February 2001

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ELSEVIER

Agricultural and Forest Meteorology 107 (2001) 71–77

AGRICULTURAL AND FOREST METEOROLOGY

www.elsevier.com/locate/agrformet

Short communication

Gap filling strategies for long term energy flux data sets[☆]

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Received 17 August 2000; received in revised form 13 November 2000; accepted 17 November 2000

[☆] Data provided by EUROFLUX: Corinna Rebmann/E.-D. Schulze/John Tenhunen; Thomas Grünwald/Christian Bernhofer; E.J. Moors/Jan A. Elbers/Han Dolman; Kim Pilegaard/Niels-Otto Jensen; Marc Aubinet; Üllar Rannik/Timo Vesala; André Granier/Patrick Gross; Robert Clement/John Moncrieff; Andrew Kowalski/Reinhart Ceulemans. AmeriFlux: Dennis Baldocchi/Kell Wilson; David Hollinger; Bill Munger/Steve Wofsy; Tilden Meyers; Shashi Verma/Andrew Suyker/George Burba; Peter Anthoni/Beverly Law; Chun Ta Lai/Gabriel Katul/Ram Oren.

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PII: S0168-1923(00)00235-5

Abstract

At present a network of over 100 field sites are measuring carbon dioxide, water vapor and sensible heat fluxes between the biosphere and atmosphere, on a nearly continuous basis. Gaps in the long term measurements of evaporation and sensible heat flux must be filled before these data can be used for hydrological and meteorological applications. We adapted methods of gap filling for NEE (net ecosystem exchange of carbon) to energy fluxes and applied them to data sets available from the EUROFLUX and AmeriFlux eddy covariance databases. The average data coverage for the sites selected was 69% and 75% for latent heat (λE) and sensible heat (H). The methods were based on mean diurnal variations (half-hourly binned means of fluxes based on previous and subsequent days, MDV) and look-up tables for fluxes during assorted meteorological conditions (LookUp), and the impact of different gap filling methods on the annual sum of λE and H is investigated. The difference between annual λE filled by MDV and λE filled by LookUp ranged from -120 to 210 MJ m^{-2} per year, i.e. -48 to $+86$ mm per year, or -13 to $+39$% of the annual sum. For annual sums of H differences between -140 and $+140$ MJ m^{-2} per year or -12 to $+19$% of the annual sum were found.

Keywords: FLUXNET; EUROFLUX; AmeriFlux; Eddy covariance; Latent heat; Sensible heat; Data filling; Interpolation techniques

1. Introduction

In 1997 FLUXNET, a global network of long term mass and energy (CO_2, water vapor, sensible heat) flux density measurement stations was established (Baldocchi et al., 1996, Running et al., 1999). Over 100 sites are in operation over a diverse set of landscapes, crops, grassland, conifer, deciduous and evergreen broadleaved forests. Data from the network has the potential to address problems relating to ecosystem carbon balance (Falge et al., 2000) and the water and heat balance of sites. In practice it is impossible to accept data, uncritically, 24 h a day, 365 days a year. Violations in micrometeorological assumptions, instrument malfunction and poor weather will force investigators to reject a proportion of the data. Yet, our interest and goals involve construction of continuous records of half-hourly fluxes measured by eddy covariance and computation of seasonal and annual sums of carbon dioxide, water and heat exchange.

Numerous filling methods for NEE have been used by others (e.g. Greco and Baldocchi, 1996, Goulden et al., 1996, Grünwald and Bernhofer, 2000, Aubinet et al., 2000, Falge et al., 2000). Studies on effects of filling methods for energy fluxes on calculated annual sums have not been reported. Long term records of energy fluxes usually are constructed on coarser time scales (months) applying for instance the water balance equation for λE and estimating H as a residual of the energy balance equation (e.g., Jaeger and Kessler, 1997). For the filling of half-hourly energy fluxes however, methods based on the water balance equation are not applicable.

In Falge et al. (2000), filling methods of NEE were compared on the basis of flux measurements for nine EUROFLUX sites and 10 AmeriFlux sites for a total of 28 unique site-year combinations between 1992 and 1999 (see Table 1). Their results emphasized the need to standardize gap filling methods for improving the comparability of annual NEE from regional and global flux networks. The purpose of this paper is to investigate whether non-standardized filling methodologies have a similar effect on annual sums of energy fluxes and whether gap filling methods can be applied universally for crops, grasslands and conifer and broad-leaved forests. We established methods based on the concepts of mean diurnal variations and look-up tables reported in Falge et al. (2000) for filling of half-hourly values of λE and H (both in W m^{-2}), and applied them to the above data sets to evaluate the need for standardized techniques.

2. Methods

Gap filling methods applied here include mean diurnal variations of previous periods (MDV), and look-up tables (LookUp) as defined in Falge et al. (2000). The gap filling methods were tested on the data from the 18 flux sites, summarized in Table 1. For four sites (HY97, HV96, BV97, and SH97), chosen to represent four major vegetation groups, conifers, deciduous

Table 1
Site information for 18 sites from the EUROFLUX and AmeriFlux projects and several years (adapted from Falge et al. (2000, their Table 1))

Site	State/country	Period	Abbreviation	Species
Coniferous forests				
WeidenBrunnen[a]	Germany	1997	WE97	Norway Spruce
Tharandt[a]	Germany	1997	TH97	Norway Spruce
Loobos[a]	Netherlands	1997	LO97	Scots Pine
Hyytiala[a]	Finland	1997	HY97	Scots Pine
Brasschaat[a]	Belgium	1997	BR97	Scots Pine, Oaks
Aberfeldy[a]	United Kingdom	1997	AB97	Sitka Spruce
Howland[b]	Maine/USA	1996	HL96	Spruce-Hemlock
Metolius[b]	Oregon/USA	1996, 1997	ME96, ME97	Ponderosa Pine
Duke forest[b]	North Carolina/USA	1998, 1999	DU98, DU99	Loblolly Pine
Deciduous forests				
Vielsalm[a]	Belgium	1997	VI97	European Beech
Soroe[a]	Denmark	1997	SO97	European Beech
Hesse[a]	France	1997	HE97	European Beech
WalkerBranch[b]	Tennessee/USA	1995, 1996, 1997	WB95, WB96, WB97	Oak-Hickory
Harvard[b]	Massachusetts/USA	1992, 1993, 1994, 1995, 1996	HV92, HV93, HV94, HV95, HV96	Oak-Maple
Grasslands				
LittleWashita[b]	Oklahoma/USA	1997, 1998	LW97, LW98	Rangeland
Shidler[b]	Oklahoma/USA	15/9/96–14/9/97	SH97	Tallgrass Prairie
Crops				
Bondville[b]	Illinois/USA	1997	BV97	Corn
Bondville[b]	Illinois/USA	1998	BV98	Soybean
Ponca[b]	Oklahoma/USA	21/8/96–20/8/97	PO97	Wheat

[a] EUROFLUX.
[b] AmeriFlux.

forests, crops, and grassland, data sets with artificially generated gaps (containing 25, 35, 45, 55, and 65% of gaps) were used to assess the accuracy of the gap filling methods. After introducing artificial gaps the respective gap filling methods were parameterised with the remaining data, and applied to fill the artificial gaps in the data sets. The absolute error for each method was calculated as the measured minus the computed value for each of the artificial gaps. The relationship between those errors summed for different time periods and the overall gap percentage in the artificial data sets were used to tabulate maximum absolute errors per percent gaps during a period (day, week, month, year), and for both filling methods (Table 2). The percentage of gaps filled during daytime and night time for a given time period was used to scale the tabulated values to an error assessment for the period. Details on these methods are given in Falge et al. (2000). In the following we report only adaptations to the methods for the filling of the gaps in the energy fluxes.

Filling by mean diurnal variations replaces missing observations by the mean for that time period (half-hourly averages) based on previous and subsequent days. For energy fluxes independent windows of 14-day-size were found to reduce errors introduced by averaging values showing nonlinear dependence on environmental variables.

The use of the mean diurnal variation to fill gaps takes no account of day to day variations in weather conditions, unlike the use of look-up table methods. For the look-up table method tables were created for each site so that missing values of λE, and H could be "looked-up" based on the environmental conditions associated with the missing data. Assigned periods were bi-monthly or seasonal, from 1 April to 31 May, 1 June to 30 September, 1 October to 30 November, and 1 December to 31 March. For λE and H look-up tables the sorting variables were Q_p (photosynthetic photon flux density) and D (vapor pressure deficit), considering D as a major driver of

Table 2
Maximum absolute errors (in kJ per m^2 and gap percentage of period) observed for the four selected sites during the artificial gap filling experiment, for two selected filling methods (MDV: mean diurnal variation, and LookUp: look-up tables, as defined in text) and for daytime and night-time, and ecosystem latent heat (λE) and sensible heat (H) sum separately[a]

Period	Method	Daytime: absolute (±) error (kJ m^{-2} per gap percentage of period)				Night time: absolute (±) error (kJ m^{-2} per gap percentage of period)			
		Coniferous	Deciduous	Crops	Grasslands	Coniferous	Deciduous	Crops	Grasslands
Latent heat (λE)									
1 day	MDV	35	30	25	25	10	25	25	20
	LookUp	20	30	25	25	10	20	25	20
7 days	MDV	140	135	80	80	25	35	70	60
	LookUp	105	55	50	125	25	20	70	40
30 days	MDV	85	480	110	125	30	90	70	125
	LookUp	75	180	95	160	25	40	55	125
365 days	MDV	220	565	460	210	40	215	70	220
	LookUp	150	380	285	215	45	155	65	240
Sensible heat (H)									
1 day	MDV	30	30	25	25	25	25	25	20
	LookUp	30	30	25	20	20	20	25	20
7 days	MDV	60	60	60	55	50	50	70	65
	LookUp	75	75	60	55	50	50	70	65
30 days	MDV	105	105	95	190	75	75	130	315
	LookUp	110	110	105	235	125	125	85	200
365 days	MDV	260	260	150	355	300	300	280	190
	LookUp	200	200	230	175	230	230	140	195

[a] To obtain an absolute error for a certain period, the values for both, daytime and night time, have to be multiplied with the respective gap percentage (e.g. 50 if half of the daytime data are missing), and the results be added. For instance, for 31% missing values during day and 25% during night, the LookUp method for "Deciduous Forest" (HV96) would result in a maximum error of ±22.89 MJ m^{-2} per year (=565 × 31 + 215 × 25).

λE. For filling λE and H missing values, average fluxes were compiled for a maximum of 6 (or 4) seasonal periods × 23 Q_p-classes × 35 D-classes. The Q_p classes consisted of 0.1 mmol m^{-2} s^{-1} intervals from 0 to 2.2 mmol m^{-2} s^{-1} with a separate class for $Q_p = 0$. Similarly, D-classes were defined through 0.15 kPa intervals ranging from 0 to 5.1 kPa. Gaps in the look-up tables (classes with no mean assigned) were interpolated linearly, the maximum gap width spanned was 0.3 mmol m^{-2} s^{-1} for a light curve at a given D, and 0.45 kPa within a D curve at given light level. The method requires complete sets of Q_p and D, thus gaps in Q_p and D were filled using MDV methods described in Falge et al. (2000).

3. Results

The 28 data sets had an average of 31% missing or rejected values of λE data and 25% for H with a slightly higher percentage for night observations (Table 3). Values that are commonly observed in eddy correlation data sets (Falge et al., 2000), yet making it necessary to estimate values for a continuous data record. The large differences in the computed gap frequencies depend on different approaches of data rejection. Some sites reported all data where the instruments were working and leave data rejection to be done later, others applied sophisticated quality assurance routines (Foken and Wichura, 1995, Mahrt, 1998).

For the computation of daily, monthly and annual sums of λE and H we filled the data sets with the above methods, and computed errors for the filled data points. The errors assigned were calculated from tabulated values of maximum errors (see Table 2) derived from the results of a sensitivity analysis of various methods for each functional group, i.e. conifers, deciduous forests, crops, and grassland (see Section 2),

Table 3
Percentages of latent (λE) and sensible (H) heat flux data, that were missing or had to be rejected for 18 sites from the EUROFLUX and AmeriFlux projects and several years[a]

Site	λE gap percentage			H gap percentage		
	Day	Total	Night	Day	Total	Night
Coniferous forests						
WE97	63.1	69.0	75.0	28.1	30.4	32.6
TH97	29.7	35.0	40.5	25.3	32.7	40.3
LO97	10.8	11.5	12.1	8.3	8.6	8.9
HY97	23.3	23.2	23.1	18.3	18.9	19.5
BR97	37.3	34.2	31.1	37.6	34.4	31.3
AB97	23.5	24.0	24.5	20.5	20.6	20.7
HL96	42.5	40.9	39.2	30.9	28.5	26.0
ME96	39.0	44.3	49.7	39.0	44.3	49.5
ME97	48.6	52.5	56.4	48.6	52.5	56.4
DU98	59.8	59.5	59.2	50.1	51.0	52.0
DU99	38.9	39.9	40.9	36.0	36.3	36.6
Deciduous forests						
VI97	11.1	10.4	9.7	–	–	–
SO97	4.7	4.7	4.6	5.1	5.4	5.6
HE97	4.6	4.2	3.7	6.2	6.3	6.5
WB95	26.5	30.5	34.6	27.5	34.3	41.0
WB96	23.8	27.4	31.0	24.2	29.7	35.2
WB97	26.5	30.1	33.8	27.0	33.1	39.2
HV92	36.5	34.4	32.3	30.3	28.0	25.7
HV93	57.0	56.5	55.9	46.5	45.6	44.6
HV94	26.6	24.7	22.7	18.2	16.0	13.8
HV95	25.8	25.7	25.6	21.2	21.8	22.4
HV96	47.8	43.4	39.0	14.9	14.3	13.7
Grasslands						
LW97	9.6	11.1	12.5	5.4	6.6	7.7
LW98	15.7	16.9	18.1	11.1	11.5	11.9
SH97	26.4	27.2	28.1	21.4	22.5	23.7
Crops						
BV97	14.0	17.4	21.0	11.4	14.6	17.8
BV98	17.3	20.6	23.9	7.8	10.2	12.7
PO97	41.3	41.7	42.2	30.8	29.2	27.5
Average	29.7	30.7	31.8	24.1	25.4	26.8
S.D.	16.3	16.5	17.1	13.2	13.7	14.7

[a] For site abbreviations, see Table 1.

and the percentage of gaps during daytime and night time.

Comparing the annual sums of data filled by mean diurnal variation methods with look-up table methods (Table 4), the effect for evapotranspiration data ranged between -121 and $205\,\mathrm{MJ\,m^{-2}}$ per year with an average of $+25\,\mathrm{MJ\,m^{-2}}$ per year, i.e. -48 to $86\,\mathrm{mm}$ per year with an average of $+10\,\mathrm{mm}$ per year. The effect for filling sensible heat with different methods ranged between -137 and $+138\,\mathrm{MJ\,m^{-2}}$ per year, with an average of $+34\,\mathrm{MJ\,m^{-2}}$ per year. On average and in percent of the annual sums, these effects are small: $+2.7\%$ for λE, and $+4.5\%$ for H. However, for single sites they could be as large as -12.9 or $+39.4\%$ of λE, and -12.2 or $+19.4\%$ of H. Since these differences are purely due to the use of alternative methods of gap filling they could be avoided by applying a common gap filling protocol.

The annual sums of energy fluxes resulting from the selected methods are not necessarily compatible with each other. A linear regression between $\lambda E_{\mathrm{LookUp}}$ and λE_{MDV} results in $a = +1.615\,\mathrm{MJ\,m^{-2}}$ per year, $b = 0.976$, $r^2 = 0.97$, indicating an overestimation by MDV compared to look-up tables (a being close to zero). Similarly, MDV filled data of H overestimate H filled by look-up tables, with linear regression coefficients between H_{LookUp} and H_{MDV} of $a = +6.051\,\mathrm{MJ\,m^{-2}}$ per year, $b = 0.952$, $r^2 = 0.96$.

4. Discussion

The filling methodologies (mean diurnal variations, look-up tables) we discussed in this paper showed good approximation to the original data and small errors. On average, annual sums filled by these methods differed by only 10 mm per year for λE, and $34\,\mathrm{MJ\,m^{-2}}$ per year for H. However, we were unable to answer which method compared best with the artificially removed data. The residuals between artificially removed and filled data could not be distinguished by ANOVA, due to the overall scatter of eddy covariance data that built the basis for the artificial data removing.

For filling of sensible and latent heat fluxes we did not apply a (nonlinear) regression model, but used MDV and LookUp methods only. Possible functions for filling λE, or H from measurements of insolation, vapor pressure deficit, or temperature would be the energy balance equation, or the Penman–Monteith equation, where the basic concept is also energy balance closure (Monteith, 1965), but would need information on canopy air, boundary, and stomatal conductances in addition. Especially for the data in hand, we avoided applying concepts based on

Table 4
Energy equivalent of ecosystem evapotranspiration (λE) and sensible heat flux sum (H), and respective errors introduced during the gap filling[a]

Site	λE (MJ m^{-2} per year)				λE	H (MJ m^{-2} per year)				H
	MDV	Error	LookUp	Error	Rel. Diff. (%)	MDV	Error	LookUp	Error	Rel. Diff. (%)
Coniferous forests										
WE97	726	17	521	13	39	–	–	–	–	–
TH97	1177	8	1205	6	−2	624	19	621	14	1
LO97	1045	3	1027	2	2	358	5	325	4	10
HY97	786	6	777	5	1	425	11	443	8	−4
BR97	495	9	568	7	−13	320	19	336	15	−5
AB97	519	6	514	5	1	330	12	278	9	19
HL96	974	11	878	8	11	1020	16	918	12	11
ME96	1307	11	1236	8	6	986	25	1123	19	−12
ME97	1041	13	944	10	10	1207	30	1138	23	6
DU98	1117	16	1238	12	−10	842	29	807	22	4
DU99	1414	10	1351	8	5	1153	20	1043	16	11
Deciduous forests										
VI97	642	8	642	5	0	–	–	–	–	–
SO97	641	4	639	2	0	766	3	751	2	2
HE97	853	3	852	2	0	371	4	394	3	−6
WB95	1370	22	1350	15	1	1015	19	954	15	6
WB96	1436	20	1372	14	5	969	17	875	13	11
WB97	1566	22	1501	15	4	1099	19	1018	14	8
HV92	953	28	937	19	2	1117	16	1061	12	5
HV93	1464	44	1390	30	5	851	25	713	20	19
HV94	1430	20	1410	14	1	986	9	998	7	−1
HV95	1292	20	1293	14	0	1114	12	1098	9	1
HV96	882	35	948	24	−7	1024	8	983	6	4
Grasslands										
LW97	1203	5	1164	5	3	1251	3	1243	2	1
LW98	974	7	980	8	−1	1346	6	1332	4	1
SH97	1613	12	1484	12	9	745	12	705	8	6
Crops										
BV97	1352	8	1321	5	2	892	7	880	3	1
BV98	1632	10	1588	6	3	653	5	646	2	1
PO97	2038	22	2099	15	−3	925	12	801	8	16

[a] Filling for λE and H involved mean diurnal variations (MDV), and look-up tables (LookUp), as described in the text. The errors were calculated by multiplying the gap percentage for a certain period (daytime and night time separately) with tabulated values of maximum errors observed during an experiment to fill artificial gaps (for details see text). Relative differences (Rel. Diff.) between annual sums derived by the two methods are calculated as $((\lambda E_{\mathrm{MDV}} - \lambda E_{\mathrm{LookUp}})/\lambda E_{\mathrm{LookUp}}) \times 100\%$, and $((H_{\mathrm{MDV}} - H_{\mathrm{LookUp}})/H_{\mathrm{LookUp}}) \times 100\%$, respectively. For site abbreviations see Table 1.

energy balance closure, since the sum of the eddy covariance fluxes was on average 13% less than the available energy, i.e. sum of the radiation, soil heat fluxes and the change in the storage terms. Energy flux underestimation seems to occur frequently when using eddy covariance measurements (Twine et al., 2000).

Errors of gap-filling can have two sources, the error introduced by different research groups applying different filling methodologies, and the error introduced during the filling process. The errors during the filling process differed slightly between methods, those introduced by MDV being on average 3.9 MJ m^{-2} per year for λE, and 3.5 MJ m^{-2} per year for H higher than those for LookUp. Maximum observed differences in errors are $13.9\,\mathrm{MJ\,m^{-2}}$ per year for λE, and $6.9\,\mathrm{MJ\,m^{-2}}$ per year for H. If fillings were performed with differing methods, the (maximum) differences in annual sums (i.e. -121 to $+205\,\mathrm{MJ\,m^{-2}}$ per year for λE, and -137 to $+138\,\mathrm{MJ\,m^{-2}}$ per year for H) would add to the error above.

5. Conclusion

The results reported here emphasize the importance of a method of standardization during the data post-processing phase, as annual sums of energy fluxes resulting from the selected methods are not necessarily compatible with each other. Annual sums resulting from filling by look-up tables are in general slightly smaller than data filled by mean diurnal variation.

For comparison with output of soil vegetation atmosphere transfer (SVAT) models driven by meteorological conditions, we would propose semi-empirical methods because they preserve the response of energy fluxes to main meteorological conditions (e.g. Q_p, D). Thus, look-up table methods should be preferred for standardized filling protocols for ecosystem fluxes, to provide for consistent data bases for synthesis issues in progress.

Acknowledgements

This work is supported by NASA's EOS Validation Project and contributes to the EUROFLUX, AmeriFlux, and FLUXNET programs. We also acknowledge and appreciate funding for the numerous sites by the European Union (EUROFLUX project), US Department of Energy's Terrestrial Carbon Program, and NIGEC Program (AmeriFlux projects).

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