We would like to thank Drs. A. Ruiz-Herrera and A. M. Mancho for their comments regarding Lagrangian descriptors and the Function M (hereinafter referred to as M). Clearly there is an ongoing discussion about cases for which Lagrangian descriptors (including M) are applicable diagnostics for elucidating flow characteristics. Although neither Dr. Ruiz-Herrera nor Dr. Mancho have suggested changes to our manuscript, we would like to expound upon our use of M, and specifically why we think it provides useful information beyond that given by the other transport barrier/mixing diagnostics used in our analysis of the 2015/2016 Arctic winter.

We have applied M to the stratospheric polar vortex, which is a well-understood system in the atmospheric sciences. There is a large body of literature that has established that the polar vortex edge, or polar night jet, acts as a significant transport barrier that dynamically and chemically separates intra-vortex air from extra-vortex air (e.g., Schoeberl et al., 1992). Maps of M in the polar winter stratosphere highlight this dynamical separation. Because high/low values of M represent the “long/short” distances traveled by parcels advected by the flow, we know that the band of high M values in the vortex edge region represents the position, strength, and approximate width of the polar night jet (see, e.g., Fig 9 in our paper). This band separates two regions with low M values -- the intra- and extra-vortex air. As the polar vortex weakens and shrinks, M values in this band are reduced to the point where there is no qualitative separation that significantly distinguishes intra- and extra-vortex air (e.g., in Fig 9, 4th column, 3rd row).

Furthermore, when binned as a function of potential vorticity (PV)-based equivalent latitude (EqL), M agrees well with other instantaneous transport barrier/mixing diagnostics. Maxima in M as a function of EqL correspond well with maxima/minima features in PV gradients, trace gas gradients, and effective diffusivity (see Fig 8 in our paper). This is no surprise since, as explained above, the largest M values occur in the vortex edge region where PV gradients are largest. Hence, M is at least as useful as these other instantaneous diagnostics, even though it incorporates 30 days’ worth of flow information (when using tau = 15 days).

Having established this agreement, M in addition allows us to examine local changes in transport and mixing that the other diagnostics, which are inherently calculated as averages around EqL contours, do not. And this in particular is what we find to be most useful about M in our context; it incorporates a history of the underlying dynamics. Investigation of instantaneous wind fields alone, for example, results in qualitatively similar maps to those of M, but M highlights the dynamical significance of short and long-lived features such as the vortex edge and vortex filaments. For example, parcels initialized within the vortex edge region obtain large values of M because, in the reverse trajectories, they very likely *originated in* the vortex edge, and in the forward trajectories, very likely *stay in* the vortex edge. Similarly, parcels initialized or drawn into a vortex filament obtain relatively large values of M because, in the reverse trajectories, they also very likely originated in the vortex edge -- but they don’t reach vortex-edge levels of M because at some point they are drawn off and stirred out in the surf zone.

Our simple/visual “distance travelled” interpretation is largely qualitative, but we think it is intuitive and helps prove our point that the 2015/2016 Arctic polar vortex decay was unusually intense and rapid, especially in light of the unusual strength and size of the vortex before the major final warming. As Dr. Mancho pointed out, we are using M in a different manner, in a way that we think does not depend on the mathematical rigour necessary for discussing flow manifolds, hyperbolic trajectories, etc.

We have included in our manuscript additional references to the literature highlighting the use and criticisms of Lagrangian descriptors pointed out by Drs. Mancho and Ruiz-Herrera. Furthermore, we have added text to our manuscript to clarify our use of M and why the ongoing discussion surrounding Lagrangian descriptors does not affect our simple use of M.

References

Schoeberl, M. R., L. R. Lait, P. A. Newman, and J. E. Rosenfield (1992), The structure of the polar vortex, J. Geophys. Res., 97(D8), 7859–7882, doi:10.1029/91JD02168.