

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

Subtext 1: Can it be done?

Subtext 2: The Science of Observations

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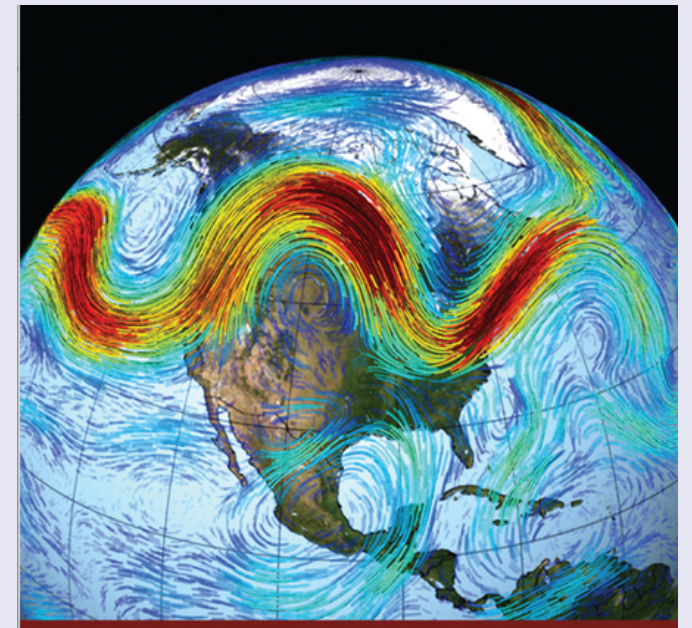
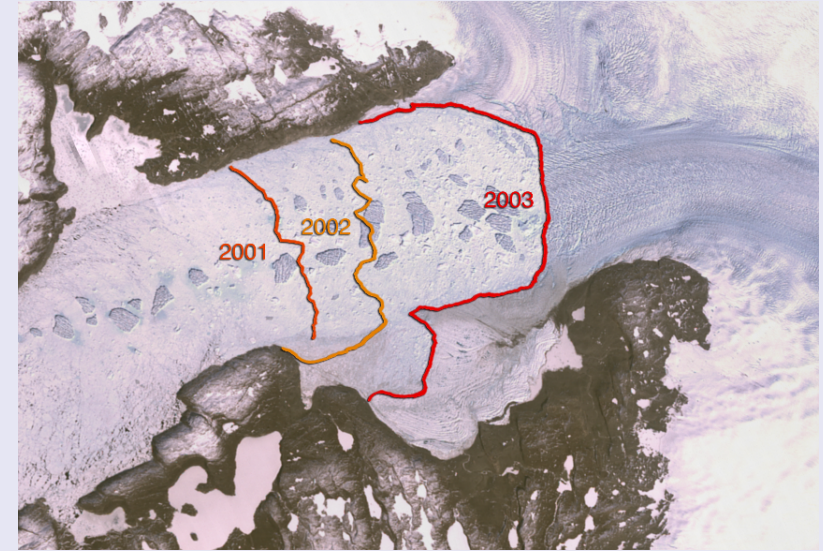
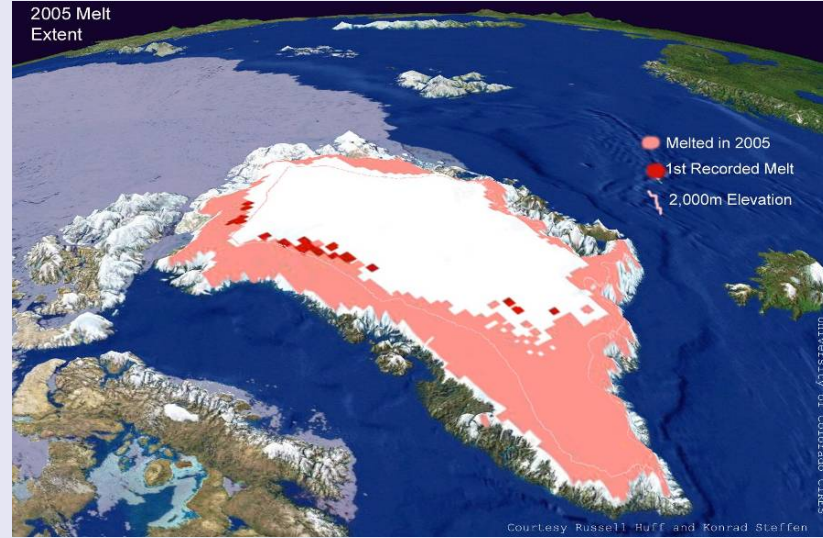
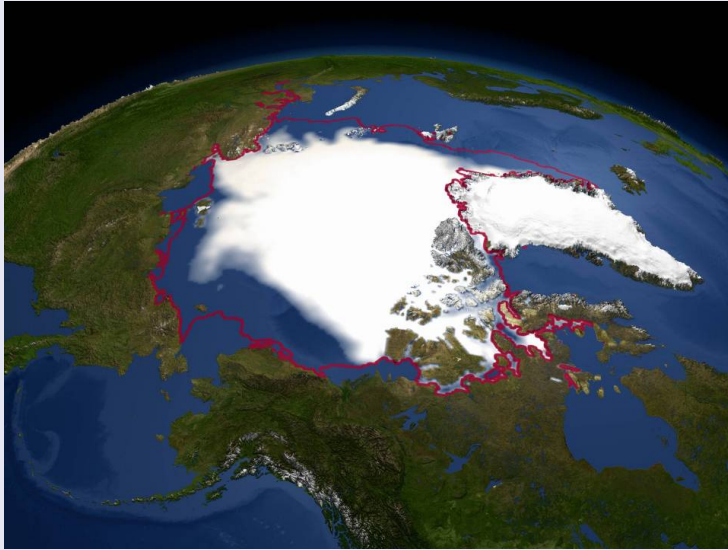
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Why the SEB is important:



Atmosphere

u, v, w, T, RH, CO_2

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

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



CO_2 Flux



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 ΔT

Vegetation

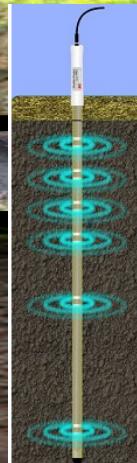
Snow

Flux Plate

Active Layer

Conductive heat Flux

Permafrost



NOAA Contacts
Project Lead: Taneli Uital
Engineer: Robert Albee
Data Manager, Logistics: Sara Crupnick

EOS/Cloudnet Contacts
Project Lead: Alexander Makshin
Engineer: Vadim Kostov
Logistics: Dmitry Apertsev
Data Manager: Tatiana Afanasyeva

Datagrams:
Tiksi fluxtower - towermet

Datagrams

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Datagrams:
Baseline Surface Radiation Network
Tiksi Downwelling Broadband Radiation

Campbell CR10X Data Loggers

Location: Clear Air TX
File name: tkYYYYMMDDH1.dat (as of 2/1/14)
File location in TDC:

Address	Case	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp
132	132B	132C	132D	132E	132F	132G	132H	132I	132J	132K	132L	132M	132N	132O	132P	132Q	132R	132S	132T

Campbell CR10X Data Loggers

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File location in TDC:

A	B	C	D	E	F	G	H	I	J	K	L	M	N
001	Year	Julian Day	Hour	Minute	Second	Temp	Temp	Temp	Temp	Temp	Temp	Temp	Temp

Calibration Values:

- Downwelling Shortwave Diffuse (Eppley B&W PSP)
8.72 $\mu\text{V/W/m}^2$ 6/1/2010 - present
- Downwelling Shortwave Diffuse (Eppley PSP)
8.76 $\mu\text{V/W/m}^2$ 6/1/2010 - present
- Downwelling Longwave Total (Eppley PIR)
329.435 $\text{W/m}^2/\text{mV}$, Dome = 3.90 6/11/2009 – present
- Downwelling Shortwave Direct (Eppley NIP)
8.01 $\mu\text{V/W/m}^2$ 6/1/2010 - present
- Downwelling Shortwave Total (K&Z CM22)
9.40 $\mu\text{V/W/m}^2$ 6/1/2010 – present
- Russian Downwelling Shortwave Direct (MF-19 (AT-50))
9.13 $\mu\text{V/W/m}^2$

Calculations:

$\text{DCF} = \text{Dome Correction Factor (for PIR instruments)}$
 $\text{Sigma} = 5.6704 * 10^{-(8)}$
 $E = \text{efficiency} = 1$
 $\text{TCR} = \text{Case Temp in mV (For Eppley PIR : data Column 9)}$
 $\text{TDR} = \text{Dome Temp in mV (For Eppley PIR : data Column 10)}$
 $\text{TC} = \text{Eppley PIR Temp [degK]}$
 $\text{TD} = \text{Eppley PIR Dome [degK]}$
 $\text{Conversion} = 1 / ((0.0010295 + 0.0002391 * \log(\text{TCR} * 1000) + 0.0000001568 * \log(\text{TCR} * 1000)^3))$
 $\text{Conversion} = 1 / ((0.0010295 + 0.0002391 * \log(\text{TDR} * 1000) + 0.0000001568 * \log(\text{TDR} * 1000)^3))$
 $V [\text{mV}] : \text{PIR} = \text{data column 7, PSP Eppley} = \text{data column 13, PSP B\&W} = \text{data Column 15, PSP K\&Z} = \text{data Column 17, NIP} = \text{data Column 11, Russian} = \text{data Column 19}$
 $\text{SF} : \text{Calibration Values (see above)}$
 $\text{PSP thermopile (W/m}^2) = 1000 * V / \text{SF}$
 $\text{PIR thermopile (W/m}^2) = \text{SF} * V + \text{SIGMA} * (E * \text{TC}^4 + \text{DCF} * (\text{TC}^4 - \text{TD}^4))$

Tiksi Data Center

BSRN Archive

FTP File locations at NOAA:

From Tiksi Data Center to: [path]

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1) K&Z Zone 2 SP Tracker
2) Radiation Shale Balls
3) Sun Sensor Tracker

Parameter	Appley NIP	K&Z CM22
Temp. AC	Temp. AC	Temp. DC
Case, Dome	no	no
3.9	via	via
no	no	no
Aspirated	Aspirated	Heated, Aspirated
Upward	Upward	Upward
Normalized	Downwelling	Downwelling
329.43	8.01 $\mu\text{V/W/m}^2$	9.40 $\mu\text{V/W/m}^2$

Legend

FTP Location

Standardized Data Format

1. Include header information
2. Include Day-Fraction time
3. Standardize file naming convention

Standardized Data Format

Definitions:

- site - site identifier (e.g., tk)
- inst - base instrument abbreviation
- Fr - facility abbreviation (e.g., wfp1), use(1), use(12)
- data - data qualifier - daily or monthly
- data processing level (level=1, level=2, products=b)

Calibration Values:
a. Upwelling Longwave Total (309.598 $\text{W/m}^2/\text{mV}$, Dome 301.03 $\text{W/m}^2/\text{mV}$)
b. Upwelling Shortwave Total (8.05 $\mu\text{V/W/m}^2$ 07026, 8.05 $\mu\text{V/W/m}^2$ 04030)

Standardized Data Format

Definitions:

- site - site identifier (e.g., tk)
- inst - base instrument abbreviation
- Fr - facility abbreviation (e.g., wfp1), use(1), use(12)
- data - data qualifier - daily or monthly
- data processing level (level=1, level=2, products=b)

Folder Name

Raw tkinst

Input tkinstinst.YY

Products tkinstinst.YY tkinstinstinst.YY tkinstinstinst.YY

Output files tkinstinstinst.YY

Example Product File:

Day/Fin	Year	JulianDay	HourMin	UVTotal[downwelling/W/m^2]	SWTotal[downwelling/W/m^2]	QualityControl
102	2014	102	0	1117.10	95.313	04804-109
102,080	2014	102	1	1172.19	67.5764	04804-109
102,081	2014	102	2	575.113	57.7943	04804-109

Home: <http://www.esrl.noaa.gov/gmd/trace/>

Data: <http://www.esrl.noaa.gov/gmd/trace/data/>

Official Data Submission to an Archive: <http://www.esrl.noaa.gov/gmd/trace/data/>

Date Cables: [Data Cables](#) [Loggers](#) [Cables](#) [NOAA server](#)

Example Product File:

Day/Fin	Year	DOY	HourMin	SWTotalDown w[m^2]	SWTotalDown w[m^2]	SWTotalDown w[m^2]	SWTotalDown w[m^2]	LWTotalDown w[m^2]	SWTotalDown w[m^2]	SWTotalDown w[m^2]	SWTotalDown w[m^2]	SWTotalDown w[m^2]
7	2014	7	0	-5.26621	0.079303	-5.37766	0.781323	196.598	-1.12462	390.277	298.896	298.896
7	2014	7	1	-6.97694	0.077294	-6.32566	0.623461	194.479	-1.18889	390.296	298.896	298.896
7	2014	7	2	-5.26982	0.077815	-6.36894	0.548913	189.247	-1.22759	392.014	298.896	298.896

Home: <http://www.esrl.noaa.gov/gmd/trace/>

Data: <http://www.esrl.noaa.gov/gmd/trace/data/>

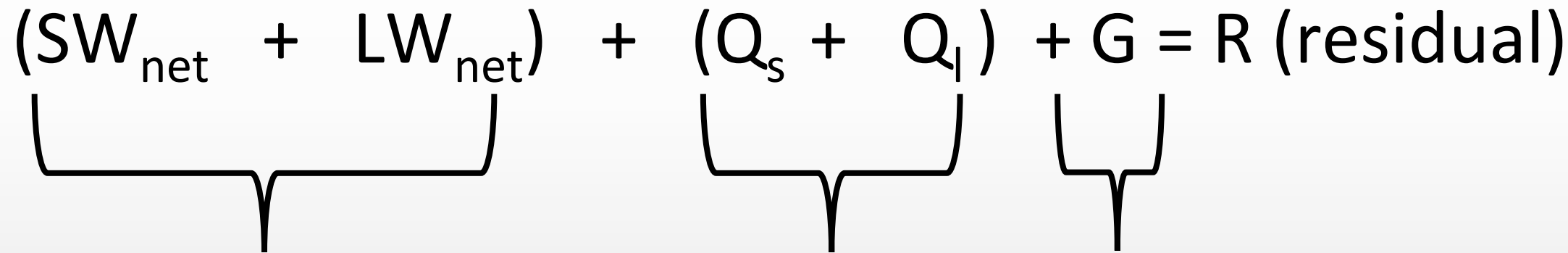
Example Product File:

Day/Fin	Year	DOY	HourMin	SWTotalDown w[m^2]	SWTotalDown w[m^2]	SWTotalDown w[m^2]	SWTotalDown w[m^2]	LWTotalDown w[m^2]	SWTotalDown w[m^2]	SWTotalDown w[m^2]	SWTotalDown w[m^2]	SWTotalDown w[m^2]
7	2014	7	0	-5.26621	0.079303	-5.37766	0.781323	196.598	-1.12462	390.277	298.896	298.896
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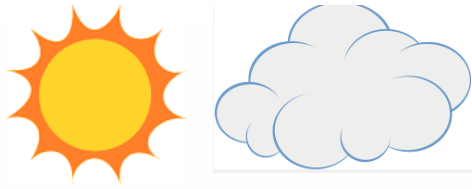
Home: <http://www.esrl.noaa.gov/gmd/trace/>

Data: <http://www.esrl.noaa.gov/gmd/trace/data/>

IASQA Portal

$$(SW_{\text{net}} + LW_{\text{net}}) + (Q_s + Q_l) + G = R \text{ (residual)}$$
The diagram shows the equation $(SW_{\text{net}} + LW_{\text{net}}) + (Q_s + Q_l) + G = R \text{ (residual)}$. Under the first group $(SW_{\text{net}} + LW_{\text{net}})$, there is a bracket pointing down to the label "Radiation Fluxes". Under the second group $(Q_s + Q_l)$, there is a bracket pointing down to the label "Turbulent Fluxes". Under the third term G , there is a bracket pointing down to the label "+ Ground Flux".

Radiation Fluxes + Turbulent Fluxes + Ground Flux



Measuring the Arctic Atmosphere-Surface Energy Balance



SW = Short Wave
 LW = Long Wave
 Q = Turbulent Fluxes
 Subscripts:

s = sensible heat
 l = latent heat
 μ = microscale
 M = mesoscale

G = Soil
 S = Storage Terms

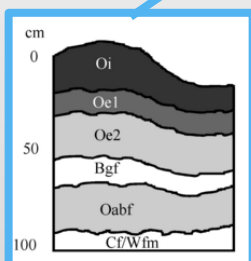
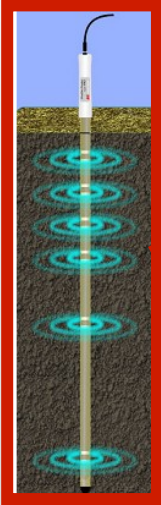
Subscripts:
 RFD = Radiative
 Flux Divergence

G = Soil
 P = Photosynthesis
 C = Canopy temp
 S = Snow

↑ = cooling
 ↓ = warming

— Measured
 - - - Working on it
 — Need additional obs

$$\begin{aligned}
 & \text{SW} \downarrow + \text{LW} \downarrow + \langle \text{Q}_s \uparrow \downarrow + \text{Q}_l \uparrow \downarrow \rangle_{\mu} + \text{S}_{\text{RFD}} \uparrow \downarrow + \langle \text{Q}_s \uparrow \downarrow + \text{Q}_l \uparrow \downarrow \rangle_{\text{M}} + \\
 & \text{G} \uparrow \downarrow + \text{S}_{\text{G}} \uparrow \downarrow + \text{SW} \uparrow \downarrow + \text{LW} \uparrow + \text{S}_{\text{P}} \uparrow \downarrow + \text{S}_{\text{C}} \uparrow \downarrow + \text{S}_{\text{S}} \uparrow \downarrow = 0
 \end{aligned}$$



$$Q_G = G \uparrow \downarrow + S_G \uparrow \downarrow$$

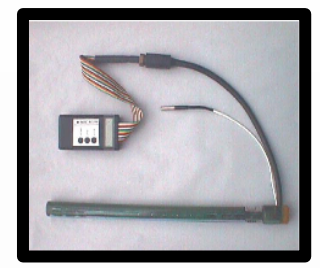
Ground Flux



1. Flux Plate instruments

$$Q \downarrow G = -\lambda \downarrow s \Delta T / \Delta z - C \downarrow s \Delta T / \Delta t$$

Ground Flux Conductive Flux Storage Term



2. Thermistor instruments

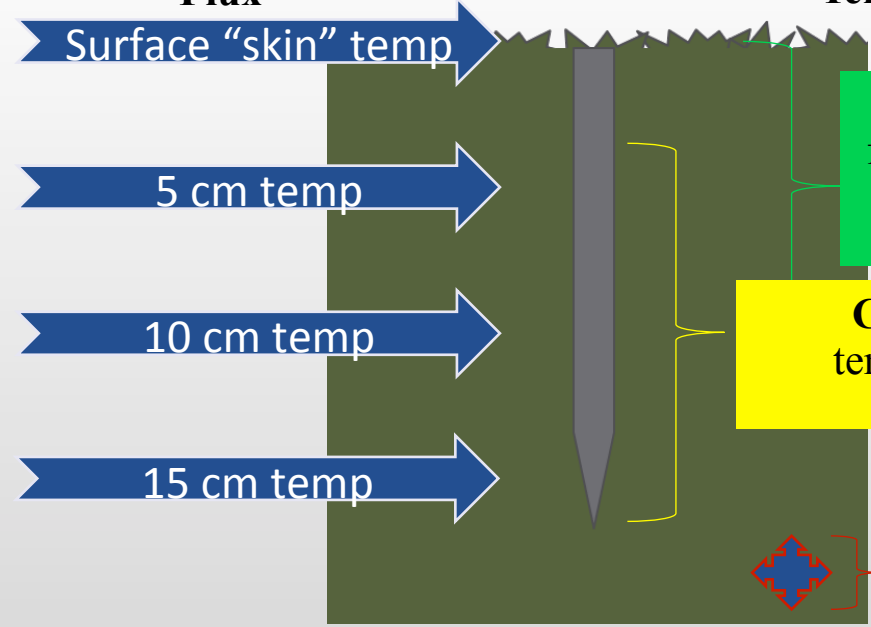
$$Q \downarrow G = G \uparrow \downarrow - C \downarrow s (T \downarrow 05 \uparrow n+1 - T \downarrow 05 \uparrow n-1 + T \downarrow sfc \uparrow n+1 - T \downarrow sfc \uparrow n-1) / 2(t \downarrow n+1 - t \downarrow n-1) (z \downarrow 05 - z \downarrow sfc)$$

Direct Flux Storage Term

$$Q \downarrow G = -\lambda \downarrow s (T \downarrow 05 \uparrow n - T \downarrow 15 \uparrow n / z \downarrow 05 - z \downarrow 15) - C \downarrow s (T \downarrow 10 \uparrow n+1 - T \downarrow 10 \uparrow n-1 + T \downarrow 05 \uparrow n+1 - T \downarrow 05 \uparrow n-1 + T \downarrow sfc \uparrow n+1 - T \downarrow sfc \uparrow n-1) / 3(t \downarrow n+1 - t \downarrow n-1) (z \downarrow 10 - z \downarrow sfc)$$

Direct Flux Storage Term

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



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

Conductive Flux: temperature gradient measurements

Soil Constants: soil thermal conductivity, soil heat capacity

$$Q_s \uparrow \downarrow + Q_l \uparrow \downarrow (\mu) (M)$$

Turbulent Fluxes

Calculations with eddy covariance methods

$$\tau = -\rho \langle w'u' \rangle$$

$$H_S = \rho C_P \langle w'\theta' \rangle$$

$$H_L = \rho L \langle w'q' \rangle$$

- 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

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

$$H_S = -\rho C_P K_H (\partial \bar{\theta} / \partial z)$$

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

where according to Monin - Obukhov Similarity Theory

$$K_M = k u_* (z - d) / \phi_m(\xi)$$

$$K_H = k u_* (z - d) / \phi_h(\xi)$$

$$K_W = k u_* (z - d) / \phi_w(\xi)$$

- 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

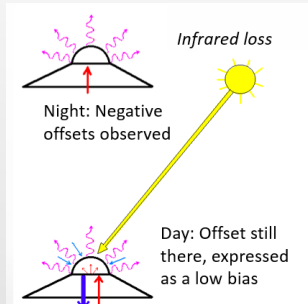
$$SW \downarrow + LW \downarrow + SW \uparrow \downarrow + LW \uparrow$$

Radiation Fluxes

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

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.



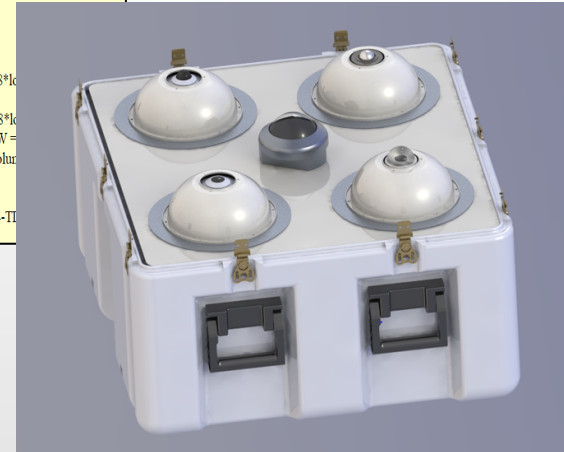
CALIBRATION

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ICING



Issues: quality control, calibration and icing

Uwelling

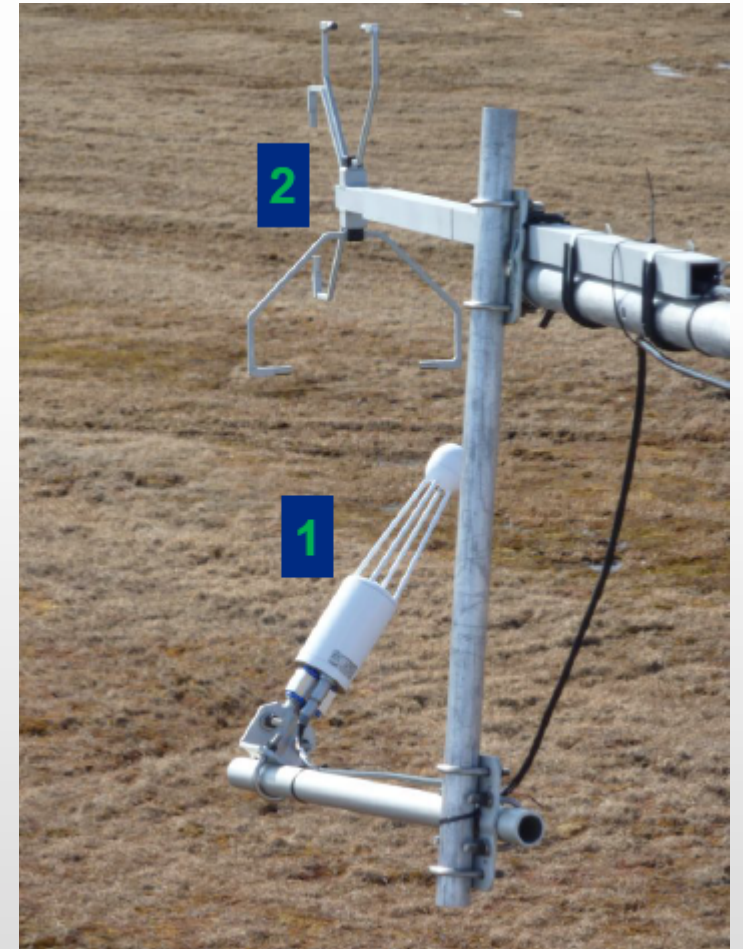
$$S_p \uparrow \downarrow + S_c \uparrow \downarrow$$

Vegetation Fluxes and Storage

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 $10 \text{ } [\mu\text{mol}/\text{m}^2 \text{ s}]$ equates to energy flux of $4.79 \sim 5 \text{ } [\text{W}/\text{m}^2]$. 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



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

Issue: need better integration with snow physicists



Tiksi Station Map

Locations of flux facilities

Tower Flux

Dry Soil Flux

Mid Soil Flux

Wet Soil Flux

Issue: Horizontal inhomogeneity
local and regional



Specialist: Ground Flux and Storage

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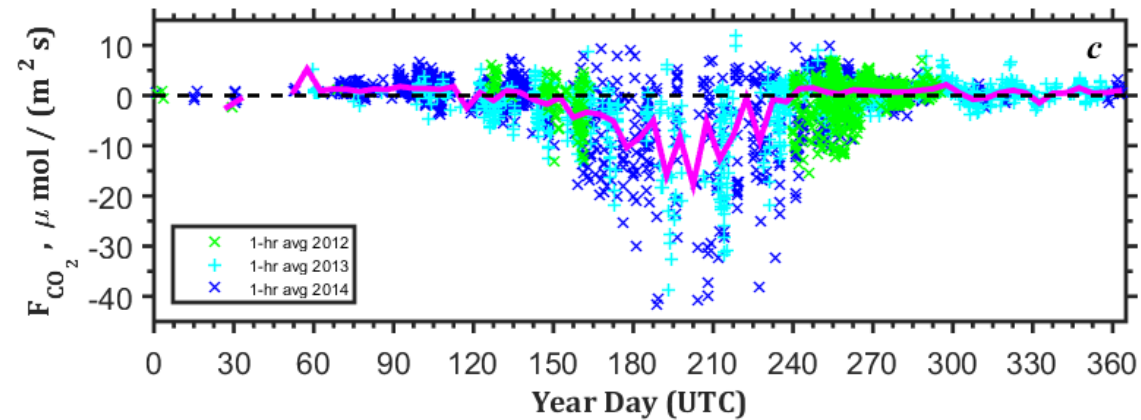
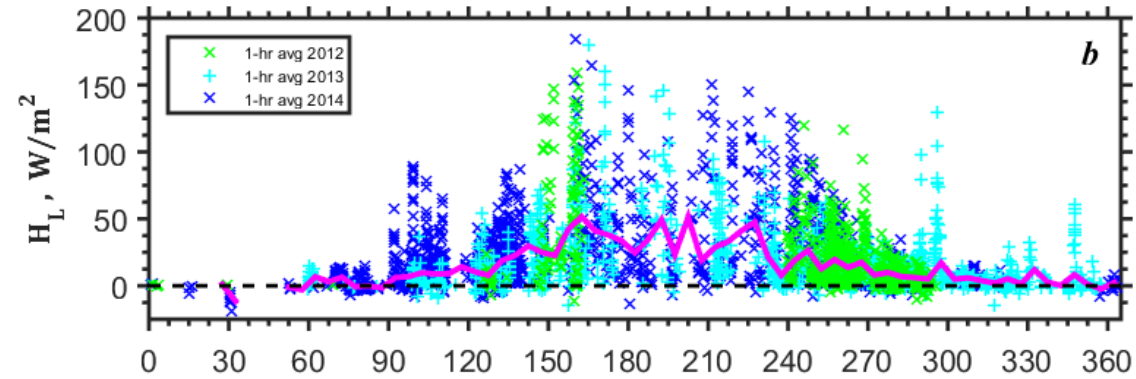
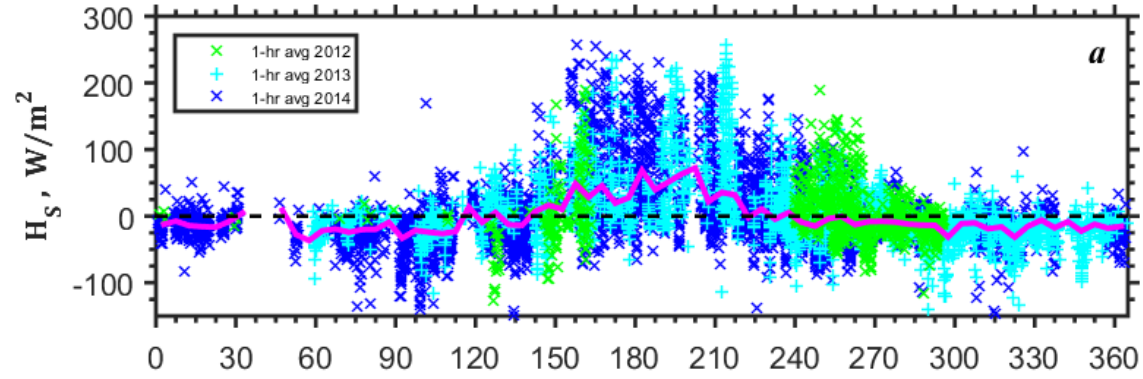
Site Description	Thermal Conductivity []	Thermal Conductivity Conversion	Heat Capacity [C]	Heat Capacity Conversion	Author/Paper
West Dock	0.60 Wm-1K-1	0.60 Wm-1K-1	2.70 MJm-3K-1	2.70 MJm-3K-1	Romanovsky & Osterkamp, 1997
Deadhorse	0.77 Wm-1K-1	0.77 Wm-1K-1	2.36 MJm-3K-1	2.36 MJm-3K-1	Romanovsky & Osterkamp, 1997
Franklin Bluffs	0.82 Wm-1K-1	0.82 Wm-1K-1	2.30 MJm-3K-1	2.30 MJm-3K-1	Romanovsky & Osterkamp, 1997
Quartz	0.021 cal cm-1 sec-1 celsius-1	8.792276 Wm-1K-1			Sellers, 1965
Clay minerals	0.007 cal cm-1 sec-1 celsius-1	2.930759 Wm-1K-1			Sellers, 1965
Organic matter	0.0006 cal cm-1 sec-1 celsius-1	0.2512079 Wm-1K-1			Sellers, 1965
Water	0.00137 cal cm-1 sec-1 celsius-1	0.5735914 Wm-1K-1			Sellers, 1965
Ice	0.0052 cal cm-1 sec-1 celsius-1	2.177135 Wm-1K-1			Sellers, 1965
Air	0.00006 cal cm-1 sec-1 celsius-1	0.02512079 Wm-1K-1			Sellers, 1965
Quartz	8.4 Wm-1K-1	8.4 Wm-1K-1	1942 Jm-3K-1	1.942 MJm-3K-1	Peters-Lidard et al., 1997
Soil minerals	2.9 Wm-1K-1	2.9 Wm-1K-1	1942 Jm-3K-1	1.942 MJm-3K-1	Peters-Lidard et al., 1997
Soil organics	0.25 Wm-1K-1	0.25 Wm-1K-1	2503 Jm-3K-1	2.503 MJm-3K-1	Peters-Lidard et al., 1997
Water	0.6 Wm-1K-1	0.6 Wm-1K-1	4186 Jm-3K-1	4.186 MJm-3K-1	Peters-Lidard et al., 1997
Ice	2.5 Wm-1K-1	2.5 Wm-1K-1	1883 Jm-3K-1	1.883 MJm-3K-1	Peters-Lidard et al., 1997
Air	0.026 Wm-1K-1	0.026 Wm-1K-1	1.20 Jm-3K-1	0.0012 MJm-3K-1	Peters-Lidard et al., 1997
Mineral-organic mixture	[0.7, 1.8] Wm-1K-1	[0.7, 1.8] Wm-1K-1			Permafrost Laboratory
Mineral-soil(silt)	[1.3, 2.4] Wm-1K-1	[1.3, 2.4] Wm-1K-1			Permafrost Laboratory
Mineral-Soil(gravel)	[2.5, 3.5] Wm-1K-1	[2.5, 3.5] Wm-1K-1			Permafrost Laboratory
Mineral-Soil(Shale)	[1.0, 2.0] Wm-1K-1	[1.0, 2.0] Wm-1K-1			Permafrost Laboratory
Quartz	8.4 Wm-1K-1	8.4 Wm-1K-1			Farouki, 1981
Soil minerals	2.9 Wm-1K-1	2.9 Wm-1K-1			Farouki, 1981
Soil organics matter	0.25 Wm-1K-1	0.25 Wm-1K-1			Farouki, 1981
Water	0.6 Wm-1K-1	0.6 Wm-1K-1			Farouki, 1981
Air	0.026 Wm-1K-1	0.026 Wm-1K-1			Farouki, 1981
Ice (temp -20 degC)	0.00581 cal cm-1 sec -1 celsius-1	2.43253 Wm-1K-1			Farouki, 1981
Ice (temp -20 degC)	0.00545 cal cm-1 sec -1 celsius-1	2.281805 Wm-1K-1			Farouki, 1981
Ice (temp 0 degC)	0.00535 cal cm-1 sec -1 celsius-1	2.239937 Wm-1K-1			Farouki, 1981
Assumed Tundra soils-organic frozen	100 cal m-1 hr-1 celsius-1	6.978011 Wm-1K-1			Farouki, 1981
Assumed Tundra soils-organic unfrozen	250 cal m-1 hr-1 celsius-1	17.44501 Wm-1K-1			Farouki, 1981
Assumed Tundra soils-mineral frozen	900 cal m-1 hr-1 celsius-1	62.80197 Wm-1K-1			Farouki, 1981
Assumed Tundra soils-mineral unfrozen	770 cal m-1 hr-1 celsius-1	53.73056 Wm-1K-1			Farouki, 1981
Units		Wm-1K-1		MJm-3K-1	
Thawed		0.25		2.503	Peters-Lidard et al., 1997
Frozen		1.375		2.193	Peters-Lidard et al., 1997
To get frozen value I took the average of soil organics and ice					

Specialist: TurbulenceTerms

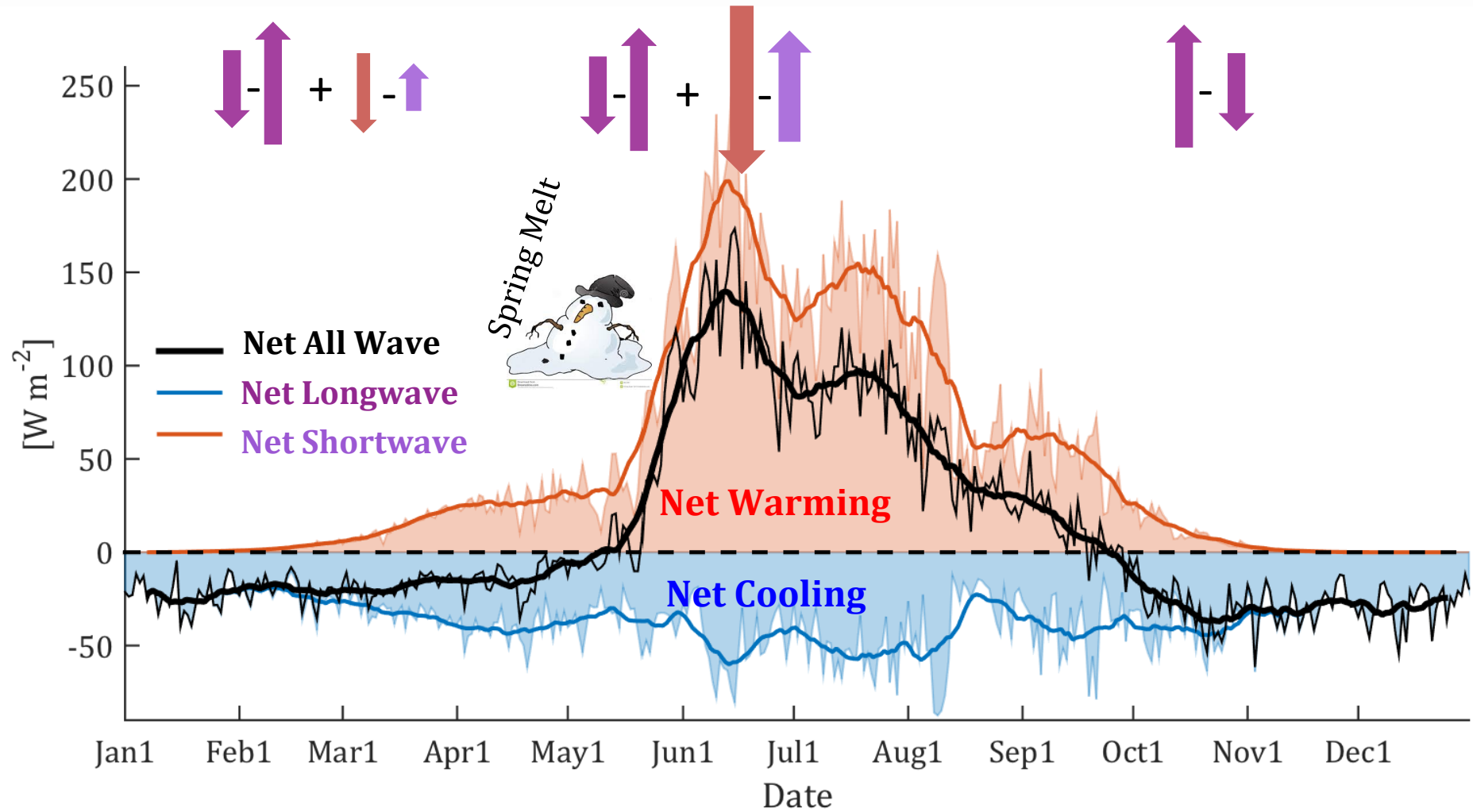
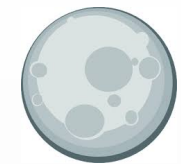
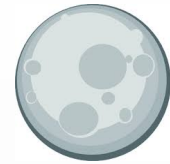
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Net Radiation Budget, Tiksi 2012-2014



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