The Effect of Coordinate Rotation on the Eddy Covariance Flux Estimation in a Hilly KoFlux Forest Catchment

Renmin Yuan, Minseok Kang, Sungbin Park, Jinkyu Hong, Dongho Lee, and Joon Kim

1Dept. of Atmospheric Sciences, Yonsei Univ., Seoul, 120-749, Korea
2Lab. for Environmental Physics, Dept. of Crop & Soil Sciences, University of Georgia,
1101 Experiment Street, Griffin, GA 30228, USA

(Received March 29, 2007; Accepted June 11, 2007)

ABSTRACT

The Gwangneung KoFlux supersite, located in a rugged mountain region, is characterized by a low wind speed due to a mountain-valley circulation and rolling terrain. Therefore, it is essential to understand the effect of coordinate rotation on flux measurements by the eddy-covariance method. In this paper, we review the properties of three orthogonal coordinate frames (i.e., double, triple, and planar fit rotations) and apply to flux data observed at the Gwangneung supersite. The mean offset of vertical wind speed of sonic anemometer was inferred from the planar fit (PF) coordinate rotation, yielding the diurnal variation of about ±0.05 m s⁻¹. Double rotation (\(\vec{v} - \vec{w} = 0\)) produced virtually the same turbulent fluxes of heat, water, and CO₂ as those from the PF rotation under windy conditions. The former, however, resulted in large biases under calm conditions. The friction velocity, an important scaling parameter in the atmospheric surface layer, was more sensitive to the choice of coordinate rotation method.

Key words: KoFlux, Gwangneung supersite, Double rotation, Planar fit, Friction velocity

INTRODUCTION

Long term measurements of surface-air exchanges by the eddy covariance depend on the accurate application of this technique to diverse conditions of the study site. Over tall canopies and in complex terrain, for example, surface fluxes may contain significant contributions at much lower frequencies (i.e., at periods much longer than the typical averaging period of 15 - 30 min) than expected from classical studies (Finnigan et al., 2003). Therefore, rotating coordinates every period (e.g., < 30 minutes) may lead to a systematic underestimation of the surface exchange. Typical coordinate rotation has been used for aligning the sensor perpendicular to the earth gravity over a flat terrain surface every averaging time (Tanner and Thurtell, 1969; Wesely, 1970). However, this natural wind system has theoretical limitations at non-ideal sites because it assumes a 1-dimensional approximation to the surface-layer mass/energy balance such that the sensor tilt is the only source of mean vertical motion, thereby forcing mean vertical flows to be zero (Lee et al., 2004). Particularly, in a mountain region, mesoscale circulation (e.g., mountain-valley circulation) and
synoptic air systems can generate the mean vertical motion and lateral Reynolds stress (Baldocchi et al., 2000). Furthermore, because of finite averaging period, in the natural wind system, the random sampling error of surface fluxes is relatively larger under light wind conditions (Wilczak et al., 2001). Over a complex terrain, the rotation to the natural wind system is contaminated not only by a sensor location bias, electronic offset, and flow distortion, but also by advective fluxes.

Recently, several rotation methods were proposed to consider the terrain variation at non-ideal sites (e.g., Paw U et al., 2000; Wilczak et al., 2001). These new rotations calculate the mean streamline from an ensemble of observation data over weeks or longer. In particular, planar fit (PF) rotation by Wilczak et al. (2001) statistically provides the sonic anemometer offset, and therefore the instrumental offset can be eliminated in the flux calculation. Furthermore, the PF rotation can be used in assessing the 2- and 3-dimensional flow field like vertical advections.

The KoFlux program (http://www.koflux.org) was launched in 2001 for understanding the surface-air exchanges of energy, water, and CO₂ in key ecosystems of Monsoon Asia and a supersite was built in Gwangneung forest (Kim et al., 2006). Noticeably, most terrestrial ecosystems are located in heterogeneous and complex terrain in Korea. The Gwangneung supersite is also located in a forested mountainous landscape. The observation and numerical modeling at the Gwangneung supersite revealed that a mountain-valley circulation is dominant and that non-zero mean vertical motion is possible with low mean wind speed (≤ 2 m s⁻¹) at 20 m above the canopy top (Hong and Kim, 2005). Thus, it is critical to investigate the effects of coordinate frames on the surface flux estimation in the KoFlux program.

This paper is organized as follows. First, we briefly review the three coordinate rotation methods, followed by the site description. Then, we examine an appropriate averaging time period for planar fit rotation and compare the computed turbulent fluxes from different coordinate frames. Finally, summary and conclusions are provided.

II. MATERIALS AND METHODS

2.1. Coordinate rotations

The most commonly applied technique for determining the angles necessary to place the sonic anemometer into a streamwise coordinate system (i.e., natural wind system) involves double rotations (DR) (Tanner and Thurtell, 1969; Wesely, 1970; Kaimal and Finnigan, 1994; Lee et al., 2004). By double rotations, the x-axis is aligned to the mean flow and the z-axis is perpendicular to the underlying surface as a right-hand system. The DR aligns the y-axis with the mean wind vector at the end of each averaging period. Therefore, the natural wind system allows us to calculate the online surface fluxes based on the assumption that all atmospheric quantities vary only in the vertical direction.

The first rotation sets \( \vec{v} = 0 \) so that wind components after the first rotation are given by:

\[
\begin{bmatrix}
  u_1 \\
  v_1 \\
  w_1
\end{bmatrix} =
\begin{bmatrix}
  \cos \theta & \sin \theta & 0 \\
  -\sin \theta & \cos \theta & 1 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  u_w \\
  v_w \\
  w_w
\end{bmatrix}
\]

where \( u, v, \) and \( w \) are longitudinal, lateral, and vertical wind components, respectively; \( \theta = \tan^{-1}(v_w/u_w) \); and the subscripts \( w \) and 1 denote wind components before and after the first rotation, respectively. The second rotation sets \( \vec{w} = 0 \) so that the final velocities are then given by:

\[
\begin{bmatrix}
  u_2 \\
  v_2 \\
  w_2
\end{bmatrix} =
\begin{bmatrix}
  \cos \phi & 0 & \sin \phi \\
  0 & 1 & 0 \\
  -\sin \phi & 0 & \cos \phi
\end{bmatrix}
\begin{bmatrix}
  u_1 \\
  v_1 \\
  w_1
\end{bmatrix}
\]

where \( \phi = \tan^{-1}(w_v/u_v) \) and subscript 2 denotes wind components after the second rotation.

Implicitly, the DR assumes that the mean wind direction is the same as the direction of Reynolds stress. That is, \( \vec{w} = 0 \) after the alignment of \( x \)-axis into mean flow. The third rotation (TR) was proposed to align mean flow into mean Reynolds stress. In this third rotation, the new \( y \)- and \( z \)-axes are rotated around \( x \)-axis until the cross-stream stress becomes zero (i.e., \( \vec{w} = 0 \)) and the matrix for the third set of rotation equations then becomes:

\[
\begin{bmatrix}
  u_3 \\
  v_3 \\
  w_3
\end{bmatrix} =
\begin{bmatrix}
  1 & 0 & 0 \\
  0 & \cos \varphi & \sin \varphi \\
  0 & -\sin \varphi & \cos \varphi
\end{bmatrix}
\begin{bmatrix}
  u_2 \\
  v_2 \\
  w_2
\end{bmatrix}
\]

where \( \varphi = \tan^{-1}\left(\frac{2v_2w_3}{v_2^2 + w_3^2}\right) \) and subscript 3 denotes wind components after the triple rotation (Kaimal and Finnigan, 1994). Using the triple rotation, McMillan (1988) obtained an improvement of surface flux estimation at a sloped site. However, it is apparent that the TR is only