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Academic Article

Some effects of water bodies on the n environment – numerical experiments

Günter Gross *[1]

*[1] Institute of Meteorology and Climatology, Leibniz University Hannover, Germany

Corresponding author: Günter Gross, gross@muk.uni-hannover.de

ABSTRACT

A three-dimensional micro-scale model was used to study some aspects of water bodies on the urban environment. This is of special importance in the field of urban climate, where ways and means to reduce the heat load produced by city residents need to be found. In a systematic study, the ranges and impacts for different sizes of water bodies were estimated and a fitted relation was given. Water temperature, and the resulting temperature contrast with the surrounding area, seems to be more important during nighttime than during the day. The relevance of meteorological and morphological parameters on water surface temperature was studied by adding a water model to an existing numerical framework. The coupled model system was tested against field observations. Beside external radiation forcing, wind speed and depth of the water body were identified as the most relevant parameters. In a numerical study for a realistic urban environment the different impacts of water bodies during day and night were demonstrated, and the range of the penetration of the water effect into the built-up area was estimated.

Key Words : micro-scale simulation, water model, urban water bodies, range of impact

1. Introduction

A city, as a human environment, is subject to a permanent modification and is continuously developing. Rapid urbanisation is accompanied by conversion of land, construction activities, and alteration of the local atmospheric conditions. Caused by changes in the surface energy budget of newly created surroundings, temperatures in residential areas may occasionally be more than 10 K warmer than the nearby countryside(1) . This situation will become more extreme, as we expect an overall temperature increase of 3–4 K by the end of this century. The number and frequency of extreme temperatures and heatwaves will then increase, with impacts on human comfort, well-being, and health

Against this background, it is important for city planers and health professionals to develop strategies for the adaptation of urban areas to foreseen temperature increases due to climate change. Particular attention must be paid to measures that are suitable to cool towns and cities, at least locally. To this end, green and blue design elements are very effective urban features(2). It is well known that urban greenery offers significant potential in moderating the increase of temperatures, especially in summer, through evapotranspiration and shading(3) (4) (5). A wide variety of green elements are available, such as green roofs, green facades, trees, and lawns. Water bodies are also supposed to assist in cooling the air above them and by advection from the surrounding area. This has been demonstrated by numerous field experiments around urban ponds and lakes(6) (7) , rivers(8) (9) and fountains(10) (11) .

Although some data about the daytime cooling impacts from water bodies exist, general and applicable studies are still needed. A primary reason for this deficit is the specificity of conditions for each field experiment and of research questions(2). Völker et al.(12) summarised the wide variety of uncertainties in estimating the water effect, which include weather conditions, urban morphology, the size and shape of the water body, and the arrangement and location of the reference site. The findings of all experiments indicate a daytime cooling effect by ponds and lakes on the order of 0.5 to 4.8 K(12), affecting the adjacent area up to 400 m away. However, the exact extend to which a specific water body design will impact the wider urban thermal environment, and whether the observed effects are due to the water body alone, is still not clear.

A very useful method for understanding the impact of blue elements on some aspects of local climate in built-up areas is adopting meteorological models. This type of quantitative tool can be used very efficiently to estimate the potential effects of water body designs on the urban thermal environment. While numerous numerical experiments concerning the influence of vegetation on urban temperature are available, studies reporting the effectiveness of water in mitigating urban heat are relatively scarce[(13) (14)]. In the present study, such a numerical model will be used to gain additional knowledge about the interactions between blue areas and their surroundings. Emphasis will be put on the effects of pond geometry and water temperatures on the impact range.

2. The model system

A strongly pronounced urban thermal environment is mainly determined by an effective exchange of heat and energy between the various surfaces and the adjacent atmosphere. While great efforts have been made to understand and to describe the relevant physical processes for a large variety of urban surfaces, like sealed areas, walls, roofs, lawns, and trees, much less attention has been given to urban water bodies, like ponds and lakes. A model system, consisting of a micro-scale meteorological model and a simple lake model, is used here to study some effects of water bodies on the microclimate of an urban environment.

2.1 The meteorological model

Meteorological variables in the atmosphere are calculated using the micro-scale model ASMUS (Ausbreitungs- und StrömungsModell für Urbane Strukturen), which has been used for various numerical studies in urban environments[(5) (15) (16)]. The model is based on the Navier–Stokes equations, the continuity equation, the first law of thermodynamics, and an equation for specific humidity. These equations are Reynolds-averaged and the resulting correlations of fluctuating quantities are parameterised by flux-gradient relationships. The eddy exchange coefficient introduced by this approach is calculated using the Prandtl-Kolmogorov relation via the turbulence kinetic energy, which is estimated by an additional prognostic equation.

Boundary conditions for wind at ground level are zero and turbulence kinetic energy is proportional to local friction velocity squared. Temperatures at surfaces are calculated by heat budgets[(5)], while for specific humidity saturation is assumed for all water surfaces and vanishing fluxes else. At the upper boundary an undisturbed situation is adopted with given values for all meteorological variables.

The equations are solved on a numerical staggered grid where all scalar quantities are arranged in the centre of the grid volume, while velocity components are defined at the corresponding side walls. Pressure disturbance is calculated by solving a three-dimensional discrete Poisson equation by Gaussian elimination in the vertical direction, and fast Fourier transforms in the horizontal[(17)]. A grid resolution of 10 m is used in this study for both horizontal directions. In the vertical, a 5 m grid resolution is adopted near the surface and has been expanded with a stretching factor of 1.1 up to 3000 m, resulting in 50 grid levels.

2.2 The water model

Urban water bodies are typically of very shallow depths. Pronounced diurnal temperature variations can be observed with decreasing amplitudes for increasing depths[(18) (19)] . There exist a number of applicable numerical models that simulate temperature evolution for different time scales. For weather prediction and climate models, the spatial scale of urban ponds is too small and detailed information is less relevant, while physically based parameterisations of different complexity are sufficient to describe water temperature[(20) (21)]. Numerical models for calculating the detailed distribution of temperatures in space and time within shallow water bodies have been described, e.g. by Losordo and Piedrahita[(22)], Jacobs et al.[(23)], and Boudhiaf[(24)], with an extension for aquatic ecosystems by e.g. Strauß[(25)].

The concept and basic framework of the HyLaM model (Hydrodynamic Lake Model, Strauß[(25)]) is used here for calculating diurnal water surface temperature. Excluding horizontal exchanges, a water body is considered locally as a water column divided into a number of horizontal layers (*i*) of constant thickness (Δz) between the atmosphere and the sediment. For the thin, uppermost water layer, the energy budget is described as[(26) (22) (23)]:

$$\Delta Q_S + Q_{Lnet} - Q_H - Q_V - Q_W = c_W \, \Delta z \, \frac{\partial T_W}{\partial t} \qquad (1)$$

where TW is the water temperature of the uppermost layer and c_W is the volumetric heat capacity. ΔQ_S is the amount of shortwave radiation absorbed in the layer depending on angle of incidence, albedo, turbidity of the water, etc. The net longwave radiation, Q_{Lnet}, consists of the longwave radiation from the atmosphere, parameterised according to Strauß[(25)], and the outgoing radiation, calculated by the Stefan–Boltzmann law which uses the water surface temperature. Flux gradient relationships have been used to determine turbulent latent heat flux, Q_V, and turbulent sensible heat flux, Q_H. This approach requires surface and atmospheric temperatures and humidity information, as well as eddy diffusivity, a characteristic of turbulence. Q_W is the heat exchange with the underlying water and depends on water temperature difference and an effective diffusion coefficient, which is determined empirically[(22)] depending mainly on surface friction velocity and density stratification of the water column.

The vertical mixing in a water column is caused by surface wind stress and adjustment of density gradients by gravity. In this study, the method published by Strauß[25], which follows strictly Losordo and Piedrahita[22], is adopted and briefly repeated and described below. In this highly parameterized approach, a number of empirical constants and approximations are necessary.

Turbulent mixing in a neutrally buoyant water column is determined by a diffusion coefficient $N_{A,i}$ in depth z_i which is estimated by

$$N_{A,i} = \frac{u_*^2}{30 u_* k_Z} \exp(-k_Z z_i) \qquad (2)$$

with

$$u_* = \sqrt{\tau_o / \rho_W} \qquad (3)$$

$$k_Z = 6U^{-1.84} \qquad (4)$$

$$\tau_o = \rho_L \, 0{,}001 U^2 \qquad (5)$$

The symbols in the equations above are

k_Z empirical decay coefficient [m^{-1}],

u_* surface friction velocity [$m\ s^{-1}$],

τ_o shear stress at the surface [$N\ m^{-2}$]

U is wind speed and ρ_L and ρ_W air density and water density respectively.

Water density is calculated depending on temperature T by

$$\rho_W = 1000\,(0{,}99987088 + 6{,}314\,10^{-5} T - 7{,}78\,10^{-6}\, T^2) \qquad (6)$$

Existing density gradients modify turbulent mixing depending on stratification, which is characterized by the Richardson number Ri. The formulation

$$Ri_i = \frac{\alpha_{W,i}\, g\, z_i^2}{u_*^2} \frac{\Delta T_i}{\Delta z_i} \qquad (7)$$

is used here with

thermal expansion α_W [K^{-1}]

$$\alpha_W = 1{,}5\,10^{-5}\,(\hat{T}_i - 3{,}85) - 2{,}0\,10^{-7}\,(\hat{T}_i - 3{,}85)^2 \qquad (8)$$

gravitational acceleration $g = 9{,}81\ m\ s^{-2}$,

ΔT_i temperature difference between adjacent water layers [K] and

$\hat{T}_i$ mean temperature of adjacent water layers [°C].

Finally, the diffusion coefficient for turbulent mixing in a stratified water column DE is estimated by

$$D_{E,i} = \frac{N_{A,i}}{1 + 0{,}05\, Ri_i} \qquad (9)$$

During night time for strong surface cooling of the water layer, convective transport due to density instabilities become a dominant source of intense vertical mixing. The descent velocity W_{Konv} in case of density instability due to gravity is approximated by

$$W_{Konv,i} = \sqrt{g \frac{\rho_{W,i} - \rho_{W,i+1}}{\rho_{W,i}} \Delta z_i} \qquad (10)$$

and the convective diffusion coefficient D_K results in

$$D_{K,i} = W_{Konv,i}\ \Delta z_i \qquad (11)$$

The effective diffusion coefficient used in this study is finally calculated by

$$D_{eff,i} = \max(D_{K,i}\ , D_{E,i}\ ) \qquad (12)$$

But, as suggested by Strauß[25] and Losordo and Piedrahita[22], D_{eff} is limited to a minimum value (here: $D_{eff} > 5\ 10^{-4}\ m^2\ s^{-1}$).

For the layers within the water body, the heat energy budget is:

$$\Delta Q_S - \Delta Q_W = c_W\, \Delta z\, \frac{\partial T_{Wi}}{\partial t} \qquad (13)$$

where the water temperature of layer i is T_{Wi}. The absorbed shortwave radiation penetrating into the water is estimated using the Lambert-Beer law with a light extinction coefficient depending on the turbidity. ΔQ_W is the difference in convective heat transport at the top and bottom of the layers, depending on water temperature difference and the local effective diffusion coefficient.

At the bottom of the water column, the heat exchange between the water and the sediment has been considered in the heat energy budget. Relevant factors for calculating sediment temperature with a heat transfer equation are the temperature difference between sediment and water, and the thermal conductivity coefficient for the sediment.

Temperatures in the water column are calculated with a grid resolution, Δz, of 10 cm for a specific forcing at the water surface. The relevant forcing parameter, like shortwave radiation, near surface wind, atmospheric temperature, or humidity, may be provided either by observation or by numerical simulation. Input parameters for the water body used in this study are mostly adopted from Strauß[25] and are summarised in Table 1.

Table 1: Input parameters for water model.

water surface albedo	0.05
water heat capacity	4182 $J\ kg^{-1}\ K^{-1}$
Secchi depth	1 m
sediment thermal conductivity	0,7 $J\ m^{-1}\ s^{-1}\ K^{-1}$
sediment thickness	0,1 m
sediment heat capacity	2000 $J\ kg^{-1}\ K^{-1}$

3. Results

The model system described above was used to study the effects of water bodies on the environment. First, a parameter study was performed to determine the relationship between the size and temperature of a small lake and the area affected. The importance of various parameters that characterise the water body and the effect of spatially variable water surface temperature will be discussed afterwards.

3.1 The role of water body size and temperature contrast

An important issue for urban planners is understanding the impact and range of a water body with regard to size and distance from the water edge. A large number of studies have analysed the effects of open water areas on urban climates. Detailed reviews are given by Manteghi et al.(2) and Völker et al.(12). Depending on the size of the lake or river and the time of the day, urban climate is affected at 30–40 m for small blue areas(8) up to several hundreds of meters(6) (27) (9). However, all observational studies have been performed in very different surroundings and the analyses are not based on common criteria.

The meteorological model introduced above can be used to perform a consistent parameter study on the range of influence of a water area for different sizes and water temperatures. In the middle of an area with an edge length of 3 km, a square-shaped lake of variable size was arranged. The water area varied between 0.01 ha (= 1 gridpoint of 10 m × 10 m) up to more than 42 ha (65 × 65 grid points) and water temperature was fixed at 295 K. The temperature of the surrounding bare soil was calculated according to a heat balance equation and two diurnal cycles were simulated. The results of the second day were used for the evaluation.

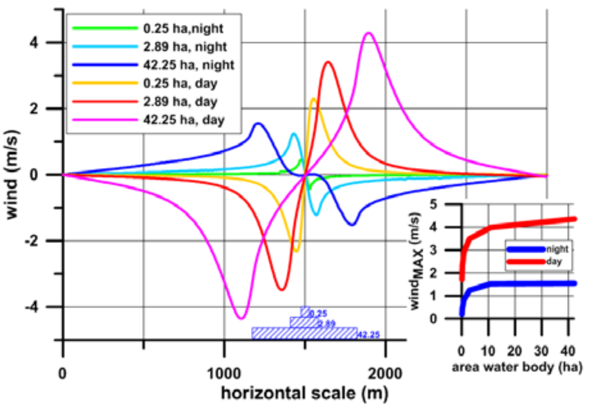

Figure 1: Simulated 10m wind for 14 hours (day) and 04 hours (night) for different water body areas (blue rectangles indicate location). Maximum wind speed for the two selected times depending on size of the pond is given in the inserted graph.

In Figure 1, the 10-m wind along the centreline of the simulation area is shown for daytime (14:00) and for nighttime (04:00). The strong horizontal pressure gradient at the borders of the water area, which is caused by large temperature differences, is the forcing of a thermally induced local flow system. During day, a lake breeze with significant wind speeds, up to 4 m/s, develops and advects cooler air from the lake into the surrounding landscape. For larger water areas, maximum wind speed increases and the effect of the water body is detectible at greater distances. Even around a small pond of 0.25 ha, significant wind speeds develop, but only at short distances. During nighttime, the generally more stably stratified atmosphere suppresses vertical diffusion and the horizontal pressure gradient is less pronounced than during daytime. As a consequence, maximum wind speed is reduced by more than a factor of two.

Diurnal variation of maximum wind speed ($wind_{MAX}$), which is an indicator for important issues in the field of urban climate like ventilation capability, reduction of heat stress, or transport of air pollutants, was well pronounced. During the night, $wind_{MAX}$ increased with the size of the water body but remained nearly constant for areas larger than 10 ha. $wind_{MAX}$ during daytime was much larger and a sharp increase for water bodies up to 10 ha was followed by a smaller, but constant, increase thereafter.

The model results can be used to estimate the range of the effects of a water body on temperature and wind. The observational findings published in the literature cover a large range, from some tens of meters for small rivers up to some hundreds of meters for larger ponds. However, the efforts to use the measured values to derive consistent, universal, and transferable results face a number of uncertainties like the lack of uniform criteria in defining the effects, completely different local landscape conditions, and different large-scale weather conditions. Here, the numerical results can provide additional valuable information and insights.

During daytime (14:00), the numerical results showed a consistent picture of the range R (in m) depending on the area of the water body A (in ha). Depending on the arbitrary predetermined threshold, either for wind or for temperature, the range for a 1 ha pond varied between 200 and 400 m (Figure 2). A good approximation seems to be the fitted relation:

$$R = a \ln(A) + b \qquad (14)$$

with values of a and b for different temperature thresholds given in Table 2.

Table 2: Regression coefficients.

Threshold for temperature	a	b
0.3 K	74	353
0.5 K	66	289
1.0 K	45	195

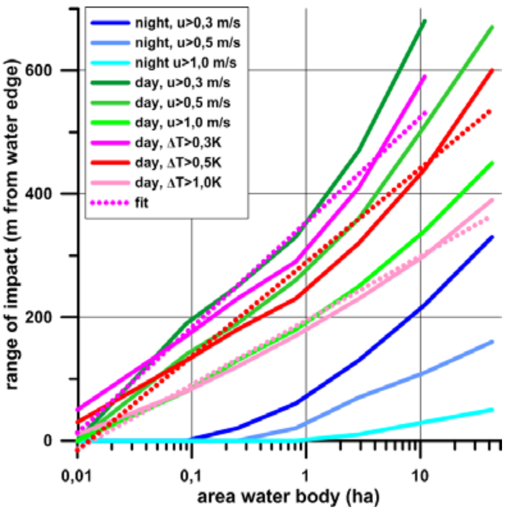

Figure 2: Simulated range of impact for various thresholds for different areas of the water body.

During nighttime (04:00), the air flow was directed towards the lake and significant temperature effects on the surrounding were small. Nevertheless, the moderate wind speeds at this time were important for the ventilation of the adjacent landscape.

However, the above-mentioned range for idealised situations will be smaller in a real urban environment, where the heat island effect modifies the temperature contrast with the water, while buildings and trees decelerate airflow significantly. During daytime, only in broad avenues can the cold air penetrate some hundred of meters into built-up areas. For narrow streets with traffic and trees, the cooling effect could not reach further than 50–150 m[27].

Data about the water temperatures of the numerous lakes and ponds within an urban area, when they exist at all, are very limited and restricted to samples monitoring water quality[28] or swimming suitability. Because of these large uncertainties and, at the same time, the great importance of the temperature contrast between water and land as a forcing for the thermally induced air flow system, the relevance of water temperature will be studied in more detail. Numerical simulations were performed for a 1 ha pond with a range of fixed surface temperatures as well as a diurnal variation with different amplitudes. The amplitudes have been prescribed with 10 and 30% according to the temperature variation of the undisturbed land surface.

As shown in Figure 3, the effect during nighttime is more significant than during daytime. The difference in maximum wind speed at 04:00 is about 0.8 m/s for a temperature variation between 293 and 297 K, while the effect during daytime is only about 0.4 m/s but on a much higher wind speed. Assuming a diurnal variation in water temperature means a reduction in the temperature difference during the day as well as during the night and consequently the system responds to the reduced forcing with lower wind speeds. Varying the water temperature, and therefore the maximum temperature difference with the bare soil (ΔT_{MAX}), over a wide range reveals that nighttime air flow and ventilation are very sensitive to temperature specification (or the accuracy of available observations), while the response of daytime maximum wind speed is comparably small.

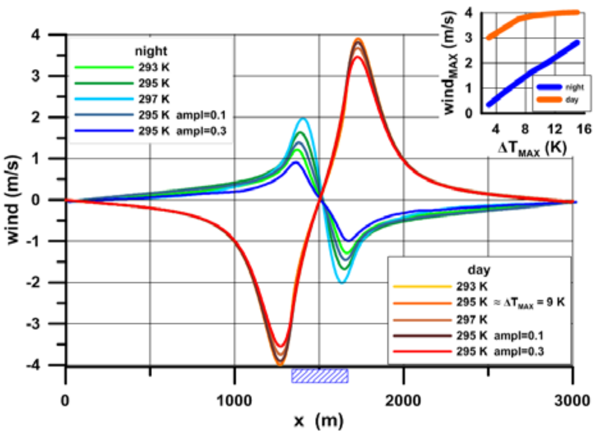

Figure 3: Simulated 10m wind for 14 hours (day) and 04 hours (night) for different water surface temperatures. Maximum wind speed for the two selected times depending on the maximum temperature difference between water and bare soil is given in the inserted graph.

3.2 Results of the water model

Water surface temperature, and the associated temperature contrast to the surrounding landscape, was the key parameter to describe the effects of urban blue spaces on urban climate. As demonstrated above, the temperature was important in estimating the wind speed, especially during nighttime, which in turn was important for nocturnal ventilation. Due to the lack of sufficient information, a model for water bodies was used to calculate water temperatures.

The model results were verified against measurements that were collected for a number of field experiments for small ponds and lakes of various sizes and depths in the Hannover urban area[19]. Depending on the depth of the water body, 1-min-mean temperatures were recorded at 3 to 6 vertical locations with a relative accuracy of 0.1 K.

Observed meteorological input data from a university site, including radiation, wind, temperature, and humidity with a time resolution of ten minutes were used to force the model. These observations were very comparable to the variables measured routinely by the German Weather Service at the airport weather station (Figure 4). As an example, the lake temperatures of the Maschsee, with an area of 78 ha and a mean depth of around 2 m, were simulated for a one week period and compared to observed data. This weather period was characterised by strong insolation and a very pronounced diurnal variation in meteorological variables. The persistent input of solar energy resulted in a continuous increase in water temperature: more than 1 K in one week (Figure 4). This warming was not restricted to the water surface, but affected the entire water body. Temperature amplitudes decreased with depth but were well-apparent even 2 m below the surface. During daytime a well-stratified water column developed, with warm water near the surface and cooler water at the bottom. The cooling at night at the interface between the water and atmosphere resulted in cold and dense water in the uppermost part of the water column, causing strong vertical mixing. As a consequence, water temperatures were nearly uniform with respect to depth during nighttime hours.

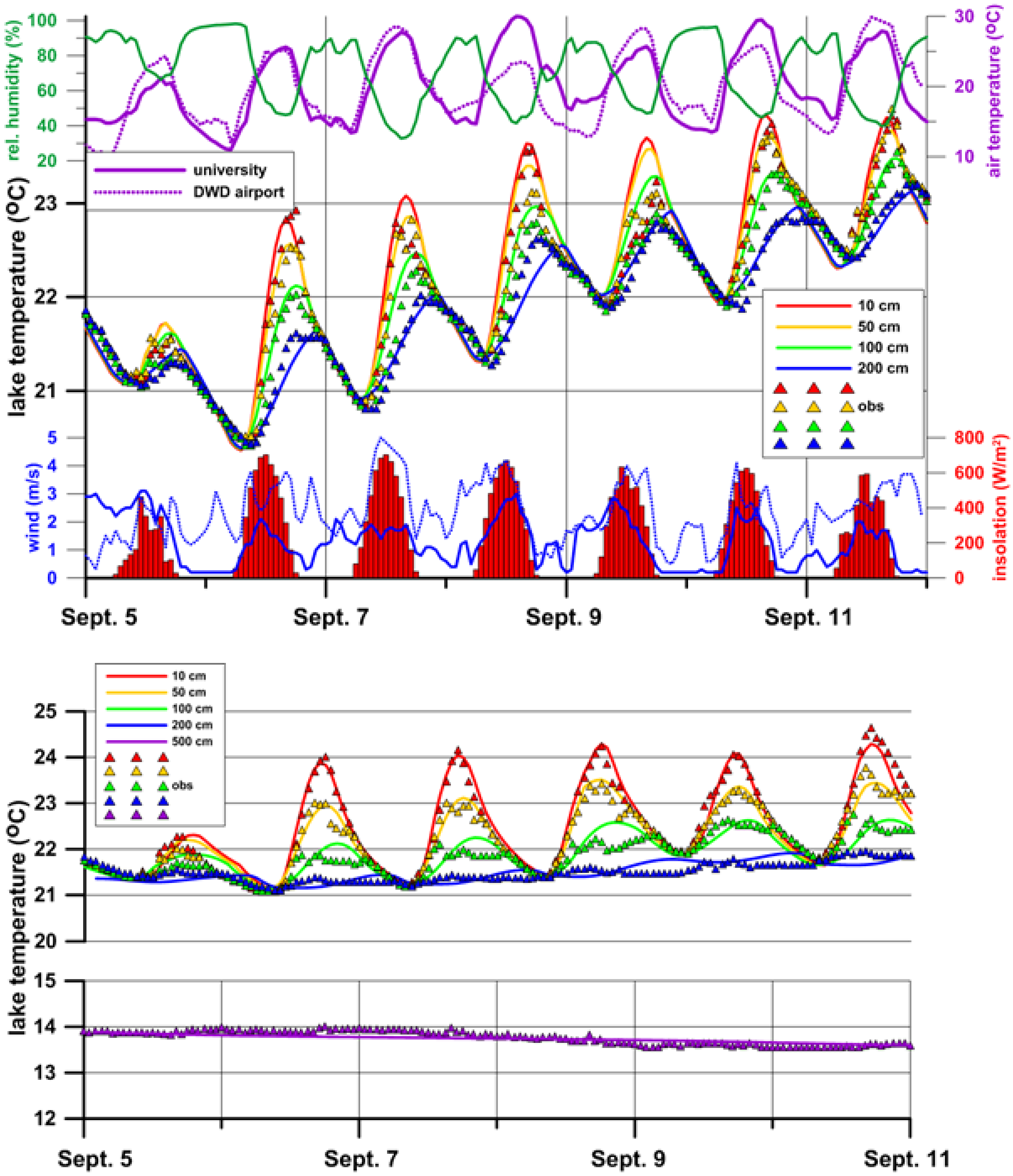

Figure 4: Above: Observed and simulated water temperatures for the centre of the Maschsee (location ❶ in Figure 7). Meteorological data are given in the upper and lower panel.
below: Observed and simulated water temperatures for the Kiesteich (location ❷ in Figure 7).

The simulated results follow the observations very satisfactorily. All main features were captured by the model, including the continuous temperature increase over the period for all depths and the significant diurnal change in water stratification. However, differences can be identified that might be attributed to an unfavorable specified input parameter or to uncertainties in the meteorological input data. As a second example, the temperature was calculated for a deeper pond of typically 6 m depth and also compared to observations. Now, the attenuating effects of the absorption and scattering of solar radiation penetrating into the water column is large and near the bottom of the pond temperature variation during the day is small. In the upper part of the water body, the model captures the main features again quite satisfactorily. Based on the results presented in this study and additionally by Strauß[25] and Losordo and Piedrahita[22] one can conclude, that the model developed primary by the latter authors and applied also by Strauß[25] is a very promising, valuable and reliable tool to calculate temperature distribution in ponds and lakes of different size and depth.

To identify the importance of different parameters on water surface temperature, model runs were performed for a period of 30 days in order to allow a steady diurnal behavior to be established. Different parameters were changed within a reasonable range compared to a reference simulation. The results are presented in Figure 5 for the daily mean temperature and maximum diurnal temperature amplitude. The largest effect was found for a variation in direct solar radiation, Q_S, which is not an unexpected result because this is the main forcing for water temperature. Wind was also a very important factor, followed by humidity and temperature of the near-surface atmosphere. Wind acted in a twofold manner by modifying the turbulent mixing within the water column and by affecting the turbulent fluxes of latent and sensible heat. Water and lake characteristics like depth or extinction coefficient were of minor importance for the daily mean temperature. This picture changed significantly when evaluating the maximum temperature amplitude over the day. This caused the depth of the water body to become important. Also for this temperature measure, the direct solar radiation and the wind speed was of great importance.

While Q_S controlled the level of the mean temperature of the water body, wind was also an important factor, modifying this value locally by several degrees. For low wind speeds, U, the mean temperature was estimated as around 23°C, which decreased by four degrees with a moderate wind speed of 4 m/s. Simultaneously, the diurnal amplitude decreased from 2.2 K to around 1.6 K (Figure 6). The strong effect of water depth on diurnal temperature amplitude was especially pronounced for shallow ponds. While mean daily temperature was very comparable, the temperature amplitude increased considerably

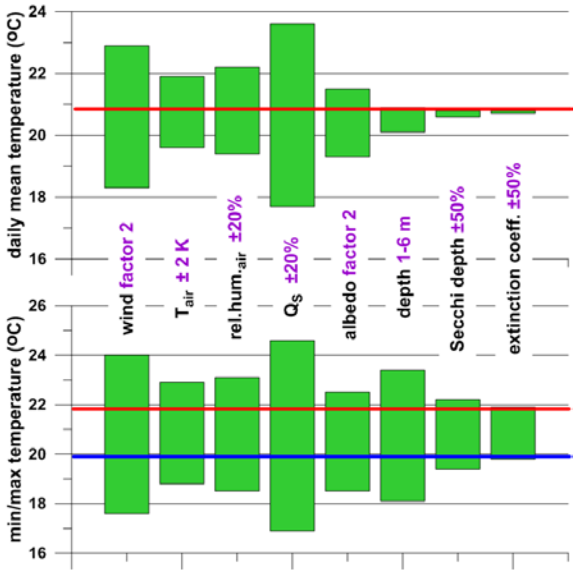

Figure 5: Sensitivity of the surface water temperature on parameter variation of the lake model.

for water bodies with a depth smaller then 1.5 m. Based on these results, a simple method to describe local water surface temperature T_S is given by:

$$T_S = -3.3 \ln(U) + T_{CLIM} \qquad (15)$$

where T_{CLIM} fixes the reference level. This value is either an observation or a climatological temperature. The variation in T_S may be modified by the diurnal temperature amplitude by roughly ±1 K.

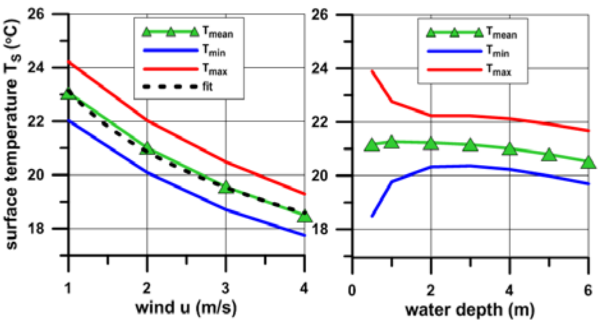

Figure 6: Sensitivity of water surface temperature for variation of wind forcing and depth of the water body.

3.2 Application for an urban setting

The importance of the findings in the previous sections were evaluated by numerical simulations in a complex urban environment. The selected study area was the lake Maschsee in Hannover and the adjacent urban areas. Input data were provided on a 10 m grid with detailed specifications of landuse and urban vegetation characteristics like building height or stand density. The vertical grid resolution was changed in these simulations to 2 m for the lowest 10 m of the atmosphere to resolve the urban structures. Numerical simulations were performed for a sunny summer day with a well-pronounced diurnal variation in surface temperatures. One main point of this investigation was to evaluate the effect of an inhomogeneous surface water temperature in space and time compared to the results with a prescribed constant value of 19˚C. The surface water temperature is estimated according to Equation 4 depending on the local near-surface wind speed.

During nighttime, water temperatures were much warmer than the surrounding open field and on the same order as the neighbouring urban areas (Figure 7). The rural areas are located south of the sports area along the river Leine, mainly in the west and to the south of the Maschsee, while the city is directly to the northeast. Because of this specific landuse arrangement and the associated surface temperatures, a well-pronounced land breeze developed along the western waterside, while the very similar temperatures in the eastern part do not produce a well-pronounced thermally-induced local wind system. Wind speeds across the Maschsee were therefore very inhomogeneous, with higher values in the western part and a calm situation in the northern part. Consequently, surface water temperatures are very different with a range between 17.5 and 19.7˚C.

Daytime water temperatures were much lower than the surrounding land, with large gradients in rural and urban areas. Significant lake breezes developed to balance these differences. In the rural area with grass, shrubs, and a sparse stand of trees, air flow was hardly impeded and penetrated into the surrounding areas. The built-up area was a major barrier for the lake breeze and only along broad roads was cooler air advected by the air flow into neighbouring city quarters.

A similar numerical simulation was performed with a constant water temperature in order to find out whether detailed knowledge of this parameter is relevant for urban studies or not. The Altenbekener Damm is a broad road that directly faces the Maschsee and air flow along this street was used for this analysis (Figure 8). During the daytime, the temperature contrast between the water and the urban area was large, and an additional variation in the water temperature of 1–2 K is of negligible importance. For both scenarios, the lake breeze entered the street and penetrated a certain distance before intense mixing decreased the forcing and winds slow down. Simulated results were not significantly different. The depth of penetration along the street was around 200 m, on the order of magnitude found by other authors (e.g. Ishii(6)). During nighttime, temperatures for water and adjacent urban areas were very similar and the interactions were not as clear as during daytime. Local wind depended strongly on the urban morphology and results are difficult to apply to other cities. In general, wind speeds are lower during the day due to the reduced temperature contrast. For the scenario adopted here, Hannover city was

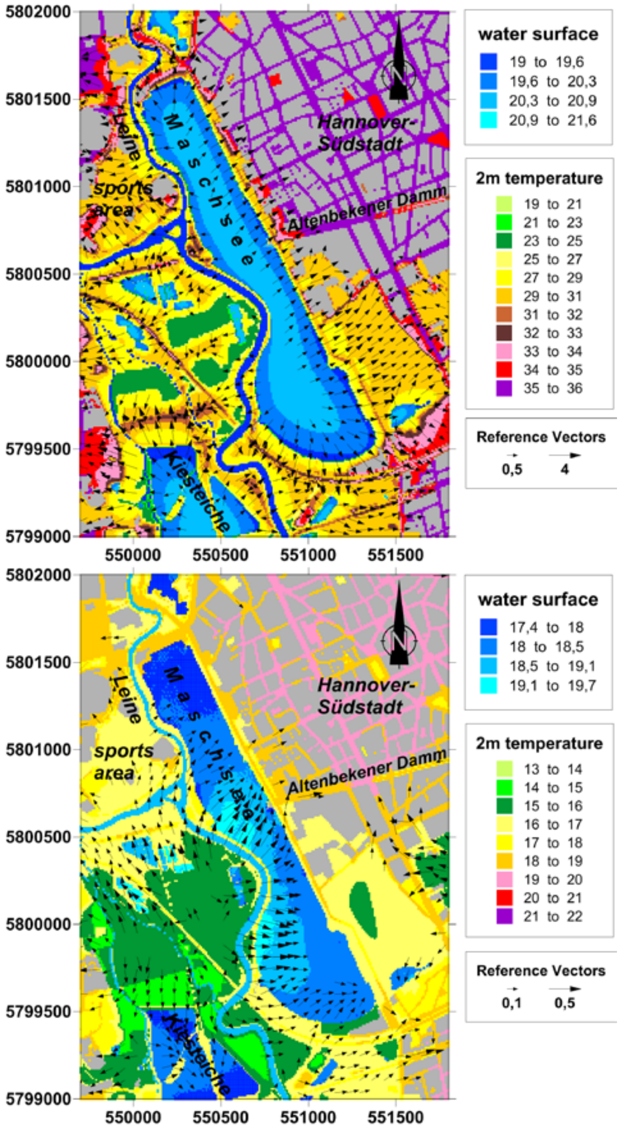

Figure 7: Simulated wind and temperature in 2m a.g. for daytime (above) and for night time (below). ❶ and ❷ indicate location of the observation sites.

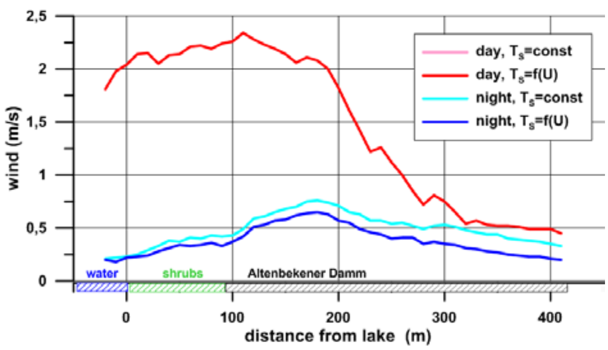

Figure 8: Simulated wind speed in 2m a.g. along the Altenbekener Damm for 14 hours (day) and 04 hours (night) for different water temperatures.

warmer than the lake and an air flow developed from the lake to the city centre. Maximum wind speed along the street was around 0.7 m/s and the modification of water temperature affected this local wind, slowing it by about 0.2 m/s. Although these wind speeds are small, especially during the night, even light breezes are helpful and valuable for ventilation and reduction of nocturnal heat stress.

As already described in detail by Völker et al.(12), observations should be treated with caution if universal findings about the effects of urban water bodies on local climate are to be derived from these data. Problems arise e.g. due to the specific weather situation during the experiment, the unique urban morphology, and the particular arrangement of the measurements. Nevertheless, the wide variety of available data yields very valuable information about the direction and order of magnitude of the impacts of blue spaces within a city. In order to exclude the experimental disadvantages, an additional numerical study for complex Hannover city was performed where temperature advection was excluded. By comparing the results of the complete simulation with the ones from the idealised simulation without advection, the effect of temperature advection from the blue spaces could be identified. The analysis was performed for the urban district of Hannover-Südstadt, to the northeast of a large urban lake. The temperature differences for the two scenarios, depending on the distance to the water's edge, were calculated for all grid points with the landuse "street". Other urban areas and forested regions were excluded.

The results for daytime are presented in Figure 9, which shows a clear decrease in the effect with increasing distance from the water body. Along the streets, the cold air from the lake penetrated into the city with a strong cooling effect near the border between water and land. For larger distances, this cooling effect became considerably smaller. Depending on the threshold for defining the effect, the range varied for a cooling of larger than 1 K from 100–150 m up to 200–300 m for a threshold of 0.5 K. These values were on the order of magnitude of other published experimental findings. Compared to the idealised situations of the parameter studies presented in section 3.1, the maximum range was only around half of the value.

4. Conclusions

A three-dimensional micro-scale model was used to study the effects of water bodies on wind and temperature in the surrounding area. Blue spaces in an urban environment have the potential to cool down cities, especially during daytime. This is of special importance for city planners and health professionals for developing strategies to adapt urban living spaces to climate change.

Existing observations and the results of field experiments

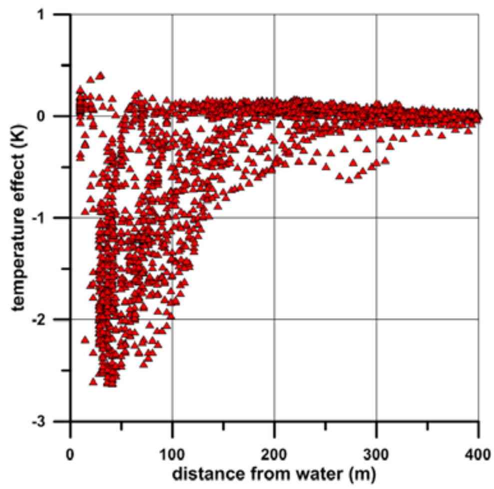

Figure 9: Temperature effect of blue spaces during daytime for grid points with landuse "street".

convey a first impression of what can be expected in relation to water bodies and urban climate. However, due to the wide variety of relevant parameters concerning city morphology, weather, experimental design, and water body geometry, general and transferable findings are limited. A literature review[12] found that during daytime and in the summer the cooling effect of ponds, lakes, and rivers is between 0.5 and 5 K, and the range of this effect is between some metres up to 400 m.

The model introduced here was used for a systematic parameter study in order to provide additional data to fill in some gaps in the present knowledge. During daytime, a cool water body produced a local wind system, resulting in ventilation and temperature advection into the surrounding area. Depending on the size of the blue space, a specific maximum wind speed and range was found using a prescribed threshold for temperature change as an indicator. The results were sufficient to derive a relationship between the size of the water body and the range of impact.

The detailed surface water temperature was found to be more important during the night than the day. Because of the strong daytime heating of bare and flat surrounding areas, the pressure gradient between the water surface and land was very large and water temperature variation of some degrees was of minor importance. To discuss this topic in greater detail, a lake model was included in the model framework to calculate water surface temperatures depending on local meteorological conditions. This lake model was successfully tested against field observations. The importance of different meteorological parameters and lake characteristics on water surface temperatures was identified. For lakes with a depth of greater than 2 m, which is a typical value for medium to larger urban water bodies, local wind speed was a very important parameter. Based on the numerical results, an empirical relationship was given.

The findings of the investigations for idealised situations were incorporated and considered in a numerical study on the effect of a larger water body on a real urban environment. It was found that the multitude of obstacles modified the local wind patterns, making the range of impact much smaller than for a plain. However, although there is a large scatter, the daytime cooling effect penetrates up to 300 m into the city, reducing the urban heat island by 1–2 K. The values calculated here are on the order of magnitude of other published experimental results.

Different blue elements are available to optimise the adaption of our cities to a changing environment. Because of the many influencing factors and the wide variety of interactions, meteorological micro-scale models are very helpful tools for a planning and design process.

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