A maximum-entropy-production perspective of the surface energy budget

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2018 CERES Fall Science Team Meeting
Boulder, CO
Sep 12, 2018

Acknowledgements: NASA CERES project
Outline

• Background and motivations
• Using maximum entropy production (MEP) principle to estimate LH and SH flux
• LH and SH flux estimated using the MEP principle and CERES-constrained surface radiative flux
  – Global mean statistics
  – Spatial patterns
• Discussions and outlooks

This is a “work-in-progress” report
LH: 88±10 (11%)  
SH: 24±7 (29%)  
compared to  
DW LW: 345.6±9 (2.6%)  
UP LW: 395±5 (1.3%)  
DW SW: 165±6 (3.6%)  
UP SW: 23±3 (13.0%)  

As a result: surface imbalance is 0.6±17
Surface LH and SH flux

• Observations: flux tower
• The (kinetics) bulk aerodynamic formulae: gradient approach

\[
F_{Hs} = C_H |V| (T_s - T_{air})
\]
\[
F_{water} = C_E |V| [q_{sat}(T_s) - q_{air}]
\]
\[
F_{water} = \gamma F_{Es} = \left(\frac{\rho_{liq}}{\rho_{air}}\right) E
\]

(Atmospheric Science: An Intro. Survey, 2nd Edition)

• Above formulas are used in NWPs, GCMs, reanalyses.
  – \(T_{air}\) & \(q_{air}\) and \(|V|\) are not resolved by the models: not predicted but diagnosed at each step
Getting LH and SH over oceans

- Flux-tower approach over oceans: direct validation of modeled LH and SH fluxes is a challenge
- On top of it, data sparsity

Fraction of missing data in 3-hourly SEAFLUX data set

From whoi.edu
Discrepancies between reanalysis are not small: esp. polar oceans

Difference of SH flux between MERRA-2 and ERA-interim for March (2003-2015)

Regional average
MERRA-2: 27.7 Wm$^{-2}$
ERA: 15.9 Wm$^{-2}$

Any other alternative ways to estimate LH and SH flux?
Max Entropy Production (MEP) principle

- **MEP:** An organizing principle governing the behavior of non-equilibrium system (Jaynes, 1957; Dewar 2005)
- Successfully used in land hydrology, bio-ecological system, etc
- Used in modeling heat fluxes over land surfaces (Wang & Bras, 2009; 2011)
- Extended to ice, snow, and water surface (Wang et al., 2014)
- A non-gradient method: input is net radiation flux and net LW flux, and $T_{surf}$, $q_{surf}$
MEP formula over water surfaces

\[
1 + B(\sigma) + \frac{B(\sigma)}{\sigma} \frac{I_{i,sn,w}}{I_0} |SH|^{-\frac{1}{6}} \]

\[
SH = R_n, \quad LH = B(\sigma)SH.
\]

\[
B(\sigma) = 6 \left( \sqrt{1 + \frac{11}{36} \sigma} - 1 \right), \quad \sigma = \sqrt{\alpha_w \frac{\Delta}{\gamma}}
\]

\(R_n\): the net downward radiation flux, \(R_{\downarrow n \uparrow l}\): the net downward long-wave radiation, \(Q\): the conductive heat flux to ground

\(I\): the thermal inertia of the medium with the subscripts “i”, “sn” and “w” standing for ice, snow and (still) water, respectively,

\(I_0\): the thermal inertia of the turbulent air

\(\alpha_w\): the ratio of eddy-diffusivity of turbulent transport of water vapor to that of heat in the boundary layer

\(\Delta\): the slope of saturation vapor pressure at surface temperature according to the Clausius-Clapeyron equation

\(\gamma\): the psychrometric constant.
MEP results over lands: Harvard forest

Harvard Forest Experiment  (Wang et al., 2014)
The modeled (a) latent heat flux $E$ and (b) sensible heat flux $H$ by the MEP (dashed red) and bulk transfer model (dashed blue) versus observations (solid black) of the Brooks Field site 10, Iowa, 9-29 June 2011.

MEP results over lands: Brooks field site (corn/soybean field)
When the MEP-based SH/LH scheme is implemented into a WRF model for a MJO hindcast experiment

Chen J., et al., *Hindcasting the Madden-Julian Oscillation With a New Parameterization of Surface Heat Fluxes*, JAMES, 2017
Use the MEP with CERES SYN 1-deg data

• CERES Ed4, 3-hourly SYN 1-degree: radiative flux at surface, Ts
• CERES Ed4, monthly-mean SRB-EBAF: radiative flux at surface, Ts
  – MEP predicts small diff. from 3-hourly results
• Surface q from MERRA-2, so do the surface type, ice fraction, LAI, etc.
• For the entire year of 2010
## 2010 annual-mean surface energy budget

<table>
<thead>
<tr>
<th></th>
<th>Down LW</th>
<th>Upward LW</th>
<th>Down SW</th>
<th>Upward SW</th>
<th>LH</th>
<th>SH</th>
<th>$Q = Dw (LW+SW) - Up (LW+SW) - LH - SH$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-hourly CERES-SYN1deg</td>
<td>347.6</td>
<td>398.1</td>
<td>183.6</td>
<td>22.3</td>
<td>86.4</td>
<td>19.9</td>
<td>4.5</td>
</tr>
<tr>
<td>Monthly EBAF</td>
<td>345.5</td>
<td>398.7</td>
<td>186.4</td>
<td>23.1</td>
<td>84.9</td>
<td>19.1</td>
<td>6.0</td>
</tr>
</tbody>
</table>

*LH and SH are calculated using MEP model ($z=20m$, $\alpha_w=5$)

### Note

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Global-mean difference and RMS: MEP results – MERRA-2 fields
Annual-mean LH and SH fluxes: MEP/3-hourly CERES-SYN vs. MERRA-2
Annual-mean LH and SH fluxes: MEP/CERES monthly-mean SRB-EBAF vs. MERRA-2
Correlation Coeff. of spatial patterns: MEP results vs. MERRA-2 fields
LH and SH fluxes in Jan 2010: MEP/3-hourly CERES-SYN vs. MERRA-2

Latent flux (91.6 Wm$^{-2}$), MEP model

Sensible flux (18.7 Wm$^{-2}$), MEP model

Latent flux (88.6 Wm$^{-2}$), MERRA-2

Sensible flux (17.7 Wm$^{-2}$), MERRA-2
LH and SH fluxes in Apr 2010: MEP/3-hourly CERES-SYN vs. MERRA-2

Latent flux (84.4 Wm$^{-2}$), MEP model

Sensible flux (20.8 Wm$^{-2}$), MEP model

Latent flux (85.9 Wm$^{-2}$), MERRA-2

Sensible flux (19.5 Wm$^{-2}$), MERRA-2
Discussions and Outlooks

• Two most sensitive parameters in the MEP scheme
  – $\alpha_w$: the ratio of eddy-diffusivity of turbulent transport of water vapor to that of heat in the boundary layer
  – $z$: the distance from the material surface above which the Monin–Obukhov similarity equations hold (goes into $I_0$)

• MEP approach has its attraction, but more studies are needed
  – A conjectured criterion for the stationary states of non-equilibrium system or a principle with theoretical basis?
  – What does it tell us when it fails or succeeds?
  – Compared to the bulk aerodynamic formula: more dominated by $T_s$ instead of wind
    • How to validate them over water surfaces?

• If MEP approach is feasible, LH/SH estimations with full consistency with CERES SYN 1-deg or SRB-EBAF products
References


