Chapter 10

ADVECTION AND MODELING

John Finnigan
John.Finnigan@csiro.au

Abstract

Horizontal heterogeneity in either the source-sink distribution or the wind field results in streamwise advection of momentum and scalars, which must be accounted for whenever we deduce surface exchange from micrometeorological measurements on flux towers. This Chapter focuses on the second of these causes, addressing scalar advection in topography covered with uniform forest canopies rather than that generated by heterogeneity in the land cover. After defining advection and its relationship with modeling we discuss flow over forested hills by looking first at the wind field, next at the transfer of a generic scalar and finally at the implications for measuring photosynthesis on a two-dimensional ridge. Using analytic approaches as far as is possible, we show that both the turbulent wind field and scalar flow and transport in the canopy on a hill have a two-layer asymptotic structure with an upper canopy layer, coupled by turbulent transfer to the surface-layer flow above, and a lower canopy layer, that is driven by the pressure gradient produced as the wind field is deflected over the hill. The dynamics of these two layers are quite different and their matching through the upper canopy layer leads to strong modulation of turbulent transport over the hill and substantial advective flux divergence, even on gentle hills. The effect of the hill-induced perturbations on photosynthesis is calculated numerically and is shown to be small, being of order of the hill slope. In contrast, their effect on the net ecosystem exchange that would be deduced from eddy-flux measurements on a single flux tower is large, being of order one.

1 Introduction

For over forty years the lynch pin of micrometeorology has been the understanding of quasi-stationary boundary-layer flows over homogeneous terrain. Although studies of advection were among the earliest...
forays away from the heartland of ‘flat earth’ micrometeorology (e. g., Rider et al. 1963, Dyer and Crawford 1965, Bradley 1968) and measurements of flow over topography in both the wind tunnel and field had a brief flowering in the 1970s and 1980s (Kaimal and Finnigan 1994), until very recently inhomogeneous flows attracted quite a small part of the total effort in our field. Part of the reason for this was undoubtedly the considerably greater effort required to make field measurements in complex terrain with the need to deploy arrays of towers and to duplicate expensive instruments. The relative paucity of wind tunnel simulations is less easily explained.

Whether measurements are made in wind tunnels or in the open air, allowing inhomogeneity in two or three dimensions instead of just the vertical multiplies enormously the set of possible configurations that we would wish to investigate. Add to this the necessity to interpolate between what are always fewer measurement locations than are ideal and we can see why modeling has always played a bigger role in advection studies than in one-dimensional micrometeorology. Surveys of the field (see Kaimal and Finnigan 1994, Chapter 3 and references therein) record as many or more mathematical simulations of advective flows as experiments. Precisely because of the expense and difficulty of making measurements in inhomogeneous terrain, workers have turned to model studies from the outset to guide experimental design and to interpret the results.

In this Chapter we will concentrate on scalar advection generated by topography. This forms a small part of the totality of advection studies but is an area of particular relevance to the FLUXNET (Baldocchi et al. 2000). We will see that measurements are very scarce indeed in this domain and much of what we can say will be deductions from models. For this reason, we will rely, where we can, on analytic modeling approaches as these give the greatest insight into the underlying physics.

In the following sections we will discuss\(^1\) in turn, modeling and its particular relevance to long term flux measurement in complex topography, and advection: what we mean by it and its relationship to the other aerodynamically important terms. In Section 3 we introduce an analytic model of the wind field over a two-dimensional ridge covered with a tall canopy and in Section 4 show how this wind field can be

---

\(^1\)Our discussion uses the following notation: Vector and tensor quantities are denoted by bold face type, e. g., the velocity vector \( \mathbf{u} \), or, when appropriate, by a set of components, e. g., \( \{ u, v, w \} \). Standard meteorological notation is used and we employ right-handed rectangular Cartesian coordinates throughout. Averaging or filtering operators are denoted by an overbar and stochastic departures from the averaged or filtered variable by a prime thus, \( c(t) = \overline{c} + c'(t) \). Other notation is introduced as encountered in the text.