Loridan T & CSB Grimmond (2012) Characterization of energy flux partitioning in urban environments: links with surface seasonal properties *Journal of Applied Meteorology and Climatology* 51, 219-241 doi: 10.1175/JAMC-D-11-038.1

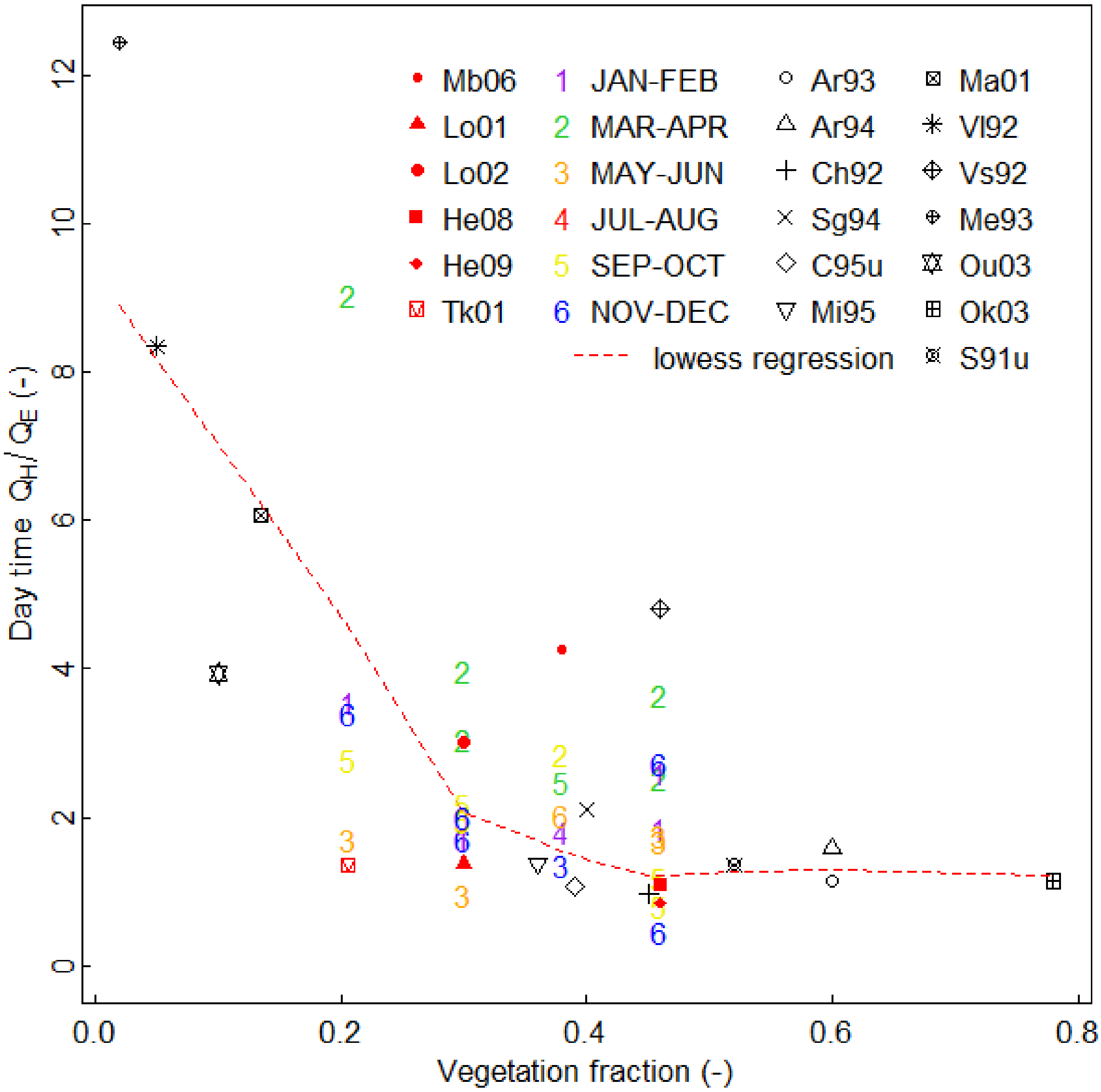

Figure 1: Mean midday (±3 h around solar noon) Bowen ratio (Q_H/Q_E) as a function of vegetation fraction. LOWESS (dashed line) regression performed using summer months and short term datasets only (i.e. only symbols). See Table 1 for site codes. The fluxes have had the Q_F contribution accounted for (see section 2). Note the color scheme for numbers is reversed for Mb06 (southern hemisphere).

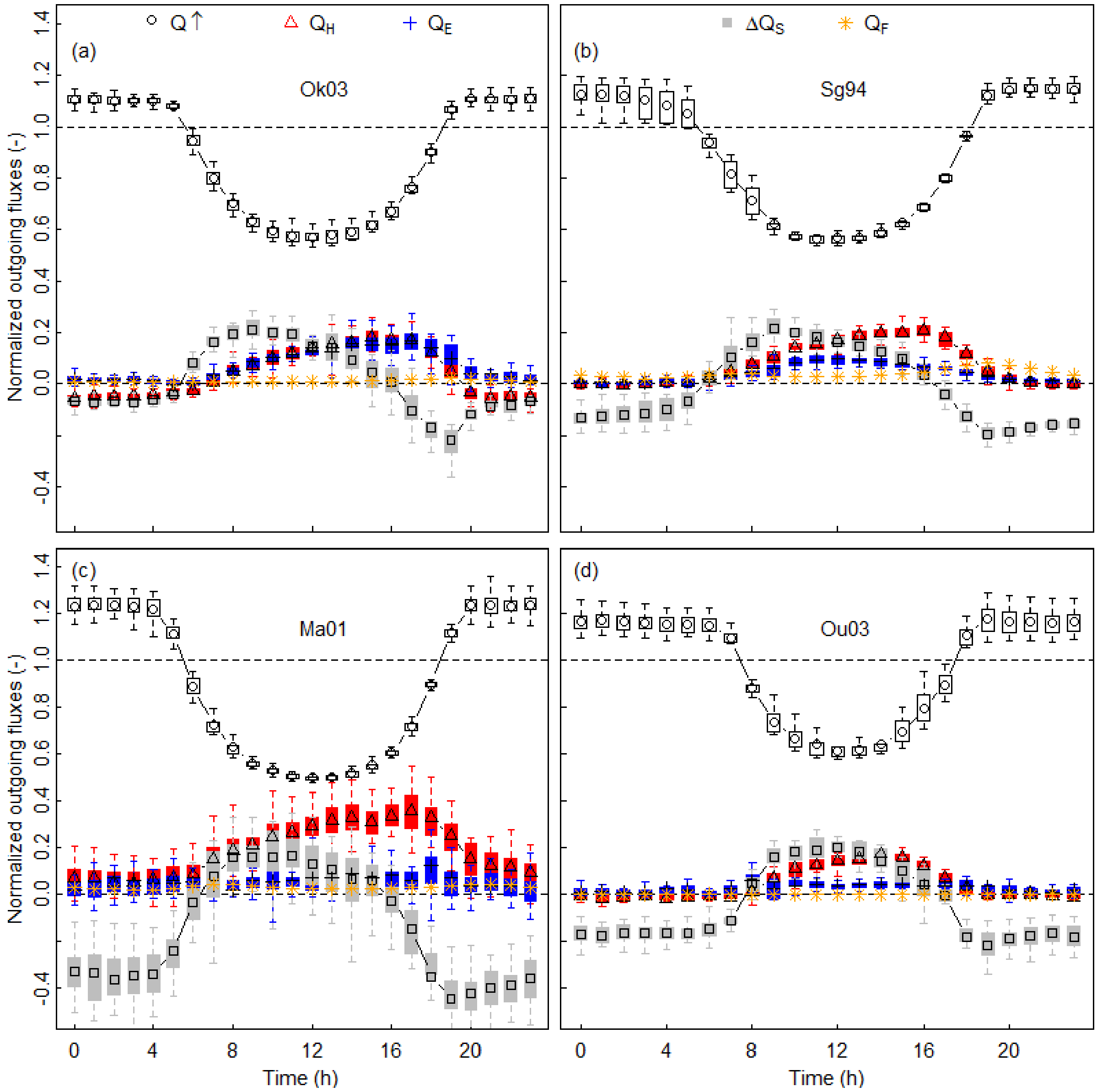

Figure 2: Mean diurnal flux ratios (symbols) and box plots (showing interquartile range (IQR) and whiskers for values within 1.5IQR) for four of the short term datasets. Positive (negative) values of Q_H, Q_E and Q↑ indicate energy lost (gained) by the surface. The opposite is true for ΔQ_S. See Table 1 and text for site codes. Plots are ordered by decreasing mean midday latent heat flux ratio (computed at ±3 h around solar noon, see Table 2).

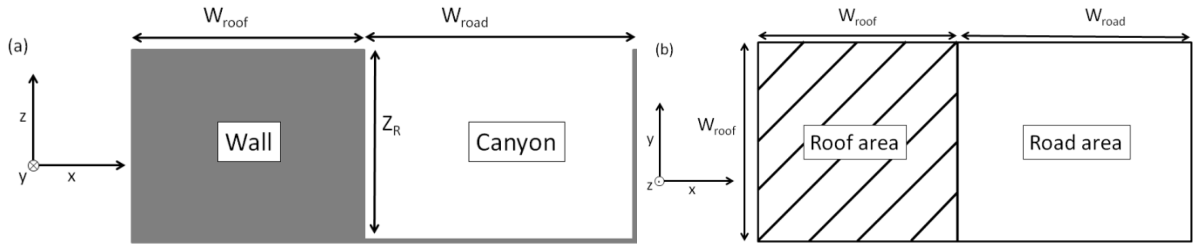

Figure 3: Geometry of the generic urban unit in the active surface model: (a) vertical (cross section) and (b) plan view.

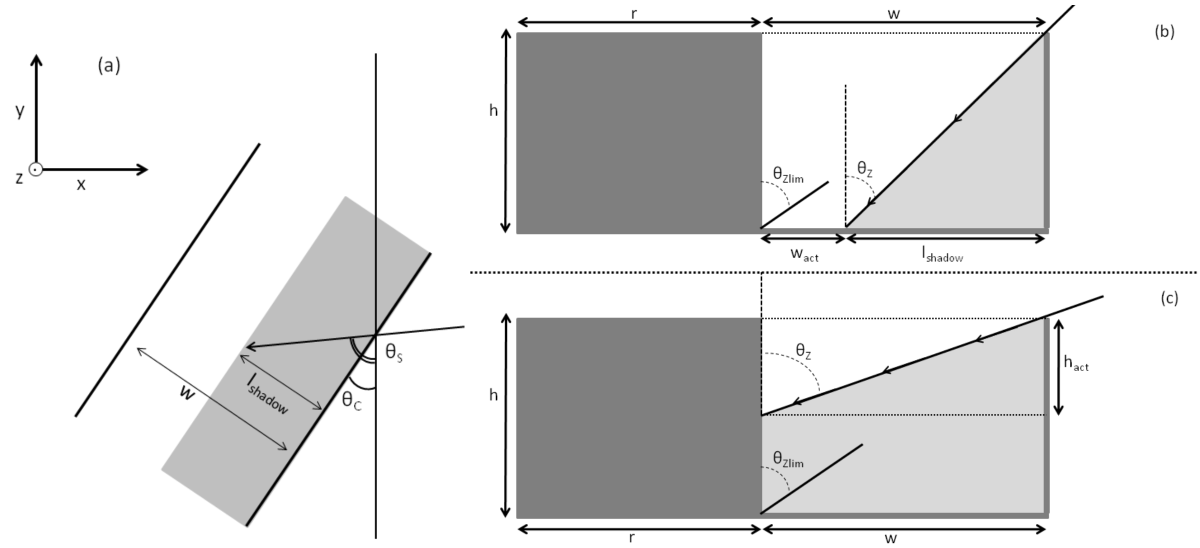

Figure 4: (a) impact of canyon orientation (θ_C) and solar azimuth angle (θ_S) on the street shading patterns (Kusaka, personal communication); where w is the normalized mean street width and l_{shadow} the normalized portion of the street that is shaded. (b) shading patterns (cross sections) for roads and (c) walls. See text for notation.

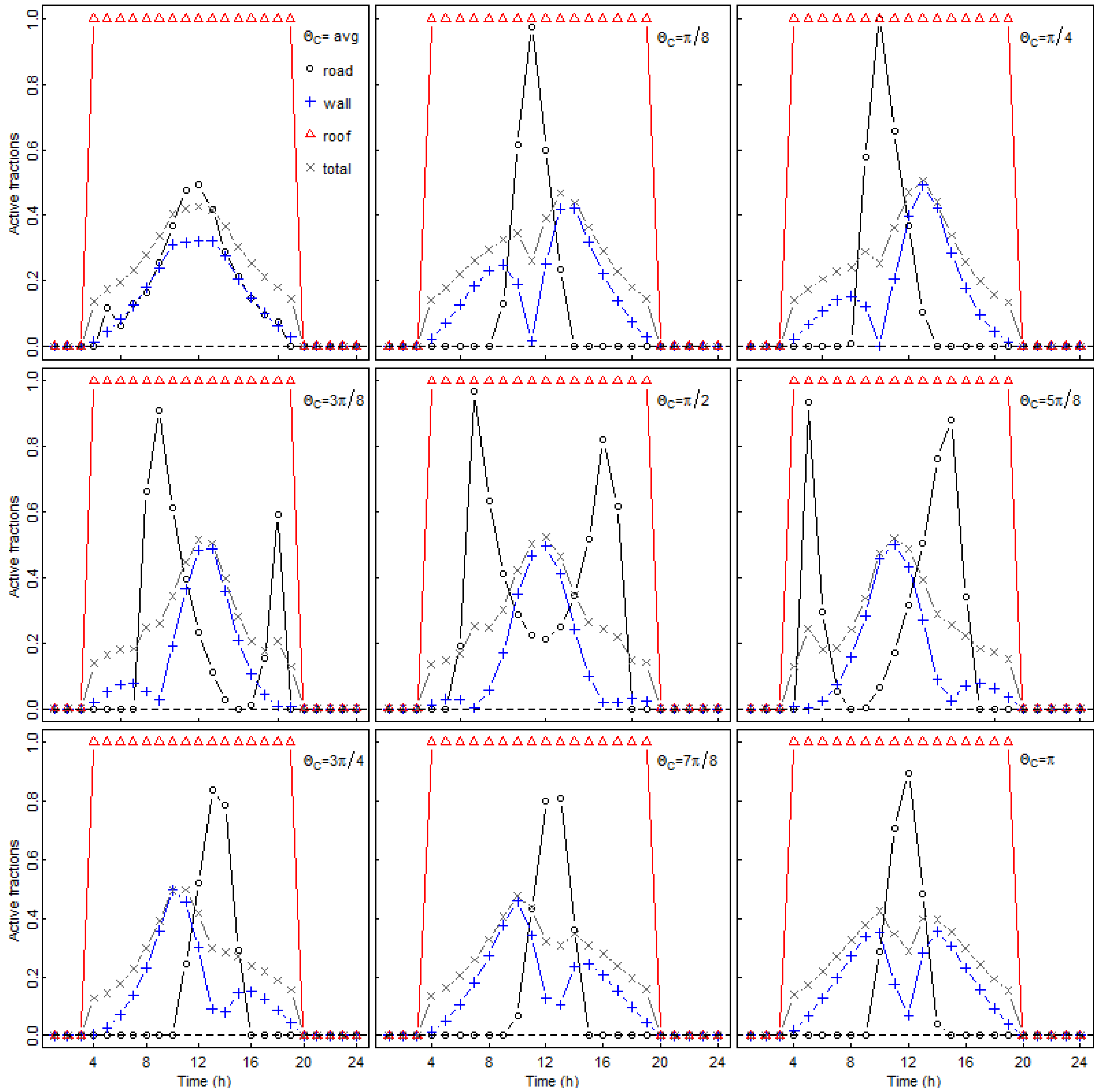

Figure 5: Fraction of total, roof, road and wall materials that are active for each hour of DOY 172 in Łódź for different canyon orientation ($\pi/8 \leq \theta_C \leq \pi$) and for the overall average (θ_C = avg; upper left).

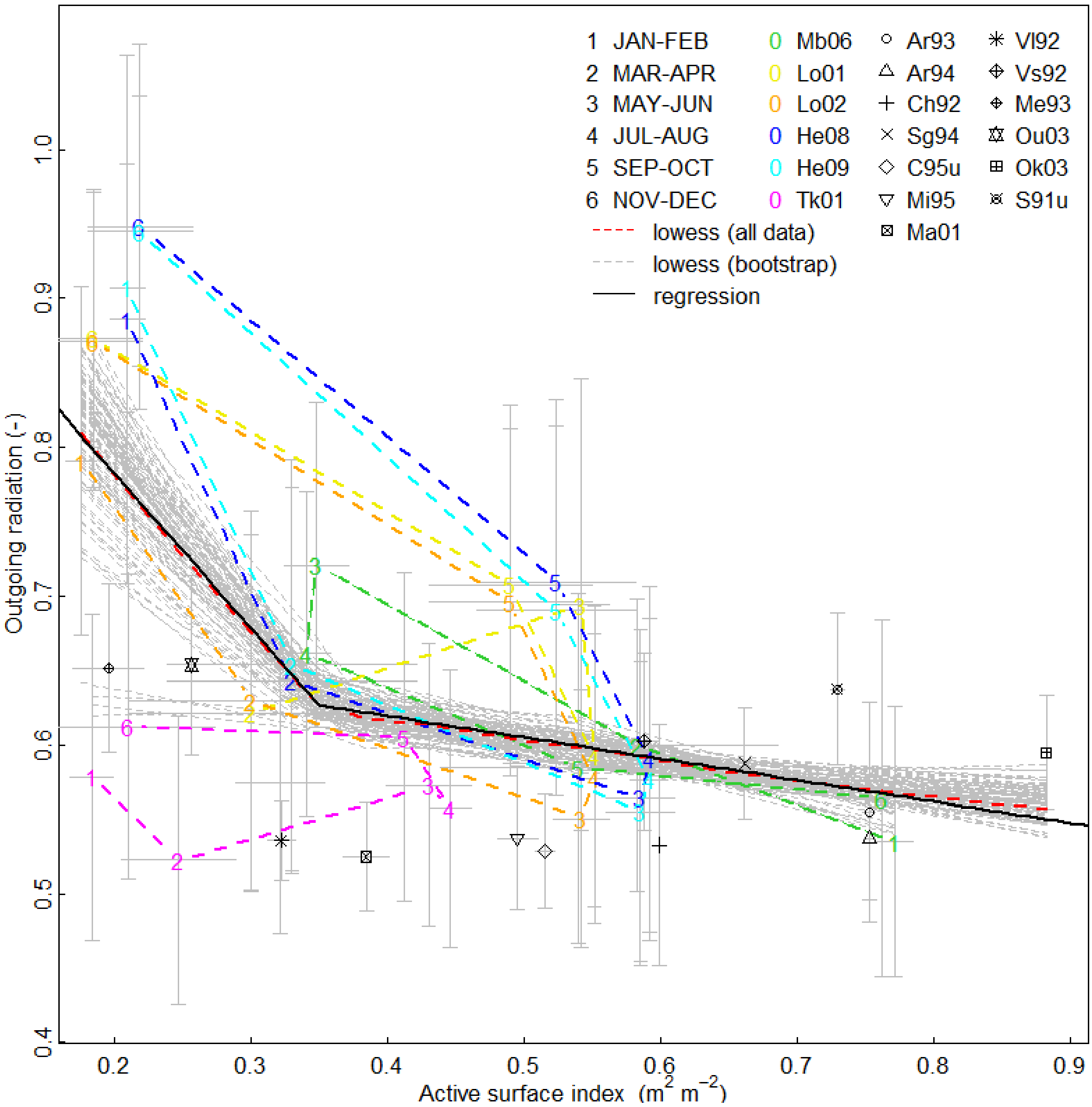

Figure 6: Q↑/Q↓ mean daytime (3 h around solar noon) ratio as a function of the mean midday χ_{tot} value for all short term sites and two-month subsets of the yearly sites. LOWESS regression shown by (red) dashed line. Error bars show ± 1 standard deviation. See text for details. The non-linear regression (black curve) is eqn (25).

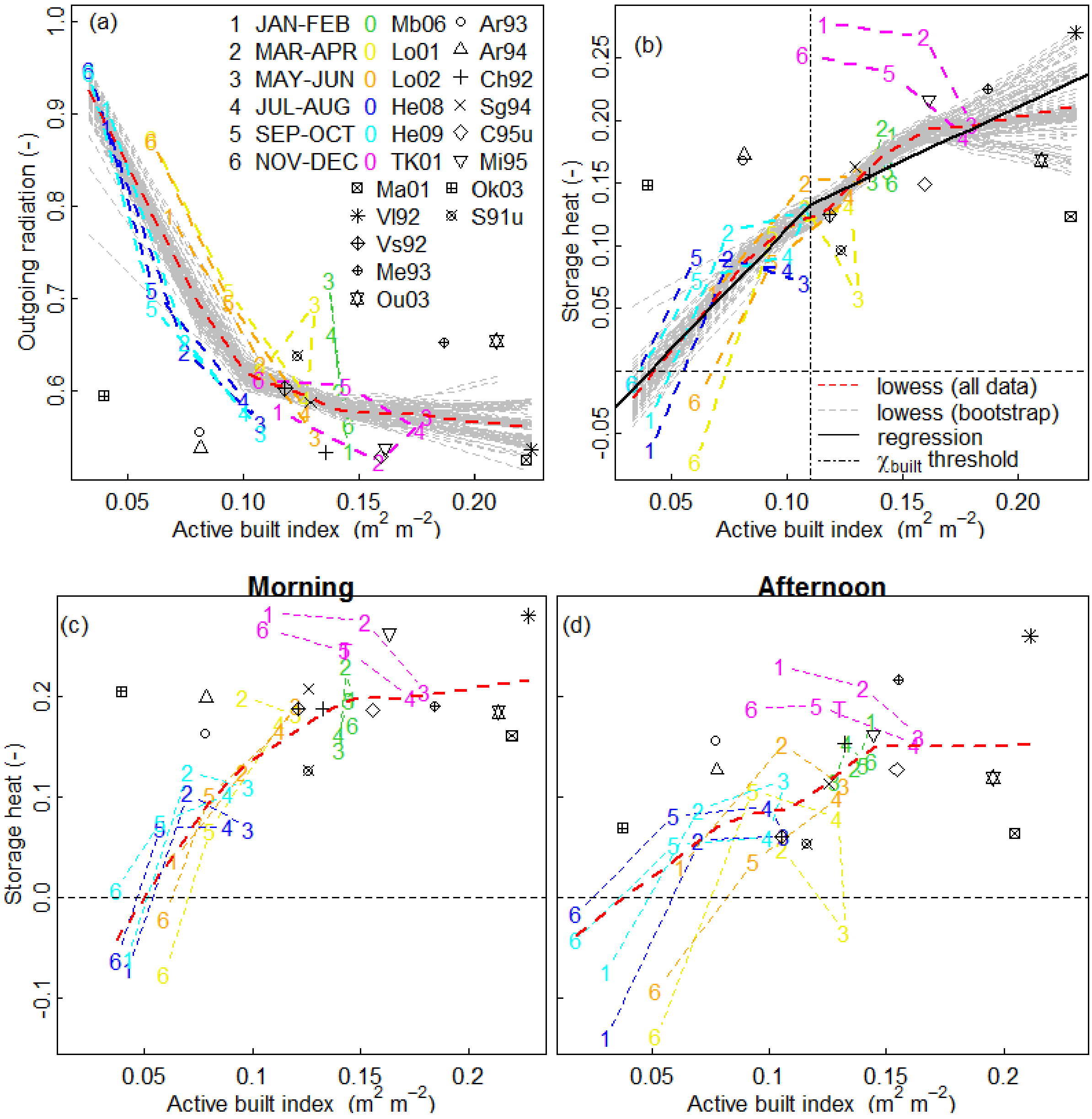

Figure 7: (a) Q↑/Q↓, (b, c, d) ΔQ_S / Q↓, mean (a, b) midday, (c) morning (2-3 h before solar noon) and (d) afternoon (2-3 h after solar noon) ratios as a function of the χ_{built} values averaged over the same periods. For (b) the non-linear regression eqn is (26).

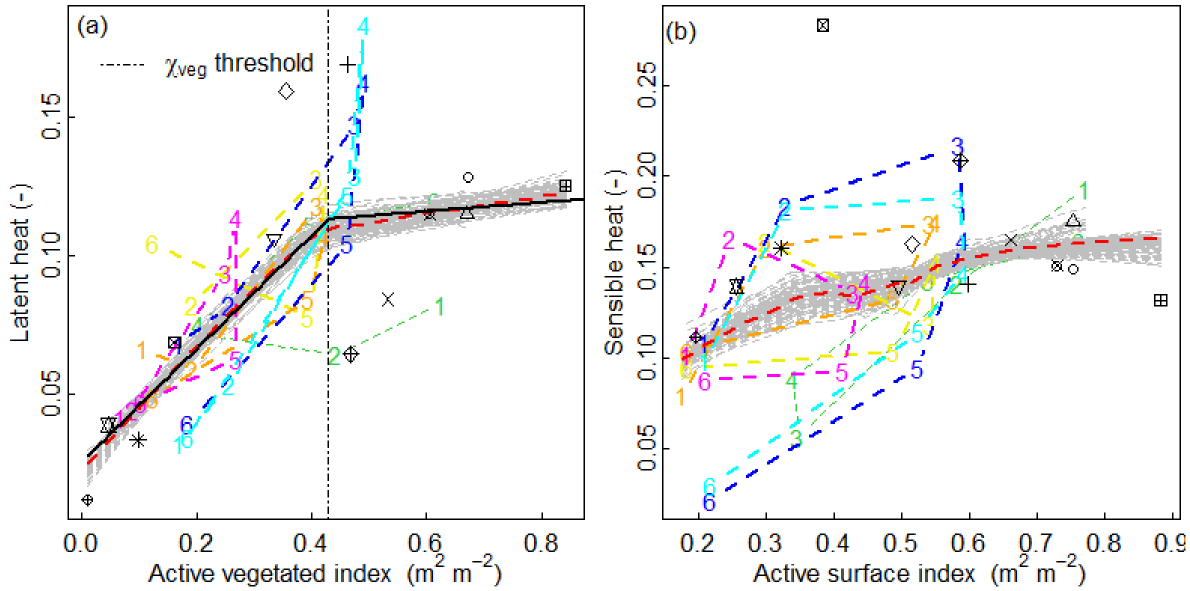

Figure 8: Mean midday ratios of (a) Q_E / Q↓ and (b) Q_H / Q↓ as a function of the mean midday (a) χ_{veg} and (b) χ_{tot} values. The non-linear regression (thick black line) for (a) is (27). For key see Figure 7.

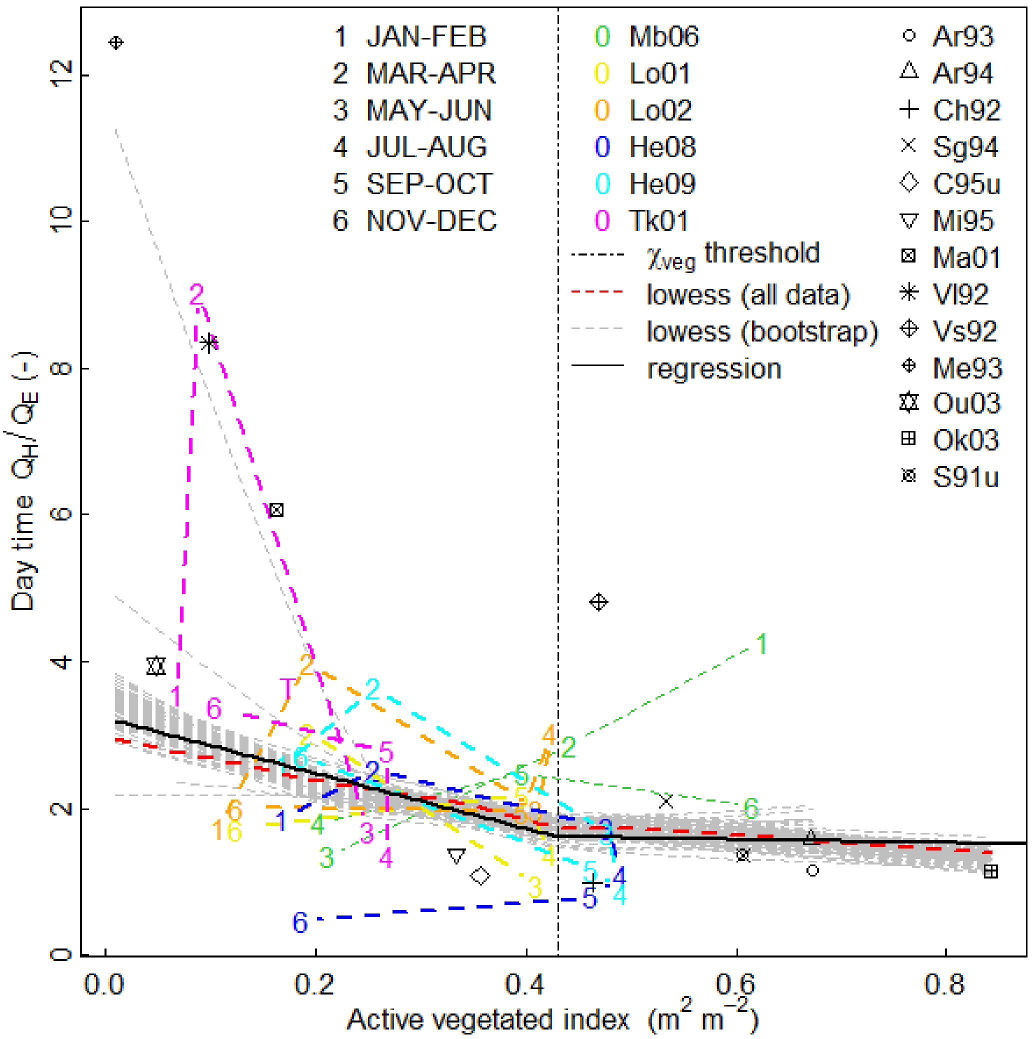

Figure 9: Mean midday (±3 h around solar noon) Bowen ratio (Q_H/Q_E) as a function of midday χ_{veg} value. The LOWESS regression is performed on all points (unlike Fig. 1). The non-linear regression (thick black line) is (29).

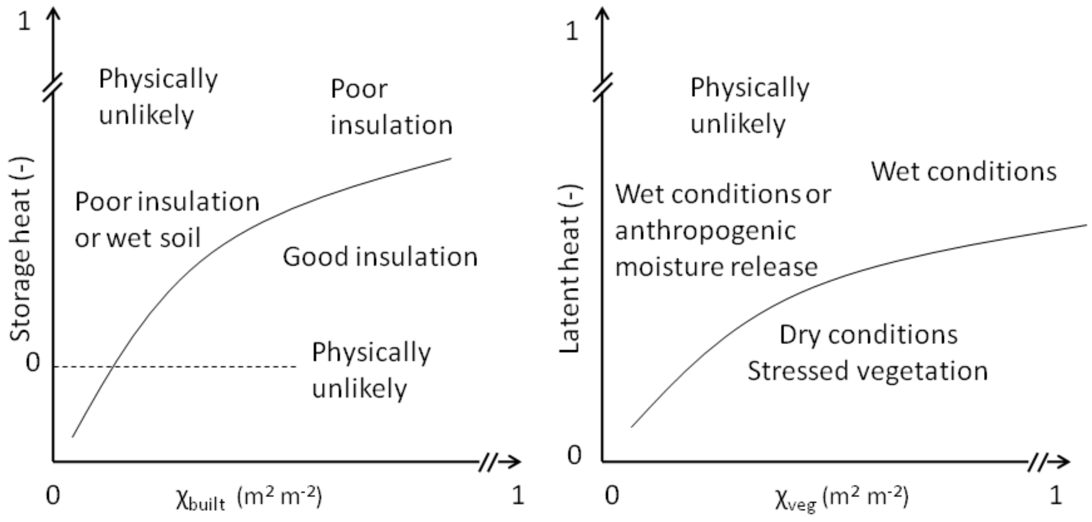

Figure 10: Theoretical flux ratio – active index diagrams

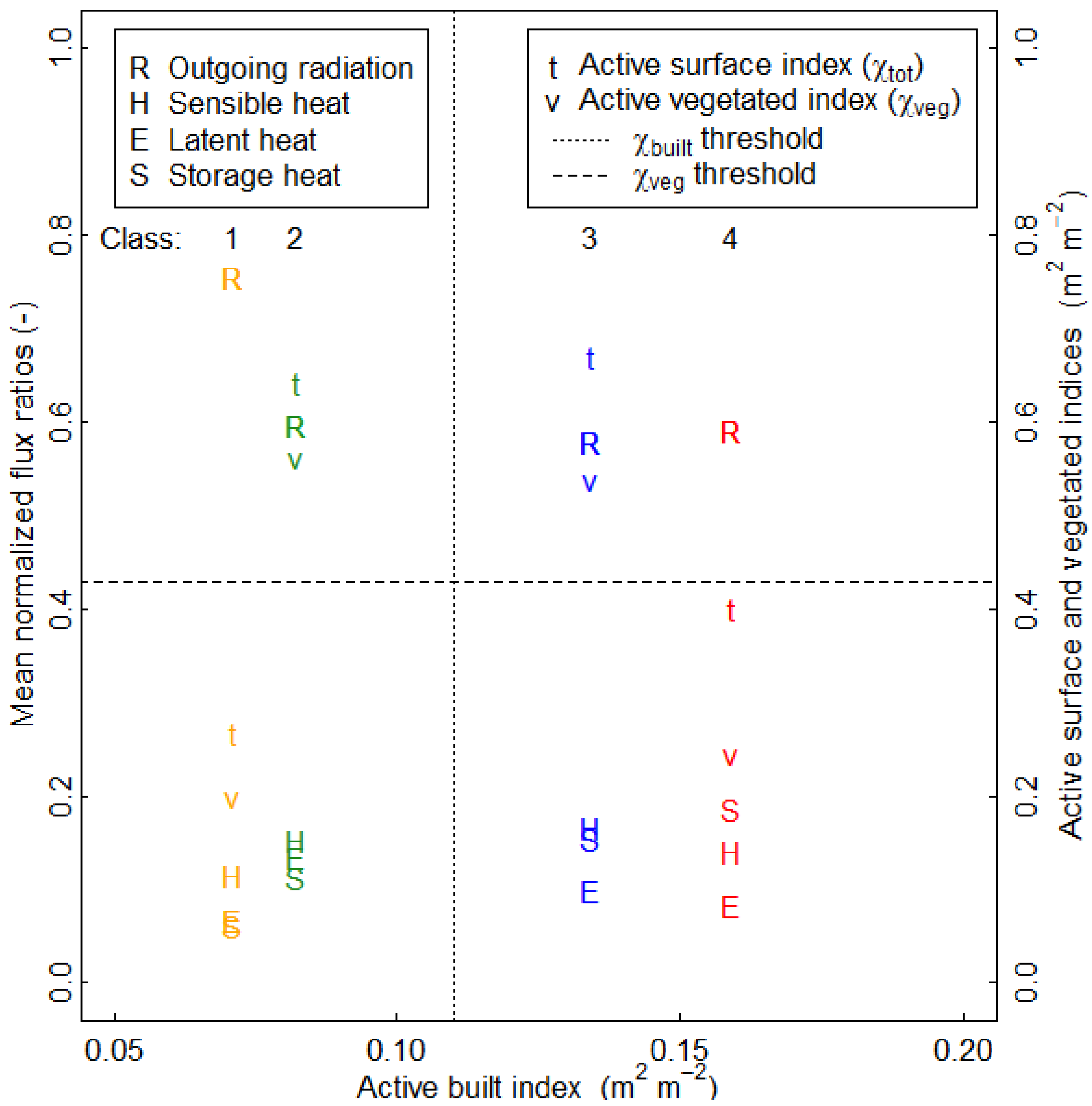

Figure 11: Mean midday flux ratios (capital letters) and indices (lower case and x-axis) of the four urban zones to characterize energy partitioning (UZE) (see text for class definition): (1) low active surface (winter); (2) most vegetated: "*Low Density*"; (3) more urban: "*Medium Density*" and (4) most urban: "*High Density*".

Code REF	Site	Lat / lon	Obs period	f_{urb}	f_{bld}	f_{imp}	Z_R (m)	W_{road} (m)	W_{roof} (m)	f_{grass}	Leaf-on Leaf-off (DOY)	N Day / Night
Ar93* GO95	Arcadia CA, USA	34°08’N, 118°03’W	Jul-Aug 1993	0.40	0.22	0.18	5.2	4.4	5.6	0.4	80/171-264/354	248 234
Ar94* GR96	Arcadia CA, USA	34°08’N, 118°03’W	Jul 1994	0.43	0.24	0.19	5.2	4.4	5.6	0.4	80/171-264/354	119 126
He08 VE08	Helsinki, Finland	60°20’N, 24°96’E	Jan-Dec 2008	0.54	0.14	0.40	20.0	19	15	0.5	69/144-281/324	2119 1606
He09 VE08	Helsinki, Finland	60°20’N, 24°96’E	Jan-Dec 2009	0.54	0.14	0.40	20.0	19	15	0.5	69/144-81/324	2346 1877
Ok03 GR04b (WH)	Oklahoma City, OK, USA (wood house)	35°26’N, 97°28’W	Jun-Aug 2003	0.22	0.10	0.12	4.5	8.5	6.8	0.6	80/171-264/354	153 155
Ch92* GR94	Chicago, IL, USA	41°57’N, 87°48’W	Jul 1992	0.55	0.33	0.22	6.7	6.9	10.3	0.75	80/171-264/354	50 22
Vs92* GO99	Vancouver, BC, Canada	49°15’N, 123°04’W	Jul/Sep 1992	0.54	0.31	0.23	4.7	5.2	7.0	0.76	80/171-264/354	154 175
Sg94 GR96	San Gabriel CA, USA	34°05’N, 118°05’W	Jul 1994	0.6	0.29	0.31	4.7	10.9	10.2	0.62	80/171-264/354	133 140
S91u GR93	Sacramento, CA, USA	38°39’N, 121°30’W	Aug 1991	0.48	0.36	0.12	4.8	4.0	12.0	0.65	80/171-264/354	63 70
Mb06 CO07	Melbourne, Australia	37°49’S, 144°53’E	Dec-Dec 2006	0.62	0.45	0.17	6.4	38.5	15.2	0.39	216/338-36/155	2191 2449
C95u* KG97	Chicago, IL, USA	41°57’N, 87°48’W	Jun-Aug 1995	0.61	0.36	0.25	5.9	5.5	7.9	0.82	80/171-264/354	87 77
Mi95 NE99	Miami, FL, USA	25°44’N, 80°22’W	May-Jun 1995	0.64	0.35	0.29	8.0	7.8	9.4	0.75	80/171-264/354	88 102
Ma01 GR04a	Marseille, France	43°17’N, 5°23’E	Jun-Jul 2001	0.86	0.59	0.27	15.6	9.6	21.2	0.5	80/171-264/354	179 182
Vl92* GO99	Vancouver, BC, Canada	49°16’N, 123°06’W	Aug 1992	0.95	0.51	0.44	5.8	10.2	11.8	0.4	80/171-264/354	103 105
Me93 OK99	Mexico City, Mexico	19°26’N, 99°08’W	Dec 1993	0.98	0.54	0.44	18.4	15.5	19	0	80/171-264/354	43 47
Ou03 OF05	Ouagadougou, Burkina Faso	12°22’N, 1°31’W	Feb 2003	0.9	0.4	0.5	3.0	7.5	9.2	0	80/171-264/354	153 155
Łó01 OF06	Łódź, Poland	51°46’N, 19°27’E	Mar-Dec 2001	0.7	0.3	0.4	10.6	14.1	10.5	0.3	69/144-81/324	1167 1151
Łó02 OF06	Łódź, Poland	51°46’N, 19°27’E	Jan-Dec 2002	0.7	0.3	0.4	10.6	14.1	10.5	0.3	69/144-81/324	1654 1729
Tk01 MK04	Tokyo, Japan	35°34’N, 139°41’E	May 01-April 02	0.79	0.33	0.46	7.3	6.6	6.1	0.3	90/150-300/330	1810 1812

Table 1: Characteristics of observational datasets used: location (lat/lon); observation periods; measurement footprints: plan area fractions urban (f_{urb}), building (f_{bld}) and impervious (f_{imp}); morphology: mean roof height (Z_R), road width (W_{road}) and roof width (W_{roof}); vegetation characteristic: plan area fraction vegetated (f_{veg}=1-f_{urb}), covered by grass (f_{grass}*f_{veg}) or trees/shrub (f_{veg} *(1-f_{grass}); eq. 20), leaf-on (start /stop) - leaf-off (start/stop) periods (day of year); number of hours (N) analysed for day and night; reference for study details: GO95 (Grimmond and Oke 1995), GR96 (Grimmond et al. 1996), GR94 (Grimmond et al. 1994), KG97 (King and Grimmond 1997), GR04a (Grimmond et al. 2004a), OK99 (Oke et al. 1999), NE99 (Newton 1999), GR04b (Grimmond et al. 2004b), OF05 (Offerle et al. 2005), GO99 (Grimmond and Oke 1999), GR93 (Grimmond et al. 1993), CO07 (Coutts et al. 2007a,b), VE08 (Vesala et al. 2008), OF06 (Offerle et al. 2006), MK04 (Moriwaki and Kanda, 2004). *Measurement sites are in the same city but at different locations. Note that sites are grouped by classes (see section 5) with yearly sites classified according to the summer data.

	Mean midday (±3 h around solar noon)										Mean midnight (12 h after solar noon)					
		Ratios										Ratios				
Site Code	**$Q\downarrow$ (W m^{-2})**	**$Q\uparrow$**	**ΔQ_S**	**Q_E**	**Q_H**	**Q_E+Q_H**	**Q_F**	**χ_{tot}**	**χ_{built}**	**χ_{veg}**	**$Q\downarrow$ (W m^{-2})**	**$Q\uparrow$**	**ΔQ_S**	**Q_E**	**Q_H**	**Q_F**
(a) Short term sites, ordered by increasing day time $Q_E + Q_H$																
Me93	945	0.652	0.225	0.011	0.112	0.123	0.026	0.196	0.187	0.009	322	1.308	-0.388	0.01	0.07	0.036
Ou03	1109	0.654	0.168	0.039	0.139	0.178	0	0.257	0.21	0.047	402	1.166	-0.171	0.016	-0.011	0
Vl92	1048	0.536	0.27	0.033	0.161	0.194	0.078	0.322	0.225	0.098	332	1.133	-0.121	0.006	-0.018	0.088
Mi95	1160	0.537	0.217	0.106	0.14	0.246	0.038	0.495	0.161	0.334	391	1.114	-0.113	0.015	-0.016	0.04
Sg94	1218	0.588	0.163	0.084	0.165	0.249	0.031	0.662	0.129	0.532	383	1.131	-0.14	0.009	0	0.035
Ok03	1243	0.595	0.148	0.125	0.132	0.257	0.009	0.882	0.04	0.842	425	1.106	-0.075	0.021	-0.051	0.01
S91u	1133	0.638	0.096	0.115	0.151	0.266	0.002	0.729	0.123	0.606	338	1.199	-0.194	0.01	-0.016	0.002
Vs92	1017	0.602	0.125	0.064	0.209	0.273	0.085	0.587	0.118	0.469	334	1.175	-0.16	0.014	-0.029	0.073
Ar93	1138	0.555	0.168	0.128	0.149	0.277	0.034	0.753	0.081	0.672	389	1.085	-0.087	0.006	-0.005	0.035
Ar94	1223	0.537	0.173	0.115	0.175	0.290	0.031	0.753	0.081	0.671	382	1.116	-0.11	0.001	-0.006	0.035
Ch92	912	0.533	0.157	0.169	0.14	0.309	0.055	0.599	0.136	0.463	354	1.14	-0.115	0.016	-0.041	0.051
C95u	1174	0.529	0.149	0.16	0.163	0.323	0.041	0.515	0.159	0.356	395	1.095	-0.089	0.02	-0.026	0.044
Ma01	1140	0.525	0.123	0.069	0.283	0.352	0.027	0.384	0.222	0.162	328	1.233	-0.357	0.04	0.084	0.024
(b) Łódź 2002																
Łó02_JF	458	0.791	0.063	0.066	0.08	0.146	0.04	0.176	0.068	0.108	268	1.21	-0.212	0.038	-0.037	0.025
Łó02_MA	668	0.63	0.151	0.059	0.161	0.220	0.024	0.3	0.108	0.193	286	1.214	-0.234	0.035	-0.015	0.025
Łó02_MJ	**960**	**0.551**	**0.157**	**0.118**	**0.174**	**0.292**	0.012	0.542	0.131	0.411	333	1.205	-0.209	0.03	-0.026	0.01
Łó02_JA	919	0.577	0.14	0.108	0.175	0.283	0.012	0.552	0.127	0.424	359	1.174	-0.188	0.031	-0.017	0.011
Łó02_SO	625	0.696	0.087	0.084	0.133	0.217	0.018	0.49	0.094	0.396	310	1.168	-0.187	0.04	-0.02	0.013
Łó02_ND	392	0.871	-0.023	0.049	0.104	0.153	0.042	0.185	0.06	0.124	275	1.172	-0.215	0.038	0.005	0.022
(c) Helsinki 2009																
He09_JF	370	0.907	-0.038	0.032	0.099	0.131	0.067	0.21	0.041	0.169	250	1.182	-0.198	0.011	0.005	0.031
He09_MA	675	0.654	0.111	0.053	0.182	0.235	0.058	0.33	0.075	0.255	259	1.227	-0.182	0.014	-0.059	0.041
He09_MJ	**912**	**0.555**	**0.128**	**0.129**	**0.188**	**0.317**	0.024	0.585	0.108	0.477	295	1.252	-0.207	0.038	-0.083	0.021
He09_JA	898	0.577	0.093	0.184	0.147	0.331	0.023	0.591	0.1	0.491	323	1.218	-0.18	0.034	-0.072	0.018
He09_SO	624	0.69	0.073	0.122	0.114	0.236	0.038	0.524	0.061	0.463	304	1.204	-0.132	0.027	-0.1	0.021
He09_ND	325	0.945	-0.009	0.034	0.03	0.064	0.103	0.219	0.033	0.186	287	1.076	-0.103	0.024	0.002	0.033
(d) Melbourne 2006																
Mb06_JA	654	0.661	0.174	0.075	0.089	0.164	0.043	0.341	0.139	0.202	300	1.162	-0.124	0.025	-0.062	0.034
Mb06_SO	897	0.585	0.161	0.111	0.143	0.254	0.031	0.54	0.144	0.397	302	1.205	-0.185	0.023	-0.042	0.025
Mb06_ND	**1024**	**0.564**	**0.151**	**0.120**	**0.164**	**0.284**	0.03	0.762	0.146	0.616	316	1.223	-0.228	0.031	-0.026	0.032
Mb06_JF	**1068**	**0.535**	**0.189**	**0.082**	**0.193**	**0.275**	0.03	0.771	0.146	0.625	315	1.234	-0.241	0.014	-0.008	0.036
Mb06_MA	864	0.6	0.195	**0.064**	0.141	0.205	0.037	0.583	0.142	0.441	322	1.169	-0.149	0.011	-0.031	0.028
Mb06_MJ	566	0.721	0.152	0.071	0.056	0.127	0.047	0.348	0.137	0.211	299	1.171	-0.117	0.027	-0.081	0.033
(e) Tokyo 2001																
TK01_JF	672	0.578	0.278	0.041	0.102	0.143	0.118	0.184	0.116	0.068	274	1.169	-0.136	0.027	-0.06	0.129
TK01_MA	901	0.523	0.267	0.044	0.166	0.210	0.075	0.247	0.159	0.088	311	1.137	-0.143	0.026	-0.019	0.097
TK01_MJ	905	0.573	0.197	0.094	0.136	0.230	0.072	0.43	0.18	0.25	372	1.085	-0.093	0.025	-0.018	0.077
TK01_JA	**1002**	**0.557**	**0.187**	**0.114**	**0.141**	**0.255**	0.078	0.446	0.177	0.269	420	1.045	-0.088	0.027	0.015	0.081
TK01_SO	800	0.605	0.239	0.063	0.093	0.156	0.082	0.412	0.145	0.268	356	1.11	-0.096	0.019	-0.033	0.083
TK01_ND	662	0.612	0.254	0.046	0.088	0.134	0.097	0.211	0.107	0.104	292	1.157	-0.138	0.026	-0.046	0.099

Table 2: Mean midday (±3 h @ solar noon) and midnight (±3 h @ 12 h after solar noon) values of $Q\downarrow$, flux ratios ($Q\uparrow / Q\downarrow$, $\Delta Q_S / Q\downarrow$, $Q_E / Q\downarrow$, $Q_H / Q\downarrow$, $Q_F / Q\downarrow$) and mean midday active surface indices (χ_{tot}, χ_{built}, χ_{veg}) for each site. Long term sites are separated in two-month subsets (JF: January-February; MA: March-April; MJ: May-June; JA: July-August; SO: September-October; ND: November-December) and only one year is shown for Łódź and Helsinki campaigns (Łó02 and HEe9). (b-e): the

periods with largest radiative forcing (Q↓) are shown in bold for comparison with (a). See text for details.

SITE	BSPR	BSPA	ALLS
f_{urb}	0.84	0.69	0.47
Z_R	14.6	12.5	7.5
W_{roof}	11.2	14.8	11.9
W_{road}	20.2	17.2	17.5
Mean daytime Q↓(W m^{-2})	**949.1**	**1038.2**	**1029.4**
χ_{tot}	0.419	0.578	0.761
χ_{built}	0.183	0.130	0.085
χ_{veg}	0.237	0.449	0.677
Urban class (UZE)	4: most urban: *High Density*	3: more urban: *Medium Density*	2: most vegetated: *Low Density*
Q↑ / Q↓ (P/O)	0.610 / 0.586	0.586 / 0.548	0.558 / 0.580
ΔQ_S / Q↓ (P/O)	0.195 / 0.116	0.147 / 0.142	0.082 / 0.133
Q_E / Q↓(P/O)	0.072 / 0.090	0.110 / 0.090	0.115 / 0.128
Q_H / Q_E (P/O)	2.335 / 2.458	1.596 / 2.43	1.546 / 1.295
Mean daytime Q* (P/O) (W m^{-2})	366.5 / 416.8	426.4 / 485.9	450.6 / 448.0
Mean daytime Q_E (P/O) (W m^{-2})	67.8 / 85.1	114.7 / 91.5	117.4 / 131.4
Mean daytime ΔQ_S (P/O) (W m^{-2})	186.3 / 128.9	154.8 / 161.1	85.9 / 148.6
Mean daytime Q_H (P [eq. 29] /O) (W m^{-2})	159.7 / 202.8	184.5 / 233.3	182.8 / 168.1
Mean daytime Q_H (P [eq. 28]) (W m^{-2})	119.7	164.2	254.6

Table 3: Evaluation of the FRAISE predictive relations (eq. 25-29 and 24) with the Basel Urban Boundary Layer Experiment (BUBBLE, Christen and Vogt, 2004; Rotach et al. 2004) data. Note the ratios correspond to those presented in eq. 5 while the flux estimates include the Q_F contribution. Averaging windows differs from the ones used in Christen and Vogt (2004, their Table 5). P/O: Predicted/ Observed