

# Seasonal surface urban energy balance and wintertime stability simulated using three land-surface models in the high-latitude city Helsinki

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The performance of three urban land-surface models, run in off-line mode, with their default external parameters, is evaluated for two distinctly different sites in Helsinki: Torni and Kumpula. The former is a dense city-centre site with 22% vegetation, while the latter is a suburban site with over 50% vegetation. At both locations the models are compared against sensible and latent heat fluxes measured using the eddy covariance technique, along with snow depth observations. The cold climate experienced by the city causes strong seasonal variations that include snow cover and stable atmospheric conditions.

Most of the time the three models are able to account for the differences between the study areas as well as the seasonal and diurnal variability of the energy balance components. However, the performances are not systematic across the modelled components, seasons and surface types. The net all-wave radiation is well simulated, with the greatest uncertainties related to snow-melt timing, when the fraction of snow cover has a key role, particularly in determining the surface albedo. For the turbulent fluxes, more variation between the models is seen which can partly be explained by the different methods in their calculation and partly by surface parameter values. For the sensible heat flux, simulation of wintertime values was the main problem, which also leads to issues in predicting near-surface stabilities particularly at the dense city-centre site. All models have the most difficulties in simulating latent heat flux. This study particularly emphasizes that improvements are needed in the parametrization of anthropogenic heat flux and thermal parameters in winter, snow cover in spring, and evapotranspiration, in order to improve the surface energy balance modelling in cold-climate cities.

**Key Words:** CLM; eddy covariance; high-latitude; stability; SUEWS; surface energy balance; SURFEX; urban

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## 1. Introduction

With the increasing number and density of people living in urban areas (World Bank, 2014) it is crucial to be able to forecast the atmospheric conditions in these areas for a wide range of reasons. This includes for extreme conditions (e.g. heatwaves, intense precipitation) but also day-to-day variations in air quality, plus for long-term planning and design (McMichael *et al.*, 2006; IPCC, 2013). Enhanced urban effects, combined with large exposure to these adverse effects, require appropriate actions to be taken.

In particular, tools capable and appropriate to examine and predict high-latitude atmospheric conditions are needed, as the most dramatic climate change is expected in these areas (IPCC, 2013). High-latitude areas, in comparison to mid- or tropical latitude areas, are characterized by strong seasonal variability in meteorological conditions, particularly in solar radiation and air temperature, impacting vegetation phenology and heating need. In addition, snow on the ground is common in the winter and spring, altering the surface conditions by increasing surface albedo and modifying surface water availability and heat

storage (Semádeni-Davies and Bengtsson, 1998). Additionally, the boundary layer can remain very stable in urban areas during winter, restricting pollutant dispersion and creating the potential for hazardous conditions. Therefore, prediction of atmospheric stability is important for high-latitude communities. However, the stable conditions commonly cause challenges for weather prediction and air-quality models (Holtslag *et al.*, 2013).

The description of different surfaces in atmospheric models is provided by land-surface models (LSMs) that parametrize the surface–atmosphere exchanges. Many urban LSMs, with varying degree of complexity, were evaluated by Grimmond *et al.* (2011). They demonstrated that the models do not perform well across all components indicating lack of understanding of the urban processes, in particular evapotranspiration. Thus, a better description of the factors affecting the energy partitioning into sensible ( $Q_H$ ) and latent heat fluxes ( $Q_E$ ) in urban areas are needed. In urban areas, the energy balance equation can be written:

$$Q^* + Q_F = Q_E + Q_H + \Delta Q_S + \Delta Q_A, \quad (1)$$

where  $Q^*$  is the net all-wave radiation,  $Q_F$  is the anthropogenic heat flux, and  $\Delta Q_S$  is the net storage heat flux including both soil heat flux and heat storage and release of urban fabric.  $\Delta Q_A$  is net heat advection and typically in land-surface models microscale (or subgrid-scale) advection is included within the parametrizations of the individual energy balance terms. In Eq. (1), only  $Q^*$  and the turbulent fluxes can be easily measured. The other components require detailed measurements combined with models to be estimated.

Relatively little attention has been given to the performance of LSMs in cold-climate or high-latitude cities (Lemonsu *et al.*, 2010; Leroyer *et al.*, 2010; Järvi *et al.*, 2014). Thus the purpose of this study is to evaluate and compare the performance of three urban LSMs for two areas with different urban land cover in Helsinki. The models are run in their default mode in order to understand how the model physics and default parameters, commonly derived and successfully used in midlatitude cities, perform in a high-latitude city. The models used are the Community Land Model (CLM: Lawrence *et al.*, 2011), the Surface Urban Energy and Water Balance Scheme (SUEWS: Järvi *et al.*, 2011) and Surface Externalisée (SURFEX: Masson *et al.*, 2013). The evaluation dataset consists of: net all-wave radiation, turbulent sensible and latent heat fluxes measured using the eddy covariance (EC) technique, and snow depth. The effects of the model performances on energy partitioning and predicting near-surface stability are examined. Following the study site and measurement set-up (section 2), the model descriptions (section 3) are given. The specific model set-ups and analysis methods are provided in section 4. Finally, the results are shown and discussed (section 5) and conclusions drawn (section 6).

## 2. Study sites

The focus of this study is two sites within the capital city of Finland, Helsinki (Figure 1(a), Table 1). This northern European city (latitude 60°N) has approximately 616 000 inhabitants (Tilastokeskus, 2014). Despite the clearly reduced wintertime solar radiation (Figure 1(b)), the Atlantic Ocean and the Baltic Sea create milder winters than typically observed at this latitude. Helsinki's heating is commonly centralized and the buildings are designed to retain heat.

The intra-annual variability of daytime mean (between 1000 and 1400 local time (LT: UTC + 2 h)) of incoming short-wave radiation ( $K_{\downarrow}$ ), and daily mean air temperature ( $T_{air}$ ), relative humidity (RH) and incoming long-wave radiation ( $L_{\downarrow}$ ), plus daily total precipitation ( $P$ ) are shown in Figure 1(b) for 2012. In winter, daytime mean  $K_{\downarrow}$  stays below 100 W m<sup>-2</sup> whereas in summer it reaches 750 W m<sup>-2</sup>. The reduced solar radiation has implications for both the available energy in the system and

vegetation phenology; both of which are crucial for surface energy balance (Eq. (1)) behaviour. In February, the daily mean  $T_{air}$  is -20 °C whereas in July it is over +20 °C. As winter  $T_{air}$  for most of the time stays below freezing, most  $P$  occurs as snowfall. Thus, the significant role snow plays in the winter urban energy balance has to be taken into account. RH varies between 20 and 100% with the lowest values in spring and early summer.  $L_{\downarrow}$  follows closely the annual behaviour of  $T_{air}$  with a range of 200–350 W m<sup>-2</sup>.  $P$  is distributed through the year, with slightly higher rates observed in autumn in 2012.

The study areas (Figure 1(a)) are based on the approximate turbulent flux footprints of SMEAR (Station for Measuring Ecosystem–Atmosphere Relations) III observations. The first site, suburban Kumpula, is located 4 km north-east from the Helsinki city centre and can be characterized as a local climate zone (LCZ) 6 (Stewart and Oke, 2012). The 31 m high measurement mast is surrounded with three distinct surface-cover sectors (Vesala *et al.*, 2008). To the north (320 to 40°, referred to here as Ku1) in the foreground are the University of Helsinki campus buildings and further away suburban apartments generally with low building heights with small gardens. To the east (40–180°, Ku2) is a large road heading to Helsinki city centre (closest distance of 150 m) with mixed broadleaf forest in the foreground. Finally, to the west (180–320°, Ku3) a vegetated area consists of allotment gardens and the University Botanical Garden. As the anthropogenic activities, including heating, traffic and irrigation, as well as vegetation types vary between the three sectors, they are modelled separately.

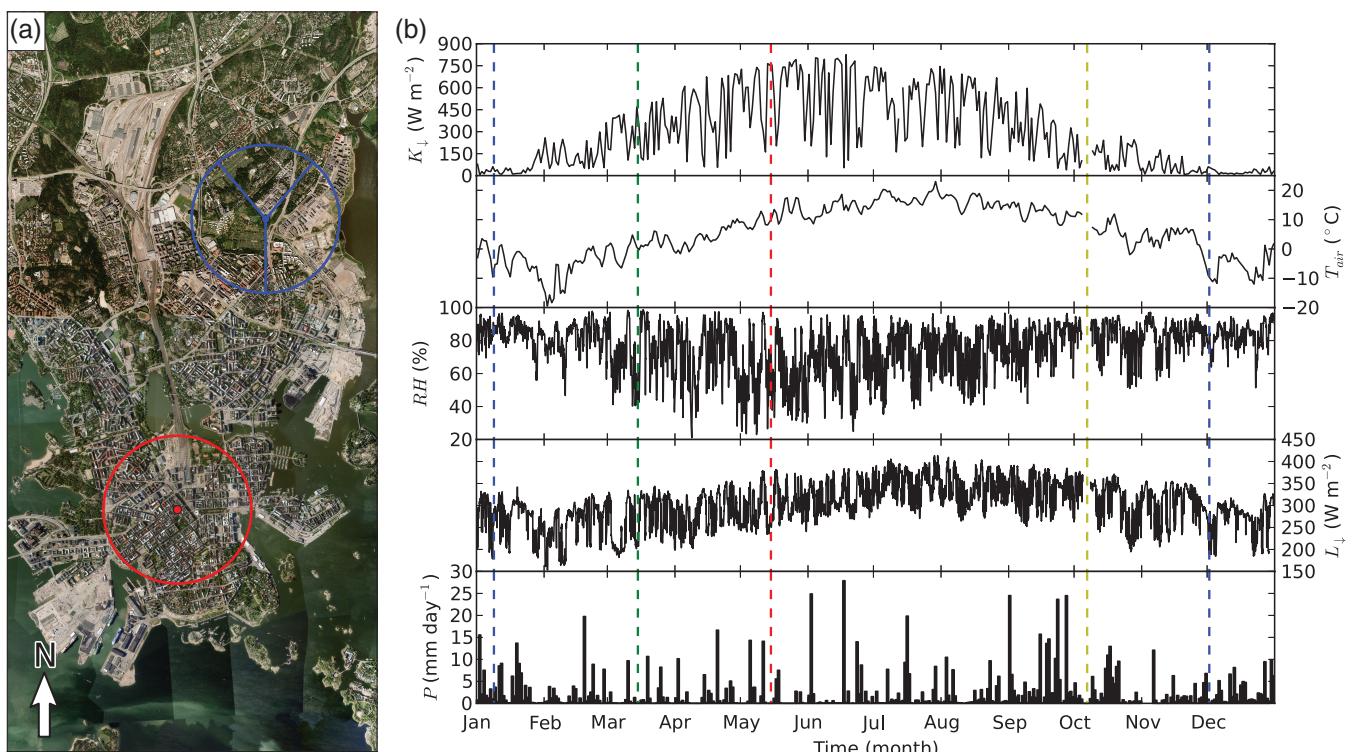
The second site (Hotel Torni), in the Helsinki city centre (Nordbo *et al.*, 2013), is highly built-up with only slightly more than 20% vegetation cover. There are a few small parks with shrubs and trees plus some street canyons with trees. Most of the buildings are 4–5 storey buildings with a mean height of 18 m. This site is classified as LCZ 2. As the city centre is located on a peninsula, the Baltic Sea is near the measurement site in three wind directions.

### 2.1. Measurements

Both sites have EC systems that allow evaluation of model performances for the turbulent heat and momentum fluxes. The EC technique directly measures the heat and moisture carried by the turbulence in the atmosphere (Aubinet *et al.*, 2012). With simultaneous measurements of vertical wind speed and the scalar of interest (e.g. temperature), the vertical exchange is calculated as a covariance between these two, from which the fluxes can be calculated.

At both sites, wind components and sonic temperature are measured with an ultrasonic anemometer (USA-1, Metek GmbH, Germany). The water vapour mixing ratio is measured at Kumpula with a closed-path infrared gas analyser (LI-7000, LI-COR, Lincoln, NE, USA) and at Hotel Torni using an enclosed path analyser (LI-7200, LI-COR). The 10 Hz measurements were analysed using commonly accepted methods (Nordbo *et al.*, 2012). The EC measurements are carried out at a sufficient height above the surrounding buildings at both sites (31 m Kumpula, 60 m Torni).

Meteorological data are needed both for model forcing and evaluation. Most of the measurements are made at Kumpula, where the measurements include tower-based  $T_{air}$  (platinum resistant thermometer, Pt-100, 'in-house'), wind speed (Thies Clima 2.1x, Göttingen, Germany) and incoming and outgoing short- and long-wave radiation (CNR1, Kipp&Zonen, Delft, Netherlands) at 31 m above ground level (a.g.l.). Air pressure (DPA500, Vaisala Oyj, Vantaa, Finland), relative humidity (HMP243, Vaisala Oyj), and precipitation (rain-gauge, Pluvio2, Ott Messtechnik GmbH, Germany) are measured from the roof of a nearby building at 24 m a.g.l. Downtown,  $T_{air}$  (HMP45D, Vaisala Oyj) and outgoing short- and long-wave radiation (CNR4, Kipp&Zonen) are measured 550 m southeast of the Torni site at



**Figure 1.** (a) Aerial photo of Helsinki city centre (© 2011 Kaupunkimittausasto, Helsinki, Finland). Kumpula measurement site is marked with a blue dot and Hotel Torni with a red dot. Circles denote the modelled areas (radius 1 km, Table 1) and the lines at Kumpula mark the different surface cover areas (Ku1 in the north, Ku2 in the east and Ku3 in the west). (b) Time series of selected meteorological variables observed in Kumpula in 2012. From top to bottom: daytime mean incoming short-wave radiation (average over hours 1000–1400 local time (UTC + 2 h),  $K_{\downarrow}$ ), daily mean air temperature ( $T_{\text{air}}$ ), relative humidity (RH) and incoming long-wave radiation ( $L_{\downarrow}$ ) plus daily sum of precipitation. The blue, green, red and yellow dashed lines indicate the starting days for thermal (changes with year) winter, spring, summer and autumn, respectively.

a height of 53 m. Snow depths are measured near the Kumpula mast and in a park in the city centre by the Finnish Meteorological Institute.

### 3. Model descriptions

Each of the LSMs can be coupled to an atmospheric model (e.g. for numerical weather prediction or climate simulation), or as in this study, used as a standalone model. Given the focus on anthropogenic heat and snow cover in urban areas, these parametrizations are discussed below (see also Table 2).

#### 3.1. CLM

Version 4 of the Community Land Model (CLM4: Lawrence *et al.*, 2011), the land-surface scheme embedded in the Community Earth System Model (CESM: Hurrell *et al.*, 2013), is used here. CLM4 uses a nested sub-grid hierarchy in which each grid cell (or tower footprint) can have up to five land units: wetlands, glaciers, vegetation, lakes and urban. The vegetated fraction is modelled with the vegetation canopy/soil model in CLM and the urban fraction, or urban land unit, with the Community Land Model Urban (CLMU: Oleson *et al.*, 2008a, 2008b). CLMU follows the concept of Oke (1987) in which the considerable complexity of an urban environment is reduced to a single-layer urban canyon that consists of five columns: roof, sunlit and shaded wall, impervious and pervious road. The walls are hydrologically inactive, while liquid and solid precipitation can be intercepted, stored and evaporated from the roof and canyon floor (both impervious and pervious road). The advantage of such a modelling framework is that the pervious fraction is an integral part of the urban canyon and will thus interact with urban canyon air properties such as humidity and temperature (Oleson *et al.*, 2008b; Demuzere *et al.*, 2013). The required model input of  $K_{\downarrow}$  is partitioned into direct and diffuse radiation based on empirical factors derived from analysis of 1 year of hourly

Community Atmosphere Model (CAM) output (Oleson *et al.*, 2010a). For full technical descriptions of CLMU and CLM, see Oleson *et al.* (2010a, 2010b).

CLMU provides three options to calculate  $Q_F$ : (1) assume that it is negligible, (2) limit the internal building temperature to a specified comfort range with no waste heat released into the urban canopy layer, or (3) with waste heat released into the urban canopy layer (see also Demuzere *et al.* (2013)). For Helsinki, option 3 is used with an internal minimum building temperature ( $T_{\min, \text{building}}$ ) of 19 °C (heating required) but no maximum internal building temperature is used as in Jackson *et al.* (2010); this is set sufficiently high for this high-latitude region such that air conditioning is never required. Here,  $T_{\min, \text{building}}$  is used as a lower boundary condition in the solution of heat conductivity in roof and walls. The total waste heat flux into the urban canopy layer is controlled by factors describing the efficiencies of space heating/air conditioning systems and the conversion of primary to end-use energy (see eq. 4.55 in Oleson *et al.* (2010a)). For this study, the factor for waste heat from space heating is set to 0.2 based on analysis by Sivak (2013).

In CLMU, a snowpack (represented by up to five snow layers) that can form on the active surfaces (roof and road fractions) influences processes in the energy and hydrological cycles. The albedo and emissivity of each urban surface are a weighted combination of snow-free and snow albedos. A fractional snow cover ( $f_s$ ) is defined for roof and canyon floor surfaces as  $f_s = s_d / 0.05 \leq 1$  with  $s_d$  being the snow depth in metres. From a hydrological perspective, the roof and impervious road are able to store snow, while the pervious road fraction includes snow accumulation and melt and water transfer between snow layers besides other hydrological processes such as infiltration, surface runoff, subsurface drainage, and redistribution within the soil column.

#### 3.2. SUEWS

The Surface Urban Energy and Water balance Scheme (SUEWS: Järvi *et al.*, 2011) simulates the urban water and energy balances

Table 1. Information about the study sites (Figure 1(a)) and parameters used in the model runs.

	Torni	Kumpula		
		Ku1	Ku2	Ku3
Latitude (WGS84)	60° 10' 04.09"N		60° 12' 10.14"N	
Longitude (WGS84)	24° 56' 19.28"E		24° 57' 40.06"E	
Initial date and time of the run	1 July 2011 0000 LT (UTC+2)		1 July 2011 0000 LT (UTC+2)	
Time zone	0200 UTC		0200 UTC	
Measurement/modelling height (m)	60		31	
Base elevation (m)	15.2		29	
Local climate zone (LCZ)	2		6	
Study area ( $m^2$ )	1 960 000	447 000	782 000	782 000
Population density (no. $m^{-2}$ ) <sup>a</sup>	0.0081	0.0031	0.0037	0.0044
Fraction of built surface	0.78	0.42	0.54	0.46
Fraction of paved surface	0.40	0.27	0.39	0.32
Fraction of buildings	0.37	0.15	0.15	0.14
Fraction of vegetation	0.22	0.58	0.46	0.54
Fraction of coniferous trees/shrubs <sup>a,b</sup>	0	0.01	0	0.01
Fraction of deciduous trees/shrubs <sup>a,b</sup>	0.15	0.38	0.2	0.29
Fraction of grass surface <sup>a,b</sup>	0.07	0.20	0.26	0.24
Fraction of boreal broadleaf deciduous trees <sup>c</sup>	0.12	0.34	0.20	0.27
Fraction of boreal needle leaf evergreen trees <sup>c</sup>	0.03	0.04	0	0.02
Fraction of C3 grass surface <sup>c</sup>	0.07	0.20	0.26	0.25
Fraction of water <sup>d</sup>	0.01	0	0.01	0
Mean building height (m)	17.9	10.4	11.5	12.6
Mean tree height (m)	8.3	9.8	8.7	8.4
Starting day for irrigation <sup>a</sup>	152	152	152	152
Ending day for irrigation <sup>a</sup>	243	243	243	243
Fraction of automatic irrigation <sup>a</sup>	0.3	0.2	0.2	0.4
Previous day $T_{air}$ (°C) <sup>a,b</sup>	21	21	21	21
Days since rain <sup>a,b</sup>	4	4	4	4
Initial $T_{soil}$ 50–230 mm (°C) <sup>e</sup>	12.7	12.7	12.7	12.7
Initial $T_{soil}$ 230–600 mm (°C) <sup>e</sup>	9.4	9.4	9.4	9.4
Init. soil water storage 0–230 mm (mm) <sup>e</sup>	54	54	54	54
Init. soil water storage 0–370 mm (mm) <sup>e</sup>	125	125	125	125
Init. surface state (mm) <sup>a</sup>	0	0	0	0

<sup>a</sup>SUEWS.<sup>b</sup>SURFEX.<sup>c</sup>CLM.<sup>d</sup>Water surface only considered in SUEWS. Water fraction replaces the respective vegetation fraction.<sup>e</sup>Obtained from soil observations conducted at a park in central Helsinki.Where model specific values are required these are indicated. Land cover fractions for Kumpula were calculated based on Nordbo *et al.* (2015) and for Torni from Nordbo *et al.* (2013).

at the local or neighbourhood scale. Here version V2014b is used. It requires basic meteorological variables and information about the surface cover of the study area including surface cover fractions, tree and building heights, and number of people. The model determines the rates of evaporation/interception at a 5–60 min time step for seven surfaces types (paved, buildings, evergreen trees/shrubs, deciduous trees/shrubs, grass, unmanaged and water). Below each surface, except water, there is a single soil layer. In SUEWS, the surface types are not separate tiles but rather water can flow between the surface types both above and below surface. Integrated evapotranspiration for the whole study area is calculated using the modified Penman–Monteith equation (Grimmond and Oke, 1991).

SUEWS can simulate all components of  $Q^*$  using the net all-wave radiation parametrization scheme (NARP; Offerle *et al.*, 2003; Loridan *et al.*, 2011) except  $K\downarrow$  that is a required model input. However, in this study the provided  $L\downarrow$  is used to be comparable in the model evaluation. Storage heat flux is simulated for each surface type using the Objective Hysteresis Model (OHM; Grimmond *et al.*, 1991). Calculation of  $Q_F$  is based on heating and cooling degree-days assuming a base air temperature of 18.2 °C, above which cooling and below which heating of the buildings is assumed.  $Q_F$  is also affected by the population density of the study area.

A single-layer snowpack (also freezing of water) can develop on all surface types. The snow energy and mass balances are calculated at each time step (Järvi *et al.*, 2014). In the model, snowfall occurs and snowpack develops and existing water on surfaces freezes when  $T_{air}$  is below 0 °C. Snowmelt is calculated

using a temperature degree-day method based on  $T_{air}$  and solar radiation and the melted water will stay in the snowpack until the water holding capacity, for each surface type, is exceeded, after which runoff occurs. Snow heat storage is calculated with OHM. The temporal evolution of snow density and albedo use snow-aging functions.  $f_s$  on ground is calculated from depletion curves, where  $f_s$  is a different function of  $W_s/W_{s,max}$  for vegetation, paved and building surfaces.  $W_s$  is snow water equivalent and  $W_{s,max}$  is the maximum value, both defined by the user. The energy and mass balances at the snow and snow-free surfaces are calculated separately and the model output is calculated as a weighted average based on their surface fractions.

SUEWS is the only model in this study where leaf area index (LAI) is allowed to dynamically vary between minimum and maximum value of each vegetation type based on growing and senescence degree days (Järvi *et al.*, 2011). Thus, changes in LAI can vary from year to year based on  $T_{air}$ .

### 3.3. SURFEX

SURFEX (Masson *et al.*, 2013) is a system of models able to calculate the exchange of sensible and latent heat, momentum, carbon dioxide and other chemical species, as well as various particles, between the atmosphere and several types of surfaces. Here version 7.3 is used. Four main types of surfaces can be considered: sea surfaces, inland waters, a large variety of vegetated land surfaces, and urban environments. Separate models, often developed and evaluated independently of SURFEX, are used to

Table 2. Model and equations most relevant for the current study.

	CLM	SUEWS	SURFEX
Version	4.0	2014b	7.3
$T_{\min, \text{building}}$ (°C)	19.0 <sup>a</sup>	18.2 <sup>b</sup>	19.0 <sup>a</sup>
$\alpha_{\text{snow}}$	0.66/0.56 <sup>c</sup>	0.18–0.85 <sup>d</sup>	0.30–0.85 <sup>d</sup> on roofs 0.15–0.85 <sup>d</sup> on roads
$\varepsilon_{\text{snow}}$	0.97	0.99	0.98
$f_{s, \text{pav}}$	$\frac{s_d}{0.05} \leq 1$	$\left(\frac{W_s}{W_{s, \max}}\right)^2$	$\frac{W_s}{(W_s + W_{s, \max})}$
$f_{s, \text{roof}}$	$\frac{s_d}{0.05} \leq 1$	$0.5 \cdot \left(\frac{W_s}{W_{s, \max}}\right), \frac{W_s}{W_{s, \max}} < 0.9$ $\left(\frac{W_s}{W_{s, \max}}\right)^8, \frac{W_s}{W_{s, \max}} >= 0.9$	$\frac{W_s}{(W_s + W_{s, \max})}$
$f_{s, \text{veg}}$	$\frac{s_d - z_{\text{bot}}}{z_{\text{top}} - z_{\text{bot}}} \text{ for trees/shrubs}$ $\frac{\min(s_d, z_c)}{z_c} \text{ for grass}$	$1 - \left(\frac{1}{\pi} \arccos\left(2 \frac{W_s}{W_{s, \max}} - 1\right)\right)^{1.7}$	$\frac{s_d}{(s_d + 5000z_0)}$
$Q^*$ (W m <sup>-2</sup> )	$\alpha + T_{\text{surf}}$	NARP ( $\alpha + T_{\text{surf}}$ )	$\alpha + T_{\text{surf}}$
$Q_H$ (W m <sup>-2</sup> )	Resistance method using difference between $T_{\text{air}}$ and $T_{\text{surf}}$	Residual of the energy balance	Resistance method using difference between $T_{\text{air}}$ and $T_{\text{surf}}$ + building and traffic $Q_F$
$Q_E$ (W m <sup>-2</sup> )	Resistance method using difference between $q_{\text{air}}$ and $q_{\text{surf}}$	Penman–Monteith equation	Resistance method using difference between $q_{\text{air}}$ and $q_{\text{surf}}$
$Q_F$ (W m <sup>-2</sup> )	Building heating	Building heating and cooling + traffic OHM	Building heating + industrial activities + traffic
$\Delta Q_S$ (W m <sup>-2</sup> )	Residual of the energy balance		Residual of the energy balance, driven by heat conduction through surfaces
$M$ (mm)	Energy balance of snow (up to five layers)	Degree day method based on $Q^*$ and $T_{\text{air}}$	Energy balance of snow (one layer)

<sup>a</sup>Minimum building temperature.<sup>b</sup>Outdoor temperature.<sup>c</sup>Visible and near-infrared waveband.<sup>d</sup>Snow aging accounted for.

$\alpha_{\text{snow}}$  = snow albedo,  $\varepsilon_{\text{snow}}$  = snow emissivity,  $s_d$  = snow depth,  $f_{s,i}$  = snow fraction of  $i$ th surface,  $z_{\text{top}}$  and  $z_{\text{bot}}$  = Plant Functional Type (PFT)-specific canopy top and bottom heights,  $z_c$  = critical snow depth when short vegetation is assumed to be completely buried by snow,  $W_s$  = snow water equivalent,  $W_{s,\max}$  = snow water equivalent when the surface is assumed to be completely buried by snow,  $z_0$  = roughness length, NARP = the Net All-wave Radiation Parametrization scheme and  $M$  = amount of snowmelt. See text for description of other terms.

describe the surface fluxes and evolution inside each main surface type. Modelling of the snowpack and hydrological processes generating surface and bottom run-off are also included.

Vegetation is treated by the Interaction Soil–Biosphere–Atmosphere model (ISBA: Masson *et al.*, 2013), which can be configured to varying degrees of complexity (Noilhan and Planton, 1989). In the present study, the soil is modelled by a three-layer force–restore formulation distinguishing between the root zone and the subroot zone, and also taking into account the freezing and melting of water in the soil (Boone *et al.*, 2000). Vegetation processes are described by the original ISBA evapotranspiration model using an externally imposed LAI. The snowpack is treated by the bulk snow model (Drouville *et al.*, 1995) with three prognostic variables ( $W_s$ , snow density and snow albedo).

The urban surface uses the Town Energy Balance model (TEB: Masson, 2000), to solve separate energy budgets for roofs, walls, and road surfaces in a homogeneous isotropic array of street canyons. Although TEB has vegetation, parks and gardens inside the TEB canyon itself (Lemonsu *et al.*, 2012), here the vegetated areas are treated separately without direct interaction with the built surface (e.g. buildings shadowing). Snow is treated as a single layer, and on the vegetation it is simulated by ISBA, and on roofs and roads by TEB. The snow temperature, albedo and density evolve governed by the energy budgets interacting with the atmosphere and the underlying surface. Prior evaluation of TEB was for winter conditions in Montreal, Canada (Lemonsu *et al.*, 2010), but it did not account for seasonal differences in model performance.

## 4. Methods

### 4.1. Model runs

The model comparisons for the two sites use the same hourly meteorological forcing data from Kumpula ( $K_\downarrow$ ,  $L_\downarrow$ ,  $P$ , wind speed, pressure and humidity) except for  $T_{\text{air}}$ , which was

measured both in Kumpula and in Helsinki city centre. Wind speed measured at 31 m (a.g.l.) at Kumpula was not scaled to the 60 m (a.g.l.) measurement height at Torni due to possible uncertainty originating from differences in surface roughness and topography. The 18-month forcing data were gap-filled (2.4% of  $K_\downarrow$ ,  $L_\downarrow$ ,  $T_{\text{air}}$ , wind speed; 0.7% of  $P$ ; 2.3% of pressure and humidity) with observations from other instruments (if available) and via linear interpolation (Järvi *et al.*, 2012).

All models use a set of the same surface parameters (Table 1) calculated for 1 km radius circles centred on both measurement masts (Figure 1(a)) to approximate the EC flux source areas (Nordbo *et al.*, 2013). These circles are chosen over the actual source areas, as footprint models only approximate source areas in heterogeneous urban areas. The Kumpula site heterogeneity is addressed by modelling the three sectors (Ku1, Ku2 and Ku3) using separate parameters and creating one time series based on the prevailing wind direction. In Helsinki, the most common wind direction is southwest, which corresponds to the most vegetated sector Ku3. In the case of  $Q^*$ , only model output from Ku3 is considered as it best describes the source area of the radiation measurements. These surface parameters include surface cover fractions, building and tree heights and the initial conditions for the run. As the three models have different approaches to the vegetation subclasses, these fractions are not identical (Table 1).

For the other model parameters, CLM uses the Jackson *et al.* (2010) database, SURFEX the ECOCLIMAP (Masson *et al.*, 2003; Faroux *et al.*, 2013) and SUEWS its own values (Järvi *et al.*, 2011). The chosen parameters are default parameters most suitable for a high-latitude city without any adjustments based on the observations. These include albedos, emissivities, roughness parameters, parameters for plant function types, geometrical and thermal parameters for the buildings and roads, and parameters for anthropogenic heating. As the snow model in SUEWS has partly been developed using observations from the Kumpula site (Järvi *et al.*, 2014), its performance is not purely independent at the site unlike SURFEX and CLM. Table 2 lists some of the parameter values important for cold-climate and high-latitude cities.

The first 6 months of the 18-month model period (1 July 2011 to 31 December 2012) are used to spin up the models. A full year (2012) is used for the model evaluation.

#### 4.2. Thermal seasons

Given the strong seasonal variability in meteorological conditions in Helsinki, analysis is based on thermally defined seasons (rather than months) in this study calculated from the 7-day running mean of  $T_{\text{air}}$ . If the running mean is below 0 °C or above 10 °C the season is winter or summer, respectively. Between these limits are spring and autumn. Seasons change when the temperature criterion is fulfilled for 3 days in a row. Thus, thermal seasons vary by length each year. In 2012, summer was the longest season (39% of the days), extending from mid-May to 6 October (Figure 1(b)). The two winter periods (9 January to 14 March, 2–31 December) resulted in a total of 95 days (26%), whereas autumn (1–8 January, 7 October to 1 December) and spring (15 March to 14 May) covered only 19 and 16% of the days, respectively.

#### 4.3. Goodness of models

The model performance is evaluated using common tools, including the Taylor diagram (Taylor, 2001; Grimmond *et al.*, 2011) and related statistical parameters of root mean square error (RMSE,  $\text{W m}^{-2}$ ), Pearson correlation coefficient ( $r$ ), standard deviation (STD,  $\text{W m}^{-2}$ ) and mean bias error (MBE,  $\text{W m}^{-2}$ ) (Grimmond *et al.*, 2010). The uncertainties of the EC measurements are taken into account by calculating the absolute difference  $|F_{\text{obs}} - F_{\text{mod}}|$  between observation ( $F_{\text{obs}}$ ) and model output ( $F_{\text{mod}}$ ) (Best and Grimmond, 2013). For forested areas, Hollinger and Richardson (2005) reported flux uncertainties for EC-based sensible ( $\delta_H$ ) and latent heat flux ( $\delta_E$ ) to be at least  $10 \text{ W m}^{-2}$  and increase linearly as a function of the absolute value of the flux:

$$\delta_H = 10 + 0.22|Q_H| \quad (\text{W m}^{-2}), \quad (2)$$

$$\delta_E = 10 + 0.32|Q_E| \quad (\text{W m}^{-2}). \quad (3)$$

Their study was conducted in a relatively homogeneous setting, so these uncertainties are likely to be lower limits for heterogeneous urban environments.

Equations (2) and (3) define the acceptable absolute difference between the model output and observed turbulent fluxes; if the absolute difference is within the uncertainty of the EC measurements, the model output is considered to be good ( $|F_{\text{obs}} - F_{\text{mod}}| \leq \delta$ ). Furthermore, the normalized acceptable deviation ( $D$ ) is the occurrence of acceptable deviations, defined as those times the mean absolute difference is within the measurement uncertainty divided by the number of observations ( $N_{\text{obs}}$ ):

$$D = \frac{\sum(|F_{\text{obs}} - F_{\text{mod}}| \leq \delta)}{N_{\text{obs}}}. \quad (4)$$

$D$  is 0 when none of  $N_{\text{obs}}$  is within the flux uncertainties and 1 when all  $N_{\text{obs}}$  are within the flux uncertainties.

### 5. Results

#### 5.1. Snow cover

Snow cover is one of the most crucial variables to be simulated correctly in cold-climate cities as it affects surface properties and surface water availability. This applies both to the amount of snow as well as its areal fraction, which are tied together via depletion curves (Table 2). In Figure 2, the modelled snow depth ( $s_d$ ) and

snow surface fraction at the vegetated surface ( $f_{\text{s,veg}}$ ) are plotted for the two sites together with the observed  $s_d$ . Unfortunately, no measured  $f_s$  from any of the surfaces is available for the sites. For evaluating the modelled snow data, the most appropriate data matching best with the location of the snow observations are shown: grass surface fraction from SUEWS and grass and trees from SURFEX and CLM simulated at the vegetated Ku3 sector to match the open field observed  $s_d$ .

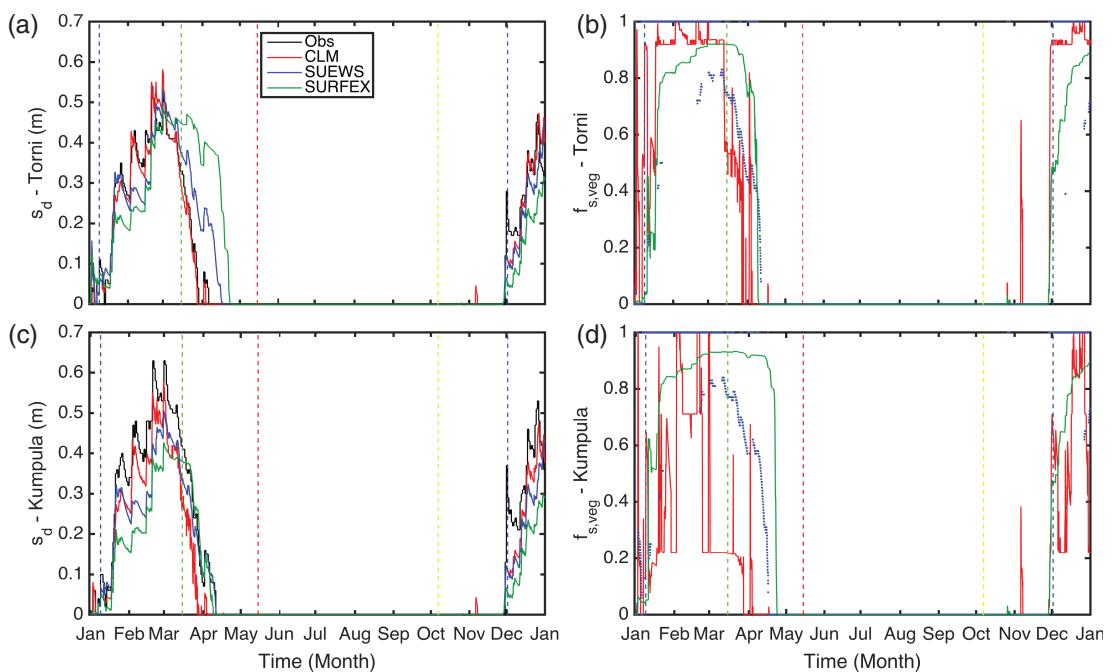
At Torni, CLM simulates  $s_d$  well and snowpack develops and melts on the correct day (Figure 2(a)). SUEWS and SURFEX reproduce the snowpack development but the melt is too slow. The complete snowmelt is 10 and 17 days later than the observations, respectively. Some of the snowmelt timing differences may relate to the observational representativeness. The models give the snow properties for the whole study area, whereas the single-point observations in an open field are not necessarily representative of the whole area. Melt especially in the shadows of trees and buildings and in snow piles can be delayed when compared to the open field. However,  $f_{\text{s,veg}}$  with SUEWS is 60% and with SURFEX 90% after the observed snow has melted (Figure 2(b)), and it is unlikely that so much snow would still be on the ground. SUEWS and SURFEX simulate more similar  $f_{\text{s,veg}}$  than CLM, with slightly smaller fractions obtained from SUEWS. Most of the time CLM gives smaller  $f_{\text{s,veg}}$  than the other two models. The snowfall events are visible in CLM and SUEWS as increasing peaks, whereas in SURFEX the snowfall episodes do not instantaneously affect  $f_{\text{s,veg}}$  as the fraction is calculated based on the absolute snow depth and not the snowfall events.

The models simulate well the accumulation of snow at Kumpula, but again differences appear during the snow-melting period (Figure 2(c)). SUEWS simulates complete snowmelt 1 day after and SURFEX 1 day before the observations, whereas CLM melts snow 8 days too early. Also at Kumpula the largest differences in  $f_{\text{s,veg}}$  are seen during the melting period (Figure 2(d)). In CLM and SURFEX, the differences in  $f_{\text{s,veg}}$  between the two sites are due to the different fraction of grass and trees at the two sites, as the models do not separate these similarly to SUEWS. The differences both in  $s_d$  and  $f_{\text{s,veg}}$  result in differences in model performances, when simulating the energy balance components. These results are further examined in the following sections.

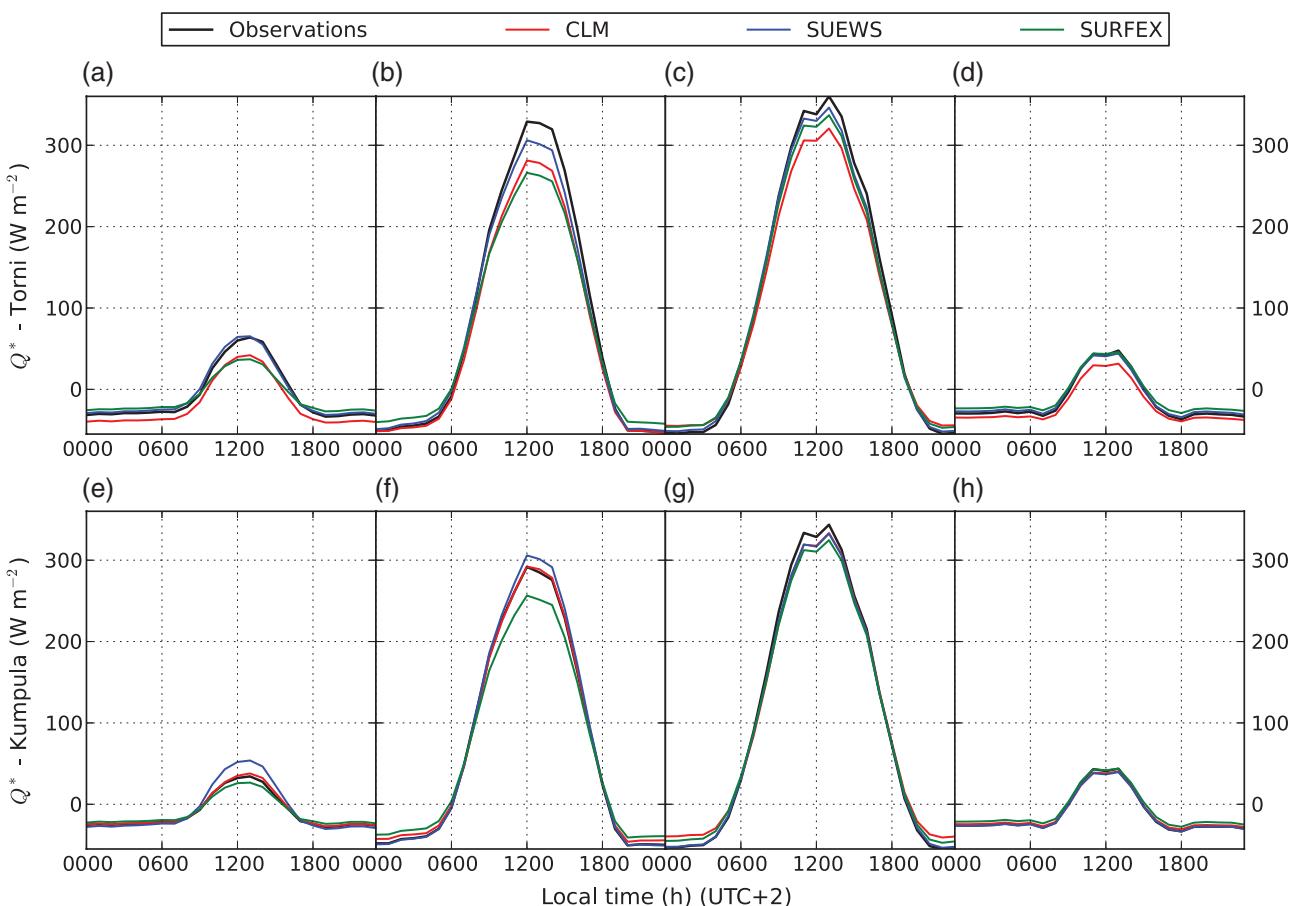
#### 5.2. Net all-wave radiation

The diurnal cycles of the modelled and measured  $Q^*$  are similar both at Torni and Kumpula (Figure 3). All models simulate  $Q^*$  well with  $r$  above 0.97 and RMSEs between 5 and  $44 \text{ W m}^{-2}$  (Table 3) with minor seasonal variance. The models tend to underestimate the daytime  $Q^*$  at Torni, with the exception of SUEWS in winter and SUEWS and SURFEX in autumn. All models systematically overestimate the outgoing short-wave radiation ( $K\uparrow$ ) at Torni indicating too high surface albedo in the models (Table 3, Figure S1). However, bias error cancellation (Shaffer *et al.*, 2015) caused by overestimated  $K\uparrow$  and underestimated outgoing long-wave radiation ( $L\uparrow$ ) improves the winter  $Q^*$  by SUEWS (RMSE =  $8.8 \text{ W m}^{-2}$ ) and spring by SUEWS and SURFEX (RMSE =  $25.1$  and  $44.0 \text{ W m}^{-2}$ ) (Table 3, Figure S2). The modelled nocturnal  $Q^*$  follow the observations, but CLM slightly underestimates  $Q^*$  in winter and autumn and SURFEX overestimates in spring and summer.

At Kumpula, more deviations between the models are seen. Part of this can be related to the heterogeneous surface cover, which causes the radiation footprint to differ from the simulated Ku3. SUEWS underestimates the daytime  $K\uparrow$  in winter and spring resulting in overestimation of  $Q^*$ . Similarly CLM underestimates daytime  $K\uparrow$ , but this is compensated for overestimation of  $L\uparrow$  resulting in well-simulated  $Q^*$  (RMSE =  $6.8$ – $16.3 \text{ W m}^{-2}$ ). SURFEX underestimates  $K\uparrow$  in winter, but this is compensated for overestimation of  $L\uparrow$  resulting in RMSE =  $10.2 \text{ W m}^{-2}$  for  $Q^*$ . In summer, all models simulate  $K\uparrow$  correctly



**Figure 2.** The observed and simulated snow depths ( $s_d$ ) at (a) Torni and (c) Kumpula vegetation sector, and simulated surface fractions of snow ( $f_{s,veg}$ , Table 1) at (b) Torni and (d) Kumpula vegetation sector. Snow observations are made on open areas so only  $s_d$  simulated at the vegetated tile of SURFEX and CLM, and at grass surface of SUEWS are shown. The dashed blue, green, red and yellow lines indicate the starting days for thermal (changes with year) winter, spring, summer and autumn, respectively.



**Figure 3.** Modelled and observed diurnal cycles of  $Q^*$ . Panels (a-d) (upper row) are for Torni in different seasons (winter, spring, summer and autumn, respectively), and panels (e-h) (lower row) for Kumpula vegetation sector (Ku3), which best describes the surface cover within the source area of the radiation sensor.

(RMSE = 4.4–10.2 W m $^{-2}$ ), but overestimate daytime  $L\uparrow$  and underestimate nocturnal  $L\uparrow$ . All models perform well in autumn, when the RMSEs vary between 5 and 7 W m $^{-2}$ .

Spring is when the models have most difficulty in reproducing the observed diurnal cycle of  $Q^*$  at both sites. This period has the highest RMSEs with a range from 16 W m $^{-2}$  (CLM at Kumpula) to 44 W m $^{-2}$  (SURFEX at Torni). Spring is when the surface

characteristics vary the most due to both snowmelt and start of the leaf-on period. Looking in more detail the model performances during this period show that the greatest model uncertainties are related to the snowmelt period rather than increase in LAI. The models particularly have problems with the late snowfall event in early April (Figure 2(a,c)) when 4-day RMSEs (not shown) reach 26, 60 and 35 W m $^{-2}$  at Torni and 32, 30 and 27 W m $^{-2}$

Table 3. Model evaluation statistics for CLM, SUEWS and SURFEX, based on 12 months of observations of (a) net all-wave radiation ( $Q^*$ ), (b) outgoing short-wave ( $K\uparrow$ ) and (c) long-wave ( $L\uparrow$ ) radiation for different seasons at Torni and Kumpula.

	Season	Torni					Kumpula				
		r	RMSE	MBE	Mean	N	r	RMSE	MBE	Mean	N
<b>(a) <math>Q^*</math></b>											
CLM	Winter	0.99	16.4	-11.8	-7.1	2245	0.98	6.8	1.1	-10.4	2302
	Spring	1.00	30.2	-17.2	83.3	1454	0.99	16.3	2.3	71.2	1464
	Summer	1.00	34.1	-10.0	104.9	3427	1.00	15.1	1.8	98.4	3431
	Autumn	0.99	10.8	-7.0	-13.4	1489	1.00	5.6	0.5	-11.7	1498
SUEWS	Winter	0.99	8.9	2.1	-7.1	2245	0.98	14.1	3.2	-10.4	2302
	Spring	0.99	25.1	-5.8	83.3	1454	0.99	20.8	3.7	71.2	1464
	Summer	1.00	19.8	-2.9	104.9	3427	1.00	8.8	-2.9	98.4	3431
	Autumn	0.99	5.5	1.4	-13.4	1489	0.99	4.7	-1.0	-11.7	1498
SURFEX	Winter	0.97	21.8	-2.1	-7.1	2245	0.98	10.2	0.5	-10.4	2302
	Spring	0.98	44.2	-13.2	83.3	1454	0.99	24.1	-4.1	71.2	1464
	Summer	1.00	27.2	-4.0	104.9	3427	1.00	16.1	-2.0	98.4	3431
	Autumn	0.99	8.9	5.0	-13.4	1489	0.99	7.2	4.1	-11.7	1498
<b>(b) <math>K\uparrow</math></b>											
CLM	Winter	0.91	10.2	2.5	6.2	2247	0.99	6.4	-2.3	15.1	2303
	Spring	0.94	25.2	14.0	17.3	1454	0.94	18.3	-5.2	30.5	1464
	Summer	0.92	29.2	15.8	20.4	3476	0.99	4.4	-1.3	29.0	3431
	Autumn	0.85	6.3	2.3	2.1	1527	0.96	2.5	-0.2	3.8	1498
SUEWS	Winter	0.90	8.6	1.1	6.2	2247	0.96	15.0	-5.4	15.1	2303
	Spring	0.82	24.3	7.5	17.3	1454	0.87	24.3	-7.2	30.5	1464
	Summer	0.92	13.6	4.1	20.4	3476	0.99	4.8	-1.8	29.0	3431
	Autumn	0.81	4.7	1.0	2.1	1527	0.92	3.7	-0.3	3.8	1498
SURFEX	Winter	0.91	16.8	5.07	6.2	2247	0.99	13.3	-5.58	15.1	2303
	Spring	0.80	31.8	11.3	17.3	1454	0.95	14.5	-3.44	30.5	1464
	Summer	0.85	17.6	2.1	20.4	3476	0.97	10.2	-2.45	29.0	3431
	Autumn	0.81	4.9	0.9	2.09	1527	0.93	3.5	-0.46	3.8	1498
<b>(c) <math>L\uparrow</math></b>											
CLM	Winter	0.94	11.9	9.4	295.9	2289	0.97	5.6	1.3	290.5	2302
	Spring	0.93	9.6	3.3	343.9	1464	0.95	10.9	2.9	342.1	1464
	Summer	0.91	13.3	-5.9	396.4	3480	0.93	15.5	-0.4	394.9	3431
	Autumn	0.94	8.1	4.4	335.7	1536	0.97	5.0	-0.3	331.5	1498
SUEWS	Winter	0.99	4.9	-3.2	295.9	2289	0.96	7.1	2.2	290.5	2302
	Spring	0.98	5.91	-1.7	343.9	1464	0.97	8.0	3.5	342.1	1464
	Summer	0.97	7.31	-1.2	396.4	3480	0.97	9.5	4.7	394.9	3431
	Autumn	0.99	3.66	-2.5	335.7	1536	0.98	4.3	1.3	331.5	1498
SURFEX	Winter	0.97	7.0	-4.8	295.9	2289	0.99	4.4	0.7	290.5	2302
	Spring	0.95	11.2	-5.5	343.9	1464	0.99	5.3	-1.3	342.1	1464
	Summer	0.95	11.8	-0.4	396.4	3480	0.98	9.4	2.0	394.9	3431
	Autumn	0.98	7.4	-5.5	335.7	1536	0.99	3.9	-2.4	331.5	1498

$r$  = Pearson correlation coefficient, RMSE = root mean square error ( $\text{W m}^{-2}$ ), MBE = mean bias error ( $\text{W m}^{-2}$ ), mean = mean of observation ( $\text{W m}^{-2}$ ) and N = number of samples.

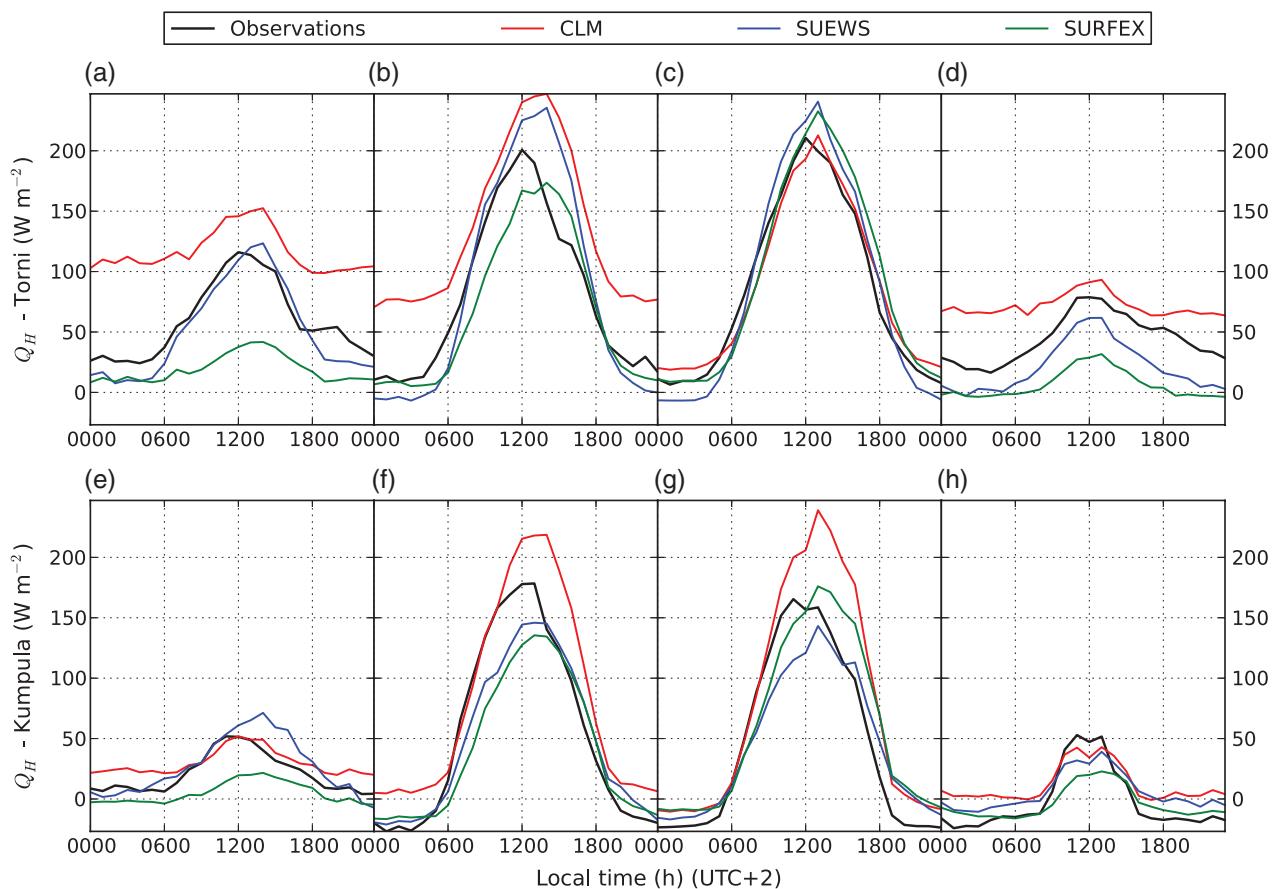
at Kumpula, using CLM, SUEWS and SURFEX, respectively. Simulating  $f_s$  can be difficult during spring, affecting particularly the weighted  $K\uparrow$  and  $Q^*$  of snow-covered and snow-free surfaces. Interestingly, the overprediction of snow cover by SUEWS and SURFEX on the vegetated surface at Torni does not decrease the model performances when simulating  $Q^*$ . This can be explained by the small fraction of vegetated surfaces around the Torni site. On built surfaces, the modelled snow melts earlier than on the vegetated surfaces (not shown) but unfortunately we do not have snow observations to verify if the timing is correct.

### 5.3. Sensible heat flux

Whereas the LSMs more or less agree upon  $Q^*$ , they differ more in simulating  $Q_H$  (Figure 4, Table 4), in agreement with previous model comparison studies (Grimmond *et al.*, 2011). In winter, the observed daytime  $Q_H$  reaches  $120 \text{ W m}^{-2}$  at Torni, whereas at Kumpula  $Q_H$  is less than half of this. The difference is partly explained by the increased anthropogenic heat emissions during the heating period and partly by the release of heat storage to the atmosphere. The larger nocturnal release of storage heat at Torni compared to Kumpula is particularly apparent in autumn.

CLM simulates the wintertime  $Q_H$  best at Kumpula ( $\text{RMSE} = 16 \text{ W m}^{-2}$ ), but overestimates  $Q_H$  at Torni ( $\text{RMSE} = 45 \text{ W m}^{-2}$ ) particularly at night. Although SUEWS is able to predict the difference between the two sites, it

underestimates nocturnal  $Q_H$  at Torni and overestimates daytime  $Q_H$  at Kumpula (RMSE of 29 and  $19 \text{ W m}^{-2}$  respectively). SURFEX underestimates  $Q_H$  at both Torni and Kumpula ( $\text{RMSE} = 36$  and  $20 \text{ W m}^{-2}$ , respectively) and is not able to predict the difference between the two sites in wintertime. As CLM's urban module (to a large extent) follows the parametrizations of SURFEX (Oleson *et al.*, 2008b; Demuzere *et al.*, 2013), it is surprising to see such large differences between the two models, especially in winter for Torni. To examine this, additional CLM simulations were performed using the same thermal (roof and wall thickness, heat conductivity and volumetric heat capacity) and radiative (albedo and emissivity for roof, road and wall) properties as used in the SURFEX simulations. As these caused  $Q_H$  to decrease by  $100 \text{ W m}^{-2}$  (not shown) and thus be more similar to the SURFEX results, it suggests the Jackson *et al.* (2010) high-latitude parameters should be revisited. The radiative parameters affected particularly the outgoing short-wave radiation, but most of the reduction resulted from the thermal parameters. Particularly noteworthy is the lack of insulation in the Jackson *et al.* (2010) roof and wall properties for this high-latitude region. This means that more space heating is needed to keep the internal building temperature from falling below the prescribed minimum comfort level. The increase in space heating is manifested as a strong sensible heat from the interior of the building to the exterior of the roofs and walls and the urban canopy air. When the SURFEX roof/wall thermal parameters are used (increased insulation), the



**Figure 4.** Modelled and observed diurnal cycles of  $Q_H$ . Panels (a–d) (upper row) are for Torni in different seasons (winter, spring, summer and autumn, respectively), and panels (e–h) (lower row) for Kumpula.

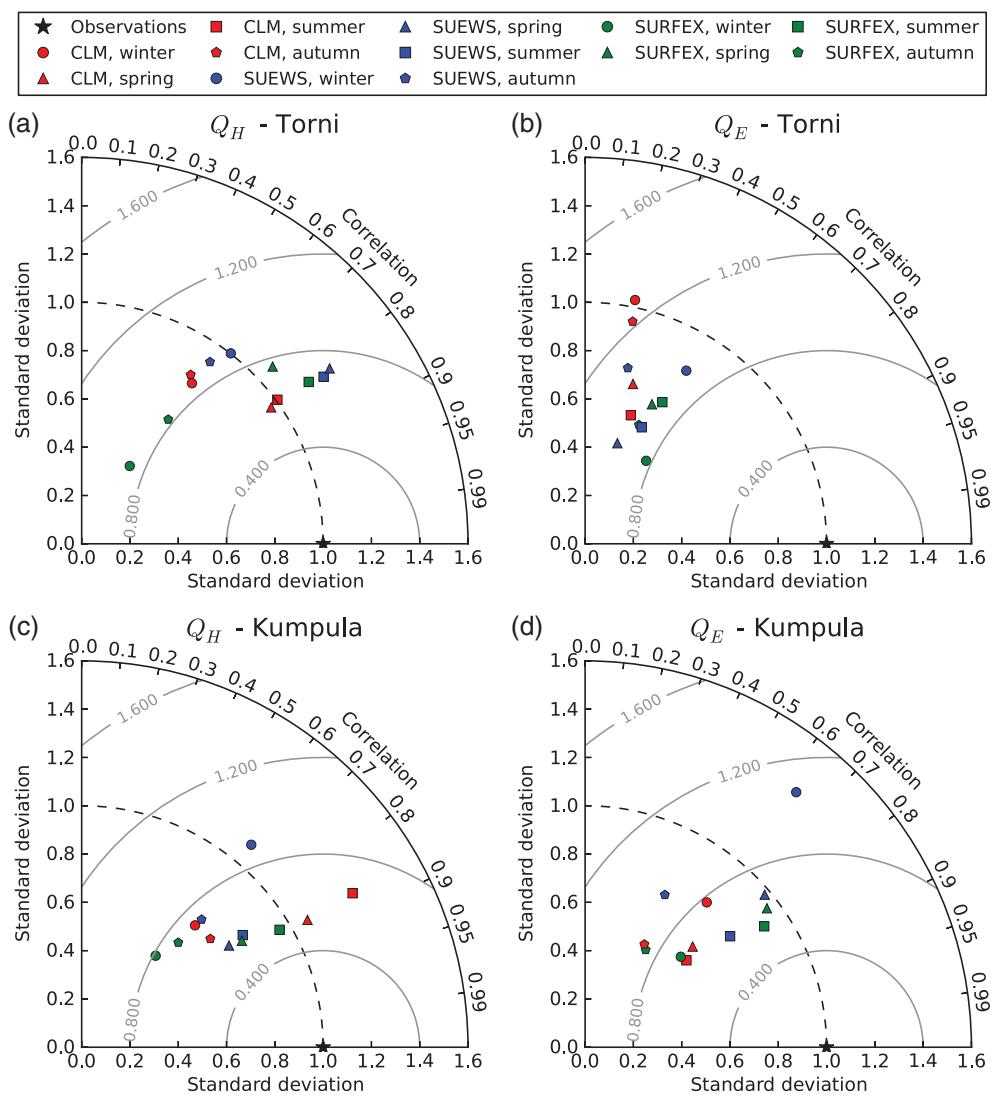
Table 4. Same as Table 3, but for (a) sensible ( $Q_H$ ) and (b) latent ( $Q_E$ ) heat fluxes.

		Torni					Kumpula					
	Season	r	RMSE	MBE	Mean	N	r	RMSE	MBE	Mean	N	
(a) $Q_H$	CLM	Winter	0.57	73.2	58.0	58.4	855	0.68	26.6	7.7	24.1	846
		Spring	0.81	75.8	54.6	82.8	906	0.87	62.6	30.2	71.0	894
	SUEWS	Winter	0.62	46.4	-8.6	58.4	855	0.64	31.8	7.3	24.1	846
		Spring	0.82	63.6	7.1	82.8	906	0.82	59.8	-8.4	71.0	894
SURFEX	Winter	0.58	38.3	-23.0	44.9	822	0.68	27.1	7.5	-2.2	628	
		Spring	0.73	67.4	-11.6	82.8	906	0.83	59.4	-16.0	71.0	894
	Summer	0.81	65.7	8.2	90.5	2156	0.86	49.6	12.7	51.5	2346	
	Autumn	0.57	47.5	-38.1	44.9	822	0.68	26.5	-1.6	-2.2	628	
(b) $Q_E$	CLM	Winter	0.20	21.8	4.8	14.4	820	0.64	11.4	-0.4	18.3	719
		Spring	0.29	33.9	-9.9	26.3	676	0.73	35.8	-24.7	44.2	811
	SUEWS	Winter	0.50	15.3	1.2	14.4	820	0.64	15.6	1.2	18.3	719
		Spring	0.31	32.6	-12.8	26.3	676	0.76	25.7	-3.7	44.2	811
SURFEX	Summer	0.44	48.7	-23.9	46.1	1938	0.79	46.7	-23.8	80.0	2121	
		Autumn	0.24	24.1	-9.6	21.3	785	0.46	27.2	-12.0	30.1	540
	Winter	0.59	16.5	-9.3	14.4	820	0.73	15.9	-12.1	18.3	719	
		Spring	0.43	32.0	-13.9	26.3	676	0.79	28.3	-16.0	44.2	811
	Summer	0.48	45.7	-17.9	46.1	1938	0.83	41.6	-18.8	80.0	2121	
	Autumn	0.41	21.2	-10.3	21.3	785	0.53	29.1	-18.3	30.1	540	

space heating required and thus the sensible heat decrease. This agrees well with previous findings of Oleson *et al.* (2008a) who found that  $Q_H$  in CLM is most sensitive to the morphological and thermal parameters.

Although in other seasons the observed difference between the two sites decreases, generally higher  $Q_H$  are measured at

Torni than Kumpula. In spring, CLM overestimates  $Q_H$  at both sites ( $\text{RMSE} = 60$  and  $49 \text{ W m}^{-2}$ ). SUEWS overestimates daytime  $Q_H$  at Torni ( $\text{RMSE} = 64 \text{ W m}^{-2}$ ) and underestimates the values at Kumpula ( $\text{RMSE} = 47 \text{ W m}^{-2}$ ) similar to SURFEX at both sites ( $\text{RMSE} = 53$  and  $46 \text{ W m}^{-2}$ ). All models have difficulties in predicting the peaks in spring, which suggests problems in



**Figure 5.** Normalized Taylor diagrams for (a) sensible ( $Q_H$ ) and (b) latent heat ( $Q_E$ ) fluxes at Torni, and (c)  $Q_H$  and (d)  $Q_E$  at Kumpula. Results are given by thermal season (symbol shape) and model (colours).

simulating the timing of the peak heat storage. A similar bias was also observed in the international model comparison study (Best and Grimmond, 2013).

In summer all models are able to simulate the daily pattern of  $Q_H$  well at Torni ( $\text{RMSE} = 61\text{--}67 \text{ W m}^{-2}$ ), but SUEWS underestimates the nocturnal  $Q_H$  by  $20 \text{ W m}^{-2}$ . At Kumpula, SURFEX is the only model to successfully simulate the overall magnitude of the flux even though its peak lags 2 h behind the observed peak ( $\text{RMSE} = 50 \text{ W m}^{-2}$ ). CLM grossly overestimates, particularly daytime flux ( $\text{RMSE} = 68 \text{ W m}^{-2}$ ), and SUEWS underestimates the flux during the day ( $\text{RMSE} = 53 \text{ W m}^{-2}$ ). In autumn, CLM systematically overestimates and SUEWS and SURFEX underestimate  $Q_H$  at Torni. At Kumpula all models perform better, but underestimate the daytime  $Q_H$  and overestimate the nocturnal values.

Although some of the differences in model performances for simulating  $Q_H$  are attributable to the use of different parameters, the turbulent flux calculation methods also vary. SURFEX and CLM use a resistance method based on the temperature difference between air and wall, roof and canyon floor (Table 2), whereas in SUEWS  $Q_H$  is calculated as a residual from the other energy balance terms. The wintertime overestimation of  $Q_H$  by CLM is largely explained by the thermal surface properties and the same properties could also affect the underestimation of  $Q_H$  by SURFEX. Other possible sources for the underestimation could be issues in simulating correct surface temperatures, waste heat or aerodynamic resistances. SURFEX has been found to be sensitive particularly to the aerodynamic resistance between the canyon and air above (Lemonsu *et al.*, 2004). This is also supported by

the current study (not shown). The resistances between the wall and canyon air, and road and canyon air are an unlikely reason for the underestimation, as the differences in simulating friction velocities (further affecting aerodynamic resistances) cannot have the observed effect. As  $Q_H$  depends also on the internal building temperature ( $T_{\text{air}}$  in the case of SUEWS), a too high set-point temperature limit reduces both  $Q_F$  and  $Q_H$ . Unfortunately, no independent data are available to verify the modelled  $Q_F$ . For CLM, the internal building temperature value was found to be less important than the effect of thermal properties (as discussed above). In SUEWS the differences between the observed and modelled  $Q_H$  are related to problems in simulating other energy balance components as it is calculated as a residual.

Taylor diagrams for  $Q_H$  at Torni and Kumpula (Figure 5(a,c)) show that none of the models is able to outperform the other models by means of systematically higher correlation, lower normalized RMSE and standard deviation close to one. Rather the performance varies with season and model. At Torni, the correlations vary between 0.5 and 0.83, normalized RMSE between 0.6 and 0.9 and normalized standard deviation between 0.35 and 1.2. Similarly at Kumpula, the correlations are between 0.6 and 0.87, normalized RMSE between 0.5 and 0.9 and normalized standard deviations between 0.4 and 1.2. Overall  $Q_H$  is simulated better at Kumpula than at Torni, as the correlation values are higher and normalized RMSE generally lower at Kumpula. At the more densely built and populated site Torni, problems related to thermal properties and anthropogenic heat emissions during the heating season in winter will affect  $Q_H$  more strongly than at the more vegetated Kumpula site. This

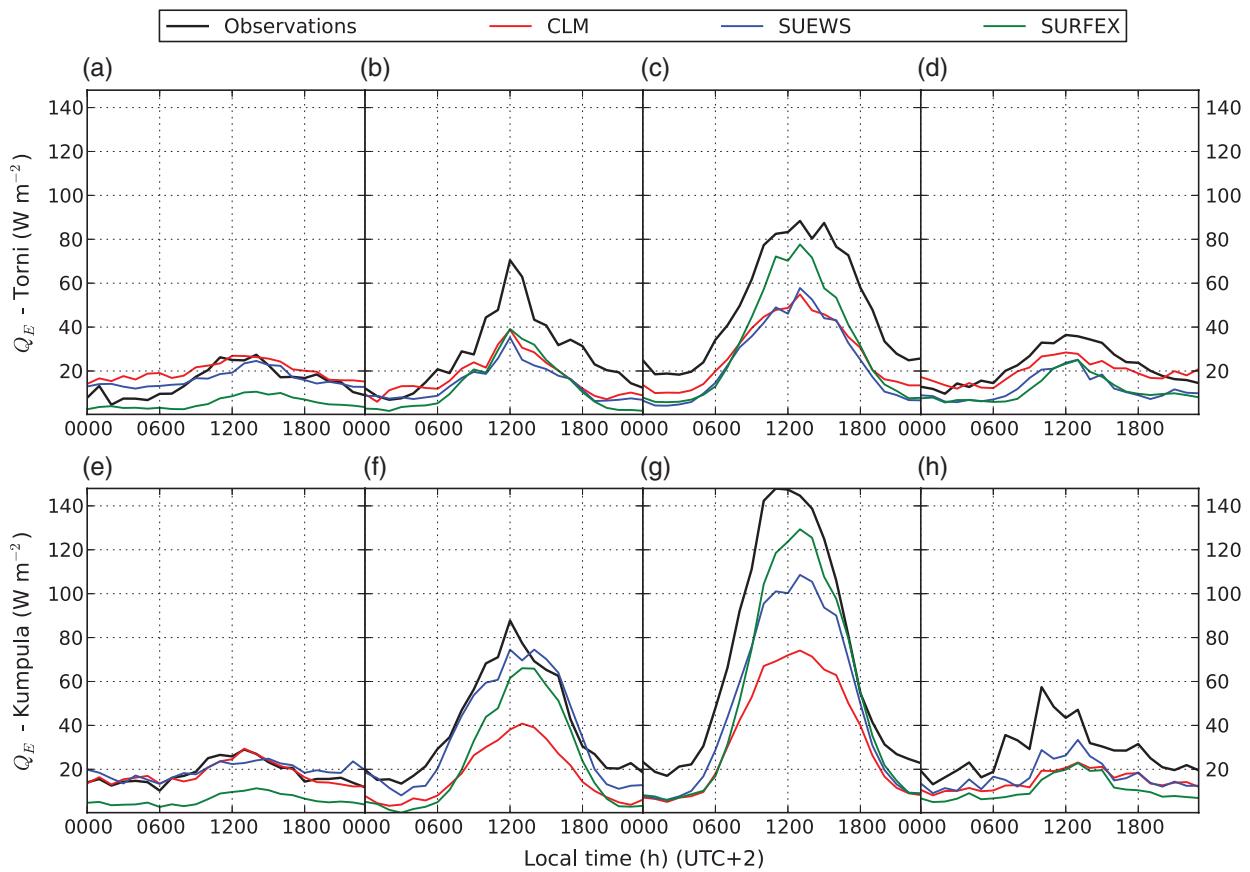


Figure 6. Modelled and observed diurnal cycles of  $Q_E$ . See Figure 4 for explanation.

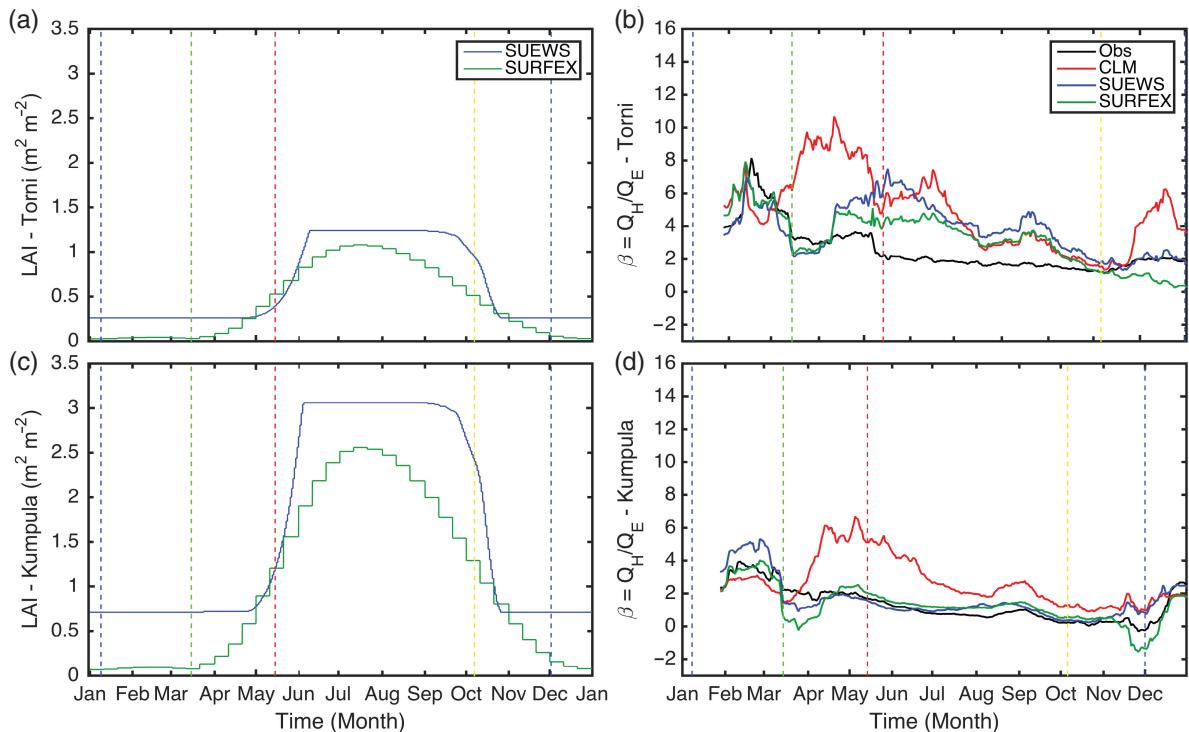


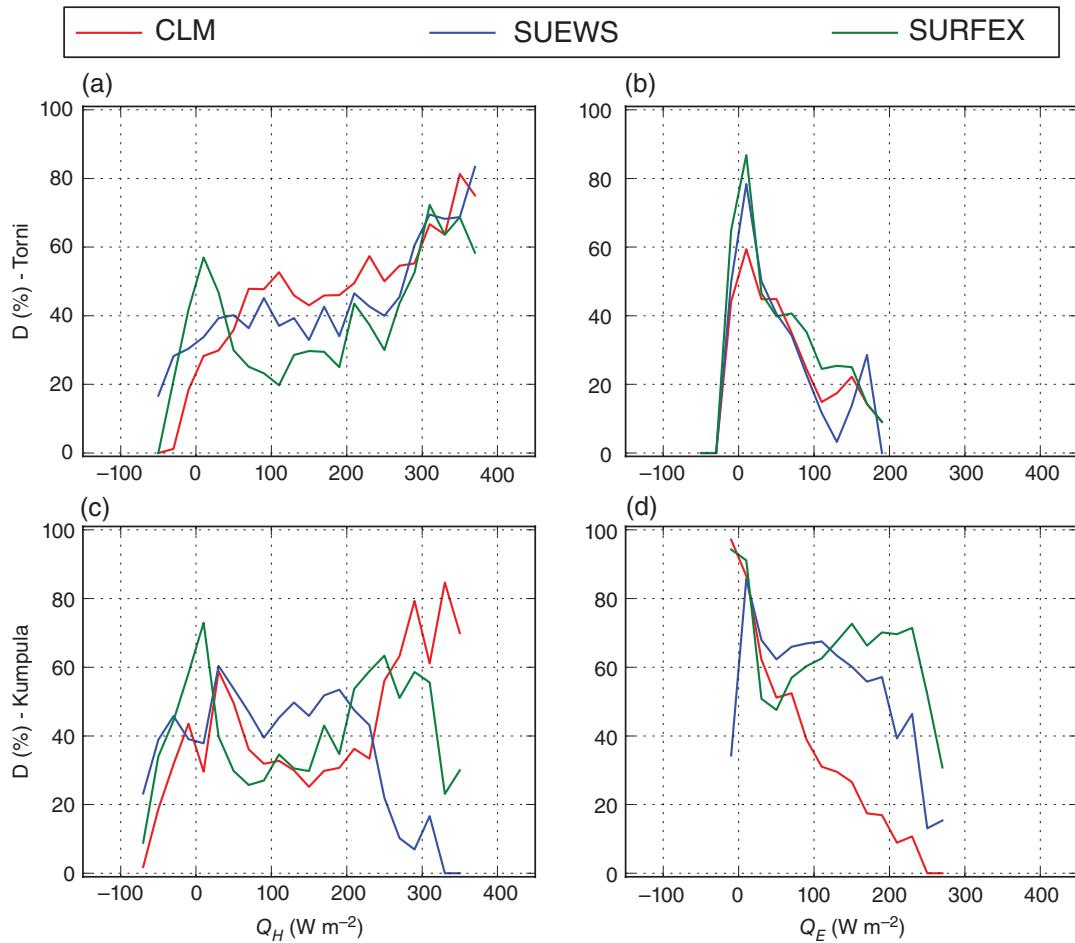
Figure 7. Behaviour of leaf area index (LAI,  $\text{m}^2 \text{m}^{-2}$ ) in SUEWS and SURFEX in (a) Torni and (c) Kumpula for the vegetation sector, and 28-day running mean of Bowen ratio ( $\beta$ ) in (b) Torni and (d) Kumpula in 2012. LAI is calculated as a weighted average over the study areas. The dashed blue, green, red and yellow lines indicate the starting days for thermal (changes with year) winter, spring, summer and autumn, respectively.

suggests that both climate and surface type have an equal effect on model performances.

#### 5.4. Latent heat flux

Large variability also occurs when simulating  $Q_E$  (Figure 6). In winter, when the vegetation is inactive, similar diurnal behaviour

of observed  $Q_E$  at both sites is observed. CLM and SUEWS simulate the diurnal cycle well at both sites and RMSEs range between 11 and 22  $\text{W m}^{-2}$ , whereas SURFEX underestimates  $Q_E$  both at Torni and Kumpula (RMSE = 17 and 16  $\text{W m}^{-2}$ ). In spring and summer, the larger surface fraction of vegetation at Kumpula results in 20 and 38%, respectively, higher observed daytime  $Q_E$  than observed at Torni. In spring, SUEWS models



**Figure 8.** Normalized acceptable deviation ( $D$ ) as a function of observed turbulent flux calculated for  $20 \text{ W m}^{-2}$  bins. (a,c)  $Q_H$ , (b,d)  $Q_E$ , (a,b) Torni, (c,d) Kumpula. See text for details.

the diurnal behaviour well at Kumpula ( $\text{RMSE} = 26 \text{ W m}^{-2}$ ), but otherwise all models underestimate  $Q_E$  at both sites resulting in  $\text{RMSE} = 28\text{--}36 \text{ W m}^{-2}$ . Spring and early summer are periods for intensive leaf growth (Figure 7(a,c)) and therefore the seasonal changes in LAI are a possible source for uncertainty especially in the case of  $Q_E$ . Both CLM and SURFEX use a fixed LAI profile for each year, whereas in SUEWS this dynamically changes with  $T_{air}$ . CLM and SURFEX were also run using LAI calculated by SUEWS, but this had only a minor effect on  $Q_E$  (not shown).

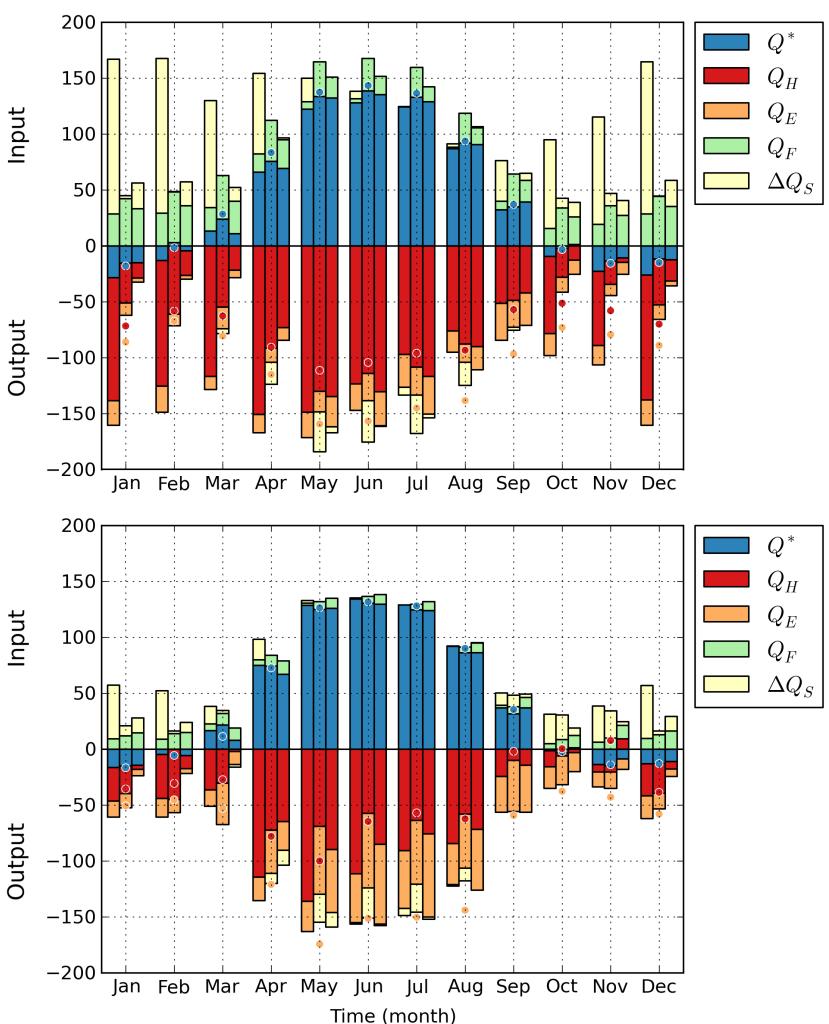
Underestimation of  $Q_E$  continues in summer with SURFEX getting the daytime peaks closest to the observations at both sites. CLM underestimates  $Q_E$  more than 50% at Kumpula with  $\text{RMSE} = 60 \text{ W m}^{-2}$ , while for SUEWS and SURFEX the RMSEs are 47 and  $42 \text{ W m}^{-2}$ . In summer, irrigation can play an important role in the urban water balance, and e.g. in SUEWS this is a default model feature. In CLM by default, no irrigation is used, whereas in SURFEX, none of the vegetation types used in Helsinki (Table 1) has irrigation. Irrigation can be particularly important at Kumpula, where the allotment and University Botanical Gardens are located and intensive watering can take place. At Torni, the small surface fraction of vegetation and minor irrigation in public parks and street trees diminish its importance. This study site dependency was also visible when SUEWS was run without irrigation resulting in increased RMSE from 47 to  $58 \text{ W m}^{-2}$  at Kumpula and decreased RMSE from 49 to  $38 \text{ W m}^{-2}$  at Torni. Thus, some of the underestimation of CLM and SURFEX at least at Kumpula can be explained by the missing irrigation. For CLM, also global simulations of summer latent heat in the high-latitude regions compared to observation-based estimates (Jung *et al.*, 2011) do indicate some negative biases with regards to latent heat from vegetation, which is consistent with the results found here. A more recent version of CLM has increased latent heat at high latitudes due to revisions in model structure and photosynthetic parameters (Bonan *et al.*, 2011).

Models systematically underestimate the nocturnal values in summer by  $15 \text{ W m}^{-2}$ . Similar strength of nocturnal  $Q_E$  has been observed, e.g. in Melbourne (Coutts *et al.*, 2007). A possible explanation could be underestimation of nocturnal anthropogenic and storage heat emissions to the urban atmosphere. In autumn, the observed difference between the two sites again diminishes and the models again underestimate  $Q_E$ , and the RMSEs range between  $21$  and  $29 \text{ W m}^{-2}$ .

Taylor diagrams indicate that again the models are able to simulate  $Q_E$  better at Kumpula than at Torni as the correlations are, respectively, between  $0.45\text{--}0.84$  and  $0.2\text{--}0.6$ , and normalized RMSE between  $0.45\text{--}1.1$  and  $0.8\text{--}1.3$  (Figure 5(b,d)). Notably  $Q_E$  is more problematic for all models than  $Q^*$  or  $Q_H$  (Tables 3 and 4, Figure 5), which is consistent with previous evaluations of urban land-surface models in midlatitude cities (Grimmond *et al.*, 2011). The underestimation of  $Q_E$  can be related to the description of vegetation, which is affected both by LAI and surface cover fractions. A recent study shows how a decrease in pixel resolution of surface cover fractions from 2 to 100 m can increase the mean bias of models by 50% (Nordbo *et al.*, 2015). At Torni, the underestimation can also be related to anthropogenic water emissions from traffic and respiration of people seen in the observations, as the model runs do not account for these. In cold climates, these sources of moisture are proportionally more significant given the typically dry natural specific humidity conditions. However, the surface resistances are a key driver in all models to calculate evaporation and related energy from urban surface and therefore future work in urban areas is clearly needed to investigate these as a potential source for the bias in  $Q_E$ .

##### 5.5. The effect of measurement uncertainty

The normalized acceptable deviation ( $D$ ), Eq. (4) for  $20 \text{ W m}^{-2}$  bins is plotted in Figure 8. The plotted distributions can be



**Figure 9.** Monthly average energy balance (in  $\text{W m}^{-2}$ ) at (a) Torni and (b) Kumpula. Different fluxes are denoted with different colours. Each month has three bars: CLM (left), SUEWS (middle), SURFEX (right), and the observations of net all-wave radiation ( $Q^*$ ), sensible ( $Q_H$ ) and latent heat ( $Q_E$ ) fluxes are shown with coloured circles.

used to study the seemingly poor model performances when simulating e.g. diurnal cycles. For example, CLM tends to overestimate  $Q_H$  at Kumpula throughout the year, but with large observed values ( $>230 \text{ W m}^{-2}$ ) the modelled values are within the measurement uncertainties 80% of the time (Figure 8(c)). This suggests that the CLM simulates  $Q_H$  well within the uncertainties of the EC measurements in daytime in summer despite the evident overestimation seen in Figure 4(g). Thus the overestimation of  $Q_H$  by CLM is considerable only with small  $Q_H$  corresponding to wintertime and nocturnal values. Similarly, all models underestimate  $Q_E$  at both sites in daytime during summer. For SURFEX and SUEWS the modelled values are 70 and 40–65%, respectively, within the measurement uncertainties at Kumpula when the observed  $Q_E > 100 \text{ W m}^{-2}$ . For CLM, less than 20% of the modelled  $Q_E$  are within the uncertainties of observations. At Torni, modelled  $Q_E$  is less than 35% of the times within the measurement uncertainties with observed  $Q_E > 100 \text{ W m}^{-2}$ . The underestimation can be explained by the small frequency of large observed  $Q_E$  values in the Helsinki city centre.

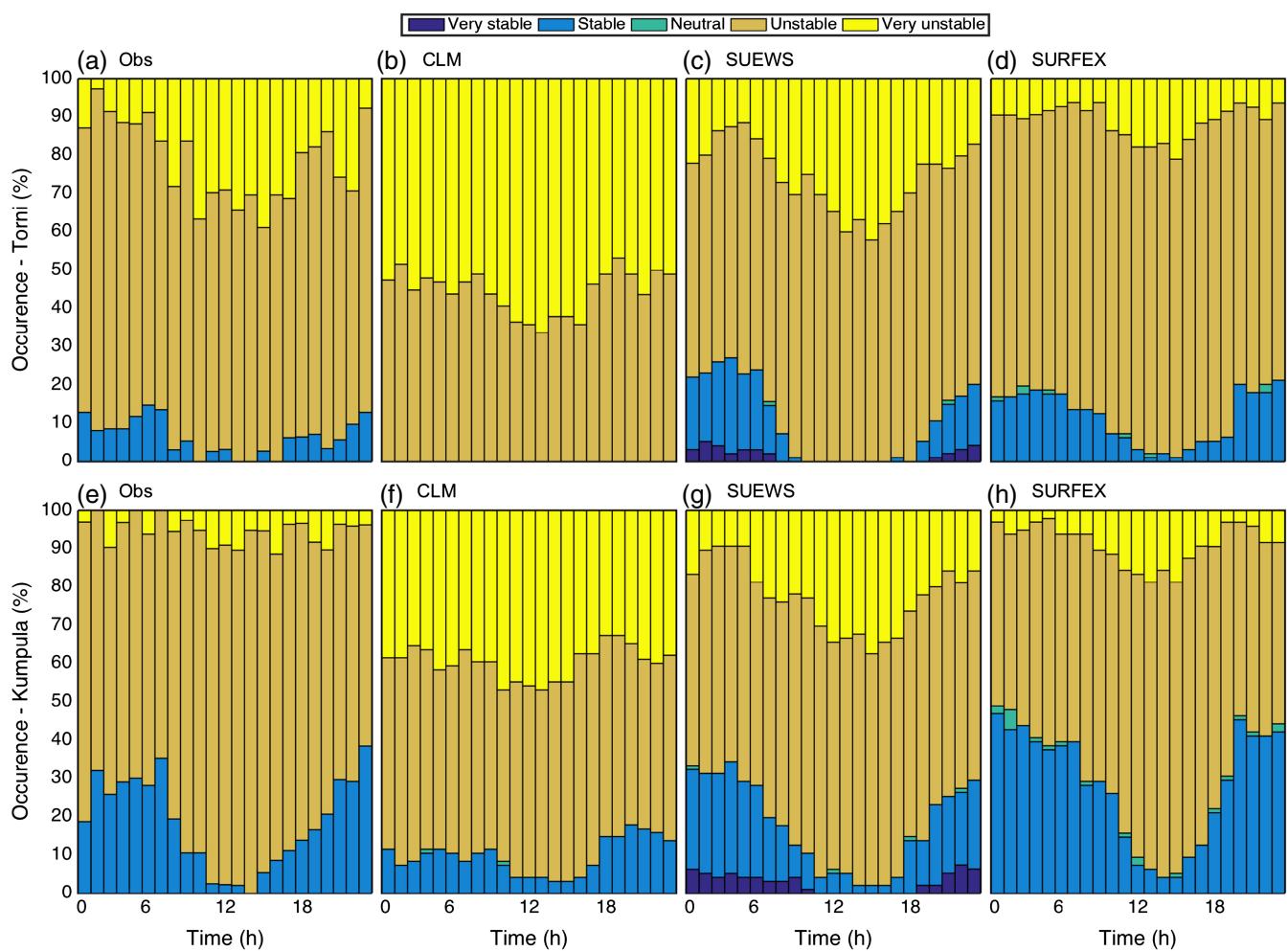
### 5.6. Surface energy partitioning

The complete surface energy balance varies between the models, throughout the year and relative to the monthly means for observations of  $Q^*$ ,  $Q_H$  and  $Q_E$  (Figure 9). From the latter, some indication of the uncertainty of the energy partitioning for high-latitude cities can be considered. In midlatitude cities,  $Q^*$  is typically the main component fuelling the turbulent exchanges (Grimmond *et al.*, 2011), but in Helsinki this is the case only for the period from April to September. During winter months,

both  $Q_F$  and  $\Delta Q_S$  become more important than  $Q^*$  due to small incoming solar radiation. The increased importance of  $Q_F$  in winter months is explained partially by the decrease of  $Q^*$ , and partially by the annual variability of  $Q_F$  driven by the heating need in Helsinki.

As was already evident from the diurnal cycles (Figure 3), the differences in monthly  $Q^*$  between the different models are rather small. At Torni, CLM throughout the year gives systematically lower  $Q_F$  ( $1\text{--}29 \text{ W m}^{-2}$ ) than the other two models ( $26\text{--}45$  and  $17\text{--}46 \text{ W m}^{-2}$  for SUEWS and SURFEX, respectively). The near-zero  $Q_F$  in summer simulated by CLM is due to lack of building cooling, energy consumption and heat emissions from traffic. Both SUEWS and SURFEX take heat emissions from traffic into account by using a constant  $Q_F$  traffic profile and constant single value of  $10 \text{ W m}^{-2}$ , respectively. Cooling of buildings is only considered in SUEWS and energy consumption only in SURFEX. In summer, the higher  $Q_F$  given by SUEWS than given by SURFEX (35% in July) can be explained by the cooling of buildings. In winter, both SURFEX and SUEWS give almost the same  $Q_F$  ( $42 \text{ W m}^{-2}$  in January). This corresponds well with the rough wintertime estimate of  $Q_F = 50 \text{ W m}^{-2}$  obtained from the EC measurements (Nordbo *et al.*, 2013). At Kumpula, the anthropogenic heat emissions are smaller than at Torni due to the less built-up and populated surface. CLM and SUEWS give lower  $Q_F$  than SURFEX, with the monthly means ranging between 0 and 10, 5 and 14, and 16 and  $27 \text{ W m}^{-2}$ , respectively (Figure 9).

The annual variability of  $\Delta Q_S$  is distinct at both sites, but all models give slightly different behaviour. SUEWS gives the largest heat storage at both sites in May and July with slightly higher



**Figure 10.** The percentage occurrence of different stability classes in winter, by local time. (a) Observations, (b) CLM, (c) SUEWS and (d) SURFEX at Torni, and (e) observations, (f) CLM, (g) SUEWS and (h) SURFEX at Kumpula. The different classes are (Eq. (5)) very stable ( $\zeta > 0.1$ ), stable ( $0.00001 \leq \zeta \leq 0.1$ ), neutral ( $|\zeta| < 0.00001$ ), unstable ( $-0.01 \leq \zeta \leq -0.00001$ ) and very unstable ( $\zeta < -0.01$ ).

values at Torni ( $34\text{--}37 \text{ W m}^{-2}$ ) than at Kumpula ( $22\text{--}24 \text{ W m}^{-2}$ ). SURFEX, on the other hand, gives the largest heat storage (around  $14 \text{ W m}^{-2}$ ) at Kumpula in April and May, whereas at Torni only  $5 \text{ W m}^{-2}$  in May is modelled. With CLM, the heat storages are small and maxima of  $10$  and  $7 \text{ W m}^{-2}$  are observed at Torni and Kumpula, respectively, in July. CLM gives the largest storage heat emissions to the atmosphere at both sites in January and December with the values reaching  $-124 \text{ W m}^{-2}$  at Torni and  $-43 \text{ W m}^{-2}$  at Kumpula. SURFEX gives the largest storage heat emissions at the same time reaching  $-23$  and  $-13 \text{ W m}^{-2}$  at the two sites, whereas SUEWS gives the maxima storage heat emissions in October and November reaching  $-3$  and  $-23 \text{ W m}^{-2}$  at Torni and Kumpula, respectively. The large storage term from CLM in winter can be explained by the calculation of  $\Delta Q_S$  as a residual from the other components of which  $Q_H$  is largely overestimated (Figures 4 and 9).

Most of the available energy is converted to  $Q_H$  particularly at Torni where the fraction of vegetation is smaller (Figure 9). The energy partitioning between  $Q_H$  and  $Q_E$  is visualized in Figure 7(b,d), where a 28-day running mean of Bowen ratio ( $\beta = Q_H/Q_E$ ) for both sites over the entire day is plotted. The observed  $\beta$  range between 1 and 8 at Torni and 0 and 4 at Kumpula, with higher values outside the growing season when trees are without leaves. The heating period (December to mid-March) has higher  $\beta$ . Also, the start and end of the growing season are seen as a strong decrease in early May and increase in mid-October at Torni. At Kumpula such strong changes are not seen. A possible explanation for this difference is that in the centre of Helsinki trees are mainly lime trees so there are little phenological differences in leaf growth. At Kumpula, there is a wider range of vegetation species so leaf-on is more variable.

Using the changes in  $\beta$  at Torni as a proxy for LAI, the timing for the leaf-growth and senescence are well simulated by SUEWS and correctly prescribed in SURFEX (Figure 7(a,c)).

During the winter, all models simulate the general behaviour of  $\beta$  correctly despite the problems related to the magnitude of  $Q_H$  and  $Q_E$  (Figure 7(b,d)). However, the underestimation of  $Q_E$  by all models in the city centre in spring and summer results in too high  $\beta$ . SUEWS and SURFEX simulate values of 5 and 8 for  $\beta$  when the observed are between 1 and 5, and CLM gives as high as  $\beta = 15$  in April. None of the models simulates the decrease in  $\beta$  due to leaf growth, whereas the timing of the senescence in late August, early September is seen with CLM and SUEWS. At Kumpula, SUEWS and SURFEX simulate the energy partitioning well during the growing season, but CLM again has  $\beta$  too high.

### 5.7. Modelling wintertime near-surface atmospheric stability

Stable conditions are a critical concern for cold-climate cities when shallow boundary layers can lead to very poor air quality. Figure 10 summarizes the occurrence of different stability conditions near the surface calculated from observations and model output for the winter period, when stable boundary layers are most common in Helsinki. The atmospheric stabilities are calculated according to (e.g. Seinfeld and Pandis, 1997)

$$\zeta = \frac{1}{L} = -\frac{\frac{g}{\theta} \overline{w' T'}}{u_*^3 k}, \quad (5)$$

where  $L$  is the Obukhov length (m),  $g$  is the gravitational acceleration ( $\text{m s}^{-2}$ ),  $\overline{\theta}$  is mean potential temperature (K),  $\overline{w' T'}$

is the kinematic heat covariance ( $\text{K m s}^{-1}$ ),  $u^*$  is the friction velocity ( $\text{m s}^{-1}$ ) and  $k$  is the dimensionless von Karman constant. The different stability classes are (Seinfeld and Pandis, 1997): very stable ( $\zeta > 0.1$ ), stable ( $0.0001 \leq \zeta \leq 0.1$ ), neutral ( $|\zeta| < 0.00001$ ), unstable ( $-0.01 \leq \zeta \leq -0.0001$ ) and very unstable ( $\zeta < -0.01$ ).

The observed nocturnal conditions are more unstable at Torni (Figure 10(a)) than at Kumpula (Figure 10(e)) following the differences in  $Q_H$ . At Torni, the occurrence of stable cases is below 15% and at Kumpula 39%. Similarly, very unstable cases are frequently measured at Torni, reaching 38% in daytime, whereas at Kumpula very stable is only observed less than 11% of the time. All models are able to simulate the differences in  $\zeta$  between the two sites, but differences in the performances are clear.

CLM and SUEWS underestimate the number of nocturnal stable cases at Kumpula and the occurrences reach 18 and 26%, respectively. SURFEX on the other hand overestimates the occurrence of stable cases with the occurrence reaching 47%. At Torni, SURFEX also overestimates the number of stable cases (maximum occurrence of 21%), SUEWS clearly overestimates their occurrence (maximum 25%) and CLM completely misses them due to the too-large simulated  $Q_H$  (Figure 4(a)). SUEWS also simulates too many very stable cases at both sites at night-time reaching an occurrence of 7% at Kumpula. All models only slightly overestimate the number of neutral cases, except CLM at Torni, and the occurrence of neutral cases range between 1% (CLM and SUEWS) and 5% (SURFEX) at Kumpula when compared to the observed  $\zeta$ . SUEWS and CLM also overestimate the number of very unstable cases at both sites and SURFEX underestimates at Torni but overestimates at Kumpula. These results show how all models are able to simulate the differences in  $\zeta$  between the two sites, but in order to improve the description of LSM in air quality models more work related particularly to wintertime  $Q_H$  is needed.

## 6. Conclusions

In this study three different urban land-surface models (CLM, SUEWS and SURFEX) are compared off-line with observations collected in Helsinki, Finland. Models are run for two study areas with different land uses: a highly built-up city centre (78% impervious cover) and a heterogeneous suburban site (42–54% impervious cover). The main focus is on the seasonal and diurnal changes of the surface energy balance components due to changes in snow cover, leaf area index and anthropogenic heat emissions.

To a reasonable degree, the models are able to account for the differences between the study sites as well as the intra-annual and diurnal variability of the energy balance components. None of the models outperforms the others, but rather one model is closer to the observations in a component for a particular season. Previously, the international urban model comparison study observed systematically lower model performances in summer in a midlatitude city (Best and Grimmond, 2013), whereas we have found that in Helsinki lowered model performances relates also to seasonality in snow and solar radiation.

Most of the uncertainties in simulating  $Q^*$  relate to the timing of the snowmelt in spring (inferred by snow depth), when snow-covered ground fraction plays an important role. Otherwise, the models simulate the formation and development of the snowpack well despite the differences in the snow parametrizations, and the effect on  $Q^*$  seem to be small. Larger variability in the model performances is seen for  $Q_H$  and  $Q_E$  than for  $Q^*$  in accordance with previous model comparison studies. The largest problem in simulating  $Q_H$  relate to  $Q_F$  and thermal surface parameters affecting particularly  $\Delta Q_S$  in winter when the importance of  $Q^*$  is small due to low incoming solar radiation.  $Q_H$  bias also results in problems in simulating the near-surface stabilities particularly at the dense city centre where the built surface fraction is high

and anthropogenic heat emissions greater. However, in most cases all three models capture the diurnal variability of stabilities, even creating too many very stable conditions, with the exception of CLM, which only generates unstable surface fluxes at Torni. Models have the most difficulties in simulating  $Q_E$ . Missing irrigation in CLM and SURFEX can explain some of the decreased model performances at the more vegetated Kumpula site, whereas at Torni the problems are more likely related to the description of vegetation.

Although CLM and SURFEX parametrize most of the surface energy balance components similarly (when compared to SUEWS) it is surprising to see such large differences between the two models. These differences partly arise from the surface radiative and thermal properties obtained from the ECOCLIMAP and Jackson *et al.* (2010) databases. In particular, the parameters in the Jackson *et al.* (2010) database should be revisited for cold-climate cities. Also for the natural surface fraction, ISBA and CLM have large differences including the processes and parameters attributed to plant types. Despite SUEWS parametrizing many processes differently to CLM and SURFEX, it gave more similar results to SURFEX than CLM.

Unfortunately most of the uncertainties relate to processes that are difficult to measure directly; i.e. melting of snow, heat storage and anthropogenic heat fluxes. Thus, their description in urban land-surface models needs to be improved in order to simulate the urban surface energy balance correctly particularly in cold-climate cities. More measurements of the surface fluxes are needed in order to cover a wide range of different cities varying in their cultural heritage, heating systems and architecture. Furthermore, the evapotranspiration in urban areas is poorly parametrized and therefore special attention should be given to its parametrization in urban areas. From these results it is clear that not only do different parameters need to be considered in cities in cold climates and at high latitudes compared to those in midlatitude cities, but also that land use (urban, suburban) can have a large effect on the model performances.

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## Supporting information

The following supporting information is available as part of the online article:

**Figure S1.** Modelled and observed diurnal cycles of outgoing short-wave radiation ( $K\uparrow$ ).

**Figure S2.** Modelled and observed diurnal cycles of outgoing long-wave radiation ( $L\uparrow$ ).

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