From Physical Principles to Prediction of Water and Energy Fluxes over the Earth Surface

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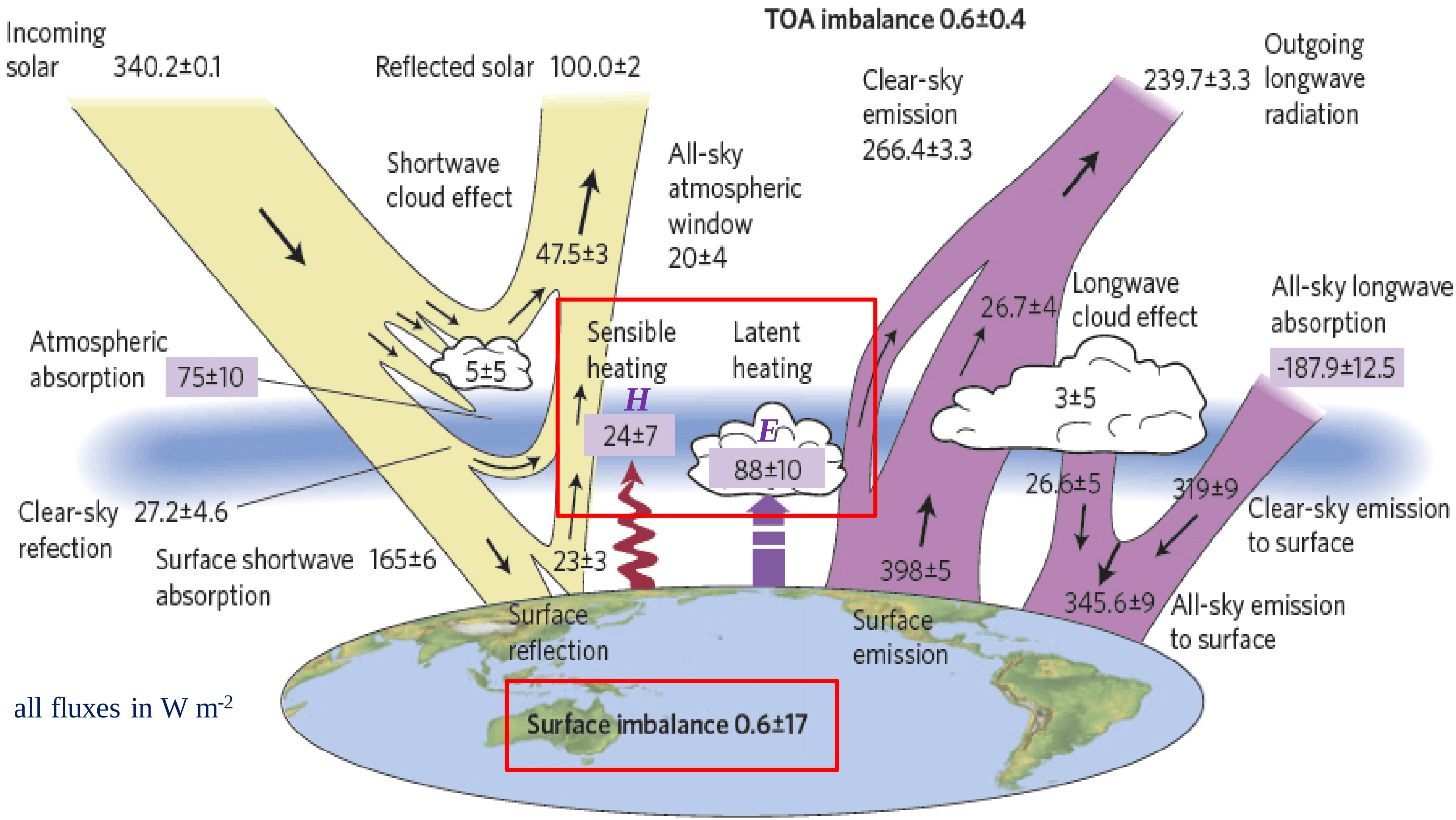
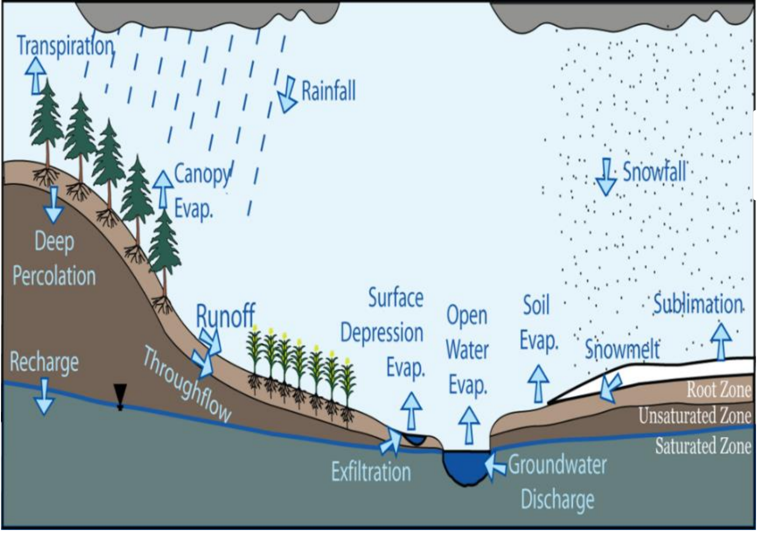
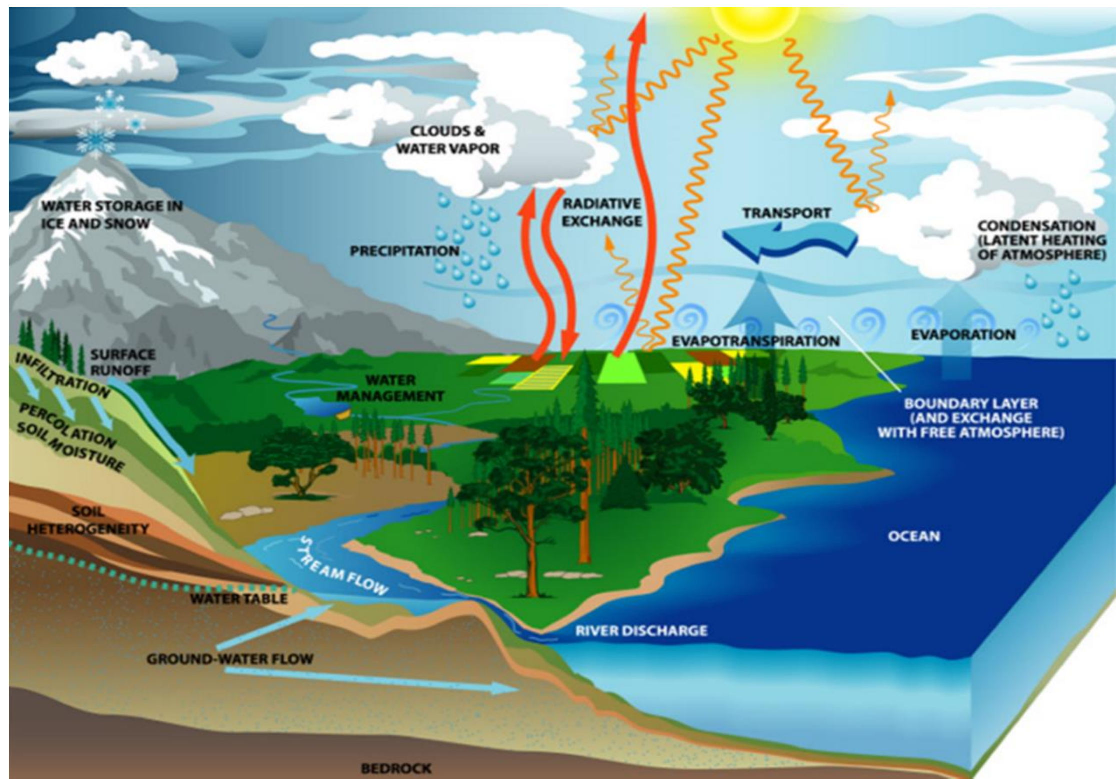


Stephens et al., An update on Earth's energy balance in light of the latest global observations, *Nature Geoscience*, **5**, 691–696 (2012).



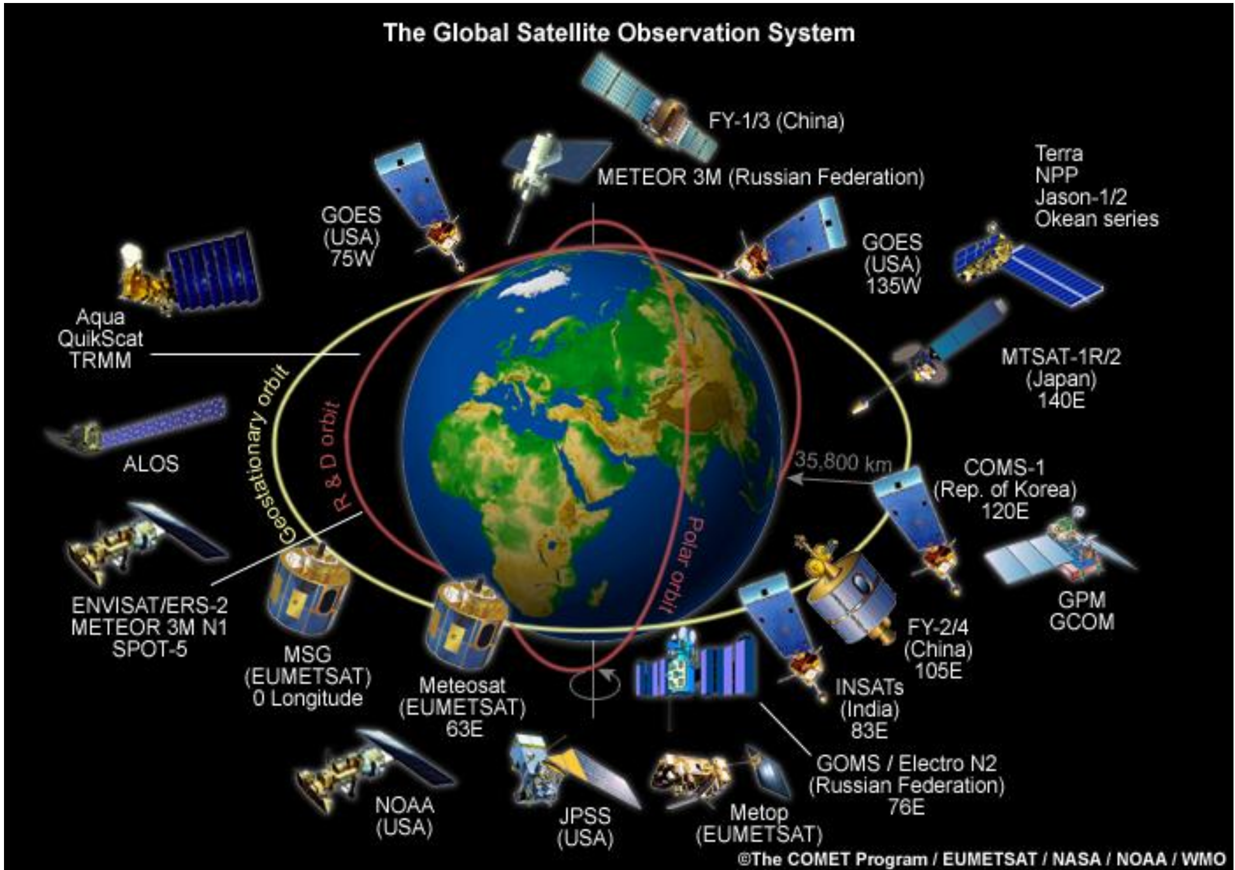
Watershed Scale

Global Scale

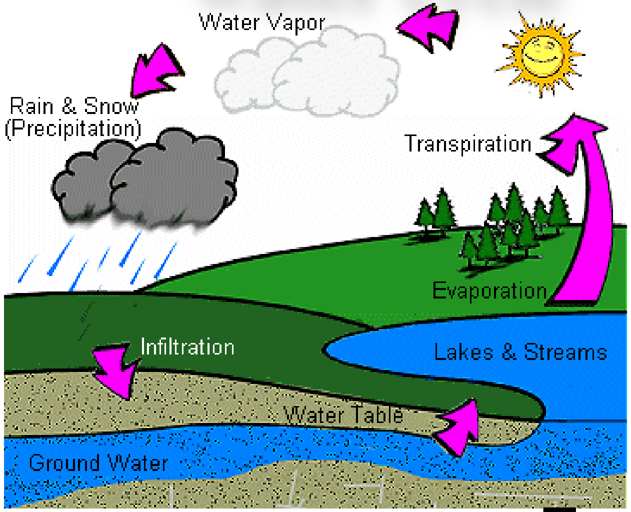


Ground Station

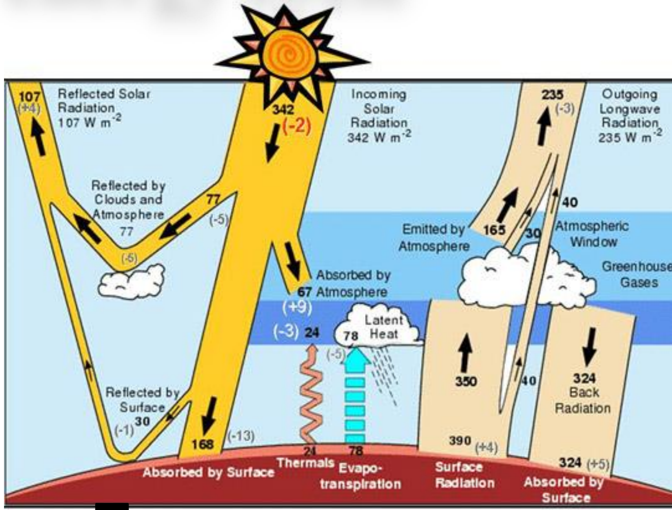
Satellites



water cycle

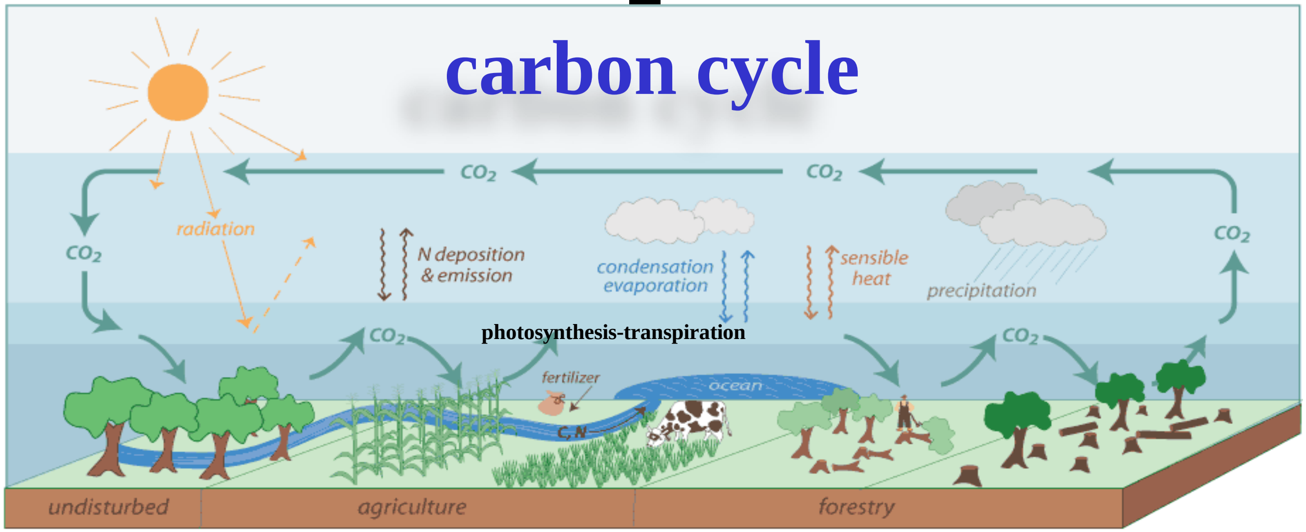


energy cycle



Evapotranspiration (ET)

carbon cycle



Maximum Principle of Evapotranspiration (MaxET)

Land-atmosphere interactive processes lead to such thermal and water states of the land surface that evapotranspiration is maximized in a given meteorological environment.

(Wang *et al.*, *WRR*, 2004; Wang *et al.*, *JGR*, 2007)

Stationary Principle of Heat Fluxes
(dry soils)

Land-atmosphere interactive processes lead to such thermal states of dry land surface that partition of net radiation into sensible and ground heat flux at a saddle-point in a given meteorological environment.

(Wang and Bras, *WRR*, 2009)

Minimum Principle of Turbulence

At a given height within an atmospheric surface layer, momentum flux reaches such values that minimize (negative) heat flux and wind shear under stable condition; while minimize (positive) heat flux and temperature gradient under unstable condition.

The new physical principles,

- **Maximum Principle of ET**
- **Stationary Principle of Heat Fluxes**
- **Minimum Principle of Turbulence**

open new opportunities to modeling ET and heat fluxes.

Physical Processes of ET

- Solar and longwave radiation,
- Dynamics of soil moisture,
- Turbulent transport of water vapor and heat,
- Thermodynamics of water phase change,
- Plant physiology,

The Project for Intercomparison of Land-surface Parameterisation Schemes (**PILPS**)

"… *no single land surface model is capable of capturing all features of the surface energy balance under all conditions* …"

(Desborough et al., 1996; Henderson-Sellers et al., 2003)

Physically-based Methods

- Bulk transfer

Bulk Transfer Models

$$H = \rho c_p C_H (T_s - T_a)$$

$$E = \rho \lambda C_E (q_s - q_a)$$

H, ***E*** surface turbulent latent and sensible heat flux,
T_s, T_a surface, air and soil temperature,
q_s, q_a surface and air humidity,
C_H, C_E transfer coefficients

Physically-based Methods

- Bulk transfer
- Penman

Penman Model

$$E = \frac{R_n - G + \frac{\gamma}{\Delta}\rho\lambda C_E U\left(q_a^* - q_a\right)}{1 + \frac{\gamma}{\Delta}}$$

$$H = R_n - G - E$$

γ: psychomatric constant

Δ: slope of saturated vapor pressure

Bulk Transfer Model

- Lack of conservation of energy,

- Measurement errors of bulk gradients,

- Uncertainties of (wind speed and roughness lengths dependent) transfer coefficients,

- Modeling errors of bulk transfer formulae (semi-empirical 1^{st} order closure of Reynolds decomposition of turbulent flow).

Penman Model

- Valid only for saturated soils,

- Uncertainties of (wind speed and roughness lengths dependent) transfer coefficients,

- Modeling errors of bulk transfer formulae (semi-empirical 1st order closure of Reynolds decomposition of turbulent flow).

Maximum Entropy Production (MEP) Model

- Bayesian probability theory (calculus of inductive logic),
- Information theory (Shannon information entropy - quantitative measure of missing information),
- Atmospheric Boundary Layer Turbulence Theory (Monin-Obukhov similarity theory),
- Maximum Entropy (MaxEnt) Principle (method of assigning probability distributions),
- Maximum Entropy Production (MEP) Principle (application of MaxEnt to non-equilibrium thermodynamic systems).

- **Information Entropy**

  (Shannon, 1948)

$$S_I = -\sum_{i=1}^{n} p_i \ln p_i$$

p_i the probability of a “random variable” x in i^{th} state, x_i.

- **Maximum Entropy (MaxEnt) Principle** (Jaynes, 1957): Out of all the possible probability distributions which agree with the given constraint information, select the one that is maximally non-committal with regard to missing information.

$$p_i = \frac{1}{Z} \exp[-\vec{\lambda} \cdot \vec{f}(x_i)]$$

$$S_I^{Max} = \max_{\{p_i\}} \{S_I \mid \sum_{i=1}^{n} p_i \vec{f}(x_i) = \vec{F}\}$$

$$= \ln Z(\vec{\lambda}) - \vec{\lambda} \cdot \vec{F}$$

$\vec{\lambda}$ Lagrange Multipliers; $\vec{F}$ constaints

- **MaxEnt to Equilibrium Thermodynamics**

  (Tribus, 1961)

$$S = \kappa S_I^{\max}$$

$$TdS = \delta Q = dU + PdV$$

1st law of thermodynamics

- **MaxEnt to Non-equilibrium Thermodynamics - Maximum Entropy Production Principle (MEP/MaxEP)** (Dewar, 2003, 2005, 2014)

Irreversibility

$$I(\vec{F}) \equiv \int p(\vec{f}) \ln \frac{p(\vec{f})}{p(-\vec{f})} d\vec{f} = 2\vec{\lambda}(\vec{F}) \cdot \vec{F}$$

where $\vec{F} = \int p(\vec{f}) \vec{f} d\vec{f}$ - macroscopic fluxes

"MaxEnt is equivalent to an extremal selection criterion of (macroscopic fluxes), i.e. MEP"

$$\vec{F}(C) = \max_{\text{all } \vec{F} | C}/\min \left\{ I(\vec{F}) \right\}$$

C: macroscopic physical constraints on $\vec{F}$

$I(\vec{F})$ is equivalent to

- physical variables thermodynamic entropy production and mechanical energy dissipation (*Dewar and Maritan, 2014*) and MEP as a physical principle;

$I(\vec{F})$ is equivalent to

- physical variables thermodynamic entropy production and mechanical energy dissipation (*Dewar and Maritan, 2014*) and “MEP” viewed as a physical principle;
- non-physical variables (*Wang and Bras, 2011*) and “MEP” treated as an inference algorithm.

$$\vec{F} = (E, H, Q)$$

$$\vec{\lambda}(\vec{F}) = \left(\frac{E}{I_E}, \frac{H}{I_H}, \frac{Q}{I_s} \right)$$

thermal inertia $I_s \equiv \sqrt{\rho_s c_s \lambda_s} = \rho_s c_s \sqrt{\kappa_s}$

(Wang and Bras, 2009; 2011)

$$\vec{F} = (E, H, Q)$$

$$\vec{\lambda}(\vec{F}) = \left(\frac{E}{I_E}, \frac{H}{I_H}, \frac{Q}{I_s} \right)$$

$$I(\vec{F}) = \vec{\lambda}(\vec{F}) \cdot \vec{F} = \frac{E^2}{I_E} + \frac{H^2}{I_H} + \frac{Q^2}{I_s}$$

Monin-Obukhov similarity equations for the atmospheric boundary layer turbulence (*Wang and Bras*, 2010),

$$I_H = I_0 \left|H\right|^{\frac{1}{6}}$$

$$I_E = \sigma I_H$$

$$I_0 = \rho c_p \sqrt{C_1 \kappa z}\left(C_2 \frac{\kappa z g}{\rho c_p T_0} \right)^{\frac{1}{6}} = C_0 z^{\frac{2}{3}},$$

$$\sigma(T_s, q_s) = \sqrt{\alpha_K}\, \frac{\lambda^2}{c_p R_v} \frac{q_s}{T_s^2}$$

surface specific humidity

surface temperature

	unstable	*stable*
C_1	$\sqrt{3}/\alpha$	$2/(1+2\alpha)$
C_2	$\gamma_2/2$	2β

α, β, γ_2 : universal empirical constants in the M-O similarity equations [*Businger et al*, 1971].

$$\vec{F}^{M}(C) = \max_{\text{all}\,\vec{F}|C}/\min\left\{ I(\vec{F}) \right\}$$

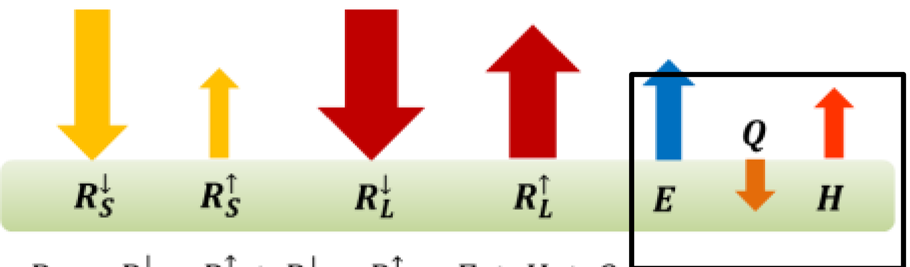
$$\boldsymbol{C}\text{:}\;\; E + H + Q = \begin{cases} R_n & \text{land} \\ R_n^L & \text{water} \end{cases}$$

Max: maximal irreversibility or farthest to equilibrium

Min: minimal irreversibility or closest to equilibrium

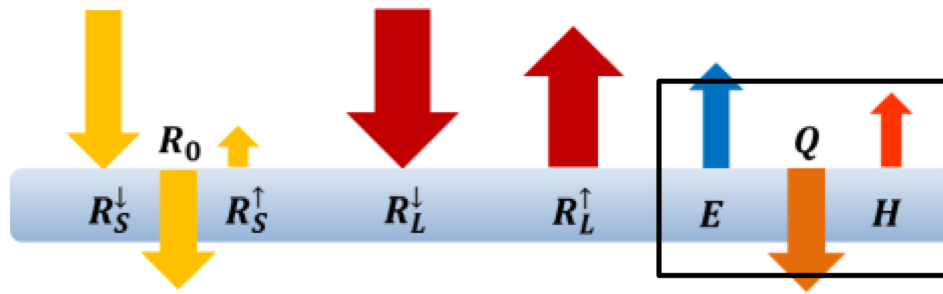
Surface Energy Budgets

Land



$$R_n \equiv R_S^\downarrow - R_S^\uparrow + R_L^\downarrow - R_L^\uparrow = E + H + Q$$

Water



$$R_n^S \equiv R_S^\downarrow - R_S^\uparrow = R_0$$
$$R_n^L \equiv R_L^\downarrow - R_L^\uparrow = E + H + Q$$

MEP Model for land Surface

$$Q = \frac{B(\sigma)}{\sigma} \frac{I_s}{I_0} |H|^{-\frac{1}{6}} H$$

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

$$E + H + Q = \boxed{R_n}$$

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

$$\sigma = \sqrt{\alpha_K} \frac{\lambda^2}{c_p R_v} \boxed{\frac{q_s}{T_s^2}}$$

(*Wang and Bras, 2011*)

MEP Model of Transpiration

$$E = \frac{R_n}{1 + B^{-1}(\sigma)}$$

$$H = \frac{R_n}{1 + B(\sigma)}$$

$$Q = 0$$

MEP Model for Water-Snow-Ice Surface

$$Q = \frac{B(\sigma)}{\sigma}\frac{I_{wsi}}{I_0}|H|^{-\frac{1}{6}} - \boxed{R_n^S}$$

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

$$E + H + Q = \boxed{R_n^L}$$

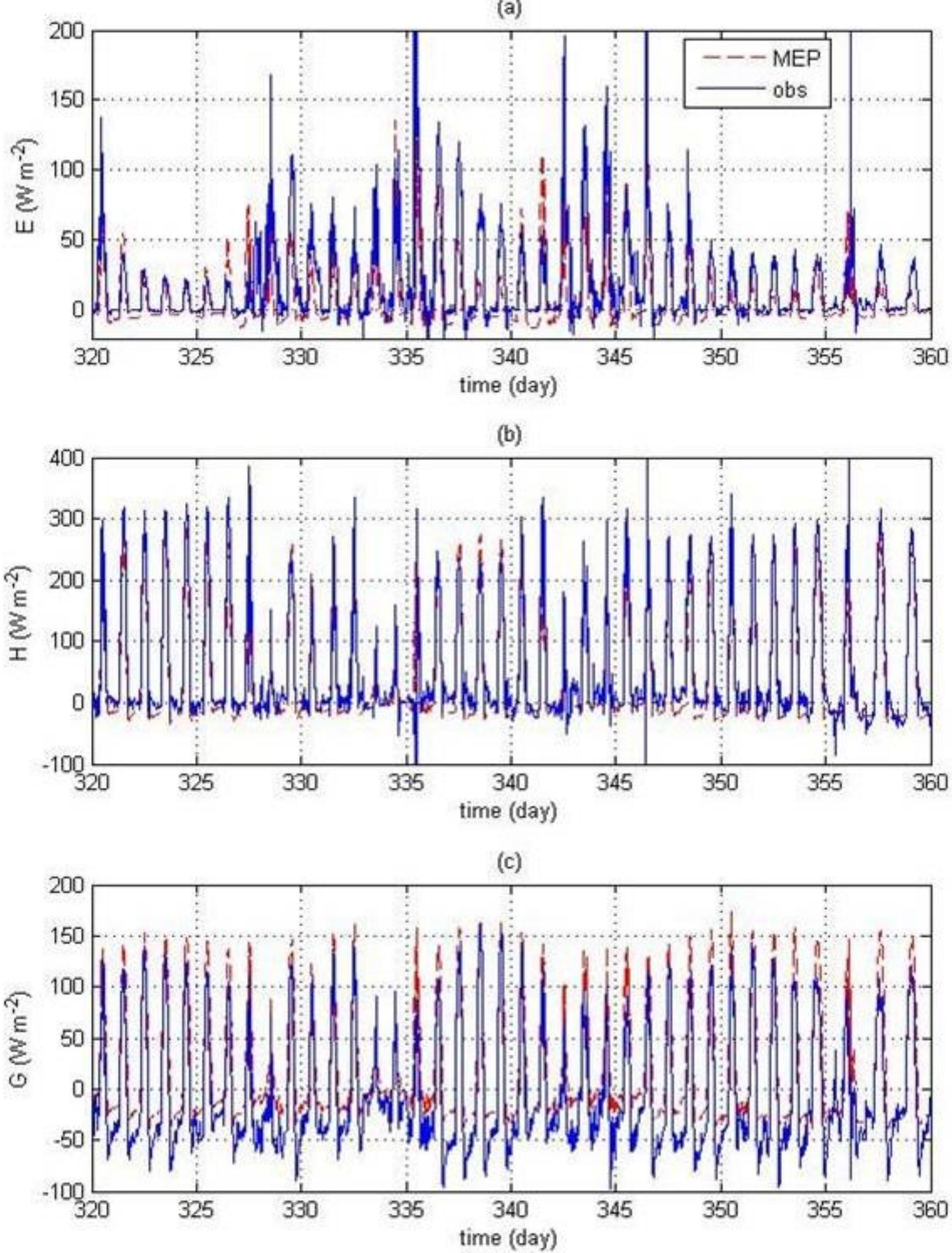
$$\sigma(\boxed{T_s}) = \sqrt{\alpha_K}\,\frac{\lambda^2}{c_p R_v}\frac{q_s^{sat}(T_s)}{T_s^2}$$

(*Wang et al, 2014*)

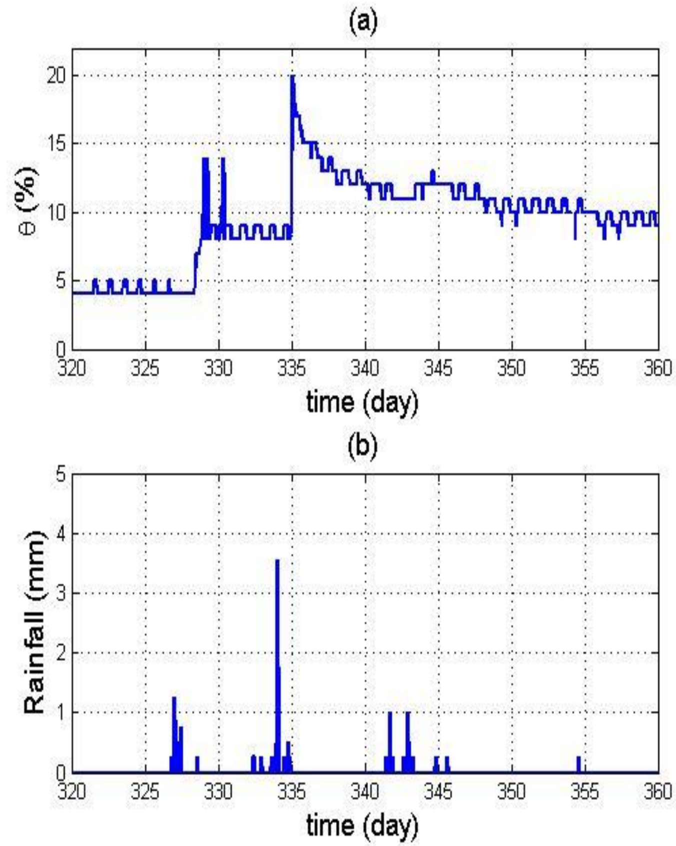
	Surface Energy Budget	Input data	Model Parameters	Modeling Error
Penman Method	Balanced	Air temperature, humidity, ground heat flux	Wind speed, roughness lengths, etc.	Semi-empirical (first order closure)
Bulk Method	Not balanced	Temperature & moisture gradient	Wind speed, roughness lengths, etc.	Semi-empirical (first order closure)
MEP Method	Balanced	Not used	Not used	First-principles (MaxEnt, MEP, MOST) constrained by radiation data

Physical Processes of ET

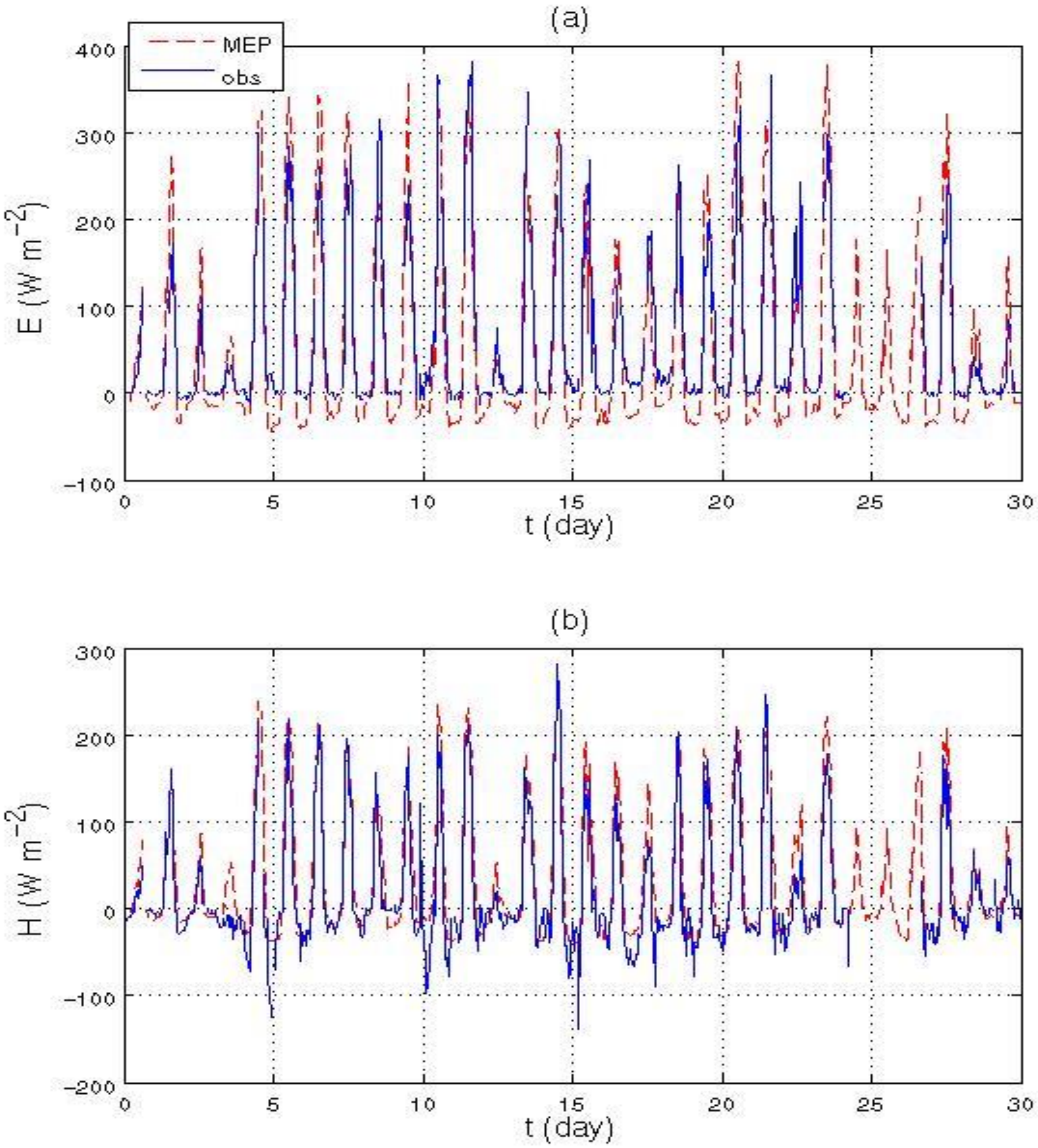
- Solar and longwave radiation: *energy balance equation*
- Dynamics of soil moisture: *thermal inertia* I_s*, surface specific humidity* q_s
- Boundary-layer turbulence: *thermal inertia* I_0
- Phase-change thermodynamics of water: $\sigma(Ts, qs)$
- Plant physiology: q_s



Bare Soil

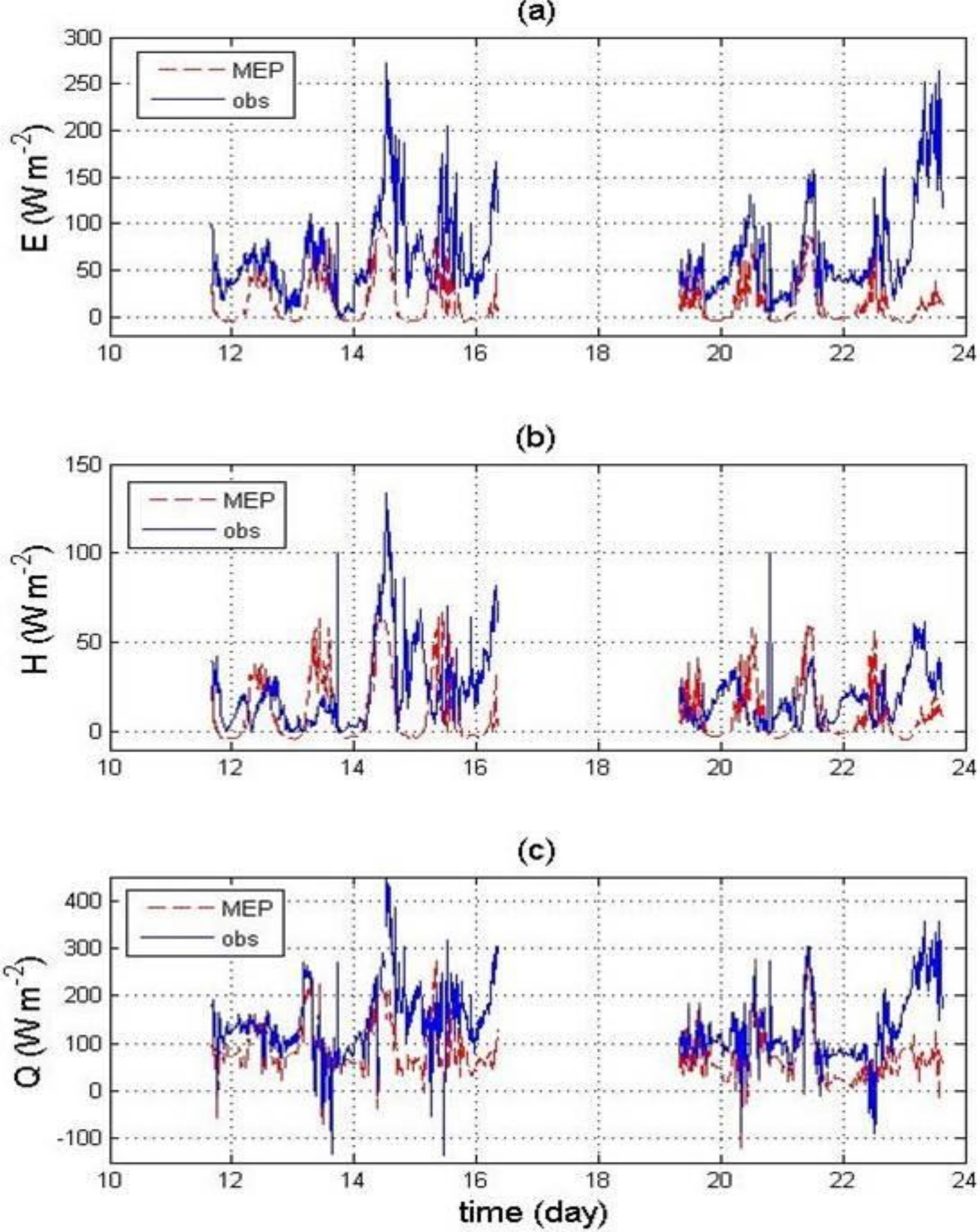


Lucky Hills site of the Walnut Gulch Experimental Watershed during 11/16 – 12/26, 2007.



Canopy

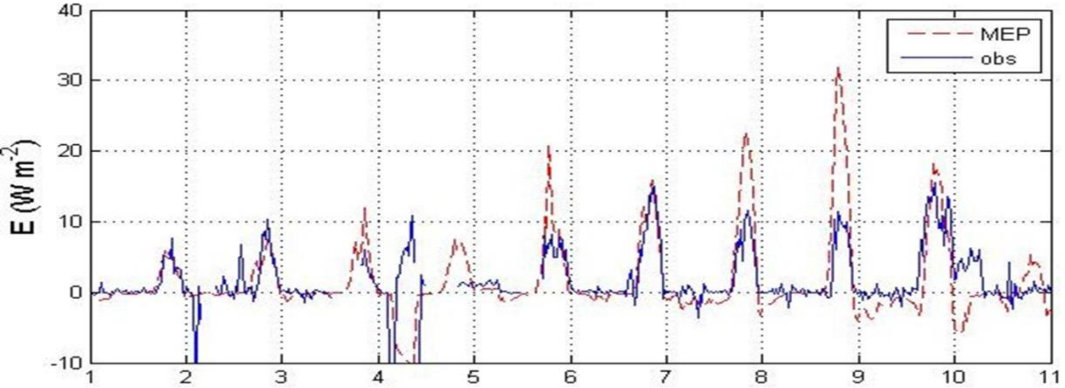
Harvard Forest site during 19 August - 18 September 1994.

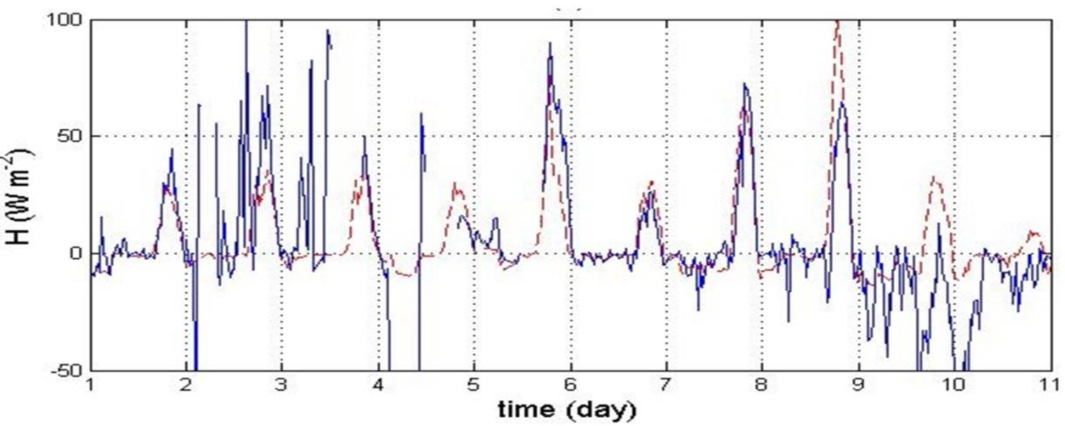


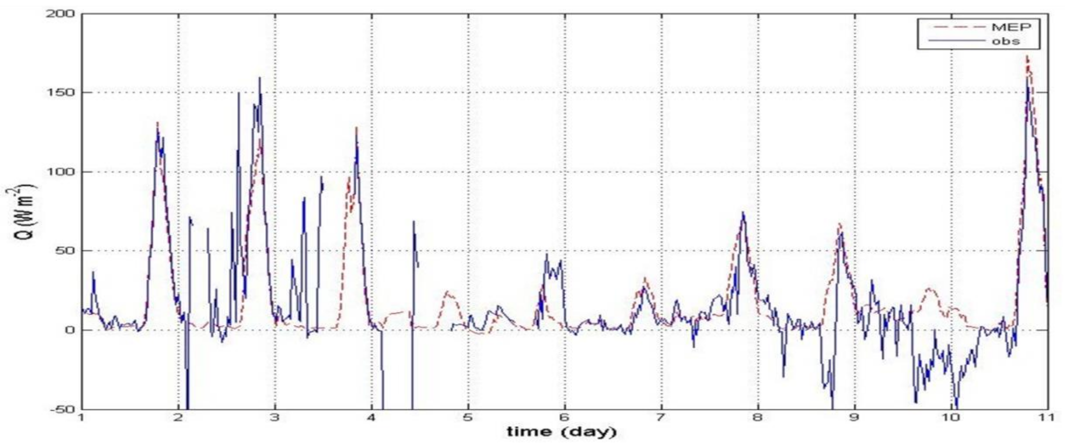
Water

NOrthern hemisphere climate Processes field Experiment (NOPEX) that made eddy-covariance measurements turbulent fluxes over Lake Raksjo (1.5 km^2 in surface area and 4m in depth) during June and July of 1994. (Data courtesy of Sven Halldin).

Snow

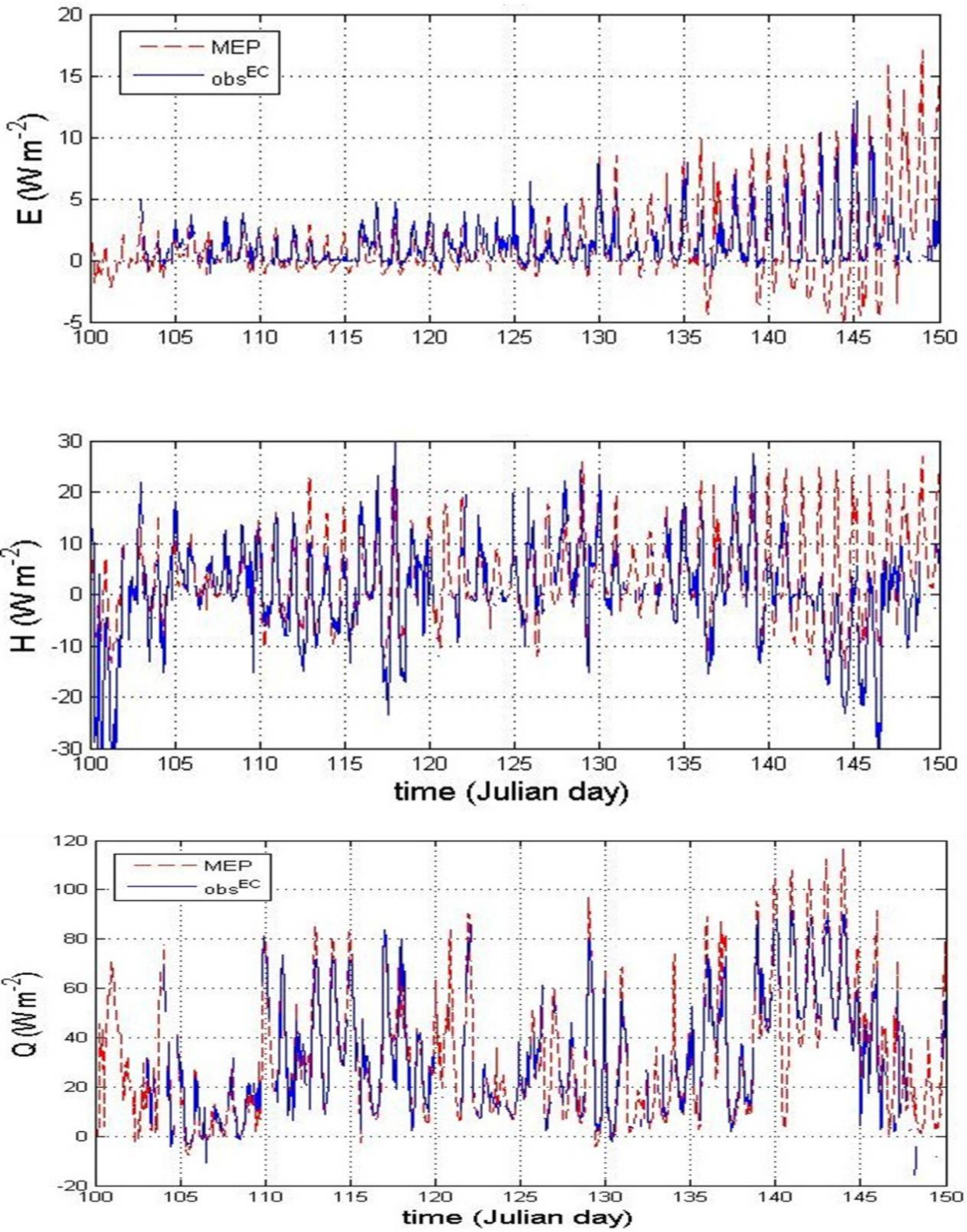






FLUXNET eddy-covariance data of surface fluxes and meteorological variables collected at a snow covered grassland site in Lethbridge, Alberta, Canada (AB-GRL) during 1 - 10 December 2007. Courtesy of Charmaine Hrynkiw, Betsy Sheffield, and Mary J. Saddington.

Sea Ice



Phase II eddy-covariance measurements of turbulent fluxes and meteorological variables from the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment at a ice pack of the Arctic Ocean during 10 April - 30 May 1998. Courtesy of Judith A. Curry and Carol Anne Clayson.

Conclusions

- The Bayesian method is a powerful tool to translate new knowledge into new models,
- The MEP model parameterizes more ET related physical processes and uses less input data than commonly used models,
- More applications of the Bayesian method in hydrologic modeling are yet to be explored.

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