The micro-climate of a mixed urban parkland environment

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6 June 2011

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Abstract

Progression of climate change, with its predicted intensification of temperature extremes and heat wave durations, combined with demographic trends towards increased urbanization makes the study of urban micro-climates desirable. Understanding of mixed urban parkland morphologies leads to insights into possible adaptation and mitigation strategies to minimize impacts due to temperature extremes and UHI (urban heat island) on human health. Observational methodologies to study these environments present difficulties in obtaining data of sufficient spatial and temporal resolution, and are expensive and time consuming as well. Modelling using mathematical computer simulations addresses some of these concerns. However, confidence in the results obtained from models requires verification of accuracy. Merely observing that the modelling output looks plausible isn't enough. Verification of underlying processes and their interactions are ultimately necessary for complete confidence.

Data collected in a mixed urban parkland study area was analysed for spatial and temporal temperature variations. Urban micro-climate drivers such as incoming shortwave radiation, wind, and humidity played a role in the variations across the area. Wind was found to be an important driver. It moderated afternoon maximums through mechanical mixing at solar exposed sites as effectively as tree cover shading did at other sites. At the same time, heat was allowed to build at wind sheltered sites. Calming winds also contributed to dropping temperatures after dusk and warming temperatures in pre-dawn hours coinciding with increasing wind speeds. On average, temperatures in parkland areas were found to be 2°C cooler than urban areas.

Modelling of this study area was carried out using ENVI-met, a urban micro-climate model. However, ENVI-met's ability to predict the temperature gradients seen in the observations was hampered by constant values, both spatial and temporal, in wind speed and humidity levels. As these were found to be important components in driving spatial temperature variability in the observations, these constant values are unable to drive variabilities as they would have in the observations. Temperature variations lag behind observed values and temperatures are also under-predicted during the day and over-predicted at night. This leads to low confidence levels about ENVI-met's accuracy in resolving temporal and spatial temperature variation and yields an inconclusive result as far as modelling predictions are concerned.

Declaration

This research paper contains no material that has been accepted for the award of any other degree or diploma in any educational institution and, to the best of my knowledge and belief, it contains no material previously published or written by another person, except where due reference is made in the text of the paper.

Signed: ………………………………………………

Acknowledgements

Thanks to Ché for patience and support.

Special thanks to Peter for boundless enthusiasm and an incredible amount of time and knowledge.

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List of Abbreviations

IPCC - Intergovernmental Panel on Climate Change
K - shortwave solar radiation
L - longwave thermal radiation
LAD - Leaf Area Density, the total one-sided leaf area (m^2) per unit layer volume (m^3)
LAI - leaf air index, the total one-sided leaf surface area (m^2) per unit ground area (m^2)
UBL - urban boundary layer
UCL - urban canopy layer
UHI - urban heat island
PBL - planetary boundary layer
PET - physiologically equivalent temperature
RH – relative humidity

Introduction

Global warming

Climate change is a pressing issue which requires understanding of its impact at many different levels. Uncertainly exists over what the exact impacts will be of a changing climate, especially within urban areas, and how that will impact the health of people. We need to provide data and predictions around these issues. In Australia, recent trends have seen increased warmer nights (Figure 1c) and decreased frost days (Figure 1d), with sharp rises predicted in the future under Intergovernmental Panel on Climate Change (IPCC) B1, A1B, and A2 scenarios. More worrisome are predictions concerning increasing extremes, such as longer duration heat waves (Figure 1b) (Alexander & Arblaster 2009). Such extreme events are found to be of great significance in contributing to human mortality (Laschewski & Jendritzky 2002) especially after heat wave durations exceed certain thresholds (Loughnan, Nicholls & Tapper 2010; Nicholls et al. 2008). Given these concerns over human health, mitigation and adaptation needs to be examined.

Increased urbanization

Much attention and study has been devoted to studying the climate and its changes at a global level and possible impacts of these changes (IPCC 2007), but much less at a micro-climate level, that at which people live. Patterns of human habitation are changing. Increased urbanization rates in Australia (Coutts et al. 2007) are running in parallel with an increasingly ageing population (Commonwealth of Australia 2010) and the greater sensitivity to increasing temperature extremes that brings (Laschewski & Jendritzky 2002). One implication of increased urbanization is urban heat island (UHI) effects (Figure 1a, showing temperature differentials during a transit across Melbourne), that is increased temperatures in the centre of cities due to night-time heat storage and decreased water evaporation (Coutts et al. 2007). These effects further exacerbate the changing climate trends towards longer heat wave durations. Housing trends in cities like Melbourne have been towards new detached dwellings in the outer suburbs with some gradual rebuild of medium and high density housing confined to the inner and middle suburbs. Market demand is also emphasising increasing the supply of low to medium density housing (DSE 2002). Cites such as Melbourne are becoming more populous, denser, and more spread out all at the same time. As urban areas are expanded and morphologies changed, micro-climates will impact those populations differently.

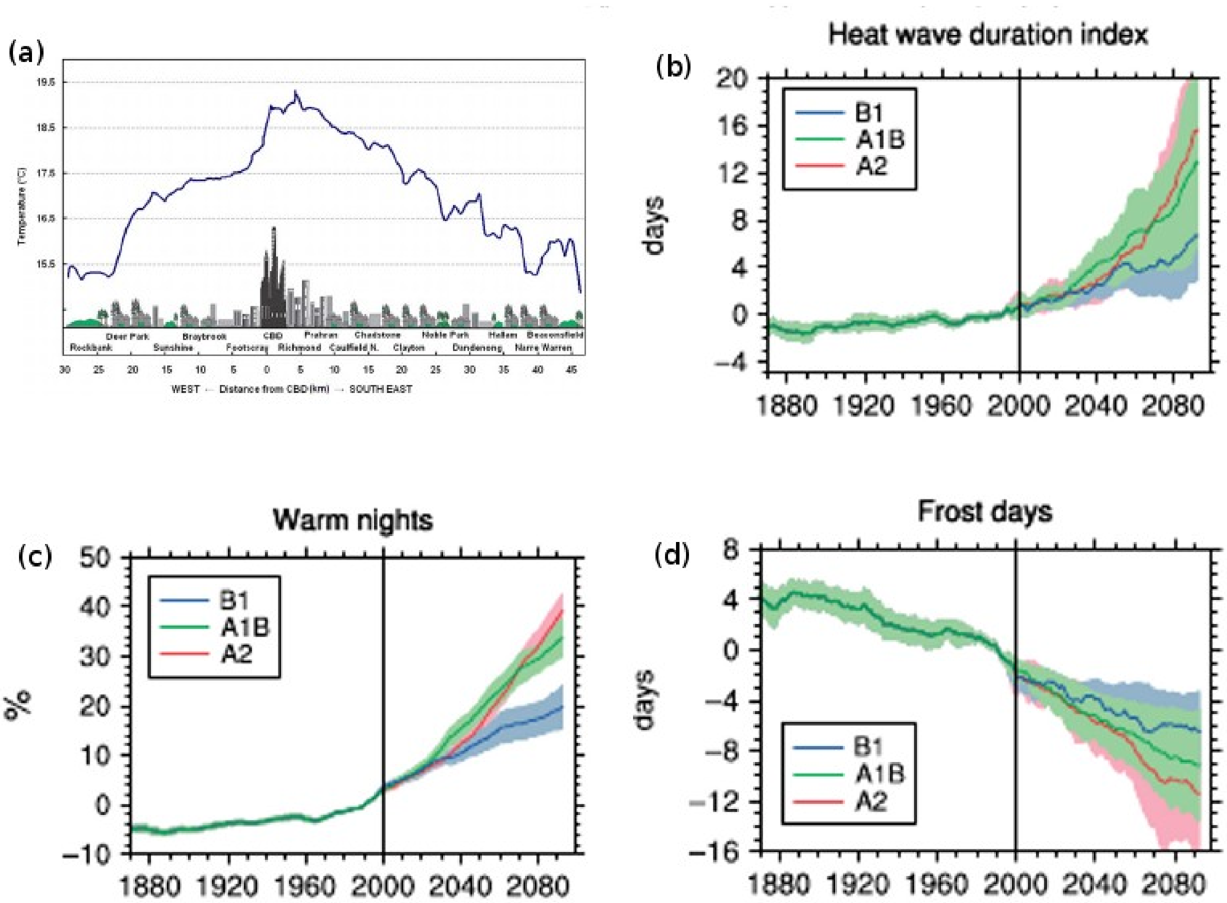

Figure 1– Urban heat island effects and warming trends for Australia predicted under IPCC B1, A1B, and A2 scenarios (adapted from Alexander & Arblaster 2009, p. 430; Coutts et al. 2010, p. 30)

Adaptation/mitigation strategies

In order to protect human health in light of projected changes to climate and urban demographic trends, response strategies will be needed. Ideally, mitigation strategies will prevent the worst impacts from eventuating, however, some impacts will arise (with or without mitigation) and will require adaptation to new circumstances. Mitigations strategies include plans to reduce CO_2

emissions through increased public transport and greater energy efficiency (ClimateWorks 2010) as well as projects to increase CO_2 storage in vegetation and trees (Coutts 2010). Adaptation includes measures to help deal with the expected increases in extremes. Adaptations can take two forms, either measures to cool buildings and houses, or measures to try and cool the surrounding areas. The first include more traditional methods using natural shading, ventilation, insulation or artificially through refrigerated or evaporative air cooling systems. They can also include redesign of urban morphologies so that buildings benefit from cooling effects through their orientation to wind flow and solar shading as well as building materials suited to reflecting solar radiation (Taylor & Guthrie 2008). Finally, in a departure from traditional town planning standards, vegetation and water can be incorporated into the urban landscape, specifically for the cooling effects (Shaw et al. 2007).

Mixed urban/park morphologies as mitigation

Adaptation strategies which include principles such as those used in Water Sensitive Cities (Wong & Brown 2009) can be incorporated into an urban landscape of medium density mixed urban parkland as part of this adaptation. Water is captured and stored and reused instead of being expelled from the system as stormwater. Trees and other vegetation fulfil a number of services such as nutrient/pollution filtration, shading, and cooling through evapotranspiration, in addition to the benefits of providing a more resilient water supply for the urban area. While these strategies act as adaptation strategies, using the cooling benefits of water to bring down temperatures in the urban environment, their benefits can also act as mitigation strategies. New urban development designed to encourage evapotranspiration and energy dispersal through latent energy fluxes, such as increased vegetation in open spaces and park lands or through green roofs and green walls can also act as a CO_2 sinks (Coutts 2010). Cooling through increased albedos on urban surfaces and passive cooling techniques can decrease the amount of anthropogenic heat released in urban areas through air conditioners as well as a savings in CO_2 emissions due to reduced requirements for mechanical cooling (Coutts 2010). Finally, increased use of urban stormwater run off has a number of mitigation benefits. Urban areas can secure their water supply without energy and emission intensive techniques such as desalination. Filtration of nutrients and pollutants out of stormwater can take place before impacting catchment areas and oceans. All of this can happen without withdrawing water from rural areas (Coutts 2010).

Methods for researching urban/park morphologies

To accurately describe variations within a mixed urban parkland morphology, we need to find ways to collect data about these environments. In this study, two different methods will be examined, observations and modelling. Each has advantages and disadvantages. Using observational data, adequate spatial coverage is a concern. If a study area is assumed to have variations across it, observational data will have to be fine grained enough to capture those variations. Added observational equipment increases expense and time investment to collect and analyse the additional data. Additionally, real world conditions can make capturing adequate temporal data difficult. A study looking at maximum temperature differences can be greatly delayed by uncooperative weather or having to wait until summer. Other problems of instrument calibration can make data synthesis and analysis difficult.

An alternative method which addresses some of these problems is mathematical computer modelling. Models use mathematical equations to simulate natural processes. Simulations allow modelling either existing morphologies or variations projected into the past or future. These tools allow great flexibility and remove many limitations on research. Granularity of temporal and spatial resolution can be specified by the researcher. However, this runs into practical limits of computer processing power and the ability to analyse the vast amounts of data output by models. A bigger question is whether modelling can accurately reflect reality. Environmental systems are very complex and processes and interactions are only partially understood. Creating accurate models is very challenging.

To understand mixed urban parkland morphologies, both methods used together will likely yield the most complete picture. Features of both will be needed. Case studies of specific study areas are useful but the ability to predict is very important. This allows a wide variety of scenarios, with varying arrangements of buildings, trees, water and other features under many different weather conditions. Scenarios can be projected into the future to see how building a particular urban morphology will work as climate conditions change and whether they will be suitable for human health. However, collecting real world data to validate the accuracy of the modelling is critical.

Research questions

In this research project, examining a mixed urban parkland environment using a combination of observational data and modelling, there are a number of aims. In looking at temporal and spatial variations of temperature across these areas, a key aim will be to determine the size of these temperature differences.

1) What is the temperature variation across a mixed urban-parkland environment and is this significant enough to warrant adoption of such morphologies to mitigate the UHI effects?
2) Can an urban micro-climate model reproduce the observed temperature variation across a mixed urban-parkland environment?

Literature Review

Micro-climate and human health

Heat can have profound ramifications on human health, especially in urban areas. Heat waves in 2003 caused excess mortality rates to increase in 13 French cites at rates ranging from 4% to 142% with a 1 to 3 day lag found between the start of the heat wave and the increase in deaths (Vandentorren et al. 2004) striking proportionally higher in vulnerable members of society, especially those 75 and older (Kovats 2004). There was also an observed increase in levels of air pollution (tropospheric ozone) in large European centres during these heat waves (Kovats 2004). With current predictions of hotter and longer heat waves in the future, understanding micro-climates and temperature distribution through them is becoming ever more important. Information is needed on how micro-climates within urban areas can be used and influenced to help alleviate temperature extremes.

Urban morphology, urban heat island, and changing energy balances

Tall buildings and urbanization have been observed to contribute to effects of urban heat island (UHI) and change terms within the energy balances. Miao et al. (2009) found a number of changes within urban micro-climates due to urbanization. These include increased ground heat storage, increased sensible heat fluxes, increased ground heat fluxes, and additional anthropogenic heat while seeing decreased latent heat fluxes. Increased vertical mixing was seen during the day by observing boundary layer changes. Wind patterns changed above urbanized areas, showing increasing speeds above 1 km and decreased wind speeds below 1 km, while night-time winds were slowed and blocked. Finally, humidity levels were observed to decrease during the day and increase at night-time (Miao et al. 2009). All of these were found to increase UHI effects within the urbanized area.

Changes in urban morphologies, the shapes and forms of an urban environment, are observed to have changed energy budget balances from those seen in rural areas. Effects seen are reduced evapotranspiration, increased urban heat storage (from urban canopy complexity and low reflective albedos), and greater night time temperatures due to the urban canyons (Coutts et al. 2007). Coutts et al. (2007) recommend that better urban planning is needed to improve urban climates and minimize the effects of UHI.

Micro-climate drivers

There are many drivers which cause temporal and spatial variations in temperature across a micro-climate environment. Incoming solar radiation, shortwave radiation from the sun, is the main driver of the energy budget of a urban micro-climate. The surface radiation budget of an urban area is defined by Oke (1988) in Figure 2 and in the equation:

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow$$

with Q* being net radiation, balanced by terms for incoming (↓) and outgoing (↑) K (shortwave solar radiation) and L (longwave thermal radiation).

Incoming shortwave solar radiation can be scattered in the atmosphere, transmitted through and either absorbed by the surface or reflected back out. Reflected shortwave will be re-scattered or transmitted outward as well as absorbed and stored. Absorbed shortwave radiation accordingly will be re-radiated as longwave radiation, following possible paths of transmission outward or reabsorbed by the surface.

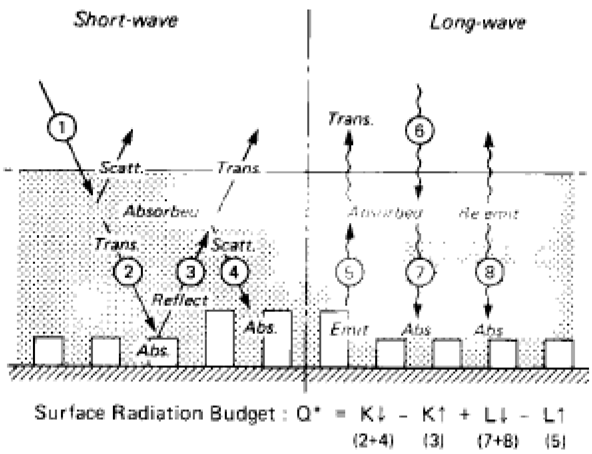

Figure 2–Urban surface radiation budget (Oke 1988, p. 473)

The surface energy budget, in more detail, within an urban environment is described by Oke (1988) (in Figure 3) in the equation:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$$

with Q* being net radiation, Q_F anthropogenic heat, Q_H sensible heat flux (heated air), Q_E latent heat flux (through water evaporation), ΔQ_S heat storage (within the environment), and ΔQ_A net advective (horizontal air movement) heat flux.

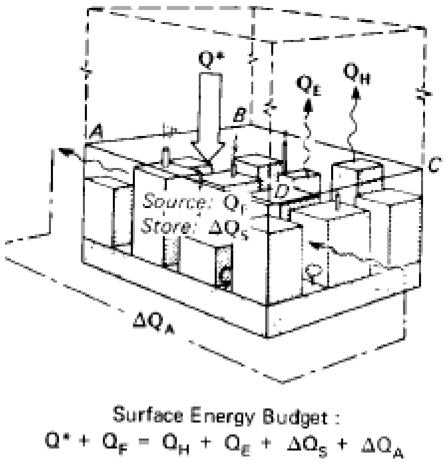

Figure 3–Urban surface energy budget (Oke 1988, p. 473)

The role water plays in an urban micro-climate can be described by the surface water budget, given by Oke (1988) (Figure 4) in the equation:

$$\mathbf{p + F + I = E + \Delta r + \Delta S + \Delta A}$$

where p is precipitation, F is moisture release by combustion, I is the piped water supply, E is evapotranspiration, Δr is net run-off, ΔS is net moisture storage, and ΔA is net moisture advection. In this study, the evapotranspiration term (E) will link together the energy and water budgets as water evaporation (latent energy) is an important cooling element in an environment.

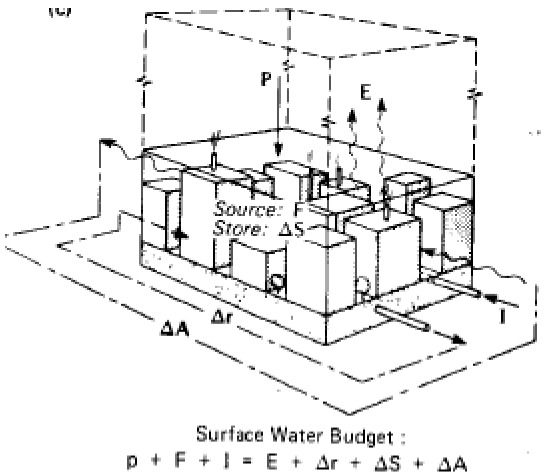

Figure 4–Urban surface water budget (Oke 1988, p. 473)

A final consideration in the drivers of an urban micro-climate is the role wind plays in temperature variations across an environment. Oke (1988) presents idealized representations of atmospheric boundary layers (Figure 5a) and the downwind effects created by features on the surface (Figure

5b). The urban canopy layer (UCL) extends from ground level to the top of urban buildings where these features create roughness with wind flow patterns and layer mixing. These effects extend upward through the urban boundary layer (UBL), finally leading to the planetary boundary layer (PBL), where effects are not seen. At a micro-climate level, wind provides mechanical mixing of atmospheric layers. Reduced wind speeds may have the effect of letting warmer temperatures build during a warm afternoon. On the other hand, a calm night will tend to be colder than one where wind mixes colder ground air with warmer air aloft (Ahrens 2004). Features within an urban micro-climate which either encourage or discourage wind and the mechanical mixing of warmer and cooler air layers will do much to create temperature variations across this area.

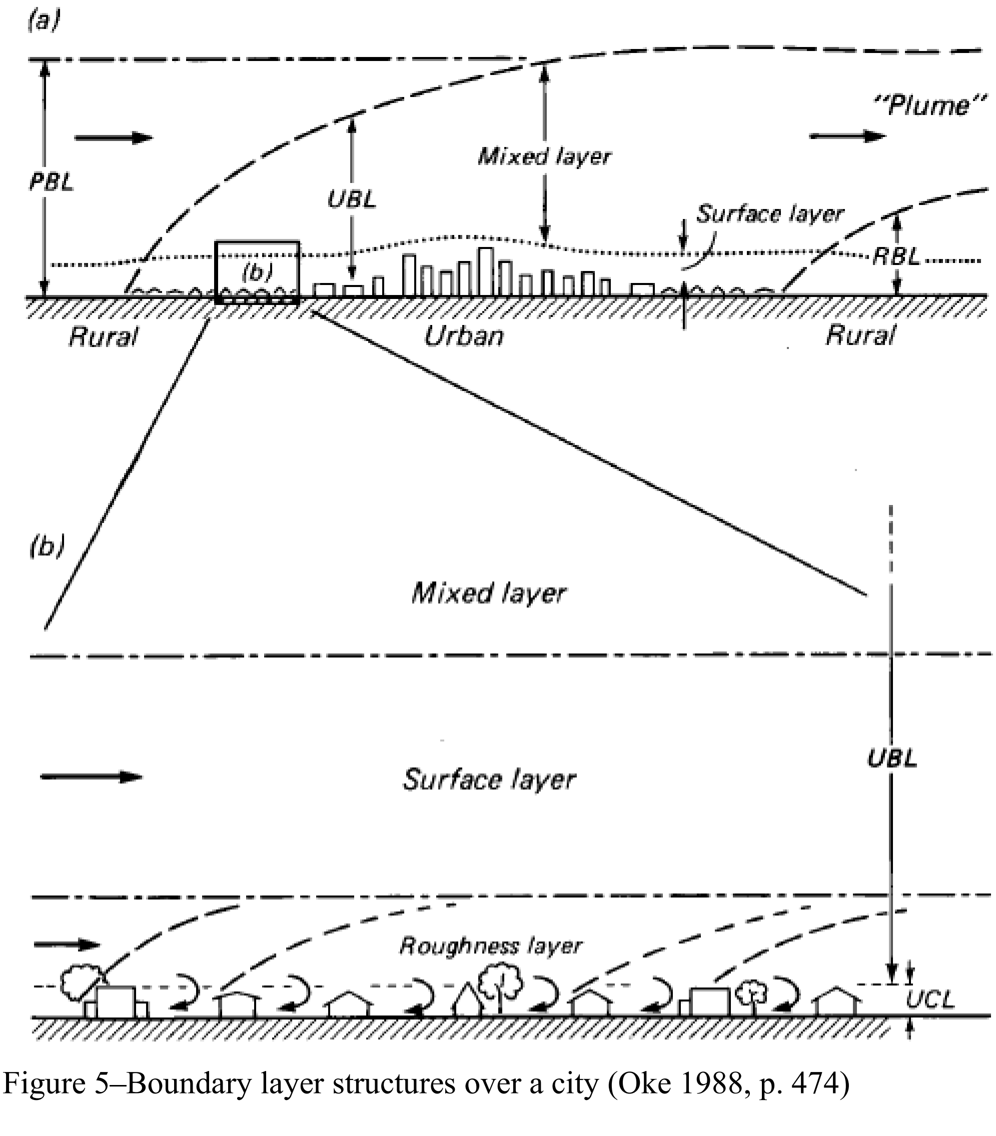

Figure 5–Boundary layer structures over a city (Oke 1988, p. 474)

Modelling as predictive tool

Modelling can be used to study urban micro-climates and make predictions. Coutts et al. (2008) use urban modelling to model on a city scale using anticipated land cover based on a few observational temperature data sets. Through this study, current plans for urban density growth are projected to intensify night-time UHI effects as well as extend daytime warm and dry periods. This points out the need for studies to help guide future urban planning to minimize effects of UHI (Coutts et al. 2008). However Coutts et al. (2008) found, these studies are limited by an incomplete ability to model urban canopies, especially canyon geometry effects. Also the lack of complete diurnal temperature data sets required having to use monthly temperature averages instead. In this, limitations due to the difficulty in collecting data and the limitations of current urban climate models are seen.

Other studies look to urban vegetation as a method to relieve heat stress. Alitoudert & Mayer (2007) find that much of the relief comes from a reduction of solar radiation reaching the ground through a more dense leaf air index (LAI) in the urban canopy. This study is also one of the first investigations of tree planting and street orientation to relieve physiologically equivalent temperature (PET). However, reductions in wind ventilation might be a trade-off in using trees for shading. In addition to vegetation, galleries placed to provide shading on streets, and other types of shading are found to help to reduce the intensity of thermal discomfort in an urban environment (Alitoudert & Mayer 2007).

ENVI-met as predictive tool

Studies about micro-climates are difficult to complete due to the complexity of the systems, with a large number of variables and processes, as well as the expense in investing in spatially and temporally complete observations of a system. Modelling can help fill the gaps. The output of a mathematical model is quite exhaustive, each grid point containing values for temperature, RH, wind speed, energy fluxes (latent, sensible, longwave, and shortwave). Models can also account for a variety of features within a micro-climate, in which a mix of buildings, trees, water bodies, vegetation of different heights, and different impervious and pervious surfaces can accurately describe a mixed urban parkland area. Their effects on spatial and temporal variations in temperature can be seen in great detail in these models. ENVI-met has emerged as a widely used modelling tool for urban micro-climates. ENVI-met models wind flows, turbulence, and radiation and water fluxes in short run simulations (days to weeks) at a micro-climate scale which allows the morphology of an area to be simulated at a scale down to a few metres (Bruse 1999; Bruse 2011).

Modelling, however, can be a challenging process and faces limitations. Arnfield (2003) found in a survey of urban climate models (however, he didn't consider ENVI-met) that validation of proper functioning of these models lagged far behind the development. Validation often relies on outputs looking plausible rather than validation of underlying processes. As these processes are already difficult to quantify by observations, this is understandable. Accurate modelling requires complete knowledge about how these processes work, but modelling energy balances within an urban canyon is limited by gaps in scientific understanding, such as the interactions of turbulent fluxes within urban canyon air spaces (Arnfield 2003).

Using ENVI-met in simulations has proven useful in a number of studies, despite these difficulties. Chen et al. (2009) used it to investigate landscaping (lakes and vegetation) impacts on micro-climate and whether this can be used as a driving mechanism for cooling. Validation of ENVI-met was attempted through iterative and grid convergence and found to be within +-0.7ºC for air temperature and +-5% for RH. A caveat they found in their study was that trees with big crowns can block cross winds around buildings, impacting ventilation and cooling (Chen et al. 2009). Cooling effects of trees through shading and evapotranspiration might be in some measure be offset by the trees' modification of wind patterns.

Validation of ENVI-met has been attempted in a number of other studies. Alitoudert & Mayer (2006) used it to study a number of theoretical orientations of streetscapes focusing on PET (physiologically equivalent temperature) and human thermal comfort. However, they found that the values predicted by the model were probably overstated due to higher than expected radiation fluxes predicted by the model. Krüger et al. (2011) focused on wind speeds as a validation for ENVI-met's accuracy and found initial wind speeds of greater than 2 m/s to be unreliable and a limitation.

Most attempts to validate ENVI-met have been through air temperature comparisons. Initial simulations using ENVI-met by Spangenberg et al. (2008) showed average air temperatures and diurnal amplitude were lower than expected when compared with observed results (Figure 6). In order to compensate, this study adjusted initial starting temperatures (as well as halving observed wind speeds) of the simulation to bring the temperatures into agreement in the morning and in the evening hours. In their observations, they found the park in their study area had a cooling effect of about 2ºC on the surrounding areas. In simulated results for street tree cover, they accounted for less cooling, 0.5ºC for areas with a less dense canopy (LAI=1), and 1.1ºC for areas of more density (LAI=5) (Spangenberg et al. 2008). The necessity of having to adjust starting conditions in order for ENVI-met to make accurate predictions at selective times of the day calls into question the ability of ENVI-met to make accurate predictions overall.

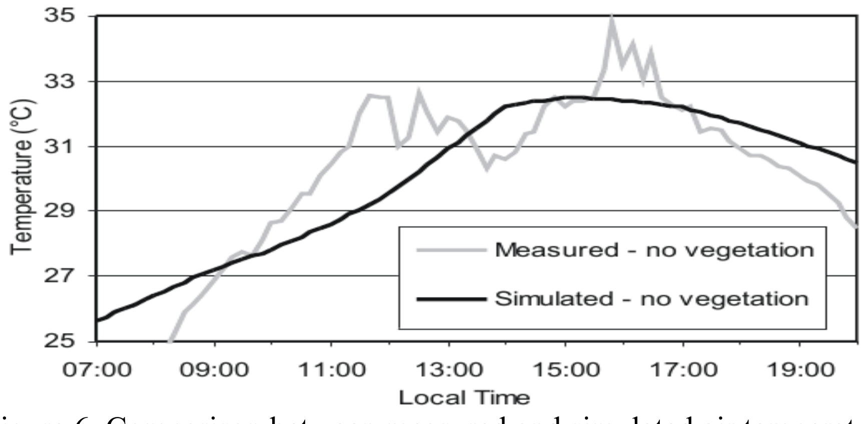

Figure 6–Comparison between measured and simulated air temperature for the existing street canyon (Spangenberg et al. 2008, p. 10)

Research gaps

In summarizing the literature in this area, a number of themes and gaps emerge. As climate change progresses, temperature extremes and heat wave durations will become more pronounced. Intense heat waves have been seen to cause rapid rises in human mortality rates and have big impacts on human health. In order to attempt mitigations and adapt to these new circumstances, micro-climates need to be better understood. Many of the drivers of micro-climates are known and can be described through energy and water budget balance equations. Other drivers such as wind and the interactions between all the drivers are less understood. Studies of urban morphologies and the spatial and temporal temperature variations across them have presented difficulties both through the difficulty in obtaining observation data of each of the components as well as incomplete understanding of how the components work and interact.

Urban micro-climate models can help. In addition to fine grained temporal and spatial resolution, they can also can be used to predict conditions in a wider arrangements of morphologies than exist in reality, as well as into any future time under any given starting conditions. However, in order to be useful, the results have to be accurate. Verification of urban micro-climate models lags far behind their development. In the case of ENVI-met, very little published work exists on the verification of accurate results, and what does exist depends on verifying accuracy through whether the output looks plausible (temperatures or wind speeds roughly match expected results). In some cases, verification is done backwards starting from expected results then tweaking input conditions to help ENVI-met reach the expected results. This research project will begin to fill this gap, describing urban micro-climate temperature variability in a mixed urban parkland environment through observational data. Also, it will address the question of whether an urban micro-climate model can accurately predict these variations.

Methods

Study area and justification of study area

The study area is a 500x500 meter square (Figure 7, showing the entire extent and included features) of the Monash University campus in Clayton, Victoria. The area is a mix of medium density student housing, open grassy areas, and wooded reserve areas. The north east corner of the study area is dominated by six large residence halls, mostly 3-4 story and one large 15 story building. These buildings are bounded on the north and east by two large busy roads and surrounded by impermeable asphalt parking lots. There is light tree cover through this area. A middle strip from the north west down to the south east contains medium dense tree coverage along with two ponds. The south west and southern edges of the study area contain predominately grassy sports grounds with little tree coverage. A section on the southern edge has been torn up and currently contains four partially constructed two and three story buildings surrounded by bare dirt.

The study area was chosen for a number of reasons. Medium density housing is a predominate form of housing in Victoria and there is a push to create higher density infill areas instead of green-field development and spreading urban sprawl (DSE 2002). The study area contains a wide range of terrain types, from medium density housing, in the north east section, to open grassy parkland. The study area also contains two water bodies, one a park-like pond, the other enclosed in a reserve, giving an approximation of undisturbed bushland remnants. The area is controlled by the university and provides access for instrumentation as well as security for the instruments to remain undisturbed. All these factors provide an area which can provide a variety of terrains to study the temperature differences between different urban arrangements of a mixed urban parkland form expected make up urban morphologies in the future.

Figure 7– Monash Campus 500 x 500 meter study site, vegetation and features

Observations

Observational data was collected from six sites in the study area from the 6th of April 2011 to the 20th. Six identical weather stations were assembled and mounted on poles approximately 1.5 meters high at each of the sites. Each station contained a measurement and control datalogger (model CR1000, Campbell Scientific International, Logan, UT, USA), a temperature and relative humidity probe (model HMP45C, Campbell Scientific International, Logan, UT, USA) lodged in a wind/temperature shield, a pyranometer solar radiation sensor (model CS300L, Campbell Scientific International, Logan, UT, USA), and an anemometer wind speed sensor (model 014A-L, Campbell Scientific International, Logan, UT, USA). Data was logged every five minutes. Stations were mounted to be as straight as possible, with possible tilt error less than 10º, or less than 1.5% error with incoming shortwave radiation measurements.

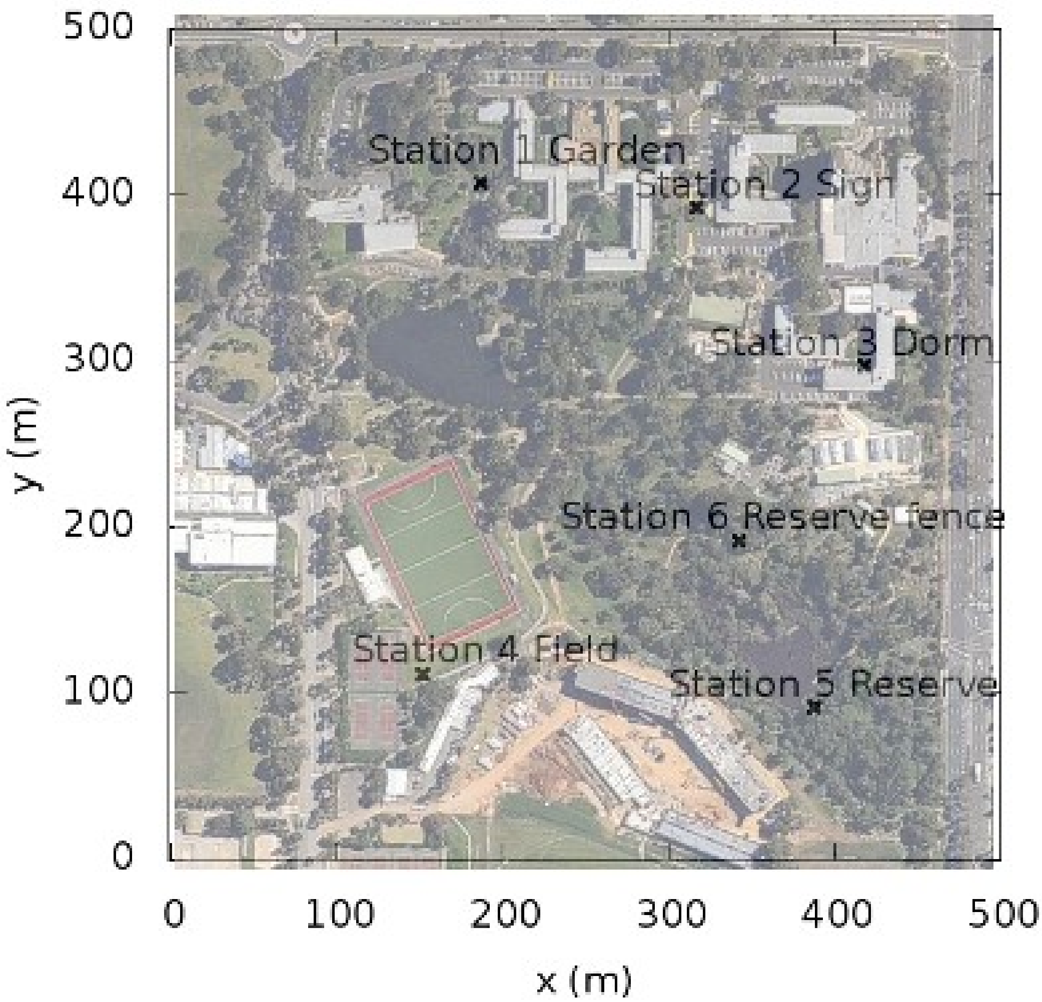

Figure 8– Monash Campus observation site locations

The six stations were located in the following areas (Figure 8):

Station 1 was placed on a fence surrounding a small garden on the west side of the main group of student housing buildings on the north side of the study area. The area was lightly covered with trees and is dominated by grassy areas on all sides except the building side to the east. Some shading is expected during the morning with a clear view of afternoon skies. This site will be referred to as “Garden”.

Station 2 was placed near the northern edge of the study area on a street sign on the side of a road in an area surrounded immediately by parking lots and to the east and west by a number of large student residences. A number of large trees in the area are expected to provide temporary shading at times during the day. This site will be referred to as “Sign”.

Station 3 was placed in a grassy courtyard of a student residence hall on the eastern edge of the study area. The building surrounds the sensor area on three sides and can be expected to provide shading during the early mornings and late afternoons. Full sun is expected all other times. This site is expected to be an extreme case to challenge the limits of collecting observational data with limited resources. The layout of the courtyard is expected to shelter the sensor from winds and allow temperatures to build in the afternoons. This station will be referred to as “Dorm”.

Station 4 was placed in a raised grassy area on the edge of a hockey sports field in the south-western area of the study area. Some tree cover is 20-30 meters to the south but the immediate surroundings are dominated by flat grassy areas. A single nearby lamp pole should provide very brief shading but uninterrupted solar exposure is expected otherwise. This site will be referred to as “Field”.

Station 5 was placed within a reserve in the south-western corner of the study area. The sensor is within medium tree cover and is expected to be shaded the majority of the day. A pond is just 20 meters to the north. This case is also expected to be an edge case, with tree cover expected to moderate both daytime heating and night-time cooling. This site will be referred to as “Reserve”.

Station 6 was placed on a fence on the northern part of the reserve, nearly in the centre of the study area. Trees dominate to the south, providing expected shading in the mornings. A clearing to the north is expected to give nearly clear skies in the afternoons. This site will be referred to as “Reserve fence”.

Six sites were chosen in the study area to give a spread of terrains to capture a wide range of temperature gradients. Preliminary ENVI-met model runs were analysed for possible hot and cold spots to which particular attention should be paid. Based on this, warmer temperatures should be expected in the northern sections of the study area, while cooler spots should be located in the strip of trees in the centre of the study area, particularly in the denser wooded sections in the south-western section. However, with only six sensors to cover a large 500 by 500 meter area, the limitations with observational data become apparent. Some of the sites, such as "Dorm" would likely benefit from a number of additional sensors to detail differences which likely occur at a smaller scale than can be captured with a single sensor. This study is faced with a trade-off of accuracy versus a larger investment in monitoring resources in resolving micro-climate features using observational data.

Modelling set-up and limitations

The modelling software used in this research project was ENVI-met version 3.1 (Bruse 2011). This software is freely available for research purposes and allows modelling of micro-climates, including energy fluxes and air movements. The study area was digitized using the Figure 7 image into a model of 100 by 100 grid squares of 5 meters each. Model settings are summarized in Table 1. Twenty grids were used in the vertical resolution. Nine nesting grids, using a mix of concrete and bare soil, were used to minimize edge effects (errors and distortions at the model's boundaries). Position (latitude and longitude) was set as 144.58 and -37.49. Buildings were modelled using their proper heights, ranging from 10 to 45 meters. Starting conditions were set to an initial wind speed to the north (0 degrees) of 2 m/s. Initial temperature was set to 288K. Soil moisture was set to 30/30/50% for upper/middle/deep layers. The simulation starting time was set to 5 April 2011, so that model would have two days to spin up before reaching the comparison days of the 7th and 8th. Finally, states were saved every 60 minutes over the modelling run.

Setting	Value
Grid size	100x100x20
Grid resolution	5 metres
Nesting grids	9
Latitude and longitude	144.58 and -37.49
Initial wind direction	north (0 degrees)
Initial wind speed	2 m/s
Initial temperature	288K
Soil moisture (upper/middle/deep)	30/30/50%
Simulation run dates	5 April 2011 to 10 April 2011
Save state	60 minutes

Table 1 – ENVI-met model set-up values

The model set-up starts to reveal some of the limitations to be encountered in using modelling for micro-climate predictions. Using relatively course grid size settings of 5 meters allows for more manageable results in a reasonable amount of time. Even then, a five day simulation generates around 4 gigabytes of data and runs nearly in real time (five day simulation requires nearly five days to compute). Increasing the resolution will multiply the data generated as well as the time required to process the simulation. However, as the accuracy of modelling results in some part depends on the accuracy of the input, this trade-off must be considered. Accurate digitization of the study area is also hampered by having to set each 5 by 5 meter square to either be filled by a single feature of trees, grass, a building, or some other feature. Difficulties arise in deciding how to accurately reflect the true environment at this coarse scale.

In order to trust results from modelling, there should be confidence that the model is getting basic climate modelling correct. Results which look implausible during validation steps lead to concerns over whether fundamental processes are being modelled incorrectly by ENVI-met. If so, making accurate predictions by this particular model of spatial and temporal differences in temperatures, both overall across the study area, and especially with more challenging areas such as the "Dorm" and "Reserve" observation sites, might not be possible.

Data analysis

Data was collected from the six sensors weekly during the period 6-20 April 2011. The data loggers produce comma separated value spreadsheets of temperature, relative humidity, wind speed, and incoming solar radiation at five minute intervals. Scripts were written using the Gnuplot scripting language (Gnuplot 2011) to plot out this data showing temperature, wind speed, incoming solar radiation and humidity. Observed relative humidity was converted to specific humidity. The data was plotted to find general trends and unusual events. It was plotted over the entire observation time period then plotted in more detail over the two days chosen to be compared to ENVI-met model results. Incoming solar radiation was normalized to account for differences in the recorded data. Peaks above and below 875 W/m^2 were normalized by multiplying “Reserve fence” shortwave radiation results by 875/760, “Dorm” by 875/900 and “Garden” by 875/825.

The ENVI-met data analysis required a larger effort to extract and analyse. ENVI-met produces hourly data files (in a closed source proprietary format) containing values for numerous variables for each grid point. The two sets of data files of interest were the surface files and the atmosphere files. The surface files contain values for the area at ground level (z=0). The atmosphere files contain a slightly different set of variables in three dimensions. With a given grid resolution of 5 metres, there were 100 x and y grid points. The z-dimension contained values for 0,1, and above metres.

ENVI-met output data files were reverse engineered in order to allow automated data extraction and plotting of a large number of scenarios. The files were found to be slight variations of the NetCDF file format (Unidata 2011). Tools were written using the Java programming language (Sun Microsystems 2011) to extract data from both the surface and atmosphere files, extracting both single points (x,y for surface files and x, y, z for atmosphere files) as well as x-y, x-z cuts and outputting tab separated data files suitable for reading by Gnuplot. A large number of plots of many aspects of the data were then scripted and plotted through the Gnuplot scripting language.

Initial ENVI-met data runs were completed to test base cases of single flat surfaces of concrete, asphalt, grass, and various heights of tree cover. Data was extracted from these test cases to construct daily energy balance plots, to ensure that the model conserves energy in its energy fluxes according to the energy budget balance equations detailed in the "Micro-climate drivers" section of this study. Some concerns were found here, but as this was not the main focus of this research project, these concerns could not be fully investigated.

Final runs of ENVI-met were completed to model the conditions for the observed days 7th and 8th of April 2011. These data sets were analysed using the Java and Gnuplot scripts and combined with the observed data sets to allow side by side comparisons of observed versus modelled results of the same locations for temperature, incoming radiation, specific humidity, and wind speed. Smoothing of data was completed to account for differences in data collected every five minutes at the observation sites and every 60 minutes in the modelling simulations. Analysis and plots were done to compare differences between observed values and values predicted by ENVI-met.

Results

Meteorological conditions during study period

The first result from the data analysis process was the observed meteorological conditions during the study period at the six observation sites. Observations recorded from the 7th to the 14th of April 2011 are shown in Figure 9. Measurements of incoming solar radiation (in W/m^2), temperatures (in ºC), specific humidity (in g/kg), and wind speed (in m/s) were plotted for this week. During the period of the 7th through the 14th, the first three days showed the widest range of temperatures under clear sky conditions. The biggest daytime temperature differences of 4.9ºC were seen between the "Dorm" site and the sites "Reserve fence" and "Garden". The warmest area is "Dorm", reaching a maximum of 29ºC. Other sites reaching highs 2-3ºC lower than that. The biggest night-time temperature differences of 3.2ºC were seen between the “Sign” site and the sites “Reserve fence” and “Reserve” from dusk into the early morning hours. The coolest areas are “Reserve” and “Reserve fence” which also cooled more rapidly at night. Observations do show limited variation between recorded temperatures in early dawn hours of the second day. Average variations, after removing the edge cases (of “Dorm” and “Reserve”) in this period are closer to 2.5ºC.

Wind speeds varied between just above 0 m/s to nearly 2 m/s at all sites except “Field” where speeds peaked at speeds closer to twice that on the first two days. The wind speeds at “Field” reached nearly 6 m/s on the third day (nearly three times the speed at the other sites), the largest recorded wind speed over the observation period. Wind speeds are slightly lower at “Reserve” and “Reserve fence” than other sites, while “Field” recorded levels generally two to three times as great as the other sites.

Humidity for all sites rise and fall inversely to temperature, with minimal difference seen between the sites except for “Reserve” and “Reserve fence” which were consistently higher than the other sites at all times and additionally showed even larger differences at night-time.

Incoming shortwave radiation readings show a large number of peaks and troughs as the sun moves across the sky and the sky view moves from sunny to shaded, except at the “Field” site which records almost constant exposure. Incoming solar radiation levels peaked at about 875 W/m^2. Calculated accumulated levels of shortwave radiation at each site (Table 2, showing daily averages over the two days) allows qualitative comparisons between the sites. Very low levels are received at the “Reserve” site. Approximately twice those amounts are received at “Garden”, three times at “Reserve fence”, and nearly four times that at “Sign” and “Dorm”. In its highly exposed position, “Field” receives about six times as much as “Reserve”.

By the third day of observations, a cold front moves in and incoming radiation levels drop. There is a sharp rise in humidity levels and drop in temperature on the evening of the 10th as this front arrives. Rainy and cloudy weather dominate the rest of the observation period. Through this period, temperature differences between the different sites are minimal, however, the patterns of higher maximum temperatures during the afternoon at "Dorm" and lower night-time minimums at "Reserve" and "Reserve fence" are still seen to some degree.

Sensors remained in place for a number of weeks after these measurements, but as the first two days of the readings (the 7th and 8th) showed the widest range of temperatures and incoming solar radiation readings, these two days were picked as comparison days for ENVI-met modelling. Looking at the rest of the days in that observational period, incoming shortwave radiation levels dropped significantly bringing with it flatter temperature variations. Observations through the rest of the April (results not presented) were similar, cool, rainy, and cloudy with low levels of incoming shortwave radiation and small ranges of temperature variations over the day.

Figure 10 shows the two comparison days (the 7th and 8th of April 2011) in more detail, plotting incoming solar radiation levels, temperature, specific humidity, and wind speed. These further highlight the differences and trends of the temporal and spatial variations between the six observation sites seen above. The temperatures rise quickly during the morning, fall rapidly during the first evening, then rise slightly before dawn as the wind speeds pick up. This pattern is repeated the second evening, but with an even stronger pre-dawn warming coinciding with increasing wind speeds.

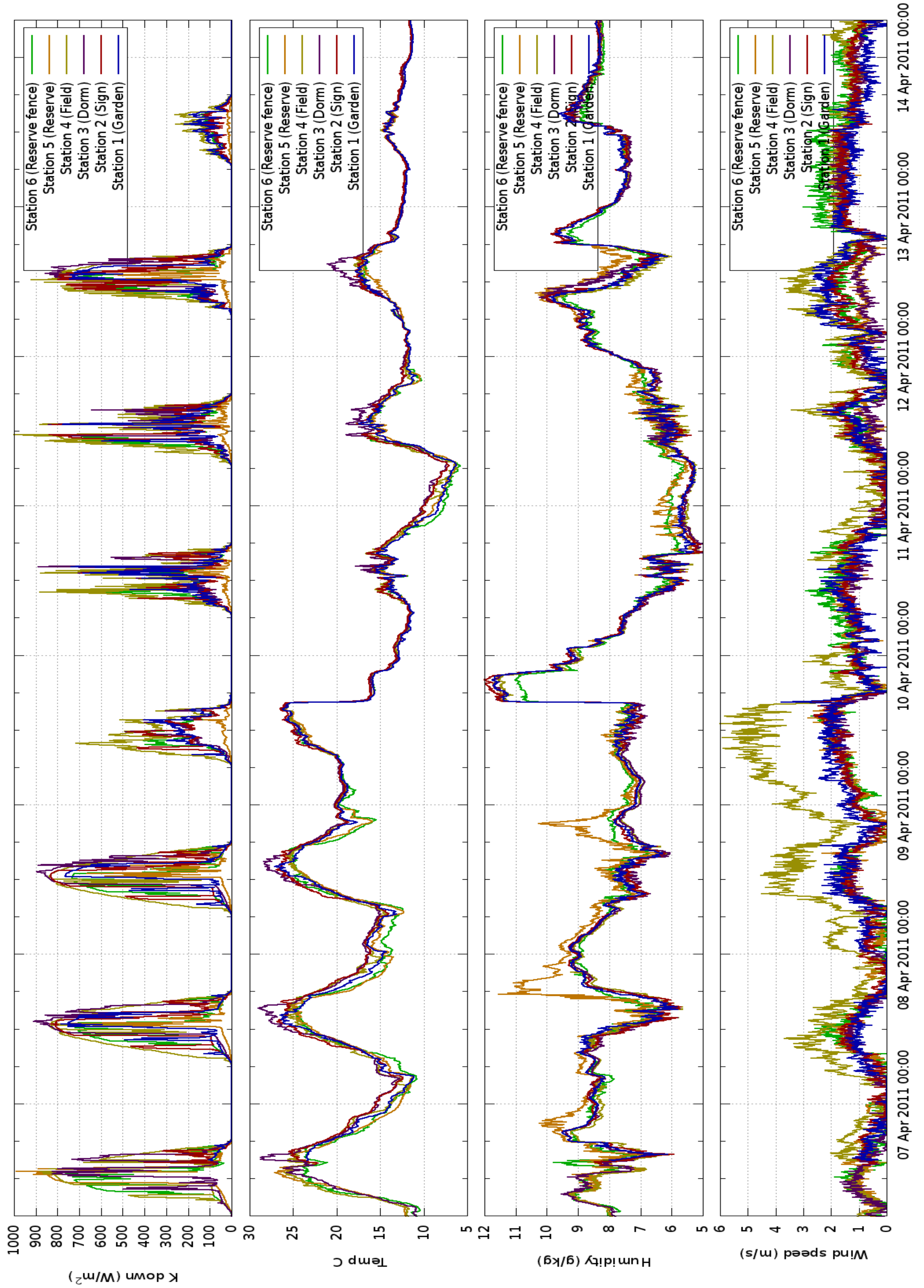

Figure 9–Observation data (K down, temperature, humidity, wind speed) for study site 7-14 April 2011

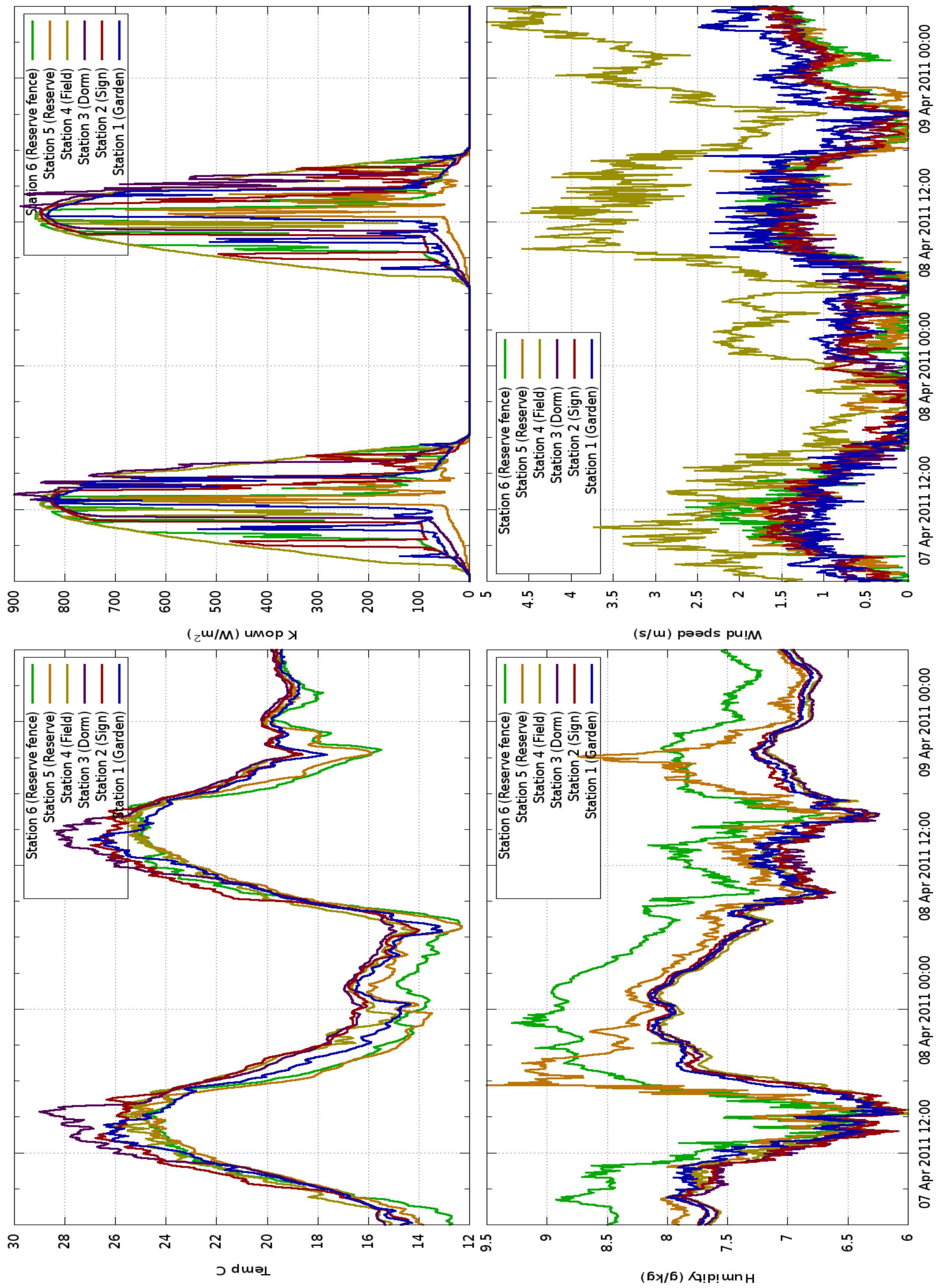

Figure 10–Observation data (Temperature, K down, humidity, wind speed) for study site 7-8 April 2011

Model versus observation for comparison period

Comparisons between each of the six observation sites and the same locations within the model run simulation are shown in Figures 11, 12, 13, and 14. These show side by side comparisons of the observed values of temperature, incoming solar radiation, specific humidity, and wind speed to the predicted values generated by model runs.

In Figure 11, observational values for temperature at the sites climb quickly during the morning, remain high during the afternoon and drop quickly in the evening. In comparison, ENVI-met under-predicts daytime temperatures and is slow to heat up. It also presents a smooth curve for afternoon peak temperatures instead of the nearly flat peak followed by a sharp drop seen in the observations. ENVI-met also over-predicts night-time temperatures, is too slow to cool down, and its flat gradual downward slope is nothing like the variations seen in the observations. Night-time ENVI-met predictions do nearly match observed temperatures when wind speeds increase (which coincide with observational temperature rises) but vary greatest when observed wind speeds are low (and observed temperatures are lower).

In Figure 12, predicted ENVI-met values for incoming solar radiation are compared to observed values. Values at non-shaded sites are over-predicted. Sites with tree cover have lower predicted values, but have smooth regular curves for peaks instead of peaks and troughs seen in the observations when breaks in the canopy allow periods of full solar exposure. When the area under these curves are calculated (Table 2, showing $MJ/m^2/day$) to show accumulated shortwave radiation received at each of these sites over a day, ENVI-met is shown to have over-predicted accumulated incoming shortwave radiation at all the sites. Predictions for “Dorm” and “Reserve fence” are nearly right but accumulated values predicted for “Reserve” and “Field” are about twice the observed values, with “Garden” and “Sign” over-predicted by three times.

In Figure 13, predicted ENVI-met values for specific humidity levels are compared to observed values. Overall, ENVI-met predicts no significant variations in humidity levels either temporally or spatially with predictions of approximately 7 g/km through the entire simulation. The variations from about 6 to 9.5 g/kg observed at the sites over the period are not resolved by ENVI-met.

Finally, in Figure 14, predicted ENVI-met values for wind speeds are compared to observed values. As with humidity levels, predicted values show an overall lack of variation. Spatially, there is some variation. Speeds of just under 1 m/s are predicted for “Reserve fence”, “Reserve”, “Garden” and “Field”. Nearly 2 m/s is predicted for “Sign” and zero wind speed is predicted for “Dorm”. Patterns of varying wind speed seen in the observations (rising wind during the mornings, calming winds towards the evenings and rising winds again through the nights) are not in evidence as the predicted values at each site remain static. Without this variation, this leads to an under-prediction of wind speed during the day and over-prediction of wind speed at night. Overall, the ENVI-met predictions appear to show a lag (as well as under-prediction) in rising daytime temperatures, followed by over-predictions for night-time temperatures, as well as a lack of variability in temperatures, humidity and wind speeds seen in the observed results.

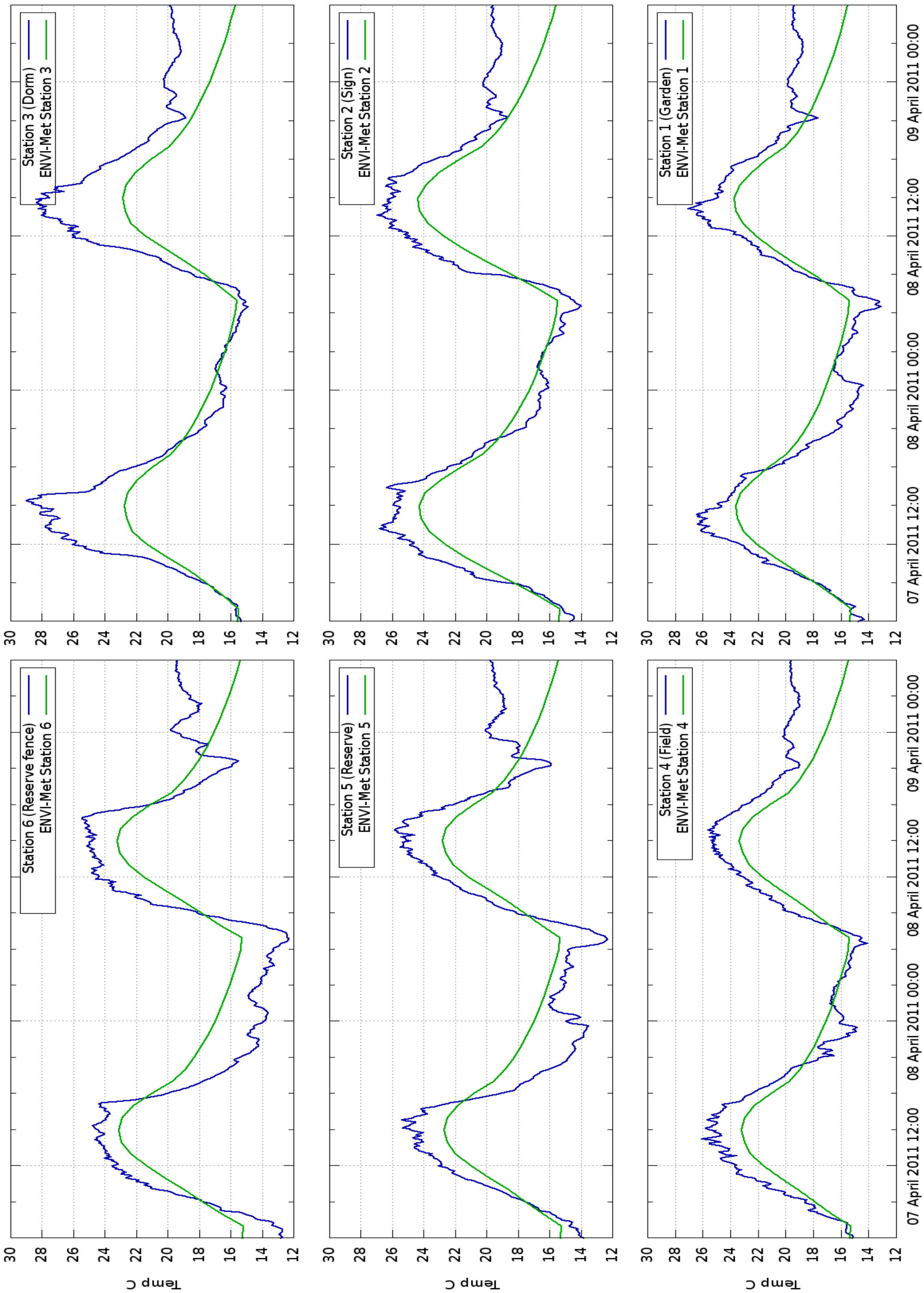

Figure 11–Comparison of temperature of observation sites versus ENVI-met model results, 7-8 April 2011

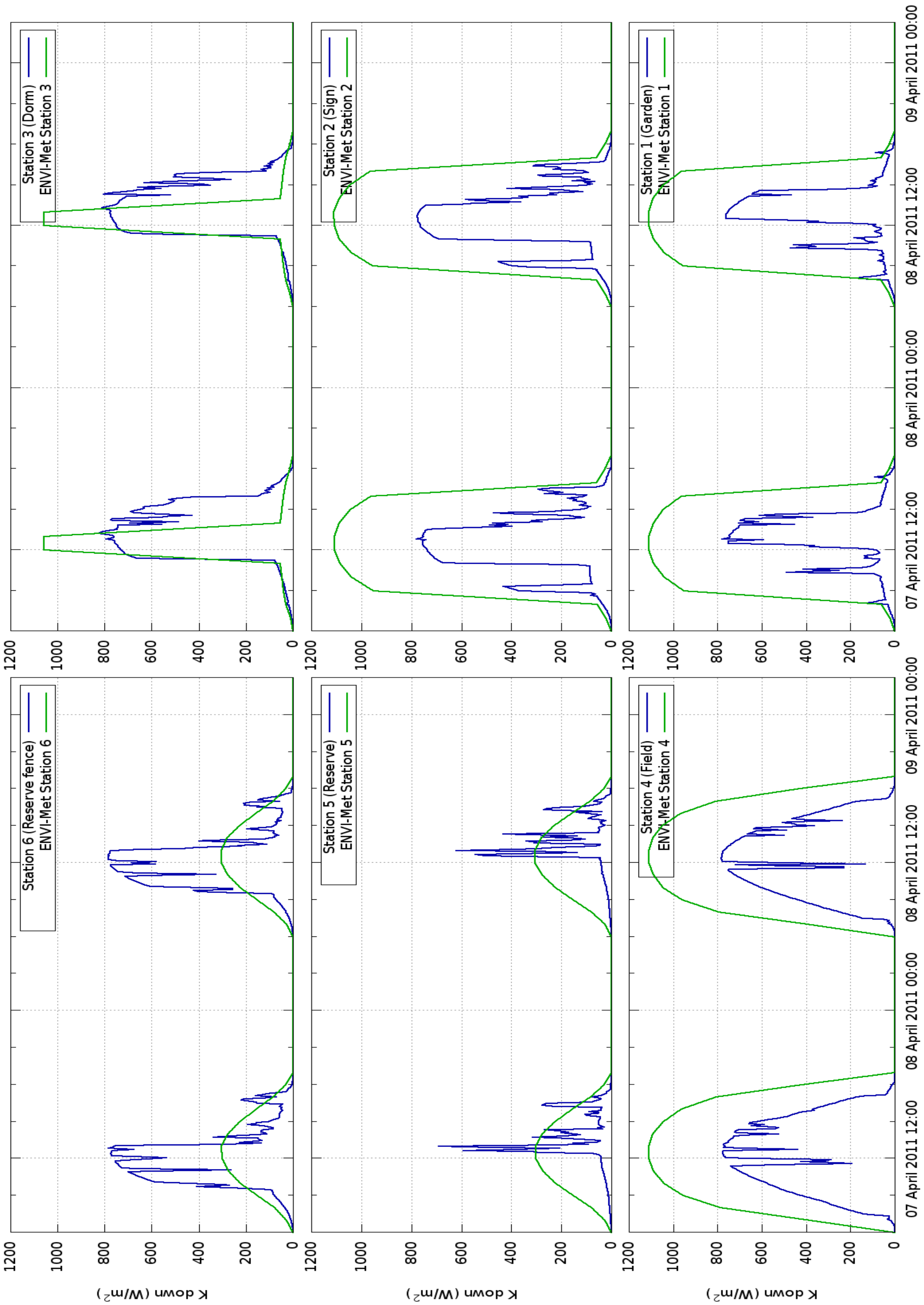

Figure 12–Comparison of K down of observation sites versus ENVI-met model results, 7-8 April 2011

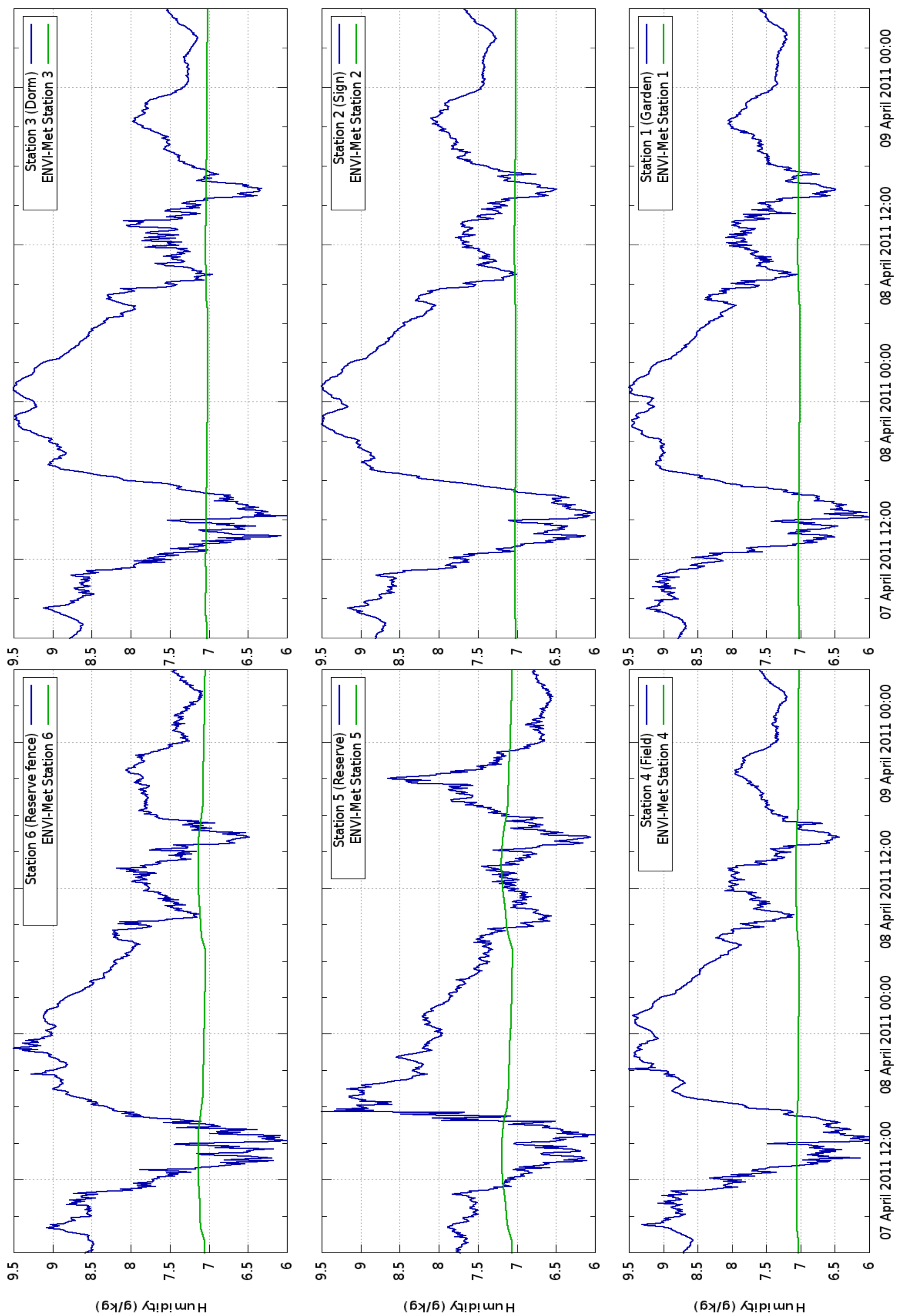

Figure 13–Comparison of humidity of observation sites versus ENVI-met model results, 7-8 April 2011

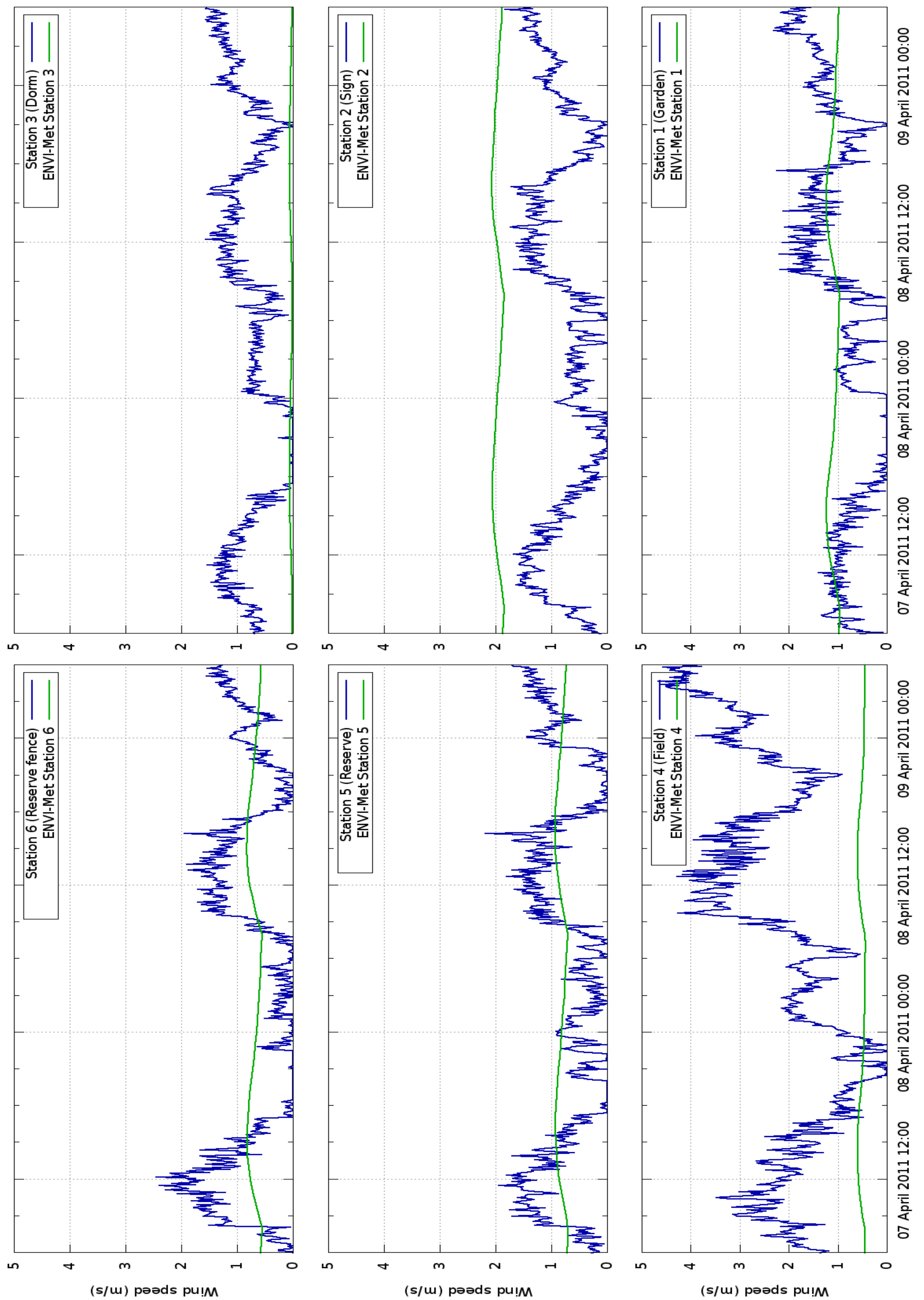

Figure 14–Comparison of wind speed of observation sites versus ENVI-met model results, 7-8 April 2011

Sites	ENVI-met	Observed
"Garden"	30.7	7.7
"Sign"	30.6	11.2
"Dorm"	8.9	12.6
"Field"	38.6	18.1
"Reserve"	7.6	3.0
"Reserve fence"	7.6	9.3

Table 2 – Accumulated shortwave radiation (in $MJ/m^2/day$) received at sites over 7-8 April 2011

Model versus observations differences

Figure 15 shows the difference between the observed air temperatures and those predicted by ENVI-met for the six sites. These results are starting to highlight the spatial differences in temperatures and ENVI-met's difficulty in resolving them. Perfect predictions by ENVI-met would result in a straight line plot at 0ºC, which is something not seen in the plot. In these results, ENVI-met's predictions diverge +6ºC to -4ºC in the edge cases, or +2ºC to -2ºC off when the edge cases are removed.

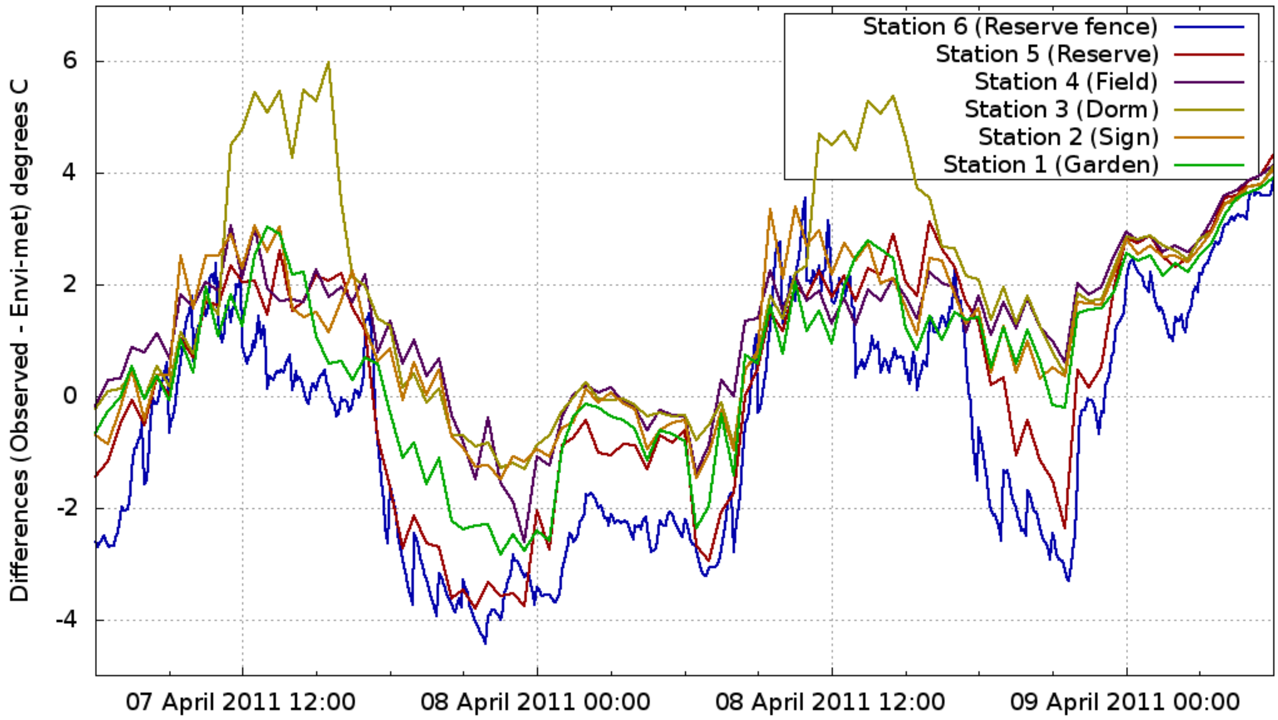

Figure 15–Differences in temperature between observation sites and ENVI-met model results, 7-8 April 2011

Temperature gradient maps annotated with sites and observed temperatures

Finally, two plots (Figures 16 and 17) show ENVI-met's resolution of temperature gradients across the study area. The plots show predicted values for 6 am on the 8th of April 2011 (the second day of the comparison period) and for 2 pm on the same day. Observation sites are annotated on the plots with the temperatures measured at that time at those locations. ENVI-met does predict broad features of the observed spatial patterns of temperatures. Warmer areas are seen in the northern urban locations and cooler areas in the southern parkland sections. For 6 am, ENVI-met predicts a tight range of temperature values, ranging from 15.1ºC to 15.8ºC, compared to the observed range of 13.3ºC to 15.4ºC. ENVI-met predicts a much narrower range than is observed as well as over-predicts temperatures at that time. On the 2 pm plot, ENVI-met has predicted a range of values from 22ºC to 25ºC. Observed values range from 24.7ºC to 27.8ºC. ENVI-met predicts a similar spread of values but predicts lower values than are observed. The range of differences between observed and predicted temperatures (+3ºC to -2ºC) shown in Figure 15 are similar to the range of temperature gradients seen in the observations between the urban and parkland areas of the study site.

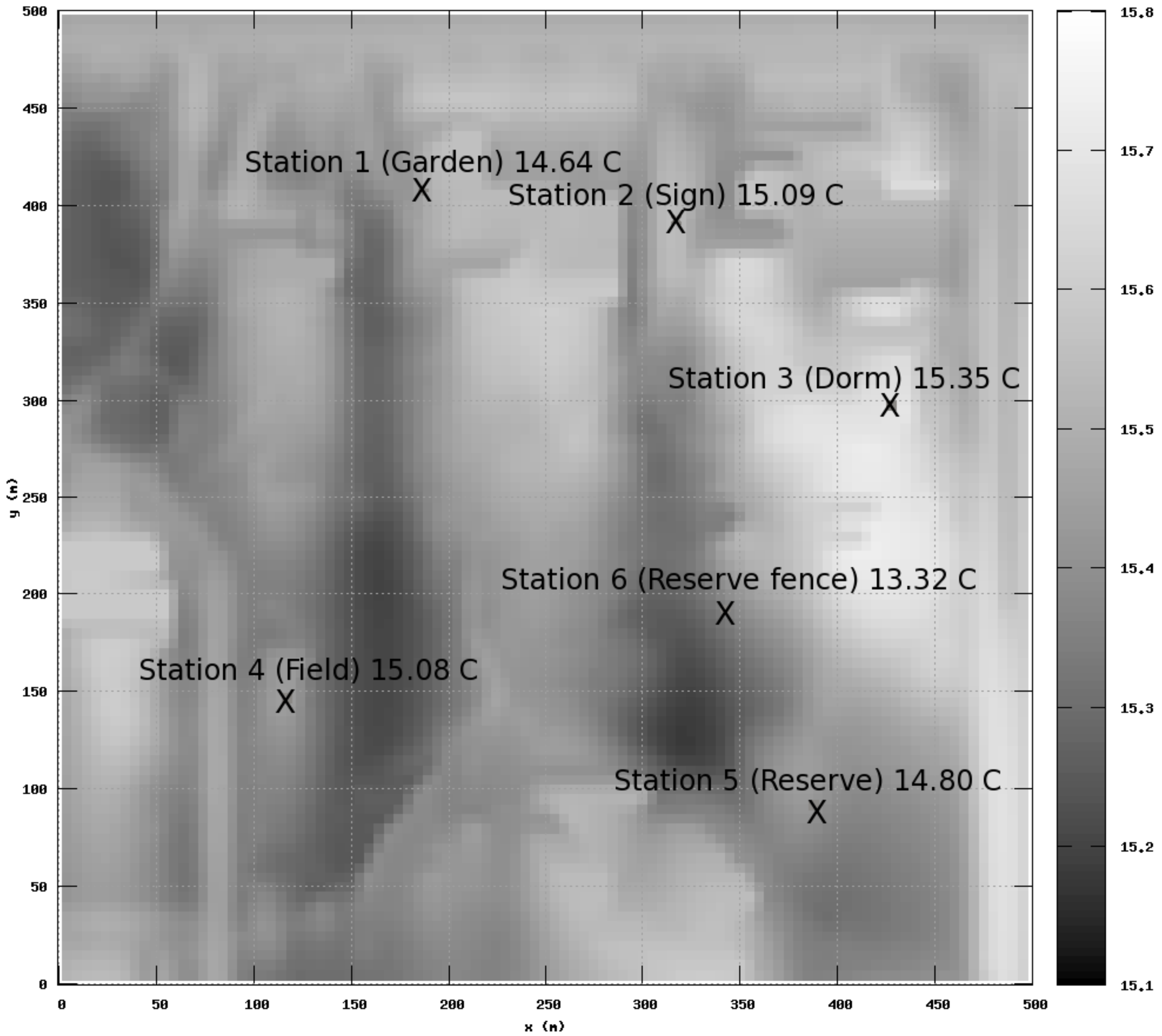

Figure 16–Temperature (in °C) results for ENVI-met model run with observational site data points, 8 April 2011 6:00 am.

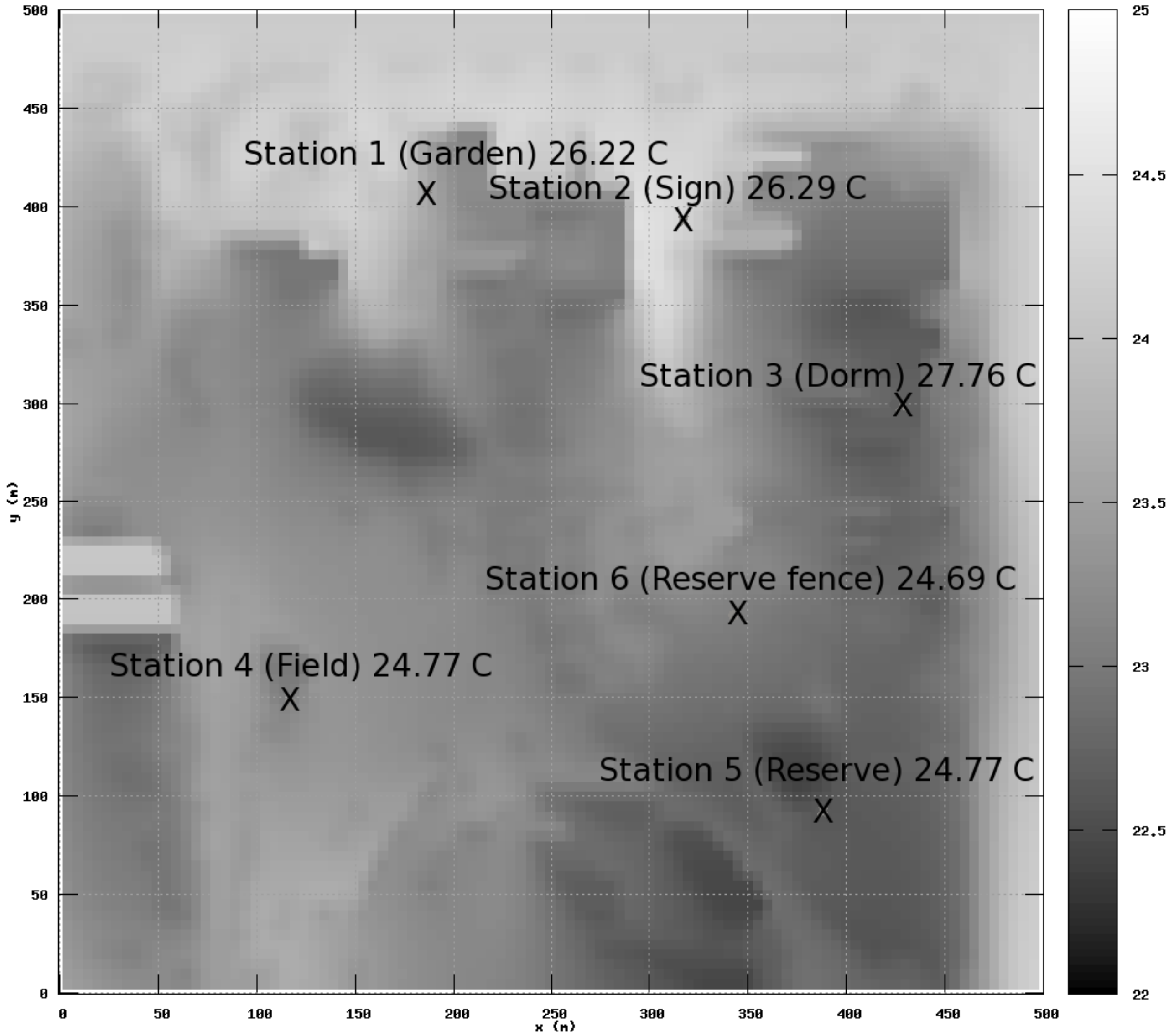

Figure 17–Temperature (in °C) results for ENVI-met model run with observational site data points, 8 April 2011 2:00 pm.

Discussion

Mixed urban parklands

In this study, a mixed urban parkland area was examined. This area contained medium density housing surrounded by paved surfaces and a moderate amount of vegetation and trees. It also contained parkland-like areas, containing water bodies and trees, as well as high percentages of grass covered surfaces. The former area is much like the urban areas of a medium density urban city. In it, temperatures were found to be warmer, up to 5°C warmer compared to the parkland-like areas. The area also held onto this heat into the night, remaining 2-3°C warmer into the early morning hours. This is consistent with UHI findings discussed in the literature review. Large buildings block winds and minimize wind mechanical mixing effects during the daytime, allowing heat to build. Heating effects are also amplified by lesser amounts of water available in the area to cool through evapotranspiration. Then, at night, the impervious surfaces continue to radiate heat trapped during the daytime.

In areas with higher levels of vegetation, temperatures under the canopy in the southern sections of the study area were found to be cooler during the daytime as well as cooler at night. This is consistent with cooling effects of vegetated areas through shading and evapotranspiration. The two water bodies in this section of the study area also provide additional cooling effects. Water Sensitive Urban Design uses this cooling effect as an important component of urban design and seeks to integrate water into an urban area instead of removing it as waste. During the longer heatwaves projected in the future, cooler temperatures in these parkland-like areas (and spatial extents into surrounding areas) can serve as a respite from the intensity of the heatwave and be an important consideration in saving lives.

A look at ENVI-met results compared to observations

In looking at the results from ENVI-met simulations, a number of trends and concerns arise. Starting with results from the shortwave radiation plots (Figure 12), divergences from expected (and observed) results are seen. Most troubling are peak values on both days that are much higher than expected. Values peak at around 1100 W/m, which are much higher than the peaks in the observed data of around 875 W/m^2. Total shortwave radiation accumulation at the sites (Table 2) are a number of times greater than what is expected. In areas with some canopy cover, ENVI-met just presents a smooth low curve for incoming radiation values. This suggests that ENVI-met's modelling of a canopy is unrealistic and lacking in natural complexity (the peaks and troughs seen in the observational values as sunlight breaks through the canopy) if the canopy is being modelled as a simple homogeneous layer.

ENVI-met predicted values for humidity and wind are quite static. Unlike the data collected from the observational sites, there is no significant temporal variation in the predictions. Spatially, wind shows some variation across the different sites in the predictions, however, there is no significant spatial variation in humidity predictions across these sites. Any possible cooling effects due to evapotranspiration cannot be accounted for by the model, or if they are, they will be constant and not vary spatially or temporally.

Perhaps a bigger source of inaccuracy in the model is modelling of wind speeds. On average, the predicted wind speeds might be reasonable approximations, such as seen at “Reserve”. ENVI-met predicts an average speed of about 0.75 m/s. This is probably slightly high compared to observed results at that site, but is still close. However, some of the sites are completely off. Predictions at “Dorm” of about 0 m/s are at least somewhat close to the average value of the observed values, but values of about 0.5 m/s at “Field” are many multiples below observed values. While “Field” received nearly 70% more solar radiation than “Dorm”, the importance of mechanical mixing by the wind (of around twice the speed) can be seen in moderating the maximum daytime temperatures to about 3ºC less than the maximum recorded at “Dorm” in the observations. This feature was not revolved by ENVI-met in this study.

In addition, a lack of temporal variations in wind speed allows the model to miss a number of the temperature variations seen in the observed data. Sharp drops in temperature after dark accompanied by relative calm winds cannot be contributed to by static wind speeds in the model. The observed slight rises in temperatures before dawn driven by increasing wind speeds and mechanical mixing also cannot be modelled in the simulations due to static wind speeds.

In addition to being hampered by driving forces (wind and humidity) which are constant values, comparing temperature predictions with observed values also reveals some problems. Temperatures in the model seem slow to warm up during the day and slow to cool down at night. Maximum daytime temperatures are under-predicted and night-time minimum temperatures are over-predicted. The temporal variations in the model seem to be lagging behind observational data. Also, spatially, the expected edge cases are not predicted. Maximum temperatures at “Dorm” are under-predicted by nearly 6ºC while night-time lows at “Reserve” are also under-predicted by nearly 4ºC. While these are edge cases, as noted earlier, the slope of the warming and cooling curves diverges from observed values, calling into question the ability of ENVI-met to make accurate predictions about spatial and temporal variations in temperature in this study.

Side by side comparisons of sites

The sites that were anticipated to be the most difficult to predict turned out to be so. Nearly +6ºC variation was found at the “Dorm” site at the warmest part of the day, while the rest of the sites were about +1.75ºC off. At night, the sites with the greatest tree cover, “Reserve” and “Reserve fence” night-time temperatures were over-predicted at 4ºC too warm, while other sites were still over-predicted 1ºC too warm. During the analysis stage, data was extracted from the ENVI-met results from the 8 grid squares surrounding each location and no significant variation was found in predicted temperatures in those surrounding grid squares from what was predicted in the centre point. The implications of this are that, even if more observation points were placed close to the “Dorm” observation site and observed temperatures dropped off quickly within a short distance (5-10 meters away), ENVI-met would not have predicted this as the predicted temperatures showed no spatial variation across these grid squares.

In looking at the gradients of temperature predicted by ENVI-met (Figures 16 and 17), the types of variations seen in the observations are not seen in the modelling predictions. In the 6 am predictions, the range found in the observations of about 2ºC are not reflected in the 0.7ºC range predicted by the model. Also, the warmer observed sites “Dorm”, “Sign” and “Field” do not seem to follow the temperate gradients predicted in the model.

However, a limitation of observational data can be seen. With only six points of observational data, comparisons to the 1000 points predicted in the model is very difficult. In addition, in the 2 pm predictions (Figure 18), the plot seems to be highly influenced by edge effects predicting warmer temperatures on the north and east edges. This makes it difficult to determine if the patterns of warmer temperatures in the northern section of the study area in the observations were accurately predicted by the model or if it was an accidental prediction through edge effects. The later might be the case as the hottest observed temperature, at “Dorm” is in the middle of a predicted cool pocket by ENVI-met. Cool pockets are also predicted at the reserve pond (directly north of “Reserve”) as well as the other pond (slightly south of “Garden”). ENVI-met does predict large scale features across the study area, but given the resolution of the observed data, it isn't possible to determine if those are accurate predictions.

Conclusion

Progression of climate change, with its predicted intensification of temperature extremes and heat wave durations, combined with demographic trends towards increased urbanization make the study of urban micro-climates desirable. Heat wave durations can have a significant impact on human health, especially in a rapidly ageing population. The morphologies of our urban environments are contributing to these effects through intensified effects of urban heat island. Measures can be taken in adapting to these changing conditions. Reforming urban environments to take advantage of natural cooling effects of wind and water and shading can help with this adaptation. Such measures might also contribute to climate change mitigation efforts, through reduced CO_2 emissions and increased storage of CO_2 in vegetation and trees. In order to maximize the impact of these efforts, urban micro-climate environments must be better understood. What sorts of temporal and spatial temperature variations exist and what conditions surround maximum and minimum differences? In addition, given the difficulties of observational studies of these systems, can modelling help and serve as an accurate tool to predict a wide variety of scenarios and help guide urban planning in the future.

The drivers of urban micro-climates are partially understood. Solar radiation is the main driver, leading to energy budget balances of incoming and outgoing long and shortwave radiations with heat storages in the environment and fluxes of sensible and latent heat. Water evaporation ties water budget balances to these through the important cooling effect of latent heat evapotranspiration. Other drivers such as wind and humidity can also be observed to have effects, even though the interactions of them, such as turbulent air flows through urban canyons, are still not completely understood.

In this study, parkland areas were found to be 2°C cooler than a medium density urban area on average. While determining the exact spatial extent of this cooling effect is hampered by limited observational data as well as uncertainty over accuracy of simulation results, it appears to extend 50-100 metres upwind of water bodies and to a lesser extent from highly vegetated areas. ENVI-met was successful at predicting gross features of spatial variations in temperatures across the study area, predicting cooler temperatures in areas of high vegetation and warmer temperatures in built up urban areas. These predictions were supported by observational data. However, ENVI-met was unable to resolve smaller scale micro-climate spatial variations. Variations in observed temperatures between the different sites were found to be similar to the range of predicted errors, the differences between ENVI-met predictions and observational values.

To further refine these findings, future study is needed using both the modelling and observational methodologies to study mixed urban parkland micro-climates. A more intensive observation network would allow deeper explorations of spatial extents of cooling effects from parkland features embedded into urban areas. Improved modelling is also necessary to help in this exploration. Future versions of ENVI-met promise the ability to vary meteorological conditions as well as more accurate modelling of tree canopies. These would be welcome developments and help further drive our knowledge of urban-micro climates.

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