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Discussion

Reply to the Comment made by C. Gualtieri on "Turbulent mixing in the Amazon River: The isotopic memory of confluences", by J. Bouchez, E. Lajeunesse, J. Gaillardet, C. France-Lanord, P. Dutra-Maia and L. Maurice

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C. Gualtieri raises three interesting points as a follow-up on our contribution reporting significant chemical and isotopic heterogeneities in a cross-section of the Solimões River. These points are (1) the potential additional interpretations for the derived value of transverse turbulent diffusivity, (2) the validity of both flow depth and width as characteristic length scales for the transverse turbulent diffusivity coefficient and (3) a more "parametric" evaluation for the characteristic distance of lateral mixing downstream from a confluence in a large river. While we acknowledge the relevance of C. Gualtieri's comments, here we would also like to emphasize the current lack of a proper theoretical description of turbulent flows in rivers (and of the related properties, e.g. transverse diffusion). Therefore, a reliable description of processes such as lateral mixing, as well as a precise and quantitative prediction of the corresponding metrics, is still hampered by this gap of knowledge. In more details, regarding the three items discussed by C. Gualtieri:

(1) The calculated value of α (1.5) in this fairly straight reach of the Solimões is comparable to values previously obtained for rivers having bends and meanders, a feature which we suggested to be due to the presence of islands and/or bedforms. C. Gualtieri's first point is that this relatively high value of α could as well be attributed to (i) the presence of a shear layer between the two flows (ii) or to helical flow in meanders (while recognizing that these processes should be the least prominent in the largest rivers). We agree with these two potential additional explanations. However, this α coefficient simply links the lateral turbulent diffusivity coefficient (ε_y) with the characteristic turbulent length (L) and velocity (U) scales of the flow. Therefore, α lumps various hydrodynamic and geomorphological features which *might* have *some* effect on the "efficiency" of transverse mixing (shear layer, helical flows, islands, bedforms, vegetation…). However, no sound analytical description of their influence on α is available to date, which also explains why one can solely rely on empirical calibrations of α (e.g. Fischer et al., 1979). In this context, none of these explanations can be favored to account for the relatively high value of α in the Solimões.

(2) Our choice of flow depth H as a characteristic length scale of lateral turbulent diffusion was initially justified in our work by the intuitive idea that the largest eddies, determining the maximum length scale on which mixing by turbulence is operating, are the size of the flow depth (Pope, 2008). C. Gualtieri reports in his discussion an analysis of exisiting data on transverse mixing in laboratory channels and meandering rivers (Gualtieri and Mucherino, 2007): ε_y/Wu^*, where W is flow width and u^* is the shear velocity, scales as $(H/W)^{0.940}$ in laboratory channels, and as $(H/W)^{0.935}$ in meandering natural rivers (including our data for the Solimões, which falls well within the range of natural rivers, as noticed by the discusser). This analysis is meant to show that either H or W can be used in the expression of ε_y. We note that C. Gualtieri's Eq. (6) shows that ε_y/u^* scales as $H^{0.94}$ and as $W^{0.06}$ (or as $H^{0.935}$ and as $W^{0.065}$ following Eq. (7)). The dependency of ε_y/u^* on W is thus rather weak. This is why we think that, at the leading order, H can be chosen as the characteristic length scale of this problem.

(3) What we define as a "mixing length" in our paper is related to the characteristic time of diffusion ($T = L^2/D$). In this particular case, the relevant diffusion process is the turbulent transverse diffusion in a river channel (hence $T_{mix} = W^2/\varepsilon_y$). Our mixing length is then simply the distance covered by the flow in the longitudinal direction within T_{mix}. While we agree with C. Gualtieri that this distance is not defined by the *extent* of transverse mixing achieved compared to some laterally-contrasted initial conditions at the confluence, we emphasize that this is still a valid definition of a characteristic mixing length downstream from a confluence. First, our attempt was never to provide a comprehensive framework for this mixing distance (which would require, as pointed out by C. Gualtieri, a *standard criteria* for the extent of mixing, e.g. only 5% of variability across the river), but rather to give an assessment of the potential persistance of these chemical heterogeneities. Furthermore, our calculation, as well as C. Gualtieri's, involves many parameters for which only a wide range of values can be given, and not a specific value (e.g. u/u^* varies between 10 and 20). Even more fundamentally, we believe that quantitative estimates of these mixing lengths are flawed by the lack of theoretical description concerning the turbulent mixing problem. Finally, the boundary conditions in these natural settings (meanders, bends, bedforms, vegetation)

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are tremendously complex, and it is still not known how to properly take them into account.

This is why we use such a simplified model to estimate this mixing length, and it should be kept in mind that this type of equation has to be used with caution. To summarize, at the current state of knowledge, we believe that the uncertainties associated with this calculation overwhelm any further refinement regarding the definition of well-mixing conditions.

Altogether, our paper and the following discussion show that, although empirical relationships (i) represent a convenient way to calibrate flow parameters (such as α) or characteristic distances of mixing (ii) yield satisfying results for solving particular problems, they are still dependent upon many uncontrolled factors. Only "first-principle" determinations of these equations and of these numbers will allow for their reliable use in a broad range of settings (natural, experimental, with or without meanders…) and for a wide range of applications. A prerequisite for these determinations is a better theoretical understanding of turbulent flows in rivers.

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