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RESEARCH NOTE

Examples of the effects of different averaging methods on carbon dioxide fluxes calculated using the eddy correlation method

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Abstract

Three hours of high frequency vertical windspeed and carbon dioxide concentration data recorded over tropical forest in Brazil are presented and discussed in relation to various detrending techniques used in eddy correlation analysis. Running means with time constants 100, 1000 and 1875s and a 30 minute linear detrend, as commonly used to determine fluxes, have been calculated for each case study and are presented. It is shown that, for different trends in the background concentration of carbon dioxide, the different methods can lead to the calculation of radically different fluxes over an hourly period. The examples emphasise the need for caution when interpreting eddy correlation derived fluxes especially for short term process studies.

Keywords: Eddy covariance; detrending; running mean; carbon dioxide; tropical forest

Introduction

Eddy correlation data are being used more and more widely in the debates on the global carbon budget and the possible offset of emissions by forest uptake of carbon dioxide. Given that such data purport to provide a sound basis for important political and economic decisions regarding pollution policy, it is vital that the limitations of the various measurement techniques are widely known and fully discussed. The recent paper by Rannik and Vesala (1999) is thus a timely study of the effect of different detrending techniques used in eddy correlation experiments. In general, however, the current ability to collect and analyse vast quantities of high frequency data with relative ease and the desire to determine long-term budgets, means that the raw, high frequency, data are rarely studied in the same detail as in the past when a researcher may have had only a few hours of data to examine. Detailed examination of short periods of high frequency data can reveal interesting effects and further illustrate and emphasise some of the results presented by Rannik and Vesala. Some examples are presented here which should be of interest to researchers who often apply the technique routinely in all conditions to determine turbulent fluxes.

Data and method

The data used here were recorded by a Solent-LiCor closed path eddy correlation system, similar to that described by Moncrieff *et al.* (1997), mounted above a tropical rainforest in central Brazil on the 'ZF-2' tower described in detail by Malhi *et al.* (1998). The system was installed just above the canopy, at a height of 33 m as part of a larger turbulence study (see Kruit *et al.*, (2000) for details), and not at an ideal height for routine flux monitoring. However, for the illustrative purposes of this comment, the data are adequate and qualitatively similar events to all those presented here can also be observed in the data from the routine monitoring system installed at the top of the tower.

The three orthogonal components of windspeed (u , v , w), the speed of sound, water vapour concentration and carbon dioxide concentration (c) were recorded by the system at 21 Hz from 17 until 26 November 1995. In the present paper, 3 individual hours from this period have been selected and running means and linear trends calculated using various parameters. For each of these periods, the raw 21 Hz vertical velocity (w) and CO_2 concentration (c) data have been averaged to 0.1 Hz to clarify the figures. This loss of the high frequencies is not a problem in this illustrative

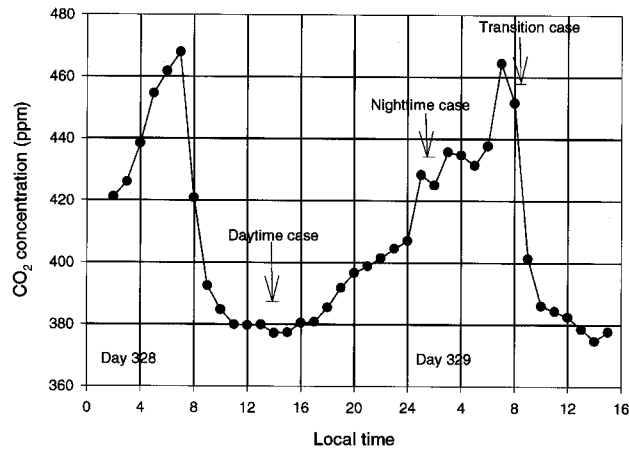


Fig. 1. Hourly average measurements of CO_2 concentration showing the slow nocturnal build-up, the rapid decline in the early hours of the morning and the relatively steady value during the period when convective conditions are dominant. The three individual hours discussed in the text are marked.

work as interest is in the effects of the detrending algorithms on low frequencies (less than about 3.3×10^{-3} Hz, i.e. periods greater than about 5 minutes) and not in the absolute value of the flux.

The most commonly used running mean in current eddy correlation applications is given by

$$\langle s \rangle_i = \alpha \langle s \rangle_{i-1} + (1 - \alpha) s_i$$

where s_i is the present input variable, $\langle s \rangle_{i-1}$ the previous value of the running mean and $\langle s \rangle_i$ the current output. The weighting function, α , is given by

$$\alpha = e^{-\frac{\Delta t}{\tau}}$$

where Δt is the time interval between inputs and τ a time constant. Here, values of τ of 200, 1000 and 1875s have been used to illustrate the different effects of a range of values. 200s is a commonly used value in current eddy correlation systems, for example in the EUROFLUX experiment (Aubinet *et al.* 2000). Longer running means are used by some groups; the Hydra (Shuttleworth *et al.* 1986) normally uses 600s (although it can be varied according to the measurement site). The long running mean example used here (1875s) is long compared to most currently used values, but was used by Shuttleworth *et al.* (1984) in the first eddy correlation measurements of heat and evaporation over Amazonian forest when it was selected in preference to shorter values after an on-line comparison. The fact that a large value of τ was found to be most appropriate over Amazonian forest, reflects the fact that τ should not be kept constant under all conditions, but should be varied according to the measurement height and the aerodynamic roughness of the surface.

In the linear detrend method, linear regression lines are

calculated for blocks of data of a specified length using standard equations (see Rannik and Vesala (1999), Eqn.3 for instance). The frequencies of fluctuations which are filtered out by this approach depends on the length chosen for the data blocks. Thirty minutes is a common choice (e.g. Goulden *et al.*, 1996), probably because it provides a compromise between a convenient output or storage interval and the division between turbulent and larger scale eddies and has been used here.

For each of the different detrends, the quantities w' and c' , where $w' = w - \langle w \rangle$; $c' = c - \langle c \rangle$ and the angled brackets represent the particular running mean or linear detrend in question, have also been determined and the instantaneous flux, $w'c'$, calculated.

Results

Figure 1 shows the hourly average CO_2 concentration for 3 days within the measurement period. The large diurnal cycle associated with the trapping of CO_2 within the nocturnal boundary layer and the subsequent breakdown of this layer in the early morning is clear. Data are presented for 3 hours selected from the period of observations illustrated in Fig. 1: one from the daytime when the change in background concentration is small, one nighttime period and one period during the early morning transition. In Figs. 2 to 4 running means with time constants 200s and linear regression lines on the two 30 minute blocks of data in each period have been plotted alongside the 0.1 Hz data for vertical velocity (w) in the top panel. The 1000 and 1875s running means have not been shown in the vertical velocity case as they are too close to the linear detrend to be seen clearly and serve simply to obscure the graph. All three running means and the linear detrend are plotted alongside CO_2 concentration data (c) in the middle panel. To avoid initiation errors in the running means, they have all been calculated from the start of the continuous run of high frequency data at 0200 on day 328. The product $w'c'$ calculated for each of the detrends is plotted cumulatively in the lowest panel of Figs. 2–4.

DAYTIME CASE

The daytime example begins at 1300 on day of the year 328. The vertical velocity and CO_2 concentration data are shown in Figs. 2 a and b along with the various detrend lines. The most obvious point is that the 200 s detrend of the CO_2 data still contains significant fluctuations with a period of about 10 minutes—leading to the systematic error associated with a running mean with such a short time constant. A similar effect can be seen in the vertical velocity graph. However, at this time of day, the fluctuations are relatively small and all four methods produce relatively similar values of $w'c'$ when

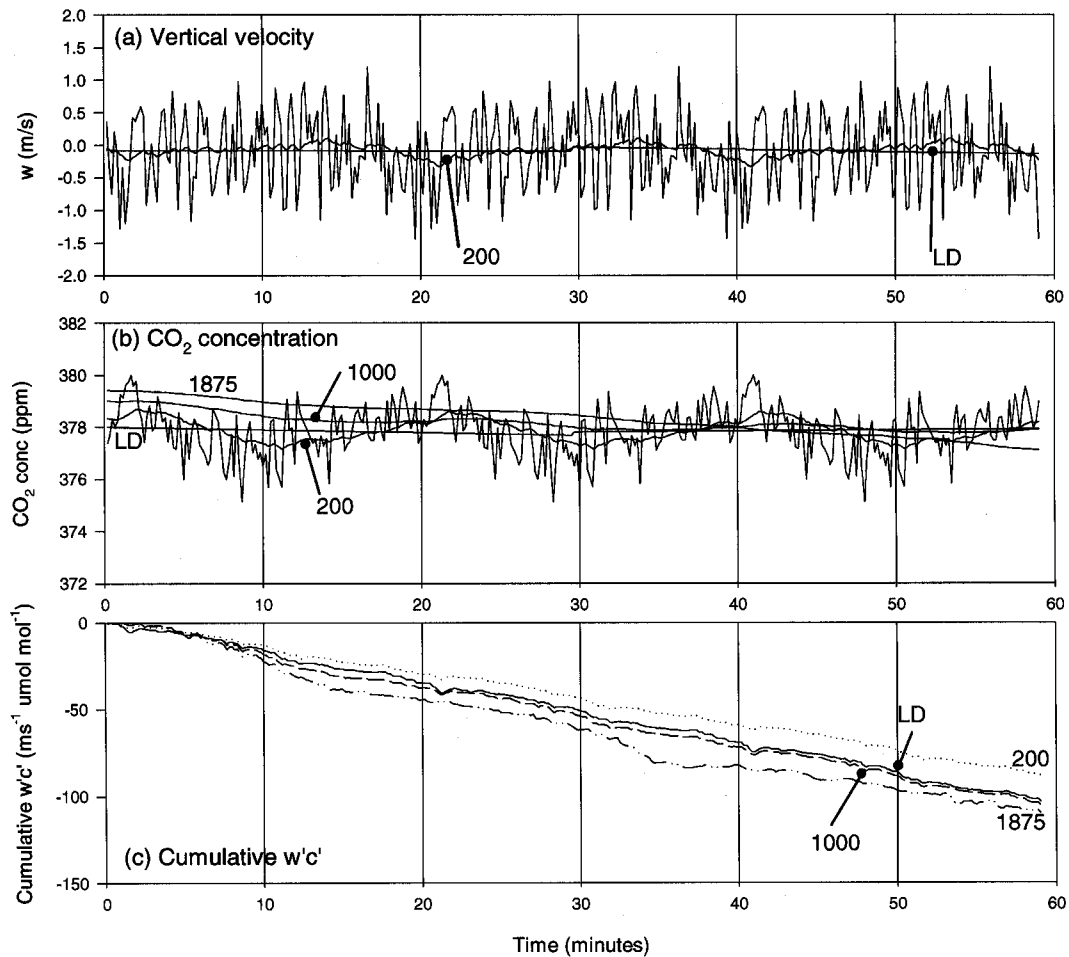


Fig. 2. Daytime case. a) Vertical velocity data with 200s running means and 30 minute linear regression lines. b) CO₂ concentration data with 200, 1000 and 1875 s running means and 30 minute linear regression lines. c) Cumulative values of $w'c'$ plotted for the 3 running mean detrends and the linear detrend.

summed over the hour, although there is a difference of some 20% in these values.

NIGHTTIME CASE

The data for the nighttime example are plotted in Fig. 3 in the same format as the previous example. This period begins at 0100 on Day 329 and is characterised by a marked increase in the CO₂ concentration over 15 minutes in the middle of the period and, as is typical, smaller fluctuations in the vertical velocity than were observed in the daytime. However, the fluctuations in the CO₂ concentration are much larger than in the previous example (note that the range of the CO₂ axis is 5 times larger than in Fig. 2). The different detrending methods respond to the rapid changes in CO₂ concentration very differently, resulting in total values of $w'c'$ for the hour ranging from +52 to -49 $\text{ms}^{-1} \mu\text{mol mol}^{-1}$.

TRANSITION CASE

The example for the transition from nocturnal to convective conditions is shown in Fig. 4. The hour of data shown starts at 0800 on Day 329. The 30 minute linear detrend and the 200 s running mean predict negative $w'c'$ (flux into the canopy) for the hour under consideration, although there is a difference of some 38% between their values. The systematic error introduced by the relatively short time constant of the running mean in this case is again illustrated by the oscillation of about 10 minute period of the running mean trend in the vertical velocity graph leading to underestimation of w fluctuations at this frequency.

The longer values of the time constant lead to background trends which are unable to fall as fast as the actual background value and remain 10 to 20 ppm higher than the regression line throughout the period under consideration. The effect in both of these cases is for a large positive $w'c'$ (flux out of the canopy) to be calculated. For the 1000s

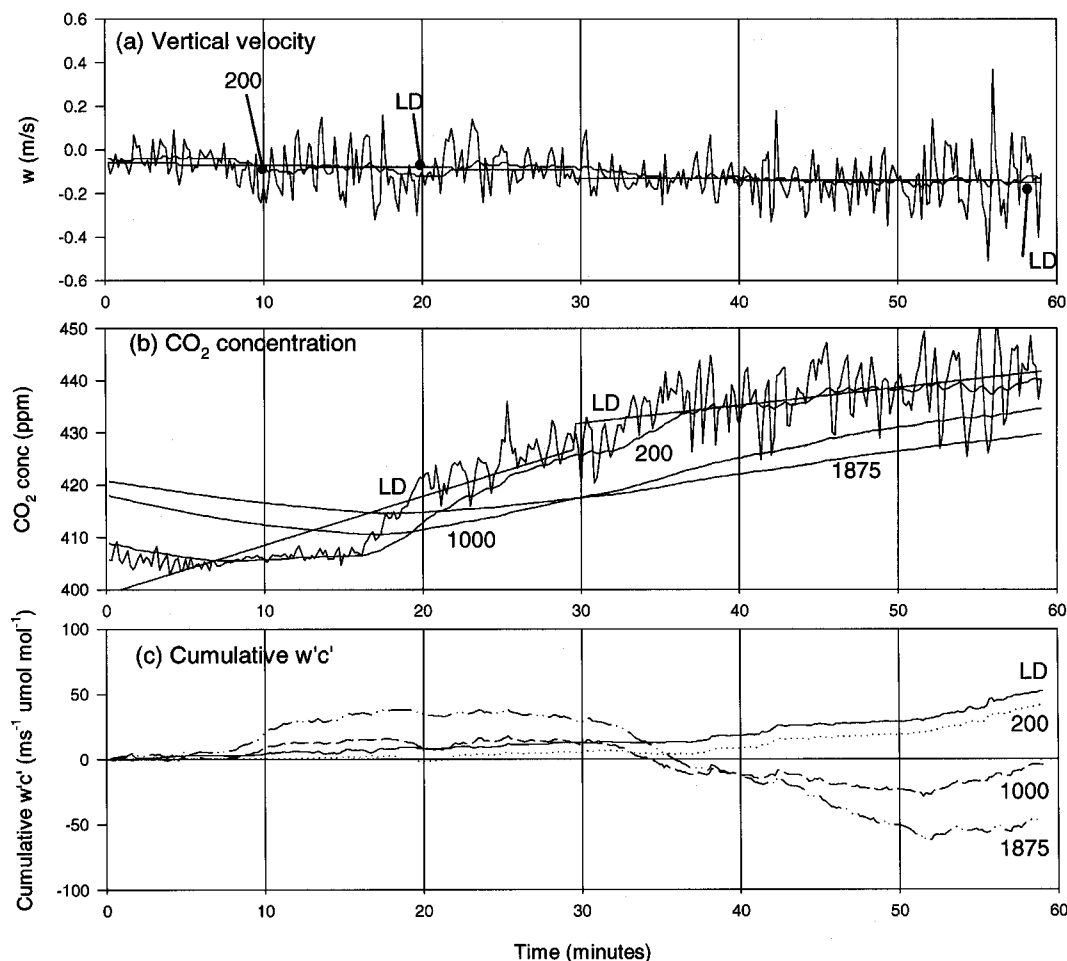


Fig. 3. As for Fig. 2 but for the nighttime example.

running mean this value is of a similar magnitude (but opposite sign) to the 200s running mean or 30 minute detrend while for the long running mean with time constant 1875s the calculated value is around 3 times larger. For both of these cases, the trend in w is almost flat and so the correction proposed by Shuttleworth (1988) would not affect these results.

Discussion

The three examples given above graphically illustrate the general results derived by Rannik and Vesala (1999). Large random errors arise in fluxes calculated for short periods when long running means are used during periods of rapid change and systematic errors are associated with the use of relatively short running means during steady conditions.

Conditions of rapid change of background concentration are not rare, especially for carbon dioxide measurements, and, importantly, a large proportion of the measured flux may occur during them. For example, during the CO_2 flux measurements (Grace *et al.*, 1995) made in south west

Amazonia as part of the Anglo-Brazilian Amazonian Climate Observation Study (Gash *et al.*, 1996) over 10% of the measured nocturnal flux of CO_2 occurred during 30 minute periods in which the background concentration fell by more than 10 ppm and over 30% during periods when it fell by more than 5 ppm. In contrast, 95% of the negative flux (into the canopy) occurred during periods when the background concentration change was -5 to $+5$ ppm in a 30 minute period. Similar problems in the measurement of the sensible heat flux can occur in dry tropical areas when the temperature rises very rapidly following sunrise.

Although the random errors associated with periods of rapid change may average out when considering long term budgets, it is important to consider these periods of rapid change carefully in short term process studies and to present flux data with an associated estimate of the likely error. As the example given above shows, data which one researcher using the linear detrend method might use to illustrate 'the rapid onset of photosynthesis after sunrise', another, using a relatively long running mean detrend, might use to show the 'flushing out of CO_2 stored in the canopy by the onset of convective turbulence'.

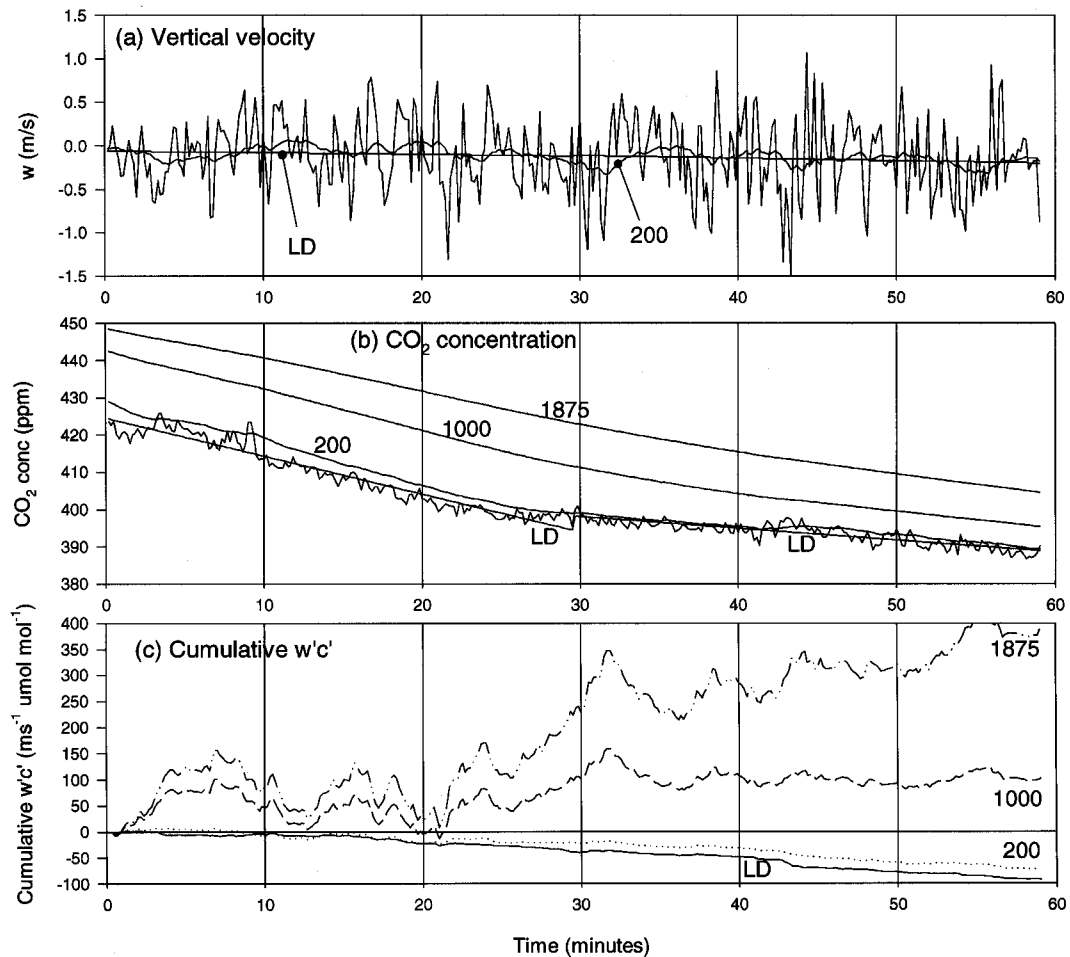


Fig. 4. As for Fig 2 but for the transition period example.

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BOOK REVIEW

Principles of Hydrology, Fourth Edition, by R.C. Ward & M. Robinson McGraw-Hill (London), 2000: ISBN 0 07 709502 2, price £23.99.

Quite some time ago, when I was a student and took an interest in hydrology, I was well advised to start off by studying 'Principles of Hydrology', Second Edition. Some ten years later I started teaching students hydrology myself and in search of a good introductory book I came across the just newly reworked Third Edition of 'Principles of Hydrology'. Since then this book has taken a prominent place in our hydrology curriculum. Now, again ten years later, a fully updated Fourth Edition has come to light. With regards to this new edition I would very much like to extend the good advice once given by me to all new students interested in hydrology, that is to start off by reading 'Principles of Hydrology'.

The general layout of the book is that it begins logically by introducing the hydrological cycle and the drainage basin hydrological system in Chapter 1, followed by Chapters 2 to 7 on Precipitation, Interception, Evaporation, Groundwater, Soil water and Runoff; thus all the components of the hydrological cycle are covered. These chapters are so written as to give the reader a firm basis in understanding the physical processes that occur within all the compartments of the hydrological system. Chemical aspects for all of these compartments are next given due attention in Chapter 8 on Water Quality. In the last Chapter, 9, The drainage basin and beyond, the book is brought to a full circle, stating the objectives and challenges that lie ahead for hydrology as a scientific discipline, probably for some time to come. With the exception of the first chapter, all chapters in the book end with a number of review problems and exercises, encouraging the reader really to come to grips with the important issues discussed in each chapter.

The book offers comprehensive and up-to-date references, conveniently placed at the end of the book.

In the Chapter on Precipitation, information is given on e.g. the estimation of areal rainfall by using radar in combination with point raingauge observations, analysis of precipitation data and the hydrological aspects of snow. Quite a lot of attention, especially in comparison to other hydrological textbooks, is given to interception. In the Chapter on Interception, interception losses from different types of vegetation are discussed, as well as interception models, e.g. the Rutter and Gash models, and the interception of snow. In the Chapter on Evaporation attention is devoted to the process of evaporation, evaporation from open water, bare soils and vegetation covers, and to models of potential evaporation, e.g. Thornthwaite and Penman-Monteith. The Chapter on Groundwater is placed before the Chapter on Soil Water, thus discussing fundamental issues of the storage and movement of water under fully saturated conditions before moving on to the unsaturated environment, where storage and movement of water are complicated by the inclusion of air in the soil pores. Much attention is given to preferential flow pathways and the effect of macropores, both as groundwater in jointed and fractured rocks

and as throughflow and/or pipeflow in the soil zone. For novice readers, essential differences between the position of the groundwater table and the potentiometric surface as well as between the macroscopic velocity (a volume flux density) and the real velocity of water flowing through the pores are made clear. Due attention is given to the process of soil water movement during and after infiltration.

The book is technically correct, with the unfortunate exception of the derivation and end result of the Richards equation (equations 6.4 and 6.9; also the continuity equation). Some typing errors have crept in that were absent in the Third Edition of the book. The tables and figures in the book are clear and have a relevant function in relation to the text, with a slight exceptions the figures 5.18b & c, where too many equipotential lines appear. The text in the book is clear, with sometimes rather long sentences, but in general the authors have made a good job of updating their text after an apparent critical evaluation of which parts of the former text to leave unchanged, which part to reshuffle and where to add new text and references.

In the Chapter on Runoff, the sources and components of runoff, e.g. overland flow, throughflow and groundwater flow are discussed, event-based variations, e.g. the Horton and Hewlett hypotheses, as well as exceptions to the Hewlett hypothesis, hydrograph separation, extremes of runoff, flow duration curves and runoff from snow covered areas. In the Chapter on Water Quality, again precipitation, interception, evaporation, soil water and groundwater and runoff are discussed, but now with regard to chemical composition and processes. Due attention is also given to human impacts.

In the concluding chapter 'The drainage basin and beyond' the importance of the accurate derivation of water balances for different sized catchments, but especially so for large drainage basins, is stressed. The dominance of macro-scale issues as research topics for the near-future and the importance of studying the inter-relationships between processes operating at very different spatial (and temporal) scales, are further stressed. It is hoped that such activity may resolve some of the current difficulties of upscaling and downscaling hydrological processes.

In conclusion, this fully updated Fourth Edition of 'Principles of Hydrology' covers a broad spectrum of hydrology, and the title of the book 'Principles' is well accounted for in the text. The book is especially suitable as a starting point for students who are new to hydrology. Due to its academic bias, the treatment of hydrology as a scientific discipline rather than e.g. an engineering or agricultural science, and also because of the philosophical notions, especially in the last chapter of the book, this Fourth Edition may make for some pleasant reading even for the more experienced hydrologist.

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