Revisit of the Global Surface Energy Balance Using the MEP Model of Surface Heat Fluxes and Remote Sensing Observations

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Summary

The climatology of global surface heat fluxes are re-evaluated using the maximum entropy production (MEP) model and surface radiation fluxes and temperature data of NASA Clouds and the Earth's Radiant Energy System (CERES) supplemented by surface humidity data from Modern-Era Retrospective analysis for Research and Applications (MERRA). The new MEP-based global heat fluxes over lands agree with the previous estimates. The new estimate of ocean evaporation is lower than previous estimates, while the new estimate of ocean sensible heat flux is higher than previously reported. The MEP model produces the first global ocean surface heat flux product.

I. Objective

Re-estimating the radiation energy constrained global surface heat fluxes using the MEP model.

II. MEP Model

A) Latent E, sensible H and ground/ocean heat flux Q are solved as the partitioning of surface radiation fluxes (Wang and Bras, 2011, Wang et al., 2014):

$$\left[1 + B(\sigma) + \frac{B(\sigma)}{\sigma}\frac{I_s}{I_0}|H|^{-\frac{1}{6}}\right] H = R_n$$

$$E = B(\sigma)H$$

$$Q = \begin{cases} R_n - E - H & land \\ R_l^n - E - H & water, snow, ice \end{cases}$$

$$B(\sigma) = 6\left(\sqrt{1 + (11/36)\sigma} - 1\right)$$

$$\sigma = \frac{L_v^2 q_s}{C_p R_v T_s^2}$$

R_n: net radiation $(W\ m^{-2})$
R_l^n: net long wave radiation $(W\ m^{-2})$
L_v: latent heat of vaporization $(J\ kg^{-1})$
R_v: water vapor gas constant $(J\ kg^{-1} K^{-1})$
C_p: specific heat of air $(J\ kg^{-1} K^{-1})$
q_s: surface specific humidity $(kg\ kg^{-1})$
T_s: surface temperature (K)
I_s: thermal inertia of Earth's surface (tiu)
I_0: apparent thermal inertia of the air

Net surface heat flux is defined as

$$R_n - E - H = \begin{cases} Q & land \\ R_0 + Q & water, snow, ice \end{cases}$$

$R_0 = R_s^n =$ net shortwave radiation $(W\ m^{-2})$

B) Model Input

Land: R_n, T_s, q_s Ocean: R_n, R_n^l, T_s

C) Properties of the MEP Model:

- ❑ **closing surface energy budget;**
- ❑ **not using bulk gradients of vapor pressure and temperature as model input;**
- ❑ **not explicitly using wind speed and surface roughness as model parameters.**

D) Model Uncertainty

The uncertainties of the MEP modeled fluxes $X = E, H, Q$ as functions of R_n, σ, and $\beta \equiv I_s/I_0$, according to the equations in A), are given as,

$$\Delta X = \frac{\partial X}{\partial R_n}\Delta R_n + \frac{\partial X}{\partial \sigma}\Delta\sigma + \frac{\partial X}{\partial \beta}\Delta\beta,$$

$$\Delta\sigma = \frac{\partial\sigma}{\partial T_s}\Delta T_s + \frac{\partial\sigma}{\partial q_s}\Delta q_s = \sigma\left(\frac{\Delta q_s}{q_s} - 2\frac{\Delta T_s}{T_s}\right)$$

$$\Delta\beta = \frac{\partial\beta}{\partial I_s}\Delta I_s + \frac{\partial\beta}{\partial I_0}\Delta I_0 = \beta\left(\frac{\Delta I_s}{I_s} - \frac{\Delta T_s}{T_s}\right),$$

$\Delta R_n, \Delta\sigma, \Delta\beta$: uncertainties of model input/parameters.

III. Data

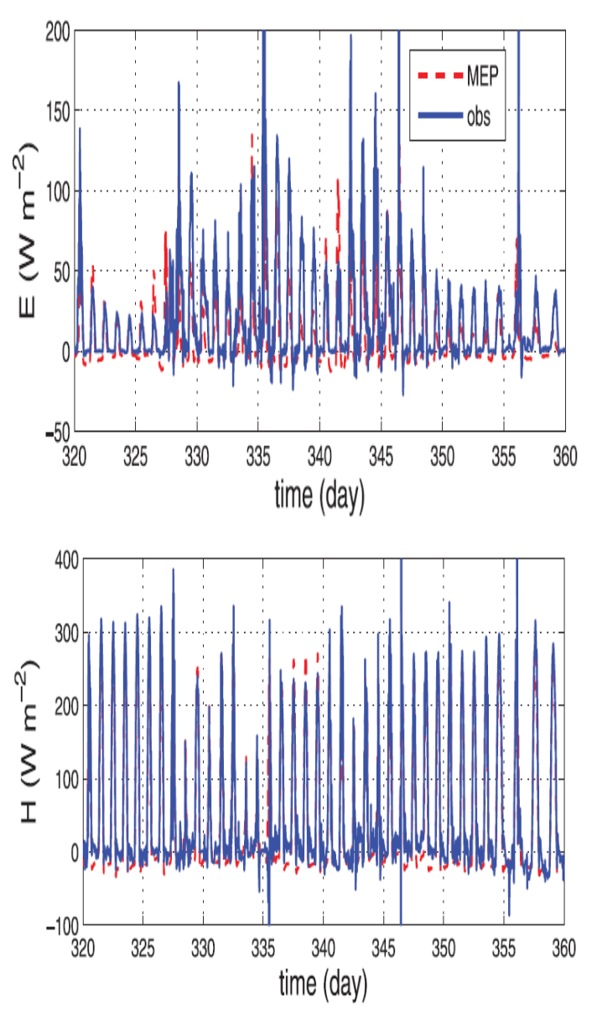
Model Input

Model Input	Data Products	Resolution	
		Spatial	Temporal
R_n, T_s	NASA CERES	$1^o \times 1^o$	3-hourly
q_s	NASA MERRA	$1^o \times 1^o$	3-hourly
Land Cover	IGBP	$1' \times 1'$	–

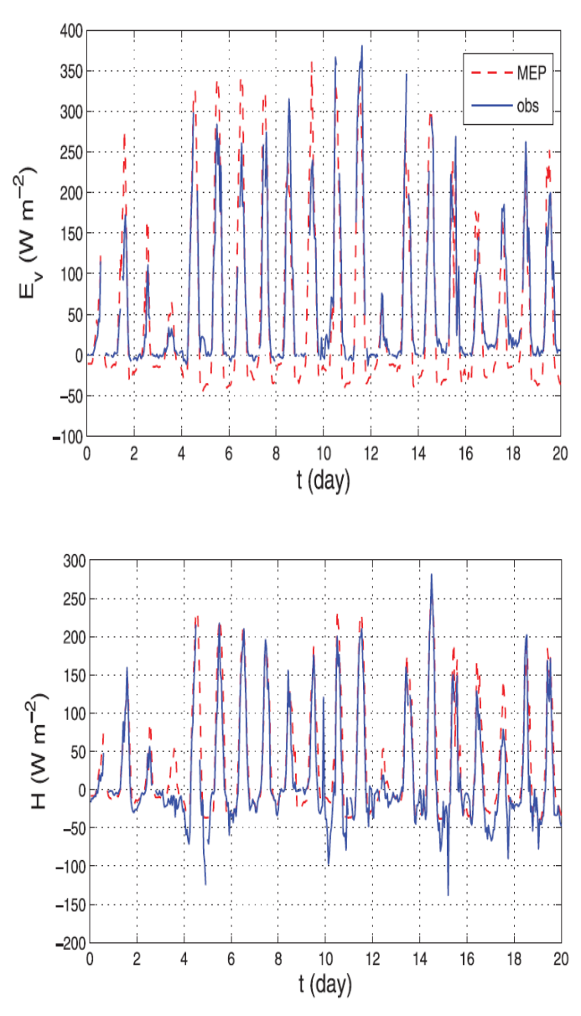
Validation

Data Set	Resolution	
	Spatial	Temporal
MERRA	$1^0 \times 1^0$	Monthly
Global Land Data Assimilation System (GLDAS)	$1^0 \times 1^0$	Monthly
National Oceanographic Data Center (NODC)	$1^0 \times 1^0$	Monthly

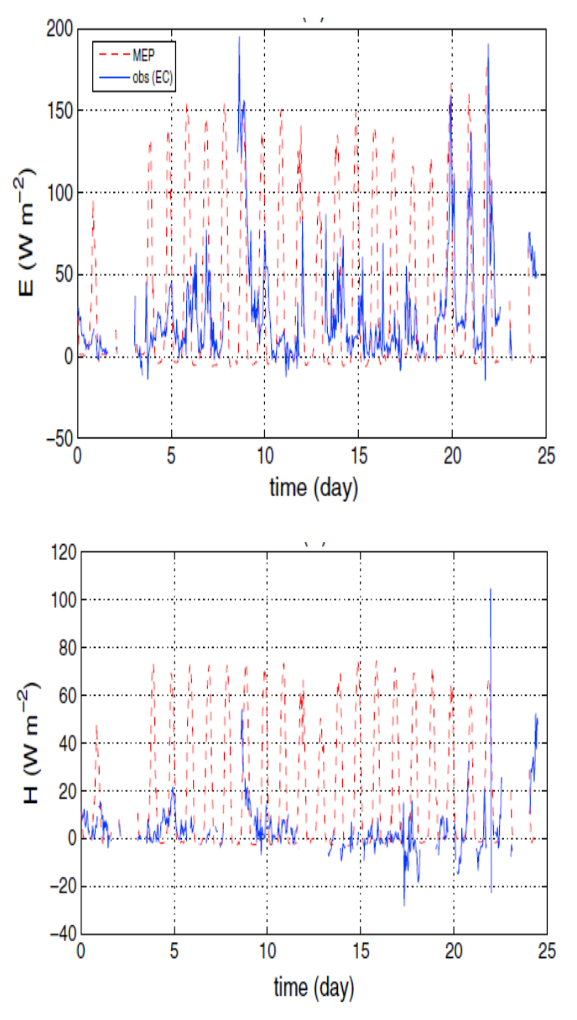
VI. Model Validation



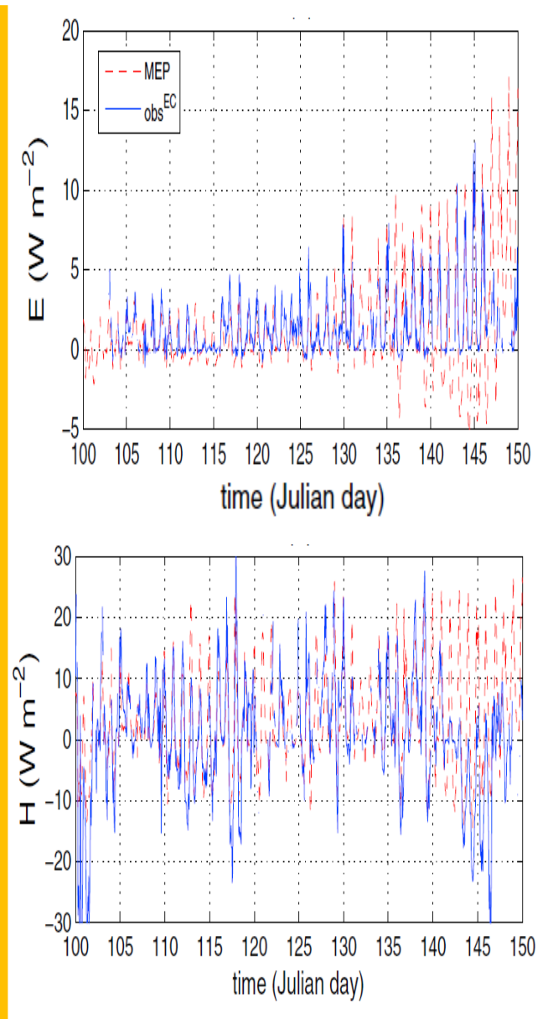
Bare Soil
MEP fluxes derived from measured R_n, T_s, and q_s versus observed fluxes at Lucky Hills site, Walnut Gulch Experimental Watershed, AZ, 2007. (Wang and Bras, 2011)



Vegetated Surface
MEP fluxes derived from measured R_n, T_s, and q_s versus observed fluxes at Harvard Forest, MA, 1994. (Wang and Bras, 2011)



Ocean Surface
MEP fluxes derived from measured R_n, R_n^l and T_s versus observed fluxes along the California coast from the CALNEX cruise, 2010. (Wang et al., 2014)



Ice Surface
MEP fluxes derived from measured R_n, R_n^l and T_s versus observed fluxes from the SHEBA experiment at an ice pack of the Arctic Ocean, 1998. (Wang et al., 2014)

VI. Uncertainty Analysis

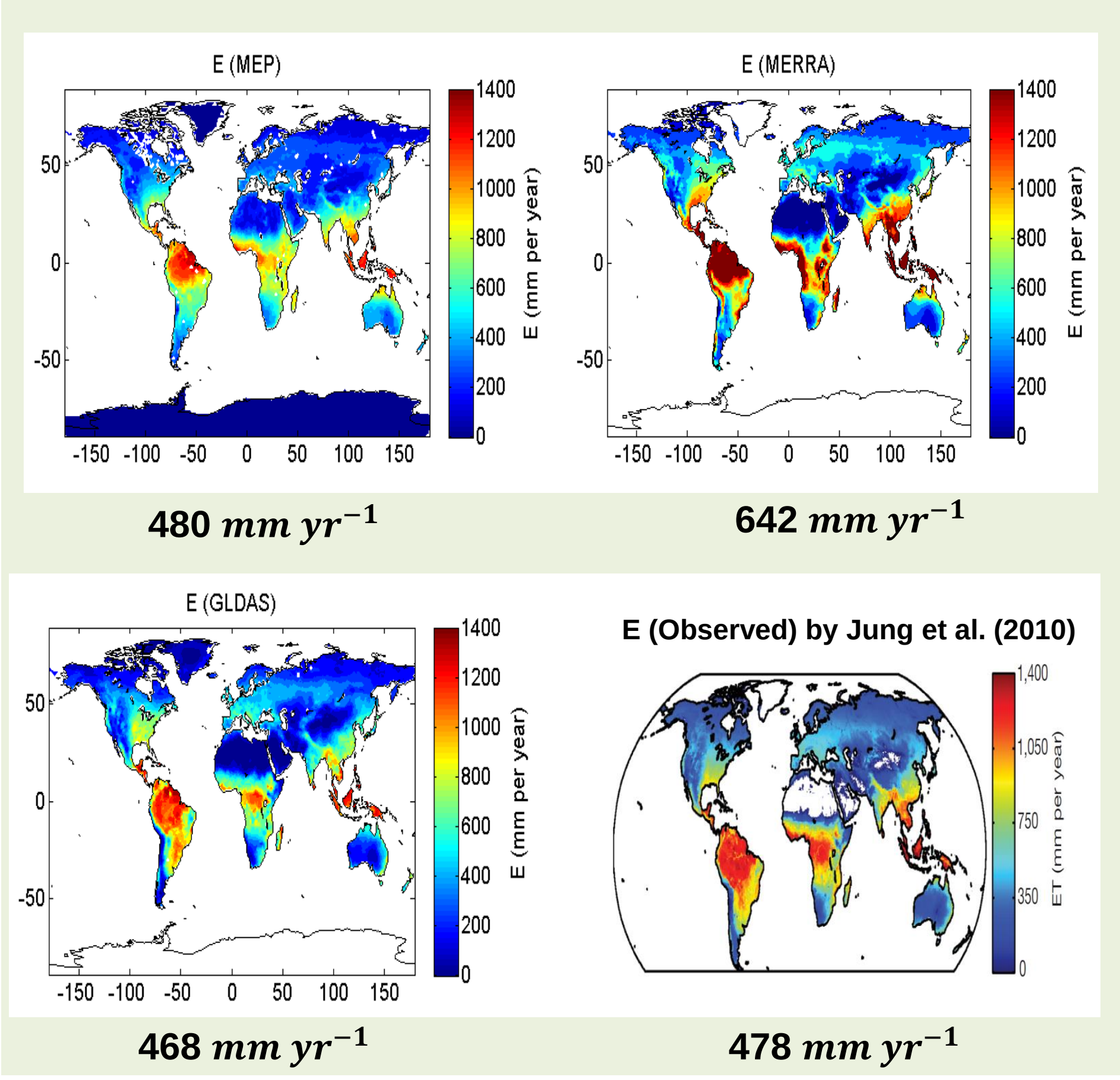
Representative Values of Derivatives and Variable/Parameter Uncertainties

Global	$\lvert\partial X/\partial R_n\rvert$	ΔR_n	$\lvert\partial X/\partial\sigma\rvert$	$\Delta\sigma$	$\lvert\partial X/\partial\beta\rvert$	$\Delta\beta$
E	0.44	12	12.82	0.05	5.39	0.07
H	0.26		4.97		3.14	
R_n- E- H (R_0+ Q)	0.3		17.77		8.53	
Land						
E	0.35	16	17.06	0.15	4.80	0.32
H	0.31		6.93		4.33	
Q	0.35		10.10		9.13	
Ocean						
E	0.47	14	11.26	0.02	5.23	0
H	0.24		4.26		2.72	
Q	0.71		7.00		7.95	

Relative Contributions of Uncertainties (%)

Global	R_n	σ	β
E	83	11	6
H	86	7	6
R_n- E- H (R_0+ Q)	71	17	12
Land			
E	57	27	16
H	67	14	19
Q	55	16	29
Ocean			
E	97	3	0
H	98	2	0
Q	99	1	0

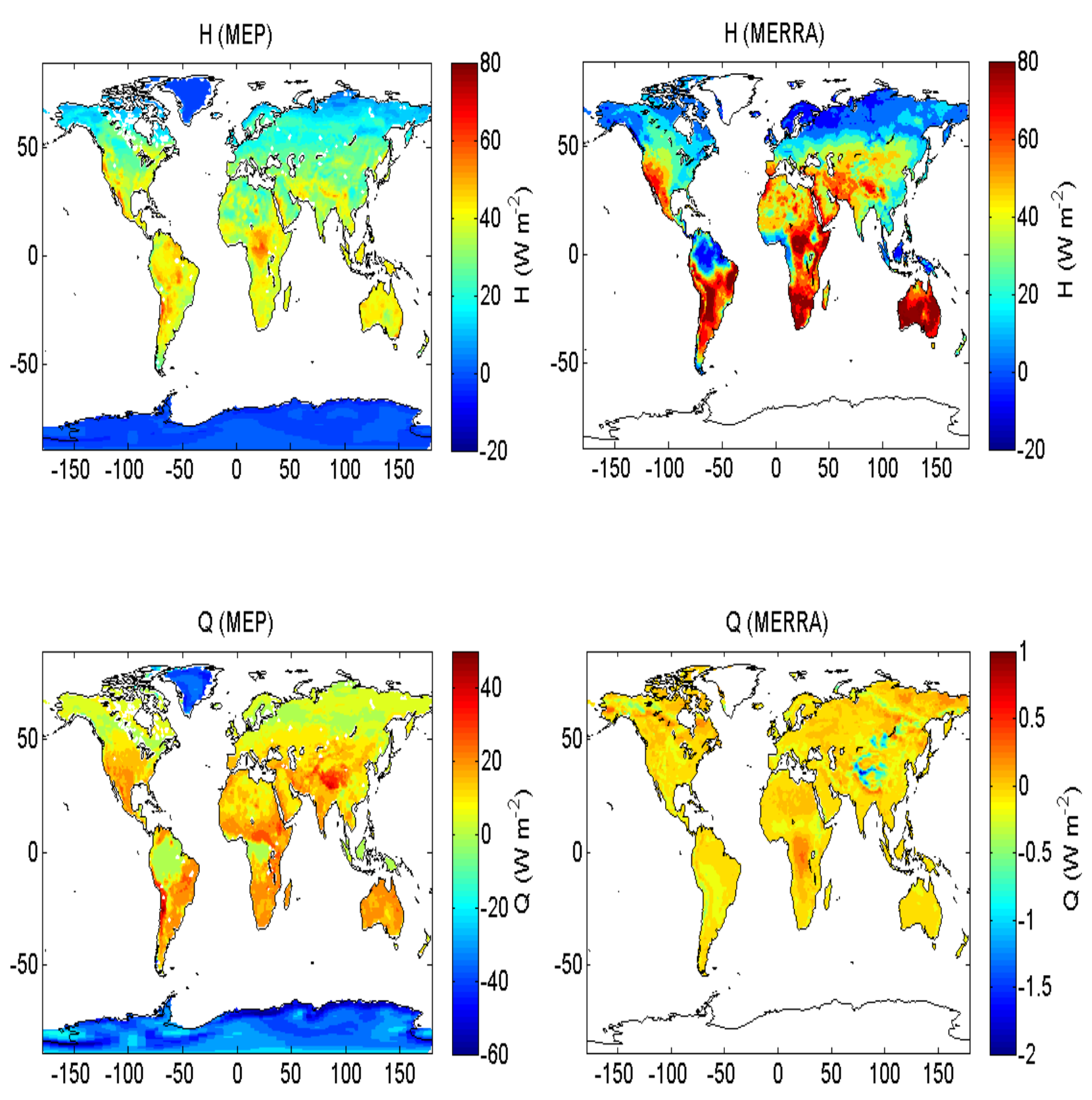
V. Climatology (2001-2010)

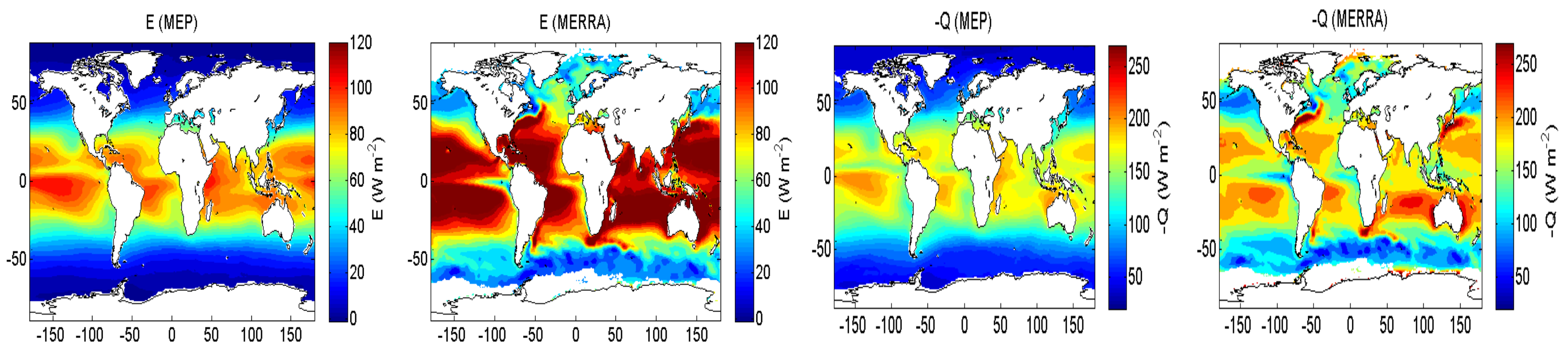


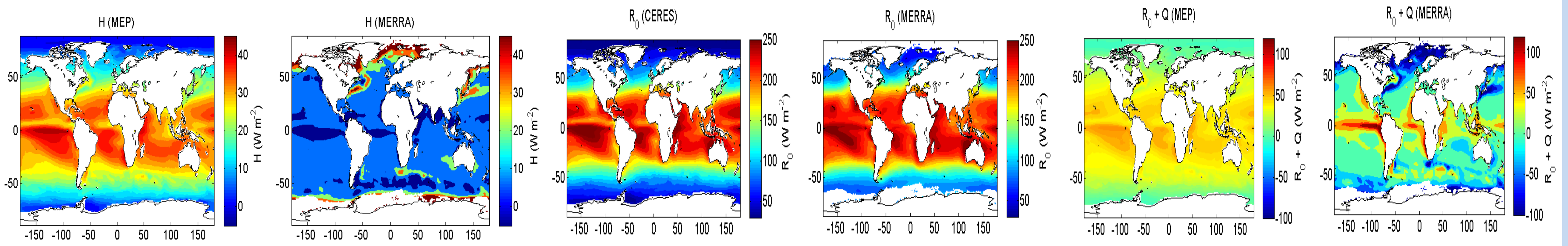
480 $mm\ yr^{-1}$ 642 $mm\ yr^{-1}$

E (Observed) by Jung et al. (2010)

468 $mm\ yr^{-1}$ 478 $mm\ yr^{-1}$





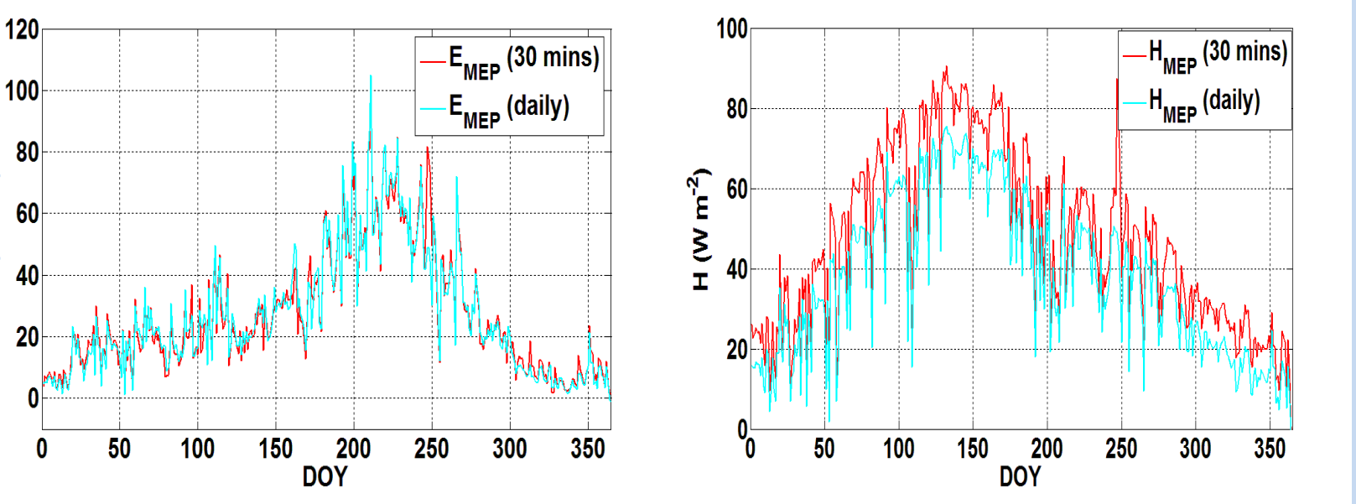


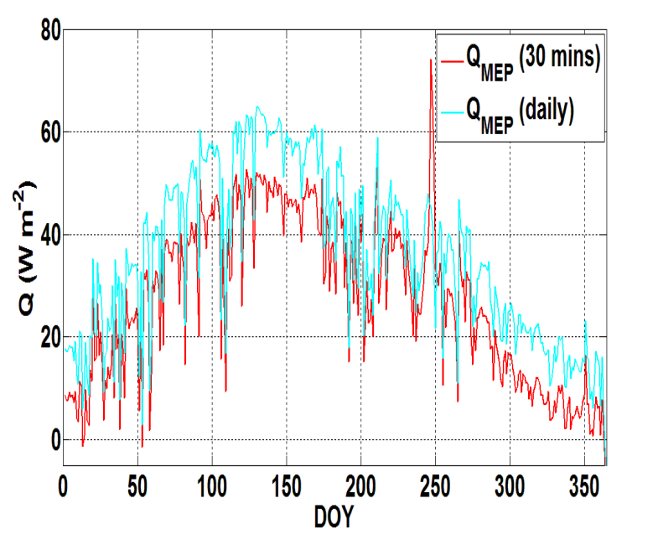
Trends of Global Annual Mean MEP Fluxes and CERES R_n, 2001-2010

$(W\ m^{-2}\ yr^{-1}\ per\ decade)$

Trend	E	H	Q	R_n
Global	0.04	0	0.02	0.02
Land	0.28	0.10	0.13	0.50
Ocean	-0.05	-0.04	-0.02	-0.17

MEP Model Sensitivity to the Resolution of Input Data





The MEP modeled heat fluxes versus observations using fine (30 mins) and coarse (daily mean) resolution of input data, Lucky Hill Site, AZ, 2010.

Global Annual Mean of Heat Fluxes $(W\ m^{-2})$

Global	E	H	Q	R_n	R_n^L	R_n- E- H (=R_0+ Q)
MEP	53±6	30±4	-	114±12	-57±10	31±5
Stephens et al. (2012)	88±10	24±7	-	113±15	-57±14	1
Trenberth et al. (2009)	80	17	-	98	-63	0
MERRA	79	19	-	110	-64	12
NCEP/NCAR[1]	81	16	-	100	-61	3
NCEP/DOE II[1]	91	8	-	103	-57	4
CFSR[1]	84	16	-	110	-57	10
JRA[2]	90	19	-	97	-73	-12
Land						
MEP	38±10	33±7	12±10	84±16	-69±11	-*
Trenberth et al. (2009)	39	27	0^a	66	-80	-*
MERRA	51	41	0^a	92	-74	-*
GLDAS	37	51	0.5	88	-65	-*
NCEP/NCAR[1]	51	26	3^a	80	-73	-*
NCEP/DOE II[1]	52	13	7^a	72	-71	-*
CFSR[1]	38	35	0^a	74	-66	-*
JRA[2]	39	27	2^a	69	-87	-*
Jimenez et al. (2011)	45±15	45±15	0^a	90±15	-	-*
Mueller et al. (2011)	48±6	-	-	-	-	-
Mueller et al. (2013)	39±12	-	-	-	-	-
Wang & Dickinson (2012)	35±9	-	-	-	-	-
Vinukollu et al. (2011)	42±5	-	-	-	-	-
Yuan et al. (2010)	33±3	-	-	-	-	-
Zhang et al. (2010)	43	-	-	-	-	-
Ocean						
MEP	58±7	28±3	-139±10	125±14	-52±12	39±4
Trenberth et al. (2009)	97	12	-166^b	110	-57	1
MERRA	92	16	-171^b	118	-63	10
OAFlux	98±7	10±1	-161^b	134	-52	25
NCEP/NCAR[1]	94	11	-161^b	109	-56	4
NCEP/DOE II[1]	106	6	-163^b	116	-51	4
CFSR[1]	103	9	-166^b	124	-54	12
JRA[2]	109	17	-194^b	107	-68	-19
HOAPS[2]	104±10	15	-	-	-	-
SeaFlux[3]	90±14	18±6	-	-	-	-

a, b: Q calculated as the residual of the energy balance equation in **II. A)**

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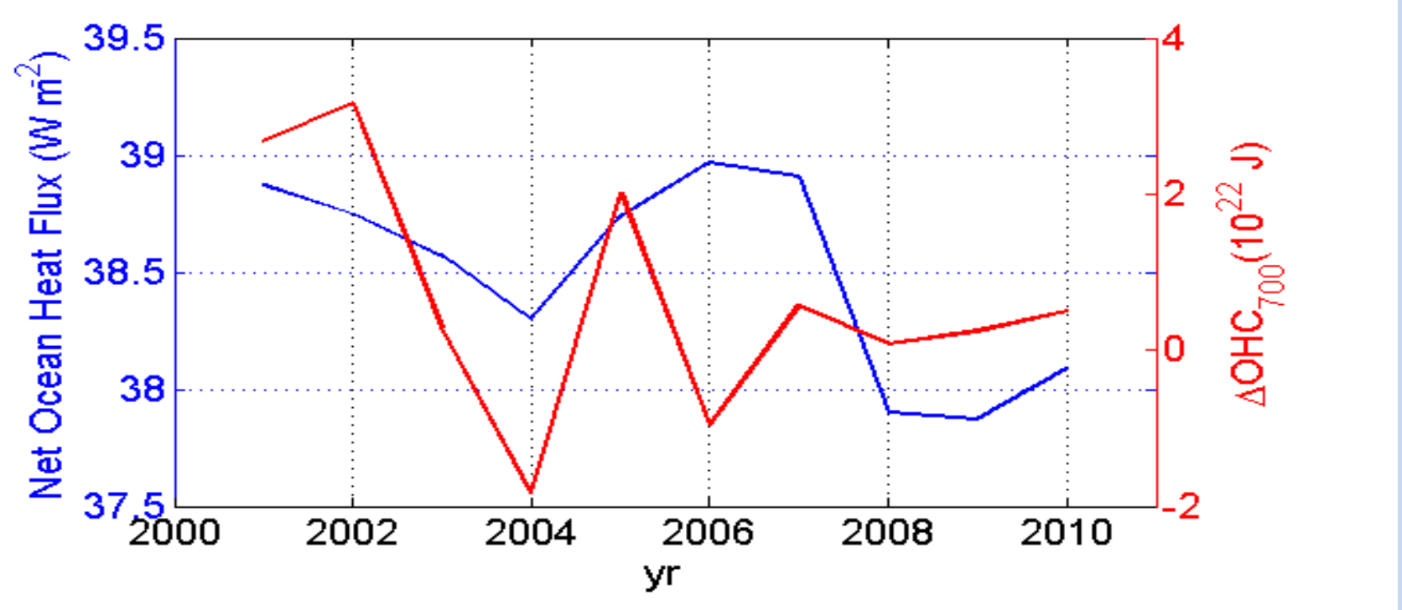

Net ocean heat flux $R_n - E - H\ (R_0 + Q)$ and the change of ocean heat content (ΔOHC) from National Climatic Data Center (NCDC).
The correlation coefficient is 0.4

Reference

1. Jung et al., 2010: Recent decline in the global land evapotranspiration trend due to limited moisture supply, *Nature*., 467, 951–954.
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4. Wang, J., R. L. Bras, V. Nieves, and Y. Deng, 2014: A model of energy budgets over water, snow and ice surfaces, *J. Geophys. Res. Atmos*., 119, 6034-6051.

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