Observationally Closing the Arctic Atmosphere-Surface Energy Budget (SEB)

Subtext 1: Can it be done?
Subtext 2: The Science of Observations

Taneil Uttal, NOAA  
Andrey Grachev, CIRES  
Christopher C0x, CIRES  
Sara Crepinsek, CIRES  
Elena Konopleva-Akish, STC  
Ola Persson, CIRES  

Taneil.Uttal@noaa.gov  
Andrey.Grachev@noaa.gov  
christopher.j.cox@noaa.gov  
sara.crepinsek@noaa.gov  
elena.a.konopleva@noaa.gov  
ola.persson@noaa.gov
Why the SEB is important:
Latent Heat Flux ($H_l$)
Heat change because of a change of state at a constant temperature (liquid to ice freezing)

Sensible Heat Flux ($H_s$)
Heat transfer by conduction (heat transfer) because of $\Delta T$

$SW_{\downarrow} + LW_{\downarrow}$
$SW_{\uparrow} + LW_{\uparrow}$

Atmosphere
Vegetation
Snow
Active Layer
Permafrost

Conductive heat Flux

CO$_2$ Flux

Flux Plate

u, v, w, T, RH, CO$_2$
Datagrams

Calibration Values:

2. Downwelling Shortwave Diffuse (Eppley B&W PSP)
   8.72 µW/m²  6/1/2010 - present

3. Downwelling Shortwave Diffuse (Eppley PSP)
   8.76 µW/m²  6/1/2010 - present

4. Downwelling Longwave Total (Eppley PIR)

5. Downwelling Shortwave Direct (Eppley NIP)
   8.01 µW/m²  6/1/2010 - present

6. Downwelling Shortwave Total (K&Z CM22)
   9.40 µW/m²  6/1/2010 – present

6. Russian Downwelling Shortwave Direct (MF-19 (AT-50))
   9.13 µW/m²

Calculations:

DCF = Dome Correction Factor (for PIR instruments)
Sigma = 5.6704 * 10^(4.8)
E = efficiency = 1
TCR = Case Temp in mV (For Eppley PIR : data Column 9)
TDR = Dome Temp in mV (For Eppley PIR : data Column 10)
TC = Eppley PIR Temp[degK]
Conversion=1/[0.0010295+0.00002391*log(TCR*1000)+0.0000001568*log(TCR*1000)^3)]
TD = Eppley PIR Dome[degK]
Conversion=1/[0.0010295+0.00002391*log(TDR*1000)+0.0000001568*log(TDR*1000)^3)]
V [mV]: PIR = data column 7, PSP Eppley = data column 13, PSP B&W = data Column 15, PSP K&Z = data Column 17, NIP = data Column 11, Russian = data Column 19
SF: Calibration Values (see above)
PSP thermopile (W/m²) = 1000*V/SF
PIR thermopile (W/m²) = SF*V + Sigma *(E*TC^4 + DCF*(TC^4-TD^4))
\[(SW_{net} + LW_{net}) + (Q_s + Q_l) + G = R \text{ (residual)}\]

Radiation Fluxes + Turbulent Fluxes + Ground Flux
Measuring the Arctic Atmosphere-Surface Energy Balance

\[
\begin{align*}
\text{SW}_\downarrow + \text{LW}_\downarrow - \text{Q}_s + \text{Q}_l + \text{S}_{\text{RFD}} + \text{Q}_s + \text{Q}_l + \text{M}_\uparrow + \text{S}_G + \text{SW}_\uparrow - \text{LW}_\uparrow + \text{S}_P + \text{S}_C + \text{S}_S = 0
\end{align*}
\]

Subscripts:
- \(s\) = sensible heat
- \(l\) = latent heat
- \(\mu\) = microscale
- \(M\) = mesoscale
- \(G\) = Soil
- \(S\) = Storage Terms
- \(RFD\) = Radiative Flux Divergence

\(\text{SW} =\) Short Wave
\(\text{LW} =\) Long Wave
\(\text{Q} =\) Turbulent Fluxes

Measured
Working on it
Need additional obs
Ground Flux

\[ Q_G = G_{\uparrow \downarrow} + S_G_{\uparrow \downarrow} \]

1. Flux Plate instruments

\[ Q_{\downarrow G} = -\lambda \downarrow s \frac{\Delta T}{\Delta z} - C \downarrow s \frac{\Delta T}{\Delta z} \]

2. Thermistor instruments

\[ Q_{\downarrow G} = -\lambda \downarrow s (T_{\downarrow 05 \uparrow n+1} - T_{\downarrow 15 \uparrow n} + T_{\downarrow sfc \uparrow n+1} - T_{\downarrow sfc \uparrow n-1})/2(t_{\downarrow n+1} - t_{\downarrow n-1}) (z_{\downarrow 10} - z_{\downarrow sfc}) \]

Issue: Accurate measurements of \( C \downarrow s \) (soil heat capacity) and \( \lambda \downarrow s \) (soil conductivity)

Surface “skin” temp

Direct Flux

Storage Term

5 cm temp

10 cm temp

15 cm temp

Soil Constants:

- Soil thermal conductivity, soil heat capacity

Storage Term: accounting for any stored energy in layer near surface layer above highest T measurement

Conductive Flux: temperature gradient measurements
Calculations with eddy covariance methods

\[ \tau = -\rho < w'u' > \]

\[ H_S = \rho C_p < w'\theta' > \]

\[ H_L = \rho L < w'q' > \]

• Double axis rotation for sonic anemometer tilt correction
• Linear detrending of raw time series (Kaimal and Finnigan, 1994)
• Compensation for air density fluctuations (Webb et al., 1980)
• Statistical tests for raw time series data (Vickers and Mahrt, 1997)

Spike count/removal (Mauder et al., 2013)
Amplitude resolution
Dropouts
Absolute limits
Skewness and kurtosis
Angle of attack
Steadiness of horizontal wind

Issue: Continuity of methodology and large scale advection fluxes

Estimates with gradient and bulk methods

\[ \tau = \rho K_M (\bar{\partial u} / \partial z) \]

\[ H_S = -\rho C_p K_H (\bar{\partial \theta} / \partial z) \]

\[ H_L = -\rho L K_W (\bar{\partial q} / \partial z) \]

where according to Monin - Obukhov Similarity Theory

\[ K_M = k u_s (z - d) / \phi_m (\zeta) \]

\[ K_H = k u_s (z - d) / \phi_h (\zeta) \]

\[ K_W = k u_s (z - d) / \phi_w (\zeta) \]

• Fluxes are driven by gradients in u, T, and q
• Fluxes are proportional to friction velocity
• These are simply definitions of KM, KH, KW
• Ohm’s Law combined with Similarity
Quality Control - QCRAD” (Long and Shi 2008)

- “Uses fluxes, 2m temperature, 2m RH (common to all BSRN stations). Primary assumption is that most of the data is “good”.
- Physically possible limits, climatological configurable limits based on relationships between variables.
- Applies correction for IR loss in shortwave measurements (Shi and Long 2007)
- SWD is combination of DIR+DIFF (“SUM”) and GLOBAL: SUM whenever available.

CALIBRATION

<table>
<thead>
<tr>
<th>Calibration Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Direct Shortwave Down (Eppley BAV/RSP)</td>
</tr>
<tr>
<td>3. Direct Shortwave Down (Eppley DIF)</td>
</tr>
<tr>
<td>4. Downwelling Radiometric Temp (Eppley RIR)</td>
</tr>
<tr>
<td>5. Downwelling Shortwave Direct (Eppley NP)</td>
</tr>
<tr>
<td>6. Downwelling Shortwave Total (KSR/K2)</td>
</tr>
<tr>
<td>7. Downwelling Total (BSRN)</td>
</tr>
<tr>
<td>8. Radiosonde Downwelling Direct (MSG/AT)</td>
</tr>
</tbody>
</table>

Calculation:
DCF = Direct Connection Factor (for PAR instrument)  
S = 0.76 + 0.19 | E = Efficiency  
T = Temp (Eppley PAR)  
IR = IR Temp (Eppley PAR)  
TC = Temp Comp(T)  
DP = Direct Comp(Eppley PAR)  
IP = IR Comp(Eppley PAR)  

ICING

Uwelling Radiation Fluxes

SW↓ + LW↓ + SW↑↓ + LW↑

SWD (K-Z CM22), DIFFUSE (Eppley PSP), DIRECT (Eppley (NIP), SWU (Eppley PSP), LWD/LWU (Eppley PIR)

Issues: quality control, calibration and icing
How much energy is stored by photosynthesis? 479 kJ of energy is stored per mole of CO$_2$ fixed into photosynthetic products. For example, a canopy assimilation rate of 10 $\mu$mol/m$^2$ s equates to energy flux of 4.79 ~ 5 [W/m$^2$]. The photosynthesis storage term (as well as the storage term because of changes in leaf temperature) is relatively small but important for understanding impacts of the changing climate on the ecosystem.

• (Nobel P.S. (1991) "Physicochemical and Environmental Plant Physiology" (Chapter 7.1, page 321)

Issue: need better integration with ecosystem colleagues
Snow Fluxes and Storage

- Storage through freeze/melt processes
- Snow chemistry as a source sink of CO2 Fluxes

Issue: need better integration with snow physicists
Issue: Horizontal inhomogeneity local and regional
<table>
<thead>
<tr>
<th>Site Description</th>
<th>Thermal Conductivity [ ]</th>
<th>Thermal Conductivity Conversion</th>
<th>Heat Capacity [C]</th>
<th>Heat Capacity Conversion</th>
<th>Author/Paper</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Dock</td>
<td>0.60 Wm-1K-1</td>
<td>0.60 Wm-1K-1</td>
<td>2.70 Mm-3K-1</td>
<td>2.70 Mm-3K-1</td>
<td>Romanovsky &amp; Osterkamp, 1997</td>
</tr>
<tr>
<td>Deadhorse</td>
<td>0.77 Wm-1K-1</td>
<td>0.77 Wm-1K-1</td>
<td>2.36 Mm-3K-1</td>
<td>2.36 Mm-3K-1</td>
<td>Romanovsky &amp; Osterkamp, 1997</td>
</tr>
<tr>
<td>Franklin Bluff</td>
<td>0.82 Wm-1K-1</td>
<td>0.82 Wm-1K-1</td>
<td>2.30 Mm-3K-1</td>
<td>2.30 Mm-3K-1</td>
<td>Romanovsky &amp; Osterkamp, 1997</td>
</tr>
<tr>
<td>Quartz</td>
<td>0.021 cal cm-1 sec-1 celsius-1</td>
<td>8.792276 Wm-1K-1</td>
<td>1.77135 Wm-1K-1</td>
<td>1.77135 Wm-1K-1</td>
<td>Sellers, 1965</td>
</tr>
<tr>
<td>Clay minerals</td>
<td>0.007 cal cm-1 sec-1 celsius-1</td>
<td>2.930759 Wm-1K-1</td>
<td>Sellers, 1965</td>
<td>Sellers, 1965</td>
<td></td>
</tr>
<tr>
<td>Organic matter</td>
<td>0.0006 cal cm-1 sec-1 celsius-1</td>
<td>0.2512079 Wm-1K-1</td>
<td>Sellers, 1965</td>
<td>Sellers, 1965</td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>0.00137 cal cm-1 sec-1 celsius-1</td>
<td>0.5758914 Wm-1K-1</td>
<td>Sellers, 1965</td>
<td>Sellers, 1965</td>
<td></td>
</tr>
<tr>
<td>Ice</td>
<td>0.0006 cal cm-1 sec-1 celsius-1</td>
<td>0.0212079 Wm-1K-1</td>
<td>Sellers, 1965</td>
<td>Sellers, 1965</td>
<td></td>
</tr>
<tr>
<td>Air</td>
<td>8.4 Wm-1K-1</td>
<td>8.4 Wm-1K-1</td>
<td>1.942 Mm-3K-1</td>
<td>1.942 Mm-3K-1</td>
<td>Peters-Lidard et al., 1997</td>
</tr>
<tr>
<td>Quartz</td>
<td>2.9 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>2.503 Mm-3K-1</td>
<td>2.503 Mm-3K-1</td>
<td>Peters-Lidard et al., 1997</td>
</tr>
<tr>
<td>Soil organic matter</td>
<td>0.25 Wm-1K-1</td>
<td>0.25 Wm-1K-1</td>
<td>2503 Mm-3K-1</td>
<td>2503 Mm-3K-1</td>
<td>Peters-Lidard et al., 1997</td>
</tr>
<tr>
<td>Water</td>
<td>2.5 Wm-1K-1</td>
<td>2.5 Wm-1K-1</td>
<td>1.883 Mm-3K-1</td>
<td>1.883 Mm-3K-1</td>
<td>Peters-Lidard et al., 1997</td>
</tr>
<tr>
<td>Air</td>
<td>0.026 Wm-1K-1</td>
<td>0.026 Wm-1K-1</td>
<td>1.20 Jm-3K-1</td>
<td>0.0012 Mm-3K-1</td>
<td>Peters-Lidard et al., 1997</td>
</tr>
<tr>
<td>Mineral-organic mixture</td>
<td>0.7, 1.8 Wm-1K-1</td>
<td>0.7, 1.8 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>Farouki, 1981</td>
</tr>
<tr>
<td>Mineral-soil(silt)</td>
<td>1.3.4 Wm-1K-1</td>
<td>1.3.4 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>Farouki, 1981</td>
</tr>
<tr>
<td>Mineral-Soil(gravel)</td>
<td>2.5, 3.5 Wm-1K-1</td>
<td>2.5, 3.5 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>Farouki, 1981</td>
</tr>
<tr>
<td>Mineral-Soil(Shale)</td>
<td>1.0, 2.0 Wm-1K-1</td>
<td>1.0, 2.0 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>Farouki, 1981</td>
</tr>
<tr>
<td>Quartz</td>
<td>8.4 Wm-1K-1</td>
<td>8.4 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>Farouki, 1981</td>
</tr>
<tr>
<td>Soil minerals</td>
<td>0.25 Wm-1K-1</td>
<td>0.25 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>Farouki, 1981</td>
</tr>
<tr>
<td>Soil organic matter</td>
<td>0.25 Wm-1K-1</td>
<td>0.25 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>Farouki, 1981</td>
</tr>
<tr>
<td>Water</td>
<td>0.6 Wm-1K-1</td>
<td>0.6 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>2.9 Wm-1K-1</td>
<td>Farouki, 1981</td>
</tr>
<tr>
<td>Ice (temp -20 degC)</td>
<td>0.00581 cal cm-1 sec-1 celsius-1</td>
<td>2.49359 Wm-1K-1</td>
<td>Farouki, 1981</td>
<td>Farouki, 1981</td>
<td></td>
</tr>
<tr>
<td>Ice (temp -20 degC)</td>
<td>0.00545 cal cm-1 sec-1 celsius-1</td>
<td>2.381805 Wm-1K-1</td>
<td>Farouki, 1981</td>
<td>Farouki, 1981</td>
<td></td>
</tr>
<tr>
<td>Ice (temp 0 degC)</td>
<td>0.0035 cal cm-1 sec-1 celsius-1</td>
<td>2.239937 Wm-1K-1</td>
<td>Farouki, 1981</td>
<td>Farouki, 1981</td>
<td></td>
</tr>
<tr>
<td>Assumed Tundra soils-organic frozen</td>
<td>100 cal m-1 hr-1 celsius-1</td>
<td>6.978011 Wm-1K-1</td>
<td>Farouki, 1981</td>
<td>Farouki, 1981</td>
<td></td>
</tr>
<tr>
<td>Assumed Tundra soils-organic unfrozen</td>
<td>250 cal m-1 hr-1 celsius-1</td>
<td>17.44501 Wm-1K-1</td>
<td>Farouki, 1981</td>
<td>Farouki, 1981</td>
<td></td>
</tr>
<tr>
<td>Assumed Tundra soils-mineral frozen</td>
<td>900 cal m-1 hr-1 celsius-1</td>
<td>62.801957 Wm-1K-1</td>
<td>Farouki, 1981</td>
<td>Farouki, 1981</td>
<td></td>
</tr>
<tr>
<td>Assumed Tundra soils-mineral unfrozen</td>
<td>770 cal m-1 hr-1 celsius-1</td>
<td>53.73056 Wm-1K-1</td>
<td>Farouki, 1981</td>
<td>Farouki, 1981</td>
<td></td>
</tr>
</tbody>
</table>

**Units**

<table>
<thead>
<tr>
<th>Wm-1K-1</th>
<th>Mm-3K-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thawed</td>
<td>0.25</td>
</tr>
<tr>
<td>Frozen</td>
<td>1.375</td>
</tr>
</tbody>
</table>

To get frozen value I took the average of soil organic and ice
Net Radiation Budget, Tiksi 2012-2014

Specialist: Radiation Terms
christopher.j.cox@noaa.gov
SUMMARY

• Models without observations are video games
  Kathy Sullivan (Under Secretary of Commerce for Oceans & Atmosphere and NOAA Administrator)
  Town Hall Meeting in Boulder, Colorado

• You only really measure voltages and resistances therefore observations are just models
  Robin Webb (Director NOAA/Physical Science Division) when I quoted Kathy Sullivan to him in the hallway