turbulent fluxes, water vapour, temperature, and ozone) apart from the turbulent **land heat fluxes**.

The **LandFlux** initiative of the GEWEX Radiation Panel (GRP):

• Objectives:

to develop the needed capabilities to produce a **global, multi-decadal** surface heat flux data product.

• Agenda:

1st workshop in Toulouse, May 2007.

2nd workshop in Melbourne, Sep 2009.

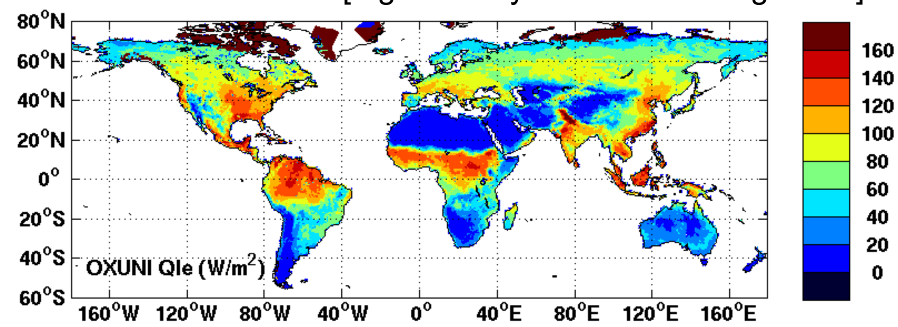
(http://www.gewex.org/projects-GRP.htm)

- Some possibilities for global estimation of **land surface heat fluxes (LE, H):**

[e.g. monthly latent fluxes August 93]

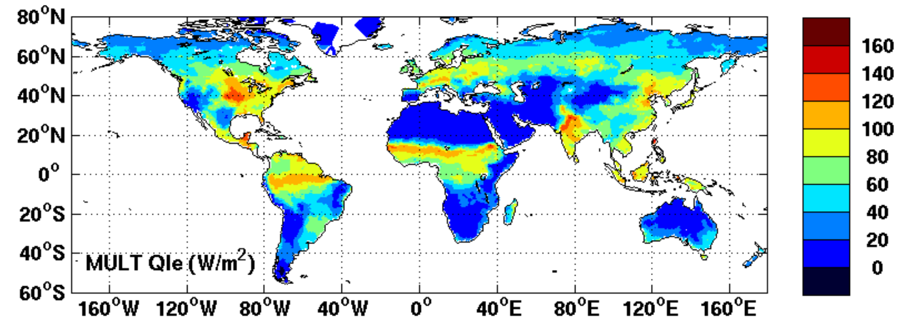
(a) using observations to infer the properties of the atmosphere and surface needed to derive the fluxes by **physically** based **formulations**

e.g. (Fisher J., 2007, Rem. Sens.Envir.)



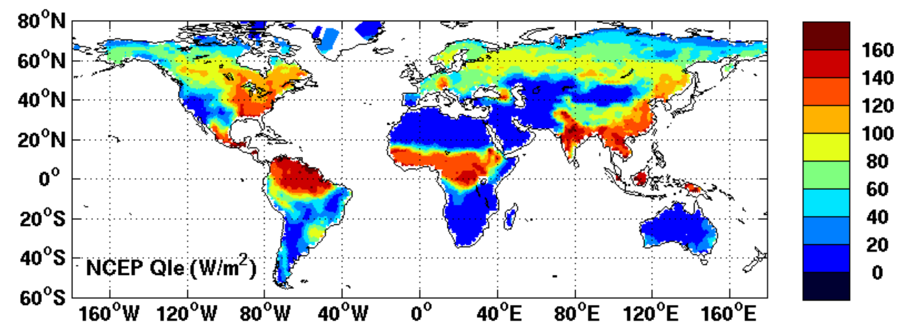
(b) using observations to **force** ‘complex’ **land surface model**, e.g GSWP-2

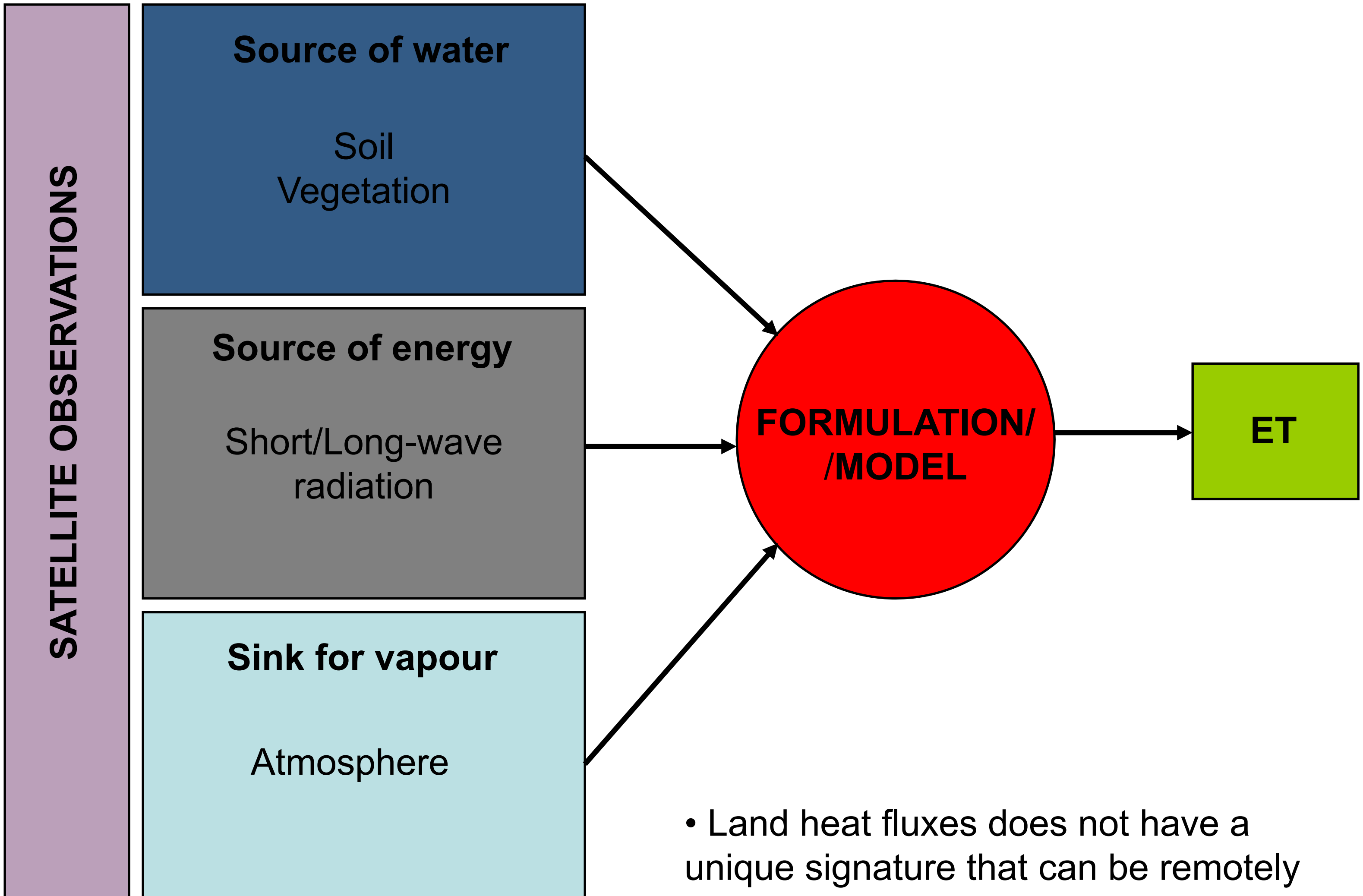
(Dirmeyer P. (2006), BAMS)



(c) **assimilating** observations into a coupled land-atmosphere model e.g NCEP reanalysis

(Kalnay. E. (1996), BAMS)





- Land heat fluxes does not have a unique signature that can be remotely detected, so satellite observations need to be **combined** to infer them.

LandFLUX

- **Energy partition** at the surface governed by:

$$H = \rho c_p \frac{T_s - T_a}{R_a},$$

$$\lambda E = \frac{\rho c_p}{\gamma} \frac{e_s - e_a}{R_a + R_s},$$

$$A = R_n - G - \Delta S = H + \lambda E,$$

where H, λE and A are the fluxes of sensible heat, latent heat and available energy, R_n is net radiation, G is soil heat flux; ΔS is the heat storage flux; T_s, T_a are the aerodynamic surface and air temperatures; e_s, e_a are the water vapour pressure at the evaporating surface and in the air; R_a is the aerodynamic resistance, R_s is the surface resistance to evaporation, λ is the latent heat of evaporation, ρ is air density, and c_p is the specific heat capacity of air. The psychometric constant γ is given by $\gamma = (M_a/M_v)(c_p P_a/\lambda)$, where M_a and M_v are the molecular masses of dry air and water vapour and P_a is atmospheric pressure.

from Cleugh et al. (2007), Regional evaporation estimates from flux tower and MODIS satellite data

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LandFLUX

- Eliminating surface temperature:

Penman-Monteith equation

$$\lambda E_{act} = \frac{\Delta}{\Delta+\gamma^*}(R_n - G_0) + \frac{\gamma}{\Delta+\gamma^*}\frac{\rho_a c_p (e_s(T_a) - e_a)}{r_{ah}}$$

T_a is atmospheric temperature [°C];

e_s is saturated vapour pressure at temperature T [mbar];

Δ is the slope of the vapour pressure curve [mbar K^{-1}];

γ^* equals $\gamma\ (1+r_c\ r_{ah}^{-1})$;

γ is the psychrometric constant [mbar K^{-1}];

$(e_s(T_0)-e_a)$ is saturated vapour pressure deficit [mbar];

Prisley-Taylor simplification

$$\lambda E = \alpha\,(R_n - G_0)\frac{\Delta}{\Delta+\gamma}$$

α is a constant [-] ranging from 1 to 1.35 for wet surfaces [78];

γ is the psychrometric constant [mbar K^{-1}];

Δ is the slope of the vapour pressure curve [mbar K^{-1}].

from Verstraeten et al. (2008), Assessment of evapotranspiration and soil moisture content across different scales of observation

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Inputs

LandFLUX

- **Radiation** at the surface

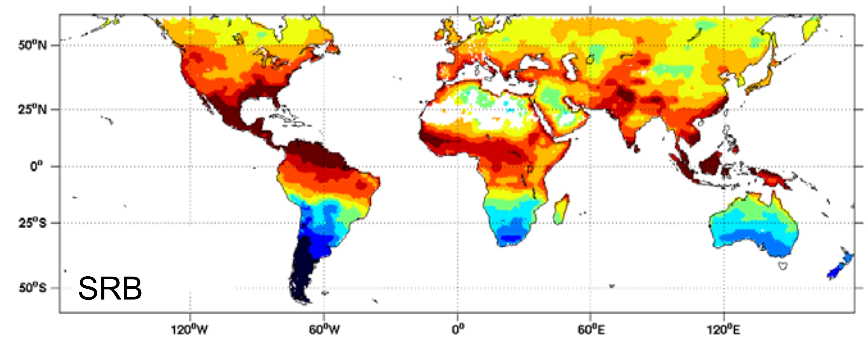
$$R_n = K\downarrow - K\uparrow + L\downarrow - L\uparrow$$

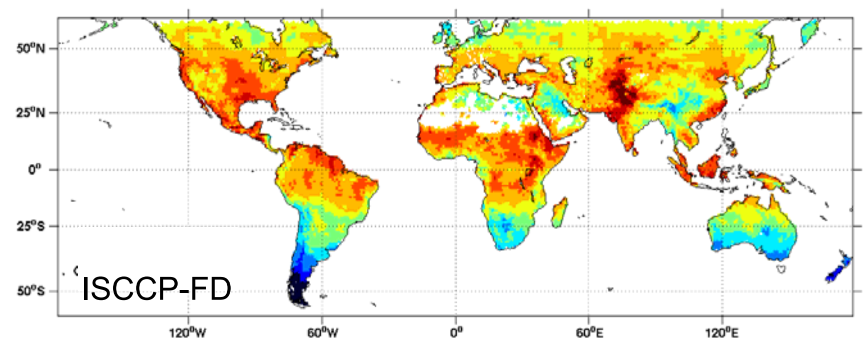
where $K\downarrow$ = down-welling shortwave radiation (which depends on atmospheric transmissivity, time-of-day, day-of-year and geographic position, $K\uparrow$ = reflected shortwave radiation which depends on surface albedo (α) and $K\downarrow$, $L\downarrow$ = down-welling longwave radiation (which depends on the atmospheric emissivity which in turn is influenced by amounts of atmospheric water vapor, carbon dioxide and oxygen and by air temperature and $L\uparrow$ = up-welling longwave radiation (which depends on land surface temperature and emissivity).

from Kalma et al. (2008), Estimating land surface evaporation: a review of methods using remotely sensed surface temperature data

  - From atmospheric reanalysis (e.g ERA-INT), or radiative transfer models fed with relevant data (SRB, ISCCP-FD), or simpler parameterizations combining estimation of down-welling components and surface properties (albedo, emissivity, Ts, …).

e.g. Aug 1993 Rn





- **Soil heat flux**

  - Cannot be measured remotely, G/Rn (5-20%) constant or parameterized

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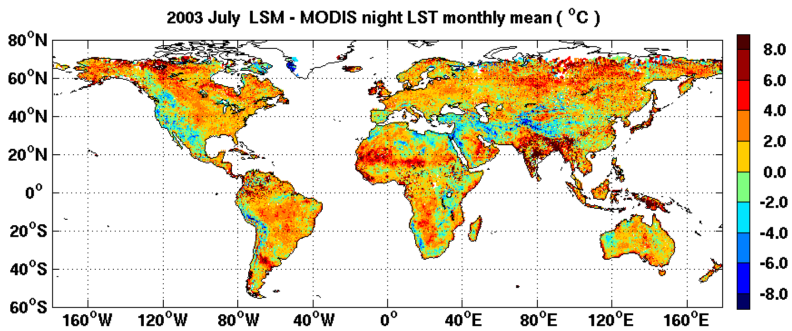
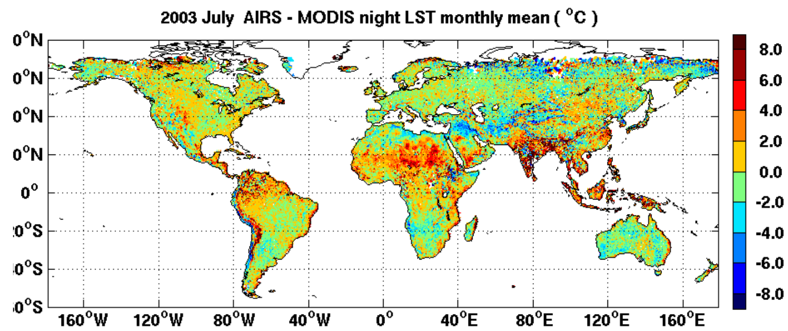
- **Land surface skin temperature** (LST)

  - Radiative temperature available from IR sensors (LandSat, ASTER, AVHRR, MODIS …) for clear-sky at different spatial (60m - 4km) and time (1/2 hour -16 days) resolutions (also from microwave sensors less clear-sky biased but less frequent and at larger spatial resolutions).

  - LST and its difference with air temperature govern the flux partitioning; its diurnal rate of change is a useful constrain for LE as soil moisture conditions have a thermal signature.

e.g. July 2003 LST differences for observations and models





- **Atmospheric forcing**

  - Meteorological inputs (e.g air temperature, vapour pressure, wind, ….) are required by some methods, datasets exist (e.g. CRU) but global coverage can be an issue.

LandFLUX

- Characterizing the **surface**

  - Ra, **aerodynamic resistance**, some of the parameters difficult to estimate globally (U, zo …)

$$R_a = \frac{1}{k^2 U}\left[\ln\left(\frac{z-d}{z_{0H}}\right) - \Psi_H\left(\frac{z-d}{L}\right)\right]\left[\ln\left(\frac{z-d}{z_0}\right) - \Psi_M\left(\frac{z-d}{L}\right)\right]. \quad (4)$$

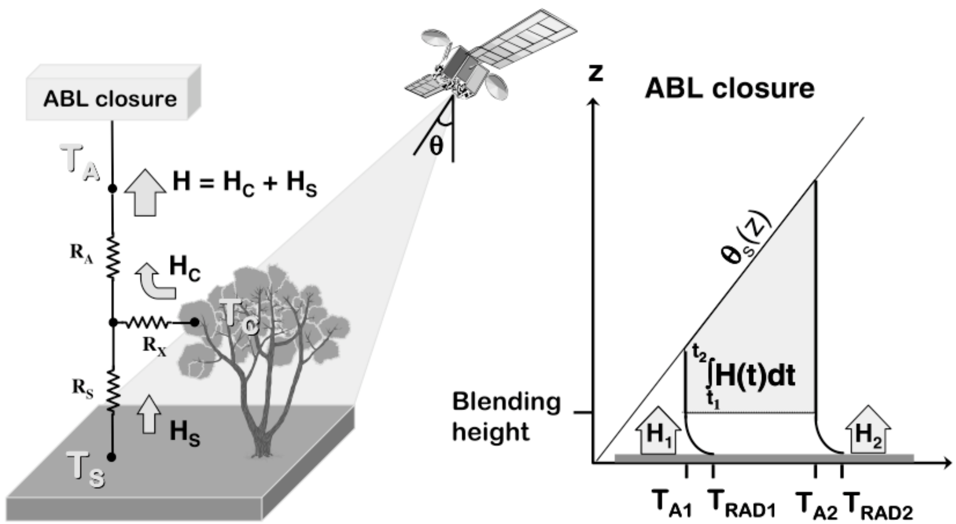
In this equation k is von Karman's constant (0.4); U is wind speed at the reference height z; d is the zero-plane displacement height; z_0, z_{0H} are the roughness lengths for momentum and sensible heat, respectively; and Ψ_M, Ψ_H are the stability correction functions for momentum and heat which depend on the Monin–Obukhov length L (Kaimal & Finnigan, 1994). λE

from Cleugh et al. (2007), Regional evaporation estimates from flux tower and MODIS satellite data

  - Rs, efective **resistance (soil+vegetation)** estimated by parameterizations requiring vegetation indexes (e.g. NDVI, SAVI, EVI) and derived measures (fractional land cover(fc), leaf area index(LAI), fraction of active radiation (PAR) intercepted and/absorbed by vegetation cover, ….)

- How to **reduce sensitivity to input errors** or lack of inputs?

e.g. two-source model with soil and canopy resistances coupled with a model simulating the growth of the ABL. Requires 2 Ts measurements (GOES) but avoids the use of absolute Ts-Ta and remove time independent biases in Ts.



Anderson et al. (2007), A climatological study of the evapotranspiration and moisture stress across the continental US based on thermal remote sensing

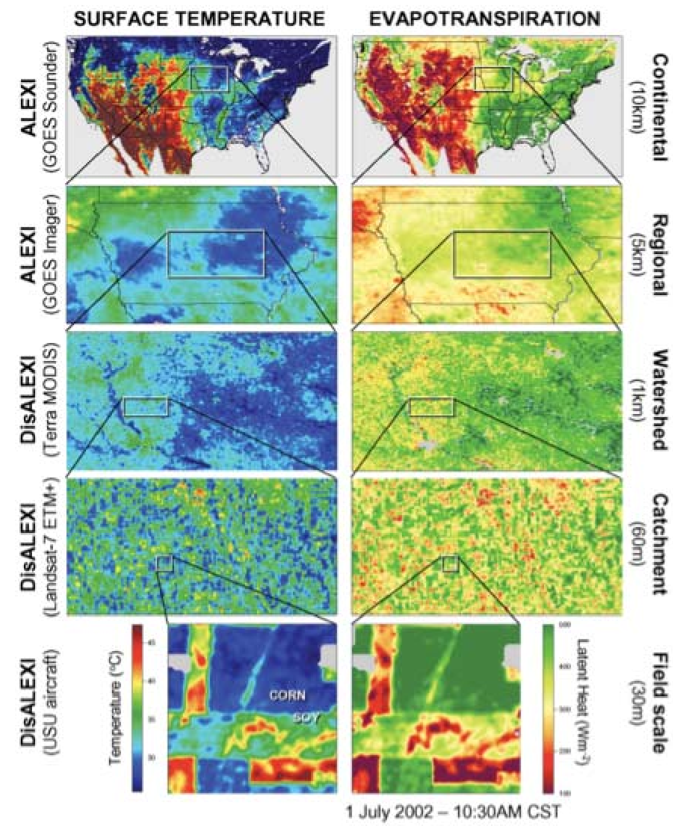
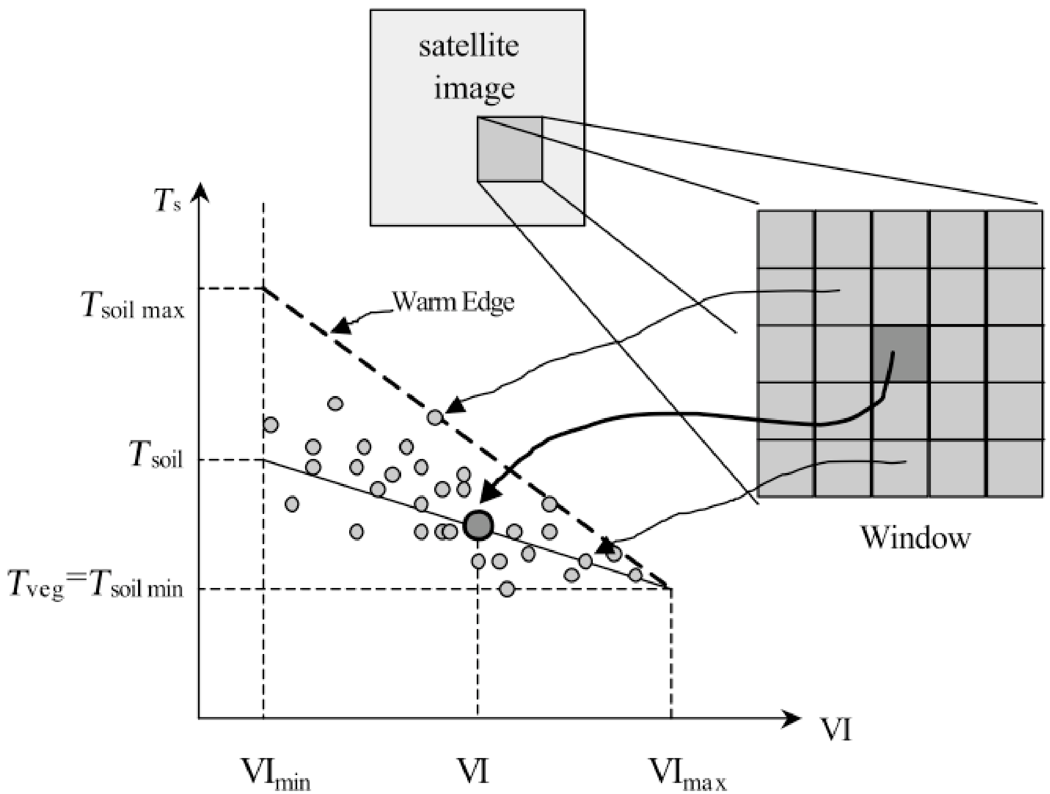


Fig. 1. Multiscale evapotranspiration (ET) maps for 1 July 2002, focused over the corn and soybean production region of central Iowa, produced with the ALEXI/DisALEXI (Atmosphere Land Exchange Inverse/Disaggregated ALEXI) surface energy balance models [Anderson et al., 2007a] using surface temperature data from aircraft (30-meter resolution), Landsat 7 Enhanced Thematic Mapper Plus (ETM+) (60-meter), Terra Moderate Resolution Imaging Spectroradiometer (MODIS) (1-kilometer), GOES Imager (5-kilometer), and GOES Sounder (10-kilometer) instruments. The continental-scale ET map is a 14-day composite of clear-sky model estimates.

Anderson and Kustas (2008), Thermal remote sensing of drought and evapotranspiration

- How to **reduce sensitivity to input errors** or lack of inputs?

  e.g. Vi-Ts methods, with changes in the slope of Vi-Ts tracking surface conductance. Here determining Tsoil and Tveg from Vi-Ts scatter plot to derive an evaporative fraction without requiring VPD or Ta.



Nishida et al. (2003), An operational remote sensing algorithm of land surface evaporation

- Possibilities to **estimate LE/H**:

1. H from formulations involving Ts, LE calculated as a residual of the surface energy balance

   e.g. Su (2002), the Surface Energy Balance System (SEBS) for estimation of turbulent heat fluxes

2. LE calculated from equations predicting the main evapotranspiration processes, H as a residual

   e.g. Cleugh et al. (2007), Regional evaporation estimates from flux tower and MODIS satellite data

3. LE and/or H calculated from empirical regressions linking the fluxes to related atmospheric/surface observations

   e.g Wang et al. (2008), An improved method for estimating global evapotranspiration based on satellite determination of surface net radiation, vegetation index, temperature and soil moisture

Methods

LandFLUX

1.Introduction

2.Equations

3.Inputs

4.Methods

5. Global fluxes

6. Inter--comparing fluxes

- Some validated **methods** for LE:

Table 2 Validation of remote sensing techniques for estimating evaporation

Section	Method	Source	Validation	Surface type	T_{rad}, NDVI and albedo	$R_n - G$	E	Time step	RMSE (W m^{-2})	r^2	Relative error (%)
4.1	One-source SEB	Kustas (1990)	Kustas (1990)	Furrowed cotton	Mast; aircraft	Observed	BR EC	30 min	24–85		10–25
4.1	One-source SEB	Boegh et al. (2002)	Boegh et al. (2002)	Wheat, grass, maize, barley	Landsat TM	Derived	EC	30 min	27	0.87	14
4.1	One-source SEB	Su (2002)	Su et al. (2005)	Corn	Mast	Observed	EC	30 min	47	0.89	
4.1	One-source SEB	Su (2002)	Su et al. (2005)	Soybean	Mast	Observed	EC	30 min	40	0.84	
4.1	One-source SEB	Su (2002)	McCabe and Wood (2006)	Corn and soybean	ASTER	Derived	EC	Instant	99	0.66	
4.1	One-source SEB	Su (2002)	McCabe and Wood (2006)	Corn and soybean	Landsat 7 ETM	Derived	EC	Instant	68	0.77	
4.1	One-source SEB	Su (2002) [SEBS]	Su et al. (2007)	Grassland, crops, (rain)forest	MODIS	Derived	EC	Daily	44		25
4.2	Two-source SEB	Kustas (1990)	Kustas (1990)	Furrowed cotton	Mast, aircraft	Observed	BR EC	30 min	48		15
4.2	Two-source SEB	Norman et al. (1995) [TSM]	Kustas and Norman (1999)	Furrowed cotton	Masts; aircraft	Observed	BR EC	Instant	37–47		12–15
4.2	Two-source SEB	Norman et al. (1995) [TSM]	Norman et al. (2000)	Shrubland, rangeland, pasture, salt cedar	Masts	Derived	BR EC	30 min	105		27
4.2	Two-source SEB	Norman et al. (1995) [TSM]	French et al. (2005)	Corn and soybean	ASTER	Derived	EC	30 min	94		26
4.2	Two-source SEB	Kustas and Norman (1999)	Li et al. (2006)	Corn and soybean	Landsat7 ETM, Landsat5TM	Observed	EC	30 min	50–55		10–15
5	Time-rate of change	Anderson et al. (1997) [ALEXI], Norman et al. (2003)[disALEXI]	Norman et al. (2003)	Wheat, pasture	GOES, Airborne TIMS, TMS	Derived	EC	Hourly	40–50		20

Kalma et al. (2008), Estimating land surface evaporation: a review of methods using remotely sensed surface temperature data

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- Some validated **methods** for LE:

Table 2 continued

Section	Method	Source	Validation	Surface type	T_{rad}, NDVI and albedo	$R_n - G$	E	Time step	RMSE ($W\ m^{-2}$)	r^2	Relative error (%)
5	Time-rate of change	Norman et al. (2000) [DTD]	Norman et al. (2000)	Shrubland, rangeland, pasture, bare, salt cedar	IRT on masts	Derived	BR EC	30 min	65		17
5	Time-rate of change	Anderson et al. (1997) [ALEXI], Norman et al. (2003)[disALEXI]	Anderson et al. (2007a, b)	Water, forest, woodland, shrubland, grassland, crops, bare, built-up	GOES, MODIS	Derived	EC	Hourly	58		25
6.1	T_{rad}, α and VIs	Bastiaanssen et al. (1998a) Bastiaanssen (2000) [SEBAL]	French et al. (2005)	Corn and soybean	ASTER	Derived	EC	30 min, during overpass	55		15
6.2	T_{rad} and α	Roerink et al. (2000) [S-SEBI]	Verstraeten et al. (2005)	Forests	AVHRR	Derived	EC	30 min during overpass	35		24
6.3	T_{rad} and VIs	Carlson et al. (1995a) [Triangle Method]	Gillies et al. (1997)	Tallgrass prairie, grasslands, steppeshrub	Aircraft M/S scanner	Observed	BR EC	During overpass	25–55	0.80–0.90	10–30
6.3	T_{rad} and VIs	Jiang and Islam (2001)	Jiang and Islam (2001)	Mixed farming, forest, tall & short grass	AVHRR	Derived	BR EC	During overpass	85	0.64	30
6.3	T_{rad} and VIs	Jiang and Islam (2001)	Jiang and Islam (2001)	Mixed farming, forest, tall &short grass	AVHRR	Observed	BR EC	During overpass	50	0.90	17
6.3	T_{rad} and VIs	Jiang and Islam (2001)	Jiang and Islam (2003)	Mixed farming, cropping, forest, tall& short grass	AVHRR	Derived	BR EC	During overpass	59	0.79	15

Kalma et al. (2008), Estimating land surface evaporation: a review of methods using remotely sensed surface temperature data

1.Introduction
2.Equations
3.Inputs
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5. Global fluxes
6. Inter--comparing fluxes

• Some validated **methods** for LE:

Table 2 continued

Section	Method	Source	Validation	Surface type	T_{rad}, NDVI and albedo	$R_n - G$	E	Time step	RMSE ($W\ m^{-2}$)	r^2	Relative error (%)
6.3	T_{rad} and VIs	Jiang and Islam (2001)	Batra et al. (2006)	Mixed farming, forest, tall &short grass	MODIS, AVHRR	Derived	BR	During overpass	51–56	0.77–0.84	22–28
6.3	T_{rad} and VIs	Nishida et al. (2003a)	Nishida et al. (2003a)	Forest, corn, soybean, wheat, shrubland rangeland, tallgrass	AVHRR	Derived	EC	Day time averages	45	0.86	
6.4	Empirical method based on EVI	Wang et al. (2007)	Wang et al. (2007)	Forest, grassland, cropping	MODIS	Observed	EC	16-day averages	32	0.81	36
7.2	T_{rad} and climate data	McVicar and Jupp (2002) [NDTI]	McVicar and Jupp (1999)	Cropping	Mast IRT	Observed	BR	AVHRR and TM overpass time	88–72	0.52–0.81	27–30
7.3	T_{rad} and compl. approach	Granger (1989) [Complementary method]	Crago and Crowley (2005)	Grassland, rangelands	Mast IRT	Observed	EC BR	10 min, 30 min	16–132		
7.3	T_{rad} and compl. approach	Venturini et al. (2008)	Venturini et al. (2008)	Rangelands, pasture, wheat	MODIS	Derived	BR	Instant. on 7 days	34	0.79	15
8.2	Assimilation of T_{rad}	Caparrini et al. (2004)	Caparrini et al. (2004)	Tall-grass prairie	IRT on masts	Observed	EC BR	30 min	56		
8.2	Assimilation of T_{rad}	Caparrini et al. (2004)	Caparrini et al. (2004)	Tall-grass prairie	IRT on masts	Observed	EC BR	Daily averages	20	0.96	

Kalma et al. (2008), Estimating land surface evaporation: a review of methods using remotely sensed surface temperature data

- Findings from previous review:

  - assessment of ~ 30 published validations showing an RMSE ~ **50 W/m²** and relative errors of **15-30%** (at different time steps and for different regions)

  - the assessment shows that more complex **physical** and analytical methods are not necessarily more accurate than empirical and **statistical** methods

  - improved temporal **scaling procedures** are required to extrapolate instantaneous estimates to daily and longer time periods

  - **gap-filling techniques** are needed when temporal scaling is affected by intermittent satellite cover

Kalma et al. (2008), Estimating land surface evaporation: a review of methods using remotely sensed surface temperature data

- **Pros** and **cons** of different methods?

Concept	Method	Parameters: EO	Parameters: Other	Advantages	Disadvantages	Ref (Sel.)
Parameterisation of the energy balance	SEBAL	LST, α_0, NDVI	T_a, v_a, ε_0, RH, surface roughness	Data requirements are minimal; Physical concept; no need for land use; multi-sensor approach.	Dry and wetland requirement to estimate H, hence heterogeneous surface needed in the ROI; only applicable for flat terrain.	[88], [89], [90], [25].
	SEBS	LST, α_0, NDVI	T_a, v_a, ε_0, LAI, e_a & e_{sat}., surface roughness	No a-priori knowledge of the actual turbulent heat fluxes needed.	Dry and wetland requirement to estimate H; combined with Penman-Monteith equation.	[68], [70].
	RMI	LST, α_0	Detailed meteorological data	Based on geostationary satellites with high temporal resolution.	Monin-Obukhov lengths require detailed meteorological data (network of synoptical stations).	[64].
	S-SEBI iNOAA	LST, α_0, NDVI	T_a, ε_0, (RH)	Data requirements are minimal; No need for land use; no need to estimate H, multi-sensor.	Dry and wetland requirement to estimate evaporative fraction (dependent on ROI).	[91], [69].
Penman-Monteith based	Trapezo-idal shape	LST, SAVI	T_a, ε_0, vapour pressure deficit, LAI	Minimal meteorological data requirement, ET estimation at regional scales.	Requirement for biome map, surface roughness, vegetation height.	[92].
	Promet	α_0,	Resistance values, LAI, soil type	Across scales, physiologically based (SVAT).	Requires a plant physiological model, land use, extensive meteorological dataset.	[54].
	Granger	LST, α_0, NDVI	T_a, saturated vapour pressure	Feedback relationship: LST is used to obtain the vapour pressure deficit in the overlying air.	Requires long term T_a and a conventional ET model including vapour transfer coefficient.	[65].
	Wang	LST, α_0, VI	Meteorological data	Gradients of T_a and LST not required.	Day and night LST required.	[93].
	Cleugh	LST, α_0, VI	Meteorological data	Linear relationship surface conductance and MODIS-LAI.	Extensive meteorological data and estimations of canopy cover required.	[94].

Verstraeten et al. (2008), Assesment of evapotranspiration and soil moisture content across different scales of observattion

• Policies for development of **global LE, H**?

[8] (1) "Stand alone." It can operate without surface meteorological data (e.g., wind speed, vapor pressure deficit (VPD), air temperature, boundary layer stability). In general, the VPD and the wind speed (or the aerodynamic resistance) are difficult to be estimated from remote sensing, yet critical for ET estimation. Therefore we tried to minimize the influence of these two meteorological elements in our algorithm.

[9] (2) "Flexibility." If meteorological data are available, the algorithm should be flexible enough to incorporate them. It should also incorporate other ancillary data such as albedo, emissivity, and roughness when they are available. Therefore we must describe these variables explicitly in the algorithm.

[10] (3) "Simplicity." It is simply constructed in order to save computational resources.

[11] (4) "Scalability." It provides information not only about instantaneous but also about daily ET. This is because daily ET is more interesting for many users than instantaneous one. Moreover, because the NASA EOS project operates the two MODIS sensors onboard the EOS-AM (Terra) satellite and the EOS-PM (Aqua) satellite [*Running et al.*, 1994] and they observe each land surface twice a day (morning and afternoon), the algorithm should consistently process these multiple data sources if required.

[12] (5) "Versatility." It should operate regardless of the type of vegetation, land cover, season, and climate.

Nishida et al. (2003), An operational remote sensing algorithm of land surface evaporation

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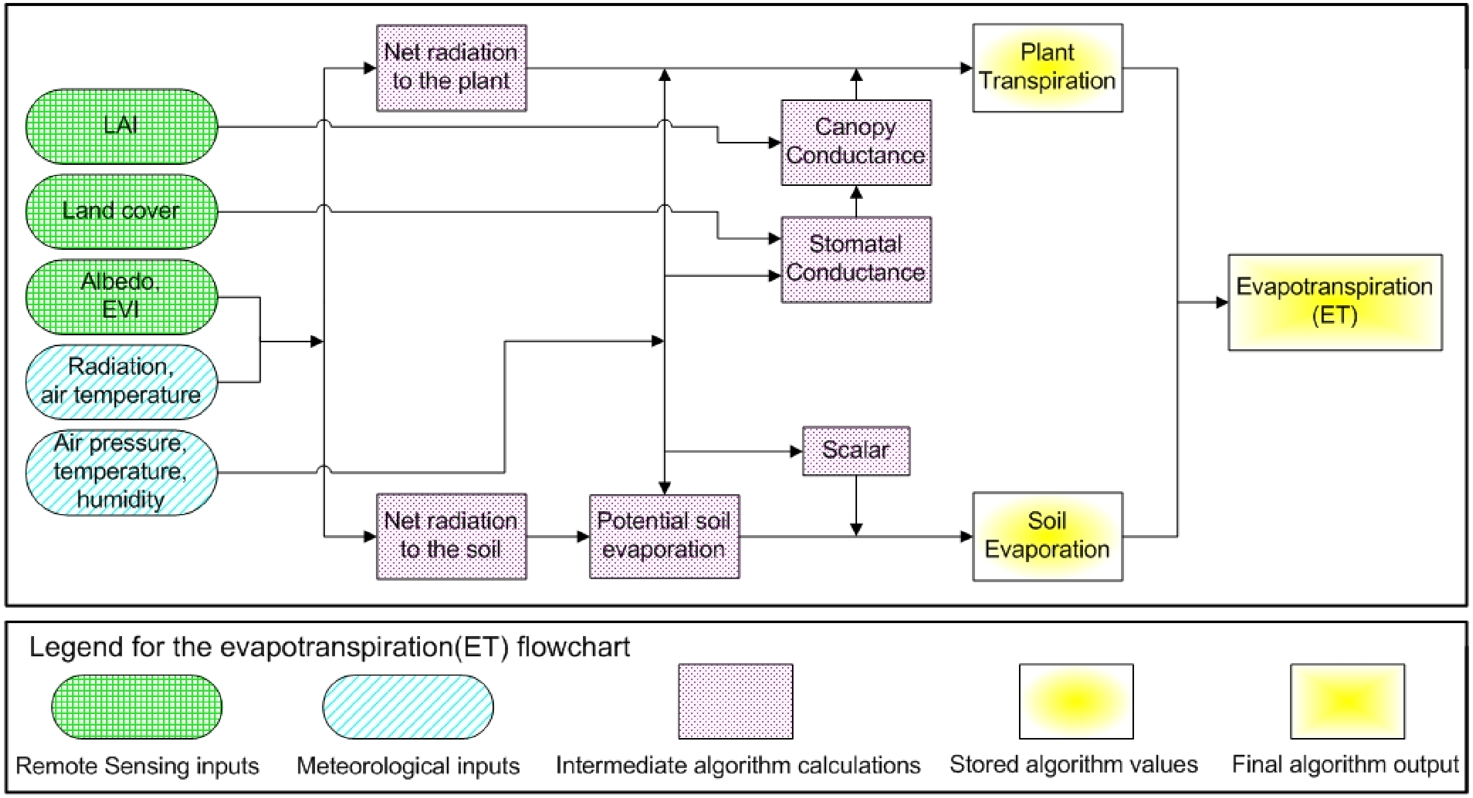
- Policies for development of **global ET**? Other ideas?



Mu et al. (2003), Development of a global evapotranspiration algorithm based on MODIS and global meteorology data

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LandFLUX

- **Published** global RS datasets:

1.

ELSEVIER

Remote Sensing of Environment 112 (2008) 901 – 919

www.elsevier.com/locate/rse

Global estimates of the land–atmosphere water flux based on monthly AVHRR and ISLSCP-II data, validated at 16 FLUXNET sites

Joshua B. Fisher [a,*], Kevin P. Tu [b], Dennis D. Baldocchi [a]

2.

712 JOURNAL OF HYDROMETEOROLOGY VOLUME 9

An Improved Method for Estimating Global Evapotranspiration Based on Satellite Determination of Surface Net Radiation, Vegetation Index, Temperature, and Soil Moisture

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JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 114, D06305, doi:10.1029/2008JD011392, 2009

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Toward an estimation of global land surface heat fluxes from multisatellite observations

Carlos Jiménez,[1] Catherine Prigent,[1] and Filipe Aires[2]

ELSEVIER

Remote Sensing of Environment 111 (2007) 519 – 536

www.elsevier.com/locate/rse

Development of a global evapotranspiration algorithm based on MODIS and global meteorology data

Qiaozhen Mu *, Faith Ann Heinsch, Maosheng Zhao, Steven W. Running

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Global heat fluxes

LandFLUX

1.Introduction

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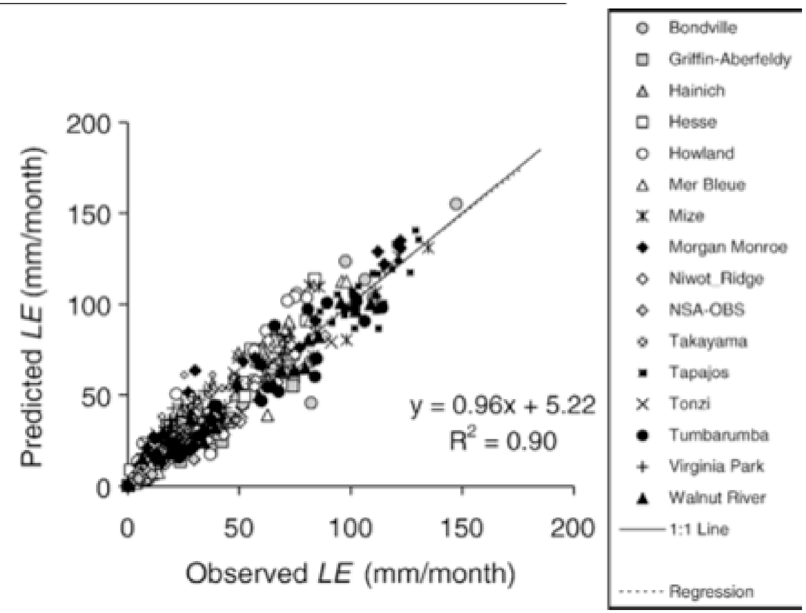
1. **Prisley-Taylor** with new **ecophysiological** ideas on how to reduce potential to actual ET when soil moisture, stomatal resistance and wind speed data are unavailable.

[1º x 1º, monthly means, 1986-1995]

- **Inputs**

Global estimates		
R_n	Net radiation	ISLSCP-II
T_{max}	Air temperature	ISLSCP-II
ea	Water vapor pressure	ISLSCP-II
r_{vis}	Visible spectrum reflectance	AVHRR
r_{NIR}	Near-infrared spectrum reflectance	AVHRR

- **Evaluation** at 16 tower EC fluxes with model using in situ meteorology



Fisher et al. (2008), Global estimates of the land-atmosphere water flux based on monthly AVHRR and ISLSCP-II data, validated at 16 FluxNet sites

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Global heat fluxes

LandFLUX

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2. **Statistical** method using a simple **regression** equation calibrated at 12 (EBBR and EC) US sites

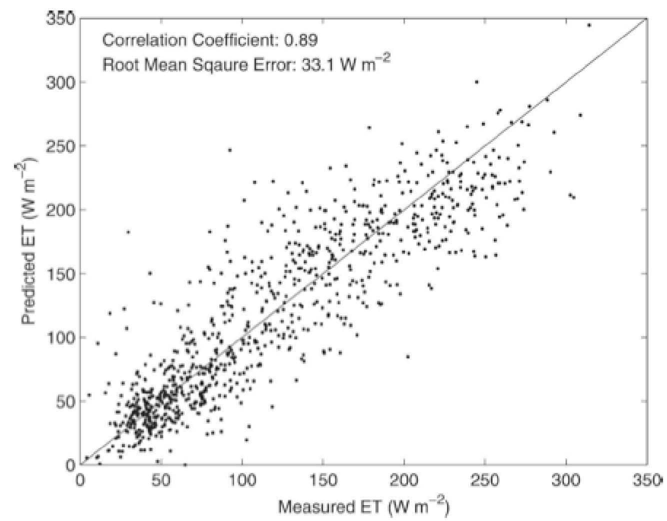
$$ET = R_n(0.1440 + 0.6495\mathrm{NDVI} + 0.0090T_{a,d} - 0.0163\mathrm{DTaR}),$$

[1º x 1º, monthly means, 1986-1993]

- **Inputs**

  R_n, $T_{a,d}$ (day time averaged air T) , DTaR (diurnal air T range) from ISLSCP-II, NDVI from AVHRR

- **Evaluation** at 12 sites using in situ meteorology



Wang et al. (2008), An improved method for estimating global evapotranspiration based on satellite determination of surface net radiation, vegeation index, temperature and soil moisture

l'Observatoire de Paris LERMA

Global heat fluxes

LandFLUX

3. **Statistical** method using regression models to relate land surface model fluxes with multi-sensor observations (aiming not only at data production but also at land model development and multi-variable assimilation)

- **Inputs**

[0.5º x 0.5º, monthly means, 1993-1999

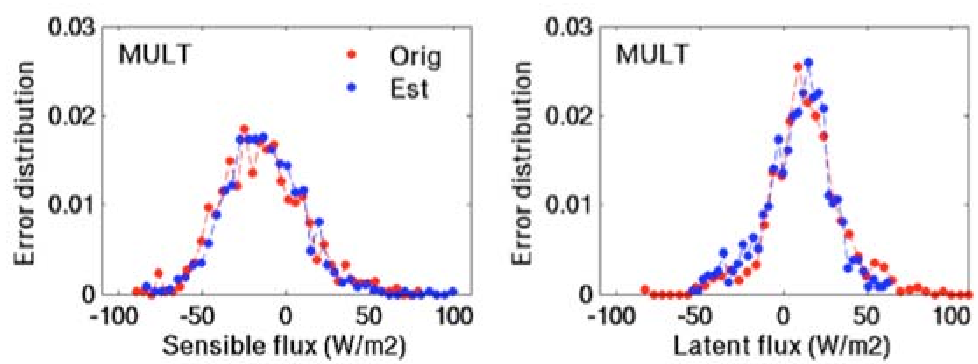
Table 1. Correlation Coefficients and RMS Errors for a Nonlinear Estimation Between Individual Groups of Satellite-Derived Variables and Sensible and Latent Fluxes (GSWP Multimodel Analysis and NCEP Reanalysis)[a]

	Correlation		RMSE	
Satellite Products	GSWP	NCEP	GSWP	NCEP
Sensible Flux				
Emissivity	0.44	0.61	27.1 (58.1)	34.9 (63.0)
Backscatter	0.32	0.52	28.6 (61.3)	37.5 (67.7)
Reflectance	0.42	0.59	27.4 (58.8)	35.4 (63.8)
Skin Temperature	0.64	0.63	23.0 (49.5)	34.1 (61.6)
Diurnal Cycle	0.59	0.71	24.4 (52.3)	30.8 (55.5)
Net Radiation	0.69	0.70	21.8 (46.8)	31.5 (56.9)
Latent Flux				
Emissivity	0.80	0.83	21.6 (46.2)	31.5 (56.9)
Backscatter	0.70	0.75	25.6 (55.0)	36.7 (66.2)
Reflectance	0.82	0.79	20.2 (43.4)	34.5 (62.4)
Skin temperature	0.48	0.48	31.5 (67.7)	49.3 (89.1)
Diurnal cycle	0.72	0.76	24.9 (53.4)	36.2 (65.3)
Net radiation	0.82	0.84	20.6 (44.3)	29.5 (53.4)

[a]The satellite-derived variables are SSM/I emissivity, ERS backscatter, AVHRR reflectance, ISCCP skin temperature, amplitude of its diurnal cycle, and net radiation. The RMS error is given in W/m^2 and as a percentage of the mean flux (in brackets).

Jimenez et al. (2008), Towards an estimation of global land surface heat fluxes from multi-satellite observations

- Coarse **evaluation** at 76 Ameriflux sites using tower flux 2002-2006 annual climatologies



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[Statistical models for LSM development]

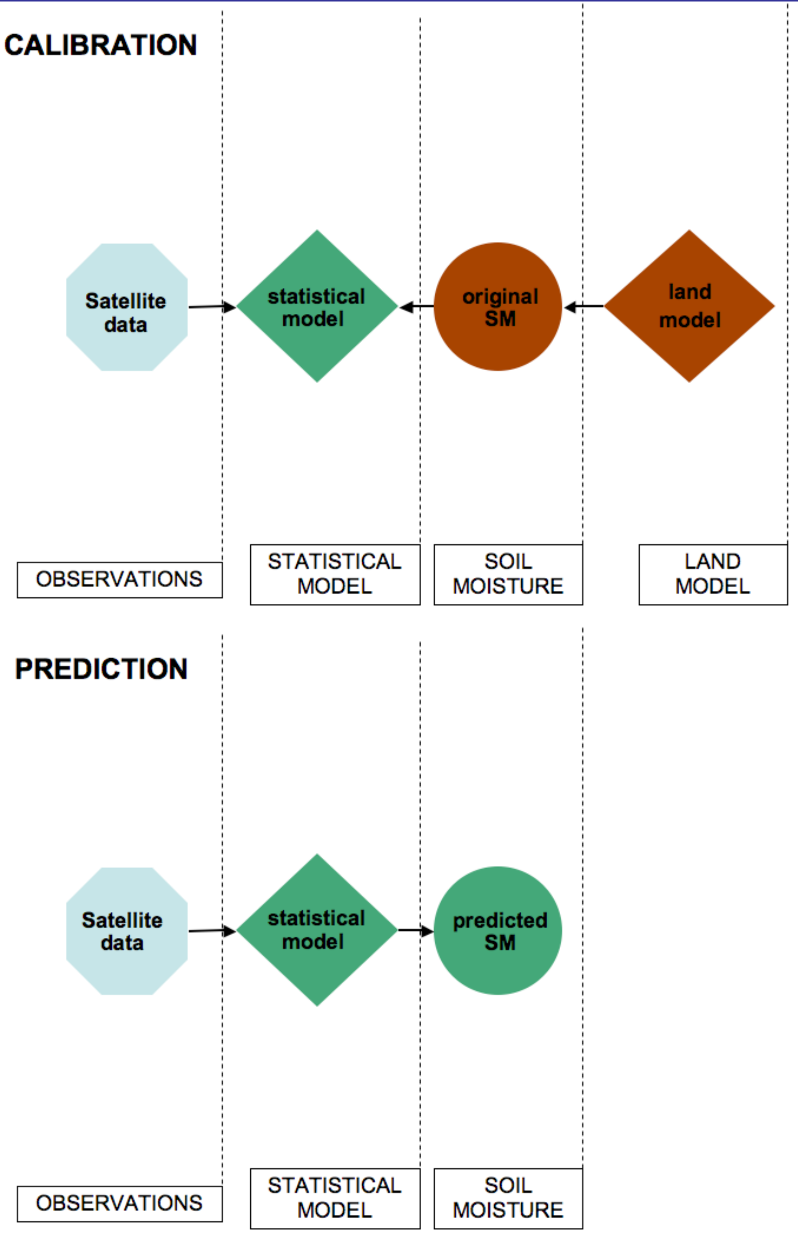
- **Methodology**

Phase 1

The statistical models learn the global relationships between observations and a land model state variable (e.g. soil moisture).

Phase 2

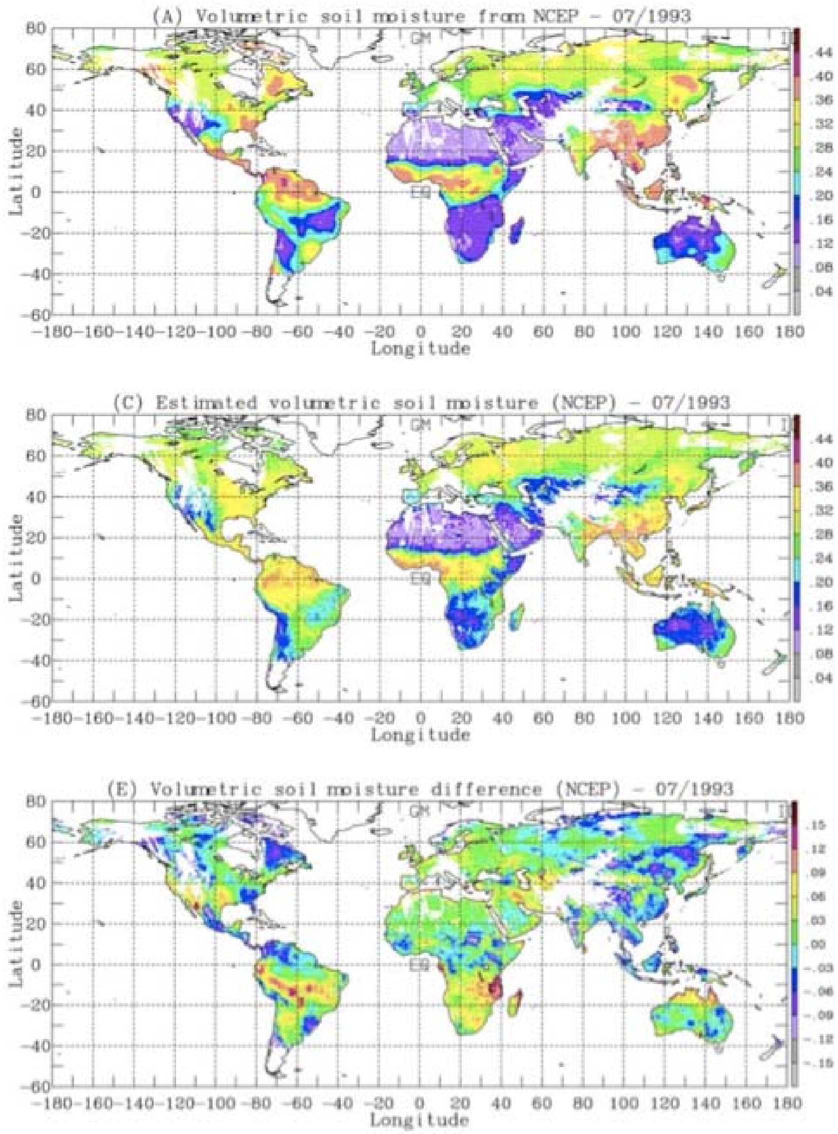
The statistical models map the observations into soil moisture using the learned global relationships.



[Statistical models for LSM development]

- **Applications [1]**

  - for specific regions and times there may be no consistency between the LSM (original) variable and the satellite-driven (statistical model) variable: this can be used to **diagnose potential LSM problems.**



e.g. (a) July 93 monthly **soil moisture** from **NCEP**, (c) associated prediction from satellite observations, and (e) difference .

[Aires, F., et al., Sensitivity of microwave and infrared satellite observations to soil moisture at a global scale. II: Global statistical relationships, JGR, 110, 2005]

- **Applications [2]**

  - the observations mapped into state variables by the statistical model could be integrated into the LSM by standard variational **assimilation schemes.**

Cost function to combine information from the observations and the LSM:

$$J(x_0) = \frac{1}{2}(x_0 - {x_0}^b)^T \boldsymbol{B}^{-1}(x_0 - {x_0}^b)$$

$$+ \frac{1}{2}\sum_{i=0}^{n}(x(t_i) - {x_i}^r)^T \boldsymbol{R}_i(x(t_i))^{-1}(x(t_i) - {x_i}^r)$$

background term

LSM variable satellite-derived variable statistical model error

  - there exist techniques to calculate $\boldsymbol{R}_i$ and give more weights to the statistical model predictions when there are more reliable.

  - as the statistical model was calibrated with the LSM outputs, we force **consistency** between **LSM** and **satellite-derived variable** and minimize the typical problems trying to assimilate exogenous inputs.

• We have started an **inter-comparison** of land surface heat fluxes within the framework of LandFLUX.

• A first comparison of **monthly heat fluxes in 1993-95** was conducted with the aim of assessing the spread in the estimated fluxes. There was no attempt to quantify the accuracy of the products, no intentions to claim that one product was superior to the others.

• We are expanding these first inter-comparison exercises into a focused activity (**LandFlux-EVAL**), that will include multi-scale (spatial and temporal) data sets, assessment over longer time-periods, and identification of specific regions for focused analysis.

• ETH Zurich and the Observatoire de Paris are the contact institutions for this activity.

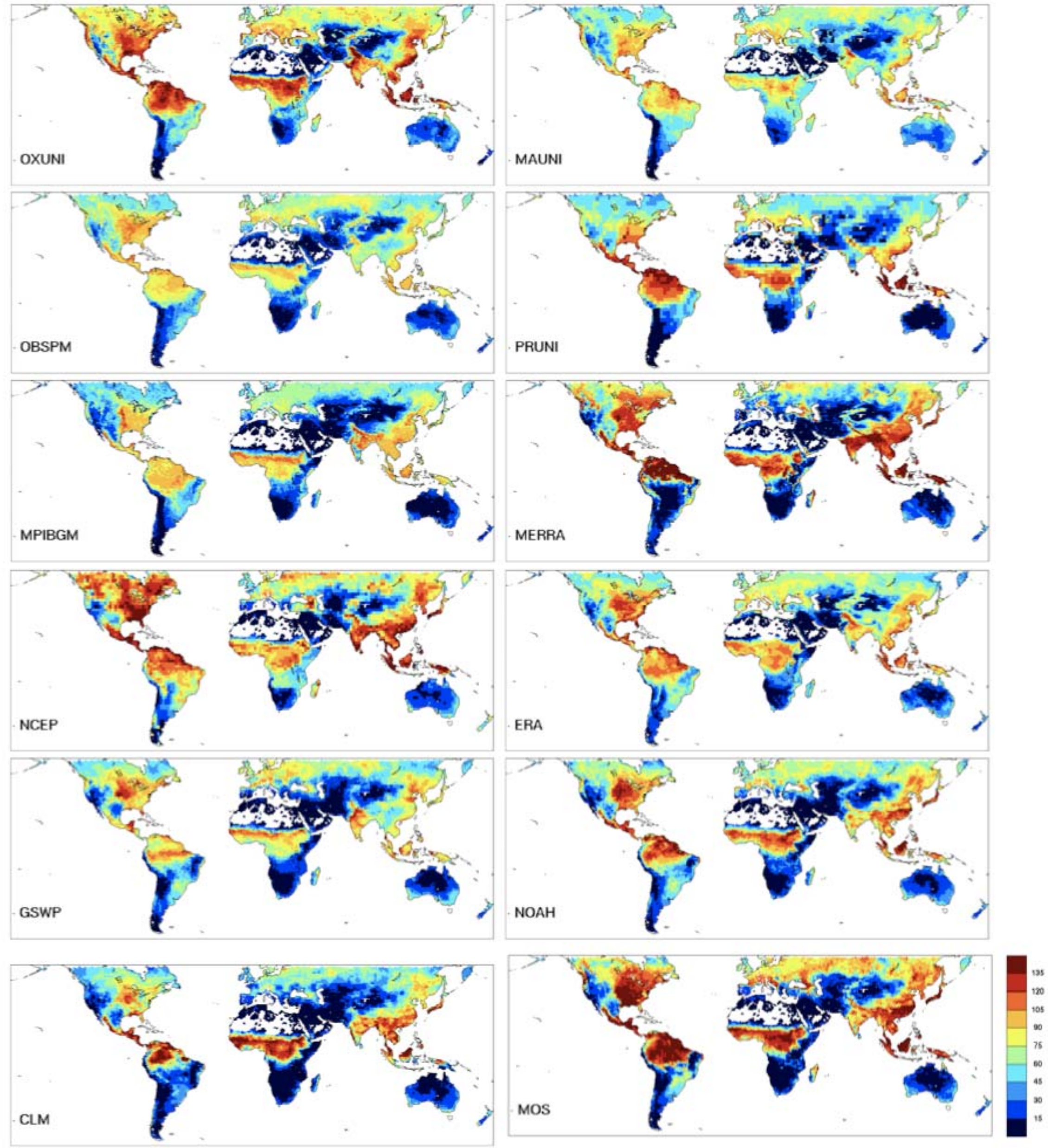
[http://www.iac.ethz.ch/url/LandFlux-EVAL]

Inter-comparing global heat fluxes

	INSTITUTION	LE	H	Rn	Resolution
PHYSICAL FORMULATIONS/STATISTICAL MODELS [driven by observational data]					
OXUNI	University of Oxford	Priestley-Taylor ET, data from ISLSCP-II (SRB, CRU, AVHRR)	Rn - LE	SRB	1986-95 monthly 1^{o} x 1^{o}
MAUNI	University of Maryland	Empirical, calibrated with Ameriflux, satellite data from ISLSCP-II (SRB, CRU, AVHRR)	Rn - LE	SRB	1986-95 monthly 1^{o} x 1^{o}
PRIUNI	Princenton University	Penman-Montheith ET, data from ISCCP, AVHRR	Rn - LE	ISCCP-FD	1986-06 daily 2.5^{o} x 2.5^{o}
OBSPM	Paris Observatory	Empirical, calibrated with GSWP fluxes, data from ISCCP, ERS, SSMI, AVHRR …		ISCCP-FD	1992-99 monthly $1/4^{o}$ x $1/4^{o}$
MPIBGM	MPI Biogeochemistry	Empirical, global upscaling of FluxNet, data from CRU, GPCC, AVHRR ….		Rn~ LE+H	1982-08 monthly $1/2^{o}$ x $1/2^{o}$
LAND SURFACE MODELS [coupled with an atmospheric model assimilating observational data]					
MERRA	NASA-GMAO	MERRA reanalysis, GEOS-5 atmospheric model coupled with NSIPP land model			1979- 6-hourly $1/2^{o}$ x $2/3^{o}$
NCEP	NCEP/NCAR	NCEP-DOE reanalysis, atmospheric model coupled with OSU land model			1979- 6-hourly $1/2^{o}$ x $2/3^{o}$
ERA	ECMWF	ERA Interim reanalysis, atmospheric model coupled with TESSEL land model			1989-98 6-hourly 1.5^{o} x 1.5^{o}
LAND SURFACE MODELS [forced off-line with model and/or observational data]					
GSWP	GLASS/ISLSCP	Multi-model ensemble, forced with ISLSCP-II		↓Rn SRB	1986-95 monthly 1^{o} x 1^{o}
NOAH	NCAR/OSU/AFWA/HL	Equally forced participating models under the GLDAS land data assimilation system		↓Rn -1993 (ERA15) -1994/5 (NCEP-R1) SRB-bias-corr.	1979- 3-hourly 1^{o} x 1^{o}
CLM	NCAR +				
MOSAIC	NASA-GSFC				

Inter-comparing global heat fluxes

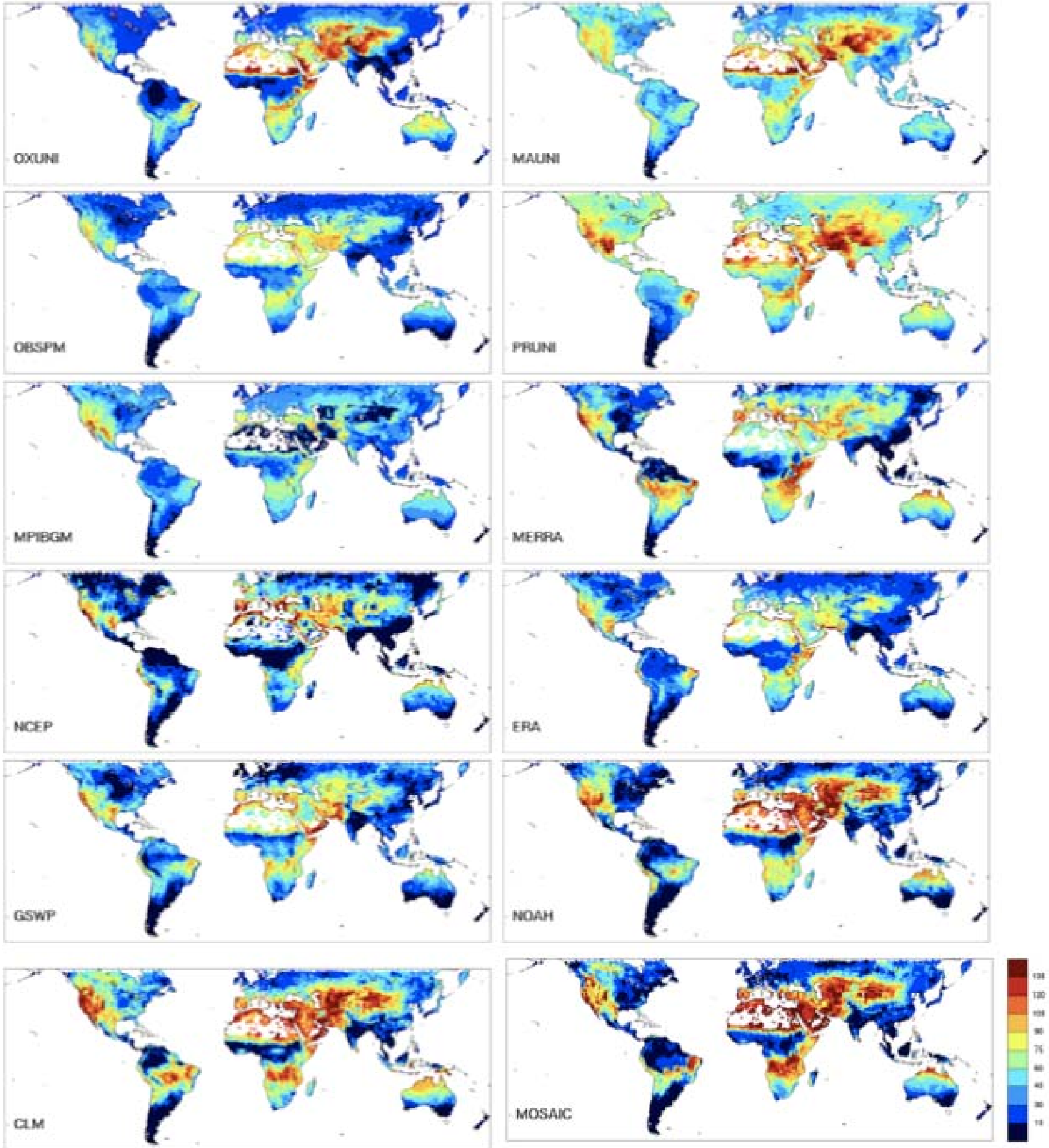
• **Monthly averaged latent fluxes** (LE)



August 1993 [W/m^2]

Inter-comparing global heat fluxes

- **Monthly averaged sensible fluxes** (H)

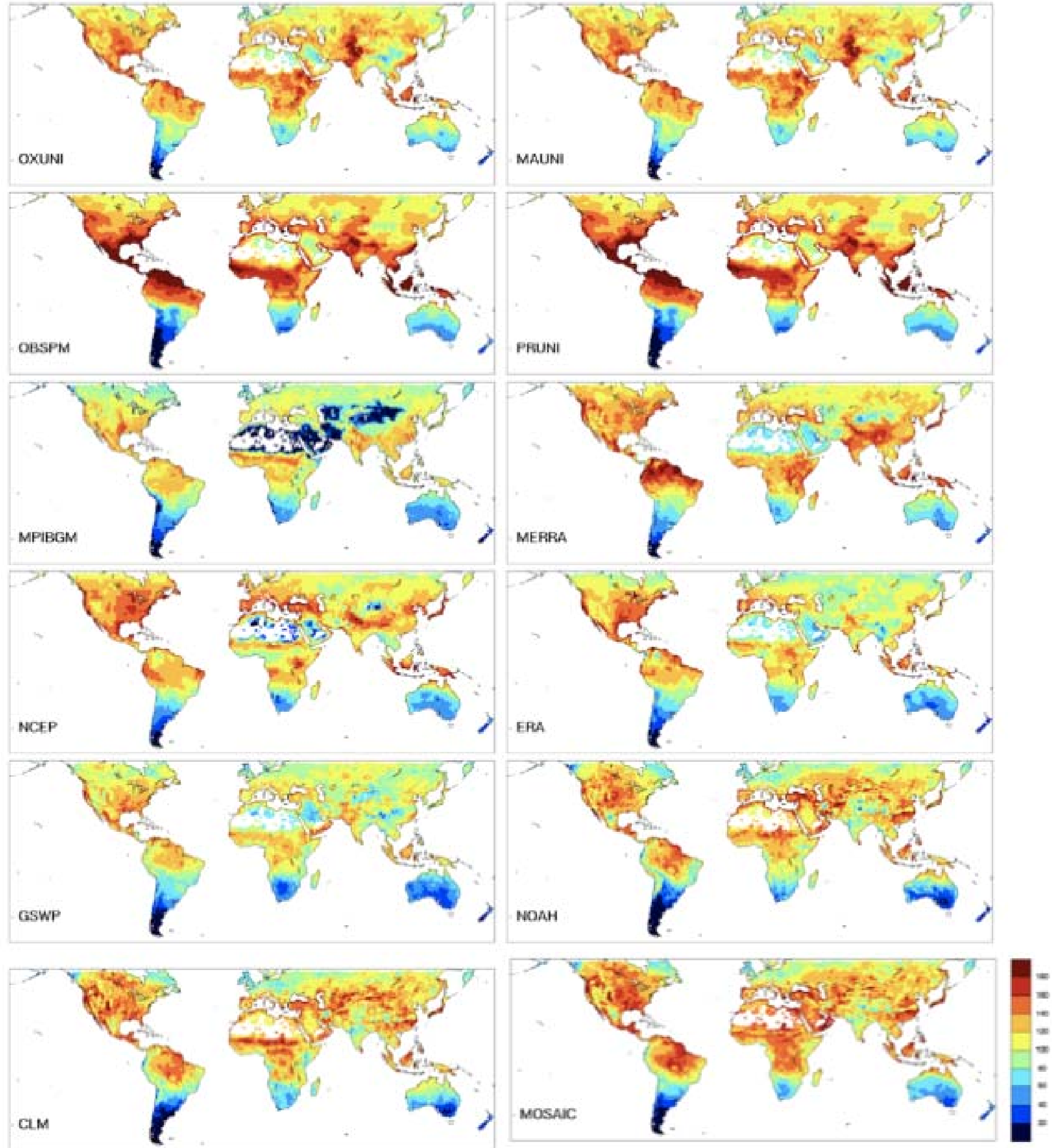


August 1993 [W/m^2]

Inter-comparing global heat fluxes

LandFLUX

- **Monthly averaged net radiation** (Rn)



August 1993 [W/m^2]

Inter-comparing global heat fluxes

LandFLUX

1.Introduction

2.Equations

3.Inputs

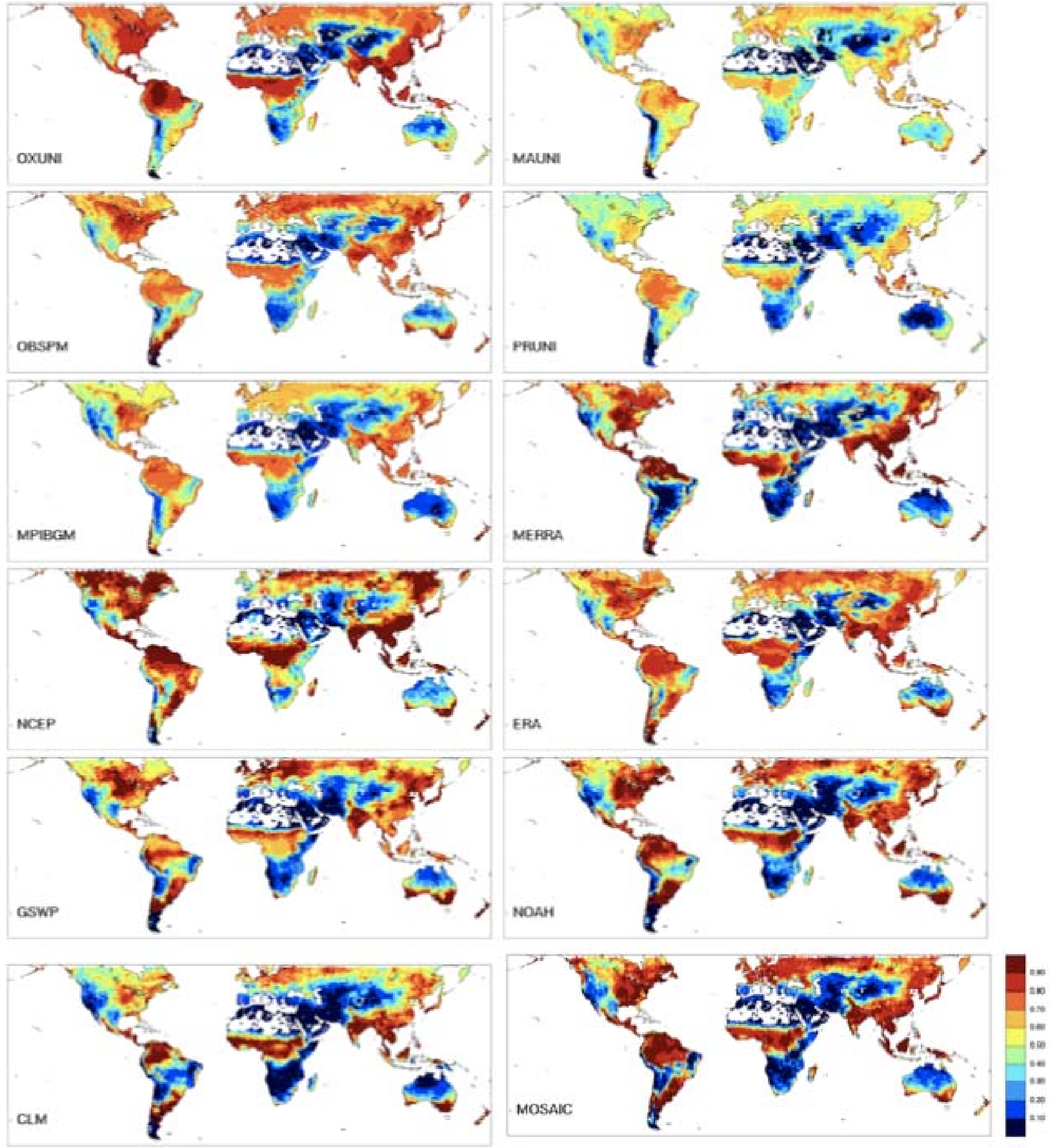
4.Methods

5. Global fluxes

6. Inter--comparing fluxes

- **Monthly averaged evaporative fraction** (EF)

EF = LE / (LE+H)



August 1993 [W/m^2]

Inter-comparing global heat fluxes

LandFLUX

1.Introduction

2.Equations

3.Inputs

4.Methods

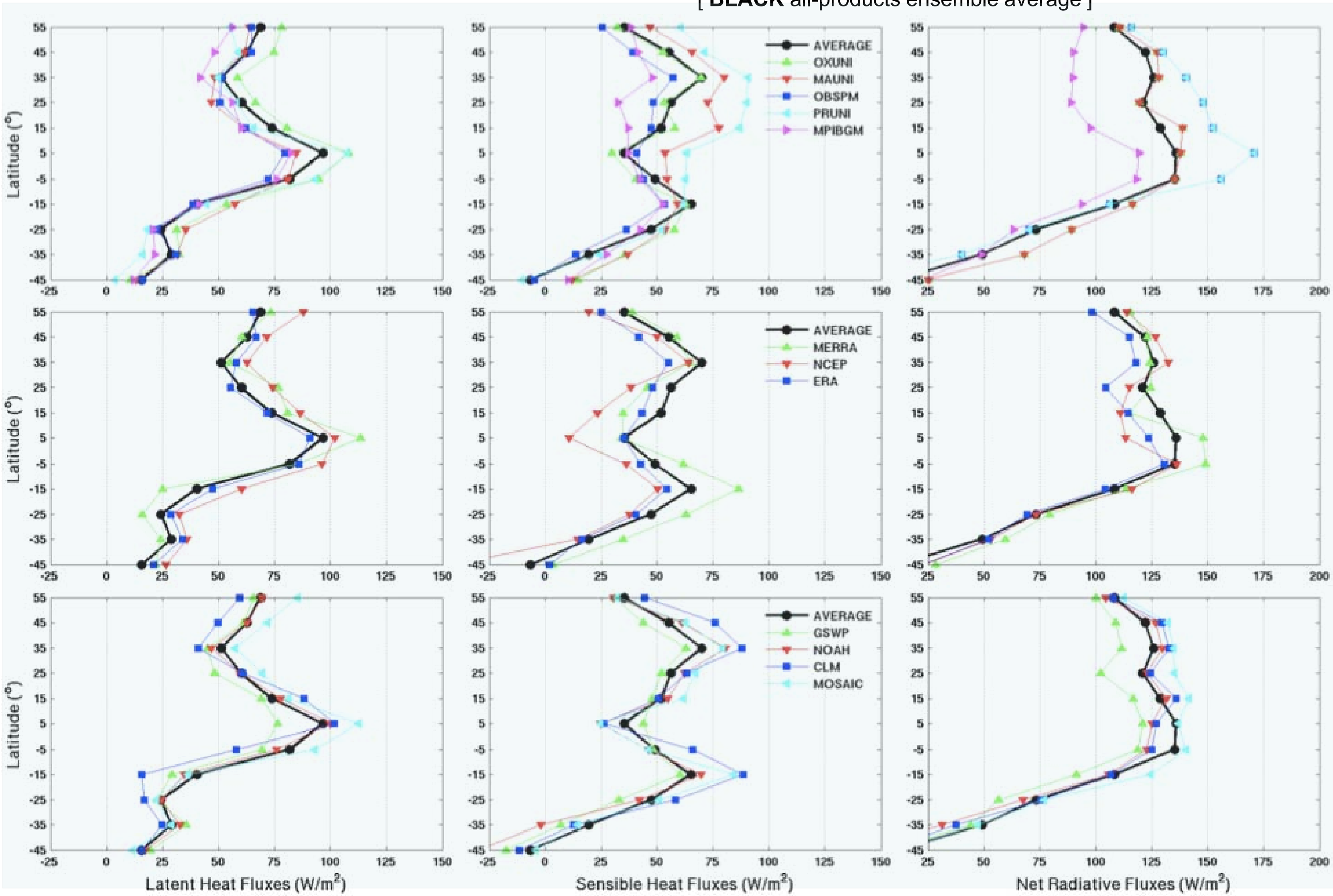
5. Global fluxes

6. Inter- -comparing fluxes

• **Example of monthly zonal means**

August 1993

[**BLACK** all-products ensemble average]



LE **H** **Rn**

LandFLUX

1.Introduction

2.Equations

3.Inputs

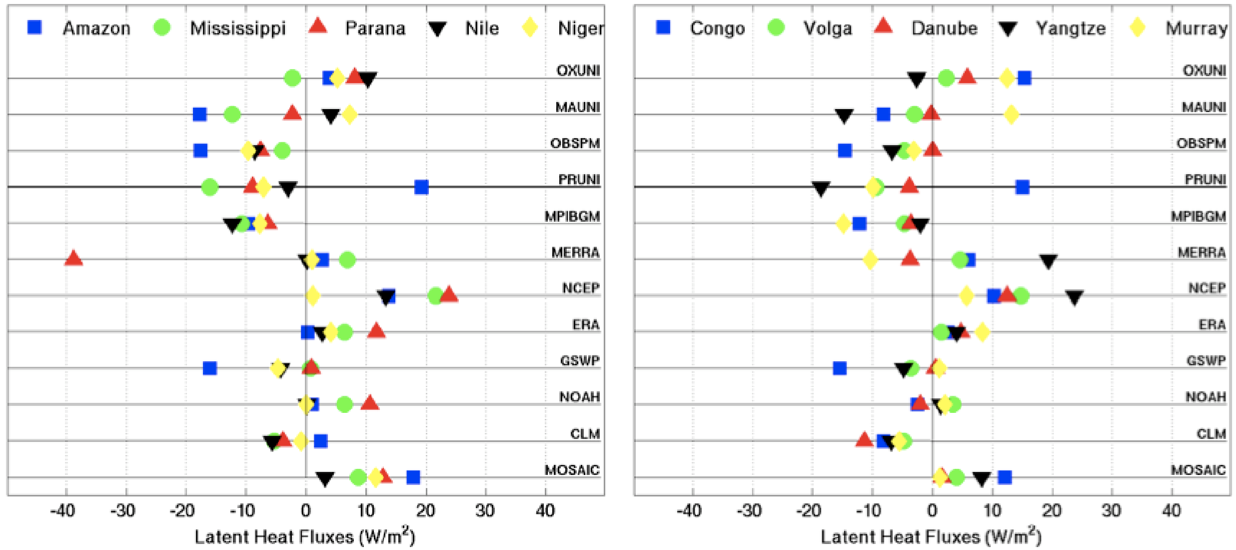
4.Methods

5. Global fluxes

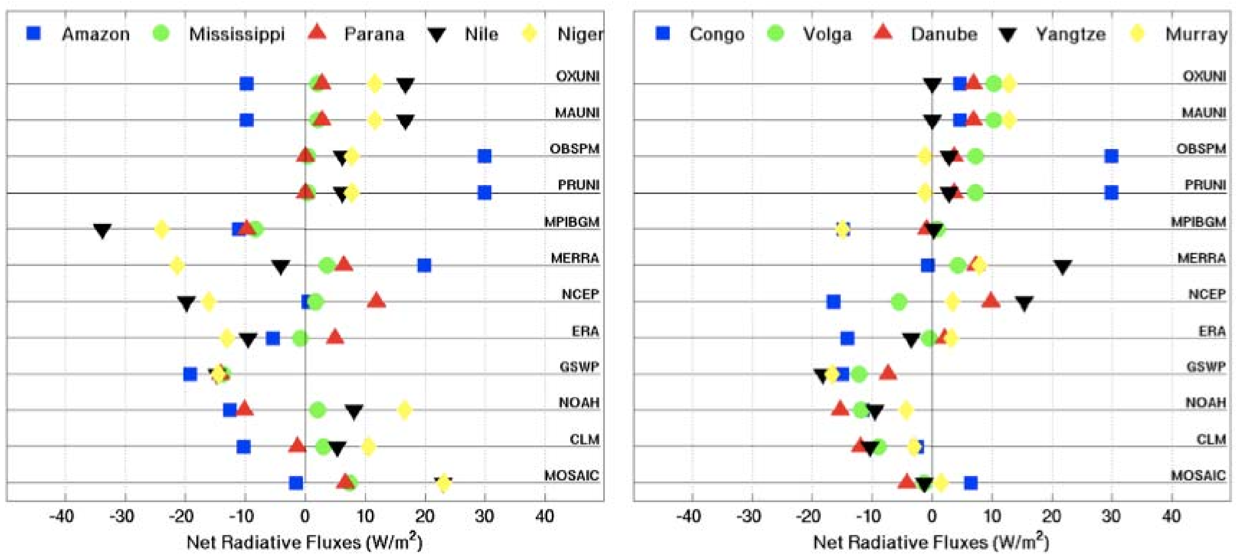
6. Inter--comparing fluxes

- **1993 annual differences**

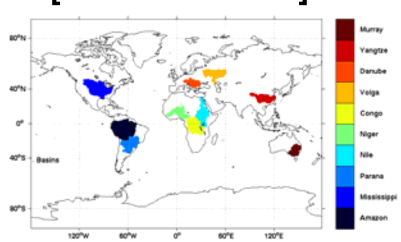
LE



Rn



[selected basins]



- Differences calculated with respect to the all-products ensemble average.

Inter-comparing global heat fluxes

LandFLUX

• **1993 annual RMSE (W/m²)** [from the global monthly mean differences]

Latent flux

	OXUNI	MAUNI	OBSPM	PRUNI	MPIBGM	MERRA	NCEP	ERA	GSWP	NOAH	CLM	MOSAIC
OXUNI	0	21.95	24.7	25.25	26.57	31.9	28.41	22.62	26.97	24.23	31.89	26.43
MAUNI	21.95	0	18.15	26.28	20.36	34.59	32.25	22.23	21.57	23.58	30.3	30.19
OBSPM	24.7	18.15	0	23.46	15.09	30.58	30.66	19.73	14.79	19.11	24.24	27.16
PRUNI	25.25	26.28	23.46	0	23.4	31.4	32.47	25.32	27.21	24.85	27.4	27.98
MPIBGM	26.57	20.36	15.09	23.4	0	31.21	31.88	22	19.06	20.29	23.57	28.24
MERRA	31.9	34.59	30.58	31.4	31.21	0	30.37	28.84	31.24	27.28	30.62	28.58
NCEP	28.41	32.25	30.66	32.47	31.88	30.37	0	25.36	30.59	26.36	32.66	27.09
ERA	22.62	22.23	19.73	25.32	22	28.84	25.36	0	20.41	19.93	26.66	23.87
GSWP	26.97	21.57	14.79	27.21	19.06	31.24	30.59	20.41	0	17.57	22.68	24.96
NOAH	24.23	23.58	19.11	24.85	20.29	27.28	26.36	19.93	17.57	0	18.37	16.27
CLM	31.89	30.3	24.24	27.4	23.57	30.62	32.66	26.66	22.68	18.37	0	23.67
MOSAIC	26.43	30.19	27.16	27.98	28.24	28.58	27.09	23.87	24.96	16.27	23.67	0

Sensible flux

	OXUNI	MAUNI	OBSPM	PRUNI	MPIBGM	MERRA	NCEP	ERA	GSWP	NOAH	CLM	MOSAIC
OXUNI	0	21.95	26.51	31.76	33.78	33.28	42.01	27.93	30.36	28.97	30.93	29.32
MAUNI	21.95	0	29.33	25.36	35.63	34.83	47.07	31.46	32.55	33.5	32.9	33.55
OBSPM	26.51	29.33	0	31.7	23.15	28.8	33.11	16.85	16.39	28.38	32.86	30.38
PRUNI	31.76	25.36	31.7	0	35.33	35.12	47.37	34.14	35.58	36.76	35.39	37.77
MPIBGM	33.78	35.63	23.15	35.33	0	31.69	40.04	25.09	28.01	38.21	39.3	40.63
MERRA	33.28	34.83	28.8	35.12	31.69	0	38.21	27.3	32.05	36.53	35.15	35.08
NCEP	42.01	47.07	33.11	47.37	40.04	38.21	0	33.2	34.86	39.55	44.74	42.98
ERA	27.93	31.46	16.85	34.14	25.09	27.3	33.2	0	20.42	30.99	33.4	30.99
GSWP	30.36	32.55	16.39	35.58	28.01	32.05	34.86	20.42	0	27.27	32.26	29.08
NOAH	28.97	33.5	28.38	36.76	38.21	36.53	39.55	30.99	27.27	0	23.36	19.95
CLM	30.93	32.9	32.86	35.39	39.3	35.15	44.74	33.4	32.26	23.36	0	23.05
MOSAIC	29.32	33.55	30.38	37.77	40.63	35.08	42.98	30.99	29.08	19.95	23.05	0

• Based on this **PRELIMINARY** results, it seems that the **fluxes spread** in the new global observation-based heat flux estimates is similar to the already existing reanalysis and LSMs heat fluxes.

Concluding remarks

• Estimation of **land surface heat fluxes** [LE/H] from observations is difficult due to the large spatial heterogeneity of vegetation and soils and the dependence of water availability on meteorology and climate.

• Nevertheless, there is a solid body of work estimating LE/H at different space and time scales by combining **observations** with physical **formulations** or statistical **models**.

• The combination of long-term satellite data records and appropriate formulations can provide the **long data record of LE/H** required to close the water and energy cycle (using observation based products). The derived products can also be of utility to benchmark land surface and climate models.

• There are already a number of groups independently pursuing global scale estimation of flux components. These **products** vary in terms of the forcing data used, the governing equations employed, and the temporal scale of their application.

• The **LandFLUX activity** will provide a framework for undertaking coordinated evaluation and assessment of these various products, ultimately identifying and delivering a robust procedure for production of a global land surface flux data set.

BACKUP SLIDES

Concluding remarks

LandFLUX

• Global estimation of **land surface heat fluxes** [LE/H] is difficult due to the large spatial heterogeneity of vegetation and soils and the dependence of water availability on meteorology and climate.

• Satellite **observations** can be used to estimate globally LE/H, but they require a **formulation/model** to infer the fluxes from the observations.

• There are already a number of groups independently pursuing global scale estimation of flux components. These **products** vary in terms of the forcing data used, the governing equations employed, and the spatial and temporal scales of their application.

• The **LandFLUX** activity will provide a framework for undertaking coordinated evaluation and assessment of these various products, ultimately identifying and delivering a robust procedure for operational production of a global land surface flux data set.

FORMULATIONS/MODELS

l'Observatoire de Paris LERMA

• The models are based on the basic ET governing **equations**, but they require to be simplified/adapted/extended to deal with the existing observations and its limitations. Do we need further work to cast them in terms of the observed

Concluding remarks

LandFLUX

OBSERVATIONS/INPUTS

• Some critical inputs to the formulation/models require further work e.g

• **Re-calibration** of **long-term satellite radiance** datasets are crucial to producing long-term LE/H: AVHRR visible and near-infrared (for albedo, NDVI, FPAR) and infrared (for surface skin temperature, cross-calibration of the geostationary satellite radiances is also needed to resolve diurnal variability) and SSM/I (also SMMR, for surface skin temperature, vegetation properties and soil moisture). These records should also be connected to more current records from MODIS/ MERIS and SSMIS/AMSR.

• Improving the estimation of radiation: newer **albedo products** based on combined analyses of MODIS, MISR, POLDER and connect them to an AVHRR-based record?

• A global surface **skin temperature** product that resolves diurnal variations for **clear and cloudy** conditions is desired: by a combined analysis of satellite infrared and microwave measurements (many different instrument combinations can be tried but the longest record would be obtained using weather satellite infrared imagery and SSM/I-AMSR)?

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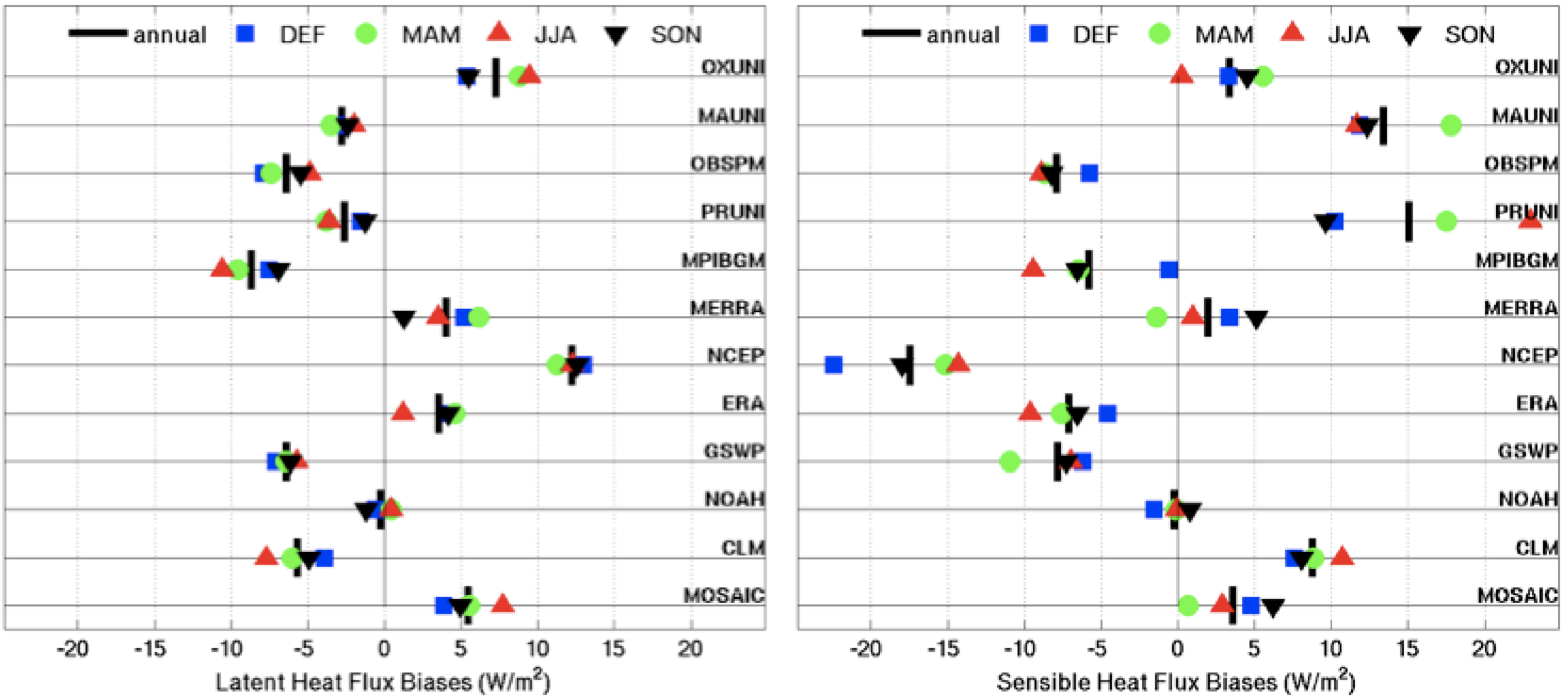
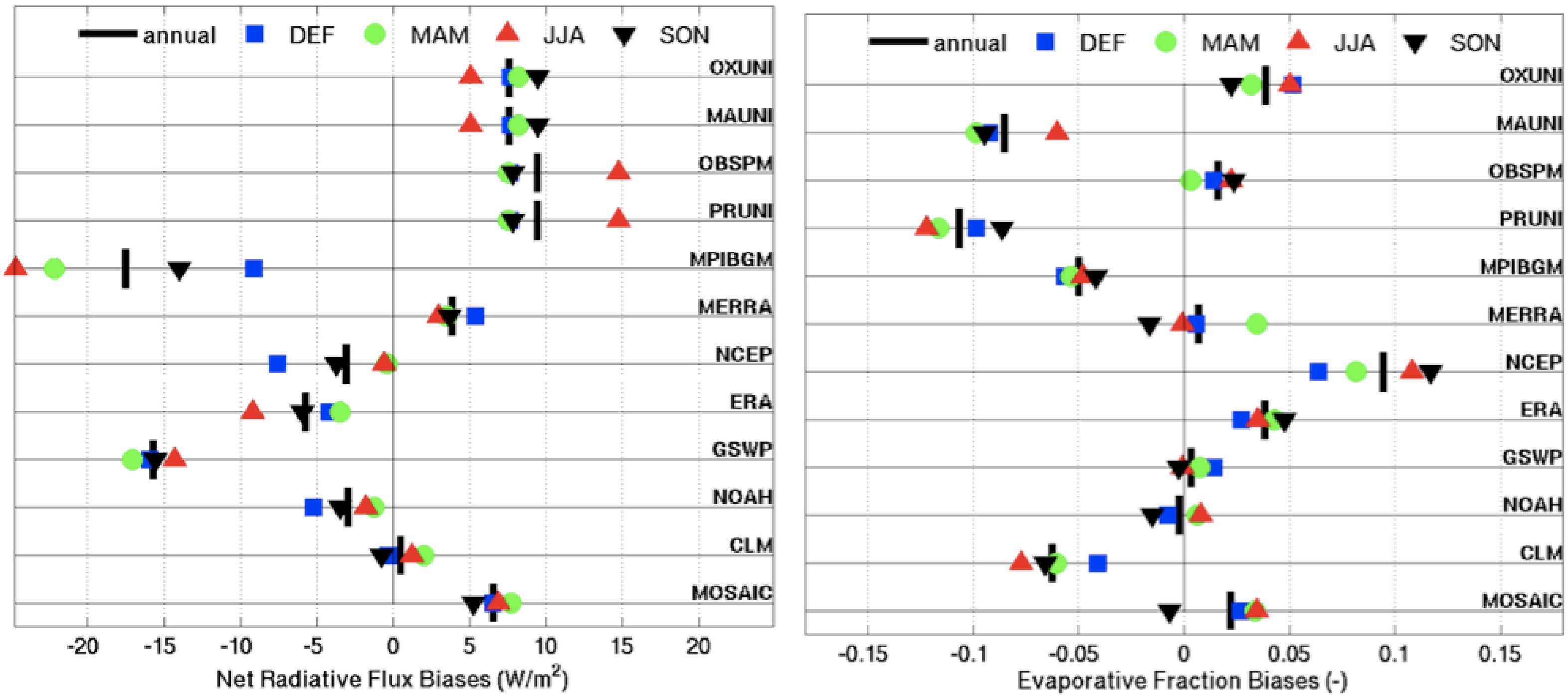
• **Global annual and seasonal LE and H biases**



- Biases calculated with respect to the all-products ensemble average.

1993

• **Global annual and seasonal Rn and EF biases**



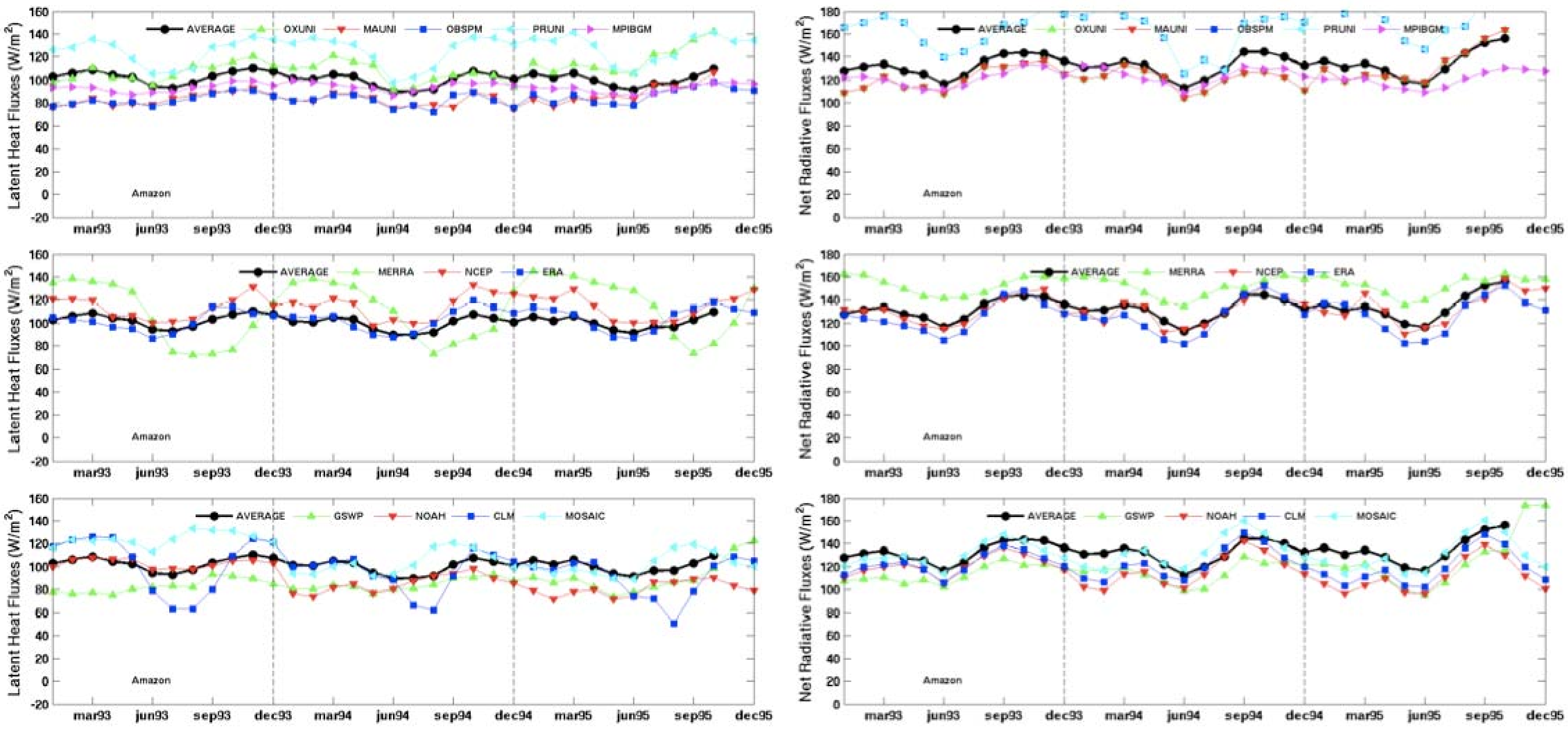
- Biases calculated with respect to the all-products ensemble average.

1993

Amazon basin

• **LE and Rn 1993-95 time series**

[**BLACK** all-products ensemble average]



LE **Rn**

Amazon basin

1.Introduction

2.Products

3.Examples

4.Annual means

5. Zonal means

6. Basins

7. Summary

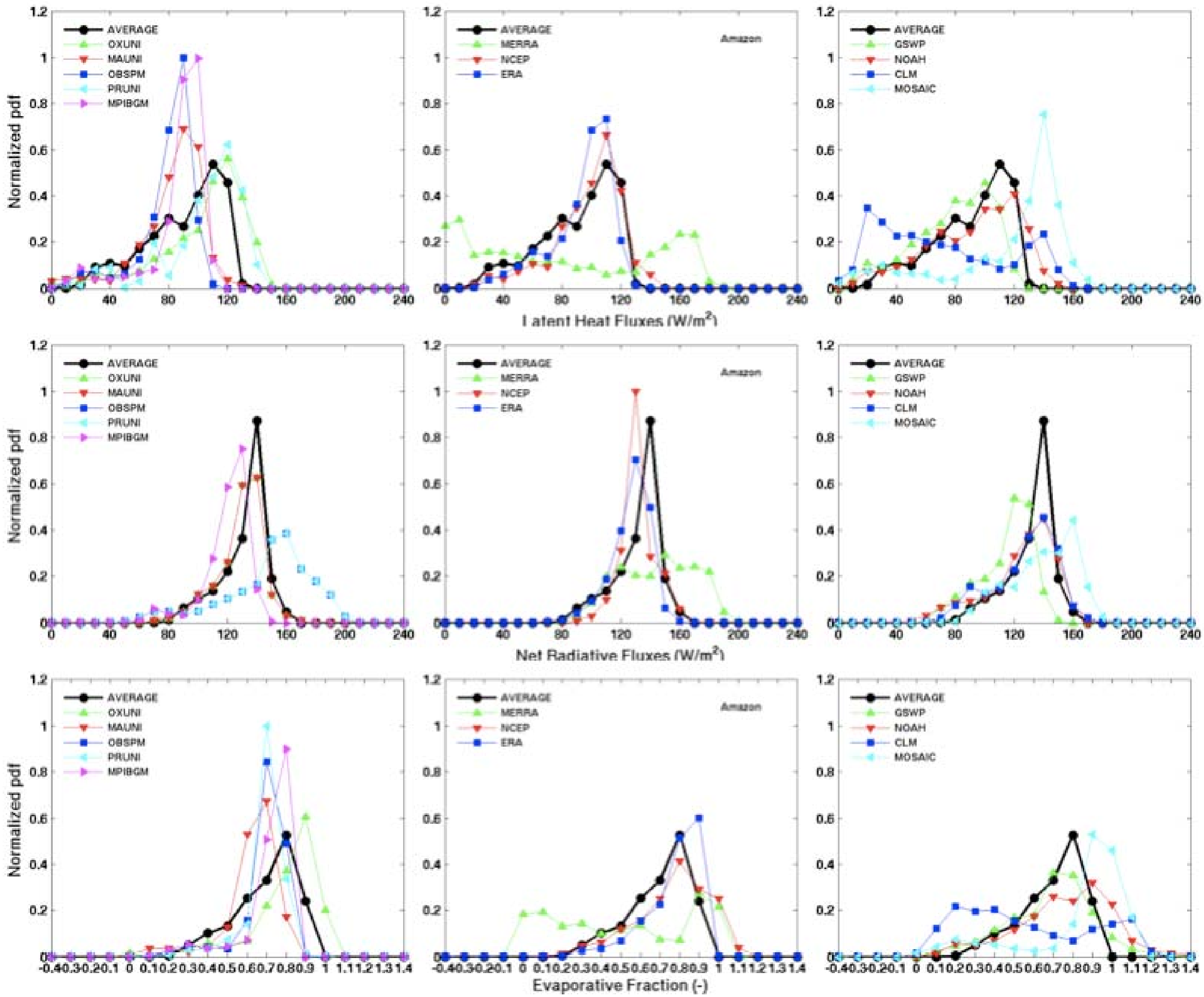
• **LE, H and EF normalized distributions for Feb 1993**

[**BLACK** all-products ensemble average]

LE

Rn

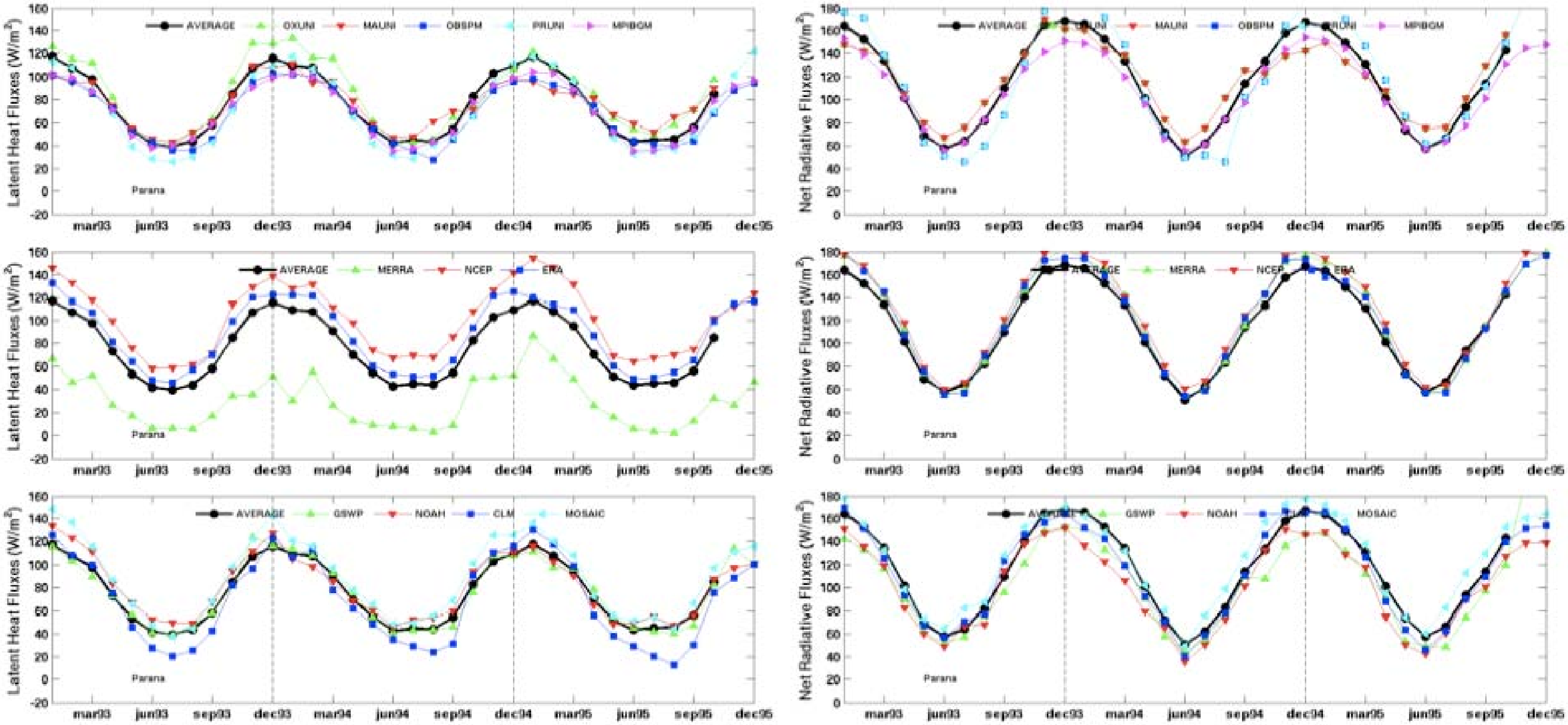
EF



Parana basin

• **LE and Rn 1993-95 time series**

[**BLACK** all-products ensemble average]



LE

Rn

<carlos.jimenez@obspm.fr>

Parana basin

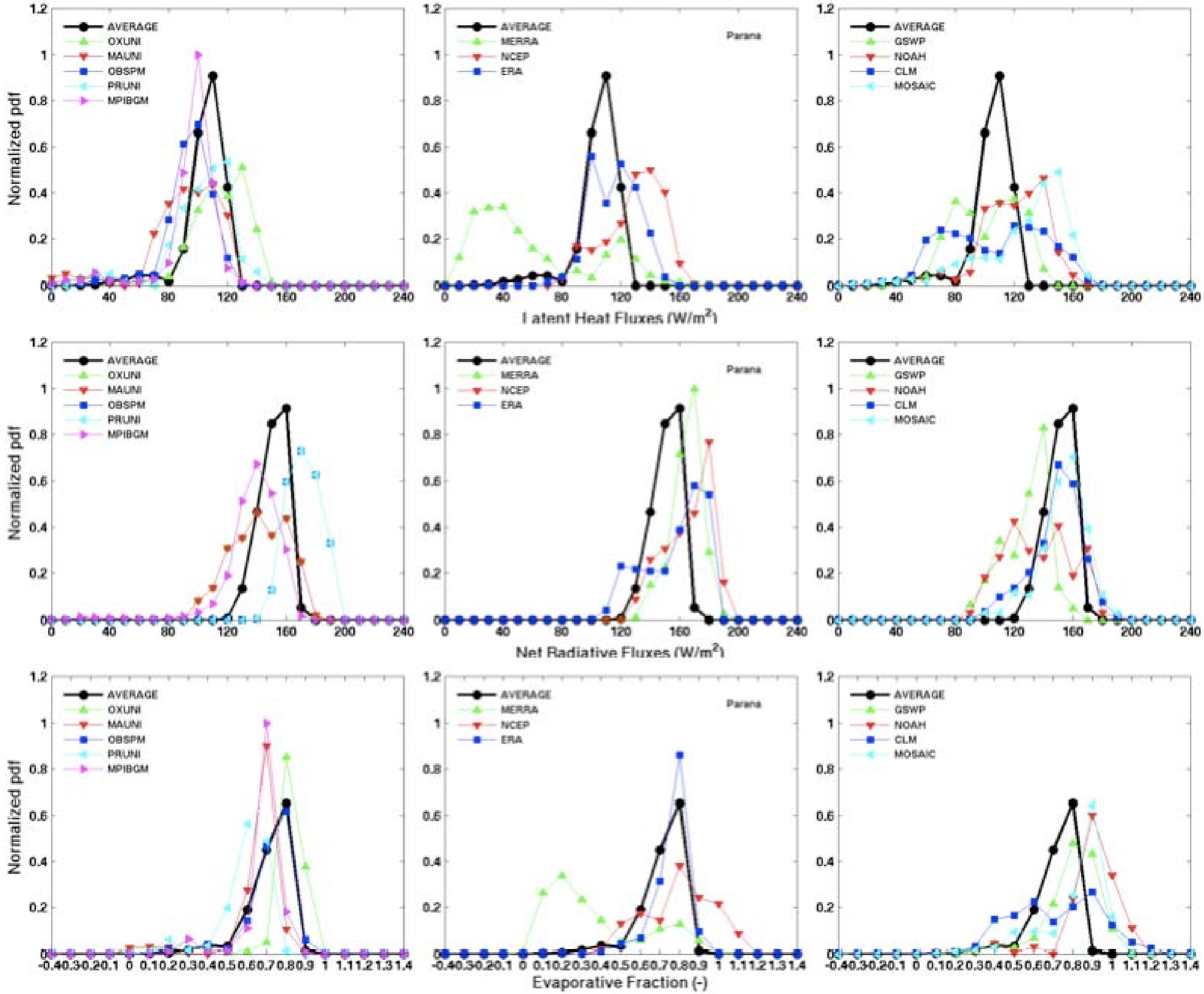
- **LE, H and EF normalized distributions for Feb 1993**

[**BLACK** all-products ensemble average]

LE

Rn

EF



Inter-comparing global heat fluxes

LandFLUX

- **Disclaimer**

We present here a global inter-comparison of 12 land surface monthly averaged heat flux products with the aim of **quantifying the range of uncertainty** from present heat flux monthly estimates. There is **NO ATTEMPT** to quantify the accuracy of the products, **NO CLAIMS** are made stating that one product is superior to the others. Biases will be reported with respect to the average

All data producers are kindly acknowledged by making their estimates available and by being available for discussions concerning their products.

- **Methodology**

Expand the workshop based intercomparison exercise into a focused activity (LandFlux-EVAL), that will include multi-scale (spatial and temporal) data sets, assessment over longer time-periods, and identification of specific regions for focused analysis. ETH Zurich and the Observatoire de Paris are the contact institutions for this activity (see http://www.iac.ethz.ch/url/LandFlux-EVAL).

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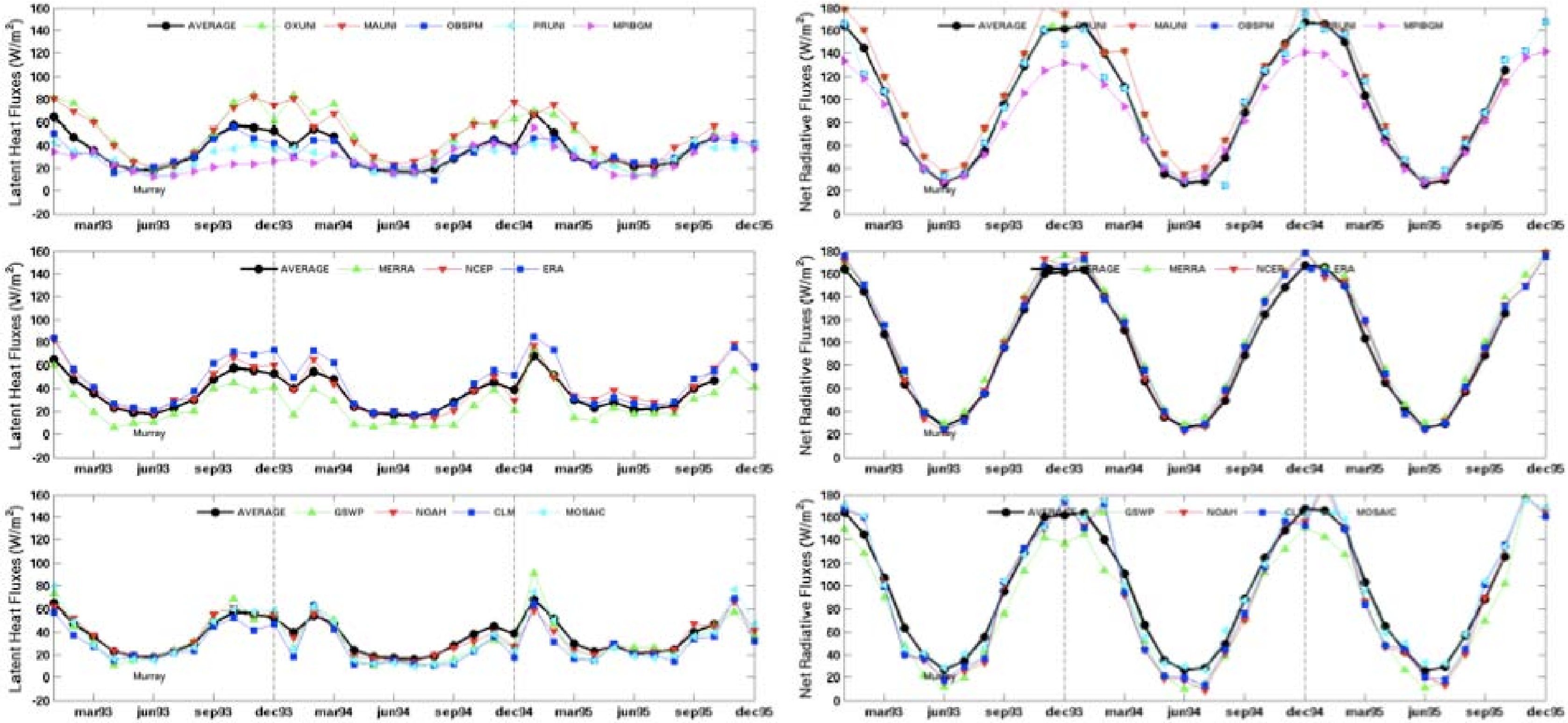
Murray basin

- **LE and Rn 1993-95 time series**

[**BLACK** all-products ensemble average]



LE **Rn**

- **LE, H and EF normalized pdfs for Feb 1993**

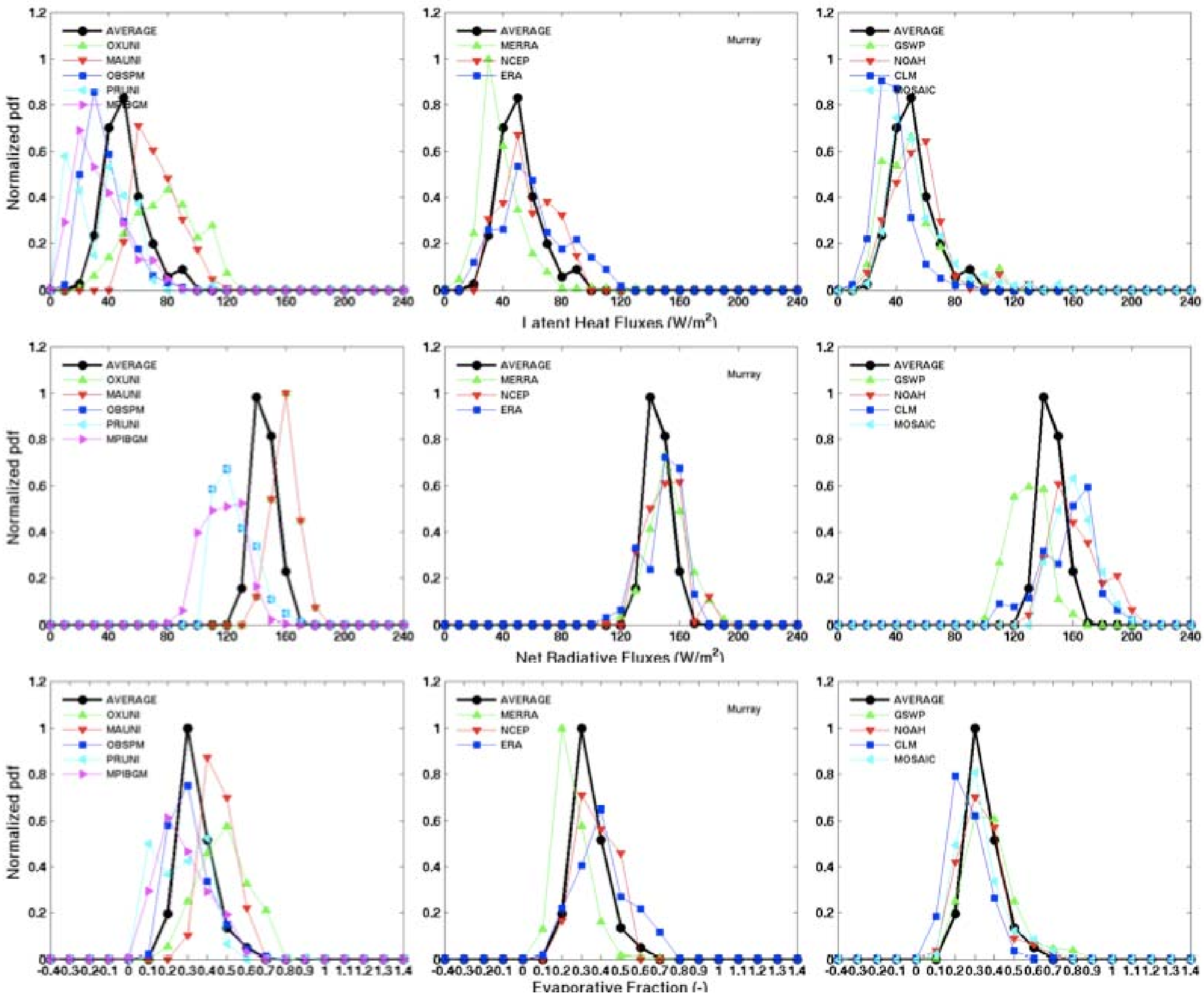
[**BLACK** all-products ensemble average]

LE

Rn

EF

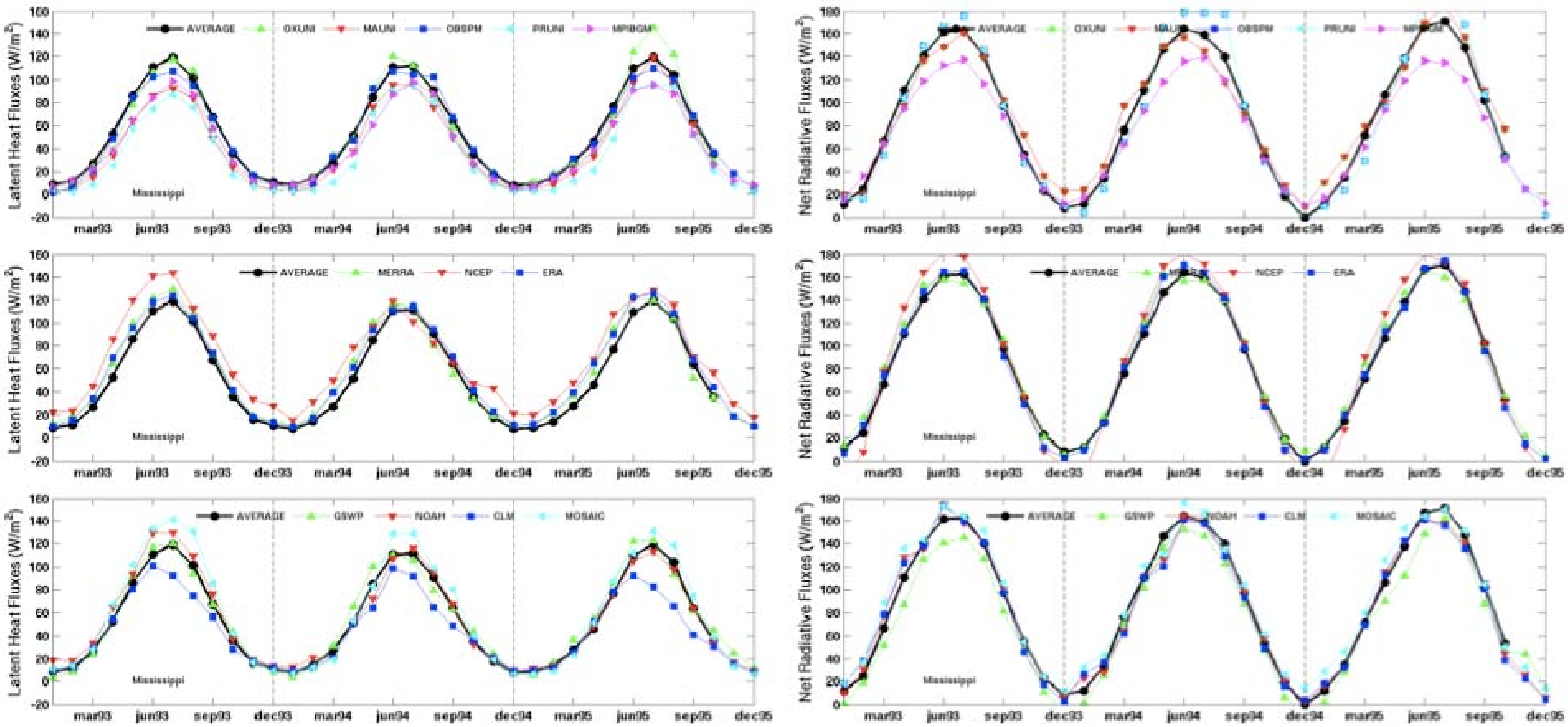
1993



Mississippi basin

- **LE and Rn 1993-95 time series**

[**BLACK** all-products ensemble average]



LE

Rn

1.Introduction

2.Products

3.Examples

4.Annual means

5. Zonal means

6. Basins

7. Summary

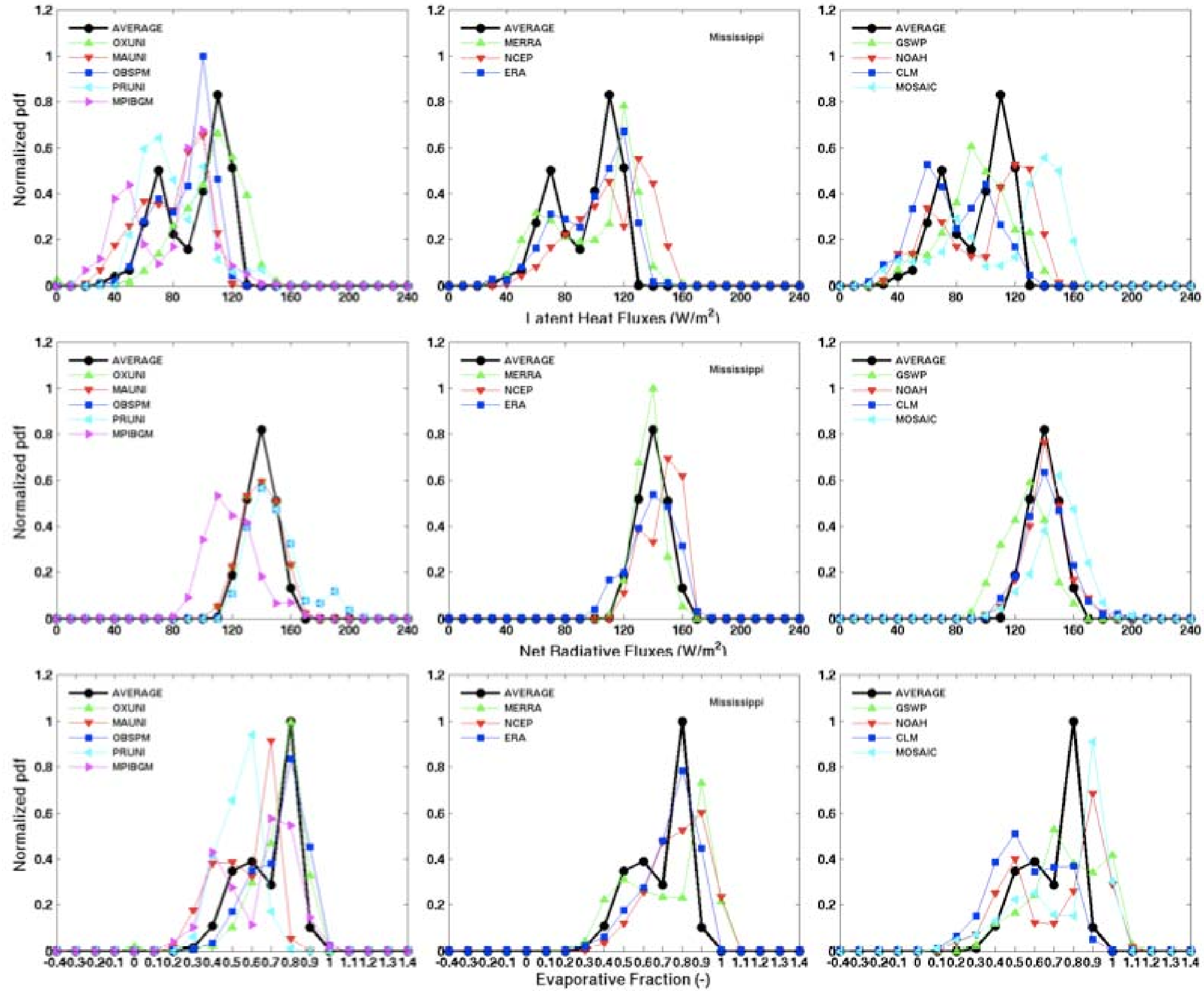
• **LE, H and EF normalized pdfs for Aug 1993**

[**BLACK** all-products ensemble average]

LE

Rn

EF



Summary

• **1993 annual RMSE (W/m²)** [from the global monthly mean differences]

Latent flux

	OXUNI	MAUNI	OBSPM	PRUNI	MPIBGM	MERRA	NCEP	ERA	GSWP	NOAH	CLM	MOSAIC
OXUNI	0	21.95	24.7	25.25	26.57	31.9	28.41	22.62	26.97	24.23	31.89	26.43
MAUNI	21.95	0	18.15	26.28	20.36	34.59	32.25	22.23	21.57	23.58	30.3	30.19
OBSPM	24.7	18.15	0	23.46	15.09	30.58	30.66	19.73	14.79	19.11	24.24	27.16
PRUNI	25.25	26.28	23.46	0	23.4	31.4	32.47	25.32	27.21	24.85	27.4	27.98
MPIBGM	26.57	20.36	15.09	23.4	0	31.21	31.88	22	19.06	20.29	23.57	28.24
MERRA	31.9	34.59	30.58	31.4	31.21	0	30.37	28.84	31.24	27.28	30.62	28.58
NCEP	28.41	32.25	30.66	32.47	31.88	30.37	0	25.36	30.59	26.36	32.66	27.09
ERA	22.62	22.23	19.73	25.32	22	28.84	25.36	0	20.41	19.93	26.66	23.87
GSWP	26.97	21.57	14.79	27.21	19.06	31.24	30.59	20.41	0	17.57	22.68	24.96
NOAH	24.23	23.58	19.11	24.85	20.29	27.28	26.36	19.93	17.57	0	18.37	16.27
CLM	31.89	30.3	24.24	27.4	23.57	30.62	32.66	26.66	22.68	18.37	0	23.67
MOSAIC	26.43	30.19	27.16	27.98	28.24	28.58	27.09	23.87	24.96	16.27	23.67	0

Sensible flux

	OXUNI	MAUNI	OBSPM	PRUNI	MPIBGM	MERRA	NCEP	ERA	GSWP	NOAH	CLM	MOSAIC
OXUNI	0	21.95	26.51	31.76	33.78	33.28	42.01	27.93	30.36	28.97	30.93	29.32
MAUNI	21.95	0	29.33	25.36	35.63	34.83	47.07	31.46	32.55	33.5	32.9	33.55
OBSPM	26.51	29.33	0	31.7	23.15	28.8	33.11	16.85	16.39	28.38	32.86	30.38
PRUNI	31.76	25.36	31.7	0	35.33	35.12	47.37	34.14	35.58	36.76	35.39	37.77
MPIBGM	33.78	35.63	23.15	35.33	0	31.69	40.04	25.09	28.01	38.21	39.3	40.63
MERRA	33.28	34.83	28.8	35.12	31.69	0	38.21	27.3	32.05	36.53	35.15	35.08
NCEP	42.01	47.07	33.11	47.37	40.04	38.21	0	33.2	34.86	39.55	44.74	42.98
ERA	27.93	31.46	16.85	34.14	25.09	27.3	33.2	0	20.42	30.99	33.4	30.99
GSWP	30.36	32.55	16.39	35.58	28.01	32.05	34.86	20.42	0	27.27	32.26	29.08
NOAH	28.97	33.5	28.38	36.76	38.21	36.53	39.55	30.99	27.27	0	23.36	19.95
CLM	30.93	32.9	32.86	35.39	39.3	35.15	44.74	33.4	32.26	23.36	0	23.05
MOSAIC	29.32	33.55	30.38	37.77	40.63	35.08	42.98	30.99	29.08	19.95	23.05	0

• Based on this **PRELIMINARY** results, can we say that the **range of uncertainties** in the new global observation-based heat flux estimates is similar to the already existing reanalysis and LSMs heat fluxes?

LandFLUX

• Benchmarking the climate models?

Hydrologic Statistics - Globe

Models	1970 - 1999 (20C3M)										
	Globe			Ocean				Land			
	Area	P	E	Area	P	E	P-E	Area	P	E	P-E
	m^2	mm/yr	mm/yr	m^2	mm/yr	mm/yr	mm/yr	m^2	mm/yr	mm/yr	mm/yr
BCCR-BCM2.0_Set1	5.09E+14	1091.8	1091.8	3.65E+14	1185.7	1287.0	-101.3	1.44E+14	854.6	598.7	255.9
CGCM3.1(t63)_Set1	5.09E+14	996.9	996.9	3.55E+14	1120.6	1220.7	-100.1	1.54E+14	711.7	480.6	231.0
UKMO-HADCM3_Set1	5.09E+14	1064.2	1064.2	3.62E+14	1181.5	1269.9	-88.3	1.47E+14	776.0	559.1	217.0
UKMO-HADGEM1_Set1	5.09E+14	1103.9	1103.9	3.62E+14	1226.5	1333.6	-107.1	1.47E+14	801.4	537.0	264.4
SUMMARY STATISTICS											
Mean		1045.0	1045.0		1156.7	1251.0	-94.3		770.2	537.5	232.7
SD		55.1	55.1		68.5	68.9	15.4		55.8	57.5	33.9
Min		916.5	916.5		1017.6	1096.3	-127.7		659.2	444.4	162.8
Max		1187.2	1187.2		1311.3	1400.5	-63.7		882.0	675.8	314.5
Number of Model Runs showing increases											
Number of Model Runs showing decreases											

from W. H. Lim and M. L. Roderick (2009) An Atlas of the Global Water Cycle Based on the IPCC AR4 Climate Models7

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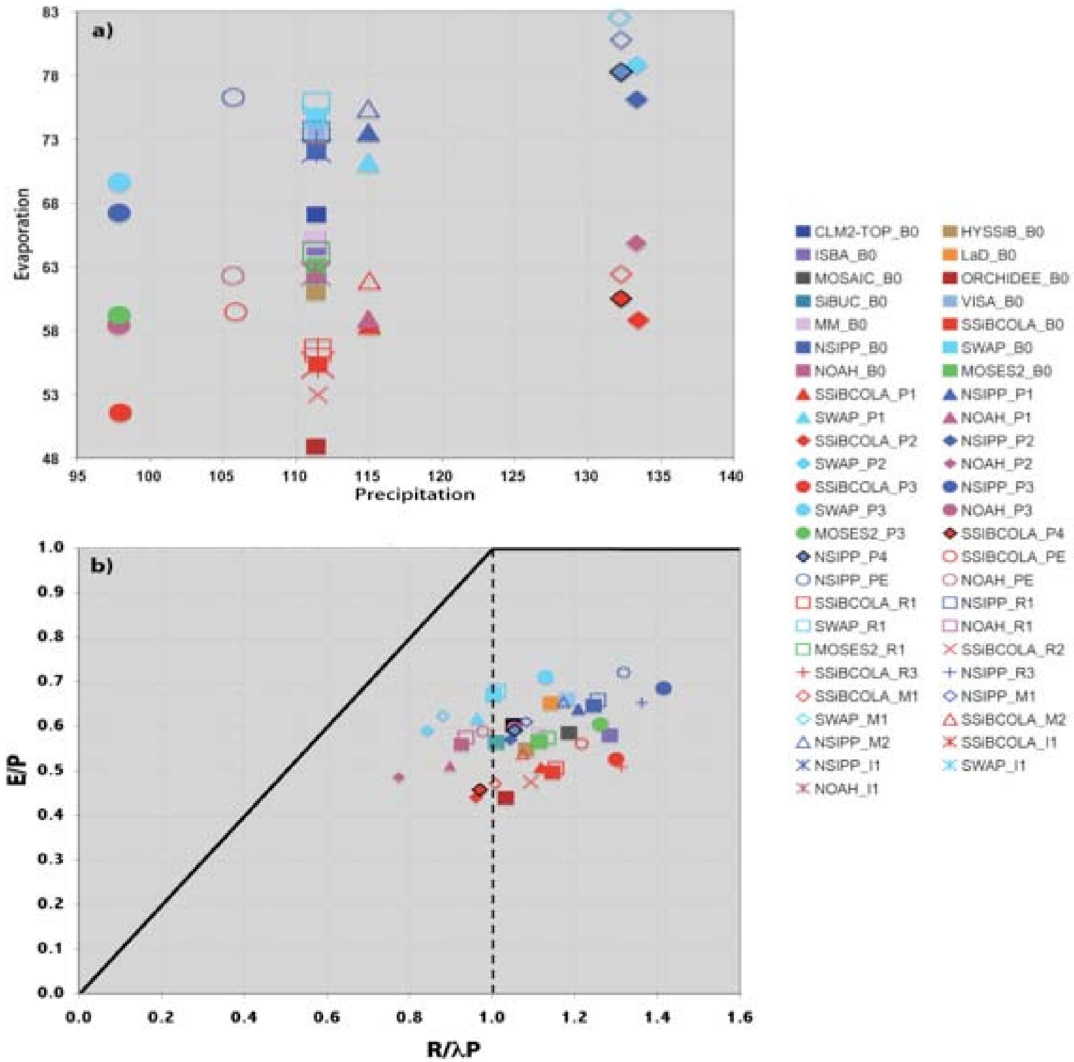
- **GSWP-2** (mean 434 mm/year)



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from Schloser and Gao (2009), Assessing Evapotranspiration Estimates from the GSWP-2 Simulations