FluxPro as a realtime monitoring and surveilling system for eddy covariance flux measurement

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Abstract

To understand how terrestrial ecosystems respond to global climate change, researchers have globally measured the energy, water and carbon dioxide flux densities (F) globally over various types of vegetation by the eddy covariance (EC) method. However, the process of F calculation and the method of quality control and quality assurance (QCQA) are complex and site specific. Moreover, instantly maintaining remote EC flux measurement sites against instrumentation problems and administrative difficulties is laborious. To overcome these issues, particularly those of realtime F monitoring and prompt site management, FluxPro was created.

FluxPro consists of three functional systems: 1) a gathering system that transports EC measurements from various sites to the FluxPro management server; 2) a cooking system that computes F and its fractional uncertainty (ε) together with micrometeorological variables (V); and 3) a serving system that presents the results of the gathering and cooking systems as charts to be distributed over the internet in realtime. Consequently, FluxPro could become an appropriate system for realtime-multi-site management, since it not only automatically monitors F with ε and V but also continuously surveils EC sites, including copious information and an email alert system.

Key words: Eddy covariance measurement, FluxPro, Frictional uncertainty, Realtime-multi-site management.

1. Introduction

During the past few decades, the number of eddy covariance (EC) flux measurement sites, installed for measuring evapotran-
Sims, 2001) and carbon dioxide flux ($F_c$), has dramatically increased. Currently, over 500 such sites are distributed in ecosystems across the world (http://fluxnet.ornl.gov). Together with numerical simulations and satellite observations, EC measurements have assisted the colleagues to estimate the $E$ and $F_c$, exchanges between land surfaces and the atmosphere, and their fluctuations under global climate change, and vice versa (Baldocchi et al., 2001; Li et al., 2009; Lu et al., 2005; Jung et al., 2011; Kim et al., 2012). The outstanding contributions of EC measurement have been facilitated by the development of instruments and the integration of micrometeorological knowledge. Taking measurements in real-time will enable present estimations and predictions of $E$ and $F_c$ for the practical management of water and biomass resources over land surfaces.

Measurement is the process of determining the value of a physical quantity and its inaccuracy using customized experimental techniques and appropriate instruments (Rabinovich, 2005). EC measurements provide both the flux density ($F$) and its frictional uncertainty ($\varepsilon$); however, few studies have shown $\varepsilon$ on the basis of hourly $F$. Meanwhile, $\varepsilon$ is relevant in hybrid model-data fusion studies when measured data are limited, and methods for estimating the hourly $\varepsilon$ have been already proposed (Finkelstein and Sims, 2001). In addition, $\varepsilon$ provides the effective heterogeneity (Kim et al., 2011b), which is closely related to the Bowen ratio (Kim et al., 2014) representing land surface variability. Therefore, the real-time estimation of $\varepsilon$ with $F$ could be anticipated to contribute to the diminishment of the data gap of flux monitoring and the improvement of the forecasting capability (Sheffield et al., 2014) through data assimilation (Kato et al., 2013).

Since the first attempt to construct a real-time monitoring and simulation system (RTMASS) for EC measurements (Kim et al., 2003), communication technology has improved to the extent that EC measurements can be relayed from remote sites to the RTMASS server, and more technical developments are expected. Using the estimation method recommended by Kim et al. (2009, 2011b), $\varepsilon$ can be estimated for a quality control and quality assurance (QCQA) and a heterogeneity parameters in the EC measurements.

Considering the points so far, this study aims to introduce FluxPro as a convenient and appropriate utensil for monitoring $F$ and surveilling sites of continuous real-time EC measurements. We also report findings obtained throughout the FluxPro operation.

2. The structure of FluxPro

FluxPro integrates three functional systems: 1) the gathering system ($G$ system) acquires EC measurements from instruments installed at various remote sites; 2) the cooking system ($C$ system) estimates $F$ together with $\varepsilon$ and several micrometeorological variables ($V$) using the measurements gathered by the $G$ system; and 3) the serving system ($S$ system) delivers the estimates computed by the $C$ system over the internet in user-friendly formats.

2.1 $G$ system for gathering EC measurements

The $G$ system transports turbulence and micrometeorological time series from remote sensors installed at EC measurement sites to the $C$ system. The $G$ system consists of commercial hardware (measurement sensors and recordable loggers), and commercial and self-created software (telecommunication and telemonitoring applications).

2.1.1 Hardware instrumentation

The EC system of the $G$ system includes a three-dimensional sonic anemometer (CSAT3: Campbell Scientific, Utah, USA; DA-600: Kaijo Corporation, Tokyo, Japan; R3-50: Gill Instruments, Hampshire, UK), an open-path CO$_2$/H$_2$O gas analyzer (LI7500: LI-COR, Nebraska, USA or EC150: Campbell Scientific), and a measurement and control datalogger (CR1000, CR3000 or CR5000: Campbell Scientific) optionally equipped with}

![Fig. 1](image-url). Schematic of the three telecommunication routes in the gathering system. Boxes to the left and right of the gray arrows are local instruments and the FluxPro management server, respectively. The names or titles of devices are given in the bold font; the remaining text gives the name of the component. Black arrows denote a wired lines; gray arrows denote wired or wireless lines (CF: compact flash; COM: communication port; LAN: local area network).
with a compact flash (CF) module (CFM100 or NL115: Campbell Scientific). The anemometer and the analyzer are operated by a synchronous device for measurements (SDM), by which the turbulence time series of vectors, i.e., the longitudinal (u), lateral (v) and vertical (w) wind velocities, and scalars, i.e., the quantities (ξ) of temperature (T) and densities of CO2 and H2O (ρ, and ρe, respectively) at atmospheric pressure (p) are sensed at 10 Hz and directly recorded into the CF card installed in the data logger module. The net radiometer (CNR4: Campbell Scientific) and weather transmitter (WXST510: Campbell Scientific) are operated by an analog signal. The micrometeorological time series, i.e., the downward short- and long-wave radiation (Rn and Rs, respectively), the air temperature and vapor pressure (T, and e, respectively), and precipitation (P) are also sensed at 10 s intervals, and the 10 min mean is recorded onto the CF card.

The G system offers three telecommunication routes, as shown in Fig. 1. The first uses the Ethernet module (NL115). By this route, the time series saved at a CF card installed in the module is transported to the FluxPro server through an internet router connected to a commercial internet service provider. The second uses the Ethernet converter (CSE-H25: Sollae Systems, Seoul, Korea or NPort 5110A: Moxa, Taipei, Taiwan) to connect with the communication port (COM) as an alternative transport route instead of NL115. The final route uses the internet protocol (IP) gateway (OnCell G3100: Moxa), without the router as equipped in a standardized virtual private cellular network.

2.1.2 Software configuration

The global IP address (GIP) is best distributed to each local Ethernet device by either the first or second route, as described in Subsection 2.1.1. However, GIP limitations may restrict this information dissemination in practice. Therefore, it is recommended that the device installed at each telecommunication site be configured with a dynamic domain name system (DDNS) served by an online provider free of charge. Suitable choices are both GIP and DDNS, the IPPort option of LoggerNet (Campbell Scientific), a telemonitoring application that runs on Windows (Microsoft, Seattle, USA). In the third telecommunication route, the OnCell Central Manager (Moxa) is additionally installed in Windows, enabling telecommunication with OnCell G3100 using the Reverse Real COM Mode. The mode requires that the GIP address be assigned to the G system of FluxPro’s management server, where the Central Manager is installed. By means of the created virtual COM port of the Central Manager, the ComPort option of LoggerNet is configured.

A time series of turbulence and micrometeorological measurements recorded in the CF card of each remote site is regularly transported to the FluxPro server and is temporarily stored in a home directory folder named mdata using LoggerNet, which runs only on Windows. The home directory folder is directly referred by several functions of FluxPro running on Darwin (Apple, Cupertino, California, USA), described below. Therefore, for ease of data management, Windows should be installed on Darwin with VMware Fusion (VMware, California, USA) or Parallels Desktop (Parallels, Washington, USA).

2.1.3 Primary database

An additional role of the G system is to construct a database of turbulence and meteorological measurements that are conveyed from each of the remote sites. The measurements temporarily stored in mdata are moved to two home directory folders named odata and rdata. The odata folder stores the original data for one day for backup purposes only, while rdata stores the raw data for one hour to enable the F computation. Although the measured contents of odata and mdata are identical, rdata is converted to a UNIX file containing a time tag, u, v, w, T, ρ, ρe, p only, which are separated by a space separator. Both data set are physically placed in a storage configured RAID (redundant array of independent disks) 5 in the FluxPro server and are mirrored to a server located in another room for security backup purposes. The odata and rdata datasets can also be mirrored to the local server, which is managed by the principal investigator (PI). Local servers retain their own data sets of measurements collected from individual flux sites. In addition, the FluxPro can automatically send an alert email to the PI to check daily the content of the turbulence time series relayed from each site.

2.2 C system for cooking EC estimates

The F computation described in Kim et al. (2011b, a) is a fundamental function of FluxPro and is processed by the C system. Operating on Darwin, FluxPro is written in Bash (Bourne Again SHELL, http://www.gnu.org/software/bash/) and GFortran (GNU Formula Translating System, http://gcc.gnu.org/fortran/), both computing languages created by GNU (http://www.gnu.org). FluxPro, it contains three process procedures: 1) initial inspection of turbulence measurements to examine the availability of time series; 2) main computation of F and ε to estimate F and secure its credibility; and 3) supplementary calculation of V to validate the quality of F (namely, ε), and to describe the circumstances under which F is estimated.

2.2.1 Initial inspection

The inspection of a turbulence time series is carried out in the six following steps, yet some steps for fundamental corrections are omitted to guarantee a communal system required by FluxPro.

1) Spike correction: Vickers and Mahrt (1997) suggested that spiking events are limited to three or fewer consecutive points, and that three times of the standard deviation (σ) is a suitable threshold for spike detection in the turbulence time series. They replaced the spikes with interpolation between before and after the spike, imposing a 1% criterion on the tolerated number of spikes. In FluxPro, however, the spiking threshold is 5σ, and the spike is substituted by the mean of the time series to minimize measurement rejection by the threshold and the effect of the infill values on F.

2) Tilt correction: Finnigan (2004) recommended the planar-fit method for the coordinated transformation, FluxPro employs the double rotation method (Kaimal and Finnigan, 1994) because the estimation of planar-fit coefficients is insufficient for realtime monitoring.

3) Trend correction: The detrending of a time series is not performed in FluxPro.

4) Frequency correction: The high frequency correction is not performed in FluxPro because the classical spectral model is applicable only to low-lying vegetation in homogeneous environments (Massman and Clement, 2004), whereas FluxPro demands wide applicability.

5) Crosswind correction: No crosswind correction (Liu et al., 2004),
in integrating EC measurements, and various methods have been suggested (Falge et al., 2001). \( F \) year is given as
\[
F_{\text{year}} = \sum_{j=1}^{12} \sum_{k=0}^{23} J F_{ik},
\]
using a weighted mean diurnal variation such as
\[
F_{ik} = \frac{\sum_{j=1}^{J} \left( F_{ijk} - F_{ik} \right)^2}{\sum_{j=1}^{J} \epsilon_{ijk}^2},
\]
where \( J \) is one of 28, 29, 30 or 31 depending on the month, and \( i, j \) and \( k \) are indexes denoting the month, day and hour, respectively. The \( \sigma \) of the weighted mean of the uncertainty of \( F_{\text{year}} \) is defined as
\[
\sigma_{\text{year}} = \sum_{i=1}^{12} \sum_{k=0}^{23} J \sigma_{ik},
\]
where
\[
\sigma_{ik} = \frac{\sum_{j=1}^{J} \left( F_{ijk} - F_{ik} \right)^2}{\sum_{j=1}^{J} \epsilon_{ijk}^2}.
\]

This method is an additional improvement in making estimates of the annual integration when \( F \) gap is continuously longer than a couple of weeks, so we are developing a numerical model to fill the gaps with its output.

### 2.2.3 Supplementary calculation

\( \text{FluxPro} \) provides several customary supplementary \( V \) s to confirm the effect of a circumstance on \( F \) and the confidence of the \( F \) measurements. The estimated \( V \) s are described below:

1) Friction velocity:
\[
U_* = \sqrt{(u' w')^2 + (v' w')^2},
\]
The \( U_* \) is traditionally applied to understand turbulence intensity in the measured \( F \). Several studies adopted \( U_* \) as the QCQA parameter of EC measurements. However, \textit{FluxPro} uses \( \epsilon \) instead of \( U_* \), since the uncertainty information contained in \( \epsilon \) is more suitable for quality estimation than for a correction threshold.

2) Integral turbulence characteristics:
\[
\phi_\xi = \frac{\sigma_\xi}{U_*},
\]
where
\[
\sigma_\xi = \sqrt{\frac{w' \xi^2}{\epsilon}},
\]
\[
\xi_* = \frac{w' \xi}{U_*}.
\]
The \( \phi \) is the ratio of the standard deviation of a turbulence parameter to the turbulence flux. It is comparable to the atmospheric stability function known as the Monin-Obukhov similarity, which describes developed turbulence conditions (Kaimal and Finnigan, 1994; Foken and Wichura, 1996), while constant parameters remain contentious.
3) The atmospheric stability:

$$\zeta = \frac{z}{L},$$

where $z$ is the height above the zero-plane displacement, and $L$ is the Monin-Obukhov length, defined as

$$L = -\frac{g}{w_0} \frac{w' \theta'}{u' \theta'},$$

with potential temperature

$$\theta = T + 273.15 + \frac{\alpha}{c_p} \Delta z,$$

In Equation (17), $g$, $c_p$ and $\Delta z$ represent the acceleration due to gravity, the specific heat at constant pressure, and the height difference relative the 100 kPa level, respectively.

4) Correlation coefficient:

$$r_{wz} = \frac{w' z'}{\sigma_w \sigma_z},$$

It is also presented in FluxPro.

2.2.4 EC database

The $F$, together with $\varepsilon$ and $V$, is computed every hour (Table 1). The results of each site are saved in the edata folder within the home directory. The edata is publicly linked to the FluxPro webpage (e.g. http://matthew.niaes.affrc.go.jp/amen/fluxpro/annual_ct007.html) at the discretion of the site PI. However, a edata which is not allowed open in public by the PI posted to the PI alone, overrides the FluxPro’s policy that data be made publicly available.

2.3 S system for serving over internet

Various $F$ and $V$ charts monitored by the G system and computed by the C system are scripted in HTML (http://www.w3.org/html/) and Bash including the GMT (Generic Mapping Tools, http://gmt.soest.hawaii.edu) commands and ImageMagic (http://www.imagemagick.org) for the FluxPro webpage. Each cart is linked to four tabs (i.e. flux, raw, meteo and annual), visible in the left frame of the FluxPro on AgroMeteorological Nowcaster webpage (http://matthew.niaes.affrc.go.jp/amen/), and is renewed on an hourly basis.

2.3.1 The flux: Fundamental analysis of $F$ and $\varepsilon$

<table>
<thead>
<tr>
<th>Column</th>
<th>Variables</th>
<th>Abbreviation</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>01</td>
<td>Timetag</td>
<td>doyhh</td>
<td></td>
</tr>
<tr>
<td>02</td>
<td>Sensible heat flux</td>
<td>H</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>03</td>
<td>Fractional uncertainty of $H$</td>
<td>$\varepsilon_H$</td>
<td>dimensionless</td>
</tr>
<tr>
<td>04</td>
<td>Latent heat flux</td>
<td>$L$</td>
<td>W m$^{-2}$</td>
</tr>
<tr>
<td>05</td>
<td>Fractional uncertainty of $L$</td>
<td>$\varepsilon_L$</td>
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</tr>
<tr>
<td>06</td>
<td>Carbon dioxide flux</td>
<td>$F_c$</td>
<td>mg m$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>07</td>
<td>Fractional uncertainty of $F_c$</td>
<td>$\varepsilon_{Fc}$</td>
<td>dimensionless</td>
</tr>
<tr>
<td>08-09</td>
<td>Wind direction</td>
<td>$W_d$</td>
<td>°</td>
</tr>
<tr>
<td>10</td>
<td>Atmospheric stability</td>
<td>$\zeta$</td>
<td>dimensionless</td>
</tr>
<tr>
<td>12</td>
<td>Frictional velocity</td>
<td>$u*$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>13</td>
<td>Variability in $w$</td>
<td>$\phi_w$</td>
<td>dimensionless</td>
</tr>
<tr>
<td>14</td>
<td>Variability in $\theta$</td>
<td>$\phi_{\theta}$</td>
<td>dimensionless</td>
</tr>
<tr>
<td>15</td>
<td>Variability in $\rho_w$</td>
<td>$\phi_{\rho_w}$</td>
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</tr>
<tr>
<td>17</td>
<td>Correlation coefficient between $u$ and $w$</td>
<td>$r_{uw}$</td>
<td>dimensionless</td>
</tr>
<tr>
<td>18</td>
<td>Correlation coefficient between $w$ and $\theta$</td>
<td>$r_{w\theta}$</td>
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</tr>
<tr>
<td>19</td>
<td>Correlation coefficient between $w$ and $\rho_w$</td>
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<tr>
<td>20</td>
<td>Correlation coefficient between $w$ and $\rho_c$</td>
<td>$r_{w\rho_c}$</td>
<td>dimensionless</td>
</tr>
<tr>
<td>21-25</td>
<td>Mean of $u$</td>
<td>$\mu_u$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>26</td>
<td>Standard deviation of $u$</td>
<td>$\sigma_u$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>27</td>
<td>Mean of $v$</td>
<td>$\mu_v$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>28</td>
<td>Standard deviation of $v$</td>
<td>$\sigma_v$</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>29</td>
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<td>30</td>
<td>Standard deviation of $w$</td>
<td>$\sigma_w$</td>
<td>m s$^{-1}$</td>
</tr>
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<td>31</td>
<td>Mean of $T$</td>
<td>$\mu_T$</td>
<td>°C</td>
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<td>32</td>
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<td>33</td>
<td>Mean of $\rho_c$</td>
<td>$\mu_{\rho_c}$</td>
<td>mg m$^{-3}$</td>
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<td>34</td>
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</tr>
<tr>
<td>35</td>
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<td>$\mu_{\rho_w}$</td>
<td>g m$^{-3}$</td>
</tr>
<tr>
<td>36</td>
<td>Standard deviation of $\rho_w$</td>
<td>$\sigma_{\rho_w}$</td>
<td>g m$^{-3}$</td>
</tr>
<tr>
<td>37</td>
<td>Mean of $\rho_w$</td>
<td>$\mu_{\rho_w}$</td>
<td>g m$^{-3}$</td>
</tr>
</tbody>
</table>

The meanings of the turbulence time series, i.e. $u$, $v$, $w$, $T$, $\rho_c$ and $\rho_w$ are provided in Subsection (2.1.1); NF: Not fixed.
Five representative charts of $F$ and $\epsilon$ together with traditional QCQA parameters are analyzed under the $S$ system tab flux on the FluxPro webpage (Table 2 and Figs. 2-6).

1) The week chart (Fig. 2) presents the $F$ trends of sensible and latent heat fluxes ($H$ and $L$E, respectively) and $F_c$ over one week, together with $F$ trends of $W_d$, $\zeta$ and $u_z$. The whiskers written in $F$ trends denote $\pm 1\sigma$ as an absolute uncertainty. Both $F$ and $F$ trends are colored according to the scale of $\epsilon$ and Taylor’s parameter $\tau$, respectively. The $\tau$ is given by

$$\tau = \frac{2\sigma_M}{M},$$

where

$$M = \sqrt{\mu^2 + \nu^2}.$$  \hspace{1cm} (19)

The range in the $F$ trend, namely $\epsilon \pm 3\sigma$, is stated in the left-upper region of each subchart. The range is calculated from the hourly fluctuations in Fig. 3. Assuming Taylor’s Hypothesis (Willis and Deardorff, 1976; Stull, 1988), the $\tau$ is fixed (between 0.6 and 1.4) over the range in the $F$ trend, indicating that the eddy scarcely changes as it advects past the sensor. This situation satisfies the measurement assumption in the EC method; namely, that the flow is not distorted by obstacles or an insufficient fetch length. The vertical gray region denotes where turbulence measurements were missing or rejected as out of range ($|L$E or $H < -300$ or $|L$E or $H > 1000$ W m$^{-2}$, $F_c < -4.0$ or $F_c > 1.5$ mg m$^{-2}$ s$^{-1}$, $\sigma_{L$E,$H} > 70$ W m$^{-2}$, $\sigma_{\epsilon} > 0.28$ mg m$^{-2}$ s$^{-1}$, and $\epsilon > 1.0$) even in regions of acceptable turbulence computations. The two numerals in the right-upper side of each subchart of Fig. 2 denote the $F$ acquisition ratio over one week within the specified $\epsilon$ range. The upper numeral specifies the total $F$ ratio (obtained by summing all circles); the lower numeral (in color) sums only the measured fluxes within the $\epsilon$ range (colored circus in the subplots).

2) The chart named epsilon (Fig. 3) plots the relationship between $\epsilon$ and $F$ (scaled by $\zeta$) in each bin of the $\epsilon$ histogram. The dotted line and grey region indicate the median $\epsilon$ and its 1sigma deviation, respectively, over the week-long period. Kim et al. (2011a) defined an expected value of $\epsilon$ called the tolerance (see Equation (2)), which combines the random uncertainty $\delta_i$ (\(\approx 0.07\), dashed line Fig.3) with an illegitimate uncertainty $\delta_y$. The $\delta_i$ is similar to white noise and is therefore considered constant, while $\delta_y$ irregular and produced by deviations from an illegitimacy of the EC measurement assumption. The numerals in the bottom-right corner of sub charts specify the weekly $\epsilon \pm \sigma$, and whereas those in the top-right corner of the insets (displaying the histograms) specify the kurtosis (upper) and skewness (lower).

3) The sigma chart (Fig. 4) plots the relationship between $\sigma$ and $F$ (scaled by $\zeta$) over one week. The subcharts in the right column are enlargements of the regions delineated by rectangles in the corresponding left subcharts. The diagonals in the right subchart denote the line of 1.00 by 0.07 decided by $\delta_i$ described in the previous section. The relationship between $\sigma$ and $F$ is clearly linear at $H$. Such a linear relationship has been previously reported by Finkelstein and Sims (2001), Hollinger and Richardson (2005), Vickers et al. (2009) and our group (Kim et al., 2008, 2009, 2011a,b). This information is significant not only for the QCQA of $F$ but also for understanding the relationship between $\delta_i$ and $\delta_y$ in $\epsilon$, where the distance from the diagonal line denotes the magneto content of $\delta_i$ in $\delta_y$. Interestingly, $\epsilon$ and $u_z$ are unrelated (data not shown) and $\epsilon$ lower than 0.07 is exist (details are presented at Subsection 3.2).

4) The variability chart (Fig. 5) presents $\phi$ (refer to Subsection 2.2.3) and the correlation coefficient $r$ against $\zeta$ (scaled by $\epsilon$) over one week. The dashed and dotted lines (be specified to $u$ and $\theta$, respectively) within the graduated gray region ($\pm 15\%$ deviation interval from the lines) denote the lines of

$$\phi_w = \left\{ \begin{array}{ll} 1.25(1+0.2\zeta), & 0 < \zeta \leq 1 \\ 1.25(1 + 3.0\zeta), & -2 \leq \zeta \leq 0 \end{array} \right.$$  \hspace{1cm} (21)

and

Table 2. List of charts in serving system of FluxPro (http://matthew.niaes.affrc.go.jp/amen).

<table>
<thead>
<tr>
<th>Tab</th>
<th>Chart</th>
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*24 panels (hourly data) are presented for one day; **Panels are presented for every measured year.
\[ \phi_\theta = \begin{cases} 
2(1+9.5\zeta) & , -2 \leq \zeta \leq 0 \\
2(1+0.5\zeta)^{-1} & , 0 \leq \zeta \leq 1 
\end{cases} \]  \quad (22)

in the $\phi$ plots, and

\[ r_{u\theta} = -0.35, \quad -1 \leq \zeta \leq 1 \]  \quad (23)

and

\[ r_{w\theta} = \begin{cases} 
0.5, & -2 < \zeta < 0 \\
0, & \zeta = 0 \\
-0.4, & 0 < \zeta < 1 
\end{cases} \]  \quad (24)

in the $r$ plot (Kaimal and Finnigan, 1994). By analyzing $\phi$ and $r$, we obtain significant information on the developed turbulence, since both parameters are sensitive to violated stationarity caused by limitations of the surface layer height, gravity waves, internal boundary layers, flow distortion, and loss of high frequency flux (Foken et al., 2004; Massman and Clement, 2004). The variability (scaled with $u_*$), $\phi_\theta$ and $\phi_e$ are also displayed on the FluxPro website. Interestingly, the close relationship between $\phi_\theta$ and $\varepsilon$ is shown in mid-subchart of Fig. 5, then more analysis will be represented at Subsection 3.2.

5) The variation chart (Fig. 6) presents the mean diurnal variation of $IE$ and $F_i$ over one week. The closed circles and light blue regions denote the weekly weighted mean trends and its 1$\sigma$ on the basis of Equation (8) and (10), respectively, over the weeklong period (in the equations, $J$ is set to 7). The circles and their whiskers denote an arithmetic mean and its 1$\sigma$, respectively. The vertical bars at the bottom of the subplots indicate the hourly acquisition ratios (ARs) over one week. The other type of variation chart displays the $H$ and $IE$. Interestingly, the arithmetic mean of $F_i$ is always smaller than the weighted mean at a given site. This result might be the clue of imbalance issue of EC measurement, because the weighted mean value generally exceeds the arithmetic mean.

Fig. 2. The chart named week in the flux cluster of FluxPro, showing the temporal trends of $H$, $IE$ and $F_i$ with 1$\sigma$ whiskers. Trends of $W_u$, $\zeta$ and $u_*$ are also plotted. Turbulence measurements were taken from 00:00:00 0 Hz on 9 April to 23:59:59 9 Hz on 15 April, 2014 at a tangerine orchard in Jeju, Korea. Title (left to right) gives: site ID_block size (min) of estimated $F_i$_start year–start month–start day_start hour~end year–end month–end day_end hour. Details are given in 1) of Subsection 2.3.1.
2.3.2 The raw analysis of turbulence time series

To facilitate identification of abnormal signals, the turbulence time series is presented in both the time and frequency domains under the S system tab on the FluxPro webpage (Table 2 and Figs. 7–8):

1) The series chart (Fig. 7) presents the auto- and cross-correlation functions ($\kappa_{\text{auto}}$ and $\kappa_{\text{cross}}$, upper left and right sub-charts) together with the turbulence time series of wind vectors and quantity scalars over one hour (plotted below the correlation sub-charts). The $\kappa$ determines the quality of the turbulence series on the basis of the atmospheric similarity and stationarity, and the time series of the spike corrections and trend analysis. In the auto-correlation plot, the purple, pink, orange, red, green and blue lines denote $u$, $v$, $w$, $T$, $\rho_c$ and $\rho_w$, respectively. The dark red, green and blue lines in the cross-correlation plot denote the $\kappa_{\text{cross}}$ between $w$ and $T$, $\rho_c$ and $\rho_w$, respectively. The dashed lines are proportional to $e^{-t/\tau}$, denoting the $\kappa$ under ideal turbulent conditions according to the ergodic and Taylor’s hypothesis. If the calculated $\kappa_{\text{cross}}$ approaches this line, the turbulence exhibits high stationarity, and the $F$ estimated from the turbulence measurement is of higher quality, even though it is just empirical line so far.

The midline in each of the series sub-charts indicates the mean $\mu$ of the hourly data (the value is indicated parallel to the y-axis at the opposite side of the range indicator). The $\mu$ and their associated $\sigma$ are also printed at the bottom of the charts, along with the total numbers of detected spikes and their ratios. The error and sigma spikes are defined at no data and over $\pm 5\sigma$ from $\mu$, respectively. Spikes are indicated by black arrows on the time series charts.

The five-digit numbers following the tabulated results are the
time tags, indicating the day of year (three digits) and the hour of day (two digits). These are followed by the $H$, $LE$ and $F_c$ with those $\varepsilon$, the $\phi$ of $T$, $\rho_e$ and $\rho_w$, the $r$ between $w$ and $T$, $\rho_c$ and $\rho_w$, and instationarity ($\delta$) calculated in that order. The $W_d$, $\zeta$ and $u^*$ are expressed as $W_d$, $\zeta$ and $u^*$, respectively (refer to Section 2.2.3).

2) The upper-left subchart of the spectrum chart (Fig. 8) presents normalized spectra of the wind vectors ($\beta_\alpha(f)/\sigma^2_\alpha$), where $f$ and $S(f)$ are the frequency and spectral densities, respectively, and the subscript $\alpha$ denotes $u$, $v$, and $w$). The upper-right subchart displays the scalar quantities ($\beta_\alpha(f)/\sigma^2_\alpha$, where $\zeta$ is $T$, $\rho_c$, and $\rho_w$), and the normalized cospectra ($\beta_{w\zeta}(f)/\sigma_w^2\sigma_{\zeta}^2$) are plotted at the lower left. The $S(f)$ is calculated by issuing the `spectrum1d` command in GMT, with the ensemble size and spacing set to 1024 and 0.1, respectively. The line in each subchart displays the expected spectral slope of the spectra ($f^{-2/3}$) and cospectra ($f^{-4/3}$), by which users can check the spectral similarity within an inertial subrange of turbulence measurements. The lower-right plot is the coherence ($\text{Coh}_{w\zeta}$), which presents the $\delta$ relative to $f$. This quantity is also calculated by `spectrum1d` under the same spectral conditions. The line colors are interpreted as described in Fig. 7. The theoretical background and the relationships between the spectral analysis and atmospheric turbulence are detailed in Chapter 8 and 9 in Stull (1988) and Chapter 2 and 3 in Kaimal and Finnigan (1994).

2.3.3 The meteo: the $V$ to support $F$ analysis

When considering environmental effects in the $F$ analysis, it is useful to display the $V$ variables. These variables are displayed as four charts under the $S$ system tab `metro` on the FluxPro webpage (Table 2 and Figs. 9–12): 1) The radiation chart (Fig. 9) plots the radiation components, (i.e. the upward and downward short- and long-wave components, denoted as $R_{\text{up}}, R_{\text{down}}$ and $R_{\text{up}}$ and

![Fig. 4.](image)
2) The meteorology chart (Fig. 10) plots the air and canopy temperatures ($T_a$ and $T_c$, respectively), the relative humidity ($\text{RH}$), wind speed and wind direction ($W_s$ and $W_d$, respectively), the precipitation ($P$), and the vapor pressure ($e$) throughout the same week.

3) The EC chart (Fig. 11) provides additional $T_a$, $W_s$, $\rho_w$, and $\rho_e$ information, along with their $\pm \sigma$ measured by turbulence sensors. From these data, users can extract the background conditions at the EC site of interest.

4) The windrose chart (Fig. 12) presents the results of the $W_d$ and $W_s$ analyses as windroses and histograms. The green windrose is weighted by $W_s$. In both windroses, $W_d$ is divided by 10˚, and the magnitudes are normalized with respect to the most frequent $W_d$, which is set to 1.0.

2.3.4 The annual: seasonal and inter-annual analysis of $F$

To assess the seasonal and inter-annual variability of $F$, the user can display the hourly and monthly $F$ throughout one year under the $S$ system tabs annual on the FluxPro webpage (Table 2 and Figs. 13–14):

1) The trend chart (Fig. 13) presents the monthly and hourly trends in $H$, $IE$, and $F_c$ over one year. The top subchart displays the integrated values of $H$ (dark red), evapotranspiration $ET$ (dark blue) and net ecosystem exchange $NEE$ (dark green) throughout the year, together with their uncertainties. In the hourly display, $F$ is scaled by $e$ and the numerals at the top-left and top-right of the subcharts state the uncertainties and acquisition ratios, respectively, during the analyzed year.

2) The contour chart (Fig. 14) displays hourly contours of $H$ and $IE$ throughout one year. This is useful if a user desires to know the daily and monthly variability of these parameters. The $F_c$ contour chart is also visible at FluxPro webpage (the chart is not shown here).
3. Results and Discussion

This section presents specific results of the FluxPro processing and ε analysis of EC measurements, and discusses their importance. The data policy of FluxPro is also presented for readers who are interested in our EC measurements and FluxPro code.

3.1 General

Since its launch in 2009, FluxPro has been subject to ongoing systems development and continuous site participation, EC measurements from 16 sites in Asia can now be accessed at the AgroMeteorological Nowcaster website links http://matthew.niaes.affrc.go.jp/amen/top/top.htm and http://matthew.niaes.affrc.go.jp/amen/sites/sites.htm. FluxPro has become a basic system for the AgroMeteorological Nowcaster (http://matthew.niaes.affrc.go.jp/amen/) enabling evapotranspiration and net ecosystem exchange estimates at any spatiotemporal scale. The top of the Nowcaster homepage features two tabs, FluxPro and sFluxPro. The first is linked to a full version of the FluxPro website presenting data from the entire 16 sites in the form of various useful charts (Subsection 2.3). The sFluxPro links to a simpler version of FluxPro, presenting 10 sites in the form of weeks and variation charts (http://matthew.niaes.affrc.go.jp/amen/simple/simple.htm). The sFluxPro allows access to realtime measurements from ten sites, enabling a quick check for site management and maintenance, whereas FluxPro allows access to an additional six sites where the measurements are manually acquired because telecommunication devices and/or financial support sources are lacking.

Any investigator interested in measurements at each individual site can access the measurements and information provided by FluxPro, not only for his or her own site but also for sites managed by others participating in FluxPro. Visitors can also scrutinize the FluxPro measurements to enhance understanding in their own fields. Specifically, an investigator managing his own site can view FluxPro-generated charts online and can receive automatic email alerts, circumventing the need to undertake troublesome instrumental or administrative procedures to manage and maintain his own remote site. Moreover, any investigator or visitor can download FluxPro measurements of special interest, and use them in their own scientific quests while investing minimal effort in site management, measurement inspection, and chart presentation. Charts comparing measurements at different sites are also available for comparative purposes. Figure 15 is an example of a chart obtained from the AgroMeteorological Nowcaster website (http://matthew.niaes.affrc.go.jp/amen/top/top.htm). This information is particularly useful to colleagues undertaking an integration or consolidation analysis of realtime measurements acquired at various sites.

Fig. 6. One of the variation charts in the flux cluster of FluxPro, showing the mean diurnal variation of LE and Fc derived from the dataset of Fig. 2. Details are given in 5) of Subsection 2.3.1.
Inspection of EC measurements is necessary for assessing the reliability of the measurements. A traditional inspection involves a stationary test, an integral turbulence test, and footprint analysis (Foken et al., 2004). The inspection reveals whether measurements obtained under real environmental conditions approach the theoretical assumptions underlying empirical criteria. The $\varepsilon$ parameter adopted by FluxPro (Figs. 3, 2) is based on the statistical background and rare empirical criteria (Fuller, 1996; Bendat and Piersol, 2000; Finkelstein and Sims, 2001) in routine QCQA and uncertainty analysis, as well as on traditional considerations. Time trends (Fig. 7) and spectra and cospectra (Fig. 8) of turbulence processed on an hourly basis ensure consistent and reliable $F$ estimation. Therefore, it is possible to consider that the inspection produced by FluxPro could be profitable for various EC measurements using diverse sonic anemometers and gas analyzers under suitable corrections applying to FluxPro for the instruments.

Fig. 7. One of the series charts in the raw cluster of FluxPro, showing the raw data analysis of turbulence measurements taken from 10:00:00 0 Hz to 10:59:59 9 Hz on 14 April, 2014 at a tangerine orchard in Jeju, Korea. Details are given in 1) of Subsection 2.3.2.
Fig. 8. One of the *spectra* charts in the *raw* cluster of *FluxPro*, showing the spectral analysis of the data in Fig. 7. Details are given in 2) of Subsection 2.3.2.

Radiation

Fig. 9. The *radiation* chart in the *metro* cluster of *FluxPro*, showing the diurnal cycle of the radiation components from 00:00:00 on 9 April to 23:50:00 on 15 April, 2014, at a tangerine orchard in Jeju, Korea. Details are given in 1) of Subsection 2.3.3.
Fig. 10. The meteorology chart in the metro cluster of FluxPro, showing the diurnal cycle of the meteorological components over the period specified in Fig. 9. Details are given in 2) of Subsection 2.3.3.

Fig. 11. The ec chart in the metro cluster of FluxPro, showing the diurnal cycle of $\mu \pm \sigma$ derived from the dataset of Fig. 2. Details are given in 3) of Subsection 2.3.3.
Fig. 12. The windrose chart in the metro cluster of FluxPro, showing the windroses (top) and histograms (bottom) of $W_d$ and $W_s$ data over the period specified in Fig. 9. Details are given in 4) of Subsection 2.3.3.

Fig. 13. The trend chart in the annual cluster of FluxPro, showing the monthly and hourly $F$ trends throughout 2013 in a cassava field at Tak, Thailand. Details are given 1) of Subsection 2.3.4.
Finally, the covariance of turbulences enables temporary $F$ estimation by the data logger itself. However, this option is not recommended because the calculation consumes significant CPU time; consequently, regular gaps may appear in the turbulence data. In addition, the procedure may yield an irregular integer output rather than a real number, and the effect on the turbulence spectrum may not be clarified. Therefore, a data logger exclusively devoted to recording the turbulence data should be installed to

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure14.png}
\caption{One of the contour charts in the annual cluster of FluxPro, showing the variation in $H$ and $LE$ derived from the dataset of Fig. 13. Details are given in 2) of Subsection 2.3.4.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure15.png}
\caption{Sample charts comparing of the mean diurnal variation of $LE$ and $F_c$ from 09:00 on 18 March to 08:59 on 24 March, 2014. Data were collected from a paddy field in Rachaburi, Thailand (prt007), Mase in Japan (pmj003) and Mymensingh in Bangladesh (pmb003).}
\end{figure}
3.2 Uncertainty in the FluxPro estimates

Any measured physical quantity representing some property of an object contains uncertainty introduced by inherent flaws in the measuring instrument. In other words, the inaccuracy of a measured quantity reflects the quality of the measurement. The uncertainty of measured value specifies an interval within which the true value lies with a given probability (Rabinovich, 2005). Therefore, knowing the uncertainty can be equally or perhaps more important than knowing the value itself. For this reason, FluxPro provides both the values and uncertainties of hourly $F$ estimates. The $F$s are then averaged or integrated over weekly, monthly and yearly timeframes by propagating the hourly uncertainty as described in Subsection 2.2.2. The resulting $e$ value is about 10%–30% (minimum about 5%–7%) over the entire set for investigative sites in FluxPro. The information could be easily compared with $F$ estimated by numerical models or satellite analysis based on statistical significance.

Atmospheric turbulence characterizes a similarity, and has a specific function of $\zeta$. Therefore, this function has been traditionally used for QCQA of EC measurement. Comparing $e$ and $\phi$ (Figs. 16, 5), we observe that $e$ could provide an alternative scaling parameter for QCQA of EC measurements. In fact, $e$ might prove more useful than $\phi$ because it contains information of statistical uncertainty in the EC measurements. As shown in Fig. 16, the minimum uncertainty in the EC measurements is approximately 7% under neutral conditions, because the $y$ intercept of $e$ is $\approx 0.07$ when $\phi = 2$ where $F$ is measured under ideally turbulence conditions. This result suggests that every EC measurement includes 7% uncertainty under neutral conditions; moreover, it sug-

![Fig. 16. Relationship between $e$ and $\phi$ based on the dataset of Fig. 2.](image-url)
gests that the uncertainty is a function of $\zeta$; even though this contrasts with previous studies (Kim et al., 2008, 2009, 2011a,b), in which the minimum uncertainty was regarded as constant.

Lastly, uncertainty information contains not only the inherent inaccuracy in $F$ but also the effective heterogeneity $\eta$ in the EC measurements. This hypothesis, suggested by Kim et al. (2011b) and Kim et al. (2014), implies that $\eta$ requires evaluation over a spatial distribution of $F$.

3.3 Data policy

The basic philosophy of FluxPro is to encourage data sharing. Every EC measurement integrated by FluxPro is available to any parties interested in our measurements, providing that they honor the site investigators engaged in flux observations. Every member of the FluxPro committee believes that every measurement collected by colleagues around the globe is a very valuable scientific resource, and that the ethical use and publication of measurements is the right and duty of everyone. Therefore, FluxPro sincerely encourages colleagues to access the FluxPro measurements, and report their interpretations and analyses in appropriate scientific publications. During contemplation and analysis, FluxPro allows users to inform each PI of flux measurement sites, and acknowledges or offers author participation when a manuscript is submitted for publication. A few sites are excluded from direct downloads of measurements from the FluxPro website. Nevertheless, visitors can access the measurements suitable for their own scientific projects with the consideration and permission of the site PI. Finally, FluxPro code can be requested via an email (wonsik@affrc.go.jp) on the basis of GNU philosophy.

4. Conclusions

We conclude this paper by summarizing the benefits of FluxPro.

1) FluxPro monitors the flux density ($F$), its uncertainty ($\varepsilon$), and several affiliated micrometeorological variables ($V$) in an internet webpage in realtime. Surveilling these measurements, FluxPro also manages multiple eddy covariance (EC) flux measurement sites with features that conveniently deal with $F$ computation and promptly cope with management disturbances.

2) FluxPro comprises a gathering system, which acquires EC measurements from each site and relays them to the FluxPro management server; a cooking system that computes $F$, $\varepsilon$ and $V$; and a serving system that presents FluxPro results online and in an accessible format for colleagues in several disciplines.

3) FluxPro is designed to estimate $\varepsilon$ of $F$, which is essential for quality control and quality assurance, to estimate land surface heterogeneity, and to weight the averaged and integrated $F$ estimate. The $\varepsilon$ might be one of the parameters of Monin-Obukhov similarity.

4) FluxPro database storing the computed $F$ and $V$ and the primary turbulence measurement is freely available for investigation by interested parties via internet download and email request.

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References


