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1 **Assessing the consistency of eddy covariance measurements under conditions of sloping**  
2 **topography within a hilly agricultural catchment.**

3

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## \*Highlights (for review)

- Eddy covariance (EC) measurements over hillslope under forced convection
- Upward flows: agreement between topography and EC derived airflow inclinations
- Downward flows: differences between topography and EC derived airflow inclinations
- Downward flows: differences ascribed to separation bubble with streamline dilatation
- Energy balance closure similar to reports on flat and mountainous topographies

24 **ABSTRACT**

25

26         The current study addressed the consistency of Eddy Covariance (EC) measurements  
27 collected in sloping conditions within a hilly agricultural catchment. In the context of  
28 operational monitoring and modelling devoted to decision support, it is important to increase  
29 the knowledge of surface fluxes under conditions of hilly topography. The two-metre-high EC  
30 measurements were collected at the field scale within the two opposite rims of a V-shaped  
31 catchment located in northeastern Tunisia on the southern shore of the Mediterranean Basin.  
32 Measurements were collected under bare soil conditions to enhance the effects of the slopes.  
33 The data pre-processing and quality control measures were conducted using standard  
34 procedures. In assessing the consistency of the EC measurements we first compared the  
35 airflow inclinations captured by the EC measurements against the topographical slopes  
36 captured by a Digital Elevation Model; we then assessed the energy balance closure. The  
37 analysis of the micrometeorological data indicated specific regimes: externally driven winds;  
38 forced convection; and stability conditions close to neutrality or low instability. The two  
39 dominant wind directions induced upward and downward flows on the two opposite rims. For  
40 the upward flows, the airflow inclinations followed the topographical slopes on both fields.  
41 For the downward flows, the flows followed the topographical slopes on the southern rim and  
42 were almost horizontal on the other rim. In all cases, and especially for the upward flows, the  
43 energy balance closure was similar to that reported in the literature. Overall, the behaviour  
44 observed for upward flows was close to that reported in the literature for flat conditions,  
45 whereas the downward flows exhibited different trends. The different trends we observed for  
46 the downward flows were ascribed to the bubble separation zone that implies streamline  
47 dilatation, turbulence and reverse flows. Future investigations should address the vegetation  
48 conditions. The expected outcomes are of importance for revisiting the operational methods  
49 devoted to the estimation of evapotranspiration.

50

51 **KEYWORDS:** agricultural hilly catchment, eddy-covariance measurements, sloping  
52 conditions, airflow inclination, land surface energy balance.

53

54 **1. INTRODUCTION**

55

56 Knowledge of land surface energy fluxes is of paramount importance for water and  
57 crop management within semi-arid regions, where the annual actual evapotranspiration  
58 amounts to more than two-thirds of the yearly precipitation (Moussa et al., 2007; Daneshkar  
59 Arasteh and Tajrishy, 2008). Numerous methods have been developed for measuring and  
60 modelling the land surface energy fluxes in flat terrain (Rana and Katerji, 2000; Olioso et al.,  
61 2002a; Courault et al., 2005). However, little research has been performed for the hilly  
62 catchments that correspond to large agricultural areas in many regions of the world (e.g.,  
63 Mediterranean countries, western Africa, eastern India). Hilly catchments allow water  
64 harvesting to be used to secure agricultural production (Mekki et al., 2006; Saha et al., 2007).  
65 Our understanding of the energy fluxes and crop evapotranspiration within hilly catchments is  
66 still incomplete; a major gap in the knowledge is the influence of the topography on the  
67 structure of turbulence within the boundary layer (Raupach and Finnigan, 1997).

68

69 Understanding the airflows and surface fluxes over hills was first investigated with  
70 wind tunnels (Jackson and Hunt, 1975; Brunet et al., 1994; Poggi and Katul, 2007), and  
71 analytical solutions have been proposed for wind and temperature profiles (Jackson and Hunt,  
72 1975; Hunt et al., 1988; Raupach et al., 1992; Kaimal and Finnigan, 1994; Finnigan and  
73 Belcher, 2004). However, applying these formulations over hilly catchments is questionable  
74 because they are limited to simple two-dimensional hills. Another possibility is the large eddy  
75 simulation (LES) technique (Tamura et al., 2007; Dupont et al., 2008). However, LES  
76 implementation is a delicate task that requires substantial computer resources, especially over  
77 the heterogeneous landscapes that involve large spatial extents and fine spatial resolutions.  
78 Furthermore, the application of LES is still limited to simple topography (Dupont et al.,  
79 2008).

80

81 As a result of the aforementioned modelling difficulties and of the increasing  
82 availability of eddy covariance (EC) systems, several experimental campaigns have  
83 investigated the effects of sloping conditions. These campaigns have involved single flux  
84 towers either under mountainous conditions with forests (Geissbühler et al., 2000; Humphreys  
85 et al., 2003; Turnipseed et al., 2003) and grasslands (Hammerle et al., 2007; Hiller et al.,

86 2008), or within hilly catchments with crop systems (Rana et al. 2007; Scott, 2010). Until  
87 recently, the experimental costs made it almost impractical to analyse turbulence and  
88 advection from the data collected by several nearby EC systems (Feigenwinter et al., 2008).

89

90 The effects of slope have been taken into account by applying rotational corrections to  
91 the EC measurements, such as the latter fitted to the airflow planes induced by the  
92 topographical slopes. When dealing with the single EC towers within hilly agricultural  
93 catchments, the energy flux data corrected for slope effects were next used to address the  
94 modelling of turbulent exchanges. Thus, Rana et al. (2007) proposed a semi-empirical  
95 correction to the turbulent exchange coefficients that accounts for the slope magnitude by  
96 extending to non-neutral conditions the neutral wind speed profile relationship proposed by  
97 Kaimal and Finnigan (1994). However, follow-up research is needed to extend the few  
98 existing works on the EC measurements from single towers; to enable such measurements to  
99 be used operationally for monitoring water consumption by crops in hilly catchments,  
100 especially in semi-arid regions.

101

102 The objective of the current study was to increase the understanding of EC  
103 measurements from single towers in sloping conditions within hilly agricultural catchments;  
104 by investigating the possible links between the topography, airflow inclinations driven by the  
105 wind direction, and surface energy balance closure. We considered a Mediterranean  
106 agricultural catchment with hilly topography, locating the EC measurements on the two  
107 opposite sides of a valley. We addressed bare soil conditions only, to minimise land-use  
108 heterogeneity effects and thus enhance the effects of topography. Section 2 presents the study  
109 area, the data collection and processing, including the flux calculation, quality control and  
110 footprint analysis, and topographical characterisation from a digital elevation model (DEM).  
111 Section 3 reports the analysis of micrometeorological conditions (wind regimes and stability  
112 conditions), as well as the results obtained when comparing the airflow inclinations against  
113 the topographical slopes and when verifying the energy balance closure according to the  
114 airflow inclinations. Section 4 discusses the main outcomes and future directions.

115

116

117

118 **2. MATERIALS AND METHODS**

119

120 **2.1 Experimental site and calendar**

121

122 The experiment was set within the agricultural Kamech catchment, which is located in  
123 the Cap Bon Peninsula in northeastern Tunisia (36°52'40"N, 10°52'40"E, Fig. 1).  
124 Comprehensive descriptions of the Kamech catchment are given by Mekki et al. (2006) and  
125 Raclot and Albergel (2006). This catchment belongs to the long-term environmental research  
126 observatory OMERE (a French acronym for the Mediterranean Observatory of Water and the  
127 Rural Environment). Within Mediterranean rural catchments, the OMERE studies the impacts  
128 of anthropogenic forcing and climate change on hydrology, erosion, and water quality in  
129 relation to pollutants (<http://www.umr-lisah.fr/omere>).

130

131 [Figure 1 about here]

132

133 The 2.45 km<sup>2</sup> Kamech catchment is crossed by the El Gameh wadi from the northeast  
134 to the southwest (Fig. 2). The catchment topography is entirely V-shaped from the middle to  
135 the south-western parts. The slopes are irregular, especially on the southern rim, which has  
136 natural embankments induced by sandstone hogbacks. The altitude ranges between 94 m and  
137 194 m. The slopes range between 0% and 30%, the quartiles being 6%, 11% and 18%. Most  
138 fields have a small size with an average area of 0.6 ha. The soils have sandy-loam textures,  
139 with depths ranging from zero to two metres according to the location within the catchment  
140 and the local topography. These swelling soils exhibit shrinkage cracks under dry conditions  
141 during the summer (Raclot and Albergel, 2006). The main crops are winter cereals and  
142 legumes. The steepest parts of the catchment are used as rangeland for livestock and are  
143 therefore covered by natural vegetation. The regional climate is sub-humid with annual values  
144 of 600 mm and 1500 mm for the precipitation and Penman-Monteith reference crop  
145 evapotranspiration, respectively. Because of the combination of sub-humid climate and rain-  
146 fed agriculture, the catchment is under bare soil conditions from the end of spring to the  
147 middle of autumn.

148

149 [Figure 2 about here]

150

151 The flux measurements were conducted under bare soil conditions during several  
152 months in 2004 and 2006. For both years, a flux station was installed in Field A, located on  
153 the northern rim of the catchment (Fig. 2). Field A had an area of 1.1 ha with an homogeneous  
154 slope of 5° facing the south-southeast direction (Fig. 2 and Fig. 3). This field's northern (and  
155 upper) limit was close to the rim top, which forms the catchment edge. To collect data on the  
156 opposite rim and subsequently to assess the possible effect of slope orientation on energy  
157 fluxes, a second flux station was installed in 2006 in Field C, located on the southern rim of  
158 the catchment (Fig. 2) and facing northwest. Field C had an area of 2.2 ha and a rugged  
159 topography (Fig. 3). The averaged slope around the field centre was approximately 8°. The  
160 southern (and upper) limit was close to a plateau, located in the middle of the rim. The  
161 northern limit had a natural embankment induced by a sandstone hogback.

162

163

[Figure 3 about here]

164

165 Concentrating on bare soil conditions allowed (1) the removal of vegetation canopy  
166 effects, which had an influence on the turbulent fluxes that could be as strong as that of  
167 topography (Turnipseed et al., 2003), and (2) a focus on periods during which the land surface  
168 conditions were homogeneous throughout the catchment. In 2004, the measurements were  
169 collected in Field A from 18 July to 4 November. In 2006, the measurements were collected  
170 on fields A and C from 20 June to 28 July. The corresponding three data sets were labelled  
171 A04, A06 and C06, where the letter represents the field, and the two digits represent the year.

172

## 173 **2.2. Instrumentation and data acquisition**

174

175 A meteorological station located near the catchment outlet (labelled M on Fig. 2)  
176 measured: (1) the rainfall at a daily time step with a manual raingauge; (2) the solar irradiance  
177 with a SP1110 pyranometer (Skye, UK); (3) the air temperature and humidity with an  
178 HMP45C probe (Vaisala, Finland); (4) the wind speed with an A100R anemometer (Vector  
179 Instruments, UK); and (5) the wind direction with a W200P wind vane (Vector Instruments,  
180 UK). The instruments were installed 2 m above ground (except the raingauge, which was set  
181 up at 1 m) and were connected to a CR10X data-logger (Campbell Scientific, USA).



182 Variables were samples at 1 Hz and stored as 30-minute averages. All of the instruments were  
183 either new or recently new and had been calibrated by the manufacturer.

184

185 The sensible and latent heat fluxes, soil heat flux and net radiation were measured with  
186 similar flux stations at fields A and C. The instruments for each flux station are listed in  
187 Table 1. Because the CR23X data-logger has a limited storage capacity, the raw sonic  
188 anemometer and krypton hygrometer data were collected at a 10 Hz frequency and stored on  
189 the LoggerNet final storage area #2 of the CR23X data-logger. These raw data were then  
190 downloaded every minute to a laptop through the RS232 serial port. The instruments on Field  
191 A in 2004 and on Field C in 2006 were three months old. On field A in 2006, the two-year-old  
192 krypton hygrometer did not operate.

193

194

[Table 1 about here]

195

196 The three soil heat flux sensors were distributed two metres away from the station, and  
197 were buried between 20 and 50 mm below the soil surface. The net radiometers were installed  
198 1.5 m above the ground. The sonic anemometers, the krypton hygrometers, and the air  
199 temperature and humidity probes were installed at the same height above the ground during  
200 each period of data acquisition: 1.96 m for Field A in 2004 (data set A04); 1.78 m for Field A  
201 in 2006 (dataset A06); and 2.02 m for Field C in 2006 (data set C06). The sonic anemometer  
202 verticality and the net radiometer horizontality were carefully checked during the experiments  
203 with spirit levels, but no realignment needed to be performed. The accuracy of the double  
204 spirit level used for the Young sonic anemometer was 0.5 mm/m, corresponding to an angle  
205 of 0.03°. Accuracy on the integrated spirit level of the CSAT sonic anemometer was  
206 unknown. Overall, we assumed the accuracy on device alignment was better than 1°. This  
207 proposed accuracy was further indirectly confirmed when comparing the flow inclination  
208 captured in 2004 and 2006 by the EC device on the same location within Field A. Indeed, the  
209 differences between both years were less than 2° (Section 3.3.2) (Fig. 8a and 8b).

210

211 The alternation between the dry and wet periods degraded the krypton hygrometer  
212 KH20. As a result, the KH20 did not operate in 2006 at Field A, and no latent heat flux data  
213 were collected for the data set A06. The data acquisition systems were powered by batteries

214 and solar panels. Because of the high power consumption of the laptop computers, several  
215 battery failures occurred, and the 10 Hz data acquisitions were not continuous. Furthermore,  
216 only daytime data were considered for analysis in the context of quantifying  
217 evapotranspiration. The daytime periods were defined by the 30-minute intervals during  
218 which the positive values of solar irradiance were measured. After gap removal and daytime  
219 observation selection, the numbers of 30-minute intervals with 10 Hz data acquisition were  
220 375, 463 and 579 for data sets A04, A06 and C06, corresponding to 10%, 25% and 30% of  
221 the experiment durations, respectively.

222

### 223 **2.3 Calculation of net radiation and soil heat flux**

224

225 A side-by-side comparison of NR-lite net radiometer measurements was conducted  
226 during one month over a natural grass field. This comparison was aimed at ensuring that both  
227 the measurements and the subsequent behaviour on the two opposite rims of the V-shaped  
228 catchment could be cross-analysed. The comparison of the net radiation data indicated a root  
229 mean square difference of  $20 \text{ W m}^{-2}$  (5% relative). This difference was notably close to the  
230 instrument accuracies. Thus, no correction was applied.

231

232 Measurements of net radiation ( $R_n$ ) were corrected for the effects of slope following  
233 the procedure proposed by Holst et al. (2005). Only the direct solar irradiance was corrected  
234 by accounting for the angle between the solar direction and the normal to the local  
235 topography. The solar direction was derived from time, latitude and longitude with  
236 astronomical rules. The local topography was characterised by the slope (topographical zenith  
237 with nadir as origin) and aspect (topographical azimuth with north as origin). Both the slope  
238 and aspect were calculated using a four-metre spatial resolution DEM obtained by  
239 photogrammetry from a stereo pair of panchromatic Ikonos images (Raclot and Albergel,  
240 2006). The direct solar irradiance was derived from total solar irradiance measured at the  
241 meteorological station (Section 2.2). For this, the diffuse solar irradiance was expressed as an  
242 empirical function of atmospheric transmittance; the latter was estimated as the ratio of the  
243 solar irradiance measured at the meteorological station to the extra-terrestrial solar irradiance  
244 derived from the astronomical rules. The empirical function was calibrated beforehand over  
245 the ReSeDA meteorological database that is representative of typical Mediterranean climates

246 (Oliosio et al., 2002b). The obtained calibration was notably close to that proposed by  
247 Collares-Pereira and Rabl (1979) and used by Holst et al. (2005).

248

249 The average correction of the net radiation measurements for slope effects was  
250 approximately  $40 \text{ W m}^{-2}$  (12% relative) and  $55 \text{ W m}^{-2}$  (15% relative) for fields A and C,  
251 respectively, as indicated by the root mean square differences between corrected and non-  
252 corrected data. The maximum corrections reached  $60 \text{ W m}^{-2}$  for Field A and  $100 \text{ W m}^{-2}$  for  
253 Field C, and they corresponded to the sunrise or sunset. On average, the corrections induced  
254 an increase (respectively decrease) of net radiation measurements on Field A (respectively C).  
255 Such between-field differences can be explained by field aspects, because Field A  
256 (respectively C) faced the south-southeast (respectively northwest) direction (Section 2.1).

257

258 The measurements of soil heat flux ( $G$ ) are usually corrected for the heat storage  
259 between the surface and the sensors (Heusinkveld et al., 2004; Liebenthal et al., 2005).  
260 However, no correction was performed here because the existing solutions are questionable  
261 when considering swelling soils that exhibit shrinkage cracks under dry conditions during the  
262 summer (Section 2.1). Neglecting the heat storage induced errors in the soil heat flux  
263 measurements of between  $20$  and  $50 \text{ W m}^{-2}$  (20% to 50% relative), as reviewed by Foken  
264 (2008). It was a posteriori verified when analysing the energy balance closure that such errors  
265 in soil heat flux were not critical (Section 3.4). Finally, soil heat flux was estimated as the  
266 mean value of the measurements collected by the three soil heat sensors distributed around  
267 each of the two stations.

268

#### 269 **2.4 Calculation of the EC-based convective fluxes and airflow inclinations**

270

271 The three convective fluxes (friction velocity  $u_*$ , sensible heat flux  $H$  and latent heat  
272 flux  $\lambda E$ ) and the angles for characterising the airflow inclinations were calculated from the  
273 10 Hz data collected with the sonic anemometer and the krypton hygrometer with the  
274 ECPACK library version 2.5.22 (<http://www.met.wau.nl/projects/jep/report/ecromp/>, van Dijk  
275 et al., 2004). We present hereafter the different steps of the calculations. We note  $u_*$  was used  
276 for both controlling the data quality and calculating the EC data footprint.

277

#### 278 2.4.1 Instrumental corrections

279

280 The entire set of instrument corrections proposed in the aforementioned version of the  
281 ECPACK library was applied. These corrections addressed the following items: (1) the  
282 calibration drift of the krypton hygrometer with the air humidity and temperature measured by  
283 the HMP45C probe over each 30-minute interval; (2) the linear trends over the 30-minute  
284 intervals; (3) the sonic anemometer temperature for humidity; (4) the hygrometer response for  
285 oxygen sensitivity; (5) the mean vertical velocity (Webb term); and (6) the correction for the  
286 frequency response (spectral loss) and path averaging. In relation to a low measurement  
287 height of approximately 2 m above surface level (Section 2.2), the correction for the  
288 frequency response increased the flux magnitudes by  $0.01 \text{ m s}^{-1}$  (2% relative),  $10 \text{ W m}^{-2}$  (5%  
289 relative) and  $5 \text{ W m}^{-2}$  (8% relative) for  $u_*$ , H and  $\lambda E$ , respectively. The resulting convective  
290 fluxes were labelled NR for Non-Rotated.

291

292 A side-by-side comparison of the EC device measurements was conducted during one  
293 month within Field A. This comparison aimed at ensuring it was possible to compare the  
294 measurements and subsequent behaviour on the two opposite rims of the V-shaped catchment.  
295 The comparison of convective flux data indicated a root mean square difference of  $20 \text{ W m}^{-2}$   
296 (15% relative). This difference was close to the accuracy of the EC data, which are widely  
297 accepted to be between 20 and  $50 \text{ W m}^{-2}$  for the latent heat and between 10 and  $30 \text{ W m}^{-2}$  for  
298 the sensible heat flux, which corresponds to 5–20% relative (Foken, 2008). Thus, no  
299 correction was applied.

300

#### 301 2.4.2 Rotational corrections and airflow inclination

302

303 The sonic anemometers were installed vertically, although the sloping conditions were  
304 suspected to induce non-horizontal airflows. The rotational corrections were applied to correct  
305 the fluxes for the airflow inclination, as explained hereafter.

306

307 The three-dimensional sonic anemometers measure wind speed in three perpendicular  
308 directions (labelled  $u$  and  $v$  in the horizontal plane and  $w$  in the vertical). When estimating the  
309 convective fluxes from the EC measurements, the rotations are usually applied to the

310 coordinate system (Kaimal and Finnigan, 1994). Over flat terrain, the aim is to account for the  
311 incorrect vertical alignment of the sonic anemometer. Over slopes, the aim is to virtually align  
312 the sonic anemometer perpendicularly to the airflow streamlines (Geissbühler et al., 2000;  
313 Humphreys et al., 2003; Lewicki et al., 2008). These rotations are usually defined by three  
314 angles: the yaw angle, which is a rotation around the vertical axis that aligns  $u$  with the wind  
315 direction; the pitch angle, which is a rotation around the horizontal axis perpendicular to the  
316 wind direction that sets  $w$  to zero; and the roll angle, which is a rotation around the horizontal  
317 axis parallel to the wind direction.

318

319       Amongst the existing possibilities for performing rotational corrections, we selected  
320 the planar fit correction introduced by Wilczak et al. (2001) and implemented in the ECPACK  
321 library. This method has been recommended by several authors (Massman and Lee, 2002;  
322 Turnipseed et al., 2003; Lee et al., 2004) for correcting EC measurements acquired over  
323 sloping terrain. Assuming the airflow streamlines are included in a plane, the latter is fitted to  
324 a set of wind speed components collected over a long time interval, typically ranging from  
325 one to several days. Thus, the planar fit correction is less sensitive to the sampling errors than  
326 the double and triple rotation corrections (Turnipseed et al., 2003), where the latter are applied  
327 to each integration interval (30 minutes in our case). Because the current study focused on the  
328 daytime data, the planar fit correction did not suffer from uncertainties resulting from low  
329 night-time wind speeds.

330

331       Over heterogeneous terrain that induces anisotropic airflow, the tilt angles (pitch and  
332 roll) are likely to depend upon the wind direction (yaw angle). Consequently, the airflow  
333 inclination for various wind directions cannot be adequately represented by a single plane  
334 only. The 10-Hz EC data were therefore grouped according to wind direction (or wind  
335 sectors). Two calculations were made to ensure that the planar fit angles were not sensitive to  
336 the time interval over which they were estimated. A single plane was fitted over all of the data  
337 belonging to a wind sector for a given data set (A04, A06, and C06). Additionally, for a given  
338 field (A or C), one plane was fitted for each wind sector and each day. We a posteriori  
339 verified that considering these two methods provided similar results for airflow inclination, as  
340 captured with planar fit angles (Section 3.3) and flux magnitude (Section 3.4).

341

342 The planar fit provided the inclination angles of the plane that fitted the wind speed  
343 components over a given time interval in which the angles are in a coordinate system fixed to  
344 the anemometer. For a given plane inclination provided by the planar fit angles, along with  
345 the anemometer orientation that had previously been determined when setting up each flux  
346 station, it was possible to calculate the airflow inclination for any wind direction, including  
347 those that corresponded to the yaw angle measurements.

348

349 Finally, the planar fit angles calculated at the daily timescale for each wind sector were  
350 introduced into the planar fit correction of the fluxes, and the resulting convective fluxes  
351 calculated over 30-minute intervals were labelled PF (Planar Fit).

352

### 353 2.4.3 Quality control

354

355 The quality control of the 30-minute flux data was performed using two standard tests  
356 that are routinely employed over sloping terrains. These tests ensure that the theoretical  
357 requirements for the EC measurements are fulfilled (Geissbühler et al., 2000; Rebmann et al.,  
358 2005; Hammerle et al., 2007, Hiller et al., 2008).

359

360 The steady-state (ST) test (Foken and Wichura, 1996) characterises the turbulence  
361 time homogeneity for the three convective fluxes. This test compares the average flux values  
362 over each 30-minute interval with the averaged values over the six corresponding 5-minute  
363 subintervals. The integral turbulence characteristics (ITC) test (Foken and Wichura, 1996;  
364 Rebmann et al., 2005) characterises the development of turbulence and therefore the spatial  
365 homogeneity in terms of the surface aerodynamic properties. For that characterisation, the test  
366 compares the measured flux-variance similarities to those obtained from the empirical models  
367 based on Monin-Obukhov similarity theory. Over each 30-minute interval, the flux-variance  
368 similarities are tested for the horizontal wind speed  $u$ , vertical wind speed  $w$  and air  
369 temperature  $T$ .

370

371 Both the ST and the ITC tests are expressed as absolute values of the relative  
372 differences. These tests allow the data to be ranked (Foken et al., 2004; Rebmann et al.,  
373 2005): the high-quality turbulence data (test values less than 0.3); good quality data for the

374 flux measurements (test values between 0.3 and 1.0); and low-quality data (test values greater  
375 than 1.0).

376

#### 377 2.4.4 Footprint of the EC fluxes

378

379 Quantifying the area that contributed to each flux measurement – the so-called  
380 footprint area – was an important step for characterising the representativeness of the  
381 measured fluxes. This step was also important for analysing any topographical influence on  
382 the flux measurements because this analysis required the knowledge of the relief within the  
383 contributing areas.

384

385 The footprint of each 30-minute sample of the EC flux data was estimated using the  
386 approach of Horst and Weil (1994), which relies on an analytical dispersion model that  
387 accounts for the effects of atmospheric stability. The Horst and Weil model offered a good  
388 compromise between ease of implementation and estimate reliability. Furthermore, the  
389 assumption of the spatial uniformity and temporal constancy of the surface roughness in the  
390 Horst and Weil model was well-fulfilled during the experiment because (1) each field and all  
391 surrounding plots were bare soil only, and (2) the flux data were filtered using the ST and ITC  
392 tests (see Section 2.4.3). For each flux estimate derived from the EC data via the ECPACK  
393 library, the footprint area was calculated from the outputs of the Horst and Weil model as the  
394 ellipsoid from which 90% of the flux originated. Each footprint ellipsoid was characterised by  
395 its length (respectively width) along (respectively across) the wind direction. The footprint  
396 ellipsoids were then combined with the digital map of the field boundaries (Fig. 3) to quantify  
397 the proportion of the measured fluxes that originated from the field on which the flux station  
398 was installed (field A or C).

399

400

401

#### 402 **2.5 Evaluation of the topographical slopes for the flux measurements**

403

404 To understand the effects of relief on the energy fluxes, the topography near each flux  
405 station needed to be characterised, especially within the footprint area. Because the wind

406 direction fluctuated on a scale of 10 to 30 minutes, the terrain slopes for the dominant wind  
407 directions needed to be evaluated within these time intervals. Thus, we calculated the terrain  
408 slopes for all wind directions. The procedure was twofold.

409

410 First, we defined a rectangle centred on the flux station and oriented along a given  
411 wind direction (yaw angle). The rectangle width was set to twice the median value of the  
412 footprint width (the ellipsoid width across the wind direction, Section 2.4.4) and its length  
413 was set to twice the median value of the footprint length (ellipsoid length along wind  
414 direction, Section 2.4.4). We considered the median values of the footprint dimension twice to  
415 account for the influence of the upstream / downstream relief on the flow structure. Once each  
416 rectangle was defined, we extracted the corresponding altitude data from the DEM  
417 (Section 2.3), and a topographical plane was fitted against the DEM data (i.e., the altitude  
418 versus northing and easting coordinates). The topographical plane equation was next used to  
419 calculate two terrain slopes geometrically similar to the angles given by the rotational  
420 correction (Section 2.4.2): the along-wind slope corresponded to the pitch angle, and the  
421 across-wind slope corresponded to the roll angle.

422

423 The above approach was chosen for three reasons: (1) it defined a wind-oriented  
424 topography (along and across slopes); (2) these slopes were evaluated in a similar way to the  
425 rotational correction characterising the airflow inclination; and (3) it accounted for the spatial  
426 extent of the footprint area. The choice of a rectangle instead of an ellipsoid simplified the  
427 calculations.

428

### 429 **3. RESULTS**

430

431 In this section we first analysed the meteorological data to characterise the  
432 micrometeorological conditions, including the wind and convection regimes (Section 3.1).  
433 Secondly, we analysed the results of the flux data quality control and the footprint estimates  
434 (Section 3.2). Thirdly, we characterised the DEM-derived topographical slopes according to  
435 the wind direction and then compared them against the airflow inclinations derived from the  
436 rotational corrections of the EC data (Section 3.3). We finally addressed energy balance



437 closure (Section 3.4). These analyses were conducted by comparing the results obtained on  
438 the two opposite rims of the catchment (e.g., over fields A and C).

439

### 440 **3.1 Climatic conditions**

441

#### 442 3.1.1 Wind regime

443

444 The data from the meteorological station showed large wind speed values with a mean  
445 daytime value of  $4 \text{ m s}^{-1}$  that was twice as large as the FAO mean value for more than 2000  
446 sites around the world (Allen et al., 1998). These wind speed measurements closely agreed  
447 with those collected by the sonic anemometers within fields A and C – the differences were  
448 less than  $1 \text{ m s}^{-1}$ . This wind speed homogeneity was observed in previous studies conducted at  
449 different locations within the Kamech catchment (Zitouna-Chebbi, 2009).

450

451 Fig. 4 presents the wind roses obtained from the data collected at the meteorological  
452 station. These wind roses clearly show the existence of two dominant directions: winds  
453 coming either from the northwest or from the south (actually south-southeast). This bi-modal  
454 regime of northwest and south winds was observed throughout the experiment (years 2004  
455 and 2006). At the daily timescale, no diurnal cycle was observed for the wind direction.

456

457 [Figure 4 about here]

458

459 To seek possible influences of wind direction on the turbulent fluxes, we distinguished  
460 two dominant wind direction classes according to the observations displayed in Fig. 4  
461 (clockwise degrees, north is  $0^\circ$ ): winds coming from directions between the southwest ( $220^\circ$ )  
462 and east-northeast ( $70^\circ$ ), known hereafter as the northwest winds; and winds coming from the  
463 other directions, known hereafter as south winds. For both 2004 and 2006, the proportions of  
464 the northwest and south winds were 70% and 30%, respectively. These two dominant  
465 directions were almost perpendicular to the valley axis (Fig. 2). Therefore, the northwest  
466 winds induced simultaneous downward flows on the northern rim (Field A) and upward flows  
467 on the southern rim (Field C). The reverse was observed with the south winds.

468

### 469 3.1.2 Micrometeorological conditions

470

471 As is typical for summer in the study site, rainfall amounts were notably low during  
472 the experiments with a total amount of 1.5 mm for the data sets A06 and C06. A larger value  
473 (81 mm) was observed for data set A04 because the experiment lasted until the beginning of  
474 autumn (Section 2.1). The reference evapotranspiration ( $ET_0$ ) was calculated from the data  
475 collected at the meteorological station by following Allen et al. (1998). For the data set A04  
476 (respectively A06 and C06), the  $ET_0$  ranged between 1.4 and 10.4 mm per day (respectively  
477 4.7 and 10.3 mm per day), with a mean value of 4.6 mm per day (respectively 6.6 mm per  
478 day).

479

480 As expected for the day-time measurements under windy conditions (Section 3.1.1),  
481 the Monin-Obukhov stability parameter (MOSP) was always negative, with notably few  
482 values less than -0.1. For the northwest (respectively south) winds, the MOSP median values  
483 were -0.042, -0.053 and -0.057 (respectively -0.059, -0.022 and -0.022) for the datasets A04,  
484 A06 and C06. These values corresponded to the conditions of neutrality or low instability.

485

## 486 **3.2 Quality control and footprints of the EC data**

487

### 488 3.2.1 Quality control of the EC data

489

490 The results of the quality control test in Table 2 are given for the EC flux data after the  
491 rotational correction. On average, 90% of the  $u_*$  and H fluxes reached the first quality class  
492 for both the ST and ITC tests. For the latent heat flux, 70% of the data reached the first quality  
493 class. The good results obtained with the ST test a posteriori justified the integration of the EC  
494 data over the 30-minute intervals. The good results obtained with the ITC test showed that the  
495 surface aerodynamic properties were spatially homogeneous near the flux stations, which was  
496 in agreement with the bare soil conditions observed throughout the catchment during the  
497 experiments.

498

499

[Table 2 about here]

500

501           The current study addressed the energy fluxes under sloping conditions within a hilly  
502 catchment in the context of operationally monitoring crop water consumption under a semi-  
503 arid climate. Thus, only the data belonging to the first two quality classes (ST and ITC test  
504 values less than 1.0) were selected for further investigation. This represented 99% of the  $u_*$   
505 and H fluxes and 76% of the  $\lambda E$  fluxes. Finally, we note applying rotational corrections  
506 induced larger amounts of data fitting the quality control test, where the number of rotated  
507 data in the first two quality classes increased by 40% relative to the number of non-rotated  
508 data.

509

### 510 3.2.2 Footprints of the EC fluxes

511

512           The footprint areas were calculated using the EC flux data after the rotational  
513 correction. For each 30-minute interval, the calculated footprint areas were superimposed on  
514 the field map (Fig. 3), which allowed an evaluation of the percentage of fluxes originating  
515 from the considered field. On average and regardless of wind direction, 55% (respectively  
516 60%) of the flux measurements originated from Field A in 2004 (respectively 2006) and 80%  
517 originated from Field C in 2006. Although these fields were selected as the best locations  
518 within the catchment, these contributions were found to be moderate. However, this result  
519 was not considered to be a critical issue because the surface conditions of the surrounding  
520 fields were similar (bare soils), which was confirmed by the good results obtained with the  
521 ITC test (Section 3.2.1).

522

523           The mono-modal distributions of the lengths and widths of the ellipsoid-shaped  
524 footprints are given in Fig. 5. The median values of the footprint lengths were 208 m, 180 m  
525 and 182 m for the A04, A06 and C06 data sets, respectively. The median values of the widths  
526 were 62 m, 58 m and 58 m for the A04, A06 and C06 data sets, respectively. No significant  
527 influence from the wind directions (northwest and south) was observed for the footprint  
528 dimensions, with the differences between median lengths being less than 15% relative. This  
529 was expected because the micrometeorological conditions did not significantly vary with the  
530 wind direction.

531

532

[Figure 5 about here]

533

### 534 **3.3 Influence of the topography on the airflow inclination**

535

#### 536 3.3.1 Determination of the terrain slopes from DEM data

537

538 According to the results from Section 3.2.2, the length of the rectangles used to  
539 determine the terrain slopes from the DEM-based altitude data was fixed at 360 m, which is  
540 twice the median value of the ellipsoid footprint lengths. The width of these rectangles was  
541 fixed to 120 m, which was twice the median of the ellipsoid footprint widths.

542

543 The fitting of the terrain slopes for the south winds (yaw angle =  $180^\circ$  from north  
544 clockwise) and the northwest winds (yaw angle =  $320^\circ$  from north clockwise) are illustrated  
545 in Fig. 6, where the slanted thick lines represent the pitch angle calculated over the 360-m  
546 long and 120-m wide rectangles (Section 2.5).

547

548 [Figure 6 about here]

549

550 In the vicinity of Field A, the topography at the 360-m scale appeared to be almost  
551 planar for both the south and northwest winds. The top of the northern rim, which  
552 corresponded to the catchment northwest limit (see Fig. 2), formed a sharp hill that is clearly  
553 visible on Fig. 6 for the south winds (right vertical arrow at  $x = 290$  m on top left subplot) and  
554 for the northwest winds (left vertical arrow at  $x = -270$  m on top right subplot). Field C had a  
555 rugged relief with more dispersion of the altitude data and a less planar shape, especially for  
556 the south winds. The hilltop at the field southern limit ( $x = -300$  to  $-200$  m on the bottom left  
557 subplot,  $x = 150$  m on the bottom right subplot) was rugged compared to the top of the  
558 northern rim. The catchment southern limit was located 700 m south from Field C (left  
559 vertical arrow on bottom left subplot, and right vertical arrow on bottom right subplot).

560

561 Following the illustrations from Fig. 6, the negative (respectively positive) angles  
562 were allocated to the downward (respectively upward) flows. Fig. 7 displays the evolution of  
563 the topographical pitch terrain slope and roll terrain slope with respect to the yaw angle. On  
564 Field A, the pitch and roll terrain slopes ranged from 0 to  $5.2^\circ$  in absolute value, whereas they

565 ranged from 0 to 8.5° in absolute value on Field C, indicating a larger slope. As expected, the  
566 pitch and roll terrain slopes were in phase quadrature for both fields. For a given field, we  
567 observed different shapes for the pitch and roll curves. This finding was explained by the use  
568 of a rectangle when extracting the DEM data to calculate the terrain slopes (Section 2.5 and  
569 3.2.2), where the pitch angle corresponded to the rectangle length, whereas the roll angle  
570 corresponded to the rectangle width. The quasi-sinusoidal shape observed for both the pitch  
571 and roll terrain slopes on Field A confirmed its almost planar shape, whereas the more  
572 complex evolution of the roll terrain slope on Field C corresponded to its rugged relief, as  
573 already observed in Fig. 6.

574

575 [Figure 7 about here]

576

577 3.3.2 Comparison of the EC-based flow inclination against the DEM-based terrain slopes

578

579 The planar fit angle calculation for a given data set (A04, A06 and C06) was twofold,  
580 either fitting a single plane over all of the data belonging to a wind sector (northwest or south)  
581 or fitting a plane for each wind sector and each day (Section 2.4.2). The first calculation  
582 yielded two planes corresponding to the northwest and south sectors for each data set. When  
583 fitting a plane for each wind sector and each day, this calculation yielded between seven and  
584 23 daily planes in accordance with the number of 30-minute intervals of 10-Hz data collected  
585 (Section 2.2).

586

587 Fig. 8a and 8b display the evolution of the pitch and roll angles according to the yaw  
588 angle when comparing the estimates from the DEM data and from the planar fit rotational  
589 correction of the EC data. The continuous lines correspond to the DEM-derived topographical  
590 slopes (Section 3.3.1). The discontinuous (dashed or dotted in accordance with year) lines  
591 correspond to the planar fit derived slopes when considering a unique plane fitted over all data  
592 belonging to a wind sector (northwest or south) for a given data set. In this case, pitch and roll  
593 angles are calculated from the fitting plane by setting a 1° step range of the yaw angle values  
594 that spread over the corresponding wind sector. The points are related to the planar fit-derived  
595 slopes when considering each wind sector and each day.

596

597 [Figure 8a about here]

598

599 [Figure 8b about here]

600

601 For each data set (A04, A06, C06) and each wind sector (northwest, south) the planar  
602 fit estimates of pitch angles at the daily scale (symbols) were in close agreement with those  
603 calculated over the entire data sets (portions of broken curves). This result was explained by  
604 the bare soil conditions during the experiments, inducing little or no variation of the surface  
605 roughness. Thus, the daily evaluation of the planar fit-derived pitch angles appeared to be  
606 stable. For the planar fit-derived roll angles, a lower but correct agreement was observed  
607 between daily estimates and the averaged values over the experiment.

608

609 For the upward flows (positive values of the pitch angles), Fig. 8a shows an excellent  
610 agreement between the pitch slope estimates from the planar fit correction and from the DEM  
611 data. This agreement indicated that the airflow inclination, as captured by the planar fit  
612 correction, followed the along-wind topographical slope deduced from the DEM data. As  
613 indicated by the discontinuous lines, the differences between 2004 and 2006 for Field A were  
614 within  $1.5^\circ$ . For the downward flows (negative values of the pitch angles), the agreement was  
615 also excellent on Field C. A different behaviour was observed on Field A, where the planar  
616 fit-derived pitch angles were close to nil, varying between  $-2.5^\circ$  and  $+1^\circ$  in 2004 and between  
617  $-1^\circ$  and  $0^\circ$  in 2006. The inclination flow, as captured by the planar fit correction of the EC  
618 data, thus appeared to be almost horizontal.

619

620 Notably similar findings were found when comparing the roll angles deduced from the  
621 planar fit correction to those calculated from the DEM data, as observed on Fig. 8b. On Field  
622 C, the planar fit roll angles were in close agreement with the topography (within  $2^\circ$ ) for all of  
623 the wind directions and for a large range of topographic slopes ( $\pm 7^\circ$ ). On Field A, the planar  
624 fit roll angles were in good agreement with the topography (within  $3^\circ$ ) under the upward  
625 flows and were close to nil (between  $-2^\circ$  and  $+3.6^\circ$ ) under the downward flows. The  
626 difference between the planar fit roll angles obtained in 2004 and 2006 remained less than  $3^\circ$ .

627

628 Summarising the observations reported above: for the upward flows, the airflow pitch  
629 (respectively roll) angles, as captured by the planar fit correction of the EC data, were in close  
630 agreement with the topographical slope along (respectively across) the wind direction. For the  
631 downward flows, the airflow pitch and roll angles were in close agreement with the  
632 topographical slopes on Field C, whereas they tended toward being horizontal on Field A.

633

### 634 **3.4 Energy balance closure**

635

636 We analysed the energy balance closure by comparing the sum of convective energy  
637 ( $H+\lambda E$ ) against the available energy ( $R_n-G$ ). The convective fluxes were those obtained from  
638 the EC flux data after the rotational correction. Although the usefulness of such analysis as a  
639 quality test may be debatable (Lee et al., 2004), it was considered an interesting comparison  
640 of the independent measurements. The data to be compared were those calculated over the 30-  
641 minute intervals (Section 2.2 and 2.4.2).

642

643 Given that no latent heat flux data were collected for the data set A06 because of the  
644 krypton hygrometer inoperability, the energy balance closure could be analysed only for the  
645 data sets A04 and C06. This issue was not critical because the previous observations noted for  
646 the A06 data set were nearly identical to those noted for the A04 data set, when comparing the  
647 planar fit angles against the terrain slopes (3.4.2). Next, the number of data involved in the  
648 energy balance closure analysis resulted from several filters. First, the convective flux data  
649 were filtered with quality control (Section 3.2.1). Second, an additional filter consisted of  
650 removing the data that corresponded to the negative values for the available energy. Finally,  
651 the number of available observations for assessing the energy balance closure was constrained  
652 by the smallest data set among the net radiation, soil heat flux, sensible and latent heat flux.

653

654 The energy balance closure is graphically presented in Fig. 9, and the corresponding  
655 statistics are given in Table 3. The energy balance closure, as expressed through the energy  
656 balance ratio, ranged between 87 and 95%, with the exception of one case (the downward  
657 flows on Field C in 2006) that corresponds to 73%. Regardless of the considered case (A04  
658 and C06 data set, the upward and downward flows), the energy balance closure was  
659 comparable to those found in the literature under various conditions, such as vegetated

660 canopies and bare soils under flat and mountainous conditions (Wilson et al., 2002; Hammerle  
661 et al., 2007; Foken, 2008). We also observed from our data set that the available energy  
662 systematically overestimated (respectively underestimated) the convective energy for large  
663 (respectively low) values, which was also in agreement with the aforementioned literature.

664

665 [Figure 9 about here]

666

667 [Table 3 about here]

668

669 The 20–50 W m<sup>-2</sup> error for the soil heat flux that resulted from neglecting the heat  
670 storage between the surface and plates (Section 2.3) was not considered to be a critical issue.  
671 Indeed, the resulting error had the same magnitude as the measurement uncertainty resulting  
672 from the instrumental errors and spatial variability (Stannard et al., 1994; Kustas et al., 2000;  
673 Olioso et al., 2002b; Shao et al., 2008). Most importantly, the energy balance closure reported  
674 in this study was similar to those reported in previous studies that accounted for the heat  
675 storage when measuring the soil heat flux (Wilson et al., 2002; Hammerle et al., 2007; Foken,  
676 2008).

677

678 When analysing the energy balance closure as a function of the upward and downward  
679 flows, the results for the energy balance closure were similar on Field A, but they were better  
680 for the upward flow compared to the downward flow on Field C. On Field A, the systematic  
681 errors were similar for the upward and downward flows with similar slope and offset values  
682 for the linear regression of the convective energy against the available energy. The random  
683 error was smaller for the upward flows (unsystematic root mean square error of 39.6 W m<sup>-2</sup>  
684 versus 47.4 W m<sup>-2</sup>), but the energy balance residual (difference between available and  
685 convective energy) was smaller for the downward flows (12.2 W m<sup>-2</sup> versus 32.7 W m<sup>-2</sup>). On  
686 Field C, the random error was larger for the upward flows (unsystematic root mean square  
687 error of 34.9 W m<sup>-2</sup> versus 25.6 W m<sup>-2</sup>), but the systematic error and the energy balance  
688 residual were larger for downward flows (slope value of 0.64 versus 0.73; energy balance  
689 residual of 81.2 W m<sup>-2</sup> versus 26.9 W m<sup>-2</sup>). The most important result for Field C was the  
690 magnitude of the energy imbalance for the downward flows, approximately 27%, compared to  
691 the other values, which ranged between 5% and 13%.



692

693 We finally analysed the impact of the rotational corrections on the energy balance  
694 closure to compare with previously published results. We expected our findings to increase  
695 our confidence in the EC measurements performed under the conditions of hilly topography.  
696 The planar fit correction increased the convective fluxes for the upward flows (between 5 and  
697  $50 \text{ W m}^{-2}$  depending on the field, year and convective flux), whereas it decreased the  
698 convective fluxes for the downward flows, especially on Field C (by as much as  $90 \text{ W m}^{-2}$ ).  
699 As expected, the magnitude of the planar fit correction was linked with the magnitude of the  
700 airflow inclination. Indeed, the horizontal airflows for the downward flows on Field A  
701 corresponded to the negligible planar fit correction for the convective fluxes. Furthermore, the  
702 planar fit correction was similar for the flux magnitude when comparing the two methods that  
703 we considered for calculating planar fit angles (Section 2.4.2), with differences of less than  
704  $10 \text{ W m}^{-2}$  being observed. Finally, the energy balance closure was systematically improved  
705 after the planar fit correction (increase of EBR ratio values from 0.8 to 0.92 on average) apart  
706 from the downward flows on Field C.

707

#### 708 **4. DISCUSSION**

709

710 For the wind regime, we had notably different findings when addressing the sloping  
711 effects within the Kamech hilly agricultural catchment compared to the previous studies that  
712 addressed slope effects within mountainous areas (Hammerle et al., 2007; Hiller et al., 2008).  
713 We did not observe the diurnal cycle of wind direction, anabatic and katabatic winds that  
714 blew up and down the slopes or the valley winds that followed the longitudinal axis of the  
715 catchment. This finding suggested the wind regime was externally driven and did not depend  
716 upon the local topography. We observed large wind speed values, which may be explained by  
717 the location of the catchment near the extremity of the Cap Bon Peninsula. The large wind  
718 speed values were in agreement with the micrometeorological data that indicated the  
719 dominant regimes of forced convection along with the conditions of near-neutrality or low  
720 instability.

721

722 When comparing the inclination flow derived from the planar fit correction of the EC  
723 measurements against the topographical slopes derived from the DEM data, different

724 situations were observed. For the upward flows, the planar fit angles were in notably good  
725 agreement with the topographical slopes, which indicated that the airflow followed the terrain  
726 slope along the wind direction. This result was observed on both fields A and C with the  
727 different EC devices (Section 2.2) and on Field A for two different years (2004 and 2006).  
728 For the downward flows, the planar fit angles were either in good agreement with the  
729 topographical slope for Field C or were close to nil for Field A.

730

731         The differences we observed between the upward and downward flows were not  
732 ascribed to the differences in the meteorological or micrometeorological conditions. Because  
733 the EC data were collected over two opposite sides of the watershed, the upward flows on a  
734 given side correspond to the downward flows on the opposite side for the same  
735 meteorological conditions and wind direction.

736

737         The verticality of the EC devices could not be set and controlled numerically.  
738 Nevertheless, the resulting inaccuracy of the alignment of the EC devices could not weaken  
739 the findings on the change in flow inclination according to the upward and downward flows.  
740 First, the same behaviour was observed in Field A in 2004 and 2006, where the agreement  
741 between the flow inclination and topographical slope was good despite small differences in  
742 the flow inclination between 2004 and 2006 (Fig. 8a and 8b). Second, the error of the  
743 alignment for each EC device did not affect the relative difference between the flow  
744 inclination for the upward and downward flows; this difference remained unchanged  
745 regardless of the EC alignment.

746

747         When comparing the airflow inclinations against the topographical slopes for the  
748 downward flows, the abovementioned differences between fields A and C were ascribed to  
749 the topographical conditions. The hillslope geometries were different because Field A  
750 depicted a twofold-lower ratio of the altitude difference to the length (0.1 versus 0.2) (Fig. 6),  
751 where this ratio is similar to the ratio of height to the half-length commonly used to  
752 characterise the flows over hills (Raupach and Finnigan 1997, Finnigan and Belcher 2004).  
753 These differences in the hillslope geometries were combined with differences in the locations  
754 of the EC flux stations within the hillslopes, closer to the rim top than to the valley bottom on  
755 Field A (top right subplot of Fig. 6 for northwest winds) and conversely for Field C (bottom

756 left subplot of Fig. 6 for south winds). Thus, the EC flux stations had different locations  
757 within the separation bubble that is characterised by the airflow variability (Raupach and  
758 Finnigan 1997, Belcher et al., 2008). Furthermore, asymmetry between the upward and  
759 downward flows, as observed on Field A but not on Field C, was also reported by Finnigan  
760 and Belcher (2004). However, a comparison with the outcomes from such modelling studies  
761 should be substantiated. First, these modelling studies addressed the downward flows within  
762 the lee of the hill without any obstacle from the downstream topography. Second, the  
763 downward flows that we addressed in this study were in equilibrium with the downstream  
764 topography induced by the opposite rim of the catchment.

765

766         Apart from the downward flows of Field C, the energy balance closure was similar in  
767 all of the cases and improved after the application of the planar fit correction. Both findings  
768 were similar to those reported in the literature (Wilson et al., 2002, Hammerle et al., 2007;  
769 Foken, 2008). The available energy tended to overestimate the convective energy, as reported  
770 by Foken (2008). The worse results for Field C may be explained by the location of the EC  
771 flux station on the hillslope. Indeed, Finnigan (2004) suggested the location of the flux station  
772 relative to the hilltop is critical for flux accuracy, which depends upon the wind direction.

773

774         Overall, applying the rotational correction improved both the data filtering and the  
775 energy balance closure. This result was in agreement with the outcomes from other studies  
776 that mainly focused on flat or mountainous conditions. Such agreement was considered as an  
777 indicator of the data consistency and reliability. This is an important outcome for the data  
778 collected under these specific conditions that has been barely addressed until now (i.e., hilly  
779 topography).

780

781         Analysis of the results was conducted by differentiating the upward and downward  
782 flows. According to this analysis, the upward flows appeared to induce behaviours similar to  
783 those observed under flat conditions. Indeed, streamlines followed the local topography,  
784 whereas the energy balance was improved after the planar fit correction that increased the  
785 fluxes. Different behaviour was observed for the downward flows, possibly induced by the  
786 streamline dilatation and reverse circulation flow (Raupach and Finnigan 1997; Belcher et al.,  
787 2008). Furthermore, the results were worse for Field C, which may be explained by the

788 complex topography of the southern rim. First, the rugged topography may induce complex  
789 turbulence structures; second, the rugged topography induced differences in the solar heating  
790 for bare soils, which may result in horizontal advection.

791

## 792 **5. CONCLUDING REMARKS**

793

794 Hilly catchments are widespread throughout the world. In arid and semi-arid climates,  
795 they have socioeconomic implications with regard to water harvesting for agricultural  
796 production. Our understanding of surface fluxes within such areas must be improved in the  
797 context of operational monitoring and modelling for decision-support purposes. The current  
798 paper offered insights regarding energy fluxes from a hilly catchment under bare soil  
799 conditions, but further research is needed. Beyond the previous studies that addressed sloping  
800 terrain vegetated with tall canopies (e.g., forests); the fluxes over agricultural canopies must  
801 also be investigated. Indeed, vegetation is known to affect the pressure gradient associated  
802 with the flow over hills (Finnigan and Brunet, 1995, Finnigan and Belcher, 2004) and thus to  
803 influence the airflow and surface fluxes (Raupach and Finnigan, 1997; Turnipseed et al.,  
804 2003). Furthermore, these vegetation effects may combine with the topography and wind  
805 direction. Finally, the aerodynamic implications must be emphasised, where the roughness  
806 length should be revisited relative to the asymmetry between the upward and downward  
807 airflows, as suggested by Finnigan and Belcher (2004). This approach will enable the  
808 expansion of the recent modelling works (Rana et al., 2007) with implications for the  
809 operational FAO-56 method (Allen et al., 1998).

810

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812

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824

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1026 **Figure captions**

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1028 Figure 1: Location of Tunisia within the Mediterranean Basin (top); location the Kamech  
1029 catchment within the Cap Bon Peninsula, northeastern Tunisia (bottom left); and a three-  
1030 dimensional view of the Kamech catchment with the corresponding perimeter in white  
1031 (bottom right).

1032

1033 Figure 2: Topography of the Kamech catchment deduced from a 4-m spatial resolution digital  
1034 elevation model (DEM). Altitude above sea level is given in metres (right greyscale bar). The  
1035 thick black line represents the catchment outline. The altitude contour lines (thin black lines)  
1036 are drawn every 10 m. The positions of the meteorological station (M) and of the flux stations  
1037 on fields A and C are represented by the white circles.

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1039 Figure 3: Detailed view of the topography near fields A and C within the Kamech catchment.  
1040 Altitude above sea level is given in metres (right greyscale bar). The thick black lines  
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1042 The positions of the flux stations are represented by white circles.

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1044 Figure 4: Distribution of the wind direction throughout the experiment for the years 2004  
1045 (left) and 2006 (right). The two wind roses indicate the occurrence of wind speeds for 16 wind  
1046 directions.

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1048 Figure 5: Distributions of the footprint dimensions for the fields A (top line; datasets A04 and  
1049 A06 are merged) and C (bottom line; dataset C06). The footprint lengths (along the wind  
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1055 Figure 6: Determination of the wind-oriented topography for fields A (top line) and C (bottom  
1056 line), for the south winds (left column, yaw angle =  $180^\circ$  from north clockwise) and northwest  
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1058 derived altitude data extracted within a 120-m-wide rectangle, oriented along each wind  
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1063 plane was fitted against these altitude data for determining the wind oriented topographical  
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1065 wind (pitch) slopes calculated with a 360-m-long and 120-m-wide wind-oriented rectangle.  
1066 The insets are zoom-ins centred on each field, showing the local topography.

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1068 Figure 7: Evolution of the wind-oriented topography (along-wind slope – equivalent to pitch  
1069 angle – and across wind slope – equivalent to roll angles – on y-axis) with respect to the wind  
1070 direction (yaw angle as x-axis,  $0^\circ$  is north,  $90^\circ$  is east) for fields A (thick lines) and C (thin  
1071 lines). The solid lines represent the pitch angles, and the dashed lines represent the roll angles.  
1072 The slope angles are calculated with a  $1^\circ$  yaw angle step.

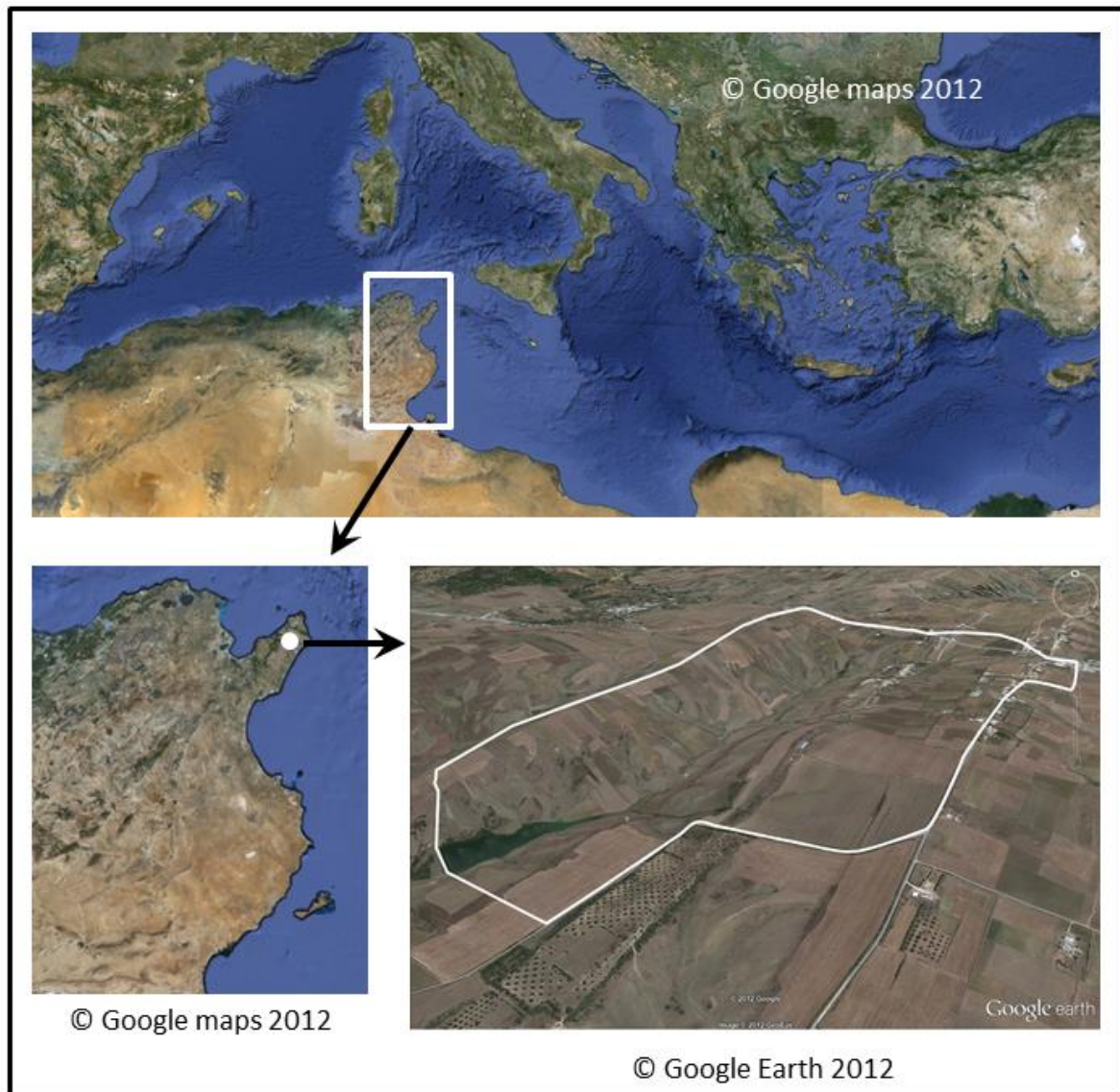
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1074 Figure 8a: Compared evolution of the planar fit derived pitch angles and the topographical  
1075 along-wind slopes (y-axis) with respect to the wind direction (x-axis,  $0^\circ$  is north,  $90^\circ$  is east)  
1076 for fields A (top) and C (bottom). The continuous curves represent the topographical along-  
1077 wind slope, as derived from the DEM data (same as Fig. 7). The planar fit-derived pitch  
1078 angles evaluated over the entire datasets (A04, A06, C06) and for each wind sector (south and  
1079 northwest) are represented by the portions of discontinuous curves (dotted lines for year 2004,  
1080 dashed lines for year 2006); they are labelled as the “PF mean pitch”. The planar fit-derived  
1081 pitch angles evaluated for each day and each wind sector are represented by symbols  
1082 (triangles for the year 2004, circles for the year 2006), where each symbol represents a day or  
1083 a portion of the day during which the wind direction was within a wind sector; they are  
1084 labelled as the “PF pitch”.

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1086 Figure 8b: Compared evolution of the planar fit derived roll angles and topographical cross-  
1087 wind slopes (y-axis) with respect to the wind direction (x-axis,  $0^\circ$  is north,  $90^\circ$  is east) for  
1088 fields A (top) and C (bottom). The continuous curves represent the topographical across-wind  
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1091 northwest) are represented by the portions of the discontinuous curves (dotted lines for the  
1092 year 2004, dashed lines for the year 2006); they are labelled as the “PF mean roll”. The planar  
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1095 a portion of the day during which the wind direction was within a wind sector; they are  
1096 labelled as the “PF roll”.

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1098 Figure 9: Energy balance closure for the datasets A04 (top line) and C06 (bottom line) and for  
1099 the upward winds (left column) and downward winds (right column). The available energy  
1100  $R_n - G$  ( $W m^{-2}$ ) is on the x-axis, and the convective energy  $H + LE$  ( $W m^{-2}$ ) is on the y-axis. The  
1101 data correspond to the 30-minute intervals. The dashed line is the 1:1 line, and the continuous  
1102 line is the y-axis data versus x-axis data regression line (regression coefficients are given in  
1103 Table 3).

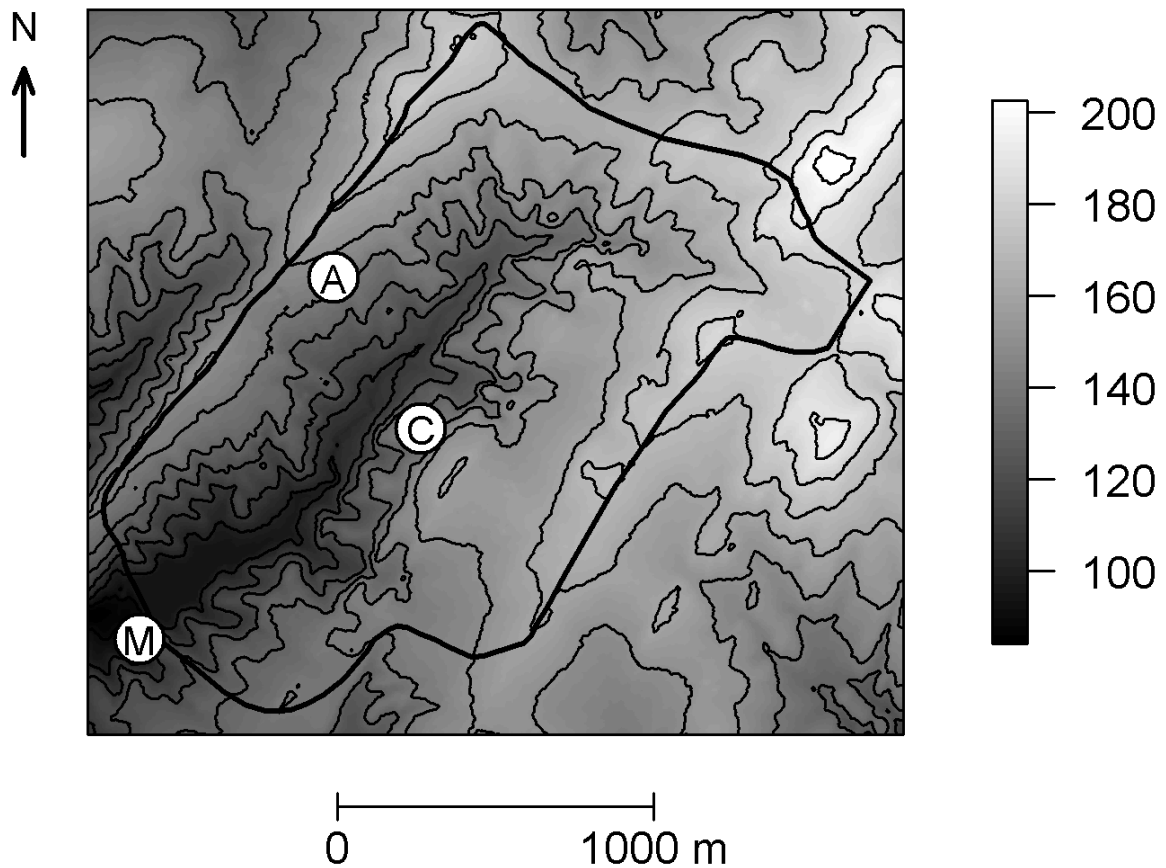
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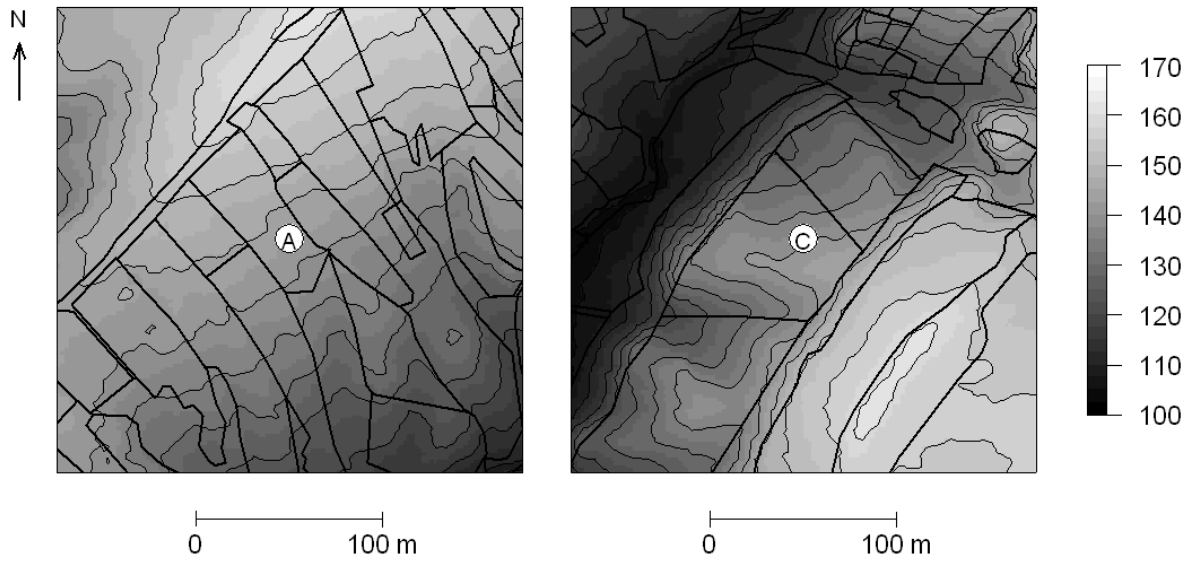
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1116 Figure 2: Topography of the Kamech catchment deduced from a 4-m spatial resolution digital  
1117 elevation model (DEM). Altitude above sea level is given in metres (right greyscale bar). The  
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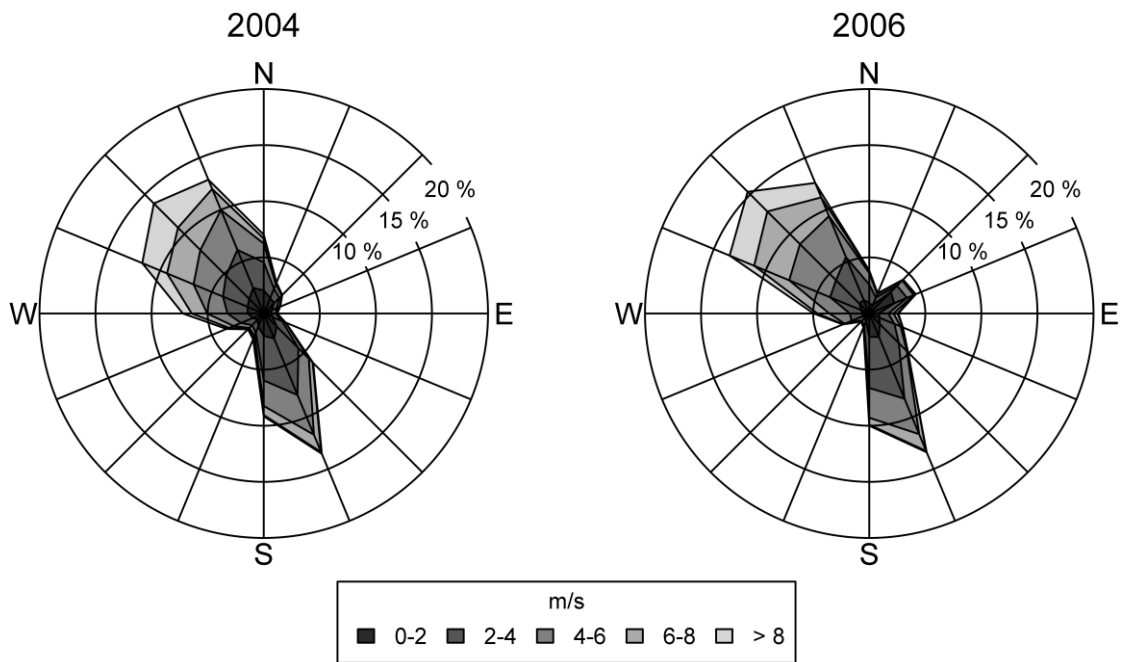
1126 Figure 3: Detailed view of the topography near fields A and C within the Kamech catchment.  
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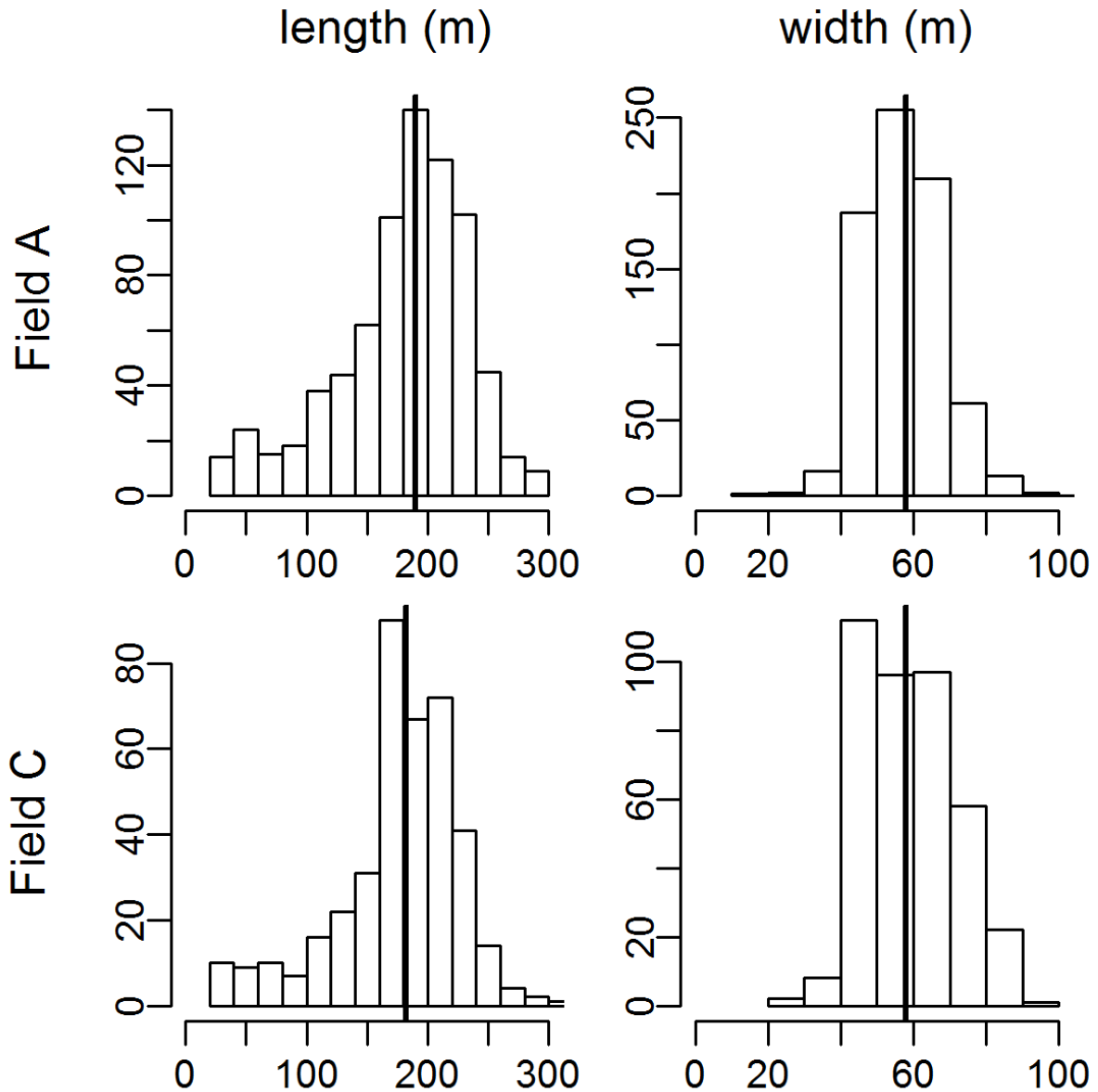


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1142 Figure 5: Distributions of the footprint dimensions for the fields A (top line; datasets A04 and

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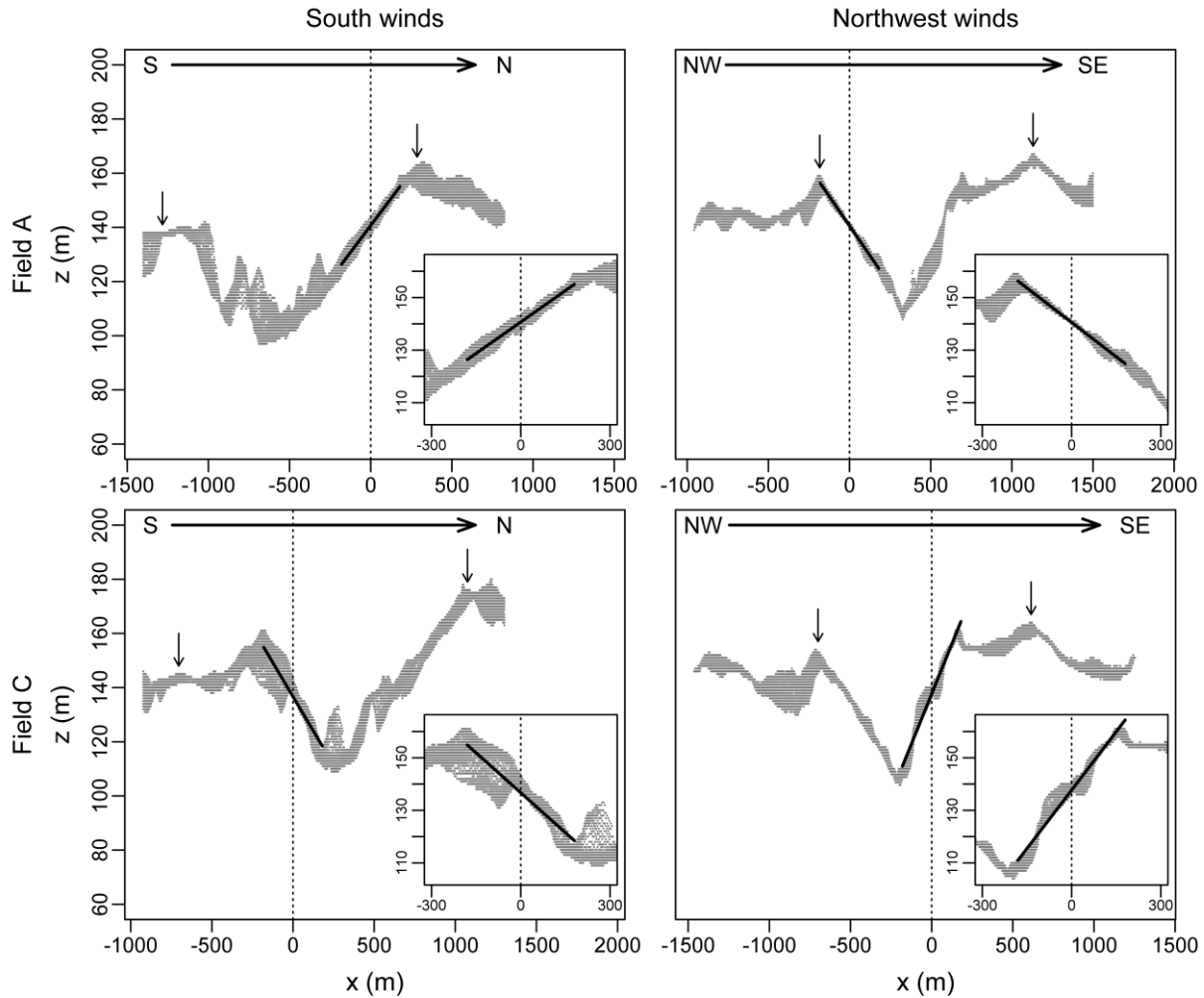
1144 direction) are in the left column, and the footprint widths (across the wind direction) are in the

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1146 (x-axis) are in metres. The y-axis is the number of 30-minute intervals belonging to each

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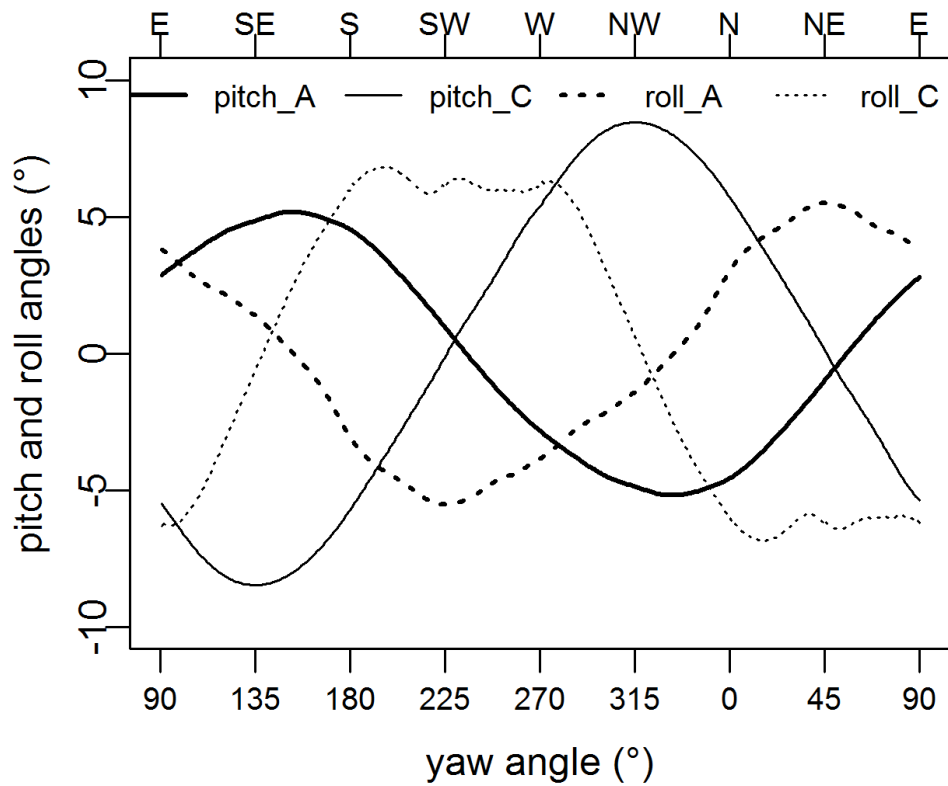


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1152 Figure 6: Determination of the wind-oriented topography for fields A (top line)  
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1168 Figure 7: Evolution of the wind-oriented topography (along-wind slope – equivalent to pitch

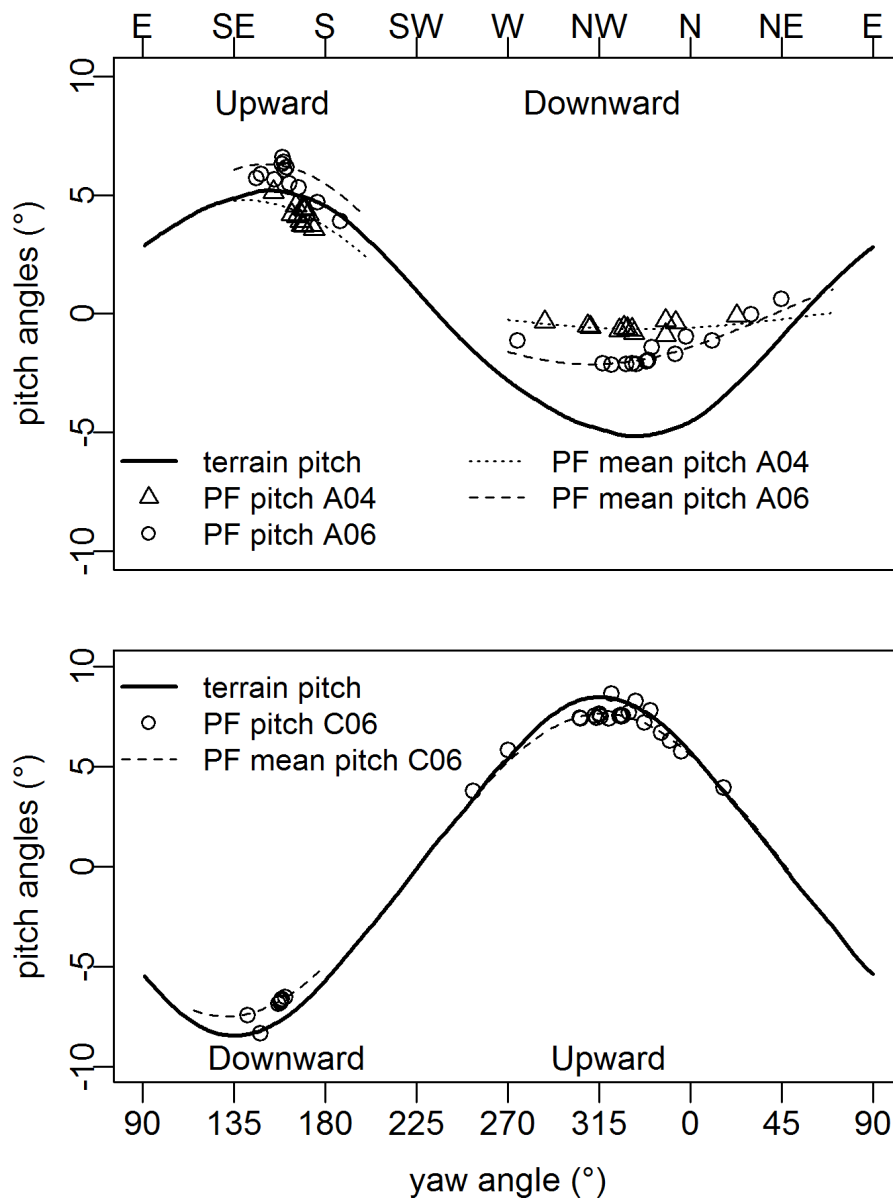
1169 angle – and across wind slope – equivalent to roll angles – on y-axis) with respect to the wind

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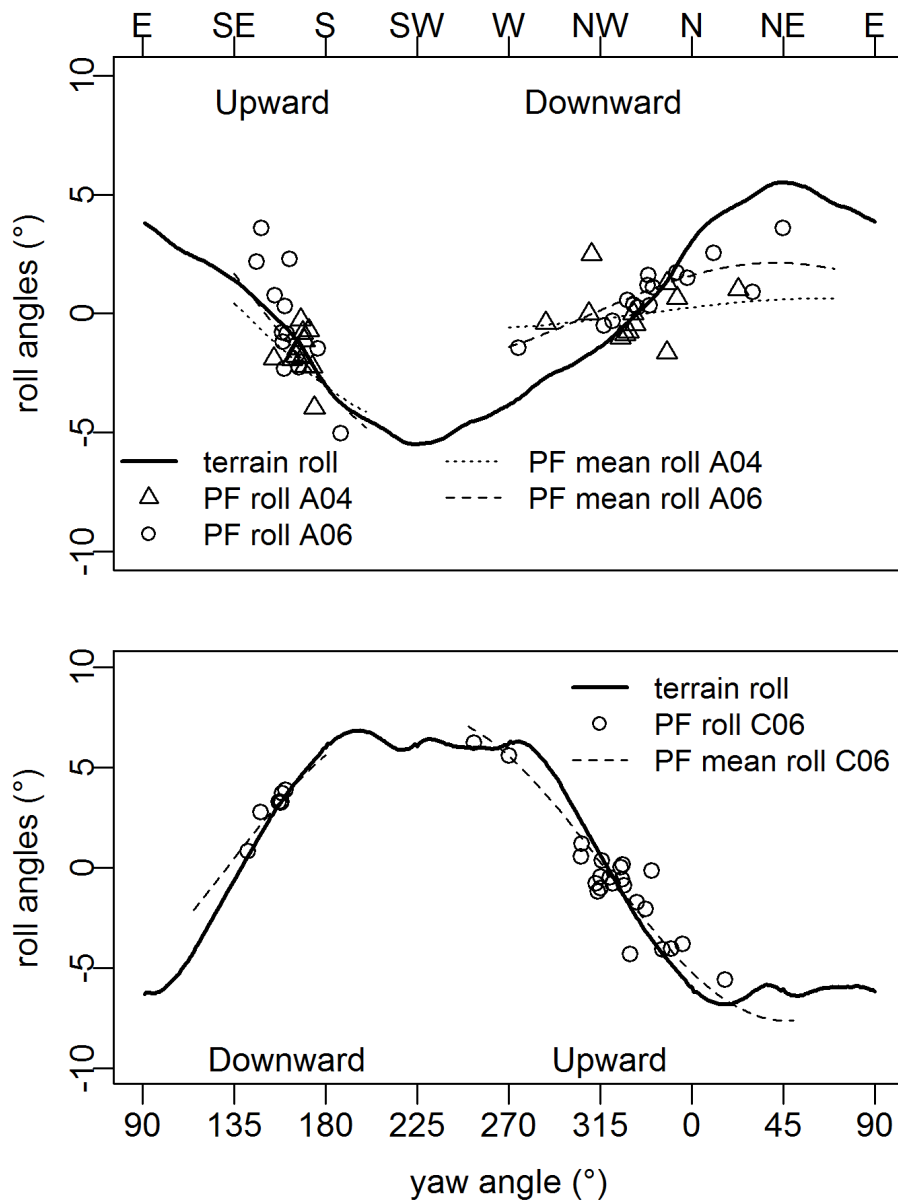
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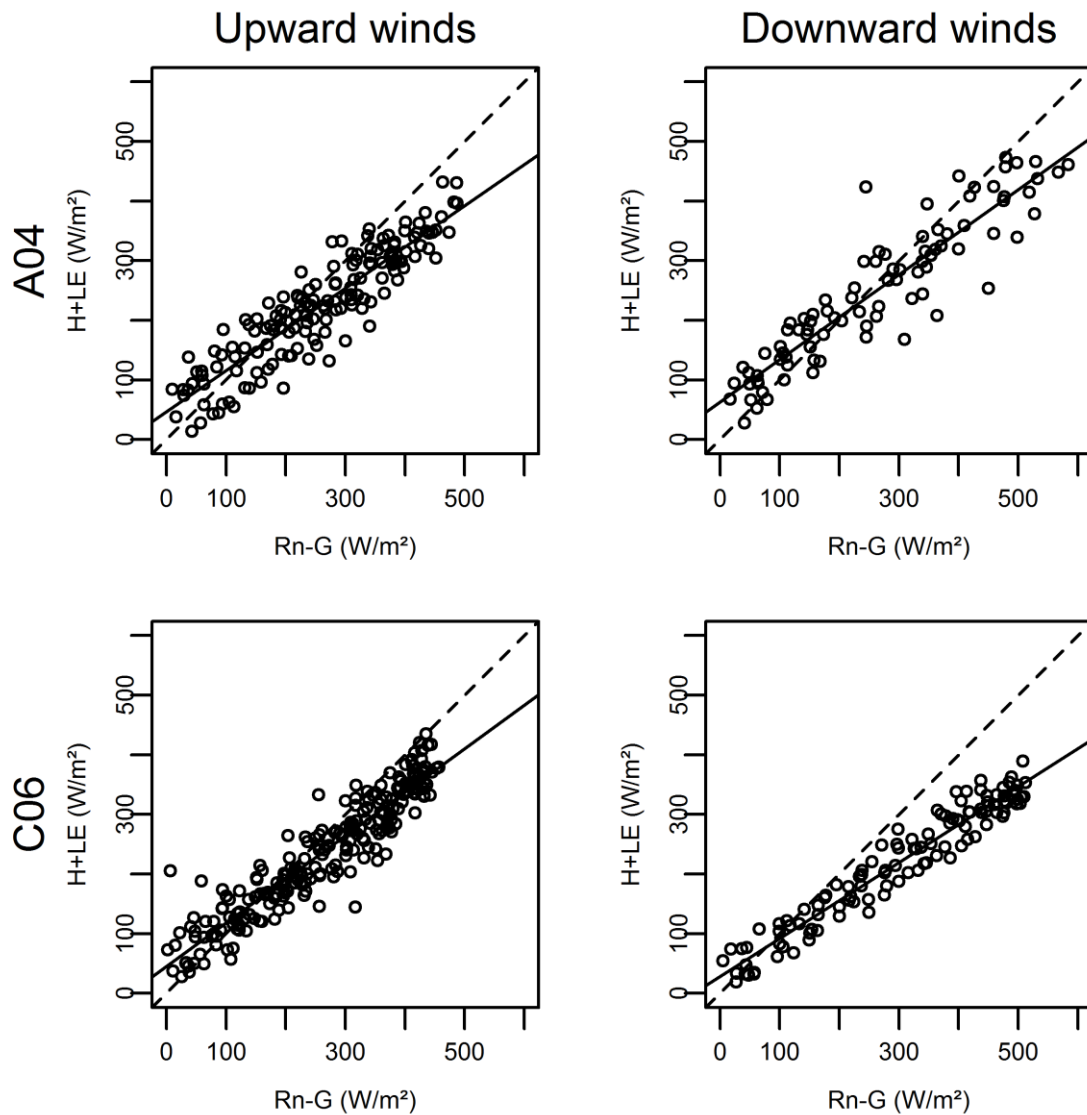
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1193 Figure 8b: Compared evolution of the planar fit derived roll angles and topographical cross-  
 1194 wind slopes (y-axis) with respect to the wind direction (x-axis, 0° is north, 90° is east) for  
 1195 fields A (top) and C (bottom). The continuous curves represent the topographical across-wind  
 1196 slope, as derived from the DEM data (same as Fig. 7). The planar fit-derived roll angles  
 1197 evaluated over the entire datasets (A04, A06, C06) and for each wind sector (south and  
 1198 north and west) are represented by the portions of the discontinuous curves (dotted lines for the  
 1199 year 2004, dashed lines for the year 2006); they are labelled as the “PF mean roll”. The planar  
 1200 fit-derived roll angles evaluated for each day and each wind sector are represented by symbols  
 1201 (triangles for the year 2004, circles for the year 2006), where each symbol represents a day or  
 1202 a portion of the day during which the wind direction was within a wind sector; they are  
 1203 labelled as the “PF roll”.

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1209 Figure 9: Energy balance closure for the datasets A04 (top line) and C06 (bottom line) and for  
 1210 the upward winds (left column) and downward winds (right column). The available energy  
 1211  $Rn-G$  ( $W\ m^{-2}$ ) is on the x-axis, and the convective energy  $H+LE$  ( $W\ m^{-2}$ ) is on the y-axis. The  
 1212 data correspond to the 30-minute intervals. The dashed line is the 1:1 line, and the continuous  
 1213 line is the y-axis data versus x-axis data regression line (regression coefficients are given in  
 1214 Table 3).

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## 1216 1 Table captions

1217

1218 Table 1: Listing of the instruments that were deployed for each flux station in fields A and C  
1219 for the years 2004 and 2006.

1220

1221 Table 2: Results from the quality control on the turbulent fluxes. The steady-state (ST) test is  
1222 applied to the friction velocity ( $u_* \propto \overline{u'w'}$ ), sensible heat flux ( $H \propto \overline{T'w'}$ ) and latent heat flux  
1223 ( $\lambda E \propto \overline{q'w'}$ ). The integral turbulence characteristics (ITC) test compares the flux-variance  
1224 similarities to those given by the Monin-Obukhov similarity theory. For both the ST and ITC  
1225 tests, the table gives the proportion of the data belonging to the three quality classes: high  
1226 quality (ST and ITC values between 0 and 0.3), good quality (ST and ITC values between 0.3  
1227 and 1.0) and data not meeting the quality requirements (ST and ITC values greater than 1.0).

1228

1229 Table 3: Statistical indicators for characterising the energy balance closure through the  
1230 comparison of convective energy ( $CE = H + \lambda E$ ) as the y-axis variable against the available  
1231 energy ( $AE = R_n - G$ ) as the x-axis variables. N is the data number. Terms a and b are,  
1232 respectively the slope and the intercept of the  $y = a x + b$  linear regression (continuous lines on  
1233 Fig. 9).  $R^2$  is the coefficient of determination between y and x. RMSD is the root mean square  
1234 difference between y and x. URMSD is the unsystematic RMSD, defined as the scattering  
1235 around the  $y = a x + b$  linear regression. EBR is the energy balance ratio defined as  
1236  $EBR = CE / AE$ . EB-RES is the energy balance residual, defined as  $EB-RES = AE - CE$ . The  
1237 metrics used here were selected from among those reviewed by Kustas et al. (1996) and  
1238 Wilson et al. (2002).

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Instrument	Field A Year 2004	Field A Year 2006	Field C Year 2006	Frequency of acquisition	Frequency of storage
Data logger	CR23X (Campbell Scientific Inc., USA)				
Sonic anemometer	CSAT3 (Campbell Scientific, USA)		Young-81000V (R.M. Young, USA)	10 Hz	10 Hz
Krypton hygrometer	KH20 (Campbell Scientific, USA)	-	KH20 (Campbell Scientific, USA)	10 Hz	10 Hz
Net radiometer	NR-lite (Kipp & Zonen, The Netherlands)			1s	30 mn
Soil heat flux sensors	Three HFP01 (Hukseflux, The Netherlands)			1s	30 mn
Thermo- hygrometer probe	HMP45C (Vaisala, Finland)			1s	30 mn

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Table 1: Listing of the instruments that were deployed for each flux station in fields A and C for the years 2004 and 2006.

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	ST			ITC		
	$\overline{u'w'}$	$\overline{T'w'}$	$\overline{q'w'}$	$\sigma_w/u_*$	$\sigma_u/u_*$	$\sigma_T/T_*$
<0.3	96%	96%	70%	99%	95%	63%
0.3 - 1	3%	2%	16%	1%	4%	34%
>1.0	2%	2%	14%	0%	0%	2%

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Table 2: Results from the quality control on the turbulent fluxes. The steady-state (ST) test is applied to the friction velocity ( $u_* \propto \overline{u'w'}$ ), sensible heat flux ( $H \propto \overline{T'w'}$ ) and latent heat flux ( $\lambda E \propto \overline{q'w'}$ ). The integral turbulence characteristics (ITC) test compares the flux-variance similarities to those given by the Monin-Obukhov similarity theory. For both the ST and ITC tests, the table gives the proportion of the data belonging to the three quality classes: high quality (ST and ITC values between 0 and 0.3), good quality (ST and ITC values between 0.3 and 1.0) and data not meeting the quality requirements (ST and ITC values greater than 1.0).

	A04		C06	
	Upward flows	Downward flows	Upward flows	Downward flows
N (-)	155	99	233	120
Slope a (-)	0.69	0.71	0.73	0.64
Intercept b ( $W m^{-2}$ )	47.0	63.3	44.8	28.2
$R^2$ (-)	0.82	0.84	0.88	0.93
RMSD ( $W m^{-2}$ )	63.7	65.5	55.6	100.9
URMSD ( $W m^{-2}$ )	39.6	47.4	34.9	25.6
EBR (-)	0.87	0.95	0.90	0.73
EB-RES ( $W m^{-2}$ )	32.7	12.2	26.9	81.2

1260

1261 Table 3: Statistical indicators for characterising the energy balance closure through the  
1262 comparison of convective energy ( $CE = H + \lambda E$ ) as the y-axis variable against the available  
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1270 Wilson et al. (2002).

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Figure

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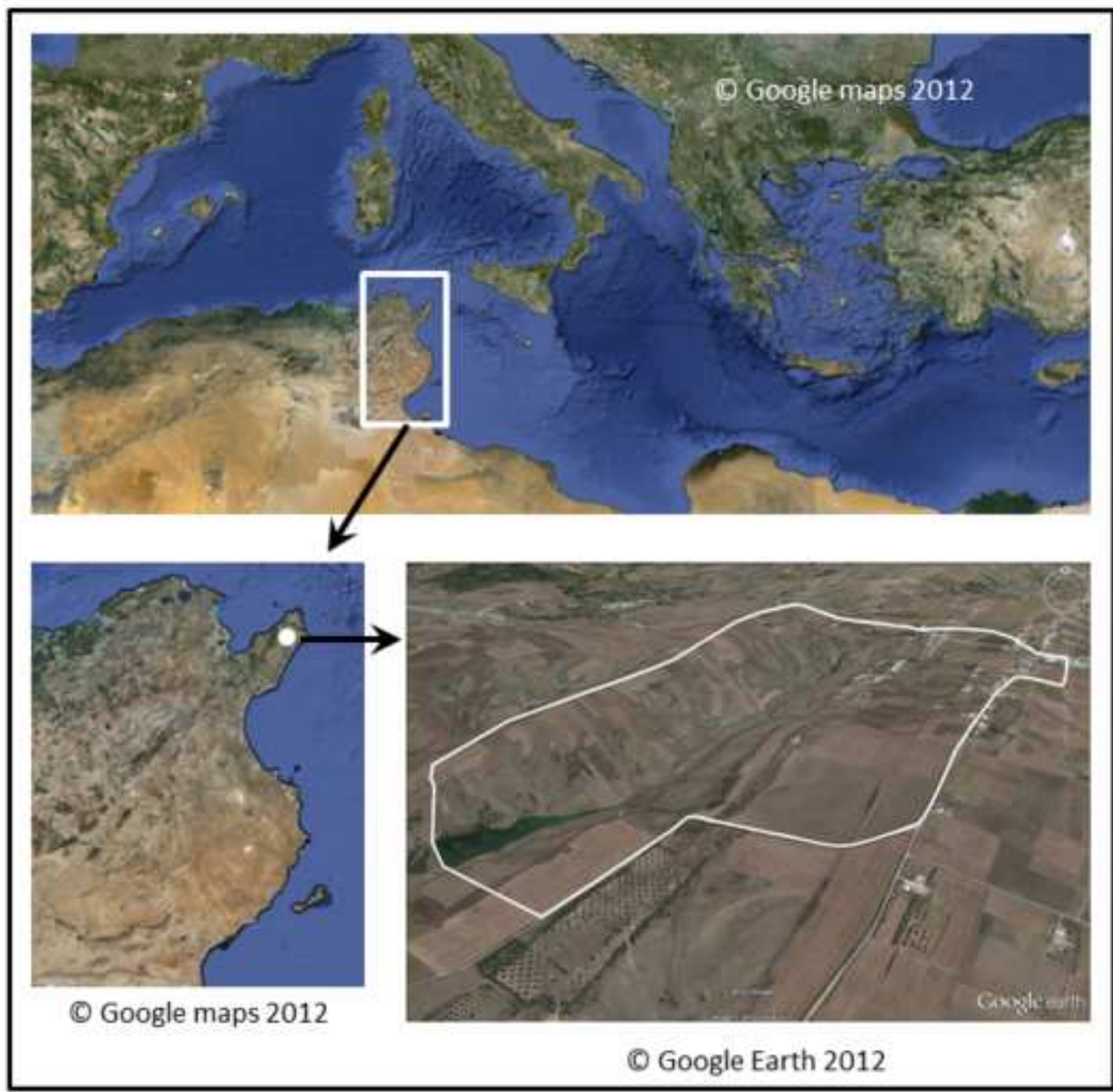


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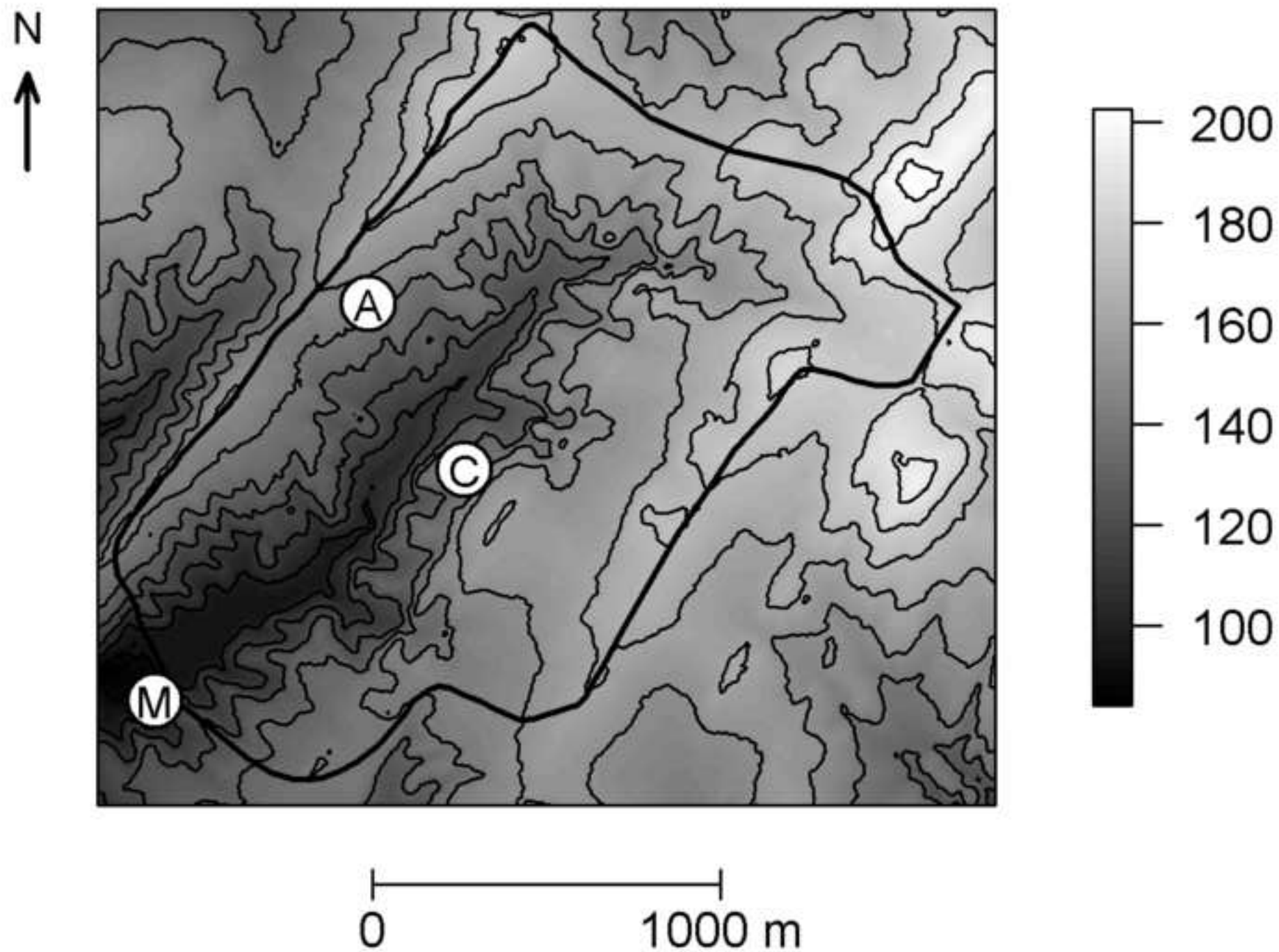


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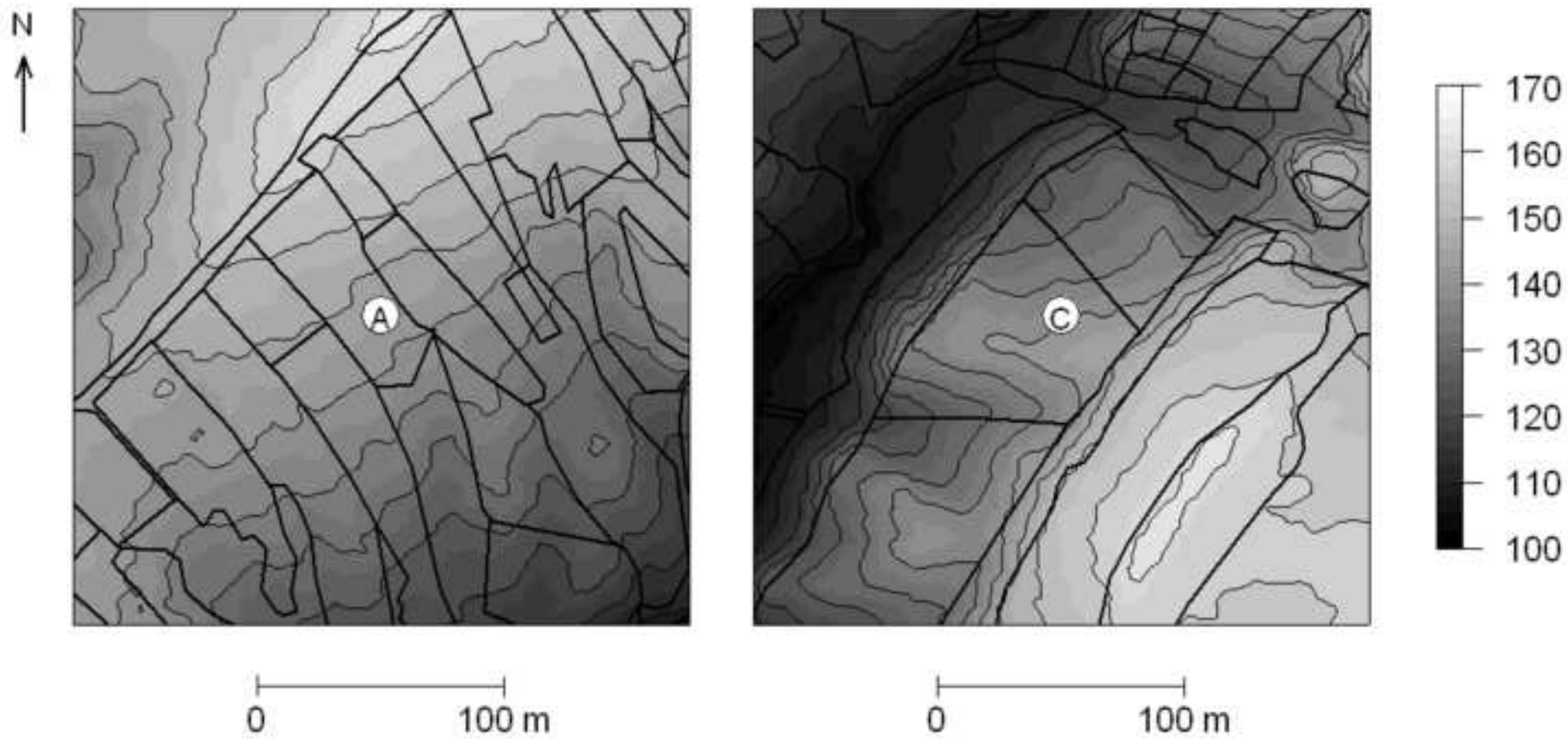
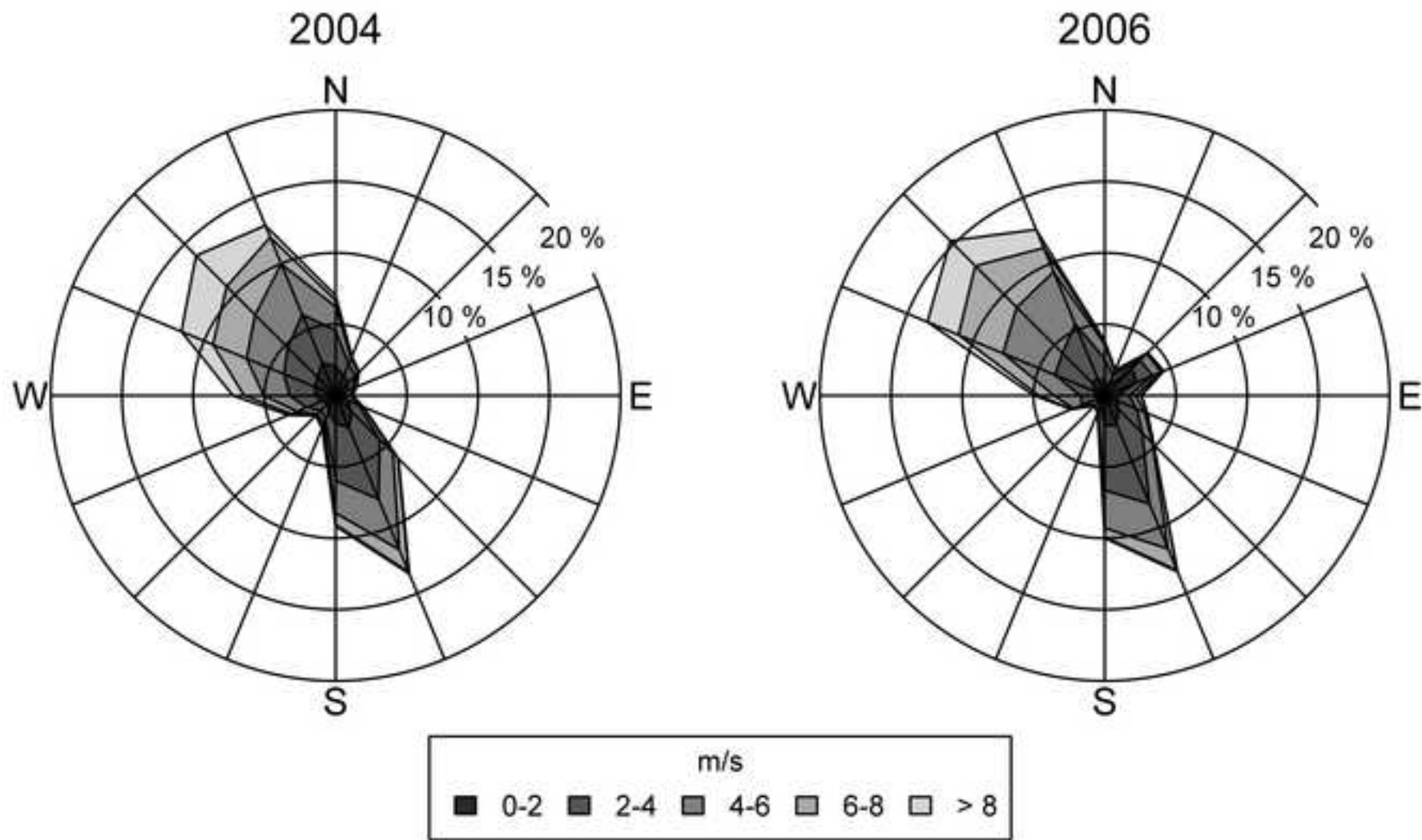
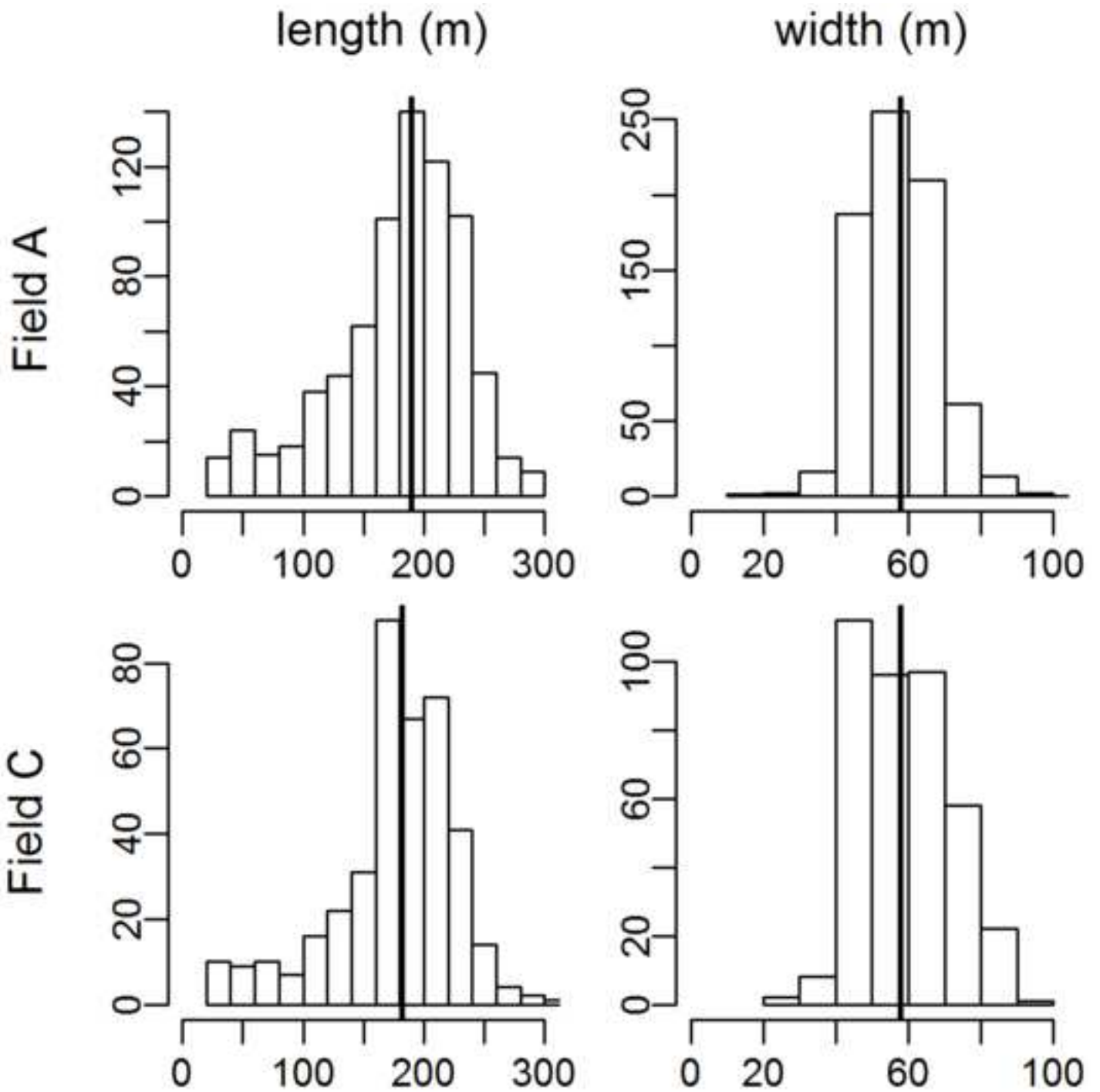




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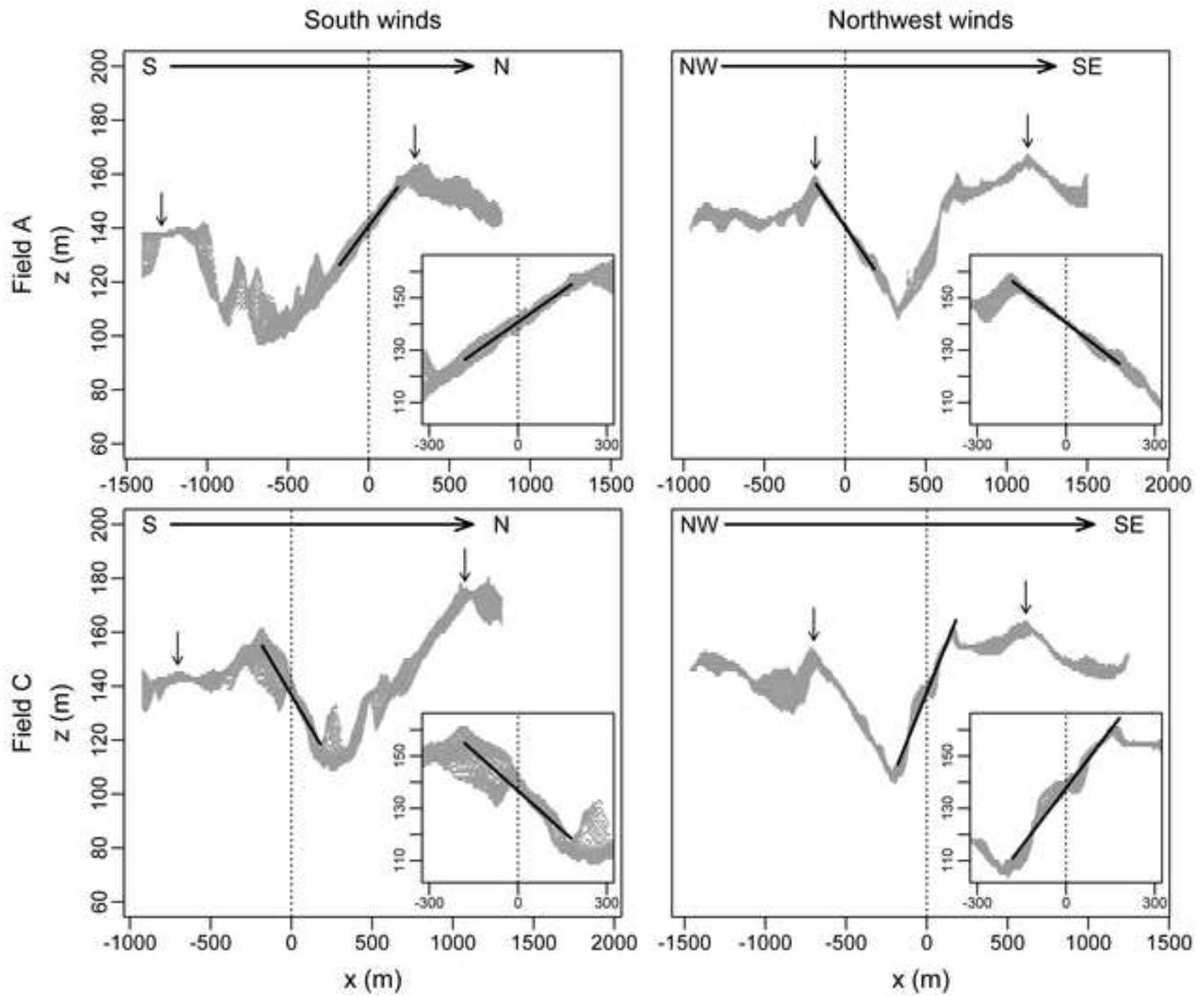


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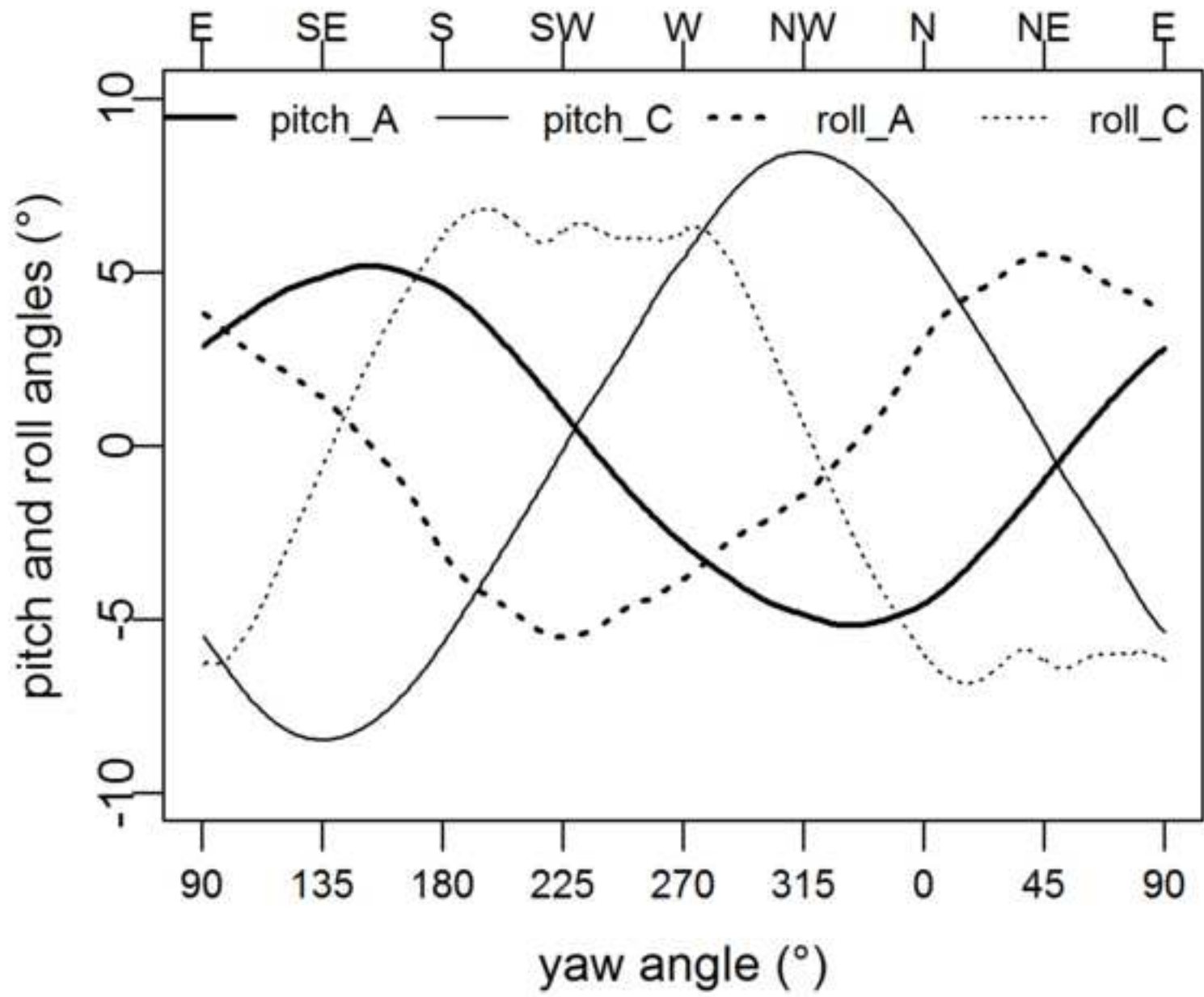


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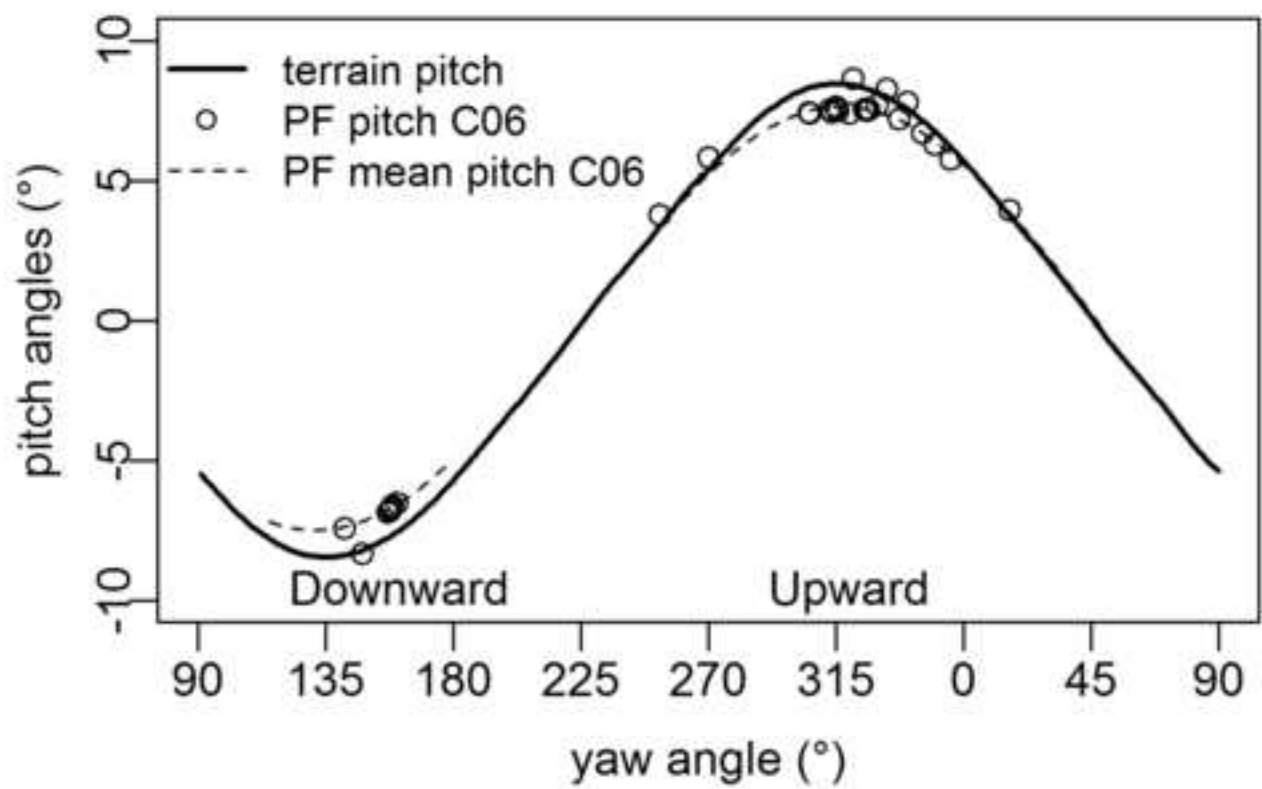
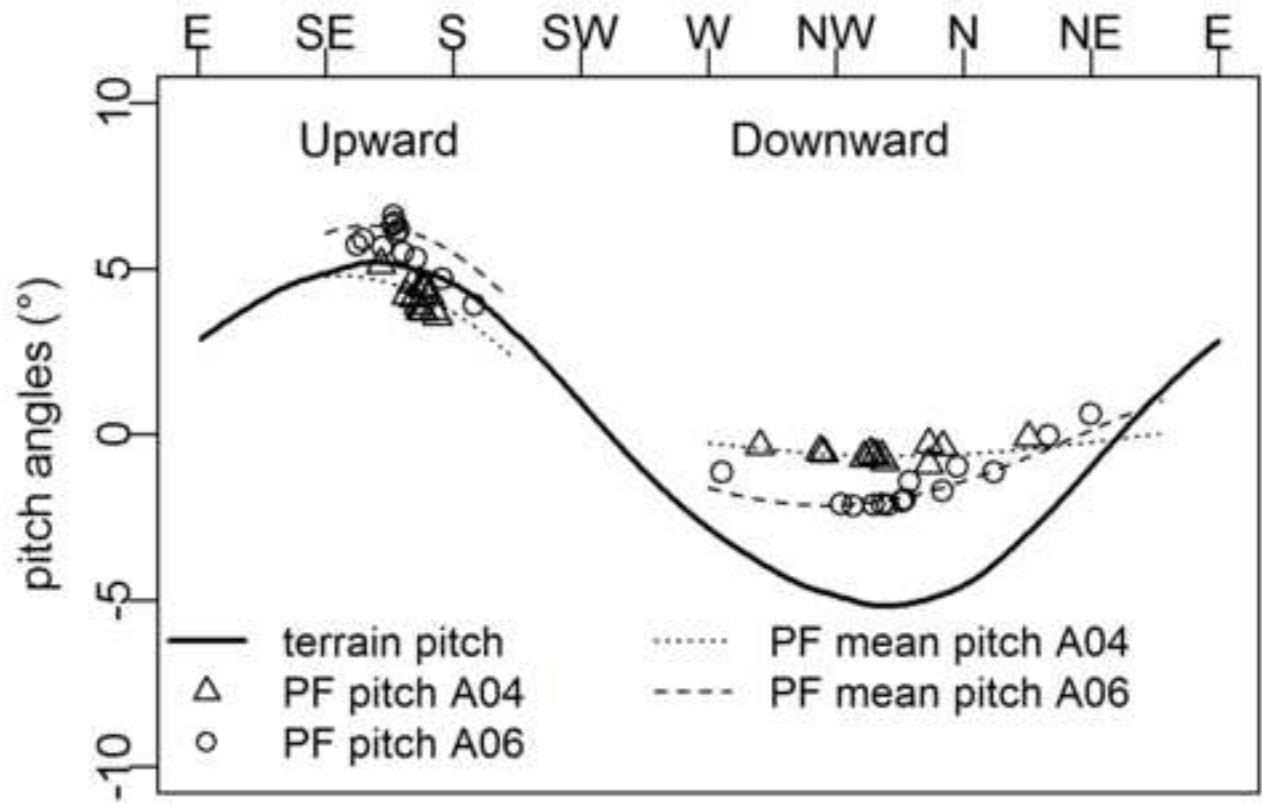


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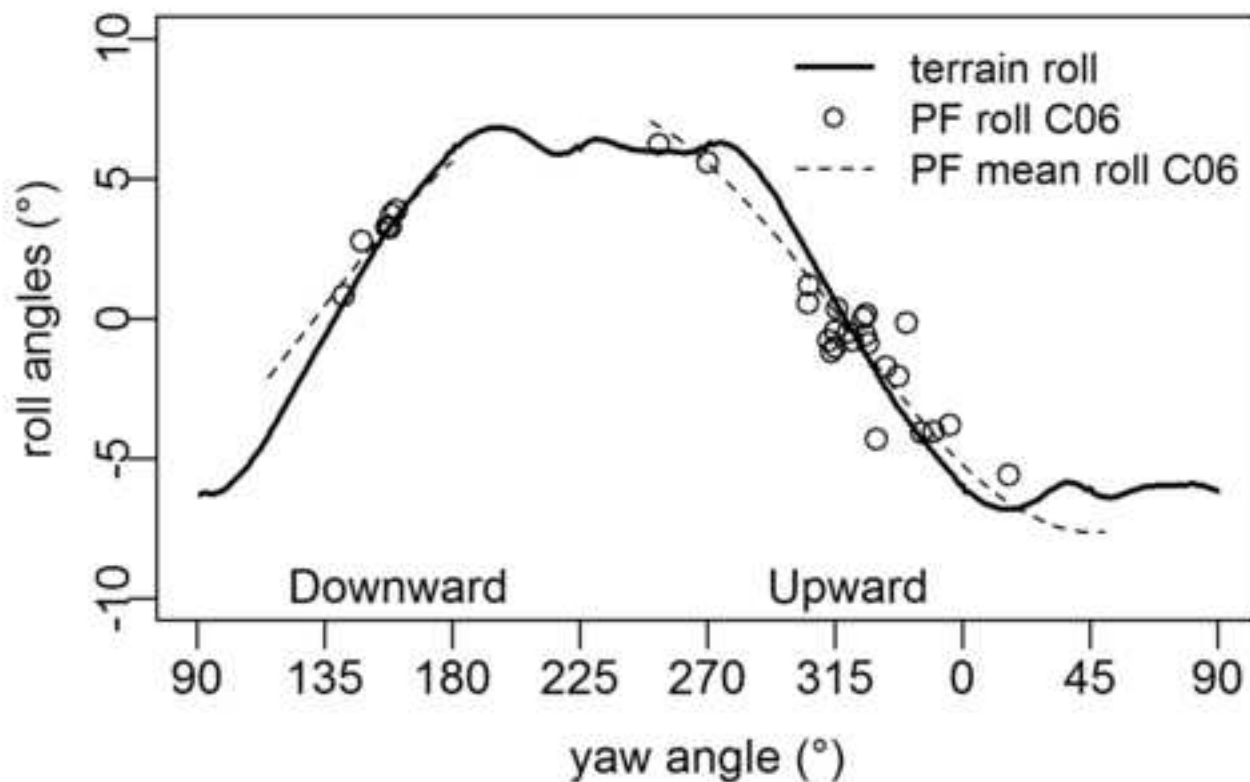
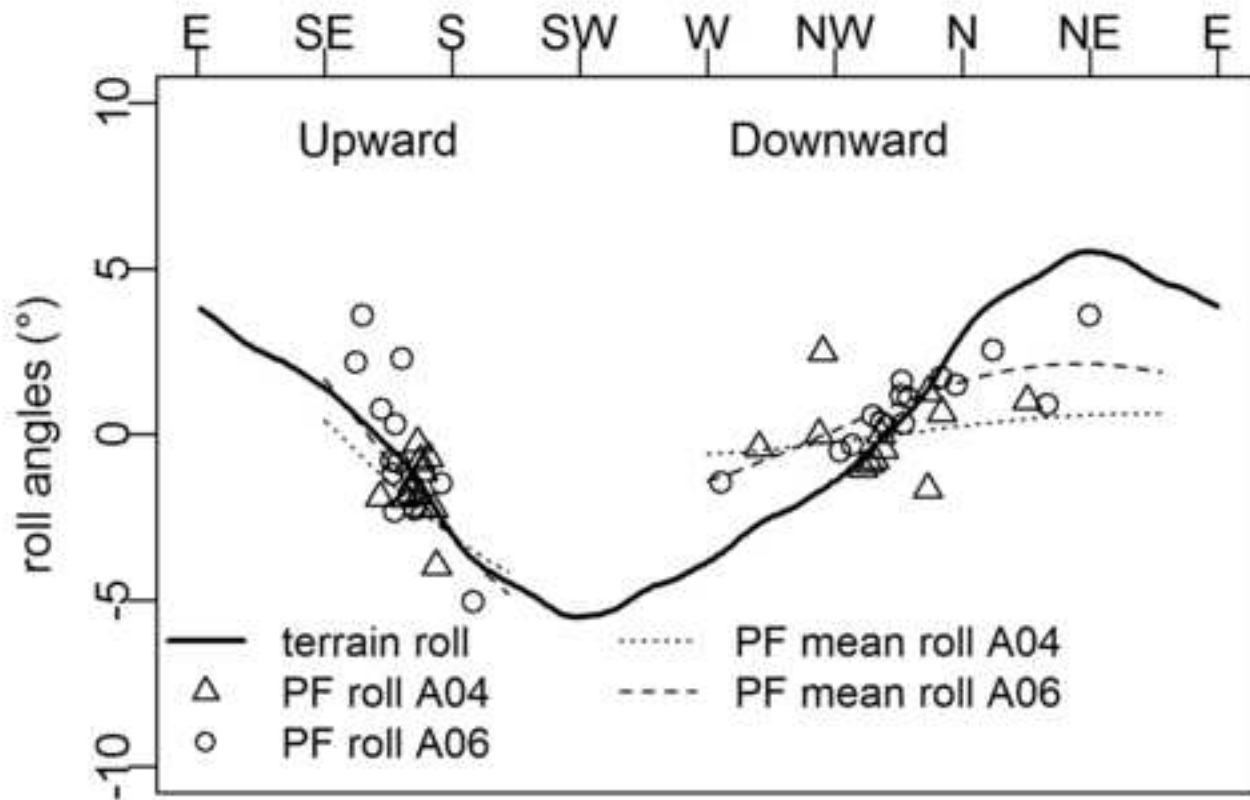


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