Final author comments: responses to Reviewers

Title: Meteorological Landscape of Tropical Cyclone
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MS type: Methods for assessment of models

We thank both reviewers for their careful and constructive assessments. We agree that the original manuscript did not yet establish (i) how MeteoScape relates to the established physics of TC motion, particularly steering-flow control, (ii) what additional value it provides relative to existing clustering and EOF/sensitivity-based diagnostics, and (iii) how the method should be interpreted by the TC community. In the revised manuscript, we will therefore narrow the scope of our claims, add direct methodological comparisons, strengthen the physics-oriented discussion, and move part of the mathematical development to the Supplement.

Responses to RC2

> The authors utilized biological principles alongside bioinformatics methods to elucidate the branching patterns observed in forecast tracks of tropical cyclones (TCs). These tracks were derived from ensemble forecasts pertaining to three typhoon cases within the JMA-MEPS model. By employing concepts such as bifurcation, separatrix, and both potential and rotational flow, the study establishes analogies for the uncertainties associated with tropical cyclones' projected movements in the ensemble predictions of these cases. I appreciate the authors' interdisciplinary efforts in drawing connections between the two fields. However, the proposed framework does not demonstrate its compatibility with the physics of TCs, and I do not see how it can meaningfully improve TC predictability.

We agree that the original manuscript did not establish compatibility with TC physics and did not demonstrate improved predictability. We will therefore revise the manuscript so that MeteoScape is presented as a complementary geometric diagnostic for ensemble-track branching, rather than as a method that improves forecast skill. This change will be reflected explicitly in the Abstract, Introduction, and Conclusions.

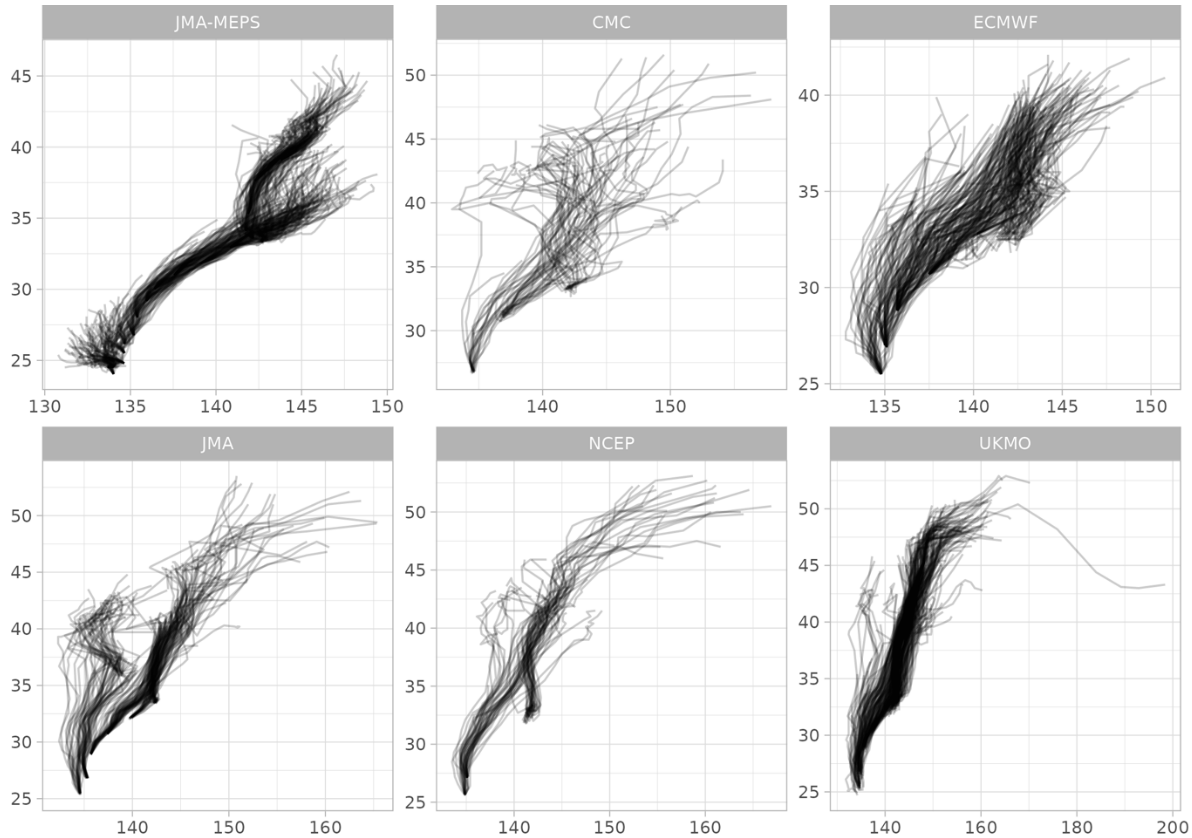
> The method used to distinguish between two states/fates in future TC tracks is overly complex and fails to offer significant improvements over simpler clustering methods, including the DBSCAN method used in Oettli & Kotsuki (2024). Irregular TC tracks can be far more complex than just having two possible fates/paths. TC

forecasts can sometimes be so uncertain that the ensemble tracks are widely dispersed across the map. However, these situations are not examined in this study.

We appreciate this criticism and agree that the original manuscript did not sufficiently demonstrate how the method behaves in more irregular or spatially dispersed forecast situations. We also agree that the previous text did not make a clear enough case for the value of MeteoScape relative to simpler clustering-based approaches.

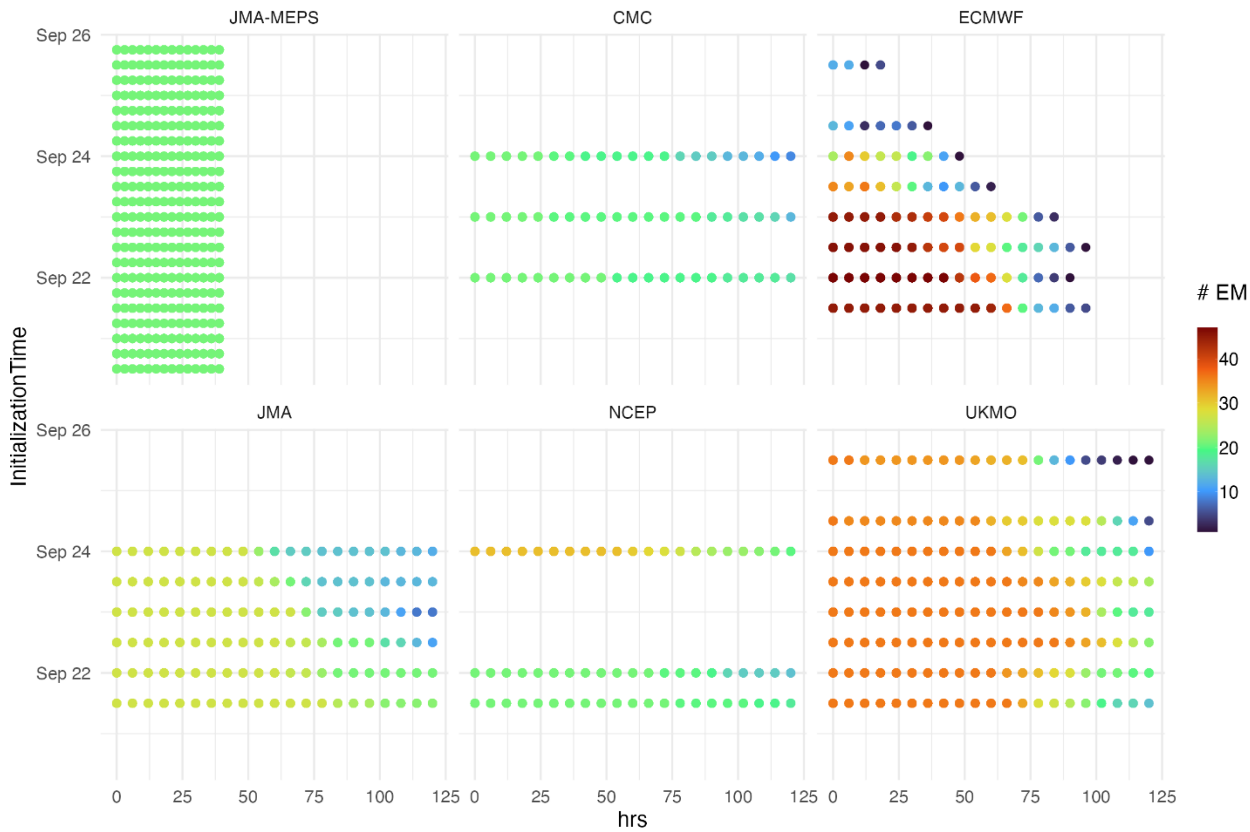
To address this concern, we will revise the manuscript in two ways. First, we will explicitly reposition MeteoScape as a complementary diagnostic rather than as a replacement for simpler clustering methods. Second, we will add an additional analysis using more spatially dispersed ensemble-track datasets and will discuss more explicitly the conditions under which the inferred landscape appears clear versus ambiguous. This revision will help us better delimit the range of situations for which the current framework is informative.

We have used tracks extracted from different TIGGE ensemble prediction systems (CMC, ECMWF, JMA, NCEP and UKMO), where there is more dispersion across the map than the data used in the submitted manuscript, to test the ability of MeteoScape to capture the landscape of TC “Dolphin” (see figure below).



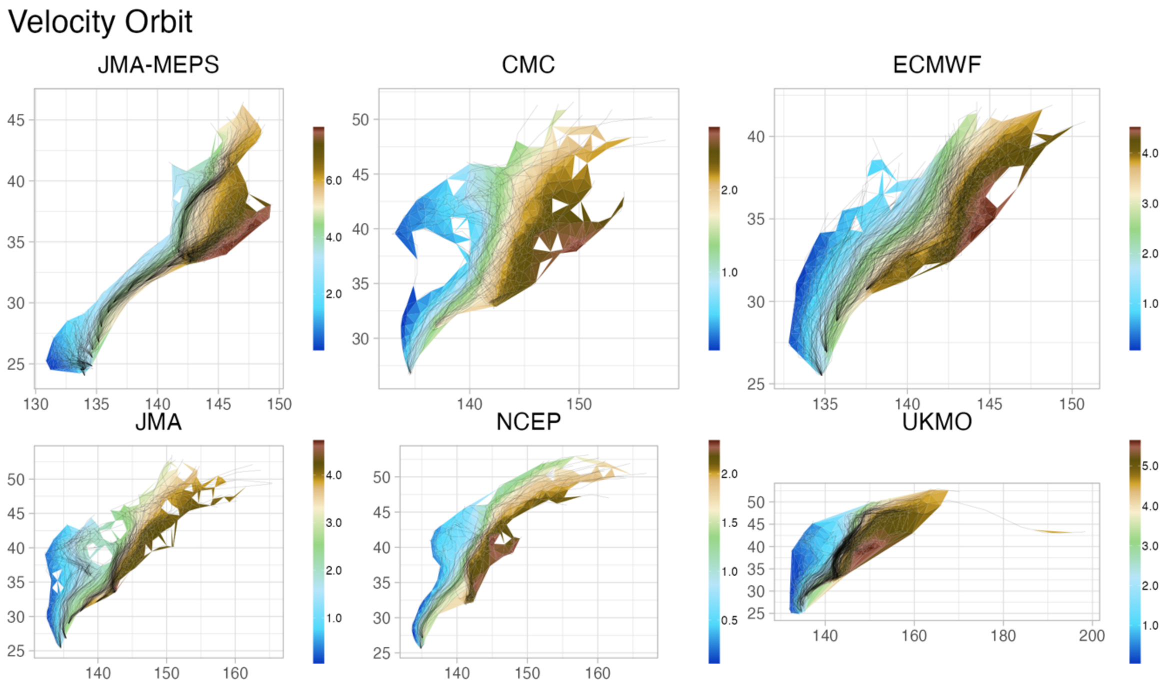
Tracks of TC “Dolphin” predicted by 6 different ensemble prediction systems. From top-left to bottom-right: JMA-MEPS, CMC, ECMWF, JMA, NCEP and UKMO.

JMA-MEPS is up to +39-h forecast, initialized every 6 hours (0000, 0600, 1200 and 1800 UTC), with 21 ensemble members. TIGGE EPS are up to +120-h and with different initialization time and various numbers of ensemble members (figure below).



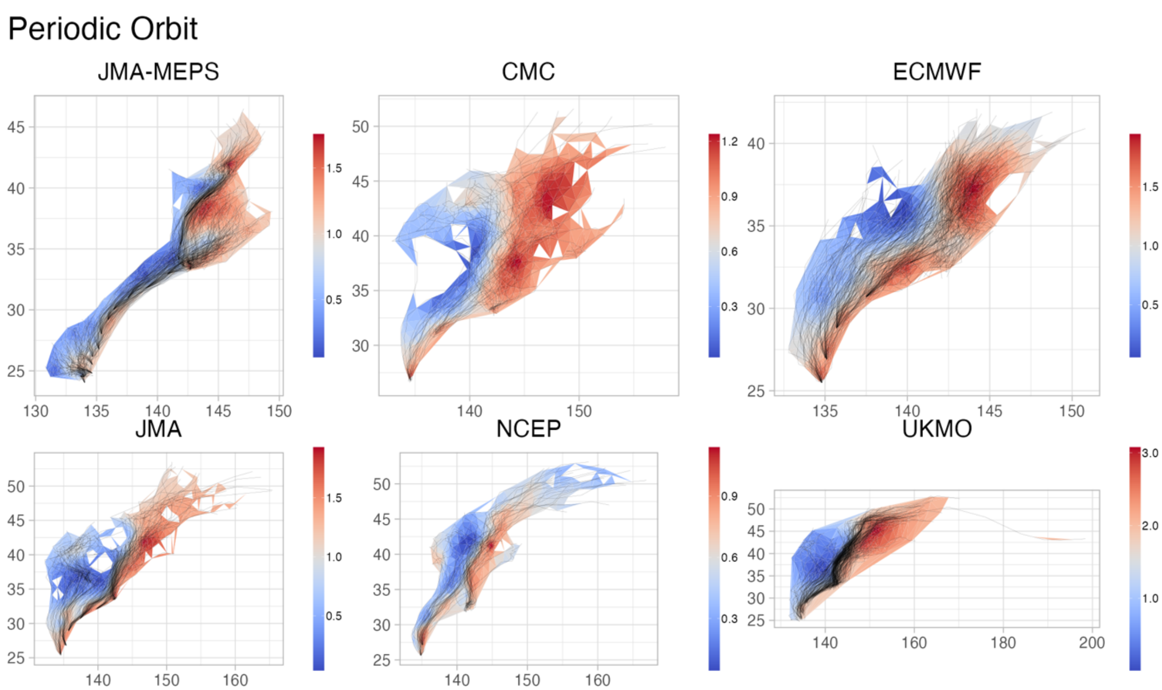
Initialization time (y-axis), forecast horizon in hours since initialization (x-axis) and number of ensemble members by EPS system (color).

We are using the default parameters of MeteoScape to calculate the graph on different cases and decompose it.



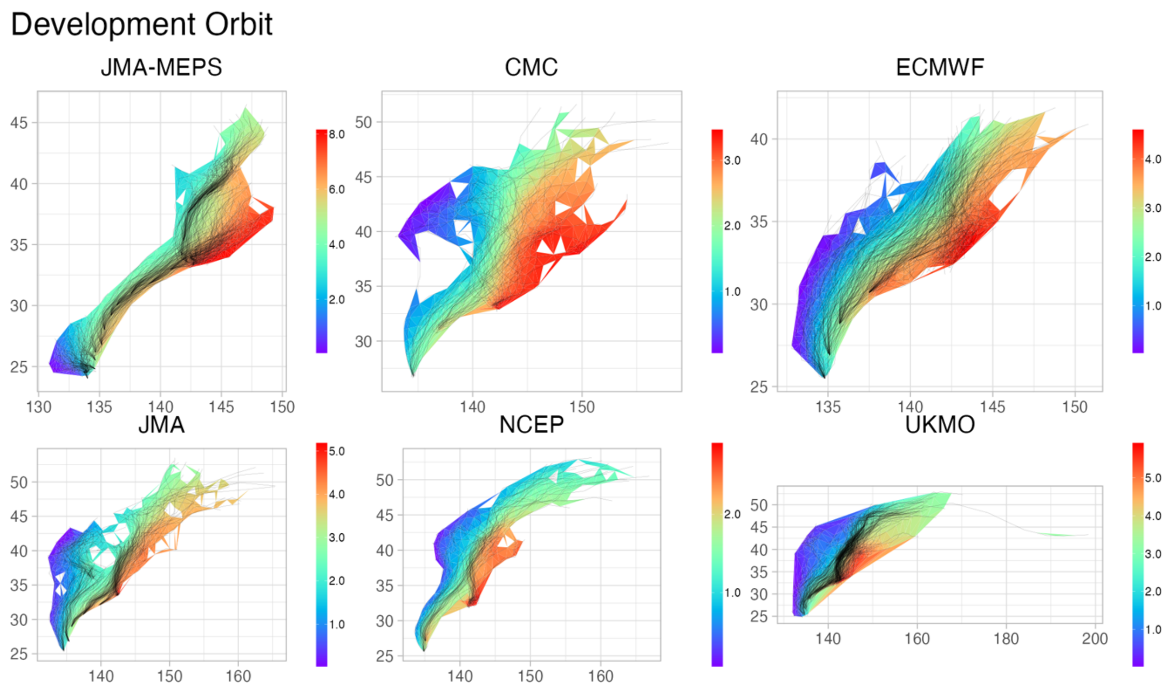
Velocity orbit and TC "Dolphin" tracks for 6 different ensemble prediction systems.

MeteoScape can manage irregular trajectories, spatially non-continuous data. The global shape is similar among systems, but values are quite different (lowest in CMC, highest in JMA-MEPS).



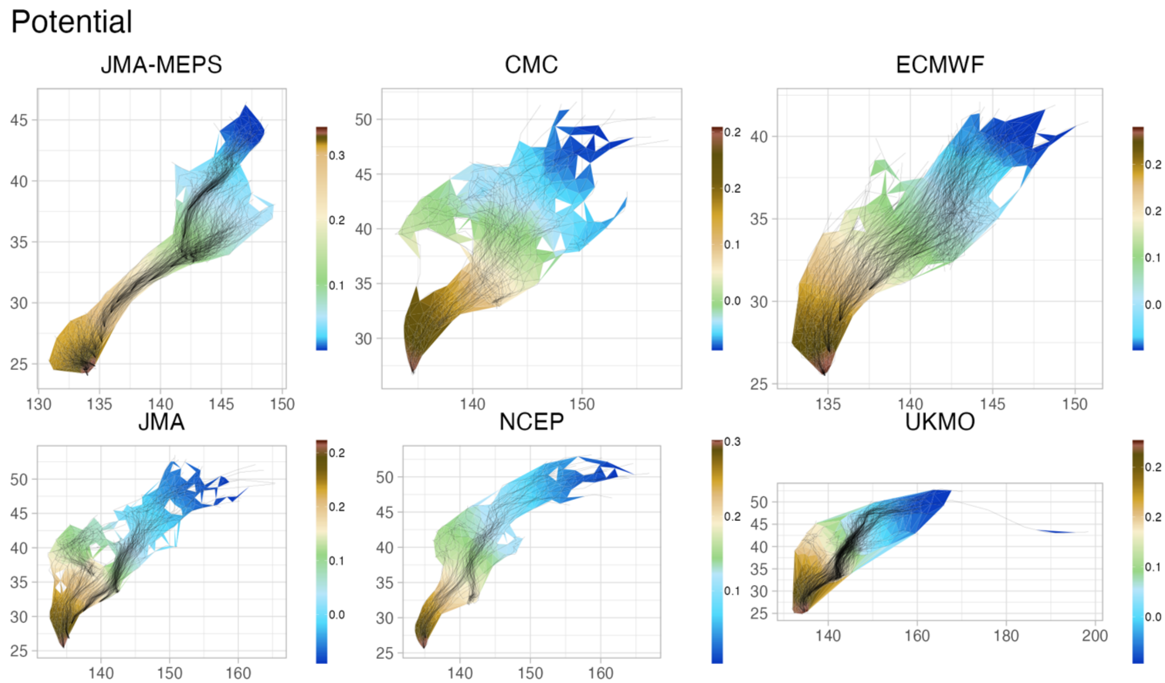
Periodic orbit and TC "Dolphin" tracks for 6 different ensemble prediction systems.

There are some regional and local orbits, where tracks are curving locally and regionally. Again, values vary among EPS.



Development orbit and TC "Dolphin" tracks for 6 different ensemble prediction systems.

Tracks are located along the isolines. We will investigate the relation with the (mean) upper atmosphere steering winds. The intensity of the development orbit is higher in JMA-MEPS and lower in NCEP.



Potential and TC "Dolphin" tracks for 6 different ensemble prediction systems.

It is clear from the potential that we find the same landscape with higher potential to the southwest and lower potential to the northeast. However, the JMA-MEPS case is some kind of ideal case (higher temporal sampling), with the regional bifurcation and separation explore in the submitted manuscript. Such signal is not that clear for the different TIGGE EPS.

> The "Naparka" case in this study demonstrates some evidence of this issue—there are considerable track points going eastward but are awkwardly classified as "Westward."

Thank you for pointing out this inconsistency. We agree that the labeling in the Napartak case was not sufficiently objective and may be misleading in its current form. In the revised manuscript, we will re-examine the cluster assignment and revise both the terminology and the corresponding figure/text description so that the labeling is based on an explicit and reproducible criterion. Where appropriate, we will replace direction-based labels with more neutral labels to avoid overinterpretation.

> I understand that the authors want to promote a deeper understanding of TC evolution using biological concepts. It is a creative approach, to be sure. However, there are several obvious caveats that call into question the suitability of using these concepts on TC evolution. First, projected TC tracks reflect only a small portion of the evolution of TCs. TC evolution involves motion, intensification/weakening, and structural changes. The latter two aspects depend

> heavily on the physics of TCs and the underlying environment, and they are not discussed in the study. TC motions, the focus of this study, are mostly controlled by upper-level steering winds/flows. Therefore, rather than viewing the ensemble forecast track points and the projected translation speed as the primary factors governing TC motion, a deeper and more direct physical connection can be established between the upper-level steering flow (streamlines) in observations and forecasts and future TC movement. For example, the "saddle points" observed in some irregular TC tracks are typically caused by saddle fields in atmospheric pressure/geopotential fields. A challenge in the modeling world is determining the fate of TCs that fall into these saddle fields, as well as how the large-scale atmospheric flow interacts with the intensity and structural changes in TCs.

We agree that the current manuscript treated forecast trajectories too abstractly and did not sufficiently connect them to the physical controls of TC motion. In the revised manuscript, we will narrow the scope to the geometry of TC-track ensembles, explicitly state that intensity and structural evolution are outside the scope of the present framework, and add a new subsection that compares MeteoScape diagnostics with environmental steering flow and large-scale pressure/geopotential patterns. We will also add a limitations paragraph clarifying that the potential and rotational components in MeteoScape are mathematical quantities defined on the trajectory graph and should not be interpreted as direct decompositions of the atmospheric flow.

> I agree with Referee #1 that the authors should consider collaborating with tropical cyclone experts to develop a stronger foundation of the atmospheric science component. While I see the potential in bridging these novel concepts to the field of meteorology and TCs, the current manuscript does not demonstrate sufficient quality in establishing the connection.

We agree that the atmospheric-science component requires substantial strengthening. In the revised manuscript, we will address this by expanding the TC literature context, revising the physical interpretation, and tempering the claims throughout the paper so that the contribution is presented more realistically.