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The influence of the depth of a very shallow cool-pool lake on nocturnal cooling

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ABSTRACT

Cold air pools (CAPs) may develop during nights in very shallow depressions. The depth of the stagnant air within a CAP influences the process of the cooling of nocturnal air and the resulting minimum temperature. A seven-month long field experiment was performed during winter 2013/2014 in an orchard near Krško, Slovenia, located inside a very shallow basin only a few metres deep and approximately 500 m wide. Two locations at different elevations inside the basin were selected for measurement. The results showed that the nights (in terms of cooling) can be classified into three main categories; nights with overcast skies and weak cooling, windy nights with clear sky and strong cooling but with no difference in temperatures between locations inside the basin, and calm nights with even stronger cooling and significant temperature differences between locations inside the basin. On calm nights with clear skies, the difference at two measuring sites inside the basin can be up to 5 °C but the presence of even weak winds can cause sufficient turbulent mixing to negate any difference in temperature. To better understand the cooling process on calm, clear nights, we developed a simple 1-D thermodynamic conceptual model focusing on a very shallow CAP. The model has 5-layers (including two air layers representing air inside the CAP), and an analytical solution was obtained for the equilibrium temperatures. Sensitivity analysis of the model was performed. As expected, a larger soil heat conductivity or higher temperature in the ground increases the morning minimum temperatures. An increase in temperature of the atmosphere also increases the simulated minimum temperatures, while the temperature difference between the higher and lower locations remains almost the same. An increase in atmosphere humidity also increases the modelled equilibrium temperatures, while an increase of the humidity of the air inside the CAP results in lower equilibrium temperatures. The humidity of the air within the CAP and that of the free atmosphere strongly influence the differences in equilibrium temperatures at higher and lower locations. The more humid the air, the stronger the cooling at the lower location compared to the higher location.

1. Introduction

The motivation for this research came from topographic modifications to an orchard in SE Slovenia, where dikes were heightened to protect against flooding. Since the dikes surround the orchard on two sides with a neighbouring hill on the third side, the orchard was in a shallow depression (ca. three metres on average). The depression floor is generally flat (on alluvial ground beside a river) but does contain some smaller recesses and bulges; the strongest recesses are those of the old river oxbows, which were filled with gravel or earth and only partly levelled. The recent elevation of dikes approximately doubled the average depth of the depression to approx. six metres (some individual recesses are deeper). The main question is how much the height of dikes or the depth of recesses influence nocturnal cooling and the resulting minimum temperatures.

It is well known that morning temperatures are lower in a concavely shaped relief features than in open terrain (e.g. Whiteman et al., 2004). The agricultural use of land thus traditionally respects such natural constraints imposed by the local microclimatic conditions; for example, in a hilly landscape, orchards are planted in the “thermal belts” defined as “an elevation band along mountain and other terrain slopes where nighttime surface temperatures remain relatively mild compared with temperatures above and below” (AMS Meteorological Glossary).

Several field campaigns have been performed to evaluate different microclimatic characteristics in orchards (e.g. Dupont and

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Patton, 2012). However, it seems that no field campaign has been focused on spatial differences inside a very shallow cold-air pools (CAPs) that are only a few metres deep. Many other field campaigns studied CAPs in different basins and valleys, but all of them were much deeper. Several conclusions from observations and from these experiments are generally valid for all CAPs, but several also depend on the relief (e.g. Petkovšek, 1978a, 1980; Whiteman et al., 2004, 2008). Although extreme temperature minima were recorded in relatively deep basins (e.g. Clements et al., 2003; Steinacker et al., 2007), it was shown by Whiteman et al. (2004) that minimum temperature depends mainly on the sky-view factor (Oke, 1978) and on the absolute elevation of the site (both influencing the net radiation), but not much on the depth of the basin. Strong temperature inversions normally develop in basins at the top of CAP (e.g. Petkovšek, 1978b; Clements et al., 2003). If fog forms in CAPs, it mainly changes the radiation regime and consequently weakens the inversion at the bottom and strengthens it at the top of CAP. Fog also supports the CAP in persisting for several days (e.g. Lareau et al., 2013). The CAPs in closed basins may fill up with cold air to the top, which usually results in calm weather inside the CAP with only weak turbulence, which was observed by Petkovšek (1992) and supported by numerical simulations (e.g. Rakovec et al., 2002; Zängl, 2005). Even with strong wind above the CAP, the turbulent mixing cannot penetrate from above into the inversion layer. CAPs also form in open-ended valleys where the outflow and drainage of cold air is present (e.g. Vosper et al., 2014). In such valleys, the outflow speed of cold air can be ~1 m/s (e.g. Price et al., 2011), and the drainage flow maximum velocity can be observed as low as 0.5 m above ground (Mahrt et al., 2014).

Thermodynamic properties of very shallow CAPs are the subject of the present study. The nearly flat terrain inside the pool may contain smaller terrain variations characterized by local depressions or convexities. As a consequence, the microclimatic conditions may vary on short distances due to natural conditions. Such concavities influence the CAP and could be quantitatively evaluated (e.g. Laughlin and Kalma, 1987; Chung et al., 2006; Lundquist et al., 2008). The microclimatic conditions can also change due to newly built infrastructure around the CAP, such as a new mound or dam. The change of microclimate inside a CAP results in changes in exposure to frost, which can affect the output of orchard produce. Sometimes artificial barriers are also used in just opposite way, i.e. for protection from frost (e.g. Snyder and de Melo-Abreu, 2005). Perhaps the closest to our consideration is the study by Horlacher et al. (2012) who reported great differences in measured temperatures on short distances that "... during stable conditions may be caused by cold air pooling at the valley site, despite the very shallow orography there."

We define a very shallow basin as a basin that is only a few metres deep, and that has a much larger horizontal extent (a few hundred metres or more) so that the ratio of the horizontal to the vertical extent is ca. 100:1 or greater. An example of a large, very shallow basin is the aforementioned orchard in SE Slovenia near the city of Krško: a horizontally large basin on a nearly flat terrain surrounded by a dike or a dam. The CAPs in such a basin differ from those in deeper basins. Compared to a deeper CAP, a very shallow CAP is much shallower, which allows it to fill up with cold air quickly. A very shallow basin also usually has a high sky-view factor. In a deeper basin, the CAP forms partly due to katabatic flow and mostly due to the net long-wave radiative loss from the uppermost soil layer, which is also affected by a reduced view of the sky due to the pronounced concave basin shape (Whiteman et al., 2004). A very shallow CAP also forms due to long-wave radiative loss from the surfaces, but the sky view factor does not play a role since any point of the terrain inside the basin can have almost a fully unobstructed view of the sky, and the katabatic flow is limited, since the basin is shallow with a small slope of the basin floor and without outflow.

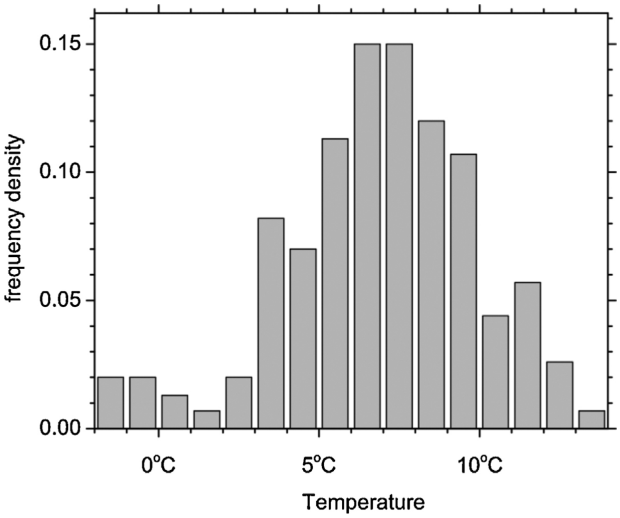

Fig. 1. Empirical frequency density for minimum daily temperatures 2 m above ground in open terrain at Krško for the last ten days of April.
Data provided by Slovenian Environmental Agency.

A phenological and climatological study of the region of interest was performed by Žust (2002). The study was performed for the 1990–1999 period and showed that apples (sp. Jonathan) and pears (sp. William) start blossoming from middle April to the beginning of May. Fig. 1 shows the frequency distribution of daily minimum temperature in the open terrain in the last ten days of April in the 1965–2010 period. The figure shows that the frequency of frost danger in open terrain is non-negligible.

The relevant questions here are the following. How big can be the observed difference between morning temperatures on open terrain and inside a shallow basin? How often does a significant temperature difference appear? How is the temperature difference influenced by cloudiness and wind? How does the minimum temperature depend on the thickness and properties of the stagnant air inside a very shallow CAP? How does the minimum temperature depend on the properties and temperature of the soil and the free atmosphere? Could the frequency of frost damage be markedly higher in deeper parts of CAP?

To answer these questions, we performed a field experiment and developed a simple one-dimensional radiative model for a very shallow CAP. The field experiment is described, including a detailed description of the orchard and the measuring equipment, in Section 2. The main experimental findings are given in Section 3. The model concepts and formulation are presented in Section 4, followed by discussion and conclusions in Section 5.

2. The field experiment

For analyzing the impact of different depths of CAP on the nocturnal cooling, we selected two locations in an orchard within a very shallow basin and performed a seven-month field experiment in winter 2013/2014. The orchard is located in SE Slovenia, where the sub-alpine climate of central Slovenia is gradually changing to the sub-continental climate of the Pannonian basin. Although the orchard is on nearly flat alluvial terrain, it is also below the slopes of the neighbouring hilly region north of it. On the west and south sides, the orchard is surrounded by approx. 3–5 m high dikes as a protection against flooding from the nearby river. On the eastern side, the terrain is more open, since the only obstacle is a road