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Wind Flow Dynamics over Complex Terrain

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Wind Flow Dynamics
over Complex Terrain

By

Eric Kutter

A dissertation submitted to the Graduate Faculty of Earth and Environmental Sciences in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

The City University of New York

2019
This manuscript, entitled “Wind Flow Dynamics over Complex Terrain”, by Eric Kutter, has been read and accepted by the Graduate Faculty in Earth and Environmental Sciences in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

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THE CITY UNIVERSITY OF NEW YORK
Global and regional climate models use a variety of parameters to approximate past climates or to predict future conditions. One crucial input variable is net ecosystem exchange (NEE). A standard method of measuring NEE is through observing mass and energy flux from sensors on towers employing the eddy covariance method. While relatively simple, the method requires assumptions that are only valid over flat terrain, with turbulent winds, and homogeneous vegetation. Those conditions are rare in the real world.

Imperfections in the methodology result in uncertainty and errors in the resulting calculations. A more accurate NEE measurement would improve global and regional climate models. Two possible sources of error in eddy covariance flux calculations are recirculation and advection. This project sought to examine the causes and effects of the two phenomena over complex, non-ideal terrain.

Recirculation was measured successfully, and the causes were determined to be wind direction relative to an obstruction, combined with the vertical potential temperature gradient. The impacts of recirculating air were significant, changing both the carbon dioxide flux and the energy flux that would be measured at the top of a typical eddy flux tower.

Vertical advection was estimated, and was found to be a significant contributor to overall vertical flux of both carbon dioxide and energy under all thermal conditions. However, the uncertainties in the horizontal advection calculations undermined the final results, though a qualitative analysis of the rough estimate provided in this work suggested that horizontal advective flux cannot be ignored as negligible under any wind flow regime.
Acknowledgements

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<th>Symbol</th>
<th>Description</th>
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<tr>
<td>BRF</td>
<td>Black Rock Forest</td>
</tr>
<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
</tr>
<tr>
<td>EBR</td>
<td>energy flux balance ratio</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz (sec⁻¹)</td>
</tr>
<tr>
<td>IRGA</td>
<td>infrared gas analyzer</td>
</tr>
<tr>
<td>NEE</td>
<td>net ecosystem exchange (mass time⁻¹)</td>
</tr>
<tr>
<td>PAR</td>
<td>photosynthetically active radiation</td>
</tr>
<tr>
<td>u*</td>
<td>friction velocity (m s⁻¹)</td>
</tr>
<tr>
<td>WPL</td>
<td>Webb, Pearman, Leuning</td>
</tr>
</tbody>
</table>
Chapter 1: Introduction and Background

Understanding the exchange of energy, moisture, and trace gases between the terrestrial biosphere and the atmosphere over complex terrain is a fundamental goal in achieving a complete model of global or regional climate (Fernando et al., 2019). Net ecosystem exchange (NEE) of carbon dioxide is often a crucial input into climate models, and is also used as a means of validating regional model outputs (e.g., Papale and Valentini, 2003; Wharton et al., 2017; Swetnam et al., 2017). Calculations obtained from eddy flux tower data provide some of the best quality sources of NEE values, typically using friction velocity \( u^* \) as an indicator of data quality (Goulden et al., 1996; Baldocchi et al., 2001; Feigenwinter et al., 2004; 2008). However, the standard formulation of the eddy covariance method assumes steady-state flow, zero advection both vertically and horizontally, and no air flow divergence or convergence. In real-world situations, terrain that includes common features such as hills, forests, cities, or other large obstructions may not meet these strict requirements.

The eddy covariance method was used to measure energy and trace gas flux using the standard assumptions as described by Baldocchi et al., 1988. Since the project site was a hillside covered by a heterogeneous forest, the calculated fluxes were bound to contain errors (Baldocchi, 2003). Many researchers have attempted to reduce or eliminate those errors by using various combinations of theoretical methods, computer simulations, and/or physical observations (e.g., Goulden et al., 1996; Foken, 2008; Finnigan, 2008; Feigenwinter et al., 2010a; 2010b; Santana et al., 2017; Ma and Liu, 2019).
Of the many potential sources of error in the eddy covariance method that were discovered during those prior attempts, several studies pointed to recirculation and advection as the two most probable culprits for the vast majority of the measurement errors. The most critical of those studies are examined in detail in the following subsections.

1.1 Recirculation

A recirculation zone is a vortex with a horizontal axis, occurring downstream of a fluid flowing past an obstruction (Whiteman, 2000). While recirculation commonly occurs after an abrupt change in topography, the phenomenon can also be caused by gentle slopes under certain atmospheric conditions (Jackson and Hunt, 1976; Hunt and Carruthers, 1990; Xu and Yi, 2012). Recirculation is associated with vertical shear and increased turbulence in the fluid (Stull, 1988; Hunt et al., 1988). Considering the atmosphere leeward of a forested hillside, recirculating air may theoretically reach from the forest floor up to an altitude above the hilltop (Stull, 1988). This air circulation influences vertical mixing of energy and trace gases (Staebler and Fitzjarrald, 2005; Xu and Yi, 2012; Banerjee et al., 2018; Montagnani et al., 2008) and the direction and magnitude of fluxes (Raupach and Thom, 1981; Feigenwinter et al., 2010a), thereby impacting the regional climate (Moreno et al., 2016) and air pollutions (Wolfe et al., 2011a; 2011b; Schaubroeck et al., 2014; Grella et al., 2019).

In some locations, large-scale, slow-moving eddies with a frequency of less than 0.1 Hz dominated the total measured flux (Goulden et al., 1996). It has been reported that sites in hilly or forested land have complex interactions with their topographies and canopy structures leading to eddies that were persistent and predictable (Finnigan 2008; Foken 2008). Paraphrasing the definition given above from Whiteman, 2000, into language relevant to the
land-atmosphere boundary, a recirculation vortex is a large-scale eddy structure caused by interactions between the synoptic wind and a terrain feature in the path of that wind. My theory envisions recirculation as a vertical mixing phenomenon molded into a persistent shape by the geometry of the topography interacting with the synoptic wind direction. This study intentionally focused on a forested hillside with the purpose of observing these complex interactions.

Imprecise accounting for fluxes caused by recirculation vortices using eddy covariance data processing methods may explain a part of the energy flux imbalance (Foken 2008). Understanding the causes and impacts of recirculation is one step towards correcting the energy flux imbalance problem, thereby causing an overall improvement in the performance of the eddy covariance method over complex terrain.

Wind tunnel and numerical model simulations combined with observations in the hydraulics field have shown recirculation eddies appearing leeward of an obstruction (Poggi and Katul, 2007; Wang and Yi, 2012), causing significant impacts on the distribution of trace gas pollutants (Dawson et al., 1991; Grella et al., 2019). Numerical simulations that focused on the wind dynamics around hills found evidence of recirculation, with potential effects on CO₂ concentration and CO₂ flux (e.g.,Katul et al., 2007; Xu et al., 2015; Xu et al., 2017). Recirculation (reversed flow) within the canopy on the hill slope was predicted by an analytical model around a hill in a thermally neutral atmosphere (Finnigan and Belcher, 2004).. However, the predicting ability of the model is highly restricted by using the height-independent algebraic equation in the bottom canopy layer, thus, the drag force from the ground cannot be taken into consideration. Wang and Yi (2012) developed a new analytical model by using the velocity-
squared law, by which recirculation over complex terrain is realistically predicted. Other studies have shown wind interactions with complex terrain features producing lee waves without recirculation (Wurtele *et al.*, 1993). However, the influence of recirculation on flux near the ground surface, and ultimately on NEE, had not been thoroughly examined in situ.

**Research Question 1:** Can recirculation be measured by using two nearby flux towers leeward of a forested hillside?

**Research Question 2:** What atmospheric conditions cause recirculation eddies as opposed to lee waves with no recirculation?

**Research Question 3:** What strengthens or weakens recirculation?

**Research Question 4:** What impact does recirculation have on the profiles and fluxes of energy and carbon dioxide?

### 1.2 Advection

In the specialized case where measurements are taken over horizontally level ground, with homogeneous vegetation and other land features, without any sources or sinks above the surface, advection is negligible, and the covariance in the vertical direction dominates over the covariances in the horizontal directions. Since most of the terrestrial portions of the Earth are not perfectly flat and devoid of vegetation, Baldocchi *et al.*, (1988) estimated that the eddy covariance observations were bound to contain at least 10-20% error due to departures from the ideal case, with elevated errors when the measurement site was over particularly complex terrain. One expected source of error was advective flux – both vertical and horizontal.
Goulden et al., (1996) discovered that the eddy covariance method underestimated fluxes during nocturnal periods where wind speed was low and the atmospheric surface layer was stably stratified. The eddy covariance method worked best when wind speed was high and turbulence was strong, causing turbulent flux to dominate over all other flux sources. During nighttime on land with any slope, cold air drainage flow occurred near the ground surface in Goulden et al., (1996), which was not measured by sensors placed high above. This is because a super-stable layer (Richardson number $\to$ infinity) exists near the highest leaf area density level within forest canopy layer during clear calm nights and the air below and above the super-stable layer is separated (Yi et al., 2005). The existence of the super-stable layer was verified by SF$_6$ observational experiments. Additionally, atmospheric stratification usually occurred at night, causing vertical gradients and incomplete vertical mixing (Oldroyd et al., 2014). According to Goulden et al., (1996), the eddy covariance method significantly underestimated turbulent fluxes whenever the friction velocity ($u^*$) was below about 0.17 m s$^{-1}$.

Lee (1998) proposed a solution to some of the eddy covariance issues found by Goulden et al., (1996), and tested the method on available observational data. In the case of a significant vertical gradient in any atmospheric parameter, or a non-zero vertical wind velocity, vertical advection could no longer be ignored in a total flux calculation. Lee (1998) estimated vertical advective flux by assuming that the vertical wind speed and the scalar (e.g., potential temperature or carbon dioxide concentration) changed linearly with height. That method could not be used without modification due to Lee (1998)’s warning that the technique was inappropriate when a project site’s geography caused a preferred wind flow direction, as this project site did (Kutter et al., 2017, summarized in Chapter 3). The gradient of vertical wind
speed with respect to height was not constant throughout the air column during this experiment.

Numerous researchers have attempted to measure, predict, or estimate advective flux, or at least to determine under what atmospheric or site conditions advection was significant and could not be ignored. Yi et al. (2000), observed vertical and horizontal advection at three different heights at a forested site. NEE was calculated using the standard eddy covariance formulation, without considering the effects of vertical or horizontal advection. Yi et al. (2000), found that vertical advection was significant during the morning, when sunrise changed the atmospheric dynamics. However, the daytime atmospheric conditions were dominated by horizontal advection, influenced by local terrain topography and vegetation. In general, Yi et al. (2000), found that vertical advection was significant on calm nights and during the morning transition period, while horizontal advection dominated during other portions of the typical day. They concluded that the eddy covariance method must be supplemented by measurements at multiple towers and at multiple levels within the same parcel of atmosphere in order to account for both vertical and horizontal advective fluxes.

Baldocchi (2003) observed that whenever the eddy covariance technique was applied to real-world situations where the terrain and atmospheric conditions were non-ideal, calculations were not complete without measuring the potential impacts of advection, atmospheric storage, and flux divergence or convergence.

Staebler and Fitzjarrald (2005) found that mixing within the canopy occurred when eddy structures penetrated the vegetation layer. Periods lacking such penetration were often characterized by stratification within the canopy, and isolation from the atmosphere well above
the canopy. This mixing phenomenon sometimes drove the transport of energy and trace gases against the concentration gradient. Additionally, a secondary wind maximum was observed within the canopy in certain vegetation conditions. This complicated flow pattern caused estimates of NEE or vertical energy exchange to be difficult to obtain. Staebler and Fitzjarrald (2005) also found that more than 90% of nocturnal measurements showed drainage flow, which was coupled with an underestimate of carbon dioxide flux measured on the tower above the canopy.

Foken et al. (2006), observed that most of the land surface and flux experiments showed a residual of approximately 20% of the available energy flux, defined as the net radiation minus ground heat flux. Heterogeneous terrain was correlated with increased energy flux imbalances. Foken (2008) concluded that the imprecise handling of large-scale eddy structures by the data processing steps of the eddy covariance method explained a part of the energy flux imbalance. Foken (2008) suggested that subsequent experiments designed to close the energy flux balance focus in part on understanding vertical and horizontal advective flux.

The field observations in this research project were sited on a forested hillside precisely to measure interactions under non-ideal conditions, where the geography and vegetation caused preferred wind flow directions, recirculation, and stratification. The second focus of the project was to measure advective flux using the available data, and to determine under what conditions vertical and/or horizontal advection were significant to the overall energy flux balance.

The significance of advective flux measurements to the energy flux balance, the relationship between energy and carbon dioxide advective fluxes, and the relationship between horizontal
and vertical advective fluxes could be probed using two towers located near each other in complex terrain, with measurements at multiple elevations at each tower, collecting data for long enough to sample varying atmospheric cases including stable, near-neutral, and unstable thermal conditions.

Others have attempted multiple-tower advection investigations. Aubinet (2008) studied the specific issue of using eddy covariance to measure the carbon dioxide flux under nocturnal conditions. He pointed out that the policy of rejecting low u* data (occurring mostly at night) preferentially excised data from those time periods when the terrestrial biosphere acted as a carbon dioxide source. Finnigan (2008) argued that the technique of replacing low u* data with soil respiration estimates garnered from soil temperature results risked replacing one bias by introducing another. His suggestion was to use the eddy covariance method wherever possible, and then supplement eddy covariance with a model that simulated complex interactions at those sites where the standard method was insufficient. Finnigan (2008) and Foken (2008) theorized that most sites have complex interactions with their topography and canopy structure that were persistent and predictable. Prevailing wind flow patterns at the project site were identified (described in Kutter et al., 2017, summarized in Chapter 3), and caused a variety of atmospheric phenomena including: non-zero mean vertical wind speeds lasting many consecutive hours; strong gradients in carbon dioxide concentration and potential temperature; and flow stratification during stable or near-neutral atmospheric conditions, where drainage flow near to the ground was disconnected from flows in the upper canopy and above.

Yi et al. (2008), used four eddy flux towers on a temperate, forested hillside, to measure turbulent and advective flux. They found that katabatic drainage flows caused significant levels
of vertical and horizontal advection during periods of low wind speed and low $u^*$. Including advection estimates, Yi et al. (2008), measured NEE at 82% lower than the NEE without considering advective flux, which was 65% lower than the NEE resulting from the classic $u^*$ filtering method. They measured advective fluxes similar in magnitude to nighttime turbulent flux.

Using a five-tower experimental setup Feigenwinter et al. (2010a; 2010b), measured vertical and horizontal carbon dioxide fluxes at a forested mountain site. Horizontal and vertical advection significantly reduced the rate of carbon dioxide sequestration in that forest. Advective flux of carbon dioxide was strong at night, and was negligible during daytime. Aubinet and Feigenwinter (2010) repeated the five-tower experimental design used by Feigenwinter et al., (2010) in three separate forests. Their advection measurements did not balance the energy flux equation because advective flux estimates at each site were subject to large variability based on the direction of the prevailing wind and the advecting flow. Aubinet and Feigenwinter (2010) concluded that while the theory behind supplementing eddy covariance with direct advection measurements was sound, implementation remained impractical.

In a discussion of the differences between CO$_2$ and energy advective fluxes, Paw U et al. (2000), found that the importance of vertical versus horizontal advection changed depending on the time of day and the parameter being considered. They cautioned that though it appeared that nighttime energy flux contained small errors due to incompletely measured advective flux, the carbon dioxide flux estimates could still contain large errors.
Novick et al. (2013), conducted an experiment to measure advection’s impact on eddy flux along with the conditions necessary for advection to be a significant contributor. They used a two-tower system at the base of a long, gently sloping forested hillside with sensors well above the canopy, and a measurement thirty meters away within the canopy at a height of two meters. Their results showed that advection and drainage flow were strong factors in total flux of carbon dioxide and energy within the canopy during both the growing season and the winter. Novick et al. (2013), also showed that carbon dioxide built up at the base of the hillside, again during both seasonal extremes.

Decades of research have built towards consensus that the eddy covariance method is far too useful to abandon as a method of finding NEE, but that correctly measuring advective flux is critical, especially over complex terrain during time periods when turbulent fluxes are low. However, the numerical techniques and experimental setups for defensible measurements of vertical and horizontal advective flux of both energy and carbon dioxide have yet to be standardized.

**Research Question 5:** Can advective flux be calculated from the two-tower experiment in this project?

**Research Question 6:** What atmospheric conditions cause vertical and/or horizontal advection to be significant contributors to total flux?

**Research Question 7:** What is the relationship between horizontal and vertical advection of both carbon dioxide and energy?
Chapter 2: Experimental Methods

This field experiment was designed to study the wind dynamics over complex terrain, focusing on the problems of recirculation vortices and time periods with non-zero advective flux. The goal of the research program was to find improvements to the eddy covariance method that would allow its usage to gather defensible atmospheric data over complex terrain.

Figure 1: A schematic of the tower installation: (a) shows an aerial view of the location, with the dominant westerly winds indicated; (b) shows the locations of the two towers and their geographic coordinates (the white circles are locations for a planned expansion); (c) shows a rough sketch of the two towers and their heights compared with the average canopy height. The slope is exaggerated in (c): the vertical scale and horizontal scales are different.

2.1 Tower Setup

Two eddy flux towers were set up on a forested hillside in Black Rock Forest (BRF), New York (Figure 1), to collect measurements of atmospheric dynamics from 21 April to 9 June, 2013. The towers were aligned in the east-west direction since historical wind data around the hillside
showed prevailing wind from the west (BRF Consortium, personal communication about unpublished data). The towers were designed to carry instrumentation to identify and then examine the stable and predictable low-frequency eddy structures (i.e., recirculation) mentioned above. As such, the tower locations were chosen to capture the wind dynamics in the lee of the hill, where recirculation was most likely to form.

The two-tower system collected eddy covariance measurements both within and above the forest canopy. Tower 1 was located at the top of the hill, which rose roughly 40 meters above the surrounding area. Tower 2 was slightly below mid-slope of the same hill, approximately 130 meters east of Tower 1. The average slope of the hill between the towers was 20% (about 11°). The forest was a mix of conifer and deciduous trees at an average maximum height of 14 meters near the towers, with significant underbrush. The canopy depth was 9 to 10 meters at each tower, which was well in excess of the minimum 1.7 meter canopy depth predicted to be required to cause recirculation (Finnigan and Belcher 2004). A small lake was located approximately 200 meters further east of Tower 2.

Open-path infrared gas analyzers (IRGAs) and 3D sonic anemometers were placed at five levels on Tower 2, plus the top level of Tower 1, to collect data at 10 Hz. The top level of each tower was approximately 26 m above the ground surface. The remaining four levels of Tower 1 used 2D sonic anemometers and a closed-path IRGA with a manifold system allowing it to sample all four levels in sequence. The lower four levels of Tower 1 sampled data at a low frequency of 1 Hz or 1/3 Hz, depending on the sensor. Temperature sensors were located at all five levels of each tower. The top level of each tower also had a net radiometer, a photosynthetically active radiation (PAR) meter, and additional sensors measuring temperature, humidity and
atmospheric pressure. The top level of Tower 2 had a basic albedo determination comprising two opposite-facing photometers. The bottom three levels of Tower 2 had additional PAR meters installed. Soil moisture and ground heat flux probes were used to measure the terrestrial dynamics near each tower. Both towers took measurements at 2, 5, 8, 14 and 26 meters above the respective tower’s base. The full suites of sensors installed on and around Towers 1 and 2 are shown in Figures 2a and 2b, respectively.

The data were captured using a combination of CR1000 and CR5000 data loggers. The entire system was powered using marine batteries charged by a gasoline-powered generator serving each tower. The generators were each located more than 100 meters north of their respective towers in order to minimize or eliminate carbon dioxide and heat contamination of the data.
Instruments were calibrated in the laboratory prior to installation. IRGAs were tested using compressed carbon dioxide gas cylinders and a dewpoint generator. At the end of the project, all IRGAs were re-examined in the lab using the same cylinders and dewpoint generator. The reanalysis confirmed no significant instrumental drift had taken place during the relatively brief observation period.

2.2 Data Processing

The collected 10 Hz data were initially processed using Eddy Pro® software (version 5.2.1) according to the methods in Burba and Anderson (2010). We used the planar fit method of coordinate rotation (Wilczak et al. 2001) over the entire project period, discarding wind flows from within the wind shadow of the towers, as well as the Webb, Pearman, Leuning (WPL) method of correcting for the effects of air density (Webb et al., 1980).

In terms of processing quality control, we used a Hamming tapering window prior to the fast Fourier transform of the time series, as suggested by Kaimal and Kristensen (1991). Footprint estimations were made according to Kljun et al. (2004), and the data were evaluated using the policies in Mauder and Foken (2004). High-pass filtering effects were corrected as set forth by Moncrieff et al. (2004), while the low-pass filtering effect corrections were conducted according to Moncrieff et al. (1997). The raw data were also examined for spikes, amplitude variance compared with instrument sensitivity, drop-outs, absolute limits (to ensure that all measured parameters were physically possible), skewness, and kurtosis prior to data processing as specified by Vickers and Mahrt (1997). The low-frequency data were converted manually into 30-minute averages that matched the time periods of the processed eddy covariance data.


\section*{2.3 Examination of Recirculation Vortices}

To identify the wave conditions in the lee of the hill, we calculated the Brunt-Väisälä frequency (adapted from Stull 1988) using:

\begin{equation}
\frac{f}{2\pi} = \sqrt{\frac{g}{\frac{\partial \theta}{\partial z}}} ;
\end{equation}

with acceleration due to gravity (g) at \(-9.8 \, \text{m} \, \text{s}^{-2}\); the potential temperature (\(\theta\)) in K calculated from the sonic temperature, or from fine-wire thermocouples for those levels that did not have 3D sonic anemometers; and the gradient of potential temperature with height (\(d\theta/dz\)) estimated using the sonic temperatures measured at the top two levels at Tower 2.

Gu \textit{et al.} (1999) modified the procedure set forth by Budyko (1958) to determine the degree of error in energy flux measurements in terms of an energy flux balance ratio (EBR):

\begin{equation}
EBR = \frac{\lambda E + F_H}{R_n - G} ;
\end{equation}

where \(R_n\) is the net radiation, \(G\) is ground heat flux, \(F_H\) is sensible heat flux, and \(\lambda E\) is latent heat flux, all units in W m\(^{-2}\). To avoid introducing bias through gap-filling of missing data points (Baldocchi 2003), EBR was calculated using only those 24-hour periods (defined as the 30-minute averages from 1730 – 1800 until 1700 – 1730 the next day) where complete or nearly complete records were available, missing no more than two (2) 30-minute averages. Any missing parameters within any 30-minute time period caused the rejection of that 30-minute period from the 24-hour EBR calculation. Given those criteria, we used 27 daily records at Tower 1 and 19 at Tower 2 (not necessarily the same days) to generate our total project EBR. The calculations resulted in an EBR of approximately 80% at Tower 1 and 86% at Tower 2. This
degree of energy flux balance error is typical for FLUXNET locations above canopies in complex terrain (Wilson et al. 2002).

In the results discussion below, note that total wind speed measured at the bottom four levels of Tower 1 were measured with two-dimensional sonic anemometers, not the 3D sonic anemometers that recorded wind speeds at the top level of Tower 1 and at all levels of Tower 2. Where possible, error bars for key parameters were established using one sample standard deviation over the 30-minute average. Since wind direction variability was not provided by the EddyPro® software, wind roses presented in the results section were generated manually using the raw, high-frequency data. The time periods discussed in the results section below have friction velocities above the minimum 0.17 m s$^{-1}$ threshold (Goulden et al. 1996) at least at the top level both towers, and often for multiple levels within the forest canopy at Tower 2 (see Figures 3h, 5h, 6h, and 7h).

2.4 Vertical Advection Calculations

Vertical advective flux was calculated starting with this basic equation (adapted from Feigenwinter et al., 2004):

$$ F_v = \frac{1}{V_m} \int_0^{z_{max}} w \bar{c} \frac{\partial \bar{c}}{\partial z} dz ; $$

(3)

where $V_m$ is the air molar volume (m$^3$ mol$^{-1}$), $\bar{w}$ is the vertical wind speed (m s$^{-1}$), $\bar{c}$ is the carbon dioxide concentration in the air (μmol CO$_2$ mol$^{-1}$ air), $z$ is the height above the ground level (m), and the overbars denote time averages. A similar equation was used for energy flux, substituting potential temperature for carbon dioxide concentration, and using density and
heat capacity instead of air molar volume to convert the result into standard flux units. Lee (1998) assumed that the gradients of vertical wind speed, horizontal wind speed, carbon dioxide, and potential temperature were constant with respect to height from the ground surface to the measurement height. Due to the heterogeneous nature of the project site, constant vertical gradients seldom occurred.

None of these key physical quantities varied with height in ways that could be consistently parameterized into functions for integration. Instead, an estimate of the vertical advective flux was calculated by assuming that the parameters varied linearly with height from sensor to sensor, meaning that the vertical gradients were assumed constant around the horizontal slice of the atmosphere centered on each sensor. Equation (3) was broken up into five pieces, each corresponding to one sensor level on the towers, and added together to approximate the total integral.

An example of the portion of the vertical energy advective flux calculation from the second level of Tower 2, at $z = 5 \text{ m}$ would be:

$$F_v = \rho C_p \int_{4m}^{6m} \frac{w}{\bar{\theta}} \frac{\partial \bar{\theta}}{\partial z} \, dz = \frac{2}{3} w_{5m} (\bar{\theta}_{5m} - \bar{\theta}_{2m}) \rho C_p .$$  \hspace{0.5cm} (4)

where $\rho$ is the air density (kg m$^{-3}$), $C_p$ is heat capacity (J kg$^{-1}$K$^{-1}$), and $\theta$ is the potential temperature (K), yielding heat flux in W m$^{-2}$.

The vertical and horizontal wind speeds were assumed to be zero at the ground surface. Without a measured temperature or carbon dioxide concentration at the ground surface, the vertical gradients at 5 m height were assumed equal to the gradients at 2 m height.
2.5 **Horizontal Advection Calculations**

Calculating horizontal advective flux using the procedure in Yi *et al.* (2008) was impractical at this site because the horizontal gradient of both carbon dioxide and potential temperature varied with height, occasionally switching signs. Assuming that the horizontal gradients of key parameters were constant with height near each sensor allowed the integral of advective flux to be approximated piece by piece from the ground surface up to the top of the tower. Data gaps due to the wind shifting out of alignment with the towers or the failure of any one of more than two dozen sensors caused the majority of collected data to be unsuitable for an estimate of horizontal advective flux. Horizontal advective flux was estimated starting with this basic equation:

\[
F_h = \frac{1}{V_m} \int_0^{26} \nu \frac{\partial c}{\partial y} \, dz \quad ;
\]  

(5)

where \( \nu \) is the horizontal wind speed along the y-axis connecting Towers 1 and 2. In the experimental setup, \( \bar{u} \) (wind speed in the x direction) was cross-slope, and was not used quantitatively for this two-dimensional analysis. Neither \( \nu \) nor the concentration gradient varied with height in ways that could be consistently parameterized into functions for integration. Instead, an estimate of the horizontal advective flux was calculated by assuming that \( \nu \) varied linearly with height throughout a small horizontal slice of the atmosphere centered on each sensor. Assuming that the concentration and temperature gradients were constant within that horizontal slice of atmosphere allowed an estimate of horizontal advective flux.
The integration was solved similarly to the vertical advective flux above. The concentration gradients were the difference between the corresponding levels of each tower, divided by the y-axis separation between the towers rather than the z-axis distance between levels. As a result, the calculated horizontal advective flux was almost certainly an overestimate for two reasons.

Firstly, the actual path of the wind flow was unlikely to be a straight line from Tower 1 directly to Tower 2. Indeed, during time periods of recirculating wind at Tower 2, the wind parcel passing any level (especially at the mid-canopy levels) of Tower 1 may not have been the same wind parcel that struck the sensor at the corresponding level of Tower 2. This was less of an issue in the case of horizontal carbon dioxide advection because the CO$_2$ in the atmosphere tended to be well-mixed at Tower 2 during recirculation, resulting in relatively minor differences in $\bar{c}$ between the sensors at Tower 2. However, vertical potential temperature gradients usually persisted for many hours at Tower 2 despite recirculation.

The second reason the calculated horizontal advective fluxes were overestimated involved the coordinate system. The calculations in this study used the unrotated $\bar{u}$, $\bar{v}$, and $\bar{w}$ measurements in order to match the coordinate system of the other calculated parameters (e.g., net radiation, ground heat flux, sensible heat flux), which are vertical with respect to a level ground, not with respect to the actual sloped ground of the side of the hill. The horizontal gradients were calculated using the y-axis separation between the towers, which was slightly less than the actual straight-line separation between the towers due to the sloped ground. For these reasons, the $\partial y$ used in the calculations was less than the actual value, resulting in a
small overestimation of horizontal advection. All of the coordinates could not simply be tilted to account for this effect because the anemometers used at levels 1 through 4 at Tower 1 were 2D, thereby missing the vertical component.

For these reasons, the approximation of horizontal advective flux of both carbon dioxide and energy was of limited use, and will be discussed only for qualitative analysis in the rest of this thesis.
Chapter 3: Recirculation

During the experiment, the aerodynamic profile around the hillside was primarily controlled by the wind direction, and by the atmospheric stability in terms of the vertical potential temperature gradient. Whenever synoptic conditions caused the background wind direction to be westerly, the two-tower system recorded one of three different atmospheric patterns, predicted by the vertical potential temperature gradient. Examples of the three cases (unstable, near-neutral, and stable) are presented below, along with analysis of the single time period when the vertical potential temperature gradient failed to predict atmospheric dynamics leeward of the hillside. Since different cases will be examined in Chapter 4, the cases in this chapter are numbered 1.x, to distinguish them from cases 2.x, in the advection analysis.

The project site experienced westerly or near-westerly winds with both towers functioning on 15 different days, often with multiple different atmospheric states and separate instances of one or more states during each day. Table 1 summarizes the results obtained. The table uses time periods when most of the Tower 1 wind results were within 45 degrees of westerly. A weak thermal stability or instability did not influence the atmospheric flow at the project site, leading to a distinction between the accepted definition of neutral conditions (i.e., 1 °C per 100 m vertically) and this study’s usage of the term “near neutral”. Here, near neutral atmospheric condition refers to a lapse rate (positive or negative) from the mid-canopy to the top of the tower below 2 °C per 100 m. The trunk space is ignored for that determination since the near-ground temperature did not appear to influence the presence, absence, or extent of recirculation during any time period.
<table>
<thead>
<tr>
<th>Thermal Stability</th>
<th>Occurrences in Days (instances)</th>
<th>Recirculation Occurrences</th>
<th>Average Duration (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unstable</td>
<td>12 (19)</td>
<td>19 full</td>
<td>3.2</td>
</tr>
<tr>
<td>Near Neutral</td>
<td>11 (13)</td>
<td>13 partial</td>
<td>2.0</td>
</tr>
<tr>
<td>Stable</td>
<td>7 (11)</td>
<td>1 partial</td>
<td>3.3</td>
</tr>
</tbody>
</table>
3.1 Case 1.1 – Unstable Atmosphere

At 1430 on 16 May, 2013, the vertical potential temperature profile at Tower 1 showed warm air close to the ground, with colder air aloft. A similar pattern was observed at Tower 2, except for slightly colder air at the very bottom of the slope tower. This profile was unstable at the hilltop and unstable on the slope generally, with the near-ground air under stable conditions on the slope (Figure 3a). The wind directions at all levels of Tower 1 were westerly. Tower 2 recorded a westerly wind at the top level above the canopy, while within the canopy the winds were generally easterly (northerly at the very top of the canopy) (Figure 3b). Wind roses provide an additional visual indication of wind direction and its variability (Figures 4a through 4f). This wind pattern is indicative of recirculation reaching the forest floor. Finnigan and Belcher (2004 – see their Figure 4) predicted a somewhat similar pattern under neutral atmospheric conditions (they did not consider unstable conditions). A conceptual sketch of the hillside air dynamics for Case 1.1 is depicted in Figure 5a. Due to the negative gradient of the potential temperature with height, the Brunt-Väisälä frequency was a non-zero complex number. Since in general a complex solution to an eigenvalue frequency equation presents in its phase space as a focus spiraling into a point or a source spiraling outwards, the air parcel was expected to follow a spiral pattern, eventually forcing air to flow to the north or south.

Due to the recirculating air and the unstable atmosphere, carbon dioxide at Tower 2 was well-mixed through both mechanical and thermal means (Figure 3c), with concentrations substantially similar at most levels of Tower 2. Vertical carbon dioxide flux at both towers was negative or downwards (Figure 3d), and vertical sensible heat flux (hereafter referred to as
Case 1.1 – Unstable Conditions
1430 on 16 May

Figure 3: Charts of the observation results at 1430 on 16 May, 2013, showing (a) potential temperature; (b) wind direction; (c) carbon dioxide concentration; (d) carbon dioxide flux; (e) heat flux; and (f) total wind speed. Tower 1 results are represented by red circles; while Tower 2 data are black triangles. Filled gray triangles indicate fluxes with $u^*<0.17$ m s$^{-1}$. 
Case 1.1 – Unstable Conditions
1430 on 16 May

Figure 3, continued: Charts of the observation results at 1430 on 16 May, 2013, showing (g) Obukhov stability parameter; (h) friction velocity; (i) relative humidity; (j) vertical latent heat flux; and (k) turbulent kinetic energy. Tower 1 results are represented by red circles; while Tower 2 data are black triangles. Filled gray triangles indicate fluxes with $u^*<0.17$ m s$^{-1}$. 
Case 1.1 – Unstable Conditions
1430 on 16 May

Figure 4: Wind roses (in degrees) at 1430 on 16 May, 2013, showing (a) top of Tower 1; (b) top of Tower 2; (c) top of canopy at Tower 2; (d) mid canopy at Tower 2; (e) lower canopy at Tower 2; and (f) trunk space at Tower 2. The wind roses were assembled using counts of the unrotated wind direction collected at 10 Hz over 30 minutes, and are not weighted by wind speed.
Figure 5: Conceptual two-dimensional sketches of wind dynamics around the experiment in various atmospheric conditions. The red coloring indicates warmer air, while the darker blues and purples represent colder air. (a) shows recirculating air reaching the ground on the slope during this time period (Case 1.1).

In (b) Case 1.2 has nearly uniform potential temperature, with a very slight warming near the top of Tower 1. Recirculating air did not reach the ground on the slope during this time period, instead changing to katabatic drainage flow near the forest floor around Tower 2.

(c) shows slightly warmer air aloft in Case 1.3. Recirculation was not evident during this time period. Note also that carbon dioxide flux is negative (downwards) at most levels during this time, which is unexpected during nighttime.
“heat flux” unless otherwise specified) upwards (Figure 3e), as expected during daytime in the growing season. The total wind speeds (Figure 3f) recorded increasing speed with height at Tower 1. However, the wind at Tower 2 was at a minimum in mid-canopy where maximum leaf density was located (Yi 2008), while the top level wind speed of 1.3 m s\(^{-1}\) was similar in magnitude to the speed in the trunk space, 0.90 m s\(^{-1}\).

The Obukhov stability parameter (Monin and Obukhov, 1954) predicted an unstable atmosphere at the upper three levels of Tower 2, switching to stable in the bottom two levels \(i.e.,\) at two and five meters above the ground \(–\) see Figure 3g). Foken (2006) argued that the Monin-Obukhov similarity theory is of limited usefulness over (or within) tall vegetation or on sloped terrain. In many other cases during our study, the Obukhov stability parameter did not provide reasonable predictions; however for the time period of Case 1.1 the unstable atmosphere was closely predicted by the Obukhov stability parameter.

Relative humidity was roughly constant at all heights of Tower 2 (Figure 3i), ranging from 25.7\% to 26.9\% within canopy, and 28.2\% above the forest. In the absence of an influx of moisture at the lower levels of Tower 2, the recirculation region did not reach the lake on the valley floor to the east of Tower 2 during this time period, and therefore the recirculation zone was similar in scale to the hill obstructing the synoptic air flow.

3.2 Case 1.2 – Near-Neutral Atmosphere

At 0230 on 21 May, 2013, both towers recorded vertical potential temperature gradients near zero, corresponding to near neutral atmospheric conditions (Figure 6a), except for slightly stable air at the top of Tower 1 and at the bottom level of Tower 2. The wind direction at the
top of Tower 1 was southwesterly, and westerly within the canopy. Tower 2 recorded wind (Figure 6b) from the southwest at the top level above the canopy, while within the canopy the winds were generally northeasterly. The wind was northerly near the ground level, apparently following the gentle gradient of the valley down towards the Hudson River in the south, similar to an effect measured by Tóta et al. (2008). Wind roses provide an additional visual indication of wind direction and its variability (Figures 7a through 7f).

This wind pattern is indicative of a partial recirculation penetrating into the forest canopy, but not reaching the ground level. A conceptual sketch of the hillside air dynamics for Case 1.2 is included as Figure 5b. Due to the nearly constant potential temperature with height, the Brunt-Väisälä frequency was approximately zero. As in Case 1.1, Tower 2 data showed no indication of lee waves above the recirculation.

Due to the partial recirculation, carbon dioxide at Tower 2 was incompletely mixed (Figure 6c), maintaining a slight negative gradient with height of about five (5) parts per million in 21 meters, with high CO$_2$ concentrations near ground level where the recirculation pattern did not reach. If the recirculation had reached the CO$_2$-rich air at the forest floor, the CO$_2$ concentration at the top of Tower 2 (where standard flux towers most commonly take measurements) would be higher. CO$_2$ flux at both towers was mostly positive or upwards (Figure 6d), with heat flux negative or downwards (Figure 6e), as expected at night in the absence of photosynthesis. Both fluxes were nearly zero at the second level of Tower 2, indicating that the recirculation of air at Tower 2’s location on the hillside reached down to a height near five (5) meters above the forest floor. A layer of air with no vertical carbon dioxide flux or heat flux then separated the
Case 1.2 – Near-Neutral Conditions
0230 on 21 May

Figure 6: Charts of the observation results at 0230 on 21 May, 2013, showing (a) potential temperature; (b) wind direction; (c) carbon dioxide concentration; (d) carbon dioxide flux; (e) heat flux; and (f) total wind speed. Tower 1 results are represented by red circles; while Tower 2 data are black triangles. Filled gray triangles indicate fluxes with $u^*<0.17$ m s$^{-1}$. 

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Figure 6, continued: Charts of the observation results at 0230 on 21 May, 2013, showing (g) Obukhov stability parameter; (h) friction velocity; (i) relative humidity; (j) vertical latent heat flux; and (k) turbulent kinetic energy. Tower 1 results are represented by red circles; while Tower 2 data are black triangles. Filled gray triangles indicate fluxes with $u^* < 0.17 \text{ m s}^{-1}$.
Case 1.2 – Near-Neutral Conditions
0230 on 21 May

Figure 7: Wind roses (in degrees) at 0230 on 21 May, 2013, showing (a) top of Tower 1; (b) top of Tower 2; (c) top of canopy at Tower 2; (d) mid canopy at Tower 2; (e) lower canopy at Tower 2; and (f) trunk space at Tower 2. The wind roses were assembled using counts of the unrotated wind direction collected at 10 Hz over 30 minutes, and are not weighted by wind speed.
recirculating upper air mass from the stable near-ground layer subjected to katabatic flow (Figure 6b), draining cold air slowly downslope (Yi et al. 2005; Chen and Yi 2012) along the valley towards the lower-elevation Hudson River to the south and east.

The total wind speeds increased with height at both towers (Figure 6f), but with a much higher gradient at Tower 1. The wind speed at Tower 2 did not have a mid-canopy minimum caused by the tree leaf maximum in this case. The wind speed of 0.80 m s\(^{-1}\) at the top level of Tower 2 was smaller than the speed in Case 1.1, while the wind within the canopy at Tower 2 ranged from 0.12 m s\(^{-1}\) in the trunk space to 0.30 m s\(^{-1}\) at the top of the canopy. At the second level of Tower 2 (five meters in height), where near-zero carbon dioxide flux and heat flux were measured, the wind speed was 0.19 m s\(^{-1}\) from the northeast. Although the air is in motion at this height, the vertical turbulent fluxes for carbon dioxide, sensible heat, and latent heat (Figure 6j) were minimal during this time period.

The Obukhov stability parameter (Figure 6g) indicated unstable atmosphere at the bottom of Tower 2, while the rest of Tower 2 and the top of Tower 1 were stable. In this case, the Obukhov stability parameter did not give reasonable predictions of atmospheric stability.

3.3 Case 1.3 – Stable Atmosphere

At 0100 on 30 May, 2013, the vertical potential temperature profile at Tower 1 had cold air at the base of the tower, with potential temperature increasing slightly (but steadily) with altitude. Tower 2 also recorded increasing potential temperature with height (Figure 8a), indicating a stable atmosphere. The wind directions were westerly at the lower levels of both towers. The top of Tower 1 recorded wind from the southwest, while the top of Tower 2
experienced southeasterly wind. As in Case 1.2, wind roses provide an additional visual indication of wind direction and its variability (Figures 9a through 9f). Air flowed north to south at the top of the canopy at Tower 2 (level 2-4), possibly indicating tri-dimensional flow (Tota et al. 2012), with air deflecting horizontally around the hill obstructing the background flow, though with only two towers this effect could not be thoroughly investigated. The mean vertical velocity at level 2-4 during this time period was -0.067 m s\(^{-1}\), indicating very little vertical motion. No vertical recirculation pattern was visible (Figure 6b). The wind rose for the top of the canopy at Tower 2 (Figure 9c) indicates airflow from the north, northeast, east, and southeast. The near-zero vertical velocity at level 2-4, combined with the wind direction and wind rose, reinforces the supposition that the air flow wrapped around the hillside horizontally rather than displacing vertically. A conceptual sketch of the two-dimensional hillside air dynamics for Case 1.3 is depicted in Figure 5c.

Under stable atmospheric conditions where potential temperature increases with height (causing a decrease in density with height), lee waves may be caused by the pressure drop as the air mass passes over the hilltop (Wurtele et al., 1993). This project’s experimental setup was not designed to confirm the theorized lee waves. However, during this time period, the Brunt-Väisälä equation determined a period of about 186 seconds for a standing atmospheric wave at the top of Tower 2, which informed the conceptual sketch (Figure 5c). A spectral analysis of vertical wind speed fluctuations during this time period did not show an obvious peak at any frequency. If lee waves formed during this time period, they would have appeared at an elevation near the top of the canopy on the hilltop, approximately 15 m above the height.
of Tower 2’s topmost sensor suite, however the effect was either not present, or was not strong enough to provide a clear signal at Tower 2.

Lower in the canopy near Tower 2, katabatic flow was observed as the dense cold air mass close to the ground, rich in carbon dioxide, flowed slowly down the hill. Carbon dioxide concentration on the slope was poorly mixed (Figure 8c), indicating a stratified atmosphere without effective vertical mixing. If the atmosphere around Tower 2 had been well-mixed by a recirculation zone, the carbon dioxide concentration measured at the top of Tower 2 would be higher. Tower 2 showed little or no carbon dioxide flux, while energy flux was generally downwards except at level 2-3 (Figure 8d and 8e). The total wind speeds (Figure 8f) recorded increasing speed with height at Tower 1, reaching a maximum at the top of the canopy and decreasing slightly with additional height. As in Case 1.1, the wind at Tower 2 was at a minimum in mid-canopy, showing the influence of trees on the air flow (Yi 2008). The top level wind speed of 0.51 m s⁻¹ was larger than the speed in the trunk space, 0.21 m s⁻¹. The large relative difference between the Tower 2 top level wind speed and the bottom level (nearly 60%) contrasts with the difference recorded in Case 1.1 (just over 30%), further supporting the evidence that the lower levels experienced a different air mass with distinct dynamics that would not be uncovered by sampling only the top level at Tower 2, despite the acceptable 0.21 m s⁻¹ friction velocity (Figure 8h).

3.4 Case 1.4 – The Inconvenient Case

Vertical potential temperature gradient did not predict the atmospheric dynamics during one evening in the middle of the project. At 2300 on 30 May, 2013, 22 hours after Case 1.3, a partial recirculation eddy was measured (Figure 10b). Wind roses provide an additional visual
Case 1.3 – Stable Conditions
0100 on 30 May

Figure 8: Charts of the observation results at 0100 on 30 May, 2013, showing (a) potential temperature; (b) wind direction; (c) carbon dioxide concentration; (d) carbon dioxide flux; (e) heat flux; and (f) total wind speed. Tower 1 results are represented by red circles; while Tower 2 data are black triangles. Filled gray triangles indicate fluxes with \(u^*<0.17\) m s\(^{-1}\).
Case 1.3 – Stable Conditions
0100 on 30 May

Figure 8, continued: Charts of the observation results at 0100 on 30 May, 2013, showing (g) Obukhov stability parameter; (h) friction velocity; (i) relative humidity; (j) vertical latent heat flux; and (k) turbulent kinetic energy. Tower 1 results are represented by red circles; while Tower 2 data are black triangles. Filled gray triangles indicate fluxes with $u_*<0.17$ m s$^{-1}$. 
Case 1.3 – Stable Conditions
0100 on 30 May

Figure 9: Wind roses (in degrees) at 0100 on 30 May, 2013, showing (a) top of Tower 1; (b) top of Tower 2; (c) top of canopy at Tower 2; (d) mid canopy at Tower 2; (e) lower canopy at Tower 2; and (f) trunk space at Tower 2. The wind roses were assembled using counts of the unrotated wind direction collected at 10 Hz over 30 minutes, and are not weighted by wind speed.
indication of wind direction and its variability (Figures 11a through 11f). At that time, the vertical potential temperature profile indicated stable atmospheric conditions (Figure 10a). The stability began at least three hours prior, between 1900 and 2000. As the stability strengthened towards midnight, the eddy dissipated for the rest of the night. The vertical profiles show a partially-mixed carbon dioxide concentration (Figure 10c), upwards carbon dioxide flux (Figure 10d), and downwards heat flux (Figure 10e). The total wind speeds recorded increasing speed with height at Tower 1 (Figure 10f). Wind speeds at Tower 2 were very low at all four lower levels, with faster wind at the top level.

A peculiarity during this time period can be seen in the wind rose for the top of the canopy (Figure 11c). Compared with the same level in Case 1.2’s partial recirculation profile, this time period’s level 2-4 (Tower 2, at 14 m height) reversed flow contains a significant but non-dominant amount of streamwise flow. This oscillating flow may indicate measurement of the wake effect caused by a single treetop near the tower, which the background wind aligned towards the sensor during this time period. This anomaly could also have been caused by stronger winds, at 5.4 m s\(^{-1}\) (Tower 1, top level), compared with 3.8 m s\(^{-1}\) for Case 1.3. Strong winds can cause stratification of the boundary layer, with a small eddy downwind of an obstruction (Stull 1988), which coincidentally may have been located near Tower 2 at the time in question. Also, while simulations (e.g., Xu et al., 2015) show that recirculation eddies may be caused over complex terrain without a background wind, a large pressure drop in the lee of the obstruction caused by strong winds might briefly cause recirculation despite the stable atmosphere, simply due to the angular momentum of the wind parcel. The Brunt-Väisälä
equation for this time period predicted a lee wave with a period of about 283 seconds, which is a significantly longer waveform than Case 1.3.
Figure 10: Charts of the observation results at 2300 on 30 May, 2013, showing (a) potential temperature; (b) wind direction; (c) carbon dioxide concentration; (d) carbon dioxide flux; (e) heat flux; and (f) total wind speed. Tower 1 results are represented by red circles; while Tower 2 data are black triangles. Filled gray triangles indicate fluxes with $u^* < 0.17 \text{ m s}^{-1}$. 


The Inconvenient Case 1.4
2300 on 30 May

Figure 10, continued: Charts of the observation results at 2300 on 30 May, 2013, showing (g) Obukhov stability parameter; (h) friction velocity; (i) relative humidity; (j) vertical latent heat flux; and (k) turbulent kinetic energy. Tower 1 results are represented by red circles; while Tower 2 data are black triangles. Filled gray triangles indicate fluxes with u*<0.17 m s⁻¹.
The Inconvenient Case 1.4
2300 on 30 May

Figure 11: Wind roses (in degrees) at 2300 on 30 May, 2013, showing (a) top of Tower 1; (b) top of Tower 2; (c) top of canopy at Tower 2; (d) mid canopy at Tower 2; (e) lower canopy at Tower 2; and (f) trunk space at Tower 2. The wind roses were assembled using counts of the unrotated wind direction collected at 10 Hz over 30 minutes, and are not weighted by wind speed.
Chapter 4: Advection

The included figures present vertical advective fluxes on different days. The advection calculations were chosen from time periods that conformed to the following criteria. All five levels of Tower 2 must have recorded all of the parameters required to calculate vertical advection: wind direction, potential temperature and/or carbon dioxide concentration, wind speed, density, air molar volume, and heat capacity. Additionally, with respect to the total energy flux balance, the advective energy flux calculations also required net radiation and sensible, latent, and ground heat fluxes at Tower 2, using the quality criteria specified in Kutter et al. (2017). These criteria were met for energy flux during 106 half-hour time periods (corresponding to 53 hours of project time), on eight separate days. They were met for 86 time periods (43 hours) on six separate days for carbon dioxide advective flux.

The time periods highlighted were chosen to examine three different atmospheric stability conditions: stable, near-neutral, and unstable. No gap-filled data were included, and all advection measurements were estimated from all five height levels. Note that Figure 13 (a) and (b) are subsets of Figure 13 (c) and (d). The analysis herein focused on the following five (5) cases, which are numbered in order to contrast them with the separate cases presented in Chapter 3:

Case 2.1 2200 on 25 April to 0500 on 26 April. Five time periods were discarded due to data gaps (missing 2.5 hours out of 7). For the times that passed the criteria, atmospheric conditions were stable, and no recirculation was observed at Tower 2. On
these days at the start of the growing season, some but not all trees in the project area had leaves.

**Case 2.2** 1230 to 1530 on 16 May. No time periods were excluded (all 3 hours included). Atmospheric conditions were unstable, with recirculation observed during the entire period. By this day, all of the living trees in the area had leaves.

**Case 2.3** 0730 to 1330 on 21 May. Excluded 1 time period (missing 0.5 hours out of 6). The atmosphere was unstable from mid-canopy to the top level, with full recirculation reaching the forest floor.

**Case 2.4** 0330 until 0730 on 31 May. One time period was excluded (missing 0.5 hours out of 4). The atmosphere was near-neutral except for 0530 to 0600, which was very mildly stable. Partial recirculation was observed, with drainage flow near the forest floor. Note that this time period was a subset of the next subject time.

**Case 2.5** 0130 on 30 May until 0730 on 31 May. One time period was excluded (missing 0.5 hours out of 30), which was the project’s longest nearly continuous time period meeting the stringent quality criteria. This time period included all atmospheric conditions: stable with no recirculation; near neutral with partial recirculation; and unstable with full recirculation.

### 4.1 Energy Advection in Various Atmospheres

For Case 2.1, Figure 12 (a) shows nighttime energy advection during stable atmospheric conditions. The warm air aloft flowed down the slope during this time period, causing a downward vertical advective energy flux. Because of the high probability that this time period
Advective Energy Flux

Figure 12: Charts of the advective flux showing (a) Case 2.1, stable conditions on 25-26 April; (b) Case 2.2, unstable conditions on 16 May; and (c) Case 2.3, unstable conditions on 21 May. Vertical advection is represented by blue squares, while horizontal advection is black diamonds.
Figure 13: Charts comparing the advective energy and carbon dioxide fluxes: (a) and (b) during near-neutral conditions on 31 May (Case 2.4); and (c) and (d) during all conditions for a long time period on 30-31 May (Case 2.5). Vertical advection is represented by blue squares, while horizontal advection is black diamonds. The dashed boxes and lines indicate the portions of Figure 2 (c) and (d) that are highlighted in Figure 2 (a) and (b).
experienced lee waves downstream of the hill rather than recirculation (see Figure 5c), it is possible that the wind flowing past Tower 1 had minimal or no connection to the air at Tower 2. The potential temperature profiles were similar at both towers, but if the air at Tower 2 did not originate from Tower 1, the calculated horizontal gradients between the two towers may not be accurate, precluding a defensible horizontal advection estimate.

In Case 2.2, Figure 12 (b) shows daytime advection during unstable atmospheric conditions from mid-canopy to the top level of Tower 2, with cold air near the ground. Measured wind flow indicated that Tower 2 experienced full recirculation during this time period, including the cold air near the ground. Warm air from mid-canopy rose up from the bottom of the recirculation bubble, while the colder air above the canopy sank down at the top of the bubble. The rising colder air at the ground surface was not enough to overcome the net positive vertical advective energy flux.

In Case 2.3, Figure 12 (c) shows advection during unstable conditions from mid-canopy to the top level of Tower 2, with stable air near the ground, echoing Case 2.2. The recirculation bubble extended to the forest floor despite the stable thermal condition near the ground. Vertical advective energy flux was positive as the cold air aloft sank down and the warm air in mid-canopy rose. The rising cold air at the forest floor did not balance out the upward sources of vertical advective energy flux.

In Case 2.4, Figure 13 (a) and (b) presents advective fluxes during near-neutral nighttime conditions. During this time period, recirculation was partial: recirculating air affected the middle and upper canopy, while the trunk space near the ground experienced drainage flow under localized stable conditions. The large positive vertical advective energy flux at 0430 to
0500 was caused by a sudden and temporary upwards wind flow in the mid-canopy, from 5 m to 10 m. The top and bottom levels continued relatively normally during this time period. Katul et al. (2006) predicted that during near-neutral conditions a small fluctuation in temperature may cause sudden and comparatively large fluxes at indeterminate intervals. The wind gusts at 0430 temporarily halted the otherwise continuously positive vertical advection of carbon dioxide.

Case 2.5 was a much larger time series that encompassed Case 2.4. Figure 13 (c) and (d) provides the advective fluxes of energy and carbon dioxide, respectively, for the 30 hour period.

4.2 Horizontal Advection

The relationship between vertical and horizontal advective flux at the project site was complex. Data results ranged from near-mirror activity where the advective fluxes almost balanced each other out over the long term (though changing at different frequencies), to time periods where one advection type (usually vertical) clearly dominated. Occasionally, horizontal and vertical advective fluxes acted in the same direction and changed together at similar timescales.

In both stable and unstable atmospheres (Cases 2.1, 2.2, and 2.3), horizontal advective energy flux was almost always opposite in sign to and smaller in magnitude than the vertical advective energy flux. While the advective fluxes often mirrored each other, this phenomenon did not always occur. For example, between 1000 and 1130 on 21 May, the vertical advective energy flux increased in magnitude, and then decreased. During that specific time period, the horizontal advective energy flux (opposite in sign) decreased in magnitude, and then increased,
causing the net energy advection over that time period to vary significantly. Indeed, from 0800 until 1130 that day, vertical energy advection generally decreased, while horizontal energy advection stayed roughly the same apart from the temporary dip in strength at 1030.

During the entire time period of Case 2.4, the vertical and horizontal energy advective fluxes traded dominance, and were usually opposite in sign. If we ignore the sudden wind gust at 0430, the net vertical advective energy flux was roughly equal and opposite to the horizontal advective energy flux. This result supports Aubinet (2003)’s speculation that during neutral conditions, advective fluxes nearly cancel each other out, absent a sudden gust phenomenon. The gusts at 0430 support another of his conclusions that large variability during neutral atmospheric conditions undermines advective flux predictions.

Horizontal CO₂ advective flux was highly variable. Horizontal energy advective flux was more predictable, usually 25 to 50 W m⁻² during the evenings, and 50 to 100 W m⁻² during the day. Negative vertical wind speed was observed during stable conditions at Tower 2. During unstable or near-neutral conditions, the situation was more mixed. Vertical wind direction above the canopy was negative, while the reversed flow portions of the canopy (the entire canopy for unstable conditions, or the top portion of the canopy during near-neutral conditions) had a positive vertical velocity as the flow recirculated back up the hill.

Over the longer term (Case 2.5), the vertical advective flux of both energy and carbon dioxide almost always dominated the total advective flux equation. Additionally, the vertical and horizontal advective fluxes of both parameters were often (but not always) opposite in sign. Curiously, when transitioning from a positive to a negative flux, the horizontal and vertical advective fluxes often switched directions at different times. Except for the CO₂ transition at
1730 on 30 May, the changes were not in phase. Further, the directions each advective flux acted in were not of consistent durations: there was no consistent lead or lag. There may be separate mechanisms causing changes in vertical and horizontal advective flux, acting on differing time scales.

### 4.3 Comparison of Advective Flux with Turbulent Flux

A critical question for researchers studying advection over complex terrain is: how useful were the advective flux calculations to improving understanding of energy and/or scalar flow? While testing the accuracy of carbon dioxide advective fluxes was not possible with this project’s dataset, the energy advective flux calculations could be evaluated using the energy flux balance ratio (EBR) adapted from Gu et al. (1999) and Budyko (1958) in equation (2). Again, the uncertainty of the horizontal advective flux estimates available preclude their use in this analysis, but a measure of the effectiveness of the vertical advective flux estimate is useful. The EBR values with and without the vertical advective flux term were compared to determine the effectiveness of the advection analysis at this project site. Table 2 is a collection of totaled vertical fluxes, compared using equation (2).
Table 2: Vertical advective Flux of Energy Compared with the Energy Flux Balance Ratio (EBR)

<table>
<thead>
<tr>
<th>Case</th>
<th>Hours</th>
<th>Atmospheric Conditions</th>
<th>Flow</th>
<th>EBR – no advection</th>
<th>Cumulative $F_v$ (W m$^{-2}$)</th>
<th>EBR with $F_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>7</td>
<td>Stable</td>
<td>No recirculation</td>
<td>21%</td>
<td>-913</td>
<td>135%</td>
</tr>
<tr>
<td>2.2</td>
<td>3</td>
<td>Unstable</td>
<td>Full recirculation</td>
<td>77%</td>
<td>1,586</td>
<td>120%</td>
</tr>
<tr>
<td>2.3</td>
<td>6.5</td>
<td>Unstable</td>
<td>Full recirculation</td>
<td>67%</td>
<td>2,148</td>
<td>116%</td>
</tr>
<tr>
<td>2.4</td>
<td>3.5</td>
<td>Neutral</td>
<td>Partial recirculation</td>
<td>22%</td>
<td>11</td>
<td>19%</td>
</tr>
<tr>
<td>2.5</td>
<td>29.5</td>
<td>Mixed</td>
<td>Varied</td>
<td>104%</td>
<td>2,988</td>
<td>144%</td>
</tr>
</tbody>
</table>
The values were obtained by summing each parameter through the entire corresponding time period, and then adding these summed values into equation (2). Without accounting for advective flux, time periods with unstable atmospheric conditions generally had better EBR than those under more stable flow regimes. In stable and unstable cases, the calculated advective fluxes improved the overall EBR. The calculations typically pulled the project farther away from energy flux balance closure during near-neutral time periods. Qualitatively, the vertical advective flux values typically scaled to roughly a quarter of the daytime net radiation for the corresponding time period.

4.4 Carbon Dioxide Advection

Due to a sensor malfunction, advective flux of carbon dioxide could not be measured during Cases 2.1 through 2.3. Carbon dioxide measurements during Case 2.4 (near-neutral conditions) indicate that advective carbon dioxide flux was clearly dominated by vertical advection, while horizontal advection was near zero for most of the time period. In Case 2.5 (variable conditions over 29.5 hours), the vertical advective CO$_2$ flux usually dominated the total advective flux equation. In order to further examine carbon dioxide advection, additional time periods were analyzed where the appropriate sensors were functioning properly.

During the time period from 0900 until 1230 on 20 May, the winds aligned the two towers and all relevant sensors were functioning properly for both energy and carbon dioxide advective flux calculations. Atmospheric conditions were strongly unstable at first, waning but remaining unstable as time went on. Full recirculation was recorded at Tower 2, reaching the forest floor despite the cold layer there. Figure 14 (a) and (b) shows the vertical advective fluxes of energy and carbon dioxide, respectively. There was little or no vertical carbon dioxide advective flux for
Carbon Dioxide and Energy Advective Fluxes

**Figure 14**: Charts comparing the advective energy and carbon dioxide fluxes: (a) and (b) during unstable conditions on 20 May; and (c) and (d) during both unstable and near-neutral conditions on 08 June. Vertical advection is represented by blue squares, while horizontal advection is black diamonds.
most of the recirculation event. The recirculating bubble mixed the atmosphere vertically, causing any vertical air motion to effectively exchange no carbon dioxide. Due to the persistent vertical potential temperature gradient, the vertical wind motion caused significant vertical energy advective flux.

On 08 June, from 0830 until 1630, advective flux was estimated through an atmospheric transition. The conditions were unstable from 0830 until 1000 (when it started raining), then near-neutral until 1130 (rain stopped), and back to unstable for the remainder of the day. Figure 14 (c) and (d) contains the results for energy and carbon dioxide, respectively. Full recirculation at Tower 2 began around 0900 and continued throughout the day, apparently having enough momentum to carry on recirculating through the short near-neutral interlude. After 1200, the vertical advective CO₂ flux was positive or near zero. In terms of energy advection, the vertical flux was mildly positive for most of the day.

As in Aubinet et al. (2003), under stable or near-neutral conditions the flow regime near the ground was decoupled from that above the canopy. Even when wind flows were in the same direction at Tower 1 compared with Tower 2 under stable conditions, as in Case 2.1 and portions of Case 2.5, the differences in horizontal wind speed and carbon dioxide concentration were significant, possibly indicating separate air masses. Only during unstable conditions did the atmosphere from above the canopy penetrate to the ground, mixing the entire air column.
Chapter 5: Conclusions and Recommendations for Future Work

Observations of atmospheric dynamics over a hilly forest provided a measure of atmospheric dynamics leeward of the hill, and a data trove used to research advective fluxes in complex terrain.

**Research Question 1:** Can recirculation be measured by using two nearby flux towers leeward of a forested hillside? Recirculation was captured (see Figures 3, 4, 6, and 7) by the experimental setup, and the data yielded a view of the phenomenon in great detail.

The causes of recirculation were visible in the data, as well as crucial indications of the impact the persistent wind flow pattern has on the movement of matter and energy in a non-ideal, real-world landscape. Using some reasonable assumptions and practical methods, a defensible estimate of vertical advective flux of energy and carbon dioxide was ascertained. Over complex terrain, where advective flux cannot be ignored (Baldocchi et al., 1988), determining vertical advection is necessary to gain a full understanding of the location’s interactions with the atmosphere. While the vertical advection measurements contributed overall towards a balanced total energy flux, the project remained unbalanced, particularly during stable or near-neutral evening time periods. However, the experimental design required by the recirculation portion of the project placed the two towers too far apart for a defensible quantification of horizontal advective flux.

5.1 Recirculation

To determine atmospheric stability over complex terrain, potential temperature proved more useful than Obukhov’s stability parameter.
**Research Question 2:** What atmospheric conditions cause recirculation eddies as opposed to lee waves with no recirculation? In almost all cases, the vertical gradient of the potential temperature determined the type of atmospheric circulation pattern observed in the lee of the project hill (see Figure 5). Whenever the vertical potential temperature gradient indicated unstable conditions and the site experienced westerly winds, Tower 2 recorded recirculation. Though there was no tower west of the hillside to measure the wind, easterly winds during unstable atmospheric conditions are expected to have caused recirculation to form west of the hill. Under stable conditions, there was no evidence of recirculation at Tower 2, except for one time period mentioned in 3.4 above. Transitions and hybrid conditions (such as the partial recirculation noted in Figure 6b) occurred during near-neutral situations.

**Research Question 3:** What strengthens or weakens recirculation? The vertical potential temperature gradient throughout the canopy and immediately above the trees determines the existence and strength of recirculation. The full recirculation condition discussed as Case 1.1 was surprising in that it reached the forest floor despite a positive vertical potential temperature gradient between the bottommost two levels. During those time periods with full recirculation, the colder, denser air from the forest floor at Tower 2 flowed uphill, rising into the warmer, less dense air aloft. The mechanically-induced recirculation flow was strong enough to drive counter-gradient air flow.

**Research Question 4:** What impact does recirculation have on the profiles and fluxes of energy and carbon dioxide? Recirculation mixed the carbon dioxide concentration vertically, causing a strong vertical flux at the start of recirculation that would then be reduced over time until the vertical concentration gradient nearly vanished after persistent recirculation. However, the
recirculation phenomenon was not sufficient to mix the atmosphere in terms of energy. This resulted in persistent recirculation events causing tremendous vertical energy flux lasting many hours.

Since recirculating air conflicts with the assumption of zero flow divergence or convergence required in standard eddy covariance calculations, additional caution must be taken when using eddy flux tower data from complex terrain during time periods of thermally unstable atmospheric conditions. The use of carbon dioxide eddy flux calculations from such time periods for net ecosystem exchange analyses may not be accurate regardless of friction velocity. Multi-tower studies are required to determine modifications to the eddy covariance method in situations where divergence or convergence occurs.

Aubinet (2008) remarked that gravity waves could cause noise in eddy flux measurements and undermine stationarity or similarity assumptions required for a complete application of the eddy covariance method. During time periods where the vertical potential temperature gradient resulted in stable conditions, the conceptual formulation of the atmospheric dynamics presented here is in the form of a standing wave locked to the hill and valley topography. While the standing wave could not be confirmed using this two-tower system, either positive or negative vertical carbon dioxide fluxes were measured on separate evenings with similar potential temperatures and potential temperature gradients. The Brunt-Väisälä equation described the frequency of such a standing wave as a function of the vertical potential temperature gradient and the temperature itself. The wavelength will vary depending on frequency and also wind speed. An additional variable to consider is the distance between the obstruction that causes the lee wave and the tower recording a part of the phenomenon (in this
case Tower 2). The vertical direction of the measured flux will depend on the frequency (i.e., the potential temperature and the vertical potential temperature gradient), the wind speed, and the distance between the obstruction and the recording instruments. All other parameters being roughly equivalent on two separate averaging periods, one wind speed may result in a positive vertical carbon dioxide flux, while another results in a negative flux, simply because of the point in the standing wave’s oscillation at which the slope tower’s sensors are situated.

5.2 Advection

Research Question 5: Can advective flux be calculated from the two-tower experiment in this project? A defensible approximation of vertical advective flux was achieved (see Figures 12, 13, and 14). The approximation of horizontal advection may not be accurate because of the possibility that the air mass sampled at Tower 1 was not the same air mass passing Tower 2’s sensors. The problems encountered attempting to estimate horizontal advective flux undermined the usefulness of the calculation.

Research Question 6: What atmospheric conditions cause vertical and/or horizontal advection to be significant contributors to total flux? While the qualitative analysis presented here indicated that vertical advective flux dominated horizontal advective flux during the majority of the project, the difference in magnitude was much less than an order of magnitude. Though horizontal advective flux was overestimated here, horizontal advection cannot be ignored, especially during times where turbulent flux was low or when vertical and horizontal advective fluxes carried the same sign.
Aubinet et al. (2003) concluded that horizontal and vertical advective fluxes were usually similar in magnitude but opposite in sign, indicating that advective fluxes should not be used in total flux calculations until improvements in experimental design and measurement were made. At Black Rock Forest, the horizontal and vertical advective fluxes approached opposite parity only during stable atmospheric conditions. However, during unstable conditions with full recirculation observed at Tower 2, vertical advective flux dominated. Over longer periods of time the advective fluxes carried the same sign, again with vertical advective flux larger than horizontal.

Grant et al. (2015) presented strong evidence that even when the incident wind had low variability, the heterogeneous forest and hilly terrain produced three-dimensional flow patterns. The 3D sonic anemometers detected flow patterns that included cross-slope components, but with two towers the resulting analysis cannot quantify advective fluxes beyond two dimensions.

The more complex the terrain at the project site is, the more measurements are necessary to examine the flows. With two towers, cross-slope fluxes cannot be measured, and must be assumed negligible. As noted by Staebler and Fitzjarrald (2004), absent proof, that assumption carries risks. The hill used in this experiment was ridge-like running approximately north-south with no strong cross-slope heterogeneity in vegetation. While cross-slope winds were observed often, a cross-slope gradient in either potential temperature or carbon dioxide concentration was not expected. Without a cross-slope gradient, a non-zero wind flow across the slope would not result in significant advective flux in the third dimension (Feigenwinter et al., 2004).
For a full closure of the energy flux balance and increased confidence in the calculated net ecosystem exchange of carbon dioxide, an additional tower collecting a vertical profile of wind flow, potential temperature, and carbon dioxide concentration must be dedicated to the measurement of horizontal advection. If possible, the additional horizontal advection tower should be located near the standard eddy flux tower, at a distance of much less than the length of the hill’s slope. Closely-placed towers are necessary in order to avoid complications caused by preferential flow patterns, which can be as large as the obstruction causing the wind flow shift. A small, localized gradient in carbon dioxide concentration or potential temperature (caused by recirculation or flow separation, for instance), combined with a moderate horizontal wind speed, can cause significant advective flux (Katul et al., 2006) that would otherwise not be captured using two towers that were not close enough together.

**Research Question 7:** What is the relationship between horizontal and vertical advection of both carbon dioxide and energy? When transitioning from a positive to a negative flux, the horizontal and vertical advective fluxes often switched directions at different times, without a consistent phase lag. There are separate mechanisms causing changes in vertical and horizontal advective flux for both energy and carbon dioxide, acting on differing time scales. Any relationship between vertical and horizontal advective flux at Black Rock Forest was caused by the atmospheric flow patterns (sketched in Figure 5), however the changing gradients impacted by numerous environmental factors (from time of day, seasonal changes, water availability, air temperature, etc.), underlined the need to measure both vertical and horizontal advection at the site. In terms of the relationship between carbon dioxide and energy advective flux in either the horizontal or vertical, the wind speed used in the calculation for any given time period will
be the same for each parameter, but there is no simple relationship between the energy and carbon dioxide gradients either vertically or horizontally. Researchers with excellent energy advective flux measurements should not assume that they have defensible carbon dioxide advective flux measurements, and the same is true for vertical versus horizontal advective flux. These parameters must be measured at each site, regardless of atmospheric conditions, especially in terrain that departs strongly from ideal conditions.
References


