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RESEARCH ARTICLE

The Nocturnal Wind Speed and Sensible Heat Flux Over Flat Terrain

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Abstract
During nocturnal cooling over land, the 10-m wind speed falls to very low values in many parts of the world while the absolute sensible heat flux increases initially after sunset but reaches a maximum before decreasing later in the night. In contrast, a one-dimensional numerical model predicts that the nocturnal wind speed is constant after an initial reduction at the evening transition. The difference between observations and the model is attributed to topographic effects which can be significant even over minor orography. Using data from exceptionally flat sites, we show that, in the absence of topography, the nocturnal wind speed is constant and the sensible heat flux tends towards a limiting value during prolonged surface cooling.

Keywords Evening transition · Flat terrain · Stable boundary layer

1 Introduction

Over land, in the absence of advective warming, the near-surface air temperature decreases in the late afternoon when the sensible heat flux becomes negative. In 1 or 2 h before sunset, the near-surface vertical air-temperature profile becomes neutral at the evening transition, after which the surface-layer air becomes stable and the sign of the sensible heat flux becomes negative, as heat is transported down to the surface. Derbyshire (1990) used an analytical model of the nocturnal boundary layer (see Nieuwstadt 1985) to show that, provided the assumed steady-state conditions exist, the downwards kinematic heat flux is limited to a maximum value given by

$$\overline{w'T'}_{max} = -\frac{T_0 R_{fc} G^2 |f|}{g\sqrt{3}} \tag{1}$$

where $\overline{w'T'}_{max}$ is the maximum turbulent kinematic heat flux, T_0 is the mean environmental temperature, g is the acceleration due to gravity, R_{fc} is the critical value of the flux Richardson number (=0.25), G is the geostrophic wind speed, and f is the Coriolis parameter.

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Nieuwstadt's stable boundary layer is capped by an infinitely sharp inversion. While a realistic mid-latitude nocturnal stable boundary layer may tend towards such a limiting case with prolonged cooling of the surface, the sensible heat flux would initially be small after the evening transition and would be expected to rise gradually thereafter towards the maximum value $\overline{w'T'}_{max}$, which is referred to below as the limiting heat flux. Although there are problems with the model, in particular the assumption of quasi-equilibrium and the critical Richardson number limiting the turbulence, Derbyshire showed that numerical-model heat fluxes tend to this limiting value after sunset.

A statistical investigation of the observed wind speed and sensible heat flux after the evening transition was reported by Lapworth et al. (2015), and references therein. The observation site at Cardington, south-east England is surrounded by relatively flat terrain bounded by undulating hills of about 100 m in height at a distance of several kilometres. The measurements show that, at this site, the absolute sensible heat flux increases to a maximum at 2 or 3 °C below the transition temperature, but again reduces as the 10-m wind speed also decreases during cooling. It was clear from the observations that the heat fluxes would tend to zero with prolonged surface cooling, which would contradict the Nieuwstadt model. The maximum of the sensible heat flux was about 25% of the limit calculated by Derbyshire.

Our purposes are, first, to determine, for a sufficiently flat terrain, if the nocturnal wind speed becomes constant with time after the initial reduction at the evening transition. Second, to determine why the measured heat flux at the Cardington site is significantly below the theoretical maximum limit and whether measurements from other sites or conditions yield heat-flux values nearer the limit. The heat flux is generally determined by a combination of the wind speed and the local temperature gradient.

Below, previous investigations are presented that indicate that the terrain type is critical in influencing the nocturnal wind speed. Measurements are then described of the nocturnal wind speed in the East Anglian Fens, which is the flattest region in England. The final section describes heat-flux and wind-speed measurements from the Great Plains of the U.S.A., and evidence is given that the nocturnal heat flux at some of these sites may approach the theoretical limit.

2 Previous Studies

Previous studies at Cardington (Lapworth et al. 2015) considered 6 years of data from a sonic anemometer mounted at 10 m above the surface and a ventilated platinum resistance thermometer mounted at 1.2 m (screen height). The geostrophic wind speed is estimated using a statistical relationship to the maximum 10-m wind speed on convective days determined using radiosonde data. This relationship is also found in numerical forecast models and has errors to within 10%, but the errors are minimized for large numbers of observations averaged into wind-speed bands.

The wind speed, air temperature, and heat flux are averaged into 17-min blocks. When the temperature is referenced to the temperature of the evening transition and the corresponding 10-m wind speed averaged over the 6-year period for a specific geostrophic wind-speed band, the 10-m wind speed decreases linearly with the reduction in air temperature with respect to the transition temperature T_{trans}. Here, the transition temperature is defined as the near-surface temperature at which the sensible heat flux changes sign. The slope of the fitted curve wind speed versus screen temperature increases with the geostrophic wind speed, with identical results regardless of whether the observations are restricted to those evenings on which the cooling is relatively high or low. Therefore, the wind speed is mainly a function of temperature only, suggesting that an internal state of quasi-equilibrium exists within the nocturnal boundary layer despite the continuously varying temperature. This implies the presence of a strong drag force dampening turbulent fluctuations.

The sensible heat flux plotted similarly against the air temperature minus the transition temperature $T - T_{trans}$, which is denoted hereafter as the nocturnal temperature deficit, also yields statistically well-defined curves, with the absolute heat flux initially increasing with the temperature deficit to a maximum before decreasing with further cooling as the wind speed decreases. For cooling typical of the Cardington site, the heat flux is slightly more dependent on the cooling than the wind speed as this affects the near-surface temperature gradient. At the maximum absolute value, the heat flux reaches about 25% of the limiting value, and it was clear that even after long nights there would be no further increase. This was unexpected as simple one-dimensional models using Monin–Obukhov similarity show the wind speed initially decreases after transition, but on further cooling maintains a fairly constant magnitude with no further decrease. The absolute sensible heat flux from such models increases monotonically with the temperature deficit until reaching the limiting flux value.

As a precursor to this study, similar plots of wind speed–temperature deficit were produced from data from a total of 21 sites around Great Britain and one at Deelen in the Netherlands. These sites are surrounded by a large number of different terrain types and include some mountainous (by U.K. standards) terrain as the effects of increased hill heights were desired for this initial study. Only during the current investigation did we consider terrain regarded as exceptionally flat. At all 21 sites, the 10-m wind speed is found to decrease during the evening and the slope of the wind speed versus temperature deficit is site dependent and correlated with the amplitude of the local topographic variations. We infer that a topographic drag force influences the nocturnal wind speed and the influence increases with stability. Simple topographic form drag is expected to decrease as the size of the eddies in the flow decrease with increasing stability and thus is unlikely to be the cause of the wind-speed reduction. An attempt to parametrize orographic form drag in a one-dimensional gradient-transfer model does not result in a 10-m wind-speed reduction similar to that observed. However, two other drag forces, flow blocking and gravity-wave drag, increase with stability. A simple parametrization of gravity-wave drag used in the model (Lapworth et al. 2015) gives a fairly good fit to the observations.

The numerical model is one-dimensional with an expanding vertical grid of 100 levels. The Navier–Stokes equations for the two horizontal velocity components together with a temperature equation are integrated in time using a leap-frog scheme. Momentum and heat fluxes are represented by Monin–Obukhov functions modified to allow some turbulence at Richardson numbers in excess of the critical value (King et al. 2001). The time step is continuously adjusted to avoid viscous instability. Temperature and wind speed are specified at the top and bottom boundaries. Gravity-wave drag is represented by a value derived from linear theory at the surface which reduces linearly with height to zero at the top of the stable surface layer. The model is initialized with a semi-analytic convective-boundary-layer solution, and is run for several hours before surface cooling is initiated.

The model results for the Cardington site are shown in Fig. 1a, b compared with observations of the wind speed and sensible heat flux, respectively, and describe the observations well except around the transition. This is the time of maximum cooling rate but it is probable that the Monin–Obukhov functions used in the model are not appropriate in such a very non-steady-state condition. As the temperature deficit increases, the initially large

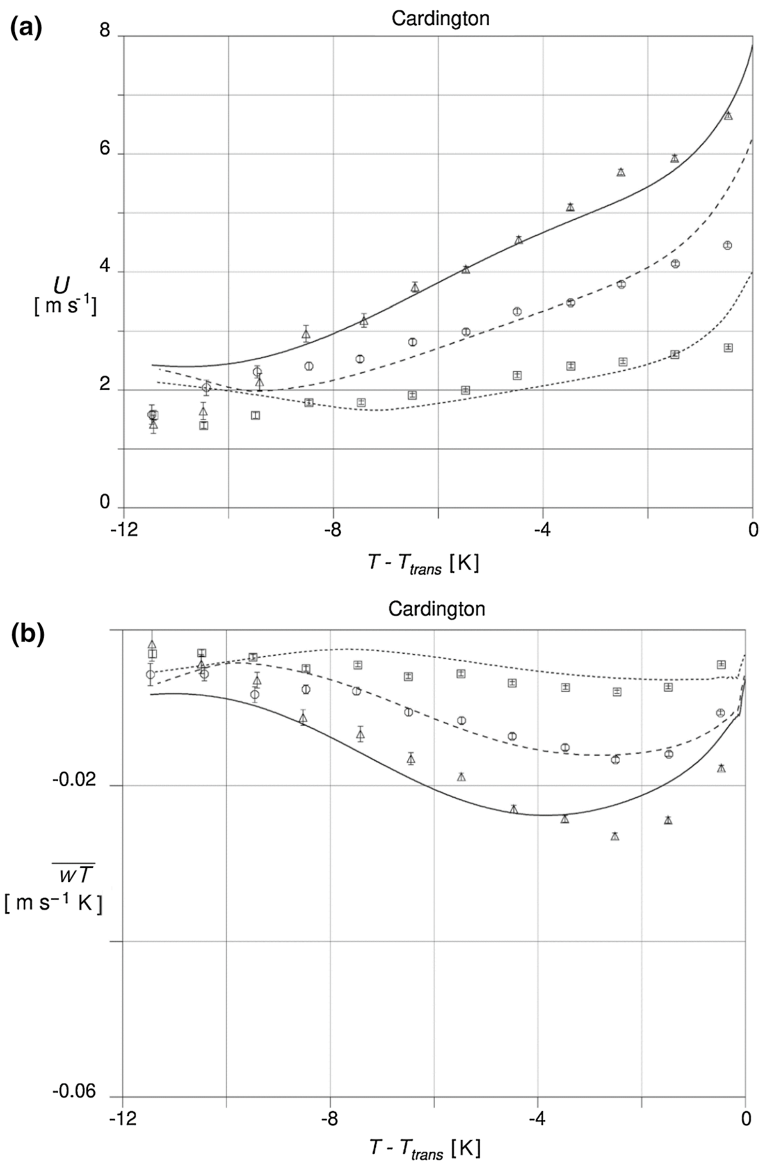


Fig. 1 Wind speed U (**a**) and kinematic heat flux $\overline{wT}$ (**b**) versus the nocturnal temperature deficit $T - T_{trans}$ averaged over six years of data at the Cardington site. Observations are shown as points for three geostrophic wind-speed bands together with the results (lines) according to the one-dimensional numerical model for $H^2/L = 0.85$ m. The three geostrophic wind-speed bands are centred on 16.0 m s^{-1} (triangles and solid line), 11.7 m s^{-1} (circles and dashed line), and 7.8 m s^{-1} (squares and dotted line)

cooling rate decreases and the increasing orographic drag force results in a boundary layer approaching equilibrium.

Linear-gravity-wave drag theory includes topography in the drag-force term containing a single topographic parameter H^2/L, where H is the height of the local terrain, and L the

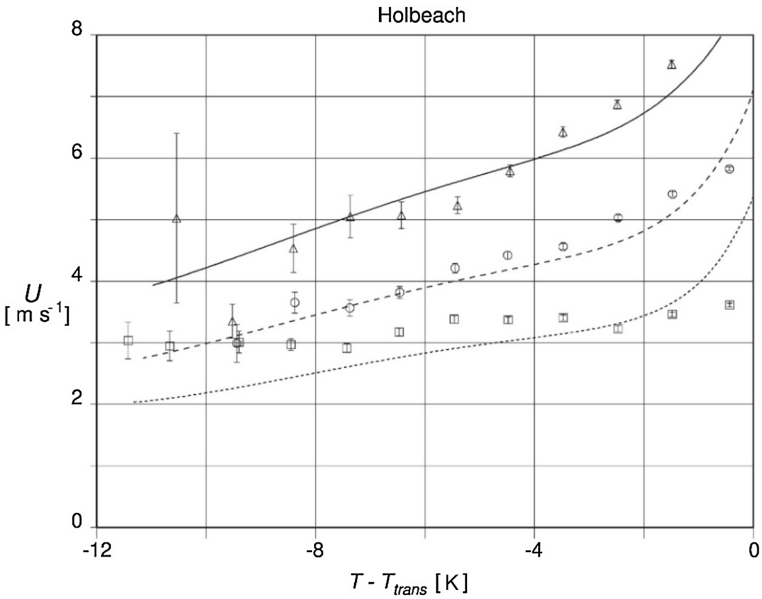


Fig. 2 Wind speed U versus the nocturnal temperature deficit $T - T_{trans}$ averaged over 10 years of data at the Holbeach site. Observations are shown as points for three geostrophic wind-speed bands together with the results (lines) according to the one-dimensional numerical model for $H^2/L = 0.49$ m. The three geostrophic wind-speed bands are centred on 17.5 m s^{-1} (triangles and solid line), 13.1 m s^{-1} (circles and dashed line), and 8.8 m s^{-1} (squares and dotted line)

horizontal wavelength of the topography. This is used as an adjustable parameter in the modelled stress term to fit the model curves to the wind-speed data. The resulting values of this topographic parameter are weakly correlated with the height of the local topography at the respective site to which the data are fitted.

It is notable that the relatively flat terrain surrounding the Cardington site, with hills more than 4 km away only reaching heights of order 100 m could produce such strong drag effects. Therefore, measurements would need to be made at an exceptionally flat site to produce data unaffected by topography and in which heat fluxes tend to the limit with prolonged surface cooling.

3 Fenland Measurements

Possibly the flattest area in the U.K. is the fenland country immediately to the south-west of the Wash, a large embayment on the east coast of England. Over an area approximately 50 km × 50 km, cartographic maps show only the very occasional 10-m contour line. A meteorological observing station is located near Holbeach on the south-west coast of the Wash. The prevailing south-westerly flow has a fetch of 50 km immediately upstream of this site. Figure 2 presents the wind speed versus the nocturnal temperature deficit from measurements made at this site. Contrary to expectations, despite the exceptional flatness of the upstream region, the wind speed decreases with the nocturnal temperature deficit although not at as great a rate as that according to the Cardington data. Model results (lines) are presented for $H^2/L = 0.49$ m, which is smaller than the value of 0.85 m used at Cardington but still non-zero.

There were two conclusions drawn from this. Either the hypothesis that topographically-induced drag causes the nocturnal wind speed to tend to near zero is wrong or, alternatively, that such drag forces have very long-range downstream effects. In the latter case, it would mean that the 100-m hills to the south-west of Peterborough, on the south-west edge of the Fens, have effects extending 50 km downstream to the site at Holbeach. It should be noted that the effect of form drag or blocking due to buildings or ditches on these observations is negligible. The results for Cardington show no difference for flow restricted to those wind directions over the buildings of the neighbouring town of Bedford to those restricted to the flat local fetch to the south-west. Numerical experiments where form drag is parametrized by a suitable dynamic pressure field at lower levels do not produce the linear behaviour observed and, in addition, the wind-speed reduction is very small compared with the gravity-wave-drag parametrizations.

As previously noted, all of the 20 U.K. sites considered reveal 10-m wind speeds decreasing with the nocturnal temperature deficit. As the nocturnal heat flux is limited by the decreasing wind speed, it seems that the limit on the nocturnal sensible heat flux is unlikely to be attained or even approached in the U.K. As suggested above, one possibility is that topographic drag effects have very long-range effects. In this case, the only way to further test the terrain-drag hypothesis and find nocturnal heat fluxes nearer to the limit would be to use observations from sites with more extensive flat areas. Below, results from the Great Plains of the U.S.A. are considered.

4 Observations from the Great Plains

4.1 Wind Speeds

The Great Plains of the U.S.A. are famous for their flatness, Kansas in particular being often cited in this respect. It is not the flattest state (Florida is) but slopes from west to east at a mean angle of 0.08°. It should be noted that the prevailing flow is parallel to the axis of this tilt. The lack of trees gives a vivid appearance of very flat terrain. The plains are famous for the regular appearance of the nocturnal low-level jet first described by Blackadar (1957), which appears in model simulations of flat terrain. He ascribed the jet to inertial oscillations resulting from the increasing stability of the nocturnal flow which, despite some debate, still appears to be correct (Parish and Oolman 2010). Kansas has been the site of observational boundary-layer campaigns in the past, especially the Kansas campaign near Liberal, Kansas in 1968 (Kaimal and Wyngaard 1990) and the CASES-99[1] experiment (Poulos et al. 2002) near El Dorado, Kansas. The latter was specifically aimed at nocturnal boundary-layer measurements, but only for a period of one month. In addition, there are a number of atmospheric-radiation-measurement (ARM) sites within the state, although mainly in the eastern half.

Here, 10 years of observations are considered from a series of sites running west to east along a latitude of 37–38° N These sites were Pueblo (104.6° W) and La Junta (103.5° W) in Colorado and Elkart (101.9° W), Liberal (100.9° W), Coldwater (99.3° W), Anthony

[1] Cooperative Atmospheric Surface Exchange Study October 1999.

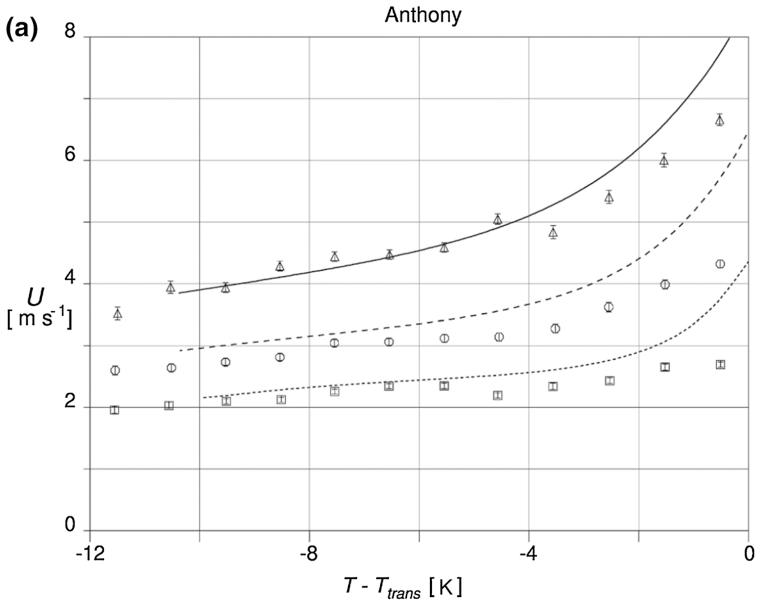
(98.0° W) and El Dorado (96.9° W) in Kansas. In general, the evening cooling at these sites is double that at the U.K. sites at around 2 K h^{-1} immediately prior to transition in contrast to 1 K h^{-1} as in the U.K. This is probably because the air is less humid over the Great Plains of the U.S.A. than in the U.K. As data from northerly wind directions show slight topographical effects, we omit data from the sector from north-west through north to north-east.

At Pueblo in the west and Anthony and El Dorado in the east, the wind speed–temperature plots are similar to those shown from Holbeach above. In these cases, the nocturnal wind speed gradually reduces, although not to the extent seen at most U.K. sites. At Liberal and Coldwater, the wind speed remains more constant during the evening but reduces slightly towards dawn. Observations from Liberal are shown in Fig. 3b with model curves assuming $H^2/L = 0.09$ m. However, at Elkart and La Junta, the wind speeds are fairly constant during the evening cooling after the initial reduction around the evening transition, with observations from these two sites shown in Fig. 4a and b, respectively. Also shown are results from the one-dimensional model without any gravity-wave-drag parametrization (i.e. $H^2/L = 0$ m). This confirms that the one-dimensional model without any drag parametrizations, which yields a constant wind speed even for large nocturnal temperature deficits, is applicable to at least some sites in the flattest terrain. This further confirms that the model is realistic and suggests that deviations from such model results are primarily caused by local topography.

4.2 The Heat Flux

Unfortunately, very few sites provide multi-year sensible-heat-flux measurements based on the eddy-correlation technique with the only such site within the area studied being the ARM site at Anthony. As noted above, observations from this site are similar to those at other sites where the H^2/L values are small but non-zero. Fitting the data requires $H^2/L = 0.25$ m, which is less than that at Holbeach.

Wind speed and the sensible heat flux from Anthony are shown in Figs. 3a and 5a respectively. As noted, the wind speed does reduce with an increase in the nocturnal temperature deficit, but not to the same extent as at the Cardington site. The heat flux is significantly larger than the equivalent values at Cardington with maxima occurring at larger nocturnal temperature deficits of a few °C. The heat-flux results at the highest wind-speed band are a fair validation of the model results shown in Fig. 5a, with the observed maxima having values of 40% of the limiting flux compared with 25% for Cardington. However, the observed flux in the lower two wind-speed bands is significantly greater than the model results, which is probably related to the greater cooling at lower wind speeds, resulting in the reduced sensible heat flux. Such rates could exceed the ability to correctly simulate the observations. The Monin–Obukhov similarity functions (on which the model fluxes are based) are measured in steady-state conditions in which the 10-m wind speed and screen temperature are constant. However, both the deceleration of the 10-m flow and the surface cooling rate are particularly high immediately after the time of evening transition, so that conditions are far from steady state. In these circumstances, the model-flux parametrizations may not be valid. The cooling rate at Anthony is double that at the Cardington site. The wind speed itself does not appear to be similarly affected, which implies that the modelled temperature gradients are less than those in the atmosphere. This suggests that the modified Monin–Obukhov functions used allow excessive turbulence at Richardson



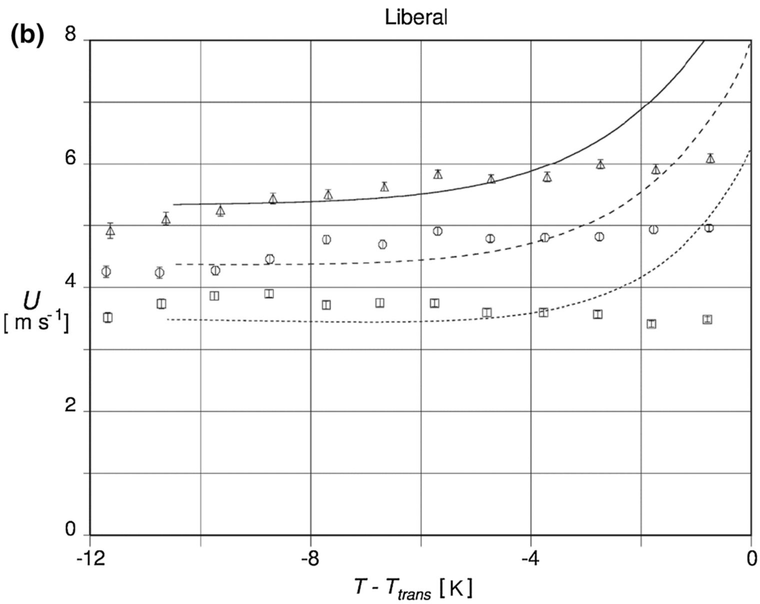


Fig. 3 Wind speed U versus the nocturnal temperature deficit $T - T_{trans}$ averaged over seven years of data at the Anthony site (**a**) and over 10 years of data at the Liberal site (**b**). Observations are shown as points for three geostrophic wind-speed bands together with the results (lines) according to the one-dimensional numerical model for $H^2/L = 0.25$ m (**a**) and 0.09 m (**b**). The three geostrophic wind-speed bands for (**a**) are centred on 15.8 m s^{-1} (triangles and solid line), 11.1 m s^{-1} (circles and dashed line), and 7.3 m s^{-1} (squares and dotted line) and the corresponding wind speeds for (**b**) are 18.2 m s^{-1}, 14.5 m s^{-1} and 10.7 m s^{-1}

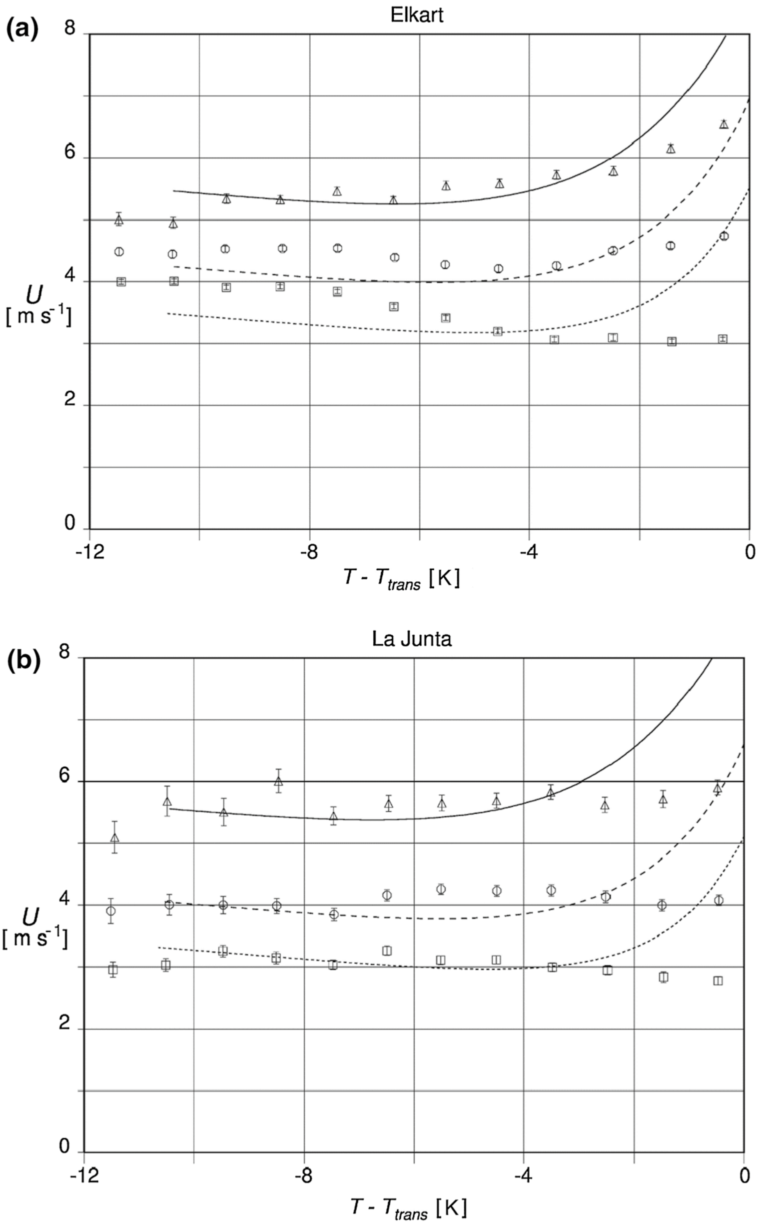
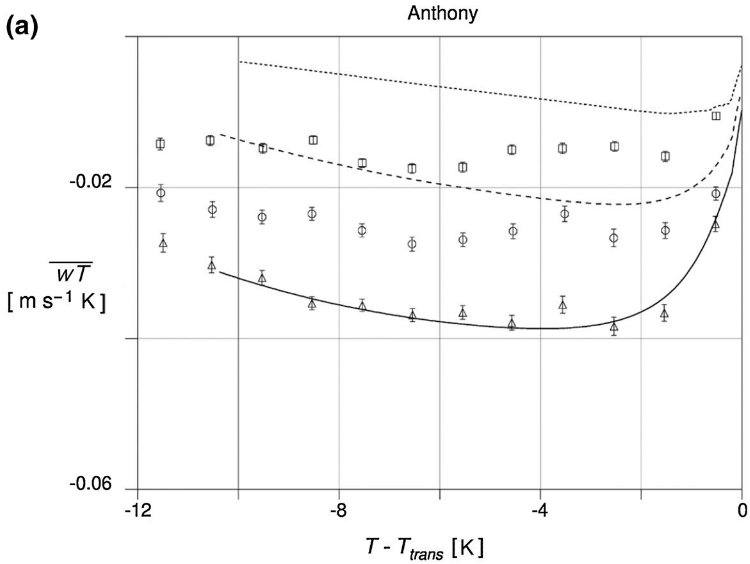


Fig. 4 Wind speed U versus the nocturnal temperature deficit $T - T_{trans}$ averaged over 10 years of data at the Elkart site (**a**) and the La Junta site (**b**). Observations are shown as points for three geostrophic wind-speed bands together with the results (lines) according to the one-dimensional numerical model for $H^2/L = 0$. The three geostrophic wind-speed bands for (**a**) are centred on 17.5 m s^{-1} (triangles and solid line), 13.4 m s^{-1} (circles and dashed line), and 9.7 m s^{-1} (squares and dotted line) and the corresponding wind speeds for (**b**) are 17.2 m s^{-1}, 12.6 m s^{-1} and 9.2 m s^{-1}



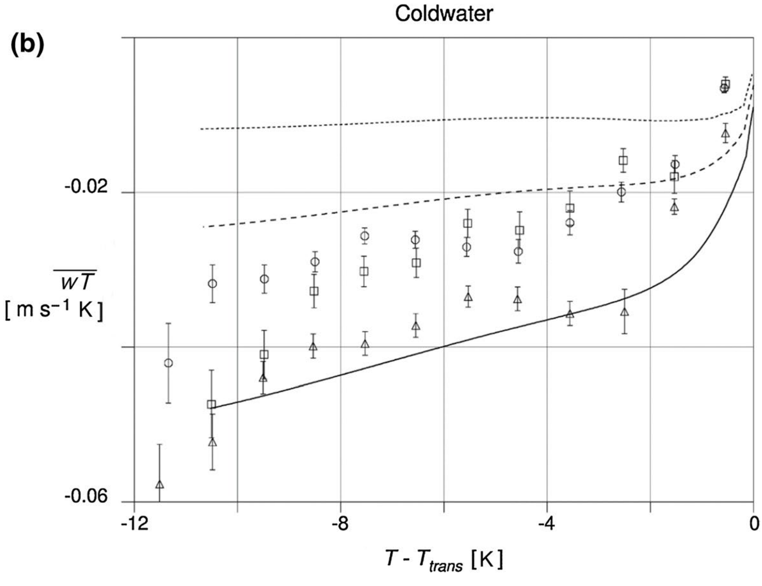


Fig. 5 Kinematic heat flux $\overline{wT}$ versus the nocturnal temperature deficit $T - T_{trans}$ averaged over seven years of data at the Anthony site (**a**) and the Coldwater site (**b**). Observations are shown as points for three geostrophic wind-speed bands together with the results (lines) according to the one-dimensional numerical model for $H^2/L = 0.25$ m (**a**) and 0.09 m (**b**). The three geostrophic wind-speed bands for (**a**) are centred on 15.8 m s^{-1} (triangles and solid line), 11.1 m s^{-1} (circles and dashed line), and 7.3 m s^{-1} (squares and dotted line) and the corresponding wind speeds for (**b**) are 16.3 m s^{-1}, 12.1 m s^{-1} and 8.3 m s^{-1}

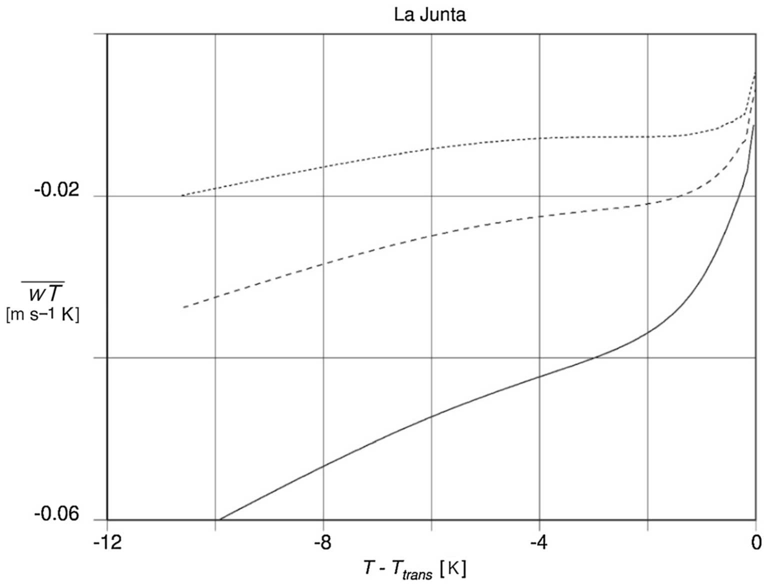


Fig. 6 Kinematic heat flux $\overline{wT}$ versus the nocturnal temperature deficit $T - T_{trans}$ from the one-dimensional numerical model for the La Junta site for $H^2/L = 0$. The three geostrophic wind-speed bands are centred on 17.2 m s^{-1} (solid line), 12.6 m s^{-1} (dashed line), and 9.2 m s^{-1} (dotted line)

numbers larger than the critical value. It is also possible that some of the differences are due to warm advection in the predominantly southerly flow.

A second ARM site was situated to the west of the Anthony site at Coldwater whose wind speed does not reduce with an increase in the nocturnal temperature deficit to the extent of that at Anthony, but is similar to that at Liberal. At the Coldwater site, the parameter $H^2/L = 0.09$ m, which is smaller than that at Anthony. Two bulk methods were available for determining the sensible heat flux. The first determines the sensible heat flux as a residual after summing all other flux measurements to give a net flux budget of zero and unsurprisingly gives very noisy results. The second uses the aerodynamic method in which the near-surface vertical temperature gradient is measured, and these results are reasonably consistent.

In contrast to the Anthony or La Junta sites, the Coldwater mean cooling rate at the time of evening transition is exceptionally high, which has a significant effect on the sensible heat flux. As noted above, whereas the high drag force acting on the flow results in a wind speed –temperature deficit relationship that is relatively independent of the cooling, the same is not true of the heat flux–temperature deficit plot. The sensible heat flux depends on both the wind speed and temperature gradient, with the near-surface temperature gradient increasing sharply at the higher cooling. In order to obtain a heat-flux plot for Coldwater comparable to those generated for Cardington and Anthony, only data from evenings with cooling rates limited to < 2.1 K h^{-1} are considered in Fig. 5b. In contrast to either of the previous two stations, the heat flux increases almost monotonically with the nocturnal temperature deficit, reaching values around 60% of the flux limit at the lowest temperatures. This behaviour appears to be associated with the low H^2/L value at this station and the model predicts that, at very low temperatures, the fluxes approach 100% of the limit. As with the observations at Anthony, the observed flux in the lower two wind-speed bands is

Table 1 Summary of topographic parameters and fluxes at the observation sites

Site	H^2/L (m)	Maximum heat flux	Terrain
Cardington	0.85	25% at 2.5 °C cooling	Low Hills
Holbeach	0.49	–	Flat Fenland
El Dorado	0.25	–	Great Plains 96.9° W
Anthony	0.25	40% at 3.5 °C cooling	Great Plains 98° W
Coldwater	0.09	50% at 12 °C cooling	Great Plains 99.3° W
Liberal	0.09	–	Great Plains 100.9° W
Elkart	0	–	Great Plains 101.9° W
La Junta	0	(60% - model at 12 °C cooling)	Great Plains 103.5° W

significantly greater than the model results. The probable explanation for this is similar to that given in the previous case.

If the absolute heat flux at Coldwater during nights with large cooling is considered, it is found to rise steeply to over 60% of the limit to within only 1–2 K of the temperature deficit before levelling off at lower temperatures. The conditions here are far from the steady state assumed in calculating the limit.

In the absence of heat-flux observations from a site in the region from La Junta to Elkart, Fig. 6 presents one-dimensional model results without gravity-wave drag illustrating a monotonic rise with the nocturnal temperature deficit up to the extent of the graph. The only limit is the total degree of cooling which results in sensible heat fluxes of up to 60% of the limit in this case. An extended simulation showed that, with sufficient cooling, the heat flux tends asymptotically to the maximum theoretical value, which is similar to that seen with the Coldwater data. It would be interesting to see the results from an eddy-correlation instrument operating for a few years in this part of the world.

The main results for topographic parameters and fluxes at the various sites are summarized in Table 1, indicating that the maximum heat flux increases with increasing terrain flatness as expressed through a decrease in the topography parameter H^2/L.

5 Conclusions

The observed wind speed versus nocturnal temperature deficit over relatively flat terrain surrounding Cardington in the U.K. tends to very low values in the presence of surface cooling. Measurements at 20 other U.K. sites reveal a similar behaviour which only varies in the magnitude of the temperature deficit at which the wind speed becomes negligible. Such wind-speed reductions result in an absolute sensible heat flux that reaches a maximum value well below the theoretical maximum after a 2 K temperature deficit and thereafter reduces towards zero. In order to demonstrate that the wind-speed reduction is a result of local topography, further observations were made at a site downstream of an area of the flattest U.K. terrain in the Fens but even in this case the wind speed reduced significantly with the temperature deficit. Finally, measurements obtained from a series of sites running east to west across the flattest parts of the Great Plains of the U.S.A. reveal relatively slight wind-speed reductions with the nocturnal temperature deficit. Two of the central sites in particular show no perceptible reduction even at the lowest deficits. Sensible-heat-flux measurements from two of these sites reveal larger values than those obtained at Cardington, with one showing a heat flux that increases continuously with the temperature deficit towards the theoretical limiting value. It is concluded that the exceptionally low wind speeds during nocturnal surface cooling are due to topographic effects, even in the relatively flat landscapes of the U.K. It has also been shown that, when these effects are absent, the nocturnal sensible heat flux can increase with the nocturnal temperature deficit towards the theoretical maximum values proposed by Derbyshire.

Acknowledgements We would particularly like to thank Larry D. Oolman for his help in providing long-term meteorological data from the University of Wyoming weather archive. Data from the Anthony and Coldwater sites were obtained from the ARM User Facility, a U.S. Department of Energy Office of Science user facility managed by the Office of Biological and Environmental Research. Data from U.K. sites were provided by the U.K. Met.Office.

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