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Interactive comment on "A robust gap-filling method for Net Ecosystem Exchange based on Cahn–Hilliard inpainting" *by* Yufeng He and Mark Rayment

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We are very glad that the reviewer found this study innovative and important. We very much appreciate his/her constructive comments, which are penetrating and inspired, and have lead to some substantial improvements on this work. Building upon the revised manuscript (our response to reviewer #1), we have made further changes to the paper to incorporate the idea/issues raised by the current reviewer. The points are listed as follows and please refer to an updated manuscript attached in the supplementary PDF file.

1. About the colour scales of the fingerprint figures

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Reviewer's comment:

"A range of NEE should be different at site by site. In fact, the range of the site DEGri 2012 is from -30 to + 20 (Figure 3), and its of the site UKAMo 2010 is from -10 to +5 (Figure 6). Even the ranges are different, color scales at the both site are the same; the lowest is blue, around zero is green, and the highest is yellow. When those ranges and scales are used for converting to gray scales, an representative NEE value of each gray scale is changeable at site by site, and it may lead to complex interpretations of "noise" because it is obtained from the difference between the gap filling values (i.e., scale of gray) and the real values. For an uniform analysis over the sites, why the fixed range for color/gray scales (for example, -30 to +20 for all site) is not applied? If there is some reason to use the specific range for color/gray scale for each site, please mention about it."

Our response:

We understand the confusion caused by the non-uniform colour scales and we did think about a consistent colour scale for all fingerprint figures, however this would reduce the intuitive understanding of these graphics (one per site), each of which has a distinct range of values. For example, if we adopted a uniform value range from -30 to $+20$, the contour plots for site UKAMo2010 would tend to be single-coloured and thus the flux variations represented by colours will become less distinguishable (see Fig. 1b below). Since we are not comparing the fingerprint figures between sites, the colour scales are better treated independently (e.g. colour yellow for one site has nothing to with the yellow for another).

As pointed out by the reviewer, the critical problem that may affect the IIP performance lies in the conversion of NEE value to grayscale (i.e. normalize NEE to (0,1)), which generates different NEE grayscale representations for different scale ranges. Originally, we used the following equation to convert/normalize the NEE values (Note: we have also included this in the manuscript at Page 3 line 25-30 and Page 4 line 1-4):

$$NEE_{gray} = \frac{NEE - NEE_{min}}{NEE_{max} - NEE_{min}}$$

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where NEE_{min} and NEE_{max} are the minimum and maximum value of NEE respectively *for a given site*. If a universe grayscale were adopted, it means that a constant NEE_{min} and NEE_{max} would be used *for all sites*, which clearly would generate different values of NEE_{gray}. The fundamental question, however, is whether this transformation of NEE would have any impact on the gap-filling results. It turns out that this normalization method does not affect the IIP performance at all (see Fig. 2 below), suggesting that a simple linear transformation of NEE like this does not affect the computation output. Intuitively, we may say that IIP "senses" the relative gradient, irrespective of the actual value scale.
This result also supports our previous point that a unified colour scale is neither desirable, nor necessary because 1) it's not visually intuitive; 2) it does not affect the simulation output at all. Moreover, the colour information shown on the contour plot is, in fact, arbitrary, and for the purpose of illustration only. For example, we could group deep blue and light blue into a single colour that would not be distinguishable by eye, but the computer retains all the value variation within that single colour. In short, value changes continuously by given time step (e.g. half-hourly here), whilst the colour is discretised into sectors to provide a more intuitive view.
The reviewer also made another comment related to the colour scale.

Reviewer's comment:

"Page 3, line 26-27: Can colored fingerprint figures (e.g., Figure 3 (b), (e), (h) and (k)) be applied to the IIP? Why are the figures converted to gray scale images? (Is the IIP limited only to the gray scale images?)"

Our response:

There are three reasons why we limit this IIP algorithm to grayscale images: 1) This inpainting algorithm was originally developed for grayscale images; 2) NEE is a one-dimensional vector and a projection of this vector onto an RGB value (3-d vector) does not add extra information; 3) Most importantly, as discussed above, we would lose information if discretised colours were used to represent NEE values because

the variation within colour (hue) is neglected. The half-hourly variation is already the finest resolution that can be "resolved" by the differential equation of this IIP (i.e. the differential equation represents function's change/gradient).
Nevertheless, this does point out a potential follow-up study on an extension of IIP to higher dimensional gap-filling. We have added the following arguments in the discussion section at Page 9, line 3-13:
"We limit the use of IIP to grayscale images because 1) This inpainting algorithm was originally developed for grayscale images [Burger et al., 2009]; 2) The NEE is a one-dimensional vector and a projection of this vector onto an RGB value (3-d vector) does not add extra information; 3) Most importantly, we would lose information if discretised colours were used to represent NEE values because the variation within colour (hue) would be neglected. In fact, the half-hourly variation is already the finest resolution that can be "resolved" by the differential equation in this IIP (i.e. the differential equation represents that function's change/gradient). Nevertheless, a recent study has extended the application of the Cahn-Hilliard IIP to colour images [Cherfils et al., 2016] and other techniques for colour image inpainting have been proposed (e.g. [Bertalmio et al., 2000]). These developments would allow us to apply IIP-based gap-filling to higher dimensions by incorporating constraining "information" derived from other fluxes or other environmental variables. Thus, potential follow-up studies could focus on improving representation of NEE in colour images, using, for example, Green for NEE, Blue for latent heat flux and Red for sensible heat flux."

2.Responses to reviewer's other comments

Reviewer's comment:

"Title: It is hard to infer the contents of the manuscript by reading the term "Cahn-Hilliard inpainting". Please try to express this in different words."

Our response:

We agree with the reviewer about the title and we now propose an alternative as: "A robust gap-filling method for Net Ecosystem CO2 Exchange based on image inpainting

(IIP)"

Reviewer's comment:
"Page 4, line 18: What does the "T" mean in equation 1? There is no explanation."
Our response:
This part indeed need a clarification. We have added the following description at Page 4 Line 29-31:
"Where a is the frequency mode in Fourier domain. Since a is a complex number, $|a|$ is the complex modulus. T is the threshold chosen to filter the frequency according to its energy (i.e. the modulus of a given frequency). One may draw a histogram of all frequency moduli (i.e. power spectral density) to help choosing a threshold."

Reviewer's comment:
"Page 6, line 14-16 and Page 14, Figure 5(d): Richardson et al. (2006) showed that random errors of fluxes follow a double exponential distribution. Though the noise in the manuscript and the random errors in Richardson et al. (2006) are different concepts, how about also trying to fit the noise to the double exponential distribution?"
Our response:
This is certainly a very interesting point raised by the reviewer and thanks to his insightful suggestion, we can further highlight the robustness of our Fourier transform-based de-noise method. The following changes have been made to manuscript:

- Fig. 5 in the original manuscript has been separated into three individual graphs as Fig. 5, Fig. 6 and Fig. 7 in this revised version, representing the de-noised temperature, de-noised NEE and the residual distributions respectively.
- The double exponential distribution was fitted to the NEE residual distribution, which was plotted with the normal fit in Fig. 7b. It was indeed a better fit than the normal distribution.

- Accordingly, the statements in the result section have been modified at Page 6 Line 20-33 and Page 7 Line 1-11.

Reviewer's comment:

"Page 8, line 9-10: The authors noticed that the IIP performed less well for long gaps which gives rise to a question. Are the "long gaps" mentioned in the context a gap percentage of total data, or an absolute gap length? If a site has a one month data gap in a one year data set, the gap percentage is ca. 8% and, in my understanding, it may lead to a less accurate result. However, in the case of a one month data gap in a ten years data set using one fingerprint figure, the absolute gap length is the same but the gap percentage changes to small (ca. 0.8%), and will it produce a different result or the same? It should be made clear whether the "long gaps" referred to are the percentage or the absolute length."

Our response:

As mentioned in the discussion section of the original manuscript, it is the "diameter" of gaps that determines the IIP performance. In fact, we have validated this by adding up to 30% random artificial gaps (of small diameter) at site UKAMo2010. Results (omitted here) showed that there was no significant difference between the case with 10% and 30% random gaps, suggesting that the IIP performance was not much affected as long as the holes in the image are small. Intuitively, this is quite understandable: the information missing from small gaps is not critical because the surrounding non-gaps still contain enough information for IIP to propagate. To answer the reviewer's question, in the context of this paper, "long gaps" means their absolute length. We agree on a clarification of the statement and the relevant sentence in the manuscript has been slightly modified as:

"Firstly, IIP performed less well for long gaps where the information density is low (i.e. the diameter of gaps or the absolute gap length is large)."

Reviewer's comment:

"Page 18, Table 2: What does the "sample size" mean? Are the data points used for the IIP?"

Our response:

Sample size in Table 2 means the total number of the "valid" artificial gaps for 12 datasets. We combine all 12 datasets for each gap type to show the RMSE of gap-filling estimation (i.e. overall performance of IIP and MDS). We have changed the term "sample size" to "Total number of valid artificial gaps" in Table 2.

The table caption has been modified as:

"Table 2 Overall gap-filling error of all 12 datasets estimated for each artificial gap type. "Valid" artificial gaps are the artificial gaps that do not overlap with real gaps."

Also, two sentences were added to Line 8-10 at Page 4:

"It should be noted that any artificial gaps that overlapped with real gaps were not included in the calculation because there were no known values at those positions. On average, more than 1000 artificial gaps were valid for each gap type at each site."

Reference:

Bertalmio, M., Sapiro, G., Caselles, V., Ballester, C., 2000. Image inpainting. Proc. 27th Annu. Conf. Comput. Graph. Interact. Tech. SIGGRAPH 00 2, 417–424. doi:10.1145/344779.344972

Burger, M., He, L., Schönlieb, C.-B., 2009. Cahn–Hilliard Inpainting and a Generalization for Grayvalue Images. SIAM J. Imaging Sci. 2, 1129–1167. doi:10.1137/080728548

Cherfils, L., Fakih, H., Miranville, A., 2016. A Cahn–Hilliard System with a Fidelity Term for Color Image Inpainting. J. Math. Imaging Vis. 54, 117–131. doi:10.1007/s10851-015-0593-9

Please also note the supplement to this comment:
http://www.geosci-model-dev-discuss.net/gmd-2016-108/gmd-2016-108-AC2-supplement.pdf

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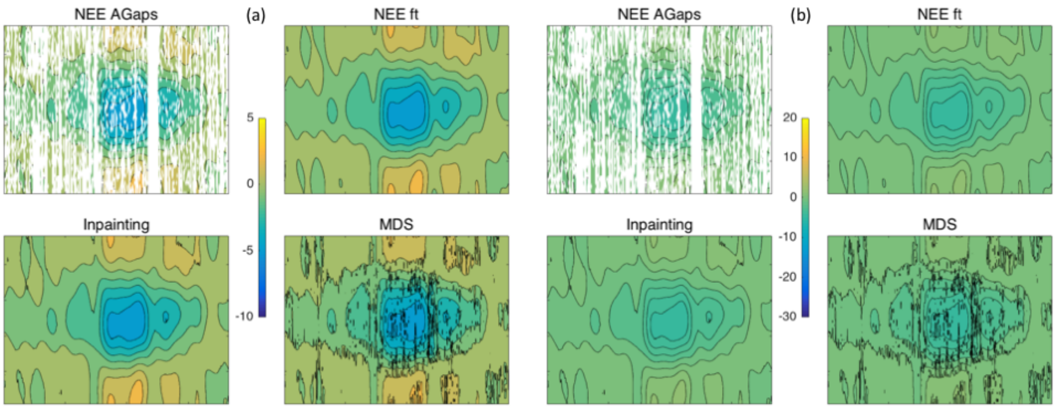

Fig. 1. Original colour scale (a) ranging from -10 to +5, compared with the scale ranging from -30 to +20 (b) for NEE data at site UKAMo_2010

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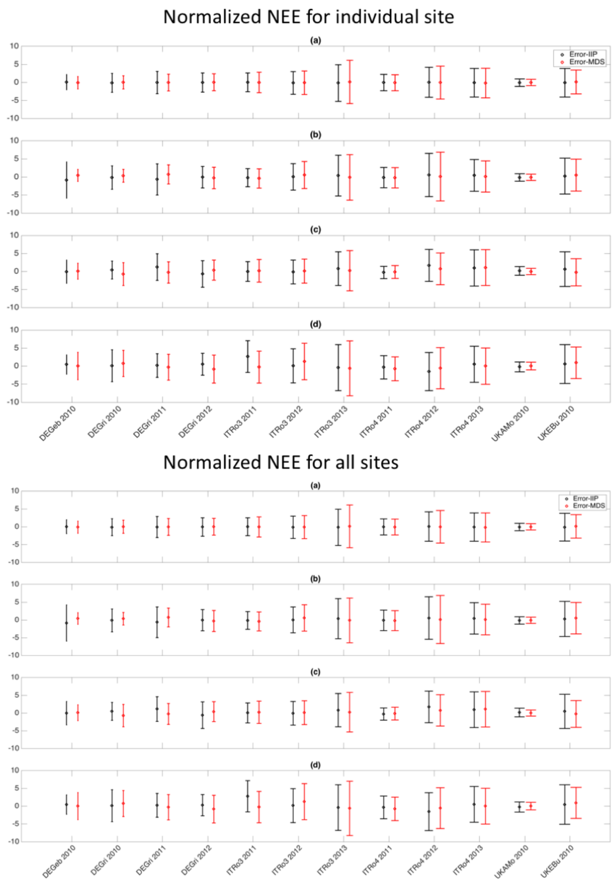

Fig. 2. IIP performance for NEE normalized per individual site (Top) and by all sites (Bottom)

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