Using the surface energy balance to understand the Antarctic stable boundary layer.

Michael S. Town\textsuperscript{1}, Von P. Walden\textsuperscript{2}, and Stephen G. Warren\textsuperscript{1}

\textsuperscript{1}University of Washington, Seattle, WA USA
\textsuperscript{2}University of Idaho, Moscow, ID USA

Session 5. Science using ground-based and satellite measurements
AMOMWF 2007, Rome, Italy.
South Pole 1994-2003, Temp ± 1°C (daily)

2m air temperature

Temperature (°C)

Jan  Feb  Mar  Apr  May  Jun  Jul  Aug  Sep  Oct  Nov  Dec  Jan

-80  -70  -60  -50  -40  -30  -20
energy transfer over South Pole

\[ G = R_N + H_S + H_L \]

- **net radiation**
- **latent heat**
- **subsurface heat**
- **sensible heat**

positive fluxes are directed downward

**Equation:**

\[ G = S_\downarrow + S_\uparrow + L_\downarrow + L_\uparrow + H_S + H_L \]

- **pyranometer**
- **pyrgeometer**

Patankar (1982)

\[ u_{10}, T_S, T_2, T_2f \]

Andreas (2002)

\[ \text{pyrgeometer} \rightarrow T_{sfc} \]

finite-volumes

numerical heat transfer model

Patankar (1982)
monthly means: prior work energy transfer over South Pole

Large discrepancies in literature
monthly means:
energy balance?

energy transfer over South Pole

\[ G = R_N + H_S + H_L \]
monthly means: energy balance? *no.*

energy transfer over South Pole

\[ G = R_N + H_S + H_L \]

\[ G - R_N = H_S + H_L \]
monthly means: energy balance? no.

energy transfer over South Pole

\[ G = R_N + H_S + H_L \]

\[ G - R_N = H_S + H_L \]

\( H_S \) magnitude is underestimated by MO theory over South Pole, probably.
monthly means: energy balance? no.

energy transfer over South Pole

\[ G = R_N + H_S + H_L \]

\[ G - R_N = H_S + H_L \]

\( H_S \) is sensitive to skin-surface temperature derivation (from LUF).
stable boundary layer: solution?

\[ G = R_N + H_S + H_L \]

\[ G - R_N = H_S + H_L \]
stable boundary layer: energy transfer over South Pole

\[ G = R_N + H_S + H_L \]

\[ G - R_N = H_S + H_L \]

```
cooling snow
heating snow
```

```
lapse
inversion
```

```
T_2 - T_{sfc} (K)
```

```
horizontal axis: wind speed (m s^{-1})
```

```
vertical axis: H_S + H_L (W m^{-2})
```

```
from thermistors during 2001 (not LUF)
```
energy transfer over South Pole

\[ G = R_N + H_S + H_L \]

\[ G - R_N = H_S + H_L \]

stable boundary layer: solution? *maybe.*

find empirical relationship between \( G-R_N, T_{inv}, ws, \ldots \)
short time scales: subsurface temperatures  
heat transfer in snow pack

A. January (°C)
short time scales: subsurface temperatures

high variability in subsurface temperatures during winter
short time scales: subsurface heating rates

January Monthly MEAN $G = 1 \text{ W m}^{-2}$

large $G$ on short time scales

large heating rates on short time scales

A. January (K day$^{-1}$)
short time scales: subsurface heating rates

heat transfer in snow pack

larger heat fluxes during winter
short time scales:
subsurface vapor pressures
heat transfer in snow pack

subsurface vapor pressures higher during summer

A. January (Pa)
B. March (Pa)
C. July (Pa)
D. November (Pa)
conclusions:

No energy balance. $H_S$ is probably larger in the monthly mean (by 10 W m$^{-2}$) than predicted by MO theory.

May be possible to develop empirical relationship for $H_S + H_L$.

No significant frost deposition at the South Pole.

Snow surface temperatures at the South Pole result in interface heat fluxes of up to 20 W m$^{-2}$ on daily time scales.

Episodic sustained heating rates of greater than 10 K day$^{-1}$ occur in the near-surface snow at South Pole.

Snow temperature gradients and heat fluxes important for depth hoar formation and $\delta^{18}O$ (or $\delta D$) fractionation.
acknowledgements:

*Ed Waddington* of UW for help with the finite-volume model.

*Ells Dutton* and *Tom Mefford* of NOAA-GMD, and the BSRN for data and advice.

*Shelley Knuth* and *Matt Lazzara* at the AMRC for data.

*Kathie Hill* at Raytheon Polar Services for data.

NSF Office of Polar Programs for general support and travel funds.
conclusions:

No energy balance. $H_S$ is probably larger in the monthly mean (by 10 W m$^{-2}$) than predicted by MO theory.

No significant frost deposition at the South Pole.

Snow surface temperatures at the South Pole result in interface heat fluxes of up to 20 W m$^{-2}$ on daily time scales.

Episodic sustained heating rates of up to 3 K day$^{-1}$ occur in the near-surface snow at South Pole.

Heat plumes puncture deeper into the snow during winter than summer.

Snow temperature gradients and heat fluxes important for depth hoar formation and $^{18}$O$_2$ fractionation.
monthly means:
prior work on $R_N$ (net radiation)
monthly means:
\( R_N \) (net radiation)

energy transfer over South Pole
\[
G = R_N + H_S + H_L
\]
Monthly means:
\( R_N \) (net radiation)

\[ G = R_N + H_S + H_L \]

More interannual variability during Summer likely due to effect of clouds on solar radiation.
monthly means:
$G$ (subsurface heat flux)

energy transfer over South Pole

$G = R_N + H_S + H_L$
monthly means: $G$ (subsurface heat flux)

energy transfer over South Pole

\[ G = R_N + H_S + H_L \]
monthly means: prior work on $H_S$ (sensible heat flux)

$G = R_N + H_S + H_L$  

energy transfer over South Pole
monthly means:
$H_S$ (sensible heat flux)

energy transfer over South Pole

$G = R_N + H_S + H_L$
monthly means: $H_s$ (sensible heat flux)

energy transfer over South Pole

$$G = R_N + H_s + H_L$$

monthly mean $H_s$ from MO theory is almost always directed toward surface
monthly means:
$H_L$ (latent heat flux)

energy transfer over South Pole

\[ G = R_N + H_S + H_L \]
heat transfer model:

finite volumes (Patankar 1982)
variable levels
no accumulation (no advection)
no sources (solar, wind pumping, ...)

boundary conditions:
  top: variable surface T (1-3 min)
  bottom: seasonal T gradient

heat transfer in snow pack

T (°C)

1 cm
2 cm
5 cm
10 cm
6.5 m
50 cm
G Model properties:
Dalrymple et al. (1966)
G Model validation: Carslaw and Jaeger (1959)

Surface set at $-30^\circ C$

Snow pack set at $-40^\circ C$

Bottom set to seasonal heat flux at South Pole
G Model validation:
Carslaw and Jaeger (1959)
Effect of clouds on $R_N$: 

![Graph showing the effect of clouds on $R_N$. The graph includes data for different periods (1958, 1975-1977, 1994-1999) and locations (LNF 1994-2003). The x-axis represents the months from January to January, and the y-axis represents the net radiation in units of $\text{W m}^{-2}$. Markers with error bars indicate the variability in the data.]