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Quality Assessment of Tibetan Plateau Eddy Covariance Measurements Utilizing Footprint Modeling

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Abstract: A quality analysis including footprint modelling has revealed spatial and temporal structures in the quality of Eddy Covariance measurements for two highland sites located on the Tibetan plateau. Fetch analysis has shown, that up to 1/3 of the measurements do not fulfill assumptions necessary for a physically correct data processing. Despite this fact, measurements of latent heat-, CO_2-and momentum flux in general fulfill the quality test criteria to an extend that the results can be regarded as suitable for fundamental research, whereby usually certain wind sectors have been found violating basic assumptions. Measurements of the sensible heat flux allow for the usage in continuously running measurement, while still few indications of the quality assessment can not be explained due to local topography, but indicate organized structures and lead to the hypothesis of mesoscale flow patterns in the boundary layer.

Key words: Alpine; EC; Footprint Climatology; GCM; Mesoscale; Tibet; QA; QC
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1 Introduction

Land surface-atmosphere interaction processes play an important role in the energy and matter cycles, such as that of CO_2 and water, over a wide magnitude of scales. Considerable deficit exists concerning the ability to properly describe these processes, especially in high elevation environments, which among others leads to systematically biased assessment of climate anomalies by Global Climate Models (GCMs).

The Eddy Covariance (EC) method is the best measurement technique currently available for the determination of matter and energy fluxes between the atmosphere and the underlying surface. Therefore, EC method has become a widely accepted tool for the determination of matter and energy fluxes, applied by several flux networks such as Ameriflux, EUROFLUX and AsiaFlux, overall coordinated within FLUXNET[1]. However, the adoption of the EC method is based on the assumption that certain statistical and meteorological requirements are fulfilled and the equipment is working reliably. The development of an automated quality control and site characterization procedure[2,3] has shown that non-ideal conditions are common for a wide range of sites. The procedure consists of quality tests[4,5] in combination with a forward Lagrangian footprint model[6] using detailed terrain data gathered by remote sensing methods. Quality tests cover e.g. steady state and developed turbulence assumptions and lead to an overall flagging of the flux data

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quality. Footprint modeling defines the spatial context of these fluxes, thereby the quality flags can be allocated to different wind directions under varying meteorological conditions. Thus, this procedure enables the collection of high-quality data sets for the assignment of these fluxes to different land use types on landscape scale which leads to representative training areas for the amendment of remote sense based GCMs.

EC method is rarely used at alpine research stations, most of them dominated by forests, e.g. Renon, Italy[8,9] and Niwot Ridge, USA[8] at elevations up to 3 050 m. This study aims to evaluate to what extent the EC method can be applied to the conditions of shallow and often very stable planetary boundary layer, low pressure and extreme daily and seasonal cycles of temperature and stratification of the atmosphere over the Tibetan plateau. Therefore results of the quality control procedure for two Tibetan plateau grassland sites at elevations up to 4 745 m are presented.

2 Materials and methods

The analysis was carried out for two sites in Tibet, China, with NaMuCuo site lying on the SE banks of Lake NaMuCuo, located 150 km N of Lhasa and the Everest site located in reach of the #1 mount Everest base camp. Exact locations and measurement periods are listed in Table 1.

Land use data of the Chinese Academy of Sciences (CAS) with a resolution of 50 m was used. Land use classes had been distinguished due to unsupervised classification of Landsat TM/ETM images, verified during on-the-spot investigations in 2000. For refinement and evaluation, the direct surrounding of the flux tower was remapped in 2006 with a resolution of 20 m due to on-the-spot investigations, covering areas of 0.3 km^2 (Everest) and 1.6 km^2 (NaMuCuo) respectively. Spatial Reference was obtained using the Garmin eMap GPS. Measurements were carried out receiving 5-9 satellites causing a spatial precision of 5~7 m. In total, 6 land use classes were distinguished, whereas thereof the target land use type grassland was divided in two classes with vegetation covering degrees exceeding or undercutting 50%, later referred to as ‘Meadow > 50’ and ‘Meadow < 50’. Covering degrees less than 5% are included in class ‘Gravel’. Elevation data with a resolution of 90 m from Shuttle Radar topography measurement (SRTM) provided by the Global Land Cover Facility (GLCF) has been utilized.

The NaMuCuo site is located between the Lake NaMuCuo in 1 km distance NW, and a NEE-SWW oriented mountain range peaking 5 700 m above sea level (asl) in 15 km distance SSE (see Fig. 1a, Plate X). The measurement itself is located on a level plane, dominating land use class is Meadow < 50. Another small lake is located 150 m NW of the tower stretching NE-SW for 2 km (Fig. 3a, Plate XI). 80 m W of the measurement the station building, 40 m and 80 m NE a 30 m profile tower and a container for trace gas measurements are established.

The Everest measurement is located in a strung-out valley inclining from SW to NE (see Fig. 1b, Plate X) with a steep slope ascending no further than 300 m N of the tower (Fig. 3b, Plate XI). The dominating land use type is Meadow > 50, small patches of harvested grain fields are located 70 m N and SE, whereas an unpaved road passes in E-W direction 60 m S of the measurement. Beyond the road, a small village stretching E is attached to the SE grain field.

Both sites are equipped with a CSAT3 sonic anemometer for three wind-speed components and air temperature measurement and a LI-COR 7 500 gas analyzer for H_2O and CO_2 concentrations. The measurement height is 3 m, both devices working with a sampling frequency of 10 Hz. For exact locations, utilized measurement periods and sensor alignment see Table 1.

The first step of data processing, the quality check, is based on the analysis of high-frequency raw data. Therefore the signals of the vertical and longitudinal wind components, sonic temperature and H_2O and CO_2-concentrations were used. This task can be divided in three parts: preliminary tests, raw data corrections and test on fulfillment of EC assumptions. All three parts plus the calculation of the fluxes after correction were carried out using the Software Package TK2 developed by the department of Micrometeorology, University of Bayreuth[9].

Table 1 Site Characteristics, coordinates for ellipsoid WGS84

Topic	Feature	Site NaMuCuo	Site Everest
Measurement	Latitude [°]	30.77281	28.31027
	Longitude [°]	90.96302	86.89597
	Elevation above sea level [m]	4745	4475
	Period [YYYY/MM/DD-MM/DD]	2005/09/11-11/02	2005/10/28-11/27
Instrument alignment	Angle (CSAT3/north) [°]	135	180
	Angle (LI-COR/north) [°]	165	192
	Horizontal disparity (Csat-Licor) [m]	0.35	0.15
Assigned roughness length [m]	Meadow (plant coverage >50%)	0.01	0.03
	Meadow (plant coverage 5%—50%)	0.01	0.01
	Lake	0.002	—
	Building	0.5	0.5
	Cultivated land (harvested)	—	0.002
	Street	—	0.002

Preliminary tests include a check for consistency limits, the raw data is checked for physically not possible values[9], and a spike test[10]. Values failing those tests were omitted, no gap filling took place.

Raw data corrections were applied in the following order: Cross correlation to maximize covariances of gas concentration and vertical wind signals and Correction of spectral loss[11], Cross wind correction of the sonic temperature[12], Conversion of the buoyancy flux into sensible heat flux[13], Correction for density fluctuations[14~17].

The quality tests consist of a stationarity test[5] and a test on fulfillment of the integral turbulence characteristics (ITC)[4,5] for each flux. For the stationarity tests, the 30-minute covariances of two raw data signals were compared with the mean out of six 5-minute covariances from the same interval. Quality flags for stationarity were then assigned to each half-hourly flux according to the range of deviations found between both values (Table 2a). ITC are basic similarity characteristics of atmospheric turbulence and indicate whether or not the turbulent flow field is fully developed. The development of turbulence was investigated by comparing the normalized standard deviations of the measured wind components and temperature with theoretical values[18~20]. Since no formulations at all exist for CO_2 and H_2O and the temperature under neutral conditions, the investigations of ITC are restricted to vertical and horizontal wind components and the temperature under stable and unstable stratification. Quality flags for each half-hourly flux were assigned according to the same deviation range between measured and modeled values as taken for the stationarity test (Table 2a). The final half-hourly quality flag for a specific flux was assigned by taking into account both, quality flags for stationarity and ITC (Table 2b).

For the calculation of the fluxes with EC the mean vertical wind component must be zero. However in reality, due to a variety of factors, such as flow distortion or local topography, the half hour values never fulfill this presumption. In order to approach the mean vertical wind field towards this criteria, Planar Fit Rotation procedure[21] is applied. This procedure often succeeds in realigning the wind field in such a manner, that the mean vertical wind is close to zero, providing that the unrotated mean vertical wind speed is below the threshold of |35 cm/s|[3,5]. Therefore, in addition to the quality flags of the individual fluxes, this threshold is used to determine the influence of the local flow field to the measurements.

In the second step of data processing, the spatial context of the quality flags and the unrotated and rotated vertical wind field is determined applying a footprint model to the quality results above.

Table 2 Classification scheme for stationarity and steady state test[4] (a), overall flag scheme[3] (b)

Class	Range
1	0-15%
2	16%-30%
3	31%-50%
4	51%-75%
5	76%-100%
6	101%-250%
7	251%-500%
8	501%-1000%
9	>1000%

a

steady state (flag)	integral turbulence characteristic (flag)	Final flag
1-2	1-2	1
1-2	3-4	2
3-4	3-4	3
3-4	5-6	4
5-9	7-9	5

b

A footprint function relates individual flux and concentration measurements of a quantity to its sources[22]. In this study, a Lagrangian stochastic (LS) forward flux footprint model[6,23] is used to define the footprints of individual measurements. The model resolves individual paths of 5×10^4 air parcels using a 3D LS trajectory model[24] to describe the parcel dispersion in the turbulent flow field. For simulations the air parcels are released from the height equal to the roughness length and their dispersal in the surface layer is followed until the upwind distance accounts for at least 90% of the total footprint. Dimensions of an individual footprint depend on measurement height, stability of stratification and aerodynamic roughness of the fetch. Because of relatively long computing times of stochastic footprint models, the source areas are precalculated separately for set of 21 stability classes, 20 roughness lengths and 28 observation heights[2]. Besides the forenamed three parameters, wind direction is the only input parameter left for a spatial allocation of the quality flags and the vertical wind field, later referred to as ‘quality features’. All meteorological input parameters (stability class, wind direction and friction velocity) are withdrawn from the first step of the data processing. The roughness length of surrounding terrain is provided as a rectangular matrix with regular grid spacing of 20×20 m covering 16 km^2, derived due to assigning a fixed roughness length value to each of the land use classes (Table 1).

To determine the so called ‘footprint climatology’[25], i.e. the characteristic source of long term measurements, it is necessary to overlay the footprints of individual measurements. This is done by assigning a contribution factor for each half hour measurement to each cell of the matrix. For every cell the contribution factor is greater than 0%, additionally the flag of the corresponding quality features for each half hour measurement are stored. Due to accumulating all contribution factors of one specific cell for a certain measurement period, the overall contribution of this cell to the measurement can be determined. By calculating the median of all flags of one quality feature assigned to one cell during this period, the dominating quality of this cell can be calculated. Additionally, the output is accessible for the three stability classes unstable ($z/L < -0.0625$), neutral ($-0.0625 < z/L < 0.0625$) and stable ($z/L > 0.0625$) separately, where z is the measurement height and L the Obukhov length. This option enables for a quality assessment due to stratification. Interpolating the matrices of accumulated contribution factors on an arbitrary level up to 100% originates the so called effect level rings, which are later shown on the maps as white contour lines (Fig. 3a, b; Fig. 4a, b, Plate XI). The extend of the 5% effect level ring is regarded as the maximum extend significantly influencing the measurement quality, later referred to as ‘central footprint’. Only quality ratings lying within this extend are taken into account for statements on the actual measurement quality. Quality ratings beyond this limit, later referred to as ‘extended footprint’, might still reveal disturbances of the local flow field, but have to be evaluated carefully, since the numbers of measurements for calculating statistics is decreasing with distance.

3 Results

The wind direction shows clear diurnal cycles for both of the sites. In case of NaMuCuo (Fig. 2a, Plate Ⅹ) general dominating wind direction is SE with a shift to SW during noontime. Further, two subsets can be detached, a period from 09/25 to 10/01 which, despite the diurnal cycle, merely shows SE directions and another period from 10/13 to 10/18 displaying dominating S directions.

For the Everest site, dominating wind direction is SW with a transition to NE during noontime (Fig. 2b, Plate Ⅹ).

At the NaMuCuo site, 4.1% of all half hour means of the unrotated vertical wind speed exceed the threshold of |35 cm/s|. A huge sector of upwind values exceeding the median of |15 cm/s| is located in the W and SW of the measurement (Fig. 3a, Plate Ⅺ). Further, two opposite narrow sectors in the NNE and SSE indicate downwind/upwind values exceeding the median threshold. Best sector regarding the elimination of the vertical wind speed for half hours means is SE. Due to coordinate rotation E and SW areas do not surpass the median of |15 cm/s| anymore, the downwind sector in the NNE remains.

Measurements at the Everest site exceed the threshold of |35 cm/s| for 29.9% of the unrotated vertical wind speed half hour mean values (Fig. 2c, Plate Ⅹ). Dominating upwind direction is NE during noontime with two additional narrow sectors N and E (Fig. 3b, Plate Ⅺ). Downward air movement is restricted to the SW sector and an additional narrow sector in the SE, occurrences exceeding the threshold of |35 cm/s| are almost restricted to afternoon and evening time (Fig. 2c, Plate Ⅹ). For the Everest site, coordinate rotation leads to a reversal of the absolute values of vertical wind speed and a better leveling for unrotated upwind values (Fig. 2d, Plate Ⅹ). Noontime measurements rarely exceed the threshold of |5 cm/s|, whereas for the rest of the daytime values do no more exceed the threshold of |35 cm/s|.

For further quality assessment results, figures are only presented where denominated, other cases are discussed without a figure related.

In accordance with the distribution of the wind direction, the central footprint at NaMuCuo site is omnidirectional with its centre shifted 40 m from the tower in SE direction, resulting especially from neutral and stable measurements (Fig. 4a, b, Plate Ⅺ). The overall quality flag for the momentum flux is 2, whereas, especially during stable conditions, the central footprint touches a large sector of bad quality flags rating 4 SE of the tower (Fig. 4b, Plate Ⅺ). The sensible heat flux during unstable stratification is rated with 2, during stable stratification, 3 is the dominating flag, but a large sector in the S is rated 4 and 5. Overall rating for CO_2 flux (Fig. 4a, Plate Ⅺ) and latent heat flux is quite similar and a nearly perfect 1. Especially for stable stratification both fluxes show the same sector rated 3 like the sensible heat flux, emphasized for the CO_2 measurement, but no worse sectors in SE and S. The extended footprint shows SE-NW and SW-N transects of worse than average quality flags (Fig. 4a, b, Plate Ⅺ), which are, in different degrees, indicated for all fluxes and all stratifications. Detailed investigation of a data subset for the SE wind sector period from 09/25 to 10/01 (later referred to as SE wind sector period) has shown that for CO_2 measurement 8% of all half hour means in the SE sector are flagged 5, compared to 2% of all half hour means in all other directions. Thereby 93% of the values in the SE sector failed due to stationarity criteria, the remaining 7% due to the ITC.

For the Everest site, due to the two dominating wind directions, the central footprint is aligned in a SW-NE corridor with its centre at the tower and exceeds 50 m only for the SW sector (Fig. 3b, Plate Ⅺ). Due to the temporal distribution (Fig. 2b, Plate Ⅹ), the SW sector is slightly dominating. The momentum flux measurement shows an overall quality rating of 2 with only few occasions of quality flag 4 in the S sector during stable stratification. The sensible heat flux shows quality flags rating as good as 2 only for the NE sector during unstable stratification, whereas the quality flags for the SE sector are flagged 4 or mostly 5 during stable and unstable stratification due to the ITC criteria. The latent heat flux shows a flawless rating of 1, as for CO_2 flux, the quality rating is dominated by flags 1 for the NE and 3 for the SE sectors. For all fluxes, worse than average flags are assigned for the extended footprint in a NW-SE transect due to the stationarity criteria.

4 Discussions

In case of NaMuCuo, winds from the mountain range aligned NEE to SWW in the S of the measurement (Fig.1a, Plate Ⅹ) lead to SW to SE wind direction. Part of the diurnal cycle might be described by an interaction of catabatic and land-lake wind effect.

At the Everest site, the wind direction is clearly related to topography (Fig.1b, Plate Ⅹ). Catabatic wind leads to SW directions for the time of low or no solar radiation, whilst anabatic wind during noontime causes NE directions.

Regarding influence of local topography on the measurements, the situation at NaMuCuo site, with only 4.1% of all half hour means of the unrotated vertical wind speed exceeding the threshold of |35 cm/s|, can be described as comparatively good. The upwind sector in the W and SW of the measurement (Fig.4a, Plate Ⅺ) can be explained by the station building located 80 m W of the measurement and the two solar panels installed in the SW. Moreover, the narrow upwind sector in the SSE can be explained by flow distortion due to the LI-COR gas analyzer located in this sector. The narrow downwind area in the NNW exceeding the median threshold of |15 cm/s| can not be attributed to the local topography, which is contraindicating (Fig.3a, Plate Ⅺ). This sector even remains after coordinate rotation, which otherwise leaves no more sectors surpassing this threshold.

For the Everest site, with 29.9% of all the half hour values exceeding the threshold of |35 cm/s| for unrotated vertical wind speed, the fluxes determined from EC results most be treated carefully. Upwind exceeding the threshold of |35 cm/s| is approaching from N where a steep slope is located within the extended footprint (300 m). During noontime, the anabatic wind deriving from NE directions is deflected here. As a consequence of the created pressure, the air is expanding not only horizontally but vertically as well, which leads to an upward tendency. This tendency is intensified by a small ridge of 30 cm height that elevates the measurement against the surface in N. Downward air movement in the SW sector can be attributed to the catabatic wind moving down the gentler slope on the SW of the tower on a large stretch. This directly effects the measurement located on a slightly towards NE declined plane. Local topography effects can not account for the high vertical wind values on the NW-SE stretch.

For the quality assessment at NaMuCuo site, reduced quality sectors in the central footprint for all fluxes under all stratifications intersect with the SE-NW and SW-N transects of reduced quality seen from the extended footprints (Fig.4a, b, Plate Ⅺ). Bad ratings in the N and SW sector can explained by flow distortion: the mast holding the installation is located N from the sonic and the SW sector bears two 1 m high solar panels installed 10 m from the measurement. In the SE-NW sector of reduced quality no obstacles in the fetch of the measurement can be found. As for the NW sector, the increased values of the vertical wind speed persisting the coordinate rotation might account for part of the failure of the quality assessment criteria. This leaves at least the SE sector, with an almost perfect level fetch and hence the best flow direction regarding the vertical wind speed, but nevertheless bad quality ratings. Here, detailed investigation of the SE wind sector period has shown that for the discussed period four times more values of the CO_2 flux are flagged 5 for the SE sector compared to all other directions, nearly all of them due to instationarity. Recalling the fact that the quality flag assigned to one cell is the median of all measurements with any contribution factor little higher than 0% emphasizes the significance of this subset analysis with throughout higher contributions. These findings give way to the hypothesis, that the instationarity is not caused locally but due to mesoscale flow patterns of the further environment, including Lake NaMuCuo and the mountain range in 15 km distance SSE.

For the Everest site, the few occasions of quality flag 4 in the S sector during stable stratification for the momentum flux can be ascribed to flow distortion leading from the roughness step between the grain field and the village. The bad quality of the sensible heat flux measurements for the SE sector due to failing the ITC criteria can be explained by heat emission from the village: Since the ITC are a test on the stochastic distribution of turbulence elements, the test must fail if organized structures occur. In the present case, these organized structures might be thermal eddies induced by heat emission from the village. As for CO_2 flux, the slightly decreased quality rating for the SE sector can be assigned to disturbances due to the village as well. Disturbances due to the road might be wiped out by the village, since there is no line transect quality feature visible in any of the fluxes and stratifications. Worse than average flags assigned for the extended footprint in a NW-SE transect are due to failure of the stationarity criteria. Since the vertical wind evaluation (Fig.3b, Plate XI) shows disturbances for only part of the discussed transect, this pattern can not be solely accounted to local effects. Further, no instruments were aligned in these directions, which arises the question, whether organized structures are superimposed rectangular to the general flow field.

5 Conclusions

The procedure applied enables for a quality assessment that has proofed substantially necessary for both of the sites investigated. Optimum and disturbed fetch characteristics have been determined due to the analysis of the unrotated vertical wind component, as well as basic assumptions underlying the EC method have been checked for all fluxes investigated. An indication for possible reasons allows for the amendment of the measurement layout as well as it indicates the limits of EC measurement technique.

Analysis of the unrotated vertical wind field for the Everest site have shown, that approximately 1/3 of the measurements do not fulfill the assumptions necessary for a physically correct processing of the data. This significantly decreases the overall representativity of the calculated fluxes and demands special caution in utilizing the results. That said, the measurements of latent heat, CO_2 and momentum flux at both sites fulfill the tests for ITC and stationarity to an extend that the results can be regarded as suitable for fundamental research. At this point it must be recalled, that no ITC criteria can be applied to the measurements of CO_2 and H_2O, which consequently leads to a comparatively good estimation of the flux quality. Special care shall be applied to the utilization of the sensible heat flux results at both sites, which was, for stable and unstable conditions, rated 1 to 2 flags worse than the other fluxes. Further, for all fluxes at both sites sectors underlying high flow-distortion were found. Both, sensible heat flux for the entire measurement as well as all other fluxes for measurement periods heavily affected by disturbed sectors only allow for the usage in continuously running measurement programs for obtaining monthly or annual sums of fluxes. To refine the findings of this study and distinguish periods of disturbed and undisturbed measurements, the presented approach will be applied to the entire available datasets of both sites.

Still, few indications for both sites are unsolved. Such are the diurnal cycle of wind direction at NaMuCuo site as well as findings of transects with vertical wind directions contradicting local topography or bad quality ratings due to instationarity despite a flawless fetch. Regarding the complex terrain at both sites, this gives way to the hypothesis, that mesoscale flow patterns are superimposed to (Everest) or even dominate (NaMuCuo) the boundary layer circulation. Consequentially, fluxes derived from point measurements can not be simply upscaled for these areas. The application of a regional atmospheric model[26], fed with training areas supplying flux data corrected for violations of EC assumptions, can help to reveal possible mesoscale flow patterns. Therewith, an instrument for proper areal upscaling of energy and matter fluxes can be created.

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利用步长模拟对青藏高原涡度方差测量法的质量评价

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摘 要:利用痕迹模拟方法对青藏高原两处地方涡度方差的测量数据进行了质量分析,揭示了其空间和时间结构。分析表明高达 1/3 的测量没有达到必要的数据正确假设。尽管这样对潜热、CO_2、动量通量的测量基本通过测试,可以适用于基础研究,但是经常发现特定的风矢量违背基本假设条件。感热通量的测量允许使用不间断的连续测量法,然而由于局地地形的影响少量评估指数未能合理解释,但能够指示出组织结构及用于导出边界层中尺度流体模型假说。

关 键 词:痕迹气候学;质量评价;质量控制;青藏高原;中尺度