Radiation in the Surface Flux Budget of the NBL: A Question of Timescale

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J. M. Edwards, 10th June 2014

Summary

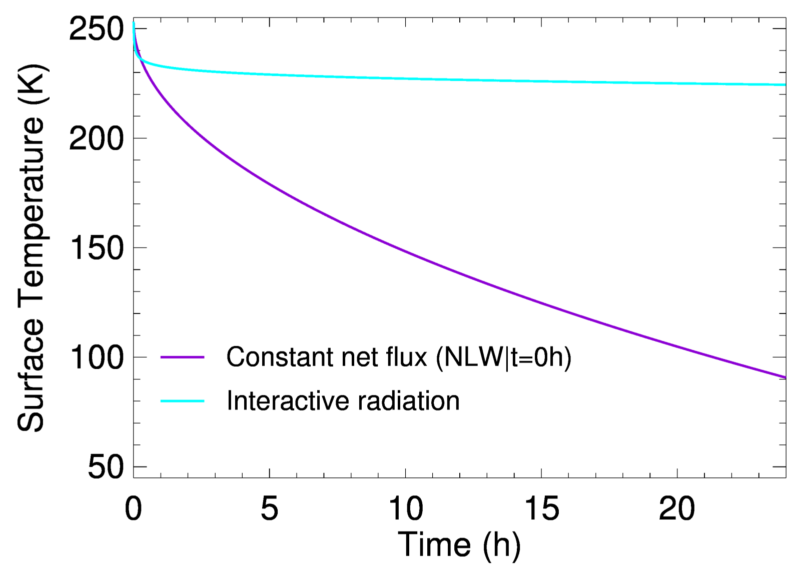
- Background and motivation
- What determines the **net** LW radiative flux at the surface?
- Idealized model of surface cooling
- Further thoughts

Background and Motivation

- D. Brunt (1932) “Notes on Radiation in the atmosphere. I.”, QJRMS, vol. 58, p. 389
  - $LW\downarrow = \sigma T^4(a + b\sqrt{e}) \rightarrow R_N = \sigma T^4(1 - a - b\sqrt{e})$
  - “*The vapour pressure has only a slight diurnal variation, and since the fall of temperature during the night is only a relatively small fraction of T, we may assume as a first approximation that R_N is constant*.” (p. 406)
- If R_N is constant and H=0:

$$\Delta T_s = -\frac{2}{\sqrt{\pi}} \frac{R_N}{\sqrt{k_s \rho_s c_s}} \sqrt{t}$$

- Over snow this equation predicts an unrealistically large fall in temperature, so in reality
  - either H is significant, or (nonexclusively)
  - R_N does decrease
- Interactive radiation model shows fall in R_N alone can arrest cooling



- GABLS3 SCM intercomparison (Bosveld et al. 2014, BLM)
  - Impact of SBL profile on LW↓
  - Extension of Brunt's formula

$$L_{ref}^{\downarrow} = (a + b\sqrt{e_{200}})\sigma T_2^4 + (c + d\sqrt{e_{200}})\sigma(T_{200}^4 - T_2^4) + f$$

  - For these conditions:
    - Brunt: $\Delta R_N \approx 0.20\ \Delta(\sigma T^4)$
    - Bosveld et al.: $\Delta R_N \approx 0.26\ \Delta(\sigma T^4)$

- A. K. Betts (2006) “Radiative scaling of the nocturnal boundary layer and the diurnal temperature range”, JGR, vol. 111, D07105:
  - “*Surprisingly, comparatively little attention has been paid to the corresponding role of radiative forcing in determining the strength and depth of the NBL…*”
- Betts’ Radiative temperature scale (2004, 2006)
  - $\Delta T_R = -\lambda_0 LW_{n24}$; $\lambda_0 = 1/(4\sigma T^3)$
  - Betts (2006) uses this to scale diurnal temperature range

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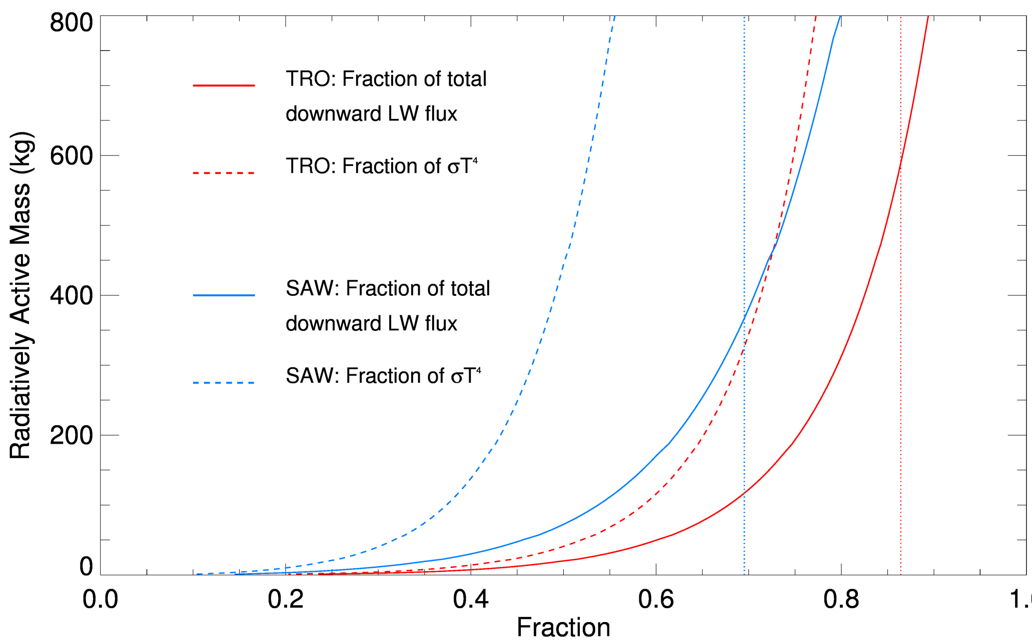
The net LW Flux at the surface

Downward LW Radiation

- Atmospheric absorbing and emitting gases:
  - Mainly water vapour (lines and continuum)
  - Carbon dioxide
  - Ozone
  - Other trace gases: methane, nitrous oxide, CFCs
- IR range of interest is ~4 – 1000 μm
  - 8 – 12 μm is relatively transparent: “Atmospheric Window”

Where does LW radiation come from?

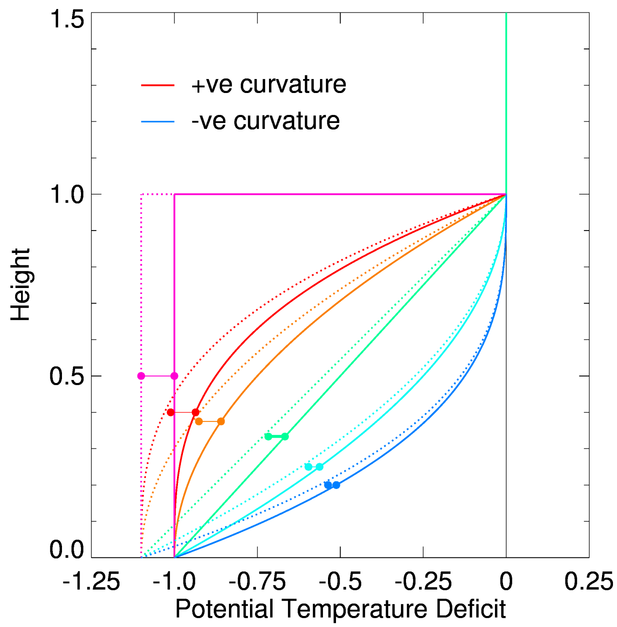
- Bosveld et al. (2014) calculate that 50% of LW↓ comes from lowest 100m of atmosphere in GABLS3 case
  - See also Ohmura 2001
- Fraction depends on atmosphere

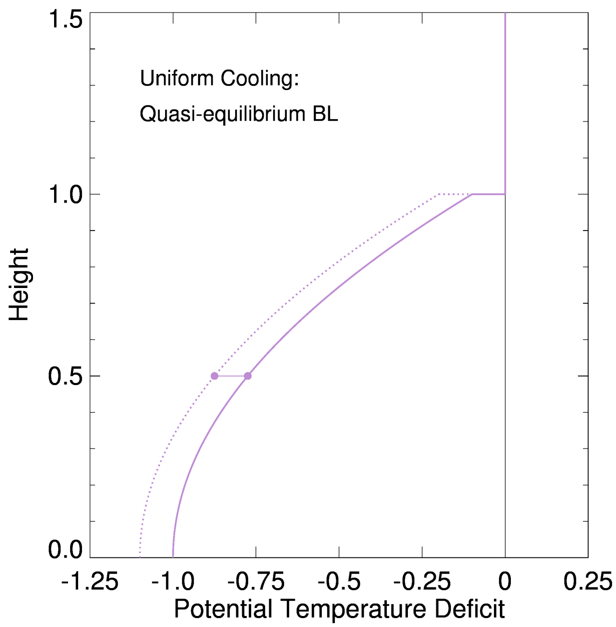


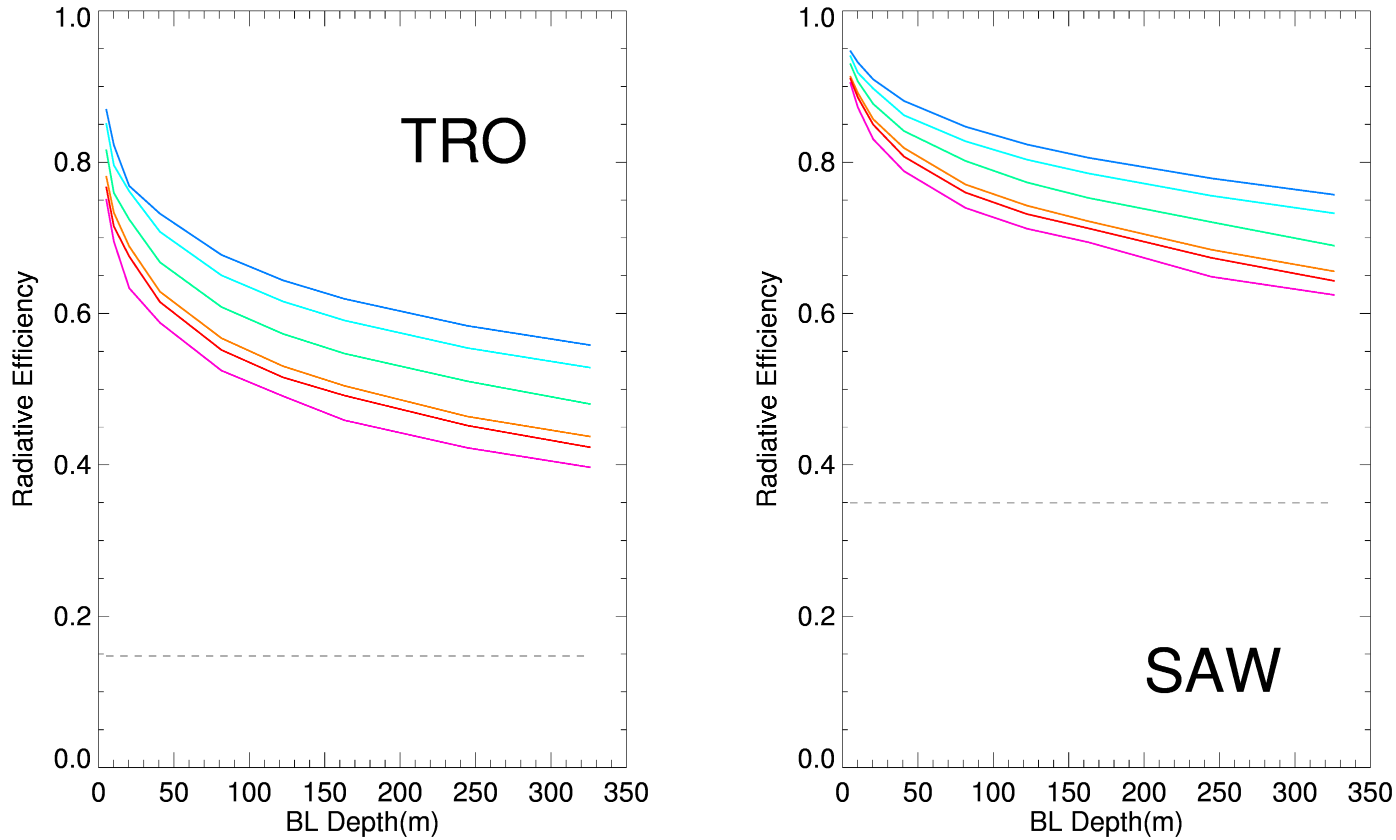
Radiative Efficiency

- Assume that BL cools in in a self-similar way
  - $\Delta\theta(z) = \Delta T(z) = \Delta T_s \text{ fnc}(z)$
- Linearizing net flux,
  - $R_N(t) = R_N(0) + (dR_N/d(\sigma T_s^4))\ \Delta(\sigma T_s^4)$
- Define “radiative efficiency”
  - $\eta = dR_N/d(\sigma T_s^4)$
- Using Brunt’s formula, $\eta = R_N/\sigma T_s^4$, but not in general

- Now calculate η for different idealized shapes for and depths of the BL







TRO
SAW
Radiative Efficiency
BL Depth(m)
0.0
0.2
0.4
0.6
0.8
1.0
0
50
100
150
200
250
300
350

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An idealized model of surface cooling

Idealized Model of Surface Cooling

- Ground initially at vertically uniform temperature T_0; net radiative flux R_{N0}
- Linearize net radiative flux:
  - $R_N = R_{N0} + \eta\ \Lambda \Delta T_s$; $\Lambda = 4\sigma T_s^3$
  - Defines temperature scale $R_{N0} / (\eta\Lambda)$ (cf. Betts 2004,2006)
- Surface boundary condition is
  - $k_s\ dT/dz = R_N = R_{N0} + \eta\Lambda\ \Delta T_s$; z in soil
  - Implies length-scale $k_s / (\eta\Lambda)$

- Diffusion in ground, $\partial T/\partial t = \kappa_s \, \partial^2 T/\partial z^2$, implies timescale $(k_s / (\eta\Lambda))^2 / \kappa_s$
- Non-dimensionalize ΔT, z and t with these scales:
  - $\partial \Delta T/\partial t = \partial^2 \Delta T/\partial z^2$
  - $\partial \Delta T/\partial z = 1 + \Delta T$; $z=0$
  - $\Delta T = 0$; $t=0$
- Solve by taking Laplace transform

- Solution

$$\Delta T = -1 + \frac{2}{\pi}\int_0^\infty \frac{e^{-tu^2}}{1+u^2}du = -1 + e^t(1-\mathrm{erf}(\sqrt{t}))$$

- Simple approximation (~10% error in ΔT):

$$e^{-tu^2} \approx 1/(1+tu^2)$$

- Giving

$$\Delta T \approx -\sqrt{t}/(1+\sqrt{t})$$

- In dimensional units

$$\Delta T \approx \frac{-N_0}{\sqrt{\kappa\rho c}}\sqrt{t}\left[1+\sqrt{t/t_D}\right]^{-1}$$

- Radiation plays a significant role in arresting fall in T_s if lifetime of SBL is long compared to t_D, ie.

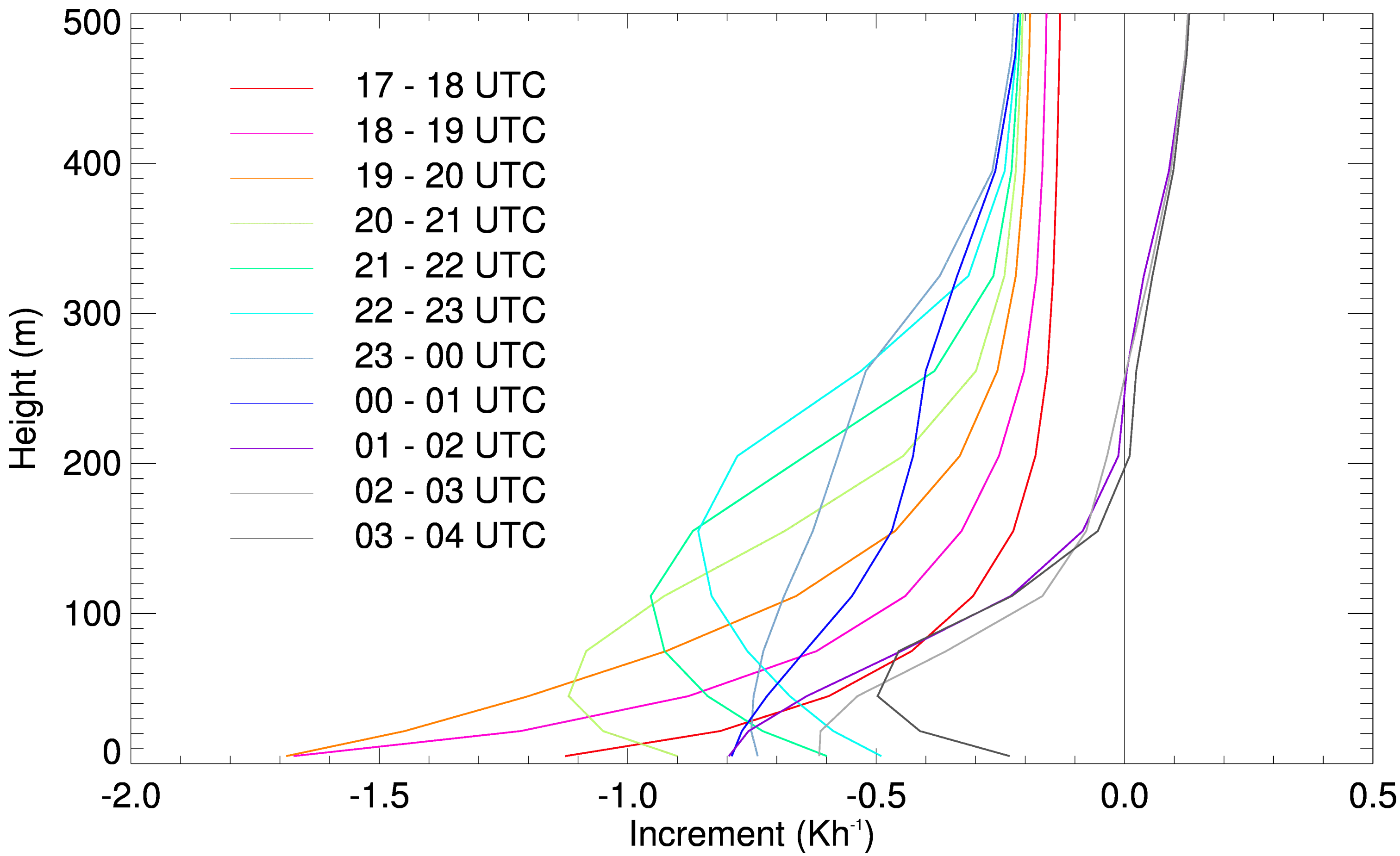
$$t_{SBL} > t_D = \frac{\rho_s c_s k_s}{\eta^2 \Lambda^2}$$

- Some typical values of t_D
  - Deep humid tropical NBL: $t_D \approx$ 10 days
  - Subtropical desert NBL: $t_D \approx$ 7 hours
  - Polar SBL over fresh snow: $t_D \approx$ 1 hour

Further thoughts

- This is an idealized model
  - More illustrative than predictive
- Caveats:
  - Cooling of the residual layer is not included, or assumed to be compensated by subsidence
  - η is at root a measure of the ratio of the BL depth to the photon mean free path -- but appropriately weighted in frequency!
  - Actual SBLs are not exactly self-similar, so the efficiency is not rigorously defined

Hourly temperature increments in GABLS3



Questions and answers