1 **An innovative eddy-covariance system with vortex intake for**

2 **measuring carbon dioxide and water fluxes of ecosystems**

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24   **Abstract.** Closed-path eddy-covariance (EC) systems are used to monitor exchanges

25   of carbon dioxide ($CO_2$) and water vapor ($H_2O$) between the atmosphere and biosphere.

26   Traditional EC intake systems are equipped with in-line filters to prevent airborne dust

27   particulates from contaminating the optical windows of the sample cell which degrades

28   measurements. In order to preserve fast-frequency response, the in-line filter should be

29   small, but small filters plug quickly and require frequent replacement. This paper

30   reports the test results of a field-performance of an innovative EC system (EC155,

31   Campbell Scientific, Inc.) with a prototype vortex intake replacing the in-line filter of

32   a traditional EC system. The vortex intake design is based on fluid dynamics theory. An

33   air sample is drawn into the vortex chamber, where it spins in a vortex flow. The initially

34   homogenous flow is separated when particle momentum forces heavier particles to the

35   periphery of the chamber, leaving a much cleaner air stream at the center. Clean air (75%

36   of total flow) is drawn from the center of the vortex chamber, through a tube to the

37   sample cell with optical windows. The remaining 25% of the flow carries the heavier

38   dust particles away in a separate bypass tube. An EC155-system measured $CO_2$ and

39   $H_2O$ fluxes in two urban forest ecosystems in the megalopolis of Beijing, China. These

40   sites present a challenge for EC measurements because of the generally poor air quality

41   with high concentrations of suspended particulate. The closed-path EC system with

42   vortex intake significantly reduced maintenance requirements by preserving optical

43   signal strength and sample cell pressure within acceptable ranges for much longer

44   periods. The system with vortex intake also maintained excellent high-frequency

45   response. For example at the Badaling site, percentage system downtime due to plugged

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46    filters was reduced from 26% with traditional in-line filters to 0% with the prototype

47    vortex intake. The use of vortex intake could extent the geographical applicability of

48    the EC technique in ecology and allow investigators to acquire more accurate and

49    continuous measurements of $CO_2$ and $H_2O$ fluxes in a wider range of ecosystems.

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## 1 Introduction

Eddy-covariance (EC) technology provides an opportunity to evaluate the fluxes of

energy, momentum, water vapor, carbon dioxide, and other scalars between the earth's

surface and the turbulent atmosphere overhead (Montgomery, 1948; Baldocchi, 2003;

Aubinet et al., 2016). The technology has been widely used in ecosystem studies

worldwide, including in forests, grasslands, agricultural lands, and wetlands (e.g., Zha

et al., 2010; Mitchell et al., 2015; Shoemaker et al., 2015; Wang et al., 2015). However,

the technology's use in many urban greenspace ecosystems has been challenged by

polluted air that contaminates the optical windows of the gas analyzer. Optical signal

strength is reduced and gas concentration measurements degrade as dust and debris are

deposited on the optical windows of the analyzer, including in both open and closed

path system. Closed path systems with traditional in-line filters can help keep the

analyzer's windows free of debris for a longer time. However, in environments with

extremely dirty air, in-line filters plug quickly (in just a few days) and as a result, require

frequent replacement (Bressi et al., 2012; Yu et al., 2013; Hasheminassab et al., 2014;

Villalobos et al., 2015). Dirty sample air can also contaminate other parts of the EC

system, leading to underestimated fluxes and data gaps (Jia et al., 2013; Xie et al., 2015).

In extreme cases, the system can stop working properly.


With expanding urbanization, urban greenspaces are expanding commensurately

(Pataki et al., 2006). Urban greenspaces have been playing a progressively more

important role in the study of ecosystem carbon balances worldwide (Mchale et al.,

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90    2007). To address the challenges associated with urban settings, an improved EC-

91    system capable to operate in polluted urban environments is needed to monitor carbon

92    dynamics in urban areas and to evaluate greenspace-ecosystem response to

93    environmental change (e.g., Pataki et al., 2006; Xie et al., 2015).

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95    The traditional approach for maintaining good trace-gas concentration measurements

96    in a closed-path EC system is to use an in-line filter to clean sampled air. The in-line

97    filter in the original EC155 design is based on a sintered stainless steel disk 1/16-inch

98    thick x 1 inch diameter of either 20 or 40 μm porosity, mounted in a rubber rain cap. In

99    practice, the porosity is chosen to maximize the maintenance-free interval at specific

100   sites. Fine-pore filters keep the analyzer windows clean for a longer time, but plug more

101   quickly. The gas analyzer sample cell windows must be cleaned when the optical signal

102   strength diminishes to 80%, and the filter must be replaced when the pressure drop

103   exceeds 7 kPa. Ideally, the filter pore size is chosen such that the windows become dirty

104   at the same interval that the filter clogs, requiring just one maintenance visit to the site.

105   The inline filter is a functional solution that can filter dirty air sufficiently to maintain

106   good gas concentration measurements. However, the maintenance labor can be

107   significant, and either a clogged filter or dirty windows can disrupt measurements until

108   the analyzer can be maintained. This maintenance can be required frequently in

109   conditions with high particulate matter in the ambient air.

110

111   To avoid the frequent replacement of filters in EC systems deployed in urban

112   environments, an advanced EC system with vortex intake (United States Patent No.

113   9,217,692）has been recently developed by Campbell Scientific, Inc. Vortex intake

114   eliminates the need for an in-line filter upstream of the gas analyzer.

115

116   This study introduces vortex-intake sampling and demonstrates its field performance

117   with *in situ* measurements collected in two urban greenspace areas within the

118   megalopolis of Beijing, China. The goals for the new design were to: (1) minimize

119   system maintenance; (2) reduce system downtime due to plugged filters; and (3)

120   maintain high-frequency response. The objective of this field test was to compare the

121   performance of a prototype vortex-intake sampling system with that of a traditional

122   system fitted with an in-line filter.

123   **2 Materials and methods**

124   **2.1 Site description and data collection period**

125   The study site is located in Beijing Olympic Forest Park (40.02° N, 116.38° E, 51 m

126   above mean sea level, AMSL) and Badaling Tree Farm (40.37° N, 115.94° E, 535 m

127   AMSL), Beijing, China. There is generally poor air quality in Beijing, with high

128   concentrations of suspended particulate in the atmosphere (Fig. 1) and hazy conditions,

129   at times with visibility < 10 km. Haze is a common problem during the winter and

130   spring because of (i) home heating with coal and other non-renewable energy sources,

131   (ii) congested traffic, (iii) industrial activity, (iv) stable synoptic conditions, and (v)

132   surrounding mountainous topography (e.g., Yang et al., 2015; Zheng et al., 2015; Zhang

133   et al., 2016).

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135    The Olympic Forest Park is the largest urban forest park in Asia, with an area of 680 ha

136    and vegetation coverage of about 90%. The site is an ecological conservation and

137    recovering area. The site is dominated by *Pinus tabulaeformis L*. Other species include

138    *Platycladus orientalis*, *Sophora japonica L*, *Fraxinus chinensis*, and *Glingo biloba*,

139    with an understory of *Iris tectorum* and *Dianthus chinensis*. All trees were tagged and

140    identified by species, with trees with diameter at breast height (DBH) > 3 cm being

141    assessed annually. Stand density was 210 trees ha$^{-1}$, with a mean tree height of 7.7 m

142    and a mean DBH of 20 cm. Cover ratio of trees to shrubs was about 7:3. The shrubs

143    were *Prunus davidiana*, *Amygdalus triloba*, *Swida alba*, and *Syzygium aromaticum*,

144    with a mean height of 2.8 m (Xie et al., 2015).

145

146    The Badaling Tree Farm is about 60-km away from downtown core of Beijing. Local

147    terrain is generally flat and uniform. The study site is composed of *Acer truncatum*,

148    *Koelreuteria paniculata, Fraxinus bungeana, Ailanthus altissima*, and *Pinus*

149    *tabuliformis*. Stand density was 975 trees ha$^{-1}$, with a mean tree height of 4 m and a

150    mean DBH of 4.7 cm. The study site has a sparse herbaceous cover layer with no well-

151    defined understory canopy (Jia et al., 2013).

152

153    Data presented in this study cover the field deployments of two EC systems; one at each

154    of the two sites. Both systems were deployed in 2011 with the original inline filter

155    intakes. Data with this inline filter design were collected from January 2011 to July

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156    2014 at the Olympic Park, and from January 2011 to September 2014 at Badaling Farm.

157    Both EC systems were switched to the vortex design in 2014. Data with vortex intakes

158    were acquired from July 2014 to December 2015 at Olympic Park and from September

159    2014 to December 2015 at the Badaling Farm.

160    **2.2 Instrument description**

161    An EC155 (model EC155, Campbell Scientific, Inc. Logan, UT, USA) is an *in situ*,

162    closed-path, mid infrared absorption gas analyzer (IRGA) that measures molar mixing

163    ratios of $CO_2$ and $H_2O$ at high frequency. The original EC155 analyzer includes a heated

164    intake tube, inline filter, and rain cap (Fig. 2a). The modified EC155 system includes a

165    prototype vortex chamber and rain cap in place of the original filter and rain cap (Fig.

166    2b).

167

168    The vortex intake is a small, light-weight device with no moving parts, and requires no

169    chemicals to clean the sample air. Its simple design makes it essentially maintenance

170    free. The vortex assembly (Fig. 2b) consists of a rain cap and inlet nozzle, a vortex

171    chamber, and two outlet ports. Schematics of both systems are shown in Fig. 3. Unlike

172    a filter, the vortex intake design is based on fluid and particle dynamics. Sampled air

173    enters the vortex chamber through a tangent port to induce rotational flow. Entrained

174    dust-particle motion is governed by centrifugal (inertia), aerodynamic drag, and

175    chamber wall-impact forces. The high rotational speed of the vortex flow provides the

176    larger heavier (relative to air) dust particles with greater centrifugal force, keeping them

177    close to the chamber wall and leaving the air in the center of the vortex free of dust.

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178    Clean sample air flows from the vortex center through a tube to the EC155 sample cell.

179    The dust particles along with the air close to the wall of the vortex chamber are pulled

180    out through the bypass tube. This dirty air passes through a relatively large filter that

181    lasts a long time without plugging. The filter protects a flow-control orifice that

182    balances the flow split ¾ to sample, ¼ to bypass. The two flows rejoin downstream of

183    the analyzer then go to the single low power vacuum pump.

184

185    For flux determination (covariances), high-frequency wind velocities are needed. Wind

186    velocities are acquired with a fast-response 3-dimensional sonic anemometer (CSAT3A;

187    Campbell Scientific, Inc. Logan, UT, USA). At Olympic Forest Park, a 12-m-tall tower

188    is surrounded by uniform forest cover with a homogeneous fetch of about 600 m in all

189    directions. The EC instruments were mounted on a tower of 11.5-m height from ground.

190    At Badaling Tree Farm, the EC instruments were mounted on a tower of 11.7-m height

191    from ground. All flux-related data were collected at 10 Hz and processed using Fluxnet-

192    supported methodologies described by Aubinet et al. (1999).

193    **2.3 Field tests**

194    High-frequency fluctuation amplitude-reduction is one of the systematic errors in EC

195    measurements, and is especially important when trace gas concentrations are measured

196    with a closed-path infrared gas analyzer (Aubinet et al., 1999). The frequency response

197    of a system is defined as a ratio of its output to its input as a function of the signal

198    frequency. In an ideal system, the value would be unity across all frequencies. In a real

199    system, fluctuations in $CO_2$ or $H_2O$ tend to be damped at higher frequencies due to

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200   adding a rain cap, filter, and intake tubing to a gas sampling system (Aubinet et al.,

201   2016). The frequency response quantifies the loss of high-frequency information and

202   tests the ability of the frequency response corrections to adequately account for this loss.

203

204   With this in mind, the frequency response of a closed-path EC system with vortex intake

205   is compared to one with an in-line filtering setup. Laboratory test of the frequency

206   response using the method of Sargent (2012) showed that closed-path eddy covariance

207   systems with vortex intake perform very well. *In situ* field measurement of system

208   frequency response is challenging because the true signal inputs (scalar variables) are

209   not known *a priori*.

210

211   *In situ* system-frequency response can be evaluated by comparing the cospectra of the

212   vertical component of wind with fluctuations of sonic temperature (WTs, where W

213   denotes the vertical component of wind and Ts the sonic temperature) to the cospectra

214   of the vertical component of wind with fluctuations of $CO_2$ (WC, where C denotes the

215   mixing ratio of $CO_2$) and $H_2O$ (WH, where H denotes $H_2O$ mixing ratio). Analysis of

216   cospectrum are based on high-frequency data at 10 Hz obtained from the Olympic

217   Forest Park over a one-hour period (12:00-13:00 Beijing Standard Time) averaged daily

218   for the month of April, 2014, for the in-line filter-based EC measurements, and August,

219   2015, for the vortex intake-based measurements. A fast Fourier transform was applied

220   for each variables' time series consisting of about 36,000 data points.

221

222    Decreases in sample-cell differential pressure and $CO_2$ optical signal strength indicate

223    when the in-line filter and optical windows need to be replaced and cleaned. Clogged

224    filters can induce substantial pressure drops (Aubinet et al., 2016). Generally, the

225    pressure drop in the original intake assembly is approximately 2.5 kPa at 7 LPM flow

226    without filter. The filter adds approximately 1 kPa pressure drop when it is clean. This

227    pressure drop will increase as the filter clogs. The filter should be replaced before the

228    differential pressure reaches +/- 7 kPa. Additionally, the windows of the analyzer should

229    be cleaned when the optical signal strength of $CO_2$ drops below 80% of the original

230    value.

231    **3 Results and discussion**

232    **3.1 Frequency response**

233    Due to damping of high-frequency signals in closed-path systems, gas cospectra

234    commonly exhibit reduced response at high frequencies causing flux loss (Leuning and

235    King, 1992; Burba et al., 2010). Brach and Lee (Brach et al., 1981; Lee et al., 2004)

236    found that the cospectrum of vertical wind velocity with sonic temperature (WTs) is

237    often very close to the ideal cospectrum. In field experiments, WTs is often used as a

238    standard to evaluate whether there is a high-frequency loss for other measured scalars.

239    To examine the effect of vortex intake, spectral analysis was applied to the

240    measurements collected *in situ*. Ensemble cospectra of vertical wind velocity with $CO_2$

241    (WC) and $H_2O$ vapor (WH) were compared to those for the sonic temperature (WTs)

242    for both the in-line filter and vortex intake-based systems (Fig. 4a, b). The normalized

243    cospectra for both systems were consistent at all frequencies, with no significant

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244    difference（$P > 0.05$), thus the EC155 sampling system with vortex intake did not result

245    in obvious $CO_2$ and $H_2O$ flux losses. Additionally, although the cospectra of WC and

246    WH for both systems showed a sharp attenuation when the frequencies > 0.1 Hz,

247    damping of high-frequency signals was within the range reported for closed-path

248    systems (Yasuda et al., 2001). The EC155 system with vortex intake can provide

249    sufficient high-frequency response to warrant automating high-frequency spectral

250    corrections during post-processing.

251    **3.2 Differential pressure and optical signal strength of $CO_2$**

252    Air quality at Olympic Park was mostly poor during the measurement periods, being

253    worse in winter than in summer. To verify performance of the vortex intake, we chose

254    periods of high and low incidence of haze to compare the differential pressure and

255    optical signal strength of $CO_2$. Fig. 5 shows time series of three months for each case.

256    Decrease in differential pressure caused by clogging of the in-line filter (Fig. 5a and c)

257    quickly exceeded the range of the pressure sensor (+/- 7 kPa), generating invalid data

258    until the filter could be replaced. The differential pressure with the vortex intake was

259    much more stable than with the in-line filter. Over a period of three months, the

260    differential pressure with vortex intake exceeded the pressure sensor range once during

261    very hazy conditions (Fig 5b). The optical signal strength of $CO_2$ with the vortex intake

262    remained above 90%, indicating the optical windows remained free of debris for a

263    substantially longer time than with the in-line filter.

264

265    At the Badaling Farm site, we also chose periods of high and low incidence of haze to

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266    compare differential pressure and optical signal strength of $CO_2$. As shown by the

267    differential pressure in Fig. 6a and c, the in-line filter clogged multiple times in a period

268    of two months resulting in large data losses. Pressure drop with the vortex intake (Fig.

269    6b and d) was typically about 3 kPa, remaining within the working range for the entire

270    observation period (two months). The optical signal strength of $CO_2$ with vortex intake

271    was higher and more stable than that of the system with an in-line filter.

272    **3.3 Field maintenance**

273    In order to further verify the performance of the EC155 system with vortex intake, field

274    maintenance records from the two sites were compared. These maintenance records

275    included the number of maintenance services, downtime due to clogged intake filters,

276    and percentage downtime, defined as a ratio of downtime due to clogged intake to the

277    actual testing-period duration × 100. Also included is the minimum and average time

278    period for the intake filter to clog.

279

280    A summary of field maintenance at Olympic Park and Badaling Farm is shown in Table

281    1. The vortex design reduced the number of maintenance services from 15 to 4 at

282    Olympic Park, and from 7 to 0 at Badaling Farm. The percentage downtime at Badaling

283    was reduced from 26% with the original in-line filter intake to 0% with the vortex intake.

284    At Olympic Park the percentage downtime was 31% for the inline filter and 5% for

285    vortex intake. The percentage downtime reflects not just the number of times the filter

286    was clogged, but also how soon the filter was replaced after it clogged. The minimum

287    and average clog times, shown in the last two columns of Table 1, highlight the reduced

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288    maintenance requirement of the vortex intake design. At Olympic Park, the in-line

289    filters clogged in as little as one day, with an average clog period of just six days. The

290    minimum maintenance interval for the vortex intake was 21 days, with an average of

291    46 days. At Badaling Farm, in-line filters clogged in as little as 9 days with an average

292    of 20 days, while the vortex intake design required no maintenance for an entire period

293    of 122 days.

294

295    Independent of high or low haze cover, the maintenance required for the vortex intake

296    EC system was markedly reduced, thus decreasing overall downtime substantially.

297    Similar field tests for the vortex intake EC system have been performed in the USA and

298    Canada (Brown et al., 2015; Somers and Sargent, 2015), where it ran well over six

299    months with no maintenance required on either the vortex sampling system or sample

300    cell windows. Overall, the vortex intake can improve long-term monitoring of $CO_2$ and

301    $H_2O$ fluxes in conditions of high particulate concentration.

302    **4 Conclusions**

303    The vortex intake significantly reduced maintenance requirements and down-time for

304    a closed-path eddy-covariance system compared to the original in-line filter design.

305    Vortex intake kept the sample cell windows cleaner, preserving the optical signal

306    strength of $CO_2$ longer. Its installation also avoided the need for an in-line filter in the

307    sample path, sustaining an acceptable sample cell differential pressure over a much

308    longer period. There was no significant attenuation of high frequencies, compared to

309    the in-line filter-based system. Vortex intake helped to overcome shortcomings

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310 associated with the traditional in-line filter-based systems in extremely polluted

311 conditions. The vortex intake design extents the geographical application of the EC

312 technique in ecology and allows investigators to acquire more accurate and continuous

313 measurements of $CO_2$ and $H_2O$ fluxes in a wider range of ecosystems.

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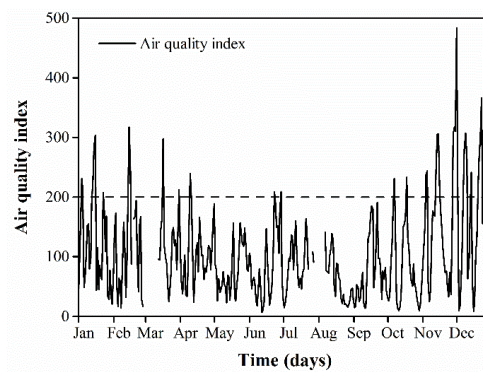432

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442 **Tables and Figures**

443 **Table 1.** Summary of field maintenance notes for the EC155 with vortex intake compared to the

444 EC155 with an in-line filter at Olympic Park (op) and Badaling Farm (bd), Beijing, China; the time

445 range includes periods of both high and low incidence of haze. Clog period is the number of days

446 for the differential pressure to reach +/- 7 kPa after installing a fresh filter.

| Site | Begin data | End data | Intake | Time range (days) | Number of maintenance services | Downtime from clogged intake (days) | Downtime percent | Minimum clog period (days) | Average clog period (days) |
|---|---|---|---|---|---|---|---|---|---|
| op | 1/11/13 | 31/1/14 | Inline filter | 184 | 15 | 57 | 31% | 1 | 6 |
| | 1/8/13 | 31/10/13 | | | | | | | |
| | 1/11/14 | 31/1/15 | Vortex | 184 | 4 | 9 | 5% | 21 | 46 |
| | 1/8/15 | 31/10/15 | | | | | | | |
| bd | 1/11/12 | 31/12/12 | Inline filter | 122 | 7 | 32 | 26% | 9 | 20 |
| | 1/9/12 | 31/10/12 | | | | | | | |
| | 1/11/14 | 31/12/14 | Vortex | 122 | 0 | 0 | 0% | >122 | >122 |
| | 1/9/15 | 31/10/15 | | | | | | | |

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**Figure 1.** Daily mean air quality index during 2015 in Beijing, China. Air quality index is stratified

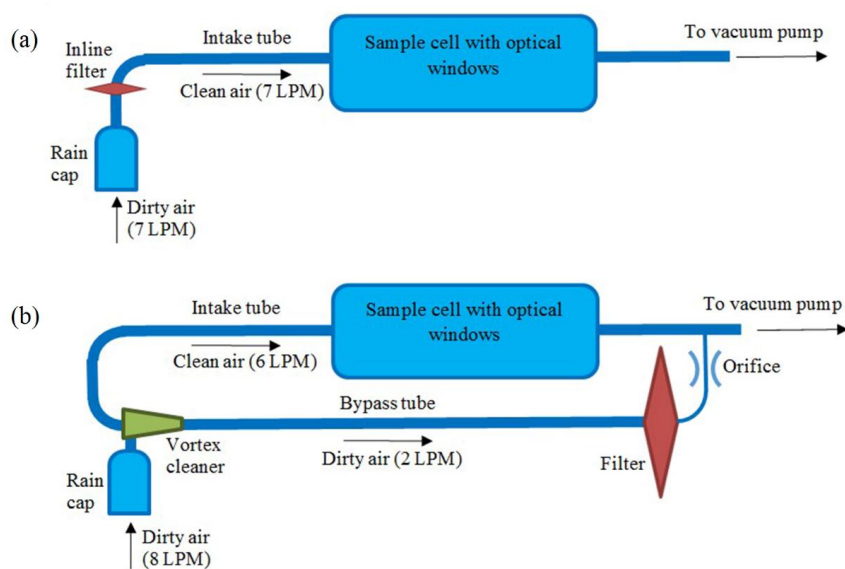into six categories: 0-50 for low, 51-100 for low to mild, 101-150 for mild, 151-200 for moderate,

201-300 for severe, and > 300 for serious air pollution levels.

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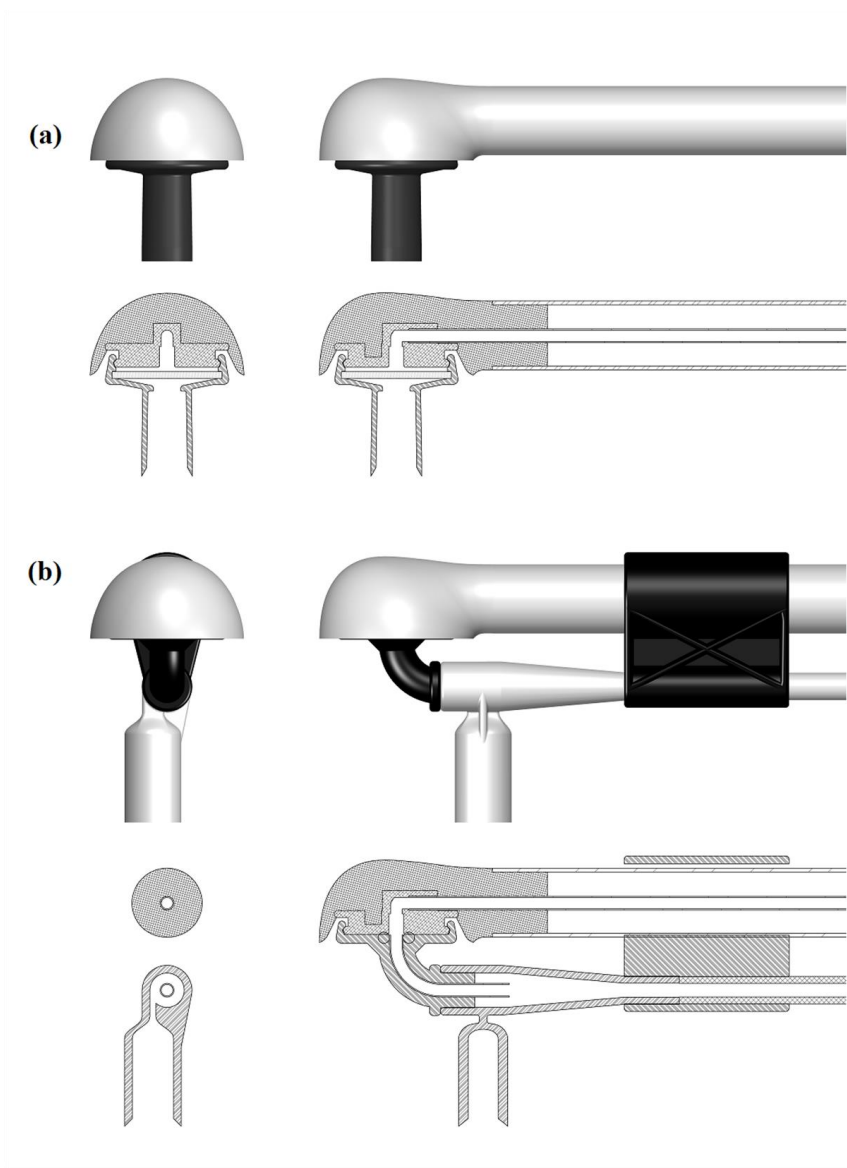
**Figure 2.** EC155 sample intakes: (a) original in-line filter and (b) prototype vortex intake cleaner

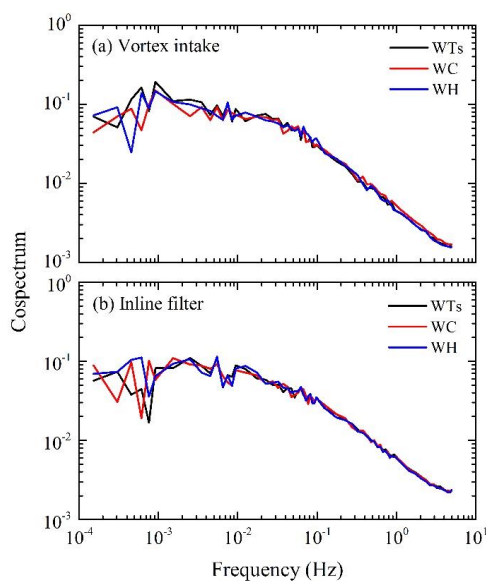454     (source: Campbell Scientific Inc., Logan UT, USA).

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456     **Figure 3.** Schematics of EC155 sampling systems with (a) an original in-line filter and (b) vortex

457     intake.

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**Figure 4.** Cospectra of the EC-system (EC155) equipped with vortex intake (a) and in-line filter (b).

WTs, WC, and WH are cospectra of vertical wind velocity with sonic temperature, $CO_2$, and $H_2O$.

Cospectra are calculated from high-frequency data at 10 Hz obtained from the Olympic Park. Data

points in the figure are binned averages from means of one-hour period (12:00-13:00 Beijing

Standard Time) for each day in April 2014 for the in-line filter-based EC measurements and in

August 2015 for the vortex intake-based measurements.

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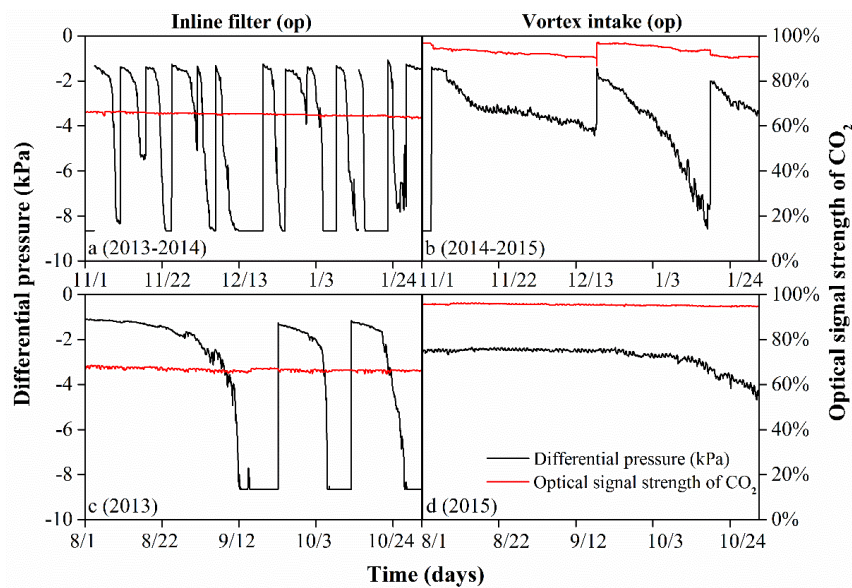


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467    **Figure 5.** Differential pressure (black line) and optical signal strength of $CO_2$ (red line) of the EC-

468    system (EC155) equipped with vortex intake as compared to an in-line filter at the Olympic Park

469    (op); sub-figures (a) and (b) are for periods of very hazy conditions, whereas sub-figures (c) and (d)

470    are for periods of low haze.

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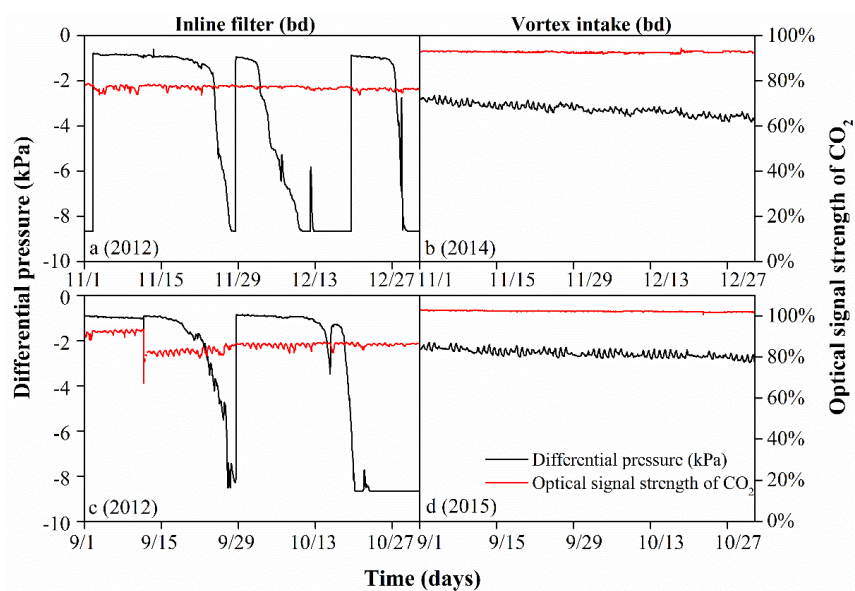


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473     **Figure 6.** Differential pressure (black line) and optical signal strength of $CO_2$ (red line) of the EC-

474     system (EC155) equipped with vortex intake as compared to an in-line filter at the Badaling Farm

475     (bd); sub-figures (a) and (b) are for periods of very hazy conditions, whereas sub-figures (c) and (d)

476     are for periods of low haze.