The simple two-dimensional parameterisation for Flux Footprint Predictions FFP

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Responses to Topical Editor

A reviewer raised an issue: The scaling is performed via four dimensionless groups. The dimensionless groups do not include directly any parameters related to ABL flow characteristics such as the convective velocity scale. Have the authors considered including this velocity scale to improve (potentially) the footprint parameterization under convective conditions and would it help to explain different parameterization coefficients obtained for the convective regime (Table6)?

To which you replied: Indeed, we have tried to include the convective velocity scale, but this did not prove to be successful. What we presented in this manuscript is the statistically best scaling approach we found and the result of research over an extended period of time.

I think it would be worth mentioning this in the manuscript (that including the convective velocity scale was not successful), as this is potentially useful information to others in the field?

Indeed, that's a good idea. We have added this information on p. 21 of the manuscript.

With regards to code availability: Rather than provide a link to a personal web-page, please provide a link to a repository such as github or bitbucket. The reason is that personal or even institutional web-pages often go offline, whereas actual repositories do not. On the repository site, you can of course link to your personal/institutional web-site.
Also, repositories such as github/bitbucket come with built-in version control. You should provide and/or make clear, how one can access the exact source code which was used for this paper, versus the latest version(s).

We have carefully looked into the suggested repositories. We agree with the above mentioned advantages, but still prefer to use footprint.kljun.net as a download-hub, for the following reasons:

- *www.footprint.kljun.net is already an established webpage – it was set up in 2004 for the one-dimensional footprint parameterisation and has had a constantly high 'hit' rate for the last 10 years (2004-2011: 8773 users, 2012-2015: 1289, 1558, 1303, 2295 users per year, respectively; i.e. over 15'000 users in total with over 30'000 page views since 2010). Many potential users will expect to find the new two-dimensional parameterisation on this webpage.*
- *The web-page is hosted by a major webhosting company (www.hosttech.ch) on a professional decentralised and virtualised server environment with automated backup. We haven't had any issues with it for the last 10 years.*
- *We would like to provide a new service to users of the code: they can register for a user mailing list (if they wish to) and will receive notices of code upgrades. This is not possible with the above mentioned repositories.*
- *With www.footprint.kljun.net we can keep track of the usage of the webpage (web stats), which we rely on for internal professional review exercises (we all get evaluated...).*
- *An example of future version of www.footprint.kljun.net can be currently accessed at ffp.kljun.net . We will transfer this webpage to www.footprint.kljun.net if the manuscript has been accepted.*

We will make sure that the exact source code that was used for this paper will be clearly distinguishable from future updates and will also make a clear link to the publication in GMDD (GMD).
We very much hope that the editor agrees with the suggested format. Thank you.

Responses to Referee #1

The manuscript is very well written, and provides a focused and well justified description of an improved approach for footprint modeling.

Many thanks.

I have several minor comments (listed below), regarding reference to recent publications that have used footprint models, and regarding the order and flow at which the formulation is described.
I salute the fact that a link to the code is provided with the manuscript. I think this should be moved to an earlier point in the paper (perhaps just after the introduction) and not hidden past all the appendices, but this is just my preference and I will accept the authors preference for the placement of the "code availability" section. However, I checked the website listed and the source code is not provided there. There is only a link to an online version of the model, which is a far cry from the code itself. I assume that a link to the code will be posted when the paper is accepted, but the editor should verify this before the final posting of the manuscript.

Indeed, we await the acceptance of the paper before the new webpage with the model code goes live. We also plan to upload the footprint code as supplement to this paper.
Thanks for the suggestion, we now do mention the availability of the code at an earlier point in the paper (end of Introduction).

P6759 Line 16- Matheny et al 2104 JGR 119:2292-2311 and Morin et al JGR 2014 119:2188–2208 are two additional example for novel applications of a 2-D footprint model, for scaling the contribution to flux measurements from a disturbance area and for gap-filling of CO2 and methane fluxes from a heterogeneous wetland site. Morin et al is also provides a relevant for Page 6761 Line 5, and for remote-sensing driven footprint climatology (see Morin's figure A1) discussed in page 6775, lines 15-20.

Many thanks for the above references. We want to stress that the articles listed in our manuscript are by far not exhaustive. As footprint modelling has become an established approach in the FLUXNET community, it is beyond the scope of this manuscript to list all articles dealing with such. We hence refrain from adding these additional references.

Page 6762 Line 8-10: What happens in airborne measurements? The vertical reference cannot be assumed as fixed there. Upon further reading, the topic of footprint for moving measurements, such as airborne flux measurements, is not addressed at all. I recommend removing the comment about airborne measurements in Page 6760 Line 8 as it is creates a false expectation that the solution you are about to present can handle these as well.

Recent research has shown that footprint models can be applied to airborne flux measurements. We refer to according studies from, for example, Hutjes et al. (2010), Kustas et al. (2006), Mauder et al. (2008) and Metzger et al. (2012, 2013). These articles are listed in our manuscript as examples for such approaches. Adding details on the processing of airborne flux measurements is beyond the scope of this manuscript.
Page 6762 – the formulation here tells us about the footprint function, but does not tell what it actually is. We end up with a symbolic representation of a footprint function (eq. 3). Took me a while to figure out where you are going with it and to get to the solution. Can you add a few words here to the effect that later in the manuscript you will derive the parameterized forms for D and (f^y)bar.

Many thanks for this suggestion. We have included the following sentences after Eq. (3) on page 6762 to clarify the aim of the parameterisation: "In the following sections, we present a scaling *approach and a parameterisation for the derivation of (f^y)bar and D_y with the aim of simple and accessible estimation of f(x,y)."*

Page 6772 – at some point around equation 13 I ran out of patience and started going over all the equations looking for a formulation of (fˆy)bar and sigma_y , which are the key to solving the footprint function (eq 10). After a somewhat frustrating quest, I finally found it, way later, on page 6772, hidden in the numerical recipe of example 5.2, and not strictly formulated (the reader is instructed to invert equations 8 or 9 and 13). I admit that my jumpy reading style and short attention span should not be considered the norm or burden the authors, but would it be possible to write the inverted forms of eq9 (or eq8) and eq13 (i.e. (fˆy)bar = . . . and sigma_y = . . .) at an earlier point, and say that they could be solved and substituted in eq10 to find the footprint function, provided empirical formulations for sigma_y* and Fˆy*. I think the end of section 3 would be a suitable spot for this, as it will provide a logical transition to the parameterization in section 4.

The structure of the manuscript is as follows: 1) real scale footprint data set, 2) scaling approach to be applied to footprint data, 3) parameterisation of scaled footprints, 4) derivation of real scaled footprints based on the parameterisation. We think that introducing an inversion of the scaling in between rather than at the end would be confusing. Nevertheless, we added a short explanation of the steps in Section 2 (see above) and hope this helps to clarify the approach.

Page 6777 Line 7 – See nice example of a flux tower-based study of the roughness parameters in a forest site in Maurer et al 2013 AFM.

Many thanks, very interesting study. We added a reference to Maurer et al. in Section 5.4.

Page 6777 lines 9-12 – the letter h is often associated with canopy height and not always with boundary layer height as in this paper. As it is mentioned immediately after z_0 (which is a function of canopy height) it confused me. Please move the explicit definition of h to this point, to prevent confusion, i.e. "Measurements of the boundary layer height, h, are available only rarely. . ." (it is currently about 5 lines later, in "a small variation in the input value of the boundary layer height, h . . .")

We have changed the sentences as suggested by the referee (Section 6.1).

References

Hutjes, R. W. A., Vellinga, O. S., Gioli, B., and Miglietta, F.: Dis-aggregation of Airborne Flux Measurements Using Footprint Analysis, Agric. For. Meteorol., 150, 966–983, 2010.

Kustas, W. P., Anderson, M. C., French, A. N., and Vickers, D.: Using a Remote Sensing FieldExperiment to Investigate Flux-footprint Relations and Flux Sampling Distributions for Tower and Aircraft-based Observations, Adv. Water Resour., 29, 355–368, 2006.

Mauder, M., Desjardins, R. L., and MacPherson, I.: Creating Surface Flux Maps from Airborne Measurements: Application to the Mackenzie Area GEWEX Study MAGS 1999, Bound.-Lay. Meteorol., 129, 431–450, 2008.

Metzger, S., Junkermann, W., Mauder, M., Beyrich, F., Butterbach-Bahl, K., Schmid, H. P., and Foken, T.: Eddy-covariance flux measurements with a weight-shift microlight aircraft, Atmos. Meas.Tech., 5, 1699–1717, 2012

Metzger, S., Junkermann, W., Mauder, M., Butterbach-Bahl, K., Trancón y Widemann, B., Neidl, F., Schäfer, K., Wieneke, S., Zheng, X. H., Schmid, H. P., and Foken, T.: Spatially explicit regionalization of airborne flux measurements using environmental response functions, Biogeosciences, 10, 2193-2217, 2013

Responses to Referee #2

The authors state that "the aim of the present study is not to present a new footprint model, but to provide a simple and easily accessible parameterisation or "short-cut" for the much more sophisticated, but highly resource intensive, model". The aim is very much welcome and invaluable for the community carrying eddy covariance flux measurements, and the paper fulfils the aim. The paper is written and structured very clearly and is "user-friendly" and I have only few minor comments and recommend its acceptance after the comments are concerned.

Many thanks!

1. p. 6758 (Abstract), line 5: the sentence can be interpreted that single site flux gives information at sub-ecosystem scale and upscaling to ecosystem scale is needed. However, it is commonly thought that eddy covariance is operating, almost by definition, at ecosystem scale (or neighbourhood scale if urban surface). Can you clarify?

We agree that ideally, a flux tower does provide information on the ecosystem scale (which in reality is not always met). To clarify, we changed the wording in the abstract and replaced 'ecosystem scale' by 'local scale'.

2. p. 6760, line 25: there is a very recent article on footprints and LES: Hellsten et al., Footprint evaluation for flux and concentration measurements for an urban-like canopy with coupled Lagrangian stochastic and large-eddy simulation models. Boundary-Layer Met. DOI 10.1007/s10546-015-0062-4, 2015. Note that I am not asking you to necessarily refer to this article but mentioning it just for your notice.

Many thanks. As we haven't mentioned so far the footprint approach using a combination of LES and LS, we added the above reference and an additional paper to fill this gap in the Introduction.

3. P. 6764, line 26: from where the value for the zero-plane displacement height is obtained? It is maybe mentioned somewhere but it would be good to say/explain it here.

We assume the referee refers to p. 6763 (there is no line 26 on p. 6764). For the simulations of LPDM-B of Section 2, only z_m is of interest, as the model does not include the roughness sublayer. For footprint estimates of 'real' receptors mounted at z_receptor on a flux tower, the zero-plane displacement height, z_d, is needed for derivation of z_m. We added a couple of sentences on the possible derivation of d in Section 5.4, where real-scale flux footprints are discussed.

4. It would be good to have a section called "Results"; Does it include sub-sections in Section 3 or only 4 and/or 5? The present titles of the sections can be kept but they would be below Results.

This is a tricky request. As we developed a novel scaling approach, a new parameterisation, and a new approach for fast and simple real-scale footprint estimates, it is not really obvious which sections would be part of a Results section. We hence prefer to leave the structure as it is.

5. Table 1 and other relevant places: Measurement heights within the roughness sublayer (RSL) are disregarded. However, in reality, many flux measurements are in fact carried within RSL, although the (strict) recommendations are against it. I am not asking you to do anything right now for the paper but by raising this issue I would welcome the continuation of your work to include also RSL effects. Do you know to which direction the omission of RSL is leading? If someone is using your parameterisation for RSL measurements, is there overestimation or underestimation of the extension of the footprint?

The referee raises an important question. In fact, the inclusion of RSL is part of current work of the authors.

6. Table 4: why for neutral cases the value of R for the standard deviation is much lower (0.37) compared to other cases?

Many thanks – we managed to improve the performance metrics for the neutral scenarios by adjusting the proportionality factor ps2 to 0.35. The metrics in Tab. 3 and Tab. 4 were adjusted accordingly.

7. Fig. 5: The measurement (receptor) height is only 12m, as far as I know the tree height at Norunda is higher. Please, clarify. In addition, the background map is said to be tree height, but no scale is given.

For Figure 5, we used measurements at 33 m above ground. However, note that throughout the manuscript, we set $z\_m = z\_receptor - z\_d$, hence with $z\_d = 21$ m, we get $z\_m = 12$ m. We added this information to the figure captions to omit confusion.

8. General comment: I am not asking you to do anything right now for the paper but by raising this issue I would welcome the continuation of your work to calculate also concentration footprints. They would be valuable for tall tower absolute concentration measurements, but I am not sure how you could deal with advection/long-distance transport.

Yes, we agree, this is an important issue and again, it is part of current work of the authors.

Responses to Referee #3

By using scaling approach and suitable fitting functions, the authors present an easy to use, full (in terms of along wind and cross-wind representations) footprint function for variety of stabilities and Atmospheric Boundary Layer (ABL) flow regimes. It is the first such footprint model enabling to make fast footprint estimation for the measurements outside the Atmospheric Surface Layer (ASL) scaling domain. The model therefore serves as a useful tool not only for tall tower sites but also for the measurement conditions violating the ASL assumptions, which are typically constrained to the measurement heights less than or equal to the magnitude of the Obukhov length scale. I fully support publication and hope that addressing the comments below helps to improve the manuscript.

Many thanks!

The scaling is performed via four dimensionless groups. The dimensionless groups do not include directly any parameters related to ABL flow characteristics such as the convective velocity scale. Have the authors considered including this velocity scale to improve (potentially) the footprint parameterization under convective conditions and would it help to explain different parameterization coefficients obtained for the convective regime (Table 6)?

Indeed, we have tried to include the convective velocity scale, but this did not prove to be successful. What we presented in this manuscript is the statistically best scaling approach we found and the result of research over an extended period of time.

The second comment is related to the third dimensionless group which is formulated based on the common phenomenon that the surface fluxes decrease approximately linearly with height in the ABL (page 6765, line 6-9). On the other hand, the footprint function is formulated such that it obeys the basic property of integration to unity (page 6769, line 13-15), which according to eq. (1) implies that the flux measured at zm equals to the surface flux. According to the given references (e.g. Kljun et al., 2004), the model LPDM-B is formulated such that the upper boundary condition of the simulation domain was not set to reflection. In forward Lagrangian approach this would imply that the surface release of particles eventually means absorption (or exit of the particles from the domain) at the upper boundary, and consequently constant particle flux with height up to the boundary layer top. The forward and backward Lagragian approaches are known to be equivalent and the same must apply to the backward approach. Please discuss the effect of the upper boundary condition used in LPDM-B on the results and help the reader to clarify the apparent inconsistency of the dimensionless scaling group 3 (or the reasoning behind it) with the footprint formulation eq. (1).

This must be a misunderstanding. Particles tracked by the model LPDM-B (Kljun et al. 2002) are reflected at either boundary, i.e. at the surface AND at the top of the planetary boundary layer. The particles are fully elastically reflected; i.e. no absorption or transformation at the boundaries is taken into account. A description of the reflection scheme can be found in Rotach et al. (1996) and in Wilson and Flesch (1993). We have added a sentenced highlighting the reflection at the surface and the top of the planetary boundary layer in Section 2.

The parameterization is based on the set of simulations for a range of values describing the flow as well as the surface conditions (the roughness length). The momentum flux (or the friction velocity used in the MS) is driven by the flow forcing as well as the surface characteristics (roughness) and therefore it the aerodynamically smooth surfaces induce lower momentum fluxes especially under stable conditions. For example for the roughness length value 0.01 m I would assume that the friction velocity 0.1 m/s is rather common under normal meteorological conditions (meaning that not under extreme stability conditions). The range of friction velocities used in the MS for stable conditions is quite narrow (Tables 1 and 2). Could the authors assure that scaling performs well also for low u*, in particular for the surfaces with low roughness?

To address the above, we have run three additional simulations with LPDM-B for a friction velocity of u = 0.1 m/s, a roughness length of z0 = 0.01 m, and a measurement height of zm = 10 m. For the stable case, we set L = 500 m and h = 280 m; for the neutral case, L = inf, h = 300 m, and w* = 0 m/s, and finally, for the convective case we set L = -50 m, h = 2500 m, and w* = 0.5 m/s.*
Figure 1R shows the same density plot of all original LPDM-B simulations as Fig. 2 of the manuscript. We added the scaled footprints of the above additional simulations (stable case: dash-dotted line, neutral case: dashed line, convective case: solid line). As can be seen in Fig. 1R, the scaled footprints of the low-u scenarios nicely fit the ensemble of other scenarios.*

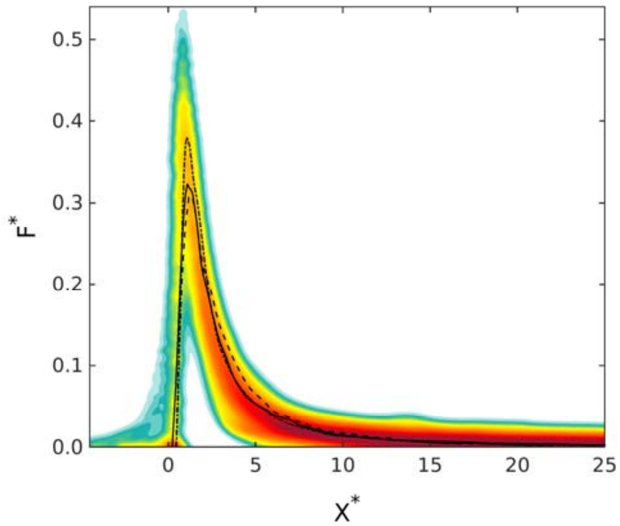

Figure 1R: Density plot of scaled crosswind-integrated footprints of LPDM-B simulations (cf. Fig. 2 of manuscript). Black lines depict additional low-u scenarios (stable: dash-dotted line, neutral: dashed line, convective: solid line).*

References

Rotach, M. W., Gryning, S.-E., and Tassone, C.: A Two-Dimensional Lagrangian Stochastic Dispersion Model for Daytime Conditions, Quart. J. Roy. Meteorol. Soc., 122, 367–389, 1996.
Wilson, J. D. and Flesch, T. K.: flow Boundaries in Random-Flight Dispersion Models: Enforcint the Well-mixed Condition, J. Appl. Meteorol., 32, 1695-1707, 1993.