SHALLOW DRAINAGE FLOWS

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Abstract. Two-dimensional sonic anemometers and slow response thermistors were deployed across a shallow gully during CASES99. Weak gully flow of a few tenths of m s^{-1} and a depth of a few metres develops in the early evening on most nights with clear skies. Flow down the gully developed sometimes even when the opposing ambient wind exceeded 10 m s^{-1} at the top of the 60-m tower. Cold air drainage from larger-scale slopes flows over the top of the colder gully flow. The gully flow and other drainage flows are generally eliminated in the middle of the night in conjunction with flow acceleration above the surface inversion layer and downward mixing of warmer air and higher momentum. As the flow decelerates later in the night, the gully flow may re-form.

The thin drainage flows decouple standard observational levels of 3–10 m from the surface. Under such common conditions, eddy correlation flux measurements cannot be used to estimate surface fluxes nor even detect the thin gully and drainage flows. The gentle gully system in this field program is typical of much of the Earth's land surface.

Keywords: Drainage flows, Gravity winds, Katabatic winds, Nocturnal boundary layer, Temperature minimum.

1. Introduction

Nocturnal airflow on clear nights is generated or modulated by terrain slope. Drainage flows may occur over even very weak slopes (e.g., Caughey et al., 1979; Mahrt and Larsen, 1990; Blumen et al., 1999) and most land surfaces experience nocturnal drainage flows with clear skies and weak synoptic flow. Drainage flows occur under a wide variety of situations (Geiger, 1961; Yoshino, 1975) and the dynamics of drainage flows vary widely (Mahrt, 1982). Most observational studies of drainage flow in valleys have concentrated on relatively deep valleys (e.g., Barr and Orgill, 1989; Banta et al., 1995 and references therein), steep slopes (e.g., Papadopoulos and Helmis, 1999) or larger-scale slopes (e.g., van den Avoird and

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Duynkerke, 1999). The gentle gully examined in this study is a small valley a few hundred metres across with side slopes of about 5%.

Drainage flows occur simultaneously on a variety of horizontal scales due to surface terrain on different scales. The flow immediately above the surface is influenced by the local slope on the smallest scales while the flow at higher levels may be influenced by slopes on a larger scale. When does local slope flow occur and when is it eliminated by larger scale flow? This question is of considerable practical interest since the surface drainage flow, no matter how thin, determines the exchange of properties between the atmosphere and ground surface. One of the difficulties in examining such thin flows is that traditional observational strategy only provides limited information on the vertical structure in contrast to larger scale drainage flows where mean profiles can be readily obtained (Oerlemans et al., 1999) and similarity theory can be evaluated (van der Avoird and Duynkerke, 1999; Smeets et al., 1999). The present study examines flow in a shallow gully observed during CASES99 (Cooperative Atmospheric Surface Exchange Study 1999; LeMone et al., 2000; G. S. Poulos et al., submitted) in south central Kansas, U.S.A. in October of 1999. Although flow down the gully is a type of drainage or slope flow, we will refer to it as the 'gully' flow to distinguish it from flow down the side slopes of the gully.

2. Data

The thermistors and 2-D sonic anemometers were deployed along a transect across the shallow gully (Figure 1), nominally called Gilliland Gully in recognition of the landowner. Some irregularity in the positioning along the transect resulted from avoiding grass above 50-cm height. There were no trees within one kilometre of the site, except for a line of trees approximately 600 m to the south. The grass cover was typically 25 cm high. Four Handar two-dimensional sonic anemometers (Vaisalla, model 425A) were installed along the transect. An additional two-dimensional sonic anemometer was located approximately 200 m up the gully in a wet region of grass and wetland plants (H2, Figure 1). Within 10 m of this sonic anemometer, the plants were 20–60 cm high. The rest of the gully was dry.

The two-dimensional sonic anemometers measured the horizontal wind components at 1 m above ground with a sampling interval of two seconds. The sonic path length is 21.5 cm. These sonic anemometers can resolve the very weak gully flow, not possible with conventional cup anemometers and wind vanes. The sonic anemometers were leveled within one degree. Periodic checks showed that the leveling was stable.

Nine Hobo TMC6-HB thermistors were installed along the east-west transect (Figure 1). Thermistor 2 was inoperative and is not included in the figure. The thermistors were suspended 0.5 m above the ground inside of 0.1-m diameter PVC (poly vinyl chloride) pipes, oriented horizontal in the north-south direction. The

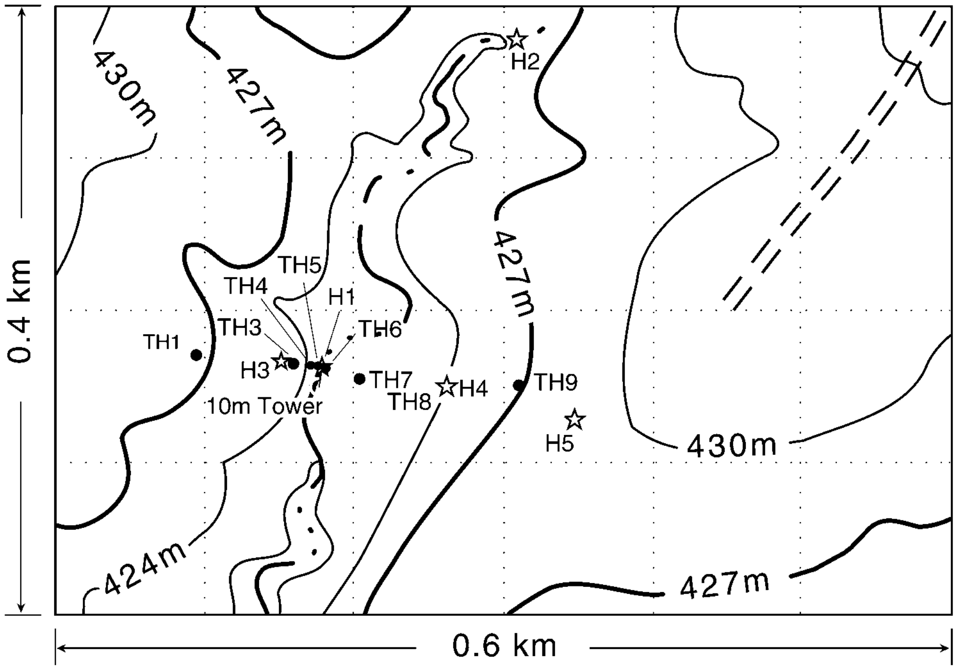

Figure 1. A map of the gully substudy for CASES99. 'H' refers to the Handar sonic anemometers and 'TH' to the thermistors. The meandering broken dotted line is the gully bottom.

PVC pipes serve as a radiation shield yet provide adequate ventilation. The resolution of the thermistors is 0.2 K with a response time of 7 minutes. Calibration studies conducted before, during and after the CASES99 field work indicated differences between thermistors on the order of 0.5 K. Although the thermistors were of sufficient accuracy to resolve the thermal structure of the gully flow, our ongoing work uses the more accurate HOBO H8 Pro (Whiteman et al., 2000).

Ten thermistors were also mounted on the 10-m tower in the gully. The radiation shields for the tower thermistors were made from styrofoam coffee cups. The PVC radiation shields would have created too much flow distortion for sonic anemometers on the tower. Radiometer measurements indicate that the nocturnal temperature of the styrofoam remains closer to the air temperature than the PVC material. The styrofoam shield was inadequate for mid-day periods and daytime thermistor data on the tower are not used. To estimate advection, we have also used data from a thermocouple network deployed by John Prueger of the National Tilth Laboratory (Ames, Iowa, U.S.A.).

This study will also use data from instrumentation deployed by the Institute of Astronomy and Meteorology from the University of Barcelona on the 10-m tower. This includes wind speed from the 1, 3 and 9 m levels (RM Young 05103 propeller anemometer, 5 Hz, threshold 0.4 m s^{-1}, accuracy 0.2 m s^{-1}) and wind vane (threshold 1 m s^{-1}). The data also include sonic anemometer measurements at

1.7 (Campbell CSAT3) and 7.4 m (Solent 1012-R2) levels, net radiation at 1.06 m (Campbell Q7), soil heat flux at 0.08 m (Campbell RECS HFT-3), soil temperature at 0.02 and 0.06 m (Campbell 107 temperature probe, 1 Hz, accuracy 0.1 °C) and soil moisture at 0.14 m (CS615).

Based on moisture fluxes measured at the main tower, the influence of moisture fluctuations on the heat flux measured by the sonic anemometer was estimated to be negligible except when both fluxes were immeasurably small. The sonic anemometers were leveled with respect to gravity and did not consider the local slope, which was highly dependent on direction from the tower, as must occur in a gully. Fluxes are difficult to measure in thin drainage flows. The sonic anemometer must be located close to the surface relative to the top of the thin drainage flow in order to avoid large (percentage-wise) change of flux between the surface and observational level. The vertical flux divergence between our lowest sonic anemometer level of 1.7 m and the surface is estimated in Section 5.1. That possible flux may be lost due to pathlength averaging is currently under investigation. Mismatches of footprints of the turbulent heat flux, net radiation and soil heat flux could be especially important for estimation of the surface energy budget in a gully where microscale variations of surface radiation temperature and soil properties can be substantial. Their impact is greatest for very stable conditions with weak turbulence since the horizontal integrating effect of the turbulent eddies is less effective in very stable conditions.

For our nocturnal case study, the surface soil heat flux is much larger than the 0.08-m heat flux due to heat storage between the surface and 0.08 m. The calculation of this storage is sensitive to the choice of soil properties including soil water content, which is measured only at 0.14 m. With this information, the soil heat capacity was estimated to be 1.5×10^6 J m^{-3} K^{-1}. The qualitative temporal evolution of the soil heat flux at the gully site is consistent with storage-corrected values based on heat flux measurements at 0.05-m depth at four stations around the main 60-m tower except that the soil heat flux reaches a larger early evening maximum in the gully. This is probably due to colder air in the gully and less vegetation.

The main 60-m tower is located approximately 1 km NNE of the gully site. We utilized the upward and downward components of the longwave radiation, measured at 2 m and 50 m on the main tower and at four locations around the main tower as a gross check on the behaviour of the radiation measurements in the gully.

To partly remove the influence of transient mesoscale and synoptic variations, we will composite the data over all of the nights where the temperature at the 9.7 m level on the gully tower averages 4 °C higher than the temperature at the 0.3 m level between 2000 and 0400 local time. This corresponds to relatively strong stratification. Nine nights beginning on 7, 9–11, 13, 20–21 and 25–26 October satisfy this criterion (add one for the UTC date). Gully flows in some form also occur on some of the other nights.

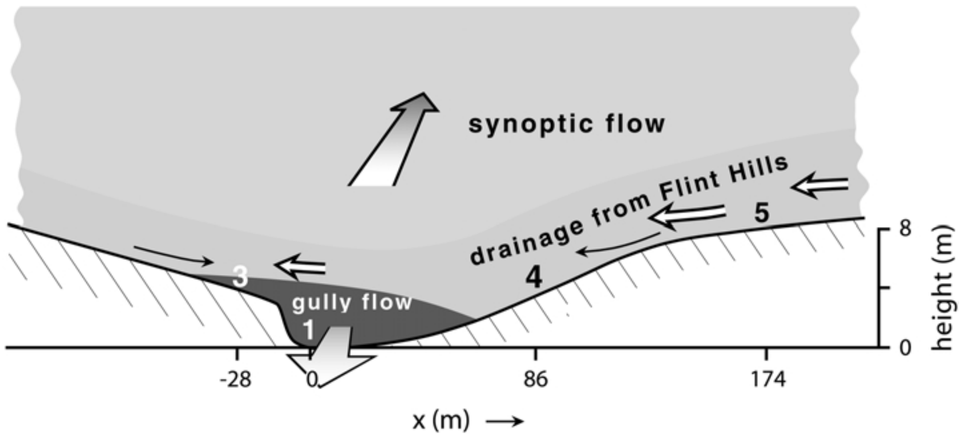

Figure 2. Schematic cross-section of the prevailing southerly synoptic flow, northerly surface flow down the gully and easterly flow thought to be drainage flow from the Flint Hills. All components of this circulation system do not occur all of the time and the circulation system is modulated by transient mesoscale motions. The numbering identifies the sonic anemometers on the east-west transect (H1–H5, Figure 1). East is directed to the right and north into the paper.

3. Multiple Gully Circulations

The nocturnal circulation in the gully region (Figure 2) consists of: (1) the synoptic flow, typically southerly, (2) easterly drainage flow responding to a 0.5% slope extending upward 10 km east of the site to the Flint Hills, (3) northerly flow down the local gully, (4) flow down the side slopes of the gully, which have a slope of about 5% on the east side and a little steeper on the west side if we include a small escarpment of 2 m just west of the gully bottom, and (5) transient mesoscale motions. Observations at the 60-m tower indicate that the larger scale easterly drainage flow is generally less than 10 m deep and occurred only occasionally. Manins (1992) introduced the term ‘skin flow’ to distinguish thin drainage flows responding to the local slope from thicker drainage flows responding to larger scale slopes.

The present study emphasizes the northerly gully flow. The gully flow is always weak, usually on the order of 0.1–0.5 m s^{-1}, and thin, usually with a depth of about 3 m or less. The mean vertical temperature profile indicates particularly cold air in the lowest 2–4 m where the stratification is strongest. Gully flow occurred even on nights with opposing southerly flow as strong as 10 m s^{-1} at the top of the 60-m tower. Previous studies have found elimination of drainage flow with weaker ambient winds. For example, Amanatidis et al. (1992) found that drainage winds did not normally develop when the wind at 84 m exceeded 3–4 m s^{-1}). Perhaps the gentle gully side slopes and the strong stratification in the gully are sufficient to protect the gully flow from erosion at moderate wind speeds. We return to this problem in Section 7.

To visualize the flow, smoke was released 1–2 h after sunset on several nights. These releases indicate that sometimes a thin drainage flow, about 0.1–0.2 m deep, descends the side slopes of the gully. This side slope current crosses over the top of colder air at the bottom of the gully. With smoke releases on the side slopes only, the colder air at the bottom of the gully, about 1 m deep at this time, remained smoke free.

In the absence of this side slope flow and easterly larger scale drainage flow, overturning developed on the interface between the northerly downslope gully flow and southerly synoptic flow at about 2 m above ground, sometimes exhibiting a regular pattern of up to 6 overturning events in a row with a horizontal wavelength of a few metres and the appearance of Kelvin Helmholtz rollup. Above 2 m, the smoke often took the form of very thin layers exhibiting gravity wave properties but little or no turbulence. The formation of thin layers of smoke is probably induced by shear-deformation and persists because of the lack of turbulent mixing in the strongly stratified air.

4. Time Evolution

The gully flow tended to be episodic but not periodic. Most nights were characterized by a couple of gully flow events occupying about half or less of the nighttime period. This episodic occurrence of the gully flow is partly controlled by the diurnal variation of the wind field above the gully, as opposed to shorter term pulses observed by Doran and Horst (1981) and oscillations in stratified shear flow modelled by McNider et al., (1995). The gully flow in CASES99 most often occurs in the early evening, is generally eliminated in the middle of the night, and then sometimes re-forms in the late evening/early morning.

4.1. Early evening very stable period

Businger (1973) and Mahrt et al. (1998) have observed a tendency for maximum stability in the early evening, followed by more mixing later in the evening (Section 4.2). Our recent analysis of tower data from a variety of geographical locations indicates that this tendency is not universal. However, the *early evening very stable period* is a systematic feature of CASES99, both inside and outside the gully. During this period, the wind speed at the gully bottom reaches a minimum (Figure 3) and the temperature stratification reaches a maximum (Figure 4). Temperature differences between the bottom of the gully and top of the side slope (about 8 m higher) average about 4 °C in the early evening.

Since the gully flow is thin, the downward heat flux to the ground surface extracts heat from a thin layer, leading to rapid cooling of the air at sunset, more than 15 °C in two hours for the composited data at the lowest levels (Figure 4).

The composited temperature in the gully bottom reaches a local minimum at about 2200 local time and then very slowly increases with time. On average over

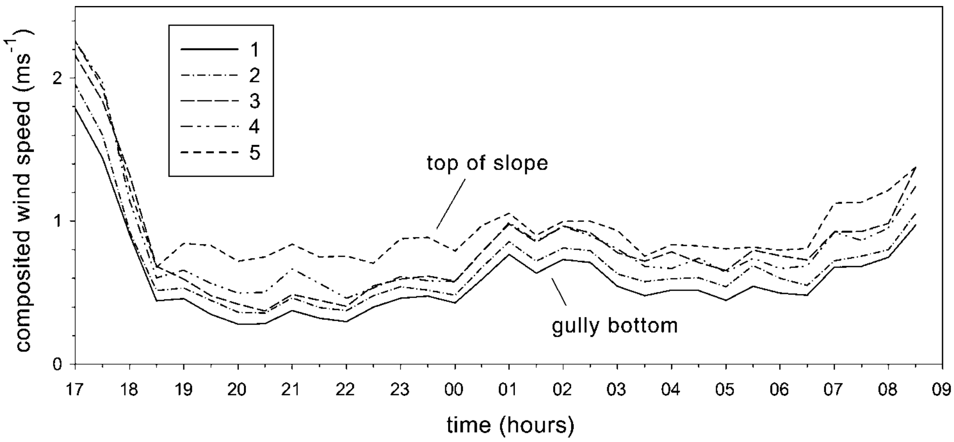

Figure 3. The 9-day composited diurnal variation of the 1-m 5-min averaged wind speed for the gully sites (stations H1-H5, Figure 1) as a function of local standard time.

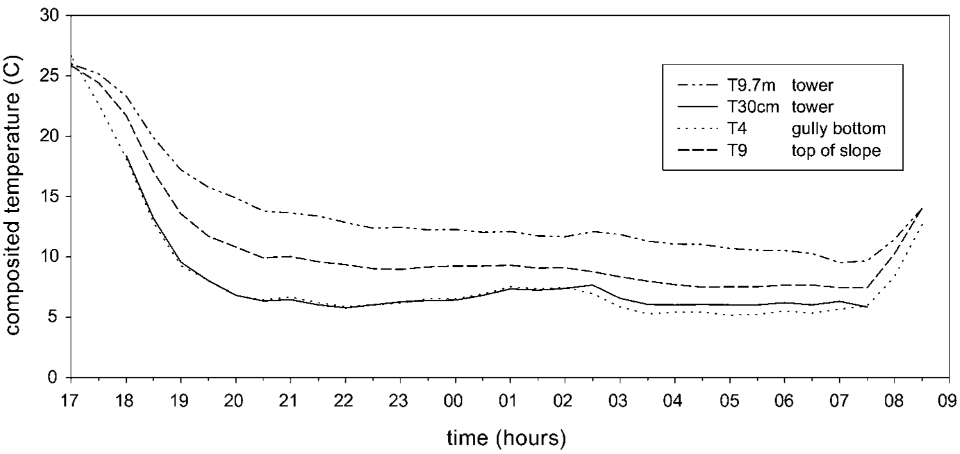

Figure 4. The composited diurnal variation of 5-min averaged temperature for the 9.7-m and 0.3-m levels on the gully tower, and for thermistors in the gully bottom (thermistor 4, Figure 1) and at the top of the slope (thermistor 9) as a function of local standard time.

the period of the field program, the sun sets around 1720 local standard time and rises around 0620. At higher levels above the gully bottom (e.g., 9.7-m level, Figure 4), the temperature continues to decrease slowly after the early evening rapid cooling. This diurnal signature is more typical of temperatures over flat surfaces compared to the special conditions at the gully bottom where the temperature reaches a minimum in the early evening. This minimum value is usually approached again in the early morning. The minimum temperature in the early evening does not appear to be limited by dew formation. The relative humidity generally increased to 80–85% during this period but often increased to near 100%

late in the evening. The latent heat flux at the main 60-m tower was generally weak upward in the early evening.

In cases where sensitive agricultural crops are grown in such gully bottoms, frost protection is required in the early evening allowing little warning time. On the other hand, failure of frost formation before midnight in the gully would indicate that frost is not likely for the rest of the evening, at least at this site. The generality of this behaviour is not known, although downward mixing of warmer air associated with flow acceleration above the gully seems to be common.

4.2. Middle-of-the-night mixing

The flow above the nocturnal boundary layer, which was part of the daytime boundary layer, becomes decoupled from the surface stress in the early evening and accelerates. This process leads to the commonly observed nocturnal low-level jet. At the 60-m tower, the winds generally reach a maximum between midnight and 0200 local standard time. The flow acceleration leads to enhanced shear and shear-generation of turbulence. This turbulence mixes momentum and warmer air downward, eliminates the gully flow and can cause warming in the gully bottom by more than 7 K on some individual nights. Based on the main-tower data, these fluxes appear to originate from much higher levels and cannot be parameterized in terms of entrainment and shear at the top of the drainage flow, as formulated in models of drainage flow (e.g., Manins and Sawford, 1979; Mahrt, 1982).

With elimination of the cold gully flow, the stratification is much weaker. The warming typically begins around midnight (Figure 4) in concert with momentum transported downward from higher levels and elimination of the gully flow. Downward mixing shortly after midnight was also observed in Cuxart et al. (2000). However, in their study, the associated warming and increased wind speed at the surface was short lived compared to the present case.

Downslope flows are sometimes reduced or eliminated when lower lying areas ‘fill up’ with cold air, as might occur here further downstream where the gully enters into a larger valley. This effect is thought to be unimportant at the gully tower site, since the elimination of the gully flow is accompanied by significant warming.

4.3. Early morning more stable period

Based on observations from the 60-m tower and sounding data (G. S. Poulos et al., submitted), the strength of the flow above the surface inversion layer weakens after 0200 local time, which would be consistent with the expected dominance of inertial oscillations (e.g., Ostdiek and Blumen, 1997 and references therein). With weaker shear-generation of turbulence, the downward mixing decreases, the near-surface temperature decreases (Figure 4), the air stabilizes and the gully flow may re-form. Above the gully bottom, the temperature cools to the minimum for the night, usually occurring just after sunrise.

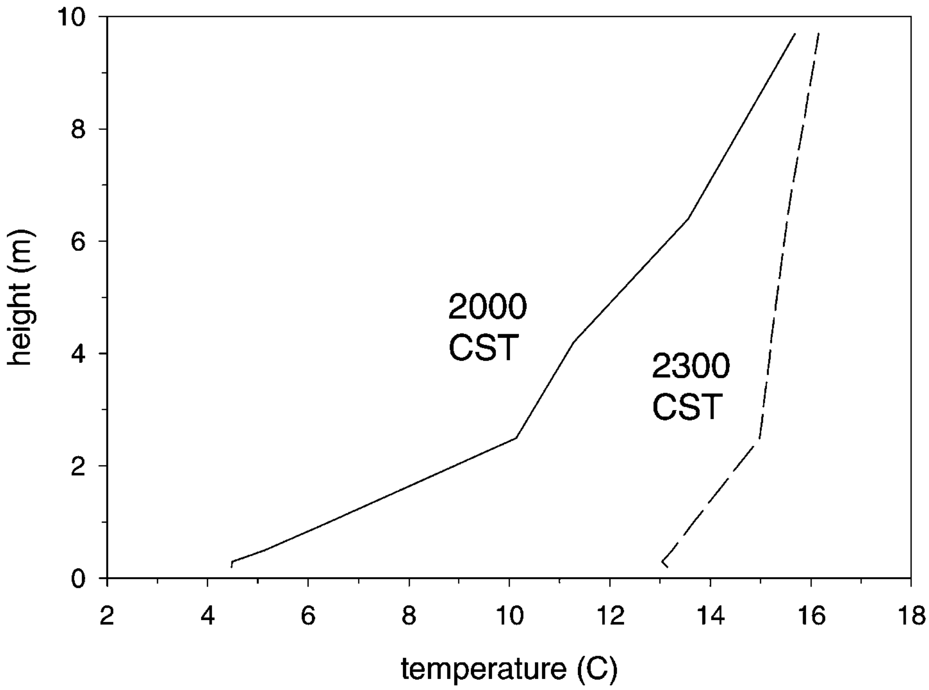

Figure 5. Vertical profiles of temperature during the early evening very stable period with gully flow (2000 local time) and after mixing (2300) on the night of 26–27 October.

5. Case study

The above discussion is based on composited results, which mask the large variation between nights. We therefore choose the night 26–27 October as a case study of a modest gully flow (Figures 5–7). The flow down the gully on this night is eliminated by downward mixing earlier than normal, around 2130, but then re-forms again after 0100. The turbulence above the gully flow is stronger than average on this night.

5.1. Layer budget

To examine the surface energy budget, we must first determine if the flux measured at 1.7 m is significantly different than the surface flux due to vertical flux divergence across the thin drainage flow. To address this query, we evaluate the vertically-integrated heat budget in the form

$$(\overline{w'\theta'})_{sfc} - (\overline{w'\theta'})_z = \int_{sfc}^{z} \left[\frac{\partial\overline{\theta}}{\partial t} + \overline{V_H} \cdot \nabla_H \overline{\theta} + \overline{w} \frac{\partial\overline{\theta}}{\partial z} + \nabla_H \cdot \overline{V'_H \theta'} \right] dz + \frac{\Delta R}{\rho c_p} \tag{1}$$

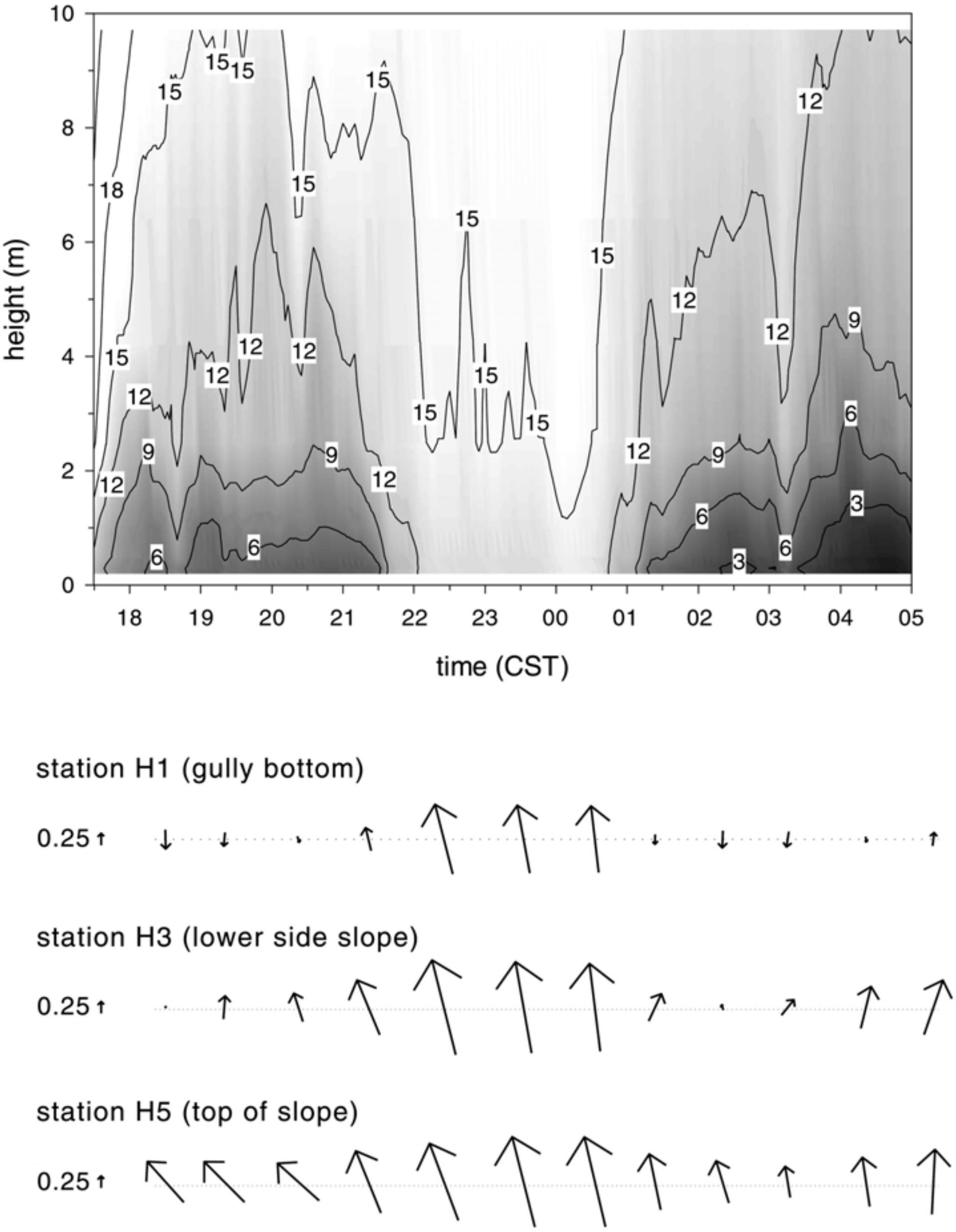

Figure 6. Temperature time-height cross-section and one-hour averaged wind vectors for the night beginning on 26–27 October showing northerly gully flow in the gully bottom before 2130 and southerly ambient flow at all stations between 2130 and 0130. Station locations are given in Figure 1. The reference vector on the left hand side represents a magnitude of 0.25 m s^{-1}.

where ρ is the air density, c_p is the specific heat, z is the 1.7-m level of the sonic anemometer within the gully flow, ΔR is the radiative flux divergence across this thin layer and V_H is the horizontal wind vector. The vertical advection by the mean flow and the horizontal flux divergence were not estimated.

We will separately analyze the early evening very stable period between 1800 and 2130 LST, with flow down the gully, and the turbulent period between 2130 and 0100 when the flow was everywhere southerly. A similar but less dramatic time evolution of turbulence occurs at the main tower, except the wind was southerly throughout the night.

Application of a two-stream radiation model (Kiehl, 1996) to the observed profiles indicates that the radiative flux divergence across the 1.7-m layer is important in the initial generation of the stratification before 1800. The importance of clear air radiative flux divergence in thin drainage flows has been emphasized by Manins (1992). However, once the strong stratification has formed, the radiative term switches to convergence in the lowest few metres and acts as a small warming term of about $\Delta R = 0.5$ W m^{-2} for the 1.7-m layer for the early evening period and becomes even smaller during the turbulent period when vertical temperature gradients are weaker. The radiative flux divergence term is not considered further.

For an average flow of 0.2 m s^{-1} down the gully with a horizontal temperature gradient of 7 K over 700 m, the vertically integrated horizontal advection of warmer air is estimated to be 3 W m^{-2}. If this advective warming was balanced by the vertical divergence of the heat flux, then the surface flux would be 3 W m^{-2} greater than that at 1.7 m.

For the rapid warming period between 2130 and 2200, the storage term (first term in the integral) due to change of air temperature is about 7 W m^{-2}. There are no thermistor measurements to the south of the gully tower on this night and advection cannot be estimated for southerly flow periods. Due to greater mixing outside as well as inside the gully, the air temperature is much more uniform and horizontal temperature advection is thought to be small. If the observed warming is due to the convergence of downward heat flux, the surface heat flux would be about 7 W m^{-2} smaller than that at 1.7 m where the downward heat flux is now about 40 W m^{-2}. After the rapid warming, the temperature is nearly time-independent and the surface heat flux is estimated to be close to that at 1.7 m.

The above results indicate that, except for the short rapid warming period, the adjustment of the estimated surface heat flux based on Equatin (1) is generally smaller than the random flux error and is probably small compared to the other flux uncertainties (Section 2). We therefore forego such adjustment in evaluation of the surface energy budget.

5.2. Surface Energy Budget

The surface energy balance is written as

$$R_{net} = G + \rho c_p(\overline{w'\theta'})_{sfc} + \rho L_v(\overline{w'q'})_{sfc} \tag{2}$$

where G is the heat flux into the soil (here negative corresponding to heat flux out of the soil), q the specific humidity, and L_v the latent heat of evaporation. The atmospheric latent heat flux was not measured in the gully. Based on the 5-m level at the main tower site, the latent heat flux is upward and about 10% of the magnitude of the sensible heat flux and, therefore, relatively unimportant. The soil moisture values at the gully and main tower sites were similar.

During the initial formation of the gully flow prior to 1800, the net radiation is balanced primarily by heat flux from the soil; the downward sensible heat flux is less important (Figure 7). On some nights, this scenario continues throughout much of the night.

The main turbulence period on this night begins around 2130 when the net radiation becomes approximately balanced by the enhanced downward heat flux. The warming of the air in the gully leads to an increase of surface temperature and a substantial decrease in the upward soil heat flux. The network of radiation measurements around the main tower (Section 2) indicate that the surface temperature and outgoing longwave radiation increase during this period even outside the gully, leading to an increase in the net radiative flux loss at the surface.

During the subsequent period of weak turbulence, which lasts until sunrise, the soil heat flux is significantly greater than the atmospheric heat flux, but unable to balance the net radiation. Since the relative humidity sometimes becomes close to 100% during this period, downward latent heat flux may become important.

6. Transient and Spatial Variability

Smoke releases effectively illustrated how transient mesoscale motions lead to significant meandering. Within an hour after the smoke release, the smoke sometimes had spread in nearly all the directions from the release point. On some nights, observations from the main 60-m tower exhibited significant mesoscale modulation of the wind and flux fields on the time scale of three hours or less. These modes modulate and sometimes eliminate the gully flow. Since these motions are of unknown origin, unpredictable and not present in mesoscale models, the gully flow itself becomes somewhat unpredictable.

The role of such transient mesoscale motions on the diurnal variation is reduced by compositing the wind vector over the 9 days. The predominant synoptic scale wind is from the south, as is evident in the late afternoon (left side of Figure 8). The composite of the diurnal variation of the wind vector (Figure 8) shows that gully flow is dominant in the early evening only at the lower gully site (station H1). The upper gully site (station H2, Figure 1) shows northeasterly composited flow in the early evening: here the flow used to compute the composite is sometimes northerly gully flow and sometimes easterly flow. Gully flow at the lower site (station H1, Figure 1) is typically stronger and more persistent than the gully flow farther up the gully (station H2). The upper station drains a smaller area compared to the lower

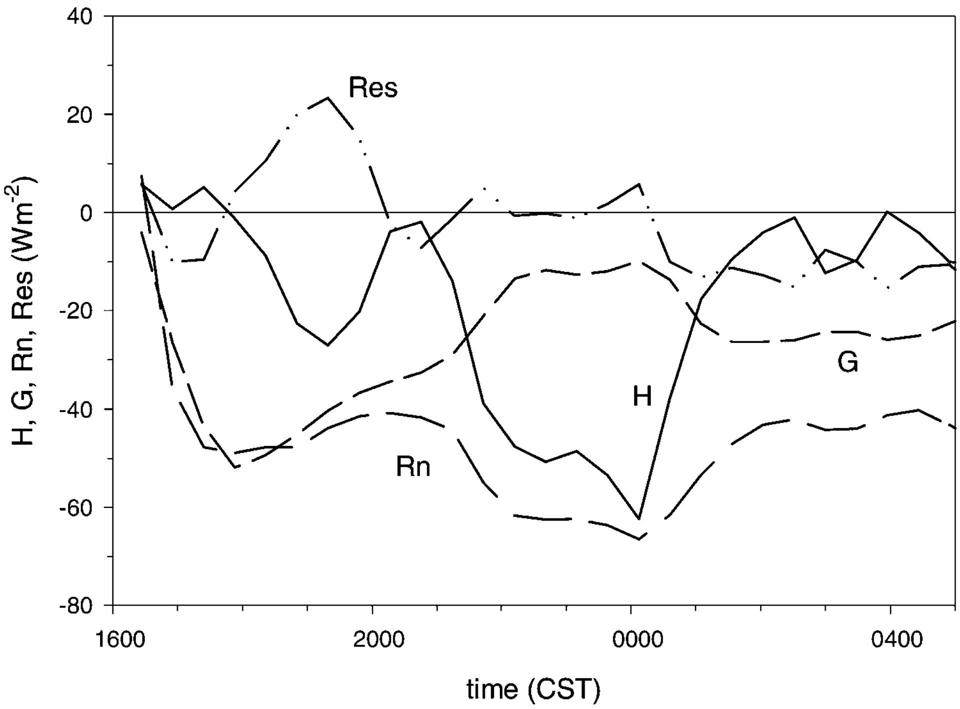

Figure 7. The surface energy balance for 26–27 October where H is the sensible heat flux, Rn, the net radiation, G, the soil heat flux and Res, the imbalance = $Rn - H - G$.

station. Gully and slope flows occur at some of the other sites a substantial fraction of the time, but periods of much stronger ambient flow dominate the composited wind vectors.

Station H3 just above the small escarpment within the gully also shows significant influence of the gully flow whereas station 4 at the eastern edge of the gully shows dominance by the easterly drainage flow, even though the two stations are about the same elevation. The easterly drainage flow may displace the gully flow toward the west, although upstream irregularities in the gully structure probably also play a role.

The easterly flow could be due to drainage down the local slope between stations H4 and H5. However, since station H5 at the top of the slope more frequently experiences easterly flow, it is likely due to drainage on the 10-km scale (Section 3). The easterly flow is occasionally observed west of the gully but rarely at the gully bottom.

The composited flow vectors are southeasterly in the middle of the night because of a combination of easterly flow events and downward mixing of ambient southerly momentum. In the late evening/early morning, the gully bottom stations show some influence of the occasional return of the gully flow while the other stations are dominated by easterly or southeasterly flow. Clearly, the gully flow is

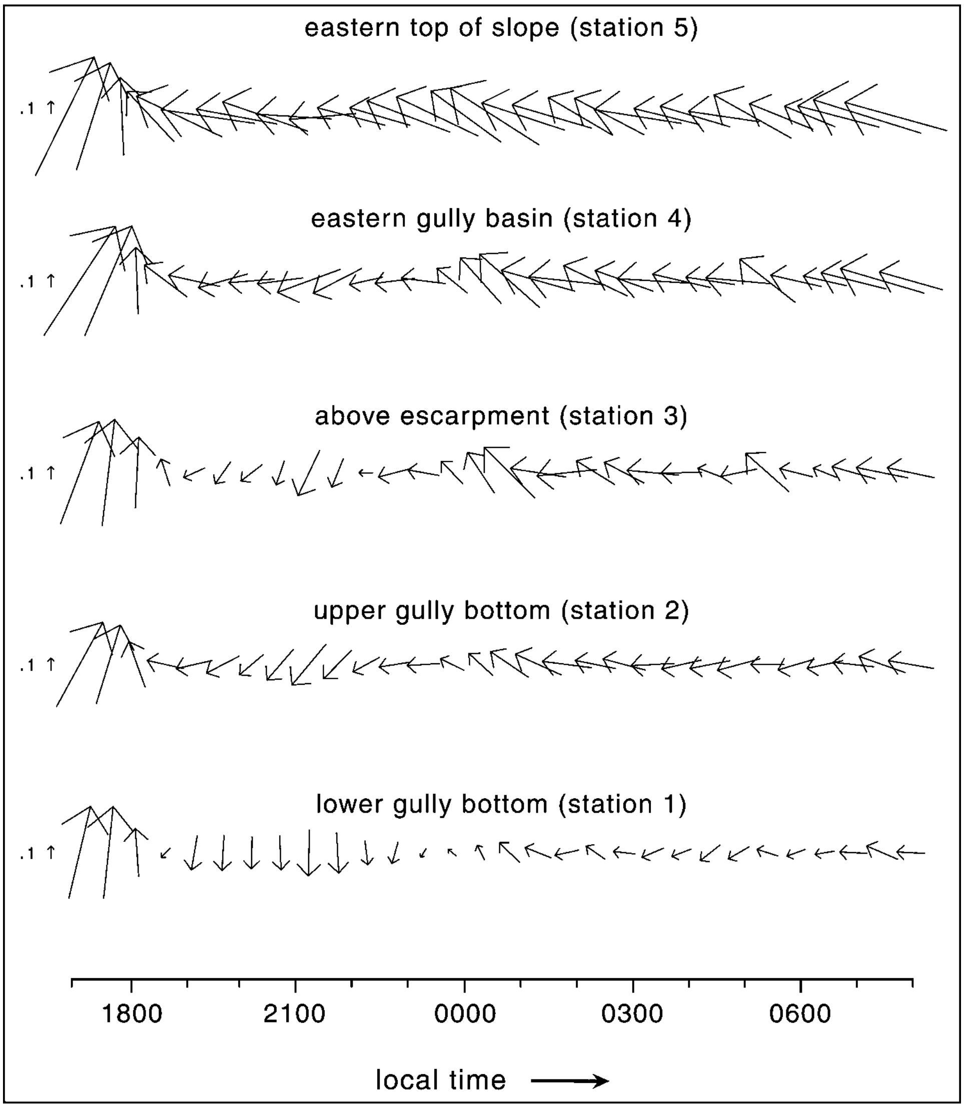

Figure 8. Vector composite (resultant winds) for the nine most stable nights for the five sonic anemometer sites.

much more dominant during the early evening very stable period than at any other time during the night.

7. Predictability

Although the gully flow is modulated by unpredictable meandering of the meso-scale wind field, some aspects of the gully flow are predictable. The existence of the gully flow is well correlated with the bulk Richardson number and the stability parameter z/L evaluated from the tower in the gully, where L is the Obukhov length. However, these two parameters are not independent of the gully flow in that the gully flow modifies the surface temperature and value of L. Here, we define a 'radiation Richardson number', which provides a more independent predictor of the potential for local slope flows and is written as

$$Ri_{rad} = -\frac{g}{\Theta \rho c_p} \frac{R_{net}\, z}{U^3} \tag{3}$$

where U is the wind speed at level z, preferably chosen to be above the drainage and gully flows. As an aside, the radiation Richardson number could be related to the flux Richardson number through scaling arguments by assuming that the turbulent buoyancy flux is proportional to the net radiative cooling, the stress is proportional to the square of the wind speed through the drag law and the shear scales as the wind speed divided by the height above ground. For the present data, U normally increases with height faster than $z^{1/3}$ in the lowest few tens of metres so that the radiation Richardson number decreases with height at these levels. It varies less systematically with height at higher levels.

We choose z to be the 55-m level on the main tower in order that U represents the ambient flow well above any influence of the various drainage flows. The wind speed at the top of the tower is normally determined by the strength and height of the low-level jet.

We consider all of the 30-minute nocturnal records where the net radiation is negative and the 'ambient flow' at 55 m opposes the flow down the gully, that is, has a southerly component. For these cases, the northerly gully flow can be isolated. For values of the radiation Richardson number larger than about 0.01, the flow in the gully is either down the gully or very weak (Figure 9). However, for values of the radiation Richardson number greater than 0.01, there is no relationship between the strength of the gully flow and the exact magnitude of the radiation Richardson number. For smaller values of the radiation Richardson number, southerly flow (positive v in Figure 9) is frequent in the gully implying downward mixing of ambient flow to the surface. Cases with a northerly component in the gully also occur for small radiation Richardson number, some of them with low-level north easterly flow outside the gully. Figure 9 excludes three offscale points corresponding to very weak 55-m winds and large radiation Richardson numbers, two of them with gully flow and one without.

8. Conclusions

This study has analyzed data from a small gully typical of gently undulating terrain over much of the Earth's surface. The thin drainage flow down the gully and down the gully side slopes cools rapidly in the early evening, since the downward

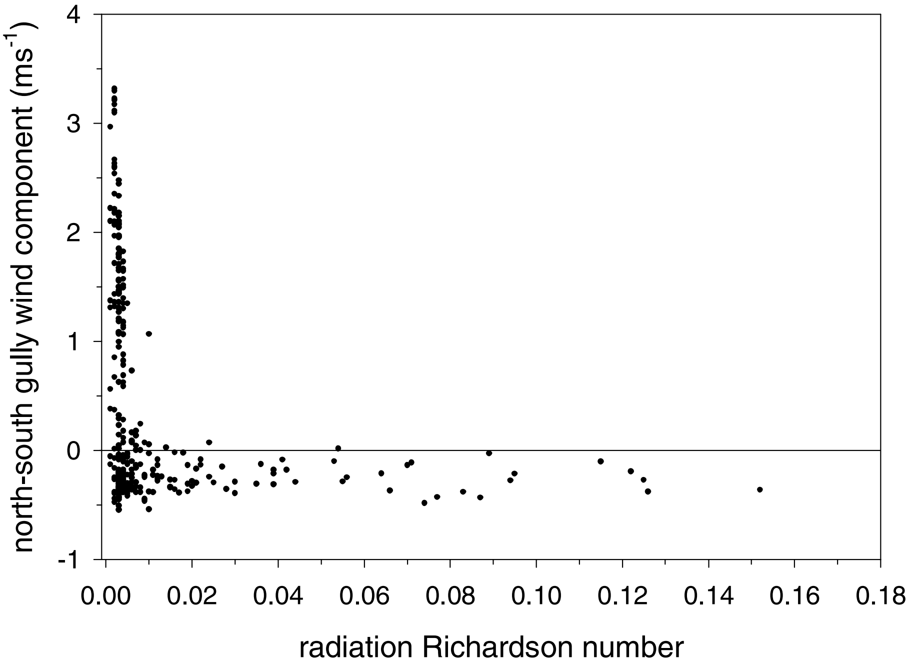

Figure 9. The dependence of the north-south wind component at station H1 in the gully on the radiation Richardson number for cases where the 55-m wind has a southerly component, and therefore opposes flow down the gully.

heat flux into the radiatively-cooled ground surface originates from these thin layers. This leads to the early evening very stable period. The air in the gully may experience minimum temperatures for the entire night during this early evening period.

As the evening proceeds, flow acceleration above the nocturnal surface inversion leads to shear-generation of turbulence and downward mixing of warmer air with stronger momentum. Consequently, the gully flow is eliminated in the middle of the night and air in the gully warms substantially. The flow above the nocturnal surface inversion decreases in intensity still later in the evening and the gully flow may reform. This diurnal scenario is modulated by transient mesoscale motions of unknown origin. As an additional complication, drainage flow on the gully side slopes and drainage flow on the horizontal scale of ten kilometres sometimes form and override the colder gully flow.

Thin drainage flows may explain previous large imbalances in some nocturnal surface energy and carbon dioxide budgets since the eddy correlation measurements at standard levels (3–10 m) will be above such flows and therefore do not capture the surface flux. Eddy correlation measurements may become poor estimates of the surface flux since horizontal transport between the sensors and ground surface may be large (Sun et al., 1998).

Here, the divergence of the heat flux between the 1.7-m observational level and the surface was estimated to be small except during warming events. In the early evening and late evening very stable periods of the case study, the net radiation is balanced primarily by heat flux from the soil. In the middle of the night during the turbulent period, the net radiation is balanced primarily by downward sensible heat flux.

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