Chapter VI

Feasibility of measuring mean vertical motion for estimating advection

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Abstract

Numerous recent studies calculate horizontal and vertical advection terms for budget studies of net ecosystem exchange of carbon. One potential uncertainty in such studies is the estimate of mean vertical motion. This work addresses the reliability of vertical advection estimates by contrasting the vertical motion obtained from the standard practise of measuring the vertical velocity and applying a tilt correction, to the vertical motion calculated from measurements of the horizontal divergence of the flow using a network of towers. Results are compared for three different tilt correction methods.

Estimates of mean vertical motion are sensitive to the choice of tilt correction method. The short-term mean (10 to 60 minutes) vertical motion based on the horizontal divergence is more realistic compared to the estimates derived from the standard practise. The divergence shows long-term mean (days to months) sinking motion at the site, apparently due to the surface roughness change. Because all the tilt correction methods rely on the assumption that the long-term mean vertical motion is zero for a given wind direction, they fail to reproduce the vertical motion based on the divergence.

Keywords

Vertical Advection, Mean Vertical Motion, Tilt Correction, Horizontal Divergence

1 Introduction

Early studies estimating net ecosystem exchange of carbon (NEE) typically included only the storeage and eddy flux components. It is now generally accepted that this method leads to what appears to be an underestimate of nocturnal respiration of carbon dioxide on nights with weak mixing. One possible interpretation of the missing carbon dioxide is that horizontal or vertical advection is important (Lee, 1998; Baldocchi et al., 2000; Aubinet et al., 2003; Staebler and Fitzjarrald, 2004). An empirical patch for this problem is the so called u_* filter approach, where the measured eddy flux during weak turbulence nocturnal periods, where advection is most likely to be important, is replaced with a model of the respiration based on the eddy flux during strong mixing nocturnal periods (Pattey et al., 2002).

The method of calculating NEE proposed by Lee (1998) added a vertical advection term to the storeage and eddy flux terms in the NEE budget. This approach was applied by Baldocchi et al. (2000) who reported that including vertical advection improved their budget closure, however, they inferred that horizontal advection may also be important. Aubinet et al. (2003) concluded that horizontal advection of carbon dioxide was mostly cancelled by vertical advection. Their hypothesis was that horizontal and vertical advection are linked by an entrainment mechanism where the air above the canopy is brought downward into the subcanopy in drainage flows. This suggests that it is inappropriate to include only the vertical component of advection in the budget. Staebler and Fitzjarrald (2004) found that vertical advection of carbon dioxide was small while horizontal advection was significant. Including horizontal advection improved their NEE budget closure, especially in the summer. Feigenwinter et al. (2004) found that horizontal and vertical advection of carbon dioxide tended to cancel at night, yet pointed out that the large scatter in the advective fluxes needs further investigation.

All of the above studies estimate mean vertical motion by applying a tilt correction (Section 3) to the vertical velocity measured by a 3-dimensional sonic anemometer, however, it has not been demonstrated that such an approach is capable of resolving a small time-averaged vertical motion. Can the true vertical motion be extracted from the measurements which are contaminated by flow distortion, tilt of the sensor and sloping terrain? In this study, we investiagate the feasibility of quantifying mean vertical motion, and thus vertical advection, using sonic anemometer measurements.

A network of towers were deployed to provide two independent estimates of mean vertical motion; 1) from measurement of vertical velocity at a central tower, and 2) from the horizontal divergence using a network of towers surrounding the central tower. From incompressible mass continuity, the time-averaged vertical velocity based on the divergence is given by

$$\overline{w}(h) = -\int_{z=0}^{z=h} (\frac{\partial \overline{u}}{\partial x} + \frac{\partial \overline{v}}{\partial y}) dz \tag{1}$$

using the usual notation where overbars denote a time-average and $\overline{w}(0) = 0$. Multiple measurement levels of the horizontal flow on the surrounding towers provide some details on the vertical structure of the horizontal gradients of the mean wind. Two levels of vertical velocity measurements above the canopy on the central tower provide a consistancy check and allow identification of complex flow situations where the magnitude of the vertical velocity may not increase with height.

A strong relationship between the mean vertical motion from the two independent methods would provide confidence for estimates of vertical motion, and subsequent estimates of vertical advection. However, when the two estimates substantially disagree, such confidence can not be established. This approach is not definitive due to potential errors in both estimates of $\overline{w}$. The comparison is complicated by the fact that $\overline{w}$ at a point responds to divgerence on a large range of spatial scales while our network for calculating the divergence resolves only one spatial scale. We attempt to address this problem by examining the relationships between the $\overline{w}$ estimates for a wide range of averaging times.

2 Field experiment

The measurements are from a semi-arid young ponderosa pine site in central OR, USA, during August, September and October of 2004. The young 3-m tall pine trees were uniformly and sparsely distributed across the site. Beneath the pines was bare sandy soil with sparse clumps of grass. A stand of much taller pines surround the site. The site was chosen in part due to the large roughness change and the expected acceleration of the mean flow (divergence) over the shorter trees. The boundary between the young and taller pines is roughly denoted by the edge of the area in Figure 1. Within the boundaries of the site, the vegetation could be classified as very homogeneous. The terrain slopes steadily upward to the southwest and west with 100 m elevation gain over the first 5 km, or a slope of 2%, and slopes weakly downward ($< 1\%$) or is flat in other directions. More than one-half the time the wind direction was in the sector 230 to 300 deg (westerly winds).

The central tower was equipped with 3-dimensional CSAT3 sonic anemometers (Campbell Scientific) at 5 and 12 m above ground recording the three wind components and the sonic temperature at 10 hz. The orientation of the anemometers was carefully measured with a SmartTool (MD Buliding Products), a digital instrument with a precision of 0.1 deg. The pitch, roll and azimuth of the 12-m anemometer were measured as 0.9, 0.0 and 272 deg, respectively. Two-dimensional sonic anemometers (Vaisala Inc, formerly Handar) were deployed at 1, 5 and 12 m above ground on towers A and C and at 1 and 5 m on towers D, E and B for measuring the mean horizontal wind. All periods with flow from 60 through 150 deg were discarded due to possible flow distortion due to flow through the tower and support structures prior to reaching the instruments.

The site is characterized by sustained synoptic high pressure and weak mean flow in summer and fall. For the 3 month experiment, the average wind speed was 0.7, 1.4 and 1.9 ms^{-1} at the 1, 5 and 12-m levels on tower B, respectively. The weak mean flow, clear skies and sparse canopy lead to strong radiational cooling of the ground at night, resulting in strong stratitifcation and very weak turbulence near the surface.

Direct comparison between the mean wind speed measured by a CSAT3 and a Handar is afforded by the dual deployment at 5 m on the central tower. The 10-minute vector average wind speed from the CSAT3 (Handar) was 1.36 (1.34) ms^{-1} for the entire experiment, and the two wind speeds were correlated at $r = 0.98$.

3 Tilt correction

3.1 Background

A tilt correction is applied to 3-dimensional sonic anemometer measurements to remove; 1) apparent vertical motion due to tilt of the sensor from true (gravitational) vertical, and 2) apparent vertical motion due to sloping topography. Both of these influences lead to an artifical wind direction dependence of the vertical velocity as measured by the anemometer. As noted by Paw U et al. (2000) and others, it is not possible to distinguish between these two effects from the vertical velocity measurements alone. A tilted sensor over flat terrain measures an apparent upward vertical motion for horizontal flow in one direction and apparent downward motion for flow in the opposite direction. The apparent vertical motion signature is identical for a perfectly levelled sensor over idealized sloping terrain with terrain following flow. Directionally dependent flow distortion effects are typically assumed to be accounted for by the internal software in the anemometer, although Högström and Smedman (2004) recently pointed out that the manufacturer's corrections, which are based on low turbulence level wind tunnel studies, may not be optimum for the higher turbulence conditions found in the field.

In earlier days of micrometeorological measurements, standard procedure was to rotate the three wind components into streamline coordinates for each 30-minute or 1-h time period individually (e.g., Kaimal and Finnigan, 1994). This approach defines the short-term mean vertical motion to be zero. The main motivation for this approach was that the mean vertical motion measurements could not be trusted due to contamination by sensor tilt and elevation slope, limited sample size and possibly flow distortion.

More recently, Lee (1998) and others identified the importance of non-zero $\overline{w}$ for calculating vertical advection of carbon dioxide. Even very small values of $\overline{w}$ can lead to significant advection in the presence of large vertical gradients, such as typically found near the surface for carbon dioxide on nights with weak mixing. Since the streamline coordinates approach exactly removes all short-term mean vertical motion, other methods were adopted which allow non-zero short-term $\overline{w}$.

In the new standard approach, the long-term $\overline{w}_m(\phi)$ averaged over weeks to months is removed from the short-term averages of $\overline{w}_m$, where ϕ is wind direction and $\overline{w}_m$ is the measured time-averaged vertical velocity (Lee, 1998; Baldocchi et al., 2000; Paw U et al., 2000; Wilzcak et al., 2000; Finnigan et al., 2003). The procedure is similar in concept to applying a high-pass filter to the mean vertical motion seperately for each wind direction. The approach assumes that the long-term mean vertical motion for a given wind direction is zero. The short-term deviations in $\overline{w}$ that remain after removing the long-term $\overline{w}_m(\phi)$ are presumed to correspond to short-term events of either horizontal convergence or divergence. Long-term measurements are required to implement this approach in order to obtain robust estimates of the long-term $\overline{w}_m(\phi)$.

While the philosophy of removing the directionally dependent, long-term mean vertical motion is present in all current tilt correction methods, the details of applying it vary between studies. Lee (1998) proposed linear regression of $\overline{w}_m$ on the mean horizontal wind speed seperately for each wind direction category, which accounts for the fact that the apparent vertical motion due to sensor tilt is proportional to the horizontal wind speed. In the planar fit technique (Wilczak et al. ,2001), multiple linear regression of $\overline{w}_m$ on the two horizontal wind components results in a tilted plane. This method applies to the idealized case where the surface is uniformly tilted (planar) with respect to the sensor, or equivalently, where the sensor is tilted over perfectly flat terrain. A third approach examines the wind direction dependence of the tilt angle (Paw U et al., 2000; Vickers and Mahrt, 2003; Feigenwinter et al., 2004). The ϕ-dependence of the long-term average tilt angle can be represented either by the bin-averaged estimate or using a regression fit to azimuthal angle. When the ϕ-dependence can be approximated by a simple sinusoidal function of azimuth angle, this method is identical conceptually to the planar fit technique (Paw U et al., 2000). In this sense, the planar fit approach is a special case of the tilt angle method. For non-idealized terrain, a planar fit may not be appropriate, and the bin-average ϕ-dependence can be used.

The regression used by Lee's approach and the planar fit method exactly remove the mean vertical motion averaged over the entire experiment, while the tilt angle method does not. Lee's approach removes the long-term $\overline{w}$ for each wind direction category individually, while the planar fit and tilt angle methods do not.

3.2 Problems

As pointed out by Lee (1998), a potential problem is that the tilt correction may remove real vertical motion associated with local circulations driven by surface heterogenity. Examples include a change in surface roughness, differential daytime heating and systematic diverging nocturnal drainage flows. The site here is influenced by a surface roughness change, however, it is not known if systematic circulations induced by daytime differential heating are important. It is also not known if the drainage flow is divergent (accelerating) or convergent (decelerating) at the site. For westerly flow, the site is approximately at the bottom of a slope in that the elevation increases faster to the west than it decreases to the east. A complication with identifying the drainage flow at this site is that the predominant flow is from the same direction as the drainage flow.

Given the rough-to-smooth surface roughness change for all wind directions, and the persistant synoptic high pressure pattern, we would expect overall mean sinking motion at the site. Such long-term mean vertical motion would be at least partially removed by any of the tilt correction methods described above.

We note that drainage flow is not a sufficient condition for horizontal divergence and mean sinking motion. Drainage flows need to converge somewhere. This is an important point because nearly every NEE study in the literature reports mean sinking motion at night and attributes it to drainage flows. If this were indeed the case, it indicates that the site selection criteria were biased in that all sites are in a similar nocturnal flow regime. Mean sinking motion coupled with decreasing carbon dioxide concentration with height results in a vertical advection term that is the correct sign to explain the missing carbon dioxide found at most sites. However, because other terms in the NEE budget, such as horizontal advection and horizontal flux divergence, are typically not known, it is impossible to make definitive conclusions. The typical reported finding of rising motion during the day and sinking motion at night could be an artifact of the tilt correction method.

3.3 Methodologies

We apply three different tilt correction methods to the data. The same procedures are applied independently to the 5 and 12-m measurements although we focus on the 12-m estimates of $\overline{w}$. All time mean quantities in this section, denoted with an overbar, represent 100-s time averages. The choice of 100-s averaging includes wind direction variability on scales down to 100 s. Longer averaging times would miss additional meandering of the mean wind which could contaminate the wind direction dependence of $\overline{w}$. It is difficult to say, because many studies do not include the details, but it appears that studies in the NEE literature often employ a 30-minute averaging time to define the mean wind direction for the purpose of developing the tilt correction. Berger et al. (2001) use the 1-h average wind direction. Wilczak et al. (2001) propose using 5-minute average wind components to derive the regression coefficients in the planar fit approach. We note that the tilt correction parameters could be developed using the high rate (e.g. 10 hz) data, although at some point it becomes impractical for the planar fit method where a matrix must be inverted to perform the multiple regression.

The Lee (1998) approach uses regression of the vertical velocity on the horizontal wind speed for each wind direction category, generating a sequence of wind direction dependent coefficients $\alpha(\phi)$ and $\beta(\phi)$. The corrected mean vertical velocity ($\overline{w}$) is then given by

$$\overline{w} = \overline{w}_m - (\alpha(\phi) + \beta(\phi)\, U) \tag{2}$$

where we use 36 wind direction categories of width 10 deg each and the mean horizontal wind speed is given by

$$U = (\overline{u}^2 + \overline{v}^2)^{1/2}. \tag{3}$$

The planar fit approach uses multiple regression of the vertical velocity on the two components of the horizontal wind, and the corrected vertical motion is given by

$$\overline{w} = \overline{w}_m - (a + b\,\overline{u} + c\,\overline{v}) \tag{4}$$

where the coeffcients a, b and c are calculated using all the data. The tilt angle approach calculates a tilt angle as

$$T_a = \arctan(\frac{\overline{w}_{mn}}{U}) \tag{5}$$

where $\overline{w}_{mn}$ is the measured vertical velocity that has the experiment wide mean (potential instrument offset) removed. The procedure temporarily removes periods with the weakest mean flow ($U < 0.5\ ms^{-1}$), where calculation of the tilt angle is not well posed and the tilt angle becomes erratic (e.g., Paw U et al., 2000). The corrected mean vertical velocity is then estimated for all the data, including the weakest wind periods, as

$$\overline{w} = \overline{w}_{mn} - U\ \tan(T_a(\phi)). \tag{6}$$

where $T_a(\phi)$ is the bin-averaged wind direction dependent tilt angle using 36 wind direction categories of width 10 deg.

3.4 Results

The three different tilt correction methods yield different $\overline{w}$ estimates (Figure 2). Although the correlations between 30-minute average $\overline{w}$ estimates are high, the root-mean-square differences of a few $cm\ s^{-1}$ are significant, and the maximum differences are as large as 10 $cm\ s^{-1}$. These large differences are discouraging for prospects of estimating mean vertical motion using a tilt correction method.

The magnitude of the tilt angles found here (Figure 3) are comparable to or smaller than what we have typically found for other sites on relatively flat terrain with carefully levelled sensors. A sinusoidal dependence is a reasonable approximation to $T_a(\phi)$, implying that the planar fit method could be appropriate for this site. Differences between the bin-averaged $T_a(\phi)$ values and a pure sinusodial dependence, as implied by the planar fit method, may be due to an insufficient number of samples (random sampling error) for the less frequent wind directions. On the other hand, some sites may be characterized by directionally dependent slopes that can not be reasonably represented by a planar fit, in which case the bin-averages of $T_a(\phi)$ may be the better representation. In addition, higher order flow distortion effects may contribute to more complex azimuthal dependencies of the tilt angle, such as a double peak. For example, Högström and Smedman (2004) highlight the calibration problems and flow distortion characteristics of Gill Solent sonic anemometers. Such problems may be less severe for the unobstructed design of the CSAT3.

One cause of significant differences between the Lee and the tilt angle methods is demonstrated in Figure 4. For Lee's method, the regression of $\overline{w}_m$ on horizontal wind speed gives negative slope (negative β) despite the fact that for 75% of the data, where the wind speed is less than 2 ms^{-1}, the measured average vertical velocity is positive and increases with increasing wind speed. The tilt angle method indicates very weak long-term mean positive vertical motion ($T_a(\phi) = 0.06$ deg). For this wind direction category, the two diffferent approaches for correcting the vertical velocity generally have the opposite sign. Because Lee's regression method includes a constant term α, the correction ($\overline{w} - \overline{w}_m$) can be of either sign depending on wind speed, while the tilt angle method correction, which is near zero for this case, is always the same sign for a given wind direction.

Lee's method appears to fail for this example due to the combination of a nonlinear dependence of $\overline{w}_m$ on wind speed and a strongly skewed wind speed distribution due to the high frequency of occurence of weak winds. The magnitude of the slope β in Lee's method decreases with increasing averaging time by removal of some of the stronger wind speed cases. Recall that the vector average wind speed decreases with increasing averaging time due to wind direction variability. The tilt angle approach is more robust for this example in that the mean tilt angle is less sensitive to the choice of averaging time than are the coefficients from the regression approach.

4 Divergence

The horizontal coordinate system was rotated for each 100-s period such that horizontal $\overline{u}$ gradients are proportional to $\overline{u}$ at tower A minus $\overline{u}$ at tower C, and v gradients by tower E minus tower D. Horizontal gradients were evaluated over a fixed distance of approximately 200 m (Figure 1). No significant wind speed bias problems were found by an intercomparison study of the Handar anemometers. The horizontal gradients of $\overline{u}$ and $\overline{v}$ were calculated at the 3 measurement levels (1, 5 and 12 m) using finite differencing. Vertical integration of the horizontal gradients from the surface to 12 m was performed using a piecewise linear fit to the four levels, where the gradients are zero at $z = 0$.

For the shorter towers D and E, where the measurements are limited to 1 and 5 m, we assume the horizontal gradient of the mean wind is constant with height between 5 and 12 m. The measured gradients on the taller towers support this assumption. The fact that the horizontal gradient of the mean wind does not significantly increase above 5 m suggests that the primary mechanism generating divergence at this site is the surface roughness change.

One issue with the divergence method of estimating $\overline{w}$ is the length scale over which the horizontal gradients are calculated. Ideally, the gradients would be calculated over a short distance in the immediate vicinity of the vertical velocity measurements, however, the limited resolution of the horizontal wind speed measurements requires a sufficient seperation distance such that wind speed differences can be resolved. In some special circumstances, such as with propogating divergence, the combination of seperation distance and averaging time could strongly influence the calculated divergence. However, if the divergence is primarily stationary and the horizontal wind components vary approximately linearily with distance, then the seperation distance and averaging time become less important. We did not find a strong averaging time dependence in the vertically integrated divergence.

The divergence calculations indicate that this is a site of mean sinking motion for all wind directions and all times of day and night. We would expect to see weaker divergence due to the surface roughness change for those wind directions with longer fetch over the clearing prior to reaching the tower network. Theoretically, the divergence is a maximum at the upwind edge of the clearing and decreases with increasing distance (e.g., Garratt, 1990). The observations do indeed show that the minimum divergence occurs with north-west flow, where the tower network is located in the south-east corner of the clearing.

5 Comparisons

In this section we compare the $\overline{w}$ estimates calculated from $\overline{w}_m$ and the different tilt correction methods (the direct methods) with the $\overline{w}$ estimate based on the horizontal divergence. There is large scatter for individual 30-minute average estimates and small correlation (Figure 5). A 30-minute mean vertical motion of 10 $cm\ s^{-1}$, which implies an increase in the mean wind speed across the network of about 1.7 ms^{-1}, is probably too large to be realistic and is not supported by the divergence measurements. Such magnitude vertical motions are found for all the direct methods, but not for the divergence method. This might indicate that the divergence approach is more robust. More spatial information is incorporated into the divergence calculation. If a 10 $cm\ s^{-1}$ $\overline{w}$ was due to an error in specification of the tilt angle, the error in the ϕ-dependence of T_a would need to be about 3 deg for a mean wind speed of 2 ms^{-1}. It appears unlikely than an error of this magnitude occurs.

The correlation between $\overline{w}$ from the tilt angle and planar fit methods and $\overline{w}$ from the divergence method increases with increasing averaging time, however, this is not the case for Lee's method (Figure 6). The RMS $\overline{w}$ differences for all the direct methods decrease with increasing averaging time. This implies that a portion of the scatter is random. The standard deviation of the direct method $\overline{w}$ estimates is typically a factor of 2 greater than the standard deviation of $\overline{w}$ based on the divergence.

All of the direct methods result in large scatter and large short-term fluctuations in $\overline{w}$ compared to the divergence method. Despite the apparent noise in the direct estimates, short-term fluctuations in $\overline{w}$ from the direct and divergence methods can be highly correlated (Figure 7). In this example, both the direct and divergence estimates clearly show enhanced sinking motion associated with stronger wind speeds, and enhanced rising motion with weaker winds. The direct method $\overline{w}$ fluctuations are too large to be due to errors in the tilt correction, despite being strongly wind speed dependent. The stronger amplitude response of the direct method $\overline{w}$ compared to the divergence estimate for this example remains unexplained.

The agreement between the direct and divergence methods is worse when the magnitude of $\overline{w}$ from the direct methods does not increase monotonically with height between the surface and 12 m (not shown). Such periods may represent complex flow situations that are impossible to resolve without a much finer grid of measurements. This situation occurred about one-half the time independent of the tilt correction method. Removing such periods improved the correlation between the 30-minute mean $\overline{w}$ estimates from the tilt angle and divergence methods from 0.39 to 0.47. These periods also include cases where $\overline{w}$ at both the 5 and 12-m levels is very small, in which case small random errors possibly due to flow distortion probably dominate the estimates.

For very shallow nocturnal boundary layers, the vertical velocity measurement at 12 m may be partially decoupled from the horizontal flow field beneath it. To test this, we compared the estimates of vertical motion at 5 m instead of 12 m above the surface. No significant improvement in the relationships was found at 5 m compared to 12 m (not shown). Interpretation is complicated by the fact that theoretically the relationship would be expected to degrade at 5 m compared to 12 m because the magnitude of $\overline{w}$ normally decreases with height (smaller signal to noise ratio) and any problems associated with surface heterogenity increase near the surface.

As a further sensitivity study, the direct method $\overline{w}$ estimates were recalculated at 12 m using the same procedures described above but only using nocturnal data. Despite this attempt to "tune" the tilt correction for nocturnal conditions, the relationship between the direct vertical motion estimates and the divergence based estimates did not significantly improve (not shown).

5.1 Composites

In the three month composite diurnal cycle, the $\overline{w}$ estimates from the planar fit and tilt angle methods have some similarities to each other, and some similarity to the divergence based estimate of $\overline{w}$ (Figure 8). The similar composite diurnal behaviour is encouraging, although agreement on individual short time scales (30-minutes to 1-h) is the critical test for the ultimate goal of estimating vertical advection for process orientated studies. Contrary to the other methods tested, the Lee approach leads to significant mean rising motion in the afternoon.

The direct and divergence methods disagree on the sign of the composite $\overline{w}$ during most of the night. Direct methods generally show rising motion of about 1 $cm\ s^{-1}$ in contrast to weak sinking motion of 0.5 $cm\ s^{-1}$ based on the divergence (Figure 8). The nocturnal sign difference could be due to the removal of the long-term mean $\overline{w}$ by the tilt correction methods. As discussed above (section 3), the tilt correction methods fail at sites with non-zero long-term mean vertical motion. Assuming that the divergence estimate is correct, and that long-term mean sinking motion due to the surface roughnesss change is realistic for this site, then the vertical advection of carbon dioxide that would be calculated using the direct method nocturnal $\overline{w}$ would be of the wrong sign for most of the night regardless of the choice of tilt correction method.

The wind direction, wind speed and time of day dependencies of the composite $\overline{w}$ residuals for the tilt angle method and the uncorrected $\overline{w}_m$ estimates are shown in Figure 9. The residual is defined as $\overline{w}$ for the direct method minus $\overline{w}$ from the divergence. The uncorrected estimate has the experiment wide mean (offset) of 0.9 $cm\ s^{-1}$ removed, and not removing the offset would make the uncorrected residuals in Figure 9 even larger positive. For the most common conditions of a 255 deg wind at 1.9 ms^{-1}, the composite residual is near zero for the tilt angle method. Assuming that the estimate based on the divergence is close to the true mean vertical motion, and comparing with the uncorrected estimate of vertical motion, it appears that the tilt angle method used here over-corrects in stronger winds and under-corrects in weaker winds. This is also seen in the diurnal pattern of the residual which is negative during the day, when the mean wind speed is significantly higher than at night.

The positive residual for south-southwest flow (Figure 9) may be due in part to an exponential rather than linear fetch dependence of the divergence. An exponential dependence would be most pronounced near the upwind edge of the clearing, which is where the network is located for south-southwest flow. If the divergence decreased exponentially with fetch, the mean $\overline{w}$ corresponding to the divergence would be found in the upwind part of the network, not in the center of the network. As such, our direct measurement at the central tower site may underestimate the mean sinking motion. A larger negative $\overline{w}$ from the divergence than from the direct method leads to a positive residual in Figure 9.

6 Conclusions

A three month field experiment was performed to contrast the mean vertical motion measured at a point on a central tower with the mean vertical motion calculated from the horizontal divergence measured using a network of towers surrounding the central tower. Three different tilt correction methods were applied. The RMS difference in the 30-minute average $\overline{w}$ estimates due to the choice of tilt correction method was 2 to 3 $cm\ s^{-1}$. The 3-month composite diurnal pattern of $\overline{w}$ was sensitive to the choice of tilt correction method.

The hour to hour variations in $\overline{w}$ from the direct methods are probably too large to be representative of a large spatial area. In such cases, the direct $\overline{w}$ estimates could be responding to divergence on horizontal scales smaller or larger than the divergence network. The RMS differences between the 30-minute average direct estimates of $\overline{w}$ and the estimates based on the divergence are 4 to 5 $cm\ s^{-1}$, and as a result, little confidence can be placed in the hour-to-hour variations in the $\overline{w}$ estimates, or in subsequent estimates of vertical advection. Of the three direct methods tested at this site, the tilt angle method best matched the divergence.

The direct methods and the divergence method agree on some features of the composite diurnal cycle of $\overline{w}$, however, the divergence indicates long-term mean sinking motion for all times of day and night, apparently due to the surface roughness change. Because the direct methods all remove the long-term mean, they fail to reproduce this result. As a consequence, the direct methods give the wrong sign of $\overline{w}$ at night, and thus would give the wrong sign of the nocturnal vertical advection of carbon dioxide.

Our conclusion is that more confidence can be attached to vertical advection estimates when the mean vertical motion is calculated from the horizontal divergence. A densor network of vertical velocity and divergence measurements would enable more definitive conclusions. Unfortuneatly, the measurements required to calculate the divergence are more costly and not normally available.

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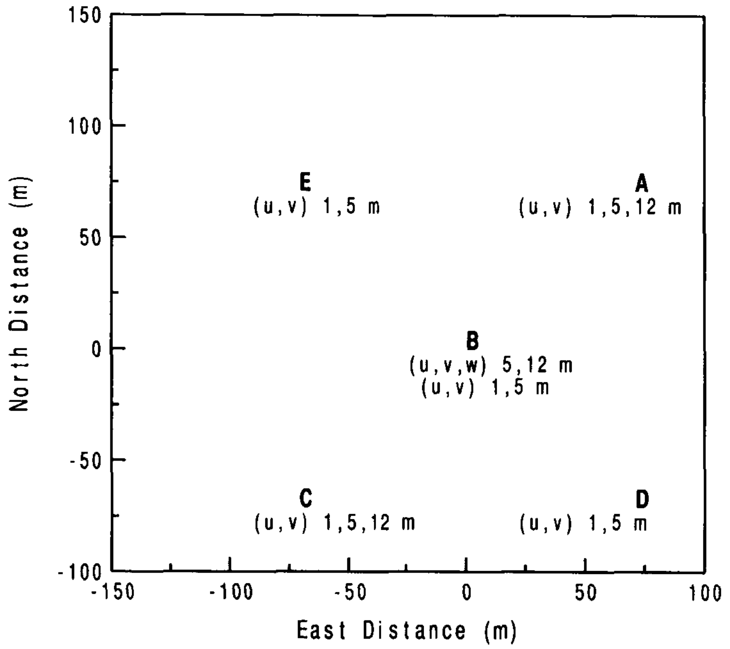

Figure 1: Schematic of young pine site with locations of five towers (A-E) and variables measured at different heights. The site is surrounded on all sides by taller pine trees.

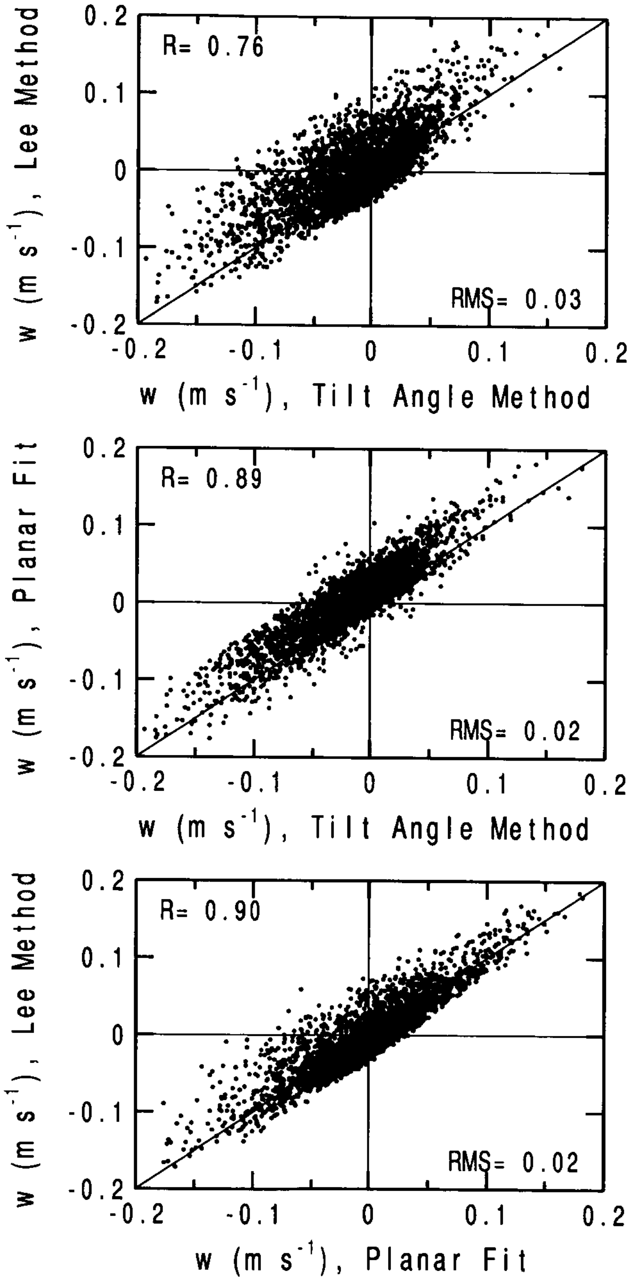

Figure 2: Comparison of 30-minute mean vertical motion at 12 m for three different tilt correction methods.

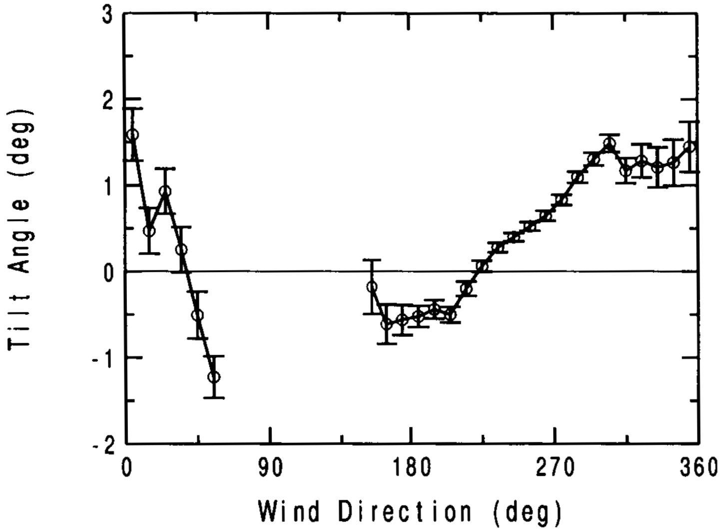

Figure 3: Mean and standard error of the tilt angle vs wind direction (100-s average data at 12 m).

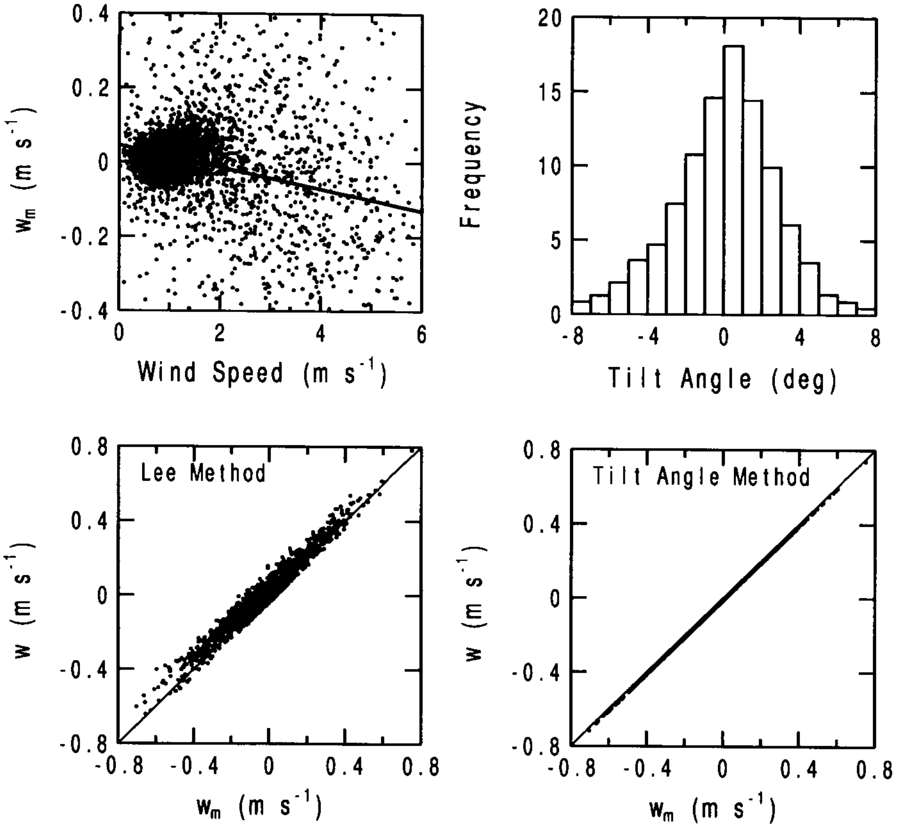

Figure 4: Comparison of the Lee and tilt angle methods for wind direction category $220 < \phi < 230$ deg. (100-s average data at 12 m).

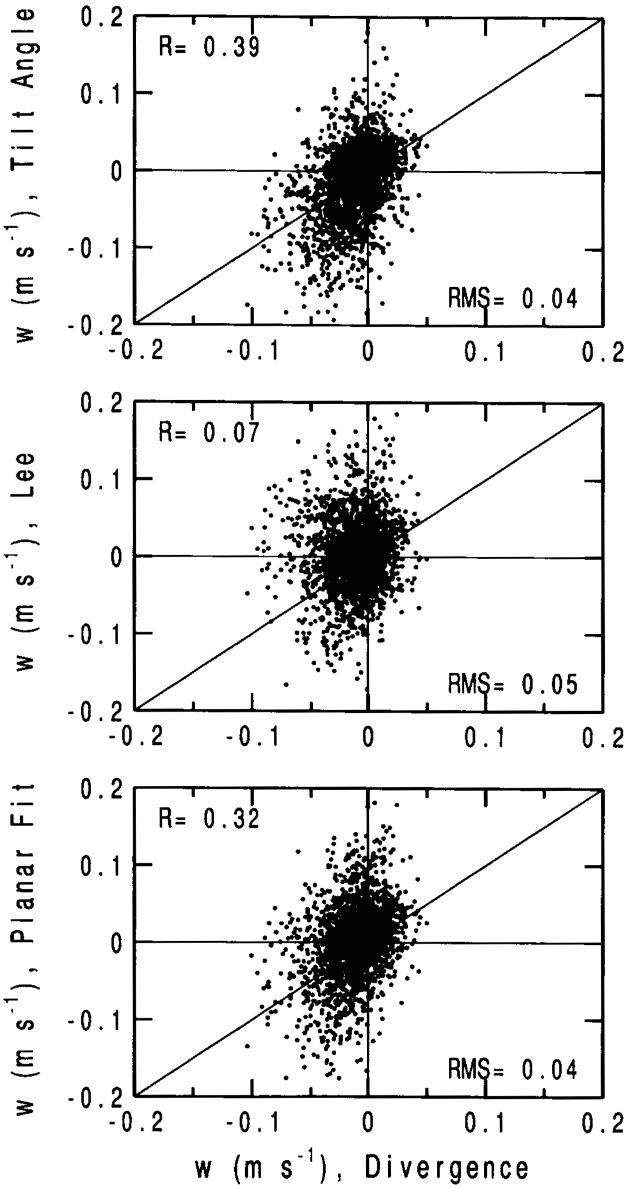

Figure 5: 30-minute mean vertical motion at 12 m for the a) tilt angle, b) Lee, and c) planar fit methods vs the estimate based on the horizontal divergence.

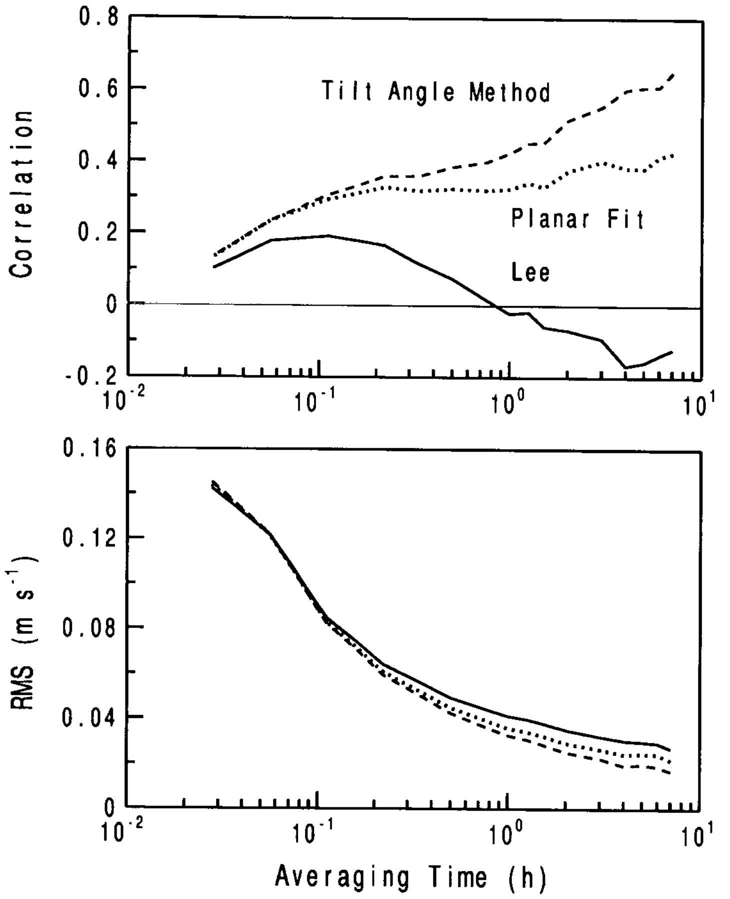

Figure 6: Averaging time dependence of the correlation and root mean square error for contrasting the three direct methods with the divergence method of estimating $\overline{w}$.

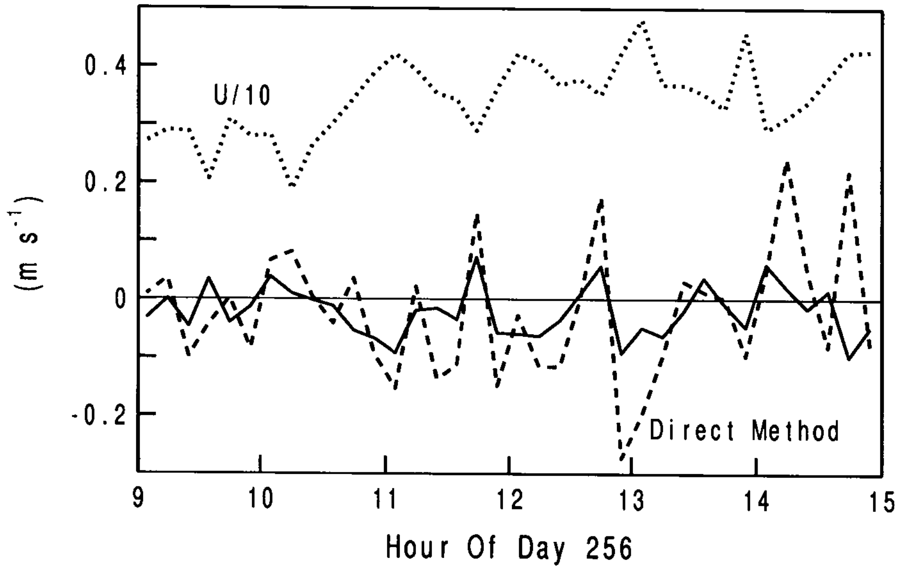

Figure 7: Time series of 10-minute average mean wind speed divided by 10 (dotted), $\overline{w}$ from direct tilt angle method (dashed), and $\overline{w}$ from divergence method (solid).

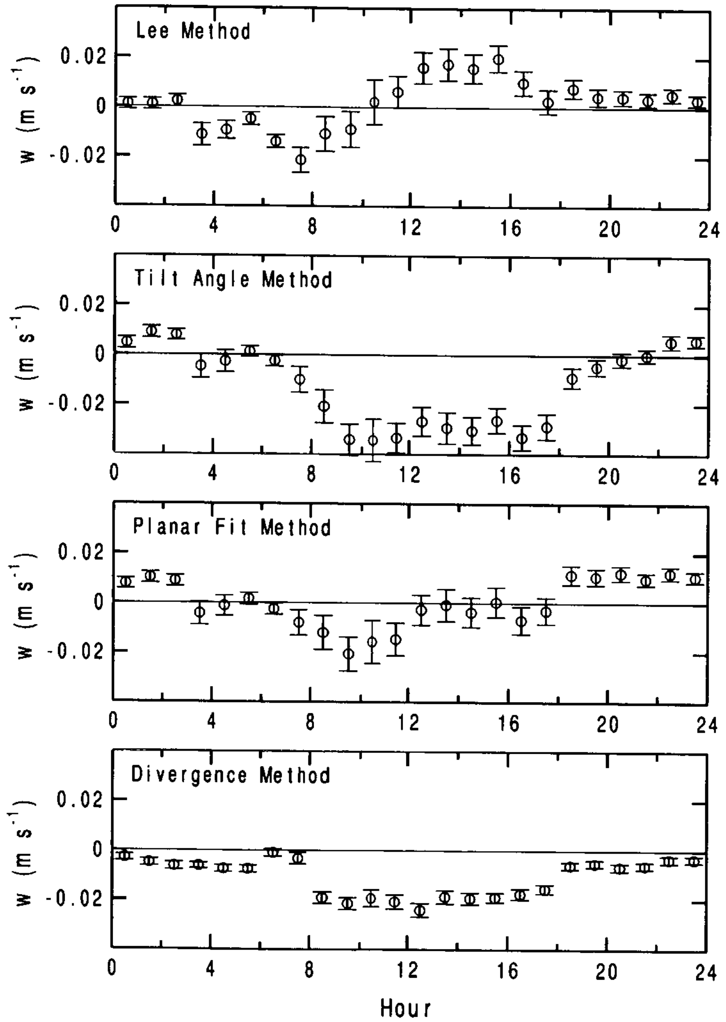

Figure 8: Mean and standard error of the three month composite diurnal cycle of mean vertical motion from four different methods.

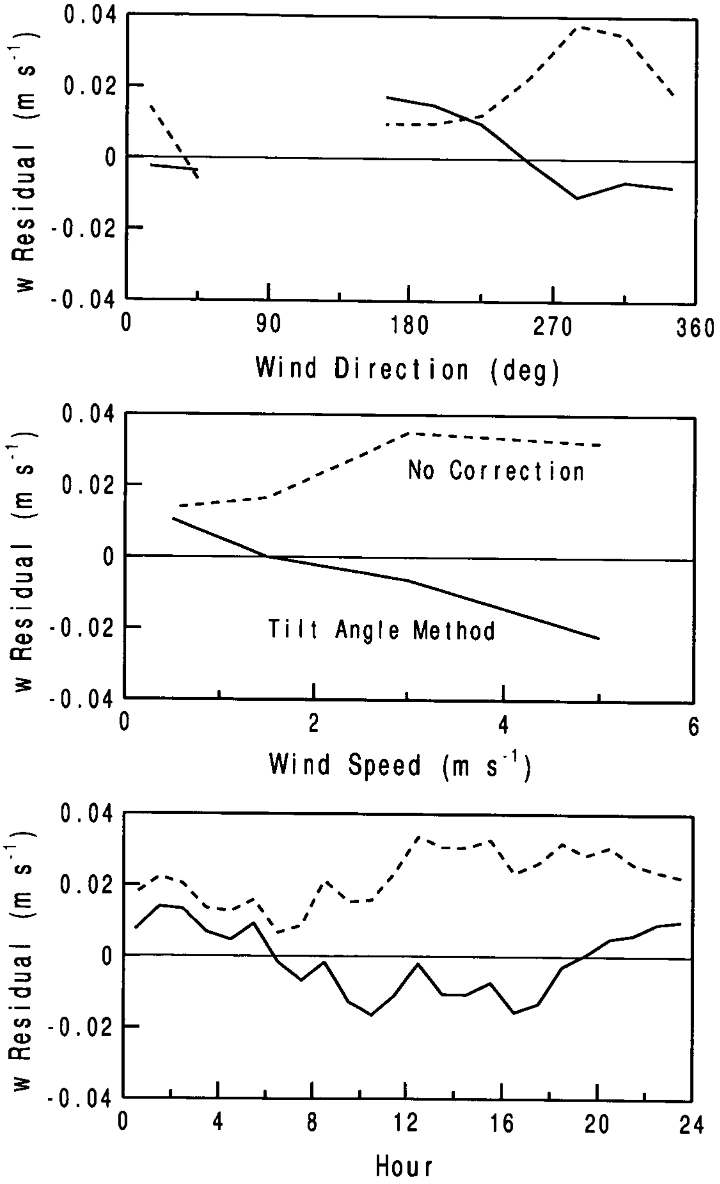

Figure 9: Dependence of the composite $\overline{w}$ residual for the tilt angle method (solid), and for the uncorrected $\overline{w}_m$ (dash), on wind direction, wind speed and time of day.