On the local day time urban heat island of an idealized 2D city

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ABSTRACT

This study investigates the energy budget of the day time urban heat island effect for an idealized 2D geometry. A transient building-resolving simulation model has been developed, which computes radiative transfer, conduction, ventilation and mean radiant temperature at a 1 meter spatial resolution. A range of canyon height to width ratios (H/W) are used, ranging from H/W=0.0, 0.5, 1.0, 2.0 and 4.0. Results indicate that absorbed short wave radiation has the largest contribution to the energy budget, and exceeds that of the flat terrain due to increased multiple reflections for lower H/W ratios. The long-wave trapping effect has the second largest contribution but becomes relatively larger with increasing H/W ratio. Sensible heat has two distinct regimes, where for H/W≤1.0, the canyon is well mixed. For deeper canyons, a stable stratification is formed in the lower part of the canyon. The latent heat flux process reduces the surface temperature by as much as 12K, which can lead to different vortex dynamics and increase air temperature at street level. Mean radiant temperature is dominated by short wave radiation, and for H/W≤1.0 exceeds that of the flat terrain. For deeper canyons, shading and the reduced sky view factor reduce mean radiant temperature quickly. Surface temperature and mean radiant temperature are closely related, since both are largely dominated by radiative properties. No straightforward link was found between surface temperature and air temperature, since air temperature is dependent on forced convection and buoyancy forces. Large variations are found within one street canyon.

1. Introduction

The night time Urban Heat Island (UHI) phenomena is a well known effect, showing a reduced decrease in air temperature of 1 to 10 Kelvin compared to the rural environment (Oke 1981; Klysik and Fortuniak 1999; Kim and Baik 2004; Grimmond 2007; Steeneveld et al. 2011). However, the day time UHI effect is much smaller and can even be negative (Taha 1997; Klysik and Fortuniak 1999; Ryu and Baik 2012). The UHI effect is defined as the air temperature difference between the urban and rural environment, but is often a difficult parameter to measure. In part this is due to the extreme difficulty in observing the urban boundary layer at multiple locations. When interpreting profiles from a single measurement location, the effect of advection across the heterogeneous urban surface should also be taken into account (Barlow 2014). To overcome this problem, surface temperature can be used which can be obtained from (for instance) satellite data and gives an overview over a large domain (city scale). Large differences between the urban and rural environment can be observed during the day, up to 10K in the summer (Klok et al. 2012) and 7K annually averaged (Peng et al. 2012). Differences are not only present between the urban and rural environment, but also within the city and even within a single street canyon due to (amongst others) shading effects and changes in the sensible heat flux, that can be between 25 - 40% within a neighbourhood area (Schmid et al. 1991). In addition to the air temperature and surface temperature, there is a third temperature which is interesting to look at during day time: mean radiant temperature. This is a radiative temperature indicative for the radiative comfort, and is used in the computation of apparent temperatures like the Physiological Equivalent Temperature PET (Höppe 1999) and the Universal Temperature Climate Index UTCI (Fiala et al. 2012).

These different temperatures are linked through radiative and convective processes, but it is hard to know the exact conversion a priori. Therefore, this study will focus not only on air temperature, but also on surface temperature and the mean radiant temperature.

Klysik and Fortuniak (1999) studied the atmospheric UHI effect of Lodz, Poland by using

fixed point measurements from a weather station in the city centre over a long time period. It was found that on days when the weather is dominated by solar radiation, there are big thermal contrasts within the city. Close to the ground in areas with high building density, the air may be cooler than the rural environment due to shading of the ground surface. Roofs play an important role in that scenario, since they can form a layer of warm air, creating a local stable inversion layer, thereby limiting the vertical exchange of air in the street canyons.

In an overview study by Taha (1997), effects of changing surface albedo and latent heat release are discussed. It was found that altering the surface albedo from 0.25 to 0.40 could reduce localized afternoon air temperatures as much as 4K. The study also indicated that vegetation canopies can create 'oases' that are 2 to 8K cooler than their surroundings due to increased evaporation of water.

A systematic study of different physical processes was performed with the meso-scale model WRF (Weather and Research Forecasting model) by Ryu and Baik (2012), where three main causative factors were identified: anthropogenic heat, impervious surfaces (which included the reduction in surface moisture availability and increased thermal inertia) and 3D urban geometry (additional heat sored in vertical walls, radiative trapping and reduction in ventilation). The building height (H) over street width (W) ratio (H/W) used in this study is H/W=1.0. Their study indicated that during day time the impervious surfaces contributes most to the urban heat island (+2.1K), while the 3D urban geometry actually cools the city (-0.5K). In total, they found that the air temperature inside the city is 2.1K warmer than the surrounding rural area.

When mean radiant temperature is considered, Lindberg et al. (2008) indicated that it can vary largely during the day, with a peak value of 328K. This was obtained from measurements in Goteborg (57° 42' N, 11° 58' E) on a large open square in the city centre. Results for measurements in a courtyard showed a mean radiant temperature of 290K when the measurement location was shaded. If the measurement location was directly illuminated by the sun, mean radiant temperature peaked at 300K, showing not only the large spatial,

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⁷⁷ but also temporal variability.

⁷⁸ The goal of this study, conducted within the Dutch Climate Proof Cities consortium

⁷⁹ (Albers et al. 2014) is to find the mechanisms that control day time surface temperature,

⁸⁰ air temperature and mean radiant temperature on the scale of individual obstacles. The

⁸¹ micro-scale model discussed in Schrijvers et al. (2014) is used, which couples a Monte-Carlo

⁸² radiative transfer model, 1D heat conduction equation for the conductive heat flux into

⁸³ buildings and ground and a Computational Fluid Dynamics (CFD model) for the convective

⁸⁴ heat fluxes. A similar case set-up is used as in Schrijvers et al. (2014), where a range of

⁸⁵ H/W ratios are considered (0.0, 0.5, 1.0, 2.0, 4.0) as well as different physical mechanisms.

⁸⁶ Starting from radiative equilibrium, complexity is added by including the conductive heat

⁸⁷ flux, sensible heat flux and finally the latent heat flux.

⁸⁸ Section 2 will shortly discuss the model and case set-up. Results will be discussed in

⁸⁹ section 3. Our final goal is two-fold: 1) disentangle the mechanisms involved in the urban

⁹⁰ heat budget and 2) study the relation between surface temperature, air temperature and

⁹¹ mean radiant temperature.

2. Methods and case set-up

⁹³ The transient building-resolving model used in this study is the same as used in Schrijvers

⁹⁴ et al. (2014). Therefore, only a short description will be given here. Extensions of the model

⁹⁵ for this study are discussed in more detail.

⁹⁶ *a. Radiative transfer*

⁹⁷ Radiative transfer is computed by a Monte-Carlo model, where photon paths are com-

⁹⁸ puted for four radiative components: 1) diffuse short wave radiation, 2) direct short wave

⁹⁹ radiation, 3) long wave radiation emitted by the sky and 4) long wave radiation emitted by

¹⁰⁰ a surface.

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Photon packets are emitted at the top of the domain (radiation types 1, 2 and 3) or at a surface (radiation type 4). A photon packet (consisting of multiple photons) is used to increase convergence speed. The photon packet's trajectory is computed from cell face to cell face until a surface is hit. A fraction of the energy $(1 - \xi)$ is absorbed, which is related to the albedo (short wave radiation) or emissivity (long wave radiation). The remainder of the energy travels further in a random direction, which is computed based on the Lambertian cosine law. Photon packets with less then 0.5% of the initial energy are discarded to decrease computation time. Periodic boundary conditions are applied, such that photon packets can only leave the domain through the top boundary. The magnitude of the short wave radiative flux is based on a parametrisation proposed by Skartveit et al. (1998). In this model, short wave radiation and the splitting between direct and diffuse radiation is based on the solar constant I, Julian date d_n, latitude, longitude, Linke turbidity factor T_L (Kasten 1996) and the solar zenith angle γ, which is computed following Iqbal (1983). Although the parameterisation allows for cloudy skies, this is not taken into account in the current model, which results in a maximum direct short wave radiative flux of 833.1 Wm^{-2} and a maximum diffuse short wave radiative flux of 84.2 Wm^{-2} at mid day for this study.

The emitted long wave radiation by the sky is computed following the Stefan-Boltzmann law, where it is assumed that all long wave radiation is emitted at the top of the domain. The emissivity of the sky is computed following Prata (1996) as

$$\epsilon_{sky} = 1 - \left(1 + c\frac{e_a}{T_a}\right) \times \exp\left[-\sqrt{1.2 + 3.0 \times c\frac{e_a}{T_a}}\right] \tag{1}$$

where e_a is the water vapour pressure (in hPa), T_a the air temperature (in K) and $c = 46.5$ K/hPa is constant based on typical values for the water vapour scale height and temperature lapse rate (Prata 1996).

Kirchoff's law is assumed for broadband radiation, indicating that the same value is used for reflection and emission of long wave radiation at the surface ($\alpha = \epsilon$).

b. Mean radiant temperature (T_{mrt})

In addition to the existing model, computation of the mean radiant temperature (T_{mrt}) is added. The mean radiant temperature is computed by

$$T_{\mathrm{mrt}} = \sqrt[4]{\frac{S_{\mathrm{str}}}{\epsilon_{\mathrm{p}}\sigma}} \tag{2}$$

where S_{str} is the local mean radiant flux density, ϵ_{p} the emissivity of the human body (with a standard value of 0.97) and σ the Stefan-Boltzmann constant.

The mean radiant flux density can be regarded as the amount of radiation (both short wave and long wave) that is absorbed by a person. It is computed by

$$S_{\mathrm{str}} = \alpha_{\mathrm{k}} \sum_{i=1}^{6} K_i F_i + \epsilon_{\mathrm{p}} \sum_{i=1}^{6} L_i F_i \tag{3}$$

where α_{k} is the albedo of the human body (with a standard value of 0.7), K_i the total short wave radiative flux, L_i the total long wave radiative flux and F_i a geometric factor representing a standing human body. A summation is done over the 6 cardinal points, where the geometric factor is set to 0.22 for radiation hitting the human body from the east, west, south and north direction, while the geometric factor is set to 0.06 for radiation entering from the top and bottom. Since a 2D setting is used in this study, the north and south component are non-existing, and are taken as the average of the east and west component.

Instead of computing T_{mrt} at each time step, this is done as a post processing action after the full simulation has converged. T_{mrt} is a function of all radiative components (and thus also surface temperature, due to emitted long wave radiation by the surface). The surface temperature for a specific time-step is used, and all radiative components are computed. Recomputing comes with the additional cost of computation time, but is less memory intensive.

Within the Monte-Carlo model, computing the mean radiant flux density is a question of book keeping, where the amount of radiative flux entering a grid cell is stored per direction

¹⁴⁷ and radiation type.

c. Mean radiant temperature validation

¹⁴⁹ The computation of T_{mrt} is validated against analytical results by Madronich (1987). In

¹⁵⁰ this paper, a clear derivation of the actinic flux (also called integrated density or flux density)

¹⁵¹ is given and analytical data is presented.

¹⁵² Validation of the Monte-Carlo model is conducted by considering two cases. In the first

¹⁵³ case direct radiation of 800 Wm^{-2} is emitted with a solar zenith angle of 0 degrees onto a

¹⁵⁴ diffuse scattering surface with albedo $\alpha{=}1$ (no absorption). Madronich (1987) derived that

¹⁵⁵ the upward reflected energy equals that of the downward radiative energy (800 Wm^{-2} in this

¹⁵⁶ case), while the sidewards components (east and west flux density) are half of the incoming

¹⁵⁷ energy (400 Wm^{-2}). Results are shown in Fig. 1, where the top left panel shows spatial

¹⁵⁸ information on the eastward flux for the whole 2D domain, while the bottom left panel shows

¹⁵⁹ extracted lines for all flux directions. The top left plot shows that the eastward component

¹⁶⁰ is 400 Wm^{-2} (50%) of the incoming direct radiation for the whole domain. There are

¹⁶¹ small spatial differences due to the Monte-Carlo method, which are around 2 Wm^{-2}. These

¹⁶² fluctuations will decrease with increasing number of photons. The bottom left panel shows

¹⁶³ extracted lines within this domain, where the top and bottom flux are 800 Wm^{-2}, while the

¹⁶⁴ east and westward flux are 400 Wm^{-2}, as expected from Madronich.

¹⁶⁵ The second case is conducted by emitting diffuse radiation (100 Wm^{-2}) from the top of

¹⁶⁶ the domain onto the same diffuse scattering surface used in the previous case. Since there

¹⁶⁷ is now also diffuse radiation from the top, it is derived that the radiative flux density is

¹⁶⁸ equal in all directions. This is shown in the right panels of Fig. 1, where the top right

¹⁶⁹ panel shows the spatial differences for the eastward flux, while the bottom panel shows the

¹⁷⁰ extracted lines. Spatial differences show indeed an uniform distribution of 100 Wm^{-2} with

¹⁷¹ fluctuations of 0.5 Wm^{-2}. Also the line plots (bottom right) show that all fluxes have the

¹⁷² same magnitude of 100 Wm^{-2}.

d. Conductive heat flux

The conductive heat transfer is computed by the temperature gradient inside the urban material

$$G_i = \lambda \frac{\partial T}{\partial x_i} \qquad (4)$$

where λ is the thermal conductivity of the material. The temperature profile is computed by the 1D heat conduction equation

$$\frac{\partial T}{\partial t} = k_{\mathrm{d}} \frac{\partial^2 T}{\partial x_i^2} \qquad (5)$$

where k_{d} is the thermal diffusivity, based on the conductivity λ, density ρ and specific heat C_{v} of the ground or obstacle

$$k_{\mathrm{d}} = \frac{\lambda}{\rho C_{\mathrm{v}}} \qquad (6)$$

A zero flux boundary condition is used at a distance Δx into the ground or obstacle. Fifty layers are used, along with a time step of 1 second. The second boundary condition that is used is the surface temperature. Although a time step of 1 second is used to compute the temperature profile, surface temperature is updated every 6 minutes, indicating that the conductive heat flux only updates the first boundary condition at this time period.

e. Computational Fluid Dynamics (CFD) model

Ventilation effects are computed by an in-house developed CFD model (Kenjeres and Hanjalic 1999, 2006, 2009; Kenjeres and ter Kuile 2013). This model uses the Transient Reynolds-Averaged Navier-Stokes (T-RANS) equation to solve the wind field and air temperature distribution.

The unknown Reynolds stress $\overline{u_i u_j}$ is computed by using the $k - \epsilon$ turbulence model, which relates the turbulent stresses to the turbulent kinetic energy (TKE) and dissipation of TKE.

$$\nu_{\mathrm{t}} = C_{\mu} k \tau \tag{7}$$

$$\frac{\partial k}{\partial t} + U_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_{\mathrm{t}}}{\sigma_{\mathrm{k}}}\right)\frac{\partial k}{\partial x_j}\right] - \\ \overline{u_i u_j}\frac{\partial U_i}{\partial x_j} - \epsilon - g_i \beta \overline{\theta u_i} \tag{8}$$

$$\frac{\partial \epsilon}{\partial t} + U_j \frac{\partial \epsilon}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_{\mathrm{t}}}{\sigma_{\epsilon}}\right)\frac{\partial \epsilon}{\partial x_j}\right] + \\ \frac{\epsilon}{k}\left(C_{\epsilon 1}\overline{u_i u_j}\frac{\partial U_j}{\partial x_i} - C_{\epsilon 2}\epsilon + C_{\epsilon 3}g_i \beta \overline{\theta u_i}\right) \tag{9}$$

where k is the turbulent kinetic energy, ϵ is the dissipation and C_{μ}, σ_k, σ_{ϵ}, $C_{\epsilon 1}$, $C_{\epsilon 2}$ and $C_{\epsilon 3}$ are constants, taken from the standard $k - \epsilon$ model (see table 1).

It is known that the standard $k - \epsilon$ model over predicts the amount of turbulent kinetic energy at stagnation points (Durbin 1996). To compensate for this, the Durbin time-scale limiter τ is used, which bounds the turbulent viscoscity and therefore also the turbulent kinetic energy.

$$\tau = \min\left[\frac{k}{\epsilon}, \frac{0.6}{\sqrt{6}C_{\mu}|S|}\right] \tag{10}$$

where $|S|$ the strain rate tensor.

Next to the velocity field, the temperature field is solved by using the T-RANS equations. The unknown turbulent heat flux $\overline{\theta u_j}$ requires modelling, and is solved by using the Simple Gradient Diffusion Hypothesis (SGDH), where the turbulent flux is related to the temperature gradient.

$$-\overline{\theta u_i} = \frac{\nu_{\mathrm{t}}}{\mathrm{Pr}_{\mathrm{t}}}\frac{\partial T}{\partial x_i} \tag{11}$$

where Pr_{t} is the turbulent Prandtl number, set to 0.86.

This allows us to compute the sensible heat flux following

$$H_i = \rho c_\mathrm{p} \overline{\theta u_i} \tag{12}$$

where ρ is the density of air (1.208 kgm^{-3}) and c_p the specific heat capacity of air (1004 Jg^{-1}K^{-1}).

f. Latent heat flux

As an extension of the model, the latent heat flux process is taken into account which is computed by using the Bowen ratio ψ. This couples the sensible heat flux to the latent heat flux in a simple but effective manner.

$$Le_i = \frac{H_i}{\psi} \tag{13}$$

The latent heat flux process is only added if the sensible heat flux is positive $H_i \geq 0$. Negative latent heat flux is not taken into account.

g. Integrated energy balance model

All sub-models compute a part of the total surface energy balance, which dictates that all fluxes should balance

$$SW_\mathrm{dir} + SW_\mathrm{dif} + LW_\mathrm{sky} + LW_\mathrm{trap}$$
$$= LW_\mathrm{out} + H + Le + G \tag{14}$$

where SW_dir is the absorbed direct component of short wave radiation, SW_dif the absorbed diffuse short wave component, LW_sky the absorbed long wave radiation emitted by the sky, LW_out is the emitted long wave radiation by the surface, LW_trap the long wave radiation emitted by one surface and absorbed by another surface, H the sensible heat flux (where a

221 positive flux is heating of air), Le the latent heat flux (positive is evaporation of water) and

222 G the conductive heat flux (positive is adding energy to the underlying layers). Note that

223 multiple reflections are included in the terms of SW_{dir}, SW_{dif} and LW_{sky}.

224 The controlling parameter for the surface fluxes is the surface temperature, where a skin

225 layer is assumed to prevent large variations in surface temperature in time

$$\Delta_{\mathrm{skin}}\rho_{\mathrm{skin}}C_{\mathrm{v,skin}}\frac{\partial T_s}{\partial t} = \Gamma \tag{15}$$

226 where Γ is the flux imbalance resulting from the surface energy balance and $\Delta_{\mathrm{skin}}\rho_{\mathrm{skin}}C_{\mathrm{v,skin}}$=0.01.

227 For a time step, all fluxes in the surface energy balance are computed based on the surface

228 temperature of the previous time step. This can result in a small flux imbalance Γ. Based

229 on this imbalance and the old surface temperature, the surface temperature for the new time

230 step is computed.

231 *h. Test cases and research methodology*

232 To create a test-case suited to study the effect of different physical mechanisms as a

233 function of H/W ratio, an idealized 2D urban geometry is created consisting of 14 obstacles

234 which are spaced W=50 meter apart. By using 14 obstacles, a fully developed flow pattern

235 is found in the last street canyons, indicating that more obstacles would not change the

236 results. All buildings are B=25 meter wide, while building height is varied between 0 meter

237 (H/W=0.0), 25 meter (H/W=0.5), 50 meter (H/W=1.0), 100 meter (H/W=2.0) and 200

238 meter (H/W = 4.0) (see Fig. 2). By using this wide range of H/W ratio, a detailed analysis

239 can be made on the effect of changing building height.

240 Next to changes in building height, different mechanisms are switched on and off. Instead

241 of doing a full factor separation analysis like Ryu and Baik (2012), the simplest case of

242 radiative equilibrium is used as a starting point. From this basic case, complexity is added

243 by adding the conductive heat flux mechanism (case 2), sensible heat flux (case 3) and latent

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244 heat flux (case 4) (see table 3).

245 Ten days are considered in the middle of June, which is the month where the sun is
246 at its maximum zenith angle in the Netherlands. By using ten days, there quasi steady
247 state results are obtained that are independent on the initial conditions (the daily cycle is
248 repetitive). The time step that is used is 6 minutes. Other input parameters are shown in
249 table 2.

250 Results for Figures 4-7 are plotted according to the inset in Fig. 2, where all vertical
251 surfaces are scaled to a length of 1. This allows us to compare different H/W ratios in a
252 single plot.

253 3. Results

254 *a. Time series*

255 As a first introduction to the results, time series are shown in Fig. 3 for one point
256 in the middle of the street canyon between obstacle 12 and 13. In this figure, the left
257 panel shows the surface temperature for different H/W ratios and the right panel the total
258 absorbed radiation (both short wave and long wave) for this single point. The radiative
259 equilibrium case 1 is used. Results for the flat plate (H/W=0.0) show a diurnal cycle in
260 surface temperature and absorbed radiation. Surface temperature has a minimal value of
261 278K during night and peaks at 358K during day. When obstacles are added, the surface
262 temperature for H/W=0.5 exceeds that of the flat plate after mid day (dashed line) due
263 to increased multiple reflections. Also, a clear shading effect can be seen in the absorbed
264 radiation, where absorbed radiation is lower during the night and after sun rise, but peaks
265 very rapidly at mid day. If higher buildings are considered, the point in the centre of the
266 street is shaded throughout the day and surface temperature and absorbed radiation are
267 much lower compared to lower H/W ratios. The diurnal cycle is also less distinct, up to a
268 point for H/W=4.0 where there is almost no daily variation in surface temperature. In this

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case, the ground surface receives only a very limited amount of short wave radiation due to shading effects. The small portion of short wave radiation that is absorbed at ground level, comes from multiple reflections and involves much less energy. Note that the surface temperatures for H/W=4.0 are extremely low, since this is only determined by the amount of absorbed radiation. There are no compensating mechanisms to increase surface temperature for this case.

The dashed line in the middle of the last diurnal cycle indicates the point in time where spatial analysis will be conducted on the different fluxes.

b. Radiation

Fig. 4 displays the absorbed radiative components for mid day for case 1 (radiative equilibrium). Absorbed long wave radiation from the sky is shown in the top left panel, and shows a decreasing absorbed long wave radiation due to the reducing sky view factor with increasing H/W ratio. For H/W=0.5, the peak absorbed radiation in the middle of the ground surface is reduced to 75.5% of the radiation absorbed by the flat plate, while the ground surface for H/W=4.0 receives 12% of the radiation absorbed by the flat terrain.

The top right panel shows the absorbed radiation due to long wave trapping. This is 0 Wm^{-2} for H/W=0.0, since there is no absorption at any surface. For H/W=0.5 a clear peak can be seen between the ground and west wall, where the amount of absorbed energy is largest. This is due to the high surface temperature in that region, combined with the corner being the favourable location for long wave trapping. For H/W=1.0, the long wave trapping effect is stronger at the shaded part of the ground compared to H/W=0.5. For the other canyon surfaces, there is less absorbed long wave radiation compared to H/W=0.5. With increasing H/W ratio, the magnitude of the long wave trapping effect reduces. Although the canyon geometry allows for more long wave trapping, the emitted long wave radiation LW_{out} is lower and thus there is less energy that can be trapped.

The total absorbed short wave radiation (direct and diffuse component) is shown in the

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bottom left panel. Multiple reflections can be observed at ground level, where the absorbed short wave radiation exceeds that of the flat terrain for H/W=0.5 and H/W=1.0. Also the shadow location on the ground can be observed, where H/W=1.0 shows more shadowing of the ground surface compared to H/W=0.5. For H/W=2.0 no part of the ground surface is directly illuminated.

If finally all absorbed radiative components are added, this balances the emitted long wave radiation from the surfaces, due to our assumption of radiative equilibrium. This is shown in the bottom right panel, and shows a clear peak in emitted radiation for H/W=0.5 and H/W=1.0 at the lower corner between ground and west wall, where emitted long wave radiation exceeds that of the flat plate. The long-wave trapping effect and absorbed short wave radiation are about equal in magnitude, while the contribution from absorbed long wave radiation emitted by the sky is much smaller.

c. Surface temperature

From the radiative equilibrium case that is used to display the spatial radiative patterns, more physical mechanisms are added to see the effect on surface temperature. This is shown in Fig. 5 for different H/W ratios (subplots) and cases (coloured lines). For the flat plate, this shows a surface temperature of 355K for the radiative equilibrium case (case 1). If the conductive heat flux process is added, energy is transferred into the ground, therefore reducing surface temperature by 20K. The sensible heat flux process reduces surface temperature further, due to the free stream air temperature of 293.15K. Latent heat flux is applied with a Bowen ratio of 1.0 (latent and sensible heat flux have the same magnitude), but only if sensible heat flux is positive. This shows a further reduction in surface temperature of 10K, resulting in a surface temperature of 312K for the flat terrain. Due to our assumption of the Bowen ratio, latent heat is a sink of energy where there is only feedback through the reduced surface temperature. This does not only affect the sensible heat flux, but also the conductive heat flux and emitted long wave radiation.

If obstacles are added, the effect of short wave radiation is clearly demonstrated for obstacles with H/W=0.5 and H/W=1.0, where a part of the ground and the west wall are directly illuminated and therefore have a much higher surface temperature compared to the east wall. This effect is smaller for deeper canyons, where only a portion of the west wall is directly illuminated.

The conductive heat flux shows different behaviour in the sunlit and shaded part of the canyon for H/W≤1.0. If the surface is in the shaded part of the canyon, the conductive heat flux shows only a small effect on surface temperature. On the sunlit part of the canyon, the conductive heat flux mechanisms reduces surface temperature, since energy is transferred into the sub-layers. For H/W>1.0, the conductive heat flux raises surface temperature throughout the canyon, except for the small part of the west wall that is directly sunlit.

The surface temperature including the sensible heat flux process (case 3) shows a different pattern for the west and east walls of the canyon. For the west wall, colder ambient air is forced over the warm surface, therefore reducing surface temperature. The air inside the canyon is heated and then forced over the colder (shaded) east wall, showing a much smaller reduction in surface temperature. For H/W≥2.0 there is an effect of the sensible heat flux in the top part of the canyon, which was also shown in the night situation (Schrijvers et al. 2014). Forced convection is only able to penetrate the top part of the canyon, showing an increase in surface temperature in that region. Further down into the canyon, wind speeds are small and a stable stratification is apparent, where the sensible heat flux shows almost no contribution to the surface temperature.

If the latent heat flux is added, this only shows an effect on the west wall and the sunlit part of the ground (regions where the sensible heat flux was positive). For H/W=0.5, the effect is modest, with a reduction in surface temperature of 4K on the west wall. For H/W=1.0 surface temperature is reduced by 12K in the corner between street and west wall compared to the case without the latent heat flux process. The case for H/W=2.0 did not converge to a solution, where the CFD model has large difficulties with the stable

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stratification. The simulation shows re-laminarization of the flow field, which violates the basic assumption (a fully turbulent flow) of the $k - \epsilon$ turbulence model. For H/W=4.0, the effect of the latent heat release is very small, since the sensible heat flux itself shows only a very small effect inside the canyon.

d. Surface fluxes

From the surface temperature plots, one can see qualitatively which processes are more important. However, to get a more quantitative view, all individual fluxes are plotted in Fig. 6 for different H/W ratios (sub plots) and surface fluxes (coloured lines) for case 3 (including conductive and sensible heat flux, but excluding latent heat). The case including latent heat will be discussed later. In this plot, all absorbed radiation entering from the sky (SW_{dir}, SW_{dif} and LW_{sky}) are combined. Also note that positive values of LW_{out} G and H indicate a cooling tendency.

This shows that for the flat plate the absorbed radiation contributes 900 Wm^{-2} to the surface, while 600 Wm^{-2} is emitted through LW_{out}. This energy surplus is compensated by the conductive heat flux (140 Wm^{-2}) and sensible heat flux (160 Wm^{-2}). The contribution of the conductive heat flux is 15% of the total absorbed radiation, which is slightly higher than the 10% that was found by De Bruin and Holtslag (1982). If the latent heat flux process is added, this 10% is exactly matched.

If cases including obstacles are considered, absorbed radiation remains the dominant factor, although the absorbed radiative fluxes are rapidly decreasing with increasing H/W ratio. This is largely due to the short wave radiation (see Fig. 4), which is rapidly decreasing. The long wave trapping effect is also reducing with increasing H/W ratio, but is in general larger than the conductive or sensible heat flux. The long wave trapping effect is relatively increasing with increasing H/W ratio, where long wave trapping is of equal magnitude as absorbed radiation for H/W=4.0 This shows the importance of radiation, where all radiative components dominate over the other fluxes.

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374 The conductive heat flux shows very small contributions at the east wall and top part of
375 the west walls. Only at the location where the absorbed radiation peaks is the conductive
376 heat flux active and transferring energy into the canyon material.

377 The sensible heat flux shows negative values at the east wall for all H/W ratios, indicating
378 that energy is added to the surface from the passing warmer air. The top west wall shows
379 the contrary, where energy is extracted from the warmer surface. For H/W=1.0, the shaded
380 part of the ground surface shows no sensible heat flux, indicating that air temperature and
381 surface temperature are equal. For deeper canyons, the sensible heat flux is very close to
382 zero for a larger part of the surface area. This is due to the low levels of turbulence in
383 combination with a small temperature gradient between surface and air, which are caused
384 by the very stable stratification that is formed during night and maintained during the day.

385 The effect of latent heat release is shown for H/W=1.0 in Fig. 7. Results for the case
386 without latent heat release are shown in the left panel (same as in Fig. 6) and results for case
387 4 (including latent heat) in the right panel. Adding the latent heat process reduces surface
388 temperature, and therefore also the amount of emitted long wave radiation, especially in the
389 bottom corner between ground and west wall. This impacts the long wave trapping effect
390 directly, since there is less energy that can be trapped. Adding the latent heat flux process
391 also impacts the sensible heat flux, where this is now negative (adding energy to the surface)
392 in the shaded part of the canyon. On the west wall, the sensible heat flux is larger compared
393 to the case without latent heat release, and is almost constant over the vertical wall. This
394 indicates a change in vortex dynamics. As a result, the conductive heat flux is also affected,
395 and is lower in the sunlit part of the canyon compared to the case without latent heat release.

396 *e. Air temperature*

397 Next to surface temperature, air temperature is of importance, which is a function of
398 wind speed, sensible heat flux and free stream air temperature. Results are shown in Fig. 8,
399 where air temperature and velocity vectors for case 3 (excluding latent heat) are shown. For

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H/W=0.5, a warm canyon is observed compared to the free stream air temperature, where one single vortex is present. From the west wall air is heated by the surface and forced towards the east wall, where the highest air temperature is found.

For H/W=1.0 there are two vortices present inside the street canyon. The first vortex covers the top right part of the canyon, where forced convection is dominant. However, since the west wall is heated, buoyancy effects become important and create a second counter rotating vortex in the lower part of the canyon. As a side effect, wind speeds are reduced due to this battle between forced and natural convection. Air in the bottom part of the street canyon is cooler then ambient air and can not escape due to the forced convection on top and the local stable inversion layer that is formed at the top of the canyon. This was also found in measurements by Klysik and Fortuniak (1999).

For H/W=2.0 there is only forced convection in the top part of the canyon and wind speeds are dramatically reduced towards ground level. As a results, sensible heat flux is diminished and air temperature is close to surface temperature. Since surface temperatures of the vertical walls are decreasing towards ground level, a very stable stratification is found, further preventing mixing of air. This stable situation is self maintaining, although the location of the top vortex is moving slight downward compared to the night situation. The same can be found for H/W=4.0, but even in a more extreme matter with air temperature close to the ground surface of 240K. This is due to our assumption of a 2D geometry, where there is only mixing through the top of the canyon.

If the case including latent heat is studied (case 4, H/W=1.0, see Fig. 9) an interesting change has occurred. While there are two vortices present when only sensible heat is included, there is only one vortex for case 4. The latent heat flux process reduces surface temperature, creating a smaller buoyancy force. This natural convection becomes smaller than forced convection and one vortex remains inside the canyon. This creates a well mixed canyon, without local inversion layers at the top of the canyon.

f. Mean radiant temperature

Next to surface temperature and air temperature, the mean radiant temperature is computed. This is shown in Fig. 10 for different H/W ratios at a height of 2 meter, where T_{mrt} is shown for case 3 (excluding latent heat, solid lines) and for case 4 (dash-dotted line). There is no scaling used on the x-axis. For the flat plate, this shows a mean radiant temperature of 345K for case 3. Inclusion of obstacles results in a large variation due to shading. The shadow location is shifted to the right when going from H/W=0.5 to H/W=1.0. The mean radiant temperature in the sunlit part exceeds that of the flat terrain due to multiple reflections and peaks at 355K. For H/W=2.0, there is no direct solar radiation, and all short wave radiation is either diffuse or reflected from obstacles, thereby lowering the amount of absorbed short wave radiation dramatically. This has a large impact on T_{mrt}, which decreases down to 270K. Mean radiant temperature is higher at the east part of the canyon for this H/W ratio, due to the multiple short wave reflections that reach this part of the canyon. T_{mrt} for H/W=4.0 is as low as 210K, and is not shown in this plot.

If the case including latent heat is considered (dash-dotted lines), lower mean radiant temperatures for all H/W ratios is found. Recall that the case including latent heat for H/W=2.0 did not converge, and is therefore not shown here. For H/W=0.0, this shows a decrease in T_{mrt} for the case including latent heat of 2.5K, while the surface temperature dropped by 7.0K in comparison to case 3. The mean radiant temperature is not only a function of surface temperature, but also of sky-based radiation (short wave and long wave emitted from the sky) and therefore shows a smaller change. This difference is however reducing with increasing building height, where H/W=1.0 shows a decrease in surface temperature of 4.2K (averaged over the canyon), while T_{mrt} is reduced by 3.0K. This shows that there is a clear relation between surface temperature change and change in mean radiant temperature.

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4. Discussion

This study focussed on the local day time urban heat island energy budget for an idealized 2D geometry. A transient building-resolving simulation model has been used, which combines radiation, conduction and ventilation at a 1 meter spatial resolution. A range of canyon height to width (H/W) ratios and physical mechanisms is considered.

Results showed that the daytime energy budget is dominated by radiation, where absorbed radiation from the sky (SW_{dir}, SW_{dif} and LW_{sky}) is the main source of energy at the surface, followed by the long wave trapping effect (energy emitted from the surface and absorbed at an other location). The radiative components are however decreasing with increasing building height, and the other fluxes become more important. The conductive and sensible heat flux are almost zero at the shaded parts of the canyon, while there is a significant contribution of both fluxes at the sunlit part. The sensible heat flux showed two distinct patterns, where for H/W>1.0 there is one vortex spanning the top of the canyon and a very stable flow situation at the lower part of the canyon. This is due to our 2D case set-up, where cold air can only leave the canyon at roof level. The addition of the latent heat flux process reduces surface temperature and can change the vortex dynamics. For H/W=1.0 there is only one vortex if the latent heat flux is taken into account, and air temperature remains warmer at street level.

Mean radiant temperature increased for H/W=0.5 and H/W=1.0 compared to the flat plate. This is due to the increased multiple reflections of short wave radiation. For deeper canyons, there is no direct sunlight reaching the street level, and mean radiant temperature drops quickly.

The link between surface temperature and mean radiant temperature can be made (at least from a quantitative point of view) relatively easy, since both are largely dependent on radiative properties. The link between surface and air temperature is much harder to make. Air temperature in the canyon is not only dependent on surface temperature, but also on free stream air temperature and wind speed. It was found that there are large

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spatial air temperature differences inside the canyon. This makes it difficult to find a proper parametrisation that holds for all H/W ratios and on every individual canyon surface. This is best displayed for H/W=1.0 for the case with and without latent heat, which shows different vortex dynamics and an increase in air temperature at street level while the surface temperature is decreasing when including the latent heat flux process.

There are some aspects that could be improved in this study, where the most obvious is off course the 2D case set-up. However, going to a 3D case, also comes with more complexity and interplay between all processes, and might therefore create less understanding of the basic phenomena. With the insights gained from this study, the additional effects when going to a 3D environment could be better understood.

Next is the simplification of using buildings which are all spaced equally and have uniform height. The same arguments as for the 2D-geometry can be made. Insight is gained for this simple case, which again comes with the cost of reduced realism.

Apart from these improvement on the case set-up, there are also model improvements, where a large improvement can be made in the CFD model that is used. It is known that the $k-\epsilon$ model has troubles with strong stratifications due to the assumption of a fully turbulent flow. It might be worth while to investigate other turbulence models (full algebraic stress models) or even a LES-framework. Next to this, the Simple Gradient Diffusion Hypothesis (SGDH) model for the closure of the turbulent heat flux can be improved by using a Generalized Gradient Diffusion Hypothesis (GGDH) or algebraic flux model. This requires more extensive validation of the CFD model, which in turn requires more wind tunnel studies including stratification effects.

The computation of the latent heat flux acts as a sink in the surface energy balance, where a direct feedback is lacking. It could be that a canyon becomes very humid by using the fixed Bowen ratio, but this has no impact on the latent heat flux. It is therefore interesting to solve the full moisture balance, which includes transport of moisture in the ground and obstacles and the transport of moisture through convective transport (using the CFD model). This

allows for a latent heat flux that is based on physical mechanisms.

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List of Tables

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C_μ	σ_k	σ_ϵ	$C_{\epsilon 1}$	$C_{\epsilon 2}$	$C_{\epsilon 3}$
0.09	1.0	1.3	1.44	1.92	1.44

TABLE 1. Model constants for the standard $k - \epsilon$ model.

Radiation	
Emissivity	0.95
Albedo	0.40
Latitude	52° 22' N
Longitude	4° 53' E
Start day	2012-06-10 00:00
End day	2012-06-20 23:59
Heat conduction	
λ	0.72 Wm^{-1}K^{-1}
ρ	1920 kgm^{-3}
C_{v}	835 Jkg^{-1}K^{-1}
CFD	
T_{a}	293.15 K
U	4.0 m/s
cell width	1.0 m
cell expansion	5 %
max cell size	25 m
ψ	1.0

TABLE 2. Input constants for radiation, heat conduction into the urban material and the CFD model.

Case	RAD	G	H	Le
1	+			
2	+	+		
3	+	+	+	
4	+	+	+	+

TABLE 3. Case set-up, where G is the conductive heat flux process, H the sensible heat flux process and Le the latent heat flux process.

List of Figures

FIG. 1. Eastward flux for direct short wave radiation (top left), eastward flux for diffuse short wave radiation (top right), direct short wave flux density for all directions (bottom left) and diffuse short wave flux density for all direction (bottom right). Input for the direct short wave radiation is 800 Wm^{-2} and 100 Wm^{-2} for the diffuse short wave radiation.

FIG. 2. Schematic of case set-up with changing H/W ratio. 14 buildings are spaced 50 meter apart, while building height (H) is varied. Plotting is done according to the inset in the top right.

FIG. 3. Time series for the radiative equilibrium case (case 1). The left panel shows the surface temperature at one point in the centre of the street canyon for different H/W ratios. The right panel shows the summation of absorbed radiation from SW_{dir}, SW_{dif} and LW_{sky}. The dotted lines indicate sunrise and sunset, the dashed line the time instance where spatial analysis is conducted for.

FIG. 4. Absorbed long wave radiation emitted by the sky (top left), absorbed radiation due to long wave trapping (top right), total absorbed short wave radiation (bottom right) and emitted long wave radiation by walls (bottom left) in case of radiative equilibrium (case 1) at mid day (indicated by the dashed line in Fig. 3). Plotting is done according to the inset at the top right.

FIG. 5. Surface temperature for different H/W ratios (sub plots) and different cases (coloured lines). Note the different temperature scale for each sub plot.

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FIG. 6. Surface fluxes for different H/W ratios (sub plots) and physical mechanisms (coloured lines) for case 3 (including conductive and sensible heat flux, but excluding latent heat flux). The same scale is used for all plots.
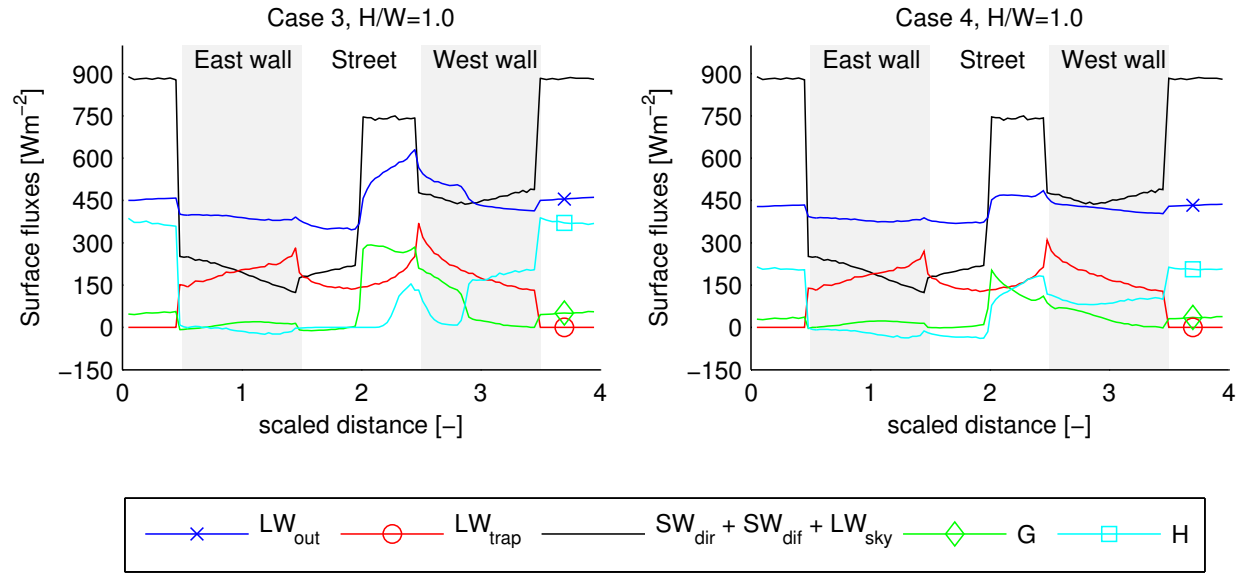
FIG. 7. Surface fluxes for H/W=1.0 and different physical mechanisms (coloured lines) for case 3 (excluding latent heat, left panel) and case 4 (including latent heat, right panel).
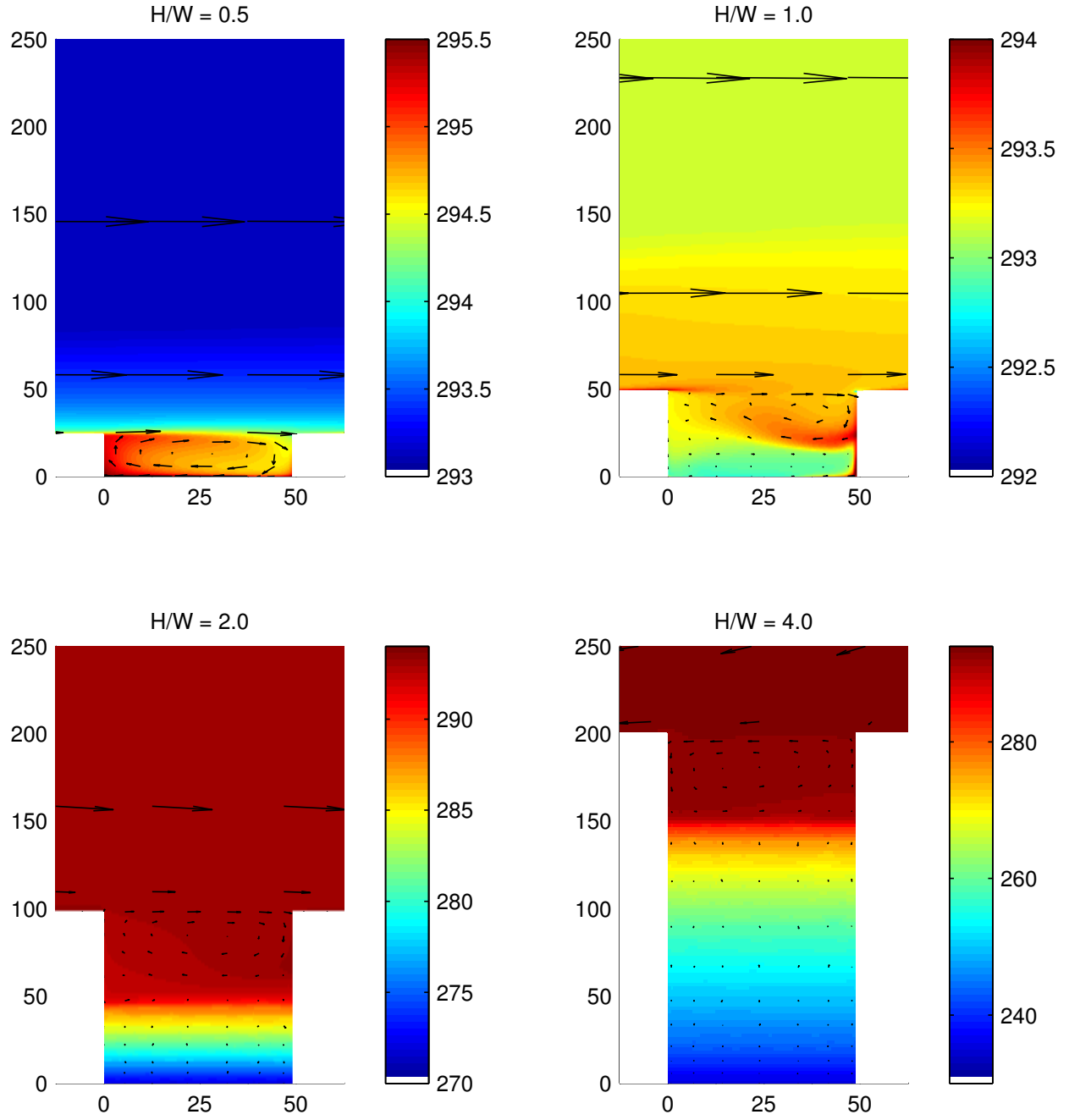
FIG. 8. Air temperature (K) and velocity vectors for case 3 (excluding latent heat) for different H/W ratios. Note the different temperature scales.
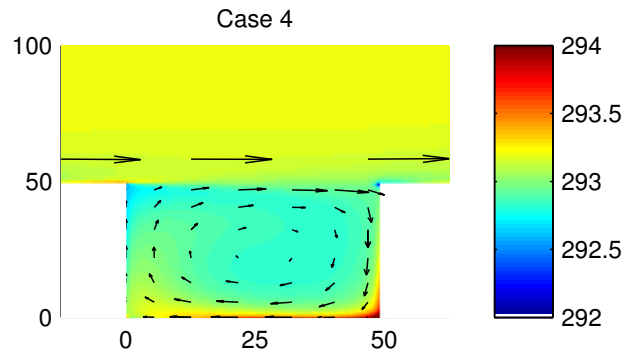
FIG. 9. Air temperature (K) and velocity vectors for H/W=1.0 for case 4 (including latent heat). The colour scale used is the same as for case 3.
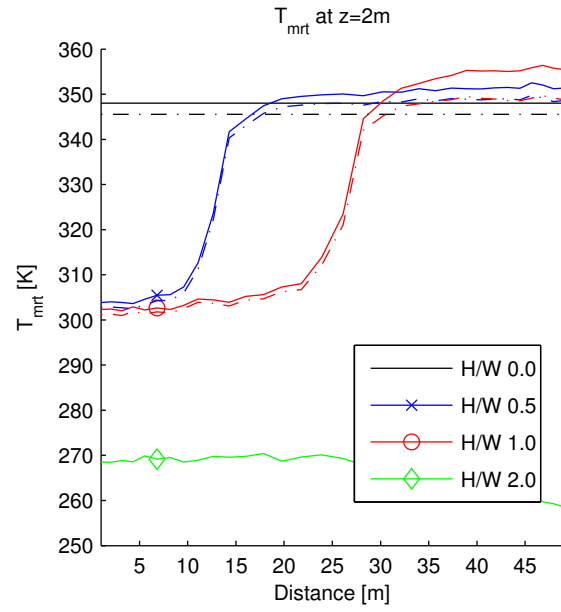
FIG. 10. Profiles of mean radiant temperature at z=2m height between canyon 12 and 13 for case 3 (excluding latent heat, solid lines) and case 4 (including latent heat, dash-dotted line). Note that H/W=4.0 is not shown here.