Response and Sensitivity of the Nocturnal Boundary Layer Over Land to Added Longwave Radiative Forcing

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One of the most significant signals in the thermometer-observed temperature record since 1900 is the decrease in the diurnal temperature range over land, largely due to rising of the minimum temperatures [Karl et al., 1993, Vose et al., 2005]. Generally, climate models have not well replicated this change in the diurnal temperature range. In a sampling of six climate models that had minimum and maximum temperatures in the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset [Meehl et al., 2007] it was found that the difference in trend between T_{max} and T_{min} was only 20% of the trend difference in the GHCN data set (see figure 1). This is almost identical to what Zhou *et al.* [2010] found in a slightly different sample of the same models.

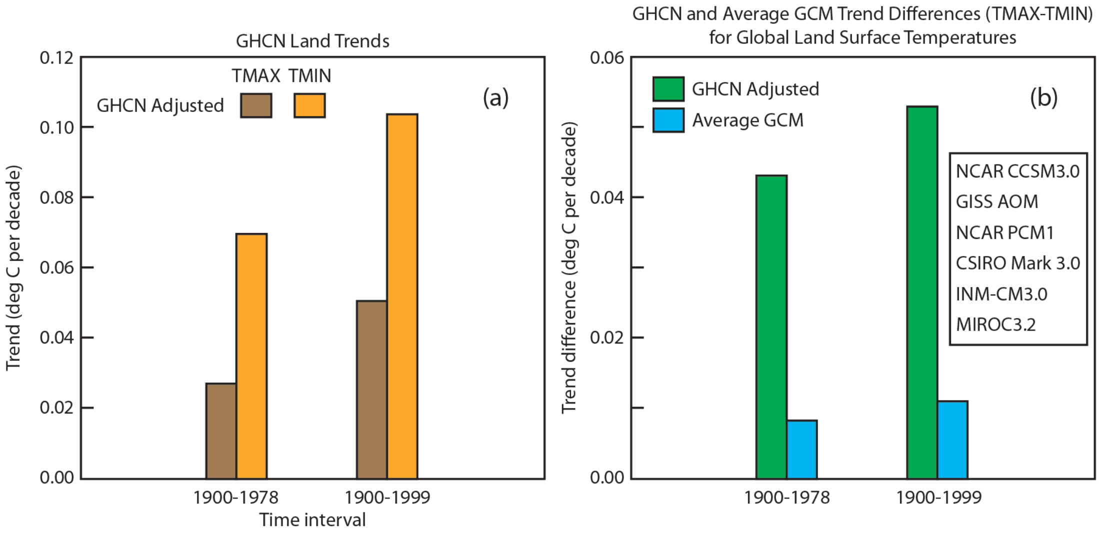

Figure 1: (a) Observed land surface trends from NOAA's Global Historical Climate Network (GHCN) (see Vose et al. 2005). (b) Trends in minimum and maximum temperatures from an average of six global models from the Climate Model Inter-comparison Project 3 (CMIP3) compared to the GHCN data set.

Since climate models with greenhouse gas forcing have understated the trend in the diurnal temperature range, investigators have attributed the change to a variety of causes not well represented in climate models such as increased cloud cover, jet contrails, or changes in surface characteristics such as land cover and land use [Dai et al., 1999; Durre and Wallace, 2001; Travis et al., 2004; and Christy et al., 2006]. We take an alternative approach to examine the role that the internal dynamics of the stable nocturnal boundary layer (SNBL) may play in impacting the response and sensitivity of minimum temperatures to added downward longwave forcing. It appears that the nightly temperature at shelter height is a result of competition between thermal stability and mechanical shear. As indicated by previous nonlinear analyses of a truncated two-layer equation system, the winner of the stability and shear contest can be very sensitive to changes in greenhouse gas forcing, surface roughness, heat capacity, and wind speed. A new single-column model growing out of these nonlinear studies of the stable boundary layer is used to examine the SNBL. Using the single-column model a detailed analysis was carried out on the behaviour of the SNBL when subjected to an added increment of longwave forcing. It extended the simple two-layer bifurcation analysis of Walters et al. [2007] to a relatively complete multi-level single column model with a state-of the-science radiative scheme. This new column model was based on a new non-iterative boundary layer scheme which allows easy testing for different stability functions.

The results from the column model show that the shelter level temperature in the SNBL can be quite sensitive to added radiation [see also Steeneveld et al. 2011]. Figure 2 shows the change in approximate shelter temperature (1.5 m) as a function of wind speed due to the added radiative increment of 4.8 Wm^{-2}. Based on the simple bifurcation analysis, Walters et al. [2007] speculated that in certain parameter spaces the SNBL might be destabilized by the added radiative increment producing a redistribution of heat. This redistribution of heat would then increase the surface temperature well beyond what the direct added energy would provide. This positive feedback conjecture was supported in the full column model. Figure 3 shows the warming as a function of height in the column model due to the added increment of downward radiation (4.8 Wm^{-2}). As can be seen most of the warming in the lower boundary layer (positive area) is due to a redistribution of heat from aloft (negative area). Figure 4 shows the actual destabilization of the temperature profile in the column model. Budget analyses (see figure 5) show that only a small fraction of the radiative energy added was actually used to heat the atmosphere since most of the added energy is radiated off the surface or goes to heat the deep soil. Thus, the large change in temperature is largely due to the destabilization of the boundary layer and redistribution of heat by the increased level of turbulence.

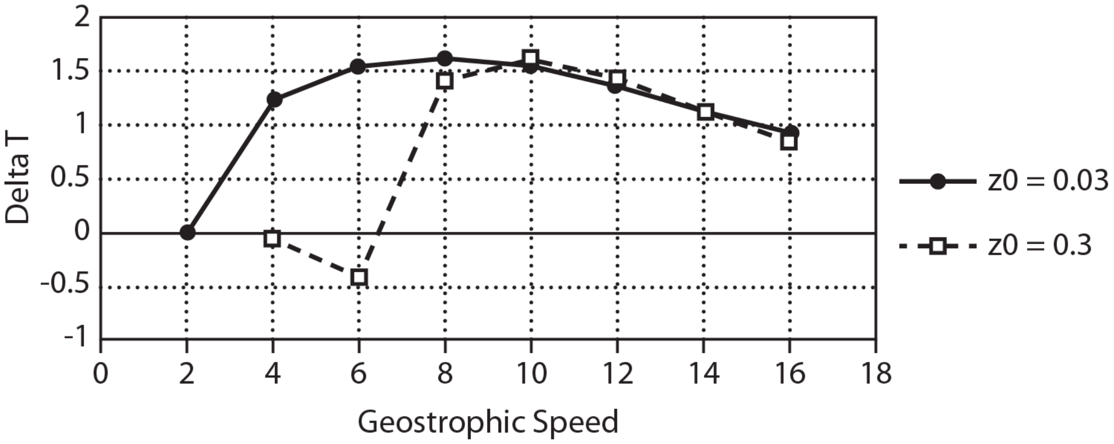

Figure 2: Differential change in temperature for the case of added longwave energy minus the base case versus wind speed for two different roughness values.

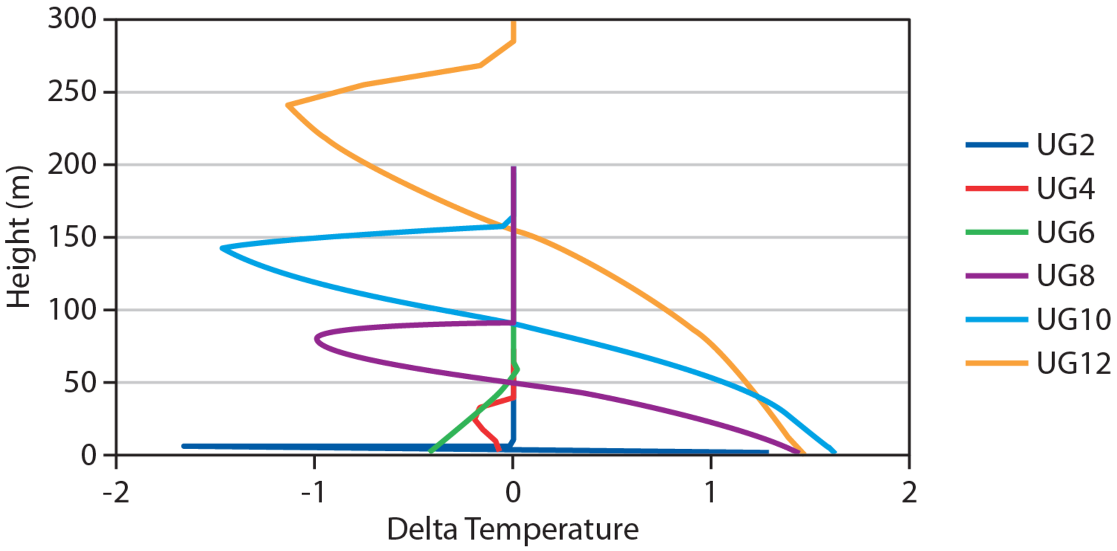

Figure 3: Difference in vertical profile between added GHG energy and base case from UAH for the case with no clear air radiative cooling.

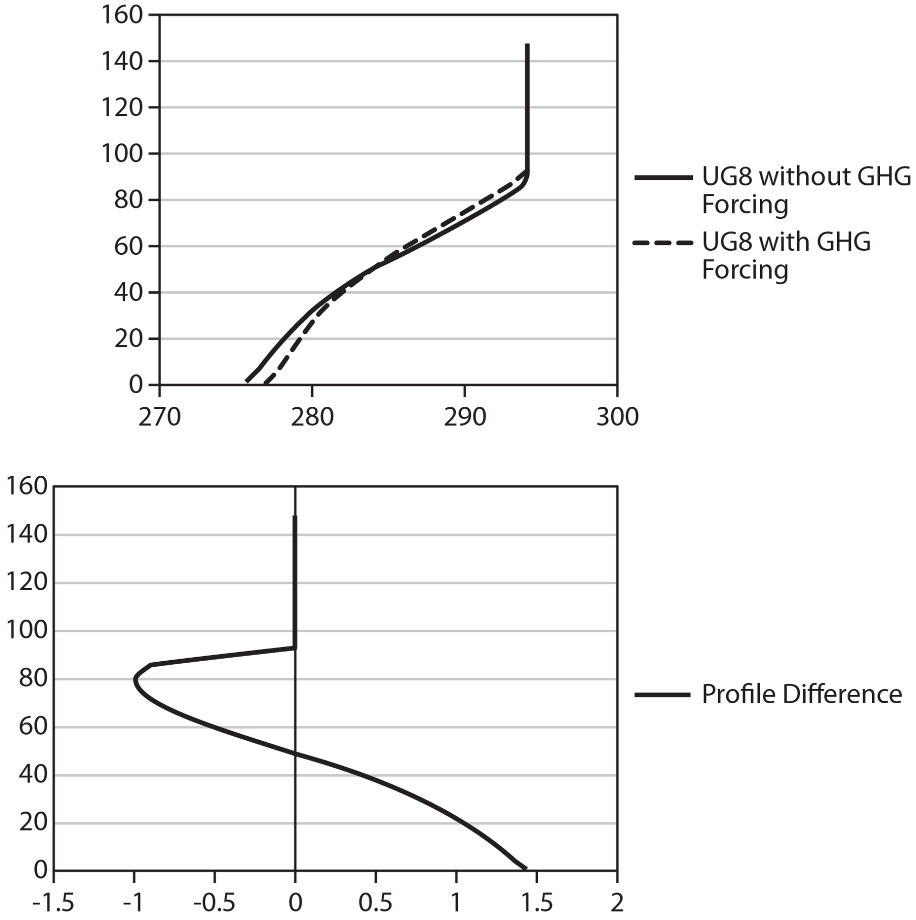

Figure 4: Expanded view of the difference in profile between the case of added GHG energy and base case for a geostrophic wind of 8 m/s.

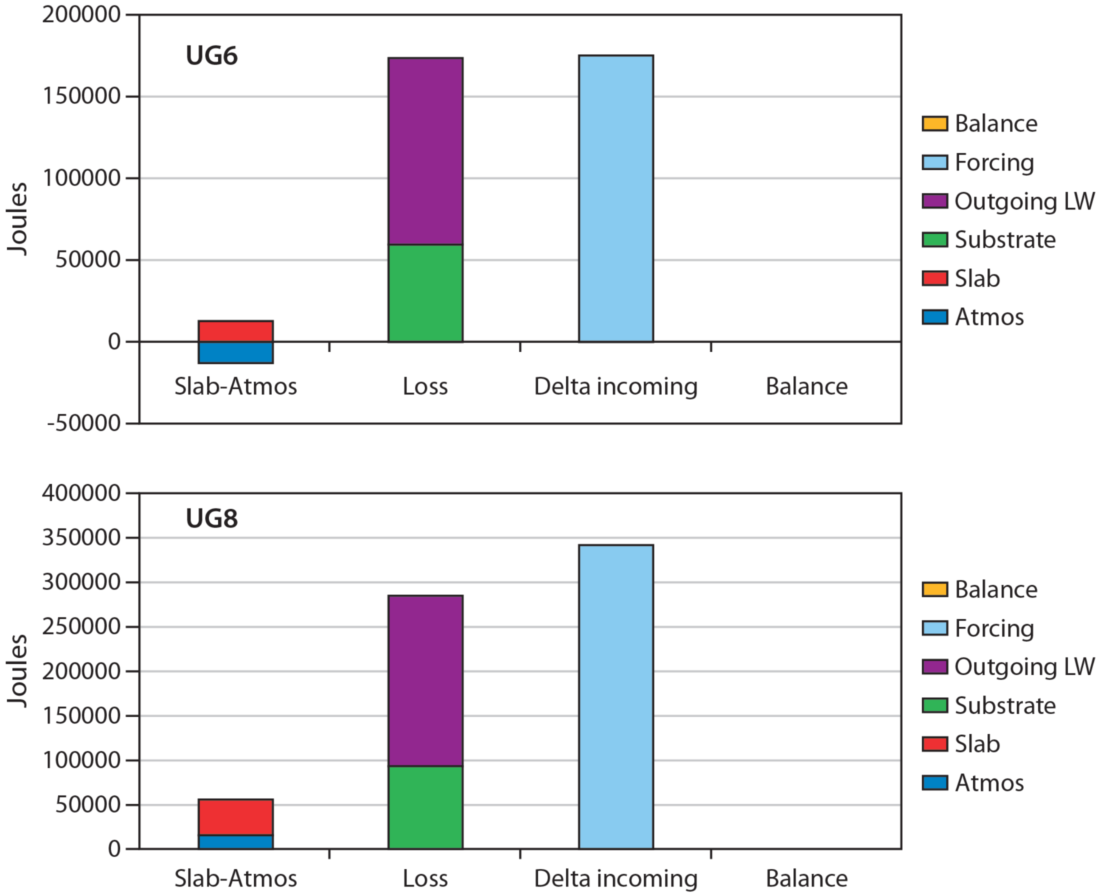

Figure 5: Model budget showing disposition of the added longwave energy (4.8 Wm^{-2} *after 12 hours of simulation for the UAH model for the case of no clear air radiative forcing.*

The analysis also showed that the final disposition and partitioning of the added energy in these short time period runs were highly dependent on the amount of mixing incorporated in the boundary layer scheme. Figure 6 shows that the energy budget is quite different for different stability functions employed. Here stability functions are employed from short-tailed forms [England and McNider, 1995] to longer tailed forms [Louis 1979] and [Beljaars and Holtslag 1991] which have more mixing. These analyses illustrate that, in climate and weather models, care must be taken to ensure that mixing processes reflect the physics of the boundary layer rather than having mixing processes tuned to replicate single level observations. While operational and some climate models are sometimes tuned by arbitrarily adding mixing to make operational performance better in the SNBL [Delage, 1997; Derbyshire, 1999; Viterbo et al., 1999], the results here indicate that climate models cannot perhaps afford this luxury in that such actions may also alter the disposition of added heat in the atmosphere and the energy budget of the atmosphere.

The present analysis reinforces previous work showing that the SNBL is a very complex dynamical system [ReVelle, 1993; McNider et al., 1995; Van de Wiel et al., 2002a,b; Delage, 1997; Derbyshire, 1999, Shi et al. 2005] that can be highly sensitive to parameters appearing in the land surface coupling and to imposed parameters such as radiation and wind speed. Given the relatively shallow nature of the SNBL and our current understanding of how to parameterize turbulence, high vertical grid resolution appears to be the key to capturing the fidelity of the NBL [Steeneveld et al., 2006;

Byrkjedal et al., 2007]. Accurately addressing the SBL may also be critical to correct a warm bias in surface air temperatures in climate models in the Arctic [Byrkjedal, 2007] and to the response of the Arctic SBL to added downward radiation of aerosols [Nair et al., 2011].

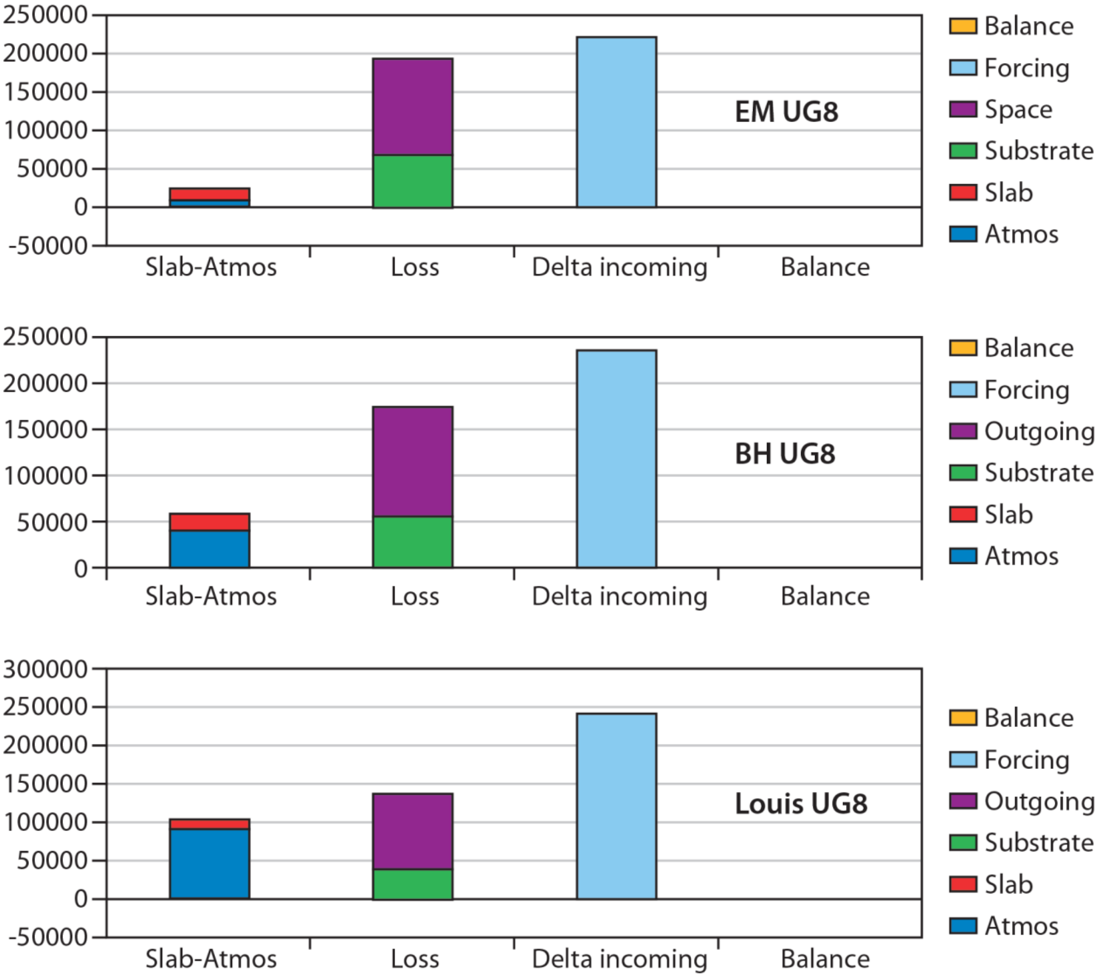

Figure 6: Model budget showing disposition of added longwave energy ($4.8Wm^{-2}$ after 12 hours of simulation for the UAH model for the case with clear air radiative forcing for the England-McNider (EM), Beljaars-Holtslag (BH) and Louis stability function.

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