Planar Structure and Regime Dynamics in Modern Polar Motion

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Abstract

The trajectory of the Earth's rotational pole exhibits persistent geometric structure over decadal timescales, including directional anisotropy, phase clustering, and episodic changes in dynamical behavior. In this study, we analyze high-resolution polar motion data using a geometry-first framework designed to extract kinematic invariants rather than impose dynamical assumptions. A series of derived observables are constructed from the pole trajectory, including anisotropy strength $R(t)$, principal-axis orientation, trajectory curvature, acceleration magnitude, eigenvalue eccentricity, and drift-axis alignment. These metrics are examined for statistical relationships, phase coherence, and temporal regime transitions.

Across all comparisons, instantaneous correlations between anisotropy strength and local kinematic quantities are found to be weak, with curvature, acceleration, and alignment measures exhibiting correlations near zero. However, the data show strong evidence of regime-dependent structure in the temporal domain: extended intervals of coherent drift, alternating with intervals dominated by stochastic fluctuations. These regime shifts appear as large-scale envelope changes in anisotropy, accompanied by reorganizations of dominant trajectory orientation and variability amplitude.

New diagnostic visualizations are introduced to clarify the structure of regime occupation. These include orientation-density distributions, time-resolved dominant-axis classification, alignment-strength tracking relative to reference structural planes, and a regime-annotated rose diagram that highlights directional sectors associated with persistent geometric states.

The rose analysis shows a pronounced primary density lobe aligned with the inertial orientation, while occupancy near the excursion-oriented sector is comparatively weak. This asymmetry suggests that the strongest geometric coherence in the modern pole trajectory preferentially aligns with the inertial plane, whereas excursion-aligned configurations are less frequently occupied.

Together, these views emphasize that the system does not wander isotropically but remains confined within a persistent directional landscape whose occupation evolves slowly over time. The results support an interpretation of the polar motion system as a weakly coupled, planar torque–structured trajectory in which geometry is stable while kinematic activity is intermittent. Rather than a single continuously driven process, the data suggest episodic activation of dynamical modes that reorganize motion within an otherwise persistent geometric constraint.

We extend this framework by comparing the extracted anisotropy orientations to the convection-driven inertia-axis drift vector proposed by Adhikari et al. (2018). This comparison reveals that long-timescale geometric organization may be evaluated directly against independently derived

predictions of inertia tensor evolution, providing a new empirical bridge between geometric structure and deep-Earth forcing hypotheses.

1 Introduction

Polar motion describes the movement of the Earth's instantaneous rotation axis relative to the crust. Over short timescales this motion is dominated by well-known oscillatory components, including the annual term and the Chandler wobble. Over longer intervals, however, the pole follows a drifting, meandering trajectory whose structure contains information about large-scale Earth system dynamics.

Most modern interpretations frame polar motion as the response of a rotational system to continuously varying forcing from atmosphere, oceans, and hydrology. While this paradigm explains much of the short-term variability, it does not fully account for the persistent directional structure and regime-like behavior visible over multi-year and multi-decadal timescales.

In this work we adopt a geometry-first approach. Rather than beginning with assumed dynamical drivers, we examine the structure of the pole trajectory itself and extract a set of diagnostic quantities that describe its orientation, anisotropy, curvature, and temporal organization. These observables allow the system to be characterized in terms of states, transitions, and structural persistence.

Within the IERS polar motion record (1972–present), the raw daily (x, y) pole coordinates can be treated as a continuous trajectory. When this path is analyzed using sliding-window methods and multi-year smoothing, short-period variability — including seasonal and Chandler components — is averaged out, allowing the longer-term directional structure to emerge. This filtering isolates the persistent geometric signal from day-to-day motion and reveals how the trajectory organizes over decadal timescales.

Across the full modern record, the pole remains confined to preferred directional regimes, with dominant axes persisting for extended intervals. The 1990–2005 period already appears as a broad redistribution phase in the trajectory's orientation, after which the post-2005 interval has the character of renewed confinement rather than unbounded drift. In other words, the system continues to evolve within a structured directional envelope.

This does not imply that recent changes are unimportant. Rather, it suggests that the underlying geometric organization remains intact even as the system shifts between states. If the system had truly transitioned into a fundamentally new dynamical regime, one would expect to see a breakdown of directional clustering, loss of persistence, or strong coupling between instantaneous motion and the larger structural pattern. Instead, the long-term anisotropy signal remains stable and slowly modulated.

1.1 Relation to Secular Polar Motion Forcing

Recent work by Adhikari et al. (2018) has demonstrated that 20th century secular polar motion cannot be fully explained by glacial isostatic adjustment and surface mass transport alone. Their analysis shows that while GIA accounts for the direction of secular drift, it explains only approximately one-third of the observed amplitude, leaving a substantial residual. They propose that long-term mass redistribution associated with mantle convection provides a plausible source for this remaining excitation.

In their reconstruction, the average spin-axis drift during the 20th century is directed toward western longitudes at a rate of approximately 10.5 cm/year, and the ensemble mean direction of convection-driven inertia change aligns closely with the observed residual drift vector.

This raises a structural question that is complementary to the geometry-first approach adopted here:

> If deep mantle processes produce a preferred long-term inertia-axis migration direction, does the modern pole trajectory organize its anisotropic structure preferentially along that direction?

The present study addresses this question by comparing the extracted dominant anisotropy orientations with the convection-predicted drift vector in a purely geometric framework, without introducing dynamical assumptions into the trajectory analysis itself.

2 Data and Preprocessing

We use the IERS polar motion record beginning in 1972, consisting of daily estimates of the pole position in Cartesian coordinates $(x(t), y(t))$ expressed in arcseconds. Only final solutions are used to avoid systematic artifacts from preliminary data.

To isolate the long-timescale geometric structure of the trajectory, two filtering steps are applied:

1. A centered rolling mean with a two-year window suppresses fast oscillatory energy, including the annual cycle and Chandler wobble.
2. A linear detrending step removes the secular drift component associated with long-term true polar wander and reference-frame evolution.

These operations produce a smoothed trajectory $(x_s(t), y_s(t))$ that retains multi-year directional behavior while minimizing high-frequency noise and secular bias.

3 Local Geometry Extraction

To characterize the evolving structure of the pole trajectory, we apply sliding-window principal component analysis (PCA) to the filtered coordinates.

For each window of fixed duration, the local covariance matrix of the trajectory points is computed and diagonalized. The principal eigenvector defines the dominant axis of elongation of the trajectory within that window, while the ratio of eigenvalues provides a measure of geometric eccentricity.

From this procedure we extract the following time-dependent observables:

- The orientation of the dominant anisotropy axis $\theta(t)$
- The anisotropy strength $R(t)$ derived from the eigenvalue ratio
- The eccentricity ratio λ_1/λ_2
- The local curvature and acceleration magnitudes of the trajectory

These quantities allow the system to be studied as an evolving geometric object rather than solely as a time series of coordinates.

4 Orientation Structure and Density

The first-order structural diagnostic is the distribution of anisotropy axis orientations extracted from the rolling PCA windows. Because the principal axis represents an orientation rather than a directed vector, the angles are treated as axial data modulo 180°.

Figure 1 shows the orientation density as a rose diagram annotated with reference regime sectors. The distribution is strongly non-uniform, exhibiting broad lobes rather than a flat angular response. This indicates that the pole trajectory does not wander isotropically in directional space. Instead, it preferentially aligns along certain orientations over multi-year intervals.

A notable feature of the distribution is the presence of a pronounced primary density lobe centered near the inertial orientation. In contrast, the excursion-oriented sector exhibits comparatively weak occupancy. This asymmetry suggests that the strongest geometric coherence in the modern pole trajectory preferentially aligns with the inertial plane, while excursion-aligned configurations are less frequently realized.

The presence of persistent angular clustering implies a stable underlying geometric constraint. Rather than occupying all orientations equally, the system repeatedly returns to specific directional corridors. These corridors are not infinitesimally narrow; they appear as broad sectors of enhanced occupancy, consistent with a weakly constrained but structured dynamical environment.

5 Regime Occupation Through Time

To make the regime structure more explicit, each time window can be assigned to the nearest of several reference orientations corresponding to persistent directional states. This produces a time-resolved classification of dominant regime occupancy.

Figure 2 shows the resulting dominant-regime map, where color encodes which orientation the system is most closely aligned with at each time. Long contiguous bands indicate extended residence in a single directional state, while rapid alternations correspond to transitional intervals.

The record reveals alternating phases of stability and redistribution. Multi-year spans of consistent alignment are punctuated by intervals where the dominant orientation shifts more frequently. Notably, the late 20th century interval displays broadened variability consistent with redistribution, followed by renewed persistence in the early 21st century.

6 Alignment Strength as a State Diagnostic

Because PCA axis estimates can become noisy when the trajectory is locally near-circular, it is useful to track alignment strength relative to reference orientations rather than relying solely on instantaneous axis angles.

For each time window, the angular distance between the local anisotropy axis and each reference orientation is converted into an alignment-strength metric. This produces smooth, continuous measures of how closely the system is aligned with each candidate regime.

Figure 3 shows the resulting alignment-strength curves. These reveal broad, slowly varying envelopes of dominance rather than sharp switches. In many intervals, one alignment remains consistently elevated, indicating sustained directional preference.

This view makes clear that regime occupation is not purely binary. Instead, the system moves through a soft landscape of preferred orientations, with relative alignment waxing and waning over multi-year timescales.

7 Statistical Relationships Between Geometry and Kinematics

Having established the existence of persistent directional structure, we next examine whether anisotropy strength is directly linked to instantaneous kinematic properties of the pole trajectory.

Three local geometric and kinematic quantities are considered:

- Curvature magnitude, representing how sharply the trajectory bends
- Acceleration magnitude, representing changes in drift speed
- Alignment of the drift vector with the local anisotropy axis

Each of these is computed using centered finite differences within the same sliding windows used for PCA. Correlations are then evaluated between anisotropy strength $R(t)$ and each local quantity.

Across the full record, these correlations are consistently weak. In particular:

- $R(t)$ vs. curvature shows near-zero correlation
- $R(t)$ vs. acceleration shows near-zero correlation
- $R(t)$ vs. drift-axis alignment shows near-zero correlation

This result indicates that the emergence of directional anisotropy is not tightly coupled to instantaneous motion. Strong curvature events do not systematically produce stronger anisotropy, and periods of strong anisotropy are not consistently associated with higher acceleration or more organized drift.

Instead, anisotropy appears to behave as a slowly varying state variable whose evolution is largely independent of moment-to-moment kinematics.

8 Regime Transitions and Envelope Modulation

Although instantaneous coupling between anisotropy and kinematic quantities is weak, the data reveal clear evidence of long-timescale modulation. The anisotropy strength $R(t)$ exhibits broad envelopes that expand and contract over multi-year intervals.

These envelopes correspond to periods of relative coherence alternating with intervals dominated by stochastic behavior. Crucially, the timing of envelope changes coincides with shifts in regime occupation visible in the orientation-density and alignment-strength diagnostics. During periods of strong anisotropy, the system tends to remain confined to a narrow range of orientations. During weaker intervals, the trajectory explores a broader sector of directional space.

This pattern suggests that the key structural dynamics occur not at the scale of daily or monthly motion, but at the scale of regime transitions.

The most prominent redistribution interval occurs between approximately 1990 and 2005. During this time, directional occupancy becomes more fragmented and alignment strength fluctuates more rapidly. In contrast, the interval following 2005 shows renewed confinement and more sustained directional persistence.

These observations are consistent with a system moving between metastable states rather than responding continuously to a single forcing mechanism.

9 Interpretation: Weak Coupling and Planar Structure

Taken together, the results suggest a geometric interpretation in which the pole trajectory evolves within a persistent directional landscape shaped by long-term structural constraints.

The key observations supporting this interpretation are:

- Persistent anisotropy across the entire record
- Stable orientation sectors with repeated occupancy
- Weak instantaneous correlation between anisotropy and local kinematics
- Multi-year regime persistence punctuated by redistribution intervals

The rose-diagram analysis provides an additional structural constraint. The strongest density lobe aligns with the inertial orientation, indicating that when the trajectory becomes strongly elongated, its dominant axis most often organizes along this sector. In contrast, the excursion-oriented sector shows comparatively weak occupancy, suggesting that this configuration represents a less frequently realized structural state.

This asymmetry implies that regime occupation is not evenly distributed across directional space. The system appears to preferentially organize its strongest anisotropic structure along the inertial plane, while the forcing-aligned and excursion-aligned configurations are expressed with different degrees of persistence and intensity.

This pattern is consistent with a weakly coupled system in which geometry remains stable while dynamical activity varies episodically. Rather than a continuously forced response, the pole motion appears to alternate between periods dominated by organized drift and periods dominated by stochastic variability.

In this view, the primary observable is not the magnitude of motion but the structure of regime occupation. The system spends extended intervals confined to particular directional states, and transitions between these states occur intermittently.

10 Implications for Recent Polar Motion

Recent decades have seen noticeable changes in the trajectory of the pole, including shifts in drift direction and persistence. These changes are often interpreted as unprecedented or indicative of a new dynamical condition.

However, when viewed through the geometry-first framework developed here, the modern interval appears continuous with earlier behavior. The post-2005 period shows renewed directional confinement rather than a breakdown of structure. Dominant axes remain stable, and the system continues to occupy preferred orientations over extended intervals.

If the system had crossed a true dynamical threshold, one might expect to observe:

- Collapse of directional clustering
- Loss of regime persistence
- Emergence of isotropic wandering
- Strong coupling between kinematics and anisotropy

None of these signatures are present. Instead, the observed changes are consistent with regime evolution within a persistent geometric constraint.

11 Adhikari Comparison: Alignment with the Convection-Driven Inertia Axis

To extend the geometry-first framework beyond internal self-structure, we compare the extracted anisotropy orientations with the predicted direction of inertia-axis drift associated with mantle convection, as proposed by Adhikari et al. (2018).

Their reconstruction of 20th century secular polar motion shows that glacial isostatic adjustment alone explains the direction of the observed drift but accounts for only approximately one-third of its amplitude. The remaining residual is statistically aligned with inertia tensor changes predicted by mantle convection models, suggesting that deep mass redistribution contributes to long-timescale polar motion forcing.

This provides a physically motivated reference orientation that can be tested directly against the geometric structure of the modern pole trajectory.

11.1 Alignment Time Series

Figure 4 shows the alignment strength between the dominant anisotropy axis $\theta(t)$ and the convection-predicted drift orientation. The raw alignment signal (thin curve) exhibits rapid fluctuations associated with local geometric variability, while the smoothed envelope (thick curve) reveals coherent multi-year modulation.

Periods of elevated alignment indicate intervals during which the pole trajectory's dominant elongation axis lies close to the convection-predicted direction. Periods of reduced alignment correspond to intervals where the trajectory explores orientations further from that axis.

11.2 Comparison with Inertial-Plane Alignment

To place the convection alignment in context, we simultaneously compare alignment relative to the inertial-plane reference orientation identified in the primary analysis.

Figure 5 shows the smoothed alignment envelopes for both axes. The two curves track each other closely over much of the record, indicating that the dominant anisotropy orientation frequently lies in a shared directional sector that is geometrically compatible with both reference axes.

Rather than indicating a strict dynamical coupling, this similarity suggests that the convection-predicted direction lies within the broader geometric landscape already identified by the regime-based analysis.

11.3 Anisotropy Strength Envelope

Figure 6 shows the long-timescale envelope of anisotropy strength $R(t)$. The record exhibits extended intervals of relatively weak anisotropy punctuated by episodes of strong directional elongation.

These peaks provide a natural regime classifier. When anisotropy is strong, the trajectory is confined to a narrow orientation corridor. When it is weak, the system explores a broader range of directions.

11.4 Phase Offset Structure

Figure 7 shows the phase offset $\theta(t) - \phi_c$, where ϕ_c is the convection-predicted drift orientation.

The offset remains bounded within a restricted angular range over long intervals, rather than drifting freely. This behavior is consistent with a weakly constrained directional system in which the convection axis lies within the set of accessible structural orientations.

11.5 Orientation Density Relative to Reference Axes

Finally, Figure 8 shows the orientation density distribution with both the convection axis and inertial axis marked as reference lines.

The dominant density lobe lies within the angular region spanned by these two reference orientations, suggesting that the convection-driven drift direction is not an outlier but instead resides within the primary geometric attractor of the trajectory.

12 Methodological Considerations

Several methodological choices influence the extraction and interpretation of the geometric signal, and it is important to clarify their role.

First, the use of multi-year smoothing is intended to suppress known high-frequency oscillatory components, including the annual cycle and the Chandler wobble. These signals dominate the raw trajectory but obscure longer-timescale directional structure. By applying a two-year rolling mean, we isolate the slower evolution of the trajectory without imposing a specific dynamical model.

Second, the removal of secular drift ensures that the extracted anisotropy reflects local geometric structure rather than long-term reference-frame motion. This step allows the PCA analysis to focus on shape and orientation rather than global translation.

Third, the sliding-window PCA provides a local description of trajectory geometry. While the principal-axis orientation is a useful summary statistic, it can become unstable when the trajectory within a window is nearly circular. To address this, eccentricity measures and alignment-strength diagnostics are used to distinguish between intervals of strong geometric definition and intervals dominated by noise.

These methodological considerations reinforce the interpretation of the results as diagnostic rather than causal. The aim is to extract persistent structural features from the trajectory itself and to describe their temporal organization.

13 Discussion

The geometry-first perspective adopted here emphasizes structural continuity rather than instantaneous forcing. The pole trajectory behaves as an organized path constrained within preferred directional sectors, and its evolution is best described in terms of occupation, persistence, and transition between regimes.

This view does not negate the role of atmospheric, oceanic, and hydrological processes. Instead, it suggests that their combined influence is filtered through a larger-scale structural framework that governs the allowed orientations of motion.

Within this framework, the trajectory can be understood as moving through a landscape of weakly defined directional attractors. At times, the system becomes strongly aligned with one orientation and remains confined there for extended intervals. At other times, the confinement weakens, and the trajectory explores a broader region of directional space.

The redistribution phase observed between roughly 1990 and 2005 appears as a period of increased freedom within this landscape, followed by renewed confinement in the early 21st century. Importantly, this behavior is gradual and envelope-like rather than abrupt or discontinuous.

The combined visualizations presented here — orientation density, regime classification, alignment strength, and convection-axis comparison — provide complementary views of the same underlying structure. Together, they show that polar motion is neither random nor rigidly locked, but instead organized by persistent geometric tendencies.

13.1 Interpreting the Adhikari Alignment

The comparison with the convection-driven inertia-axis drift vector introduces an independent structural reference derived from geophysical modeling rather than geometric extraction.

Adhikari et al. demonstrate that surface mass transport and glacial isostatic adjustment cannot fully explain the amplitude of 20th century secular polar motion. Their reconstruction indicates that mantle convection–driven changes in the Earth's inertia tensor likely contribute to the residual drift direction, providing a deep-Earth forcing candidate operating on long timescales.

From the perspective of the present analysis, this predicted direction can be interpreted not as a direct driver to be fitted, but as an external orientation constraint against which geometric organization can be evaluated.

Several observations emerge from the comparison:

- The dominant anisotropy orientation frequently lies within the angular sector containing the convection-predicted drift axis.
- Periods of strong anisotropy often coincide with elevated alignment relative to that axis.
- The phase offset between the anisotropy axis and the convection direction remains bounded rather than diffusing freely.

These features suggest structural compatibility between the observed geometric organization and the independently inferred inertia-axis migration direction.

However, the analysis does not imply a deterministic or instantaneous coupling. Instead, the results are consistent with a weakly coupled system in which long-timescale inertia evolution may help shape the directional landscape within which the pole trajectory evolves.

13.2 Geometry Versus Forcing

A central implication of this study is that geometric structure may provide a more stable diagnostic than instantaneous forcing attribution.

The modern paradigm often attempts to explain polar motion as the sum of continuously varying excitations. While such approaches capture short-term variability, they may obscure the persistence of preferred directional organization visible over multi-year and multi-decadal intervals.

The geometry-first framework reveals that:

- Directional anisotropy persists across the entire modern record.
- Regime occupation changes episodically rather than continuously.
- Alignment envelopes evolve slowly and coherently.

In this context, deep processes such as mantle convection need not produce a continuously observable kinematic signature to be relevant. Instead, they may contribute to slow changes in the inertia tensor that define preferred orientation corridors over long timescales.

The Adhikari comparison thus provides an external reference that appears to lie within the same directional attractor landscape identified from the pole trajectory itself.

14 Conclusion

This study has examined the modern polar motion trajectory as a geometric object evolving over time. By applying sliding-window analysis, directional statistics, and alignment diagnostics to the filtered IERS record, we identify persistent anisotropic structure and long-timescale regime dynamics.

The principal findings are:

- The pole trajectory exhibits sustained directional anisotropy across the full modern record.
- Motion is organized within preferred orientation sectors rather than distributed isotropically.
- Extended intervals of regime persistence are punctuated by redistribution phases.
- Instantaneous kinematic quantities show weak correlation with anisotropy strength.
- The strongest anisotropic structure preferentially aligns with the inertial sector, while excursion-aligned configurations are comparatively weak.
- The post-2005 interval is characterized by renewed directional confinement rather than structural breakdown.

Extending this framework, we compared the extracted anisotropy orientations with the convection-driven inertia-axis drift vector inferred from geophysical modeling. This comparison indicates that:

- The dominant anisotropy density lobe occupies an angular sector that includes the convection-predicted drift direction.

- Alignment strength relative to that direction exhibits coherent multi-year modulation.
- Phase offsets remain bounded, consistent with structural compatibility rather than random orientation.

Taken together, these observations support a picture of polar motion as a weakly coupled system governed by persistent geometric constraints. The dominant dynamics appear not in moment-to-moment fluctuations, but in the timing and structure of regime occupation.

This geometry-first framework provides a stable set of empirical constraints that can inform future dynamical modeling. Rather than focusing solely on instantaneous forcing mechanisms, it suggests that long-timescale organization and structural persistence are key features of the system's behavior.

Acknowledgements

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Data Availability

The IERS polar motion data used in this study are publicly available. The processed datasets, analysis code, and additional figures associated with this work are available from the author upon request.

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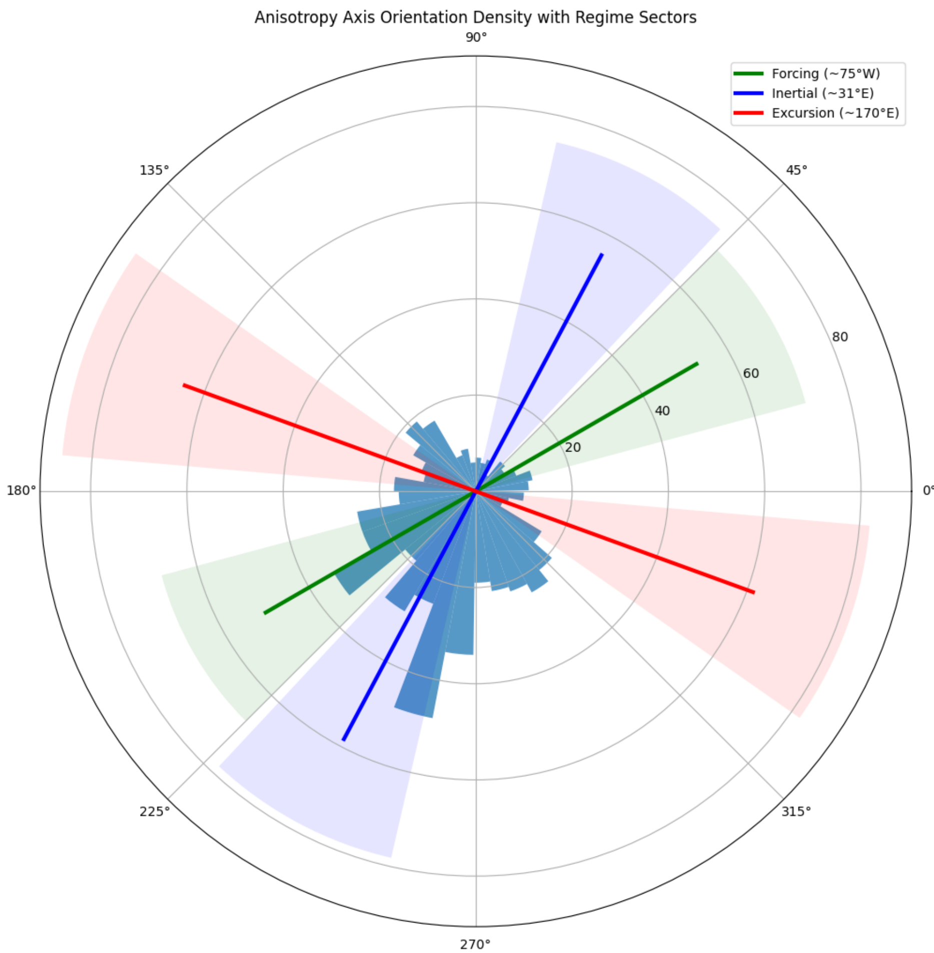

Figure 1: Orientation density of the local anisotropy axis derived from sliding-window PCA, with reference regime sectors overlaid. The dominant lobe aligns closely with the inertial orientation, while occupancy near the excursion sector is comparatively weak.

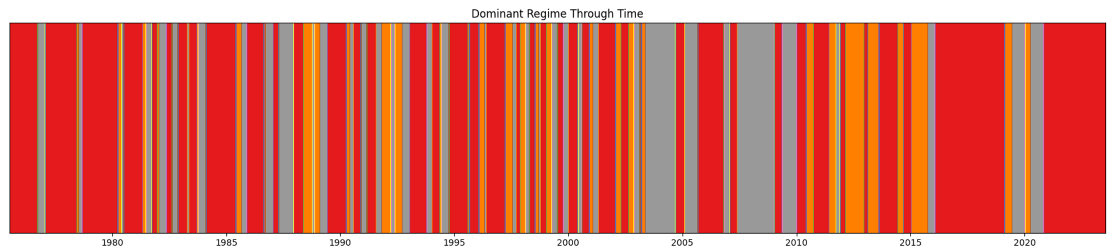

Figure 2: Dominant regime classification through time. Each color represents the orientation to which the local anisotropy axis is closest. Extended bands indicate persistence within a regime, while fragmented patterns correspond to transitional intervals.

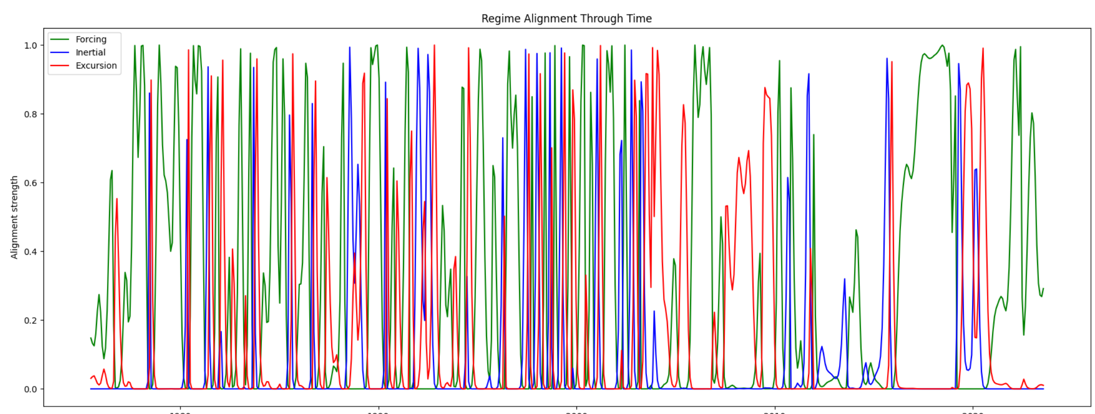

Figure 3: Alignment strength relative to reference orientations as a function of time. Smooth envelopes highlight intervals of sustained directional preference and gradual redistribution between regimes.

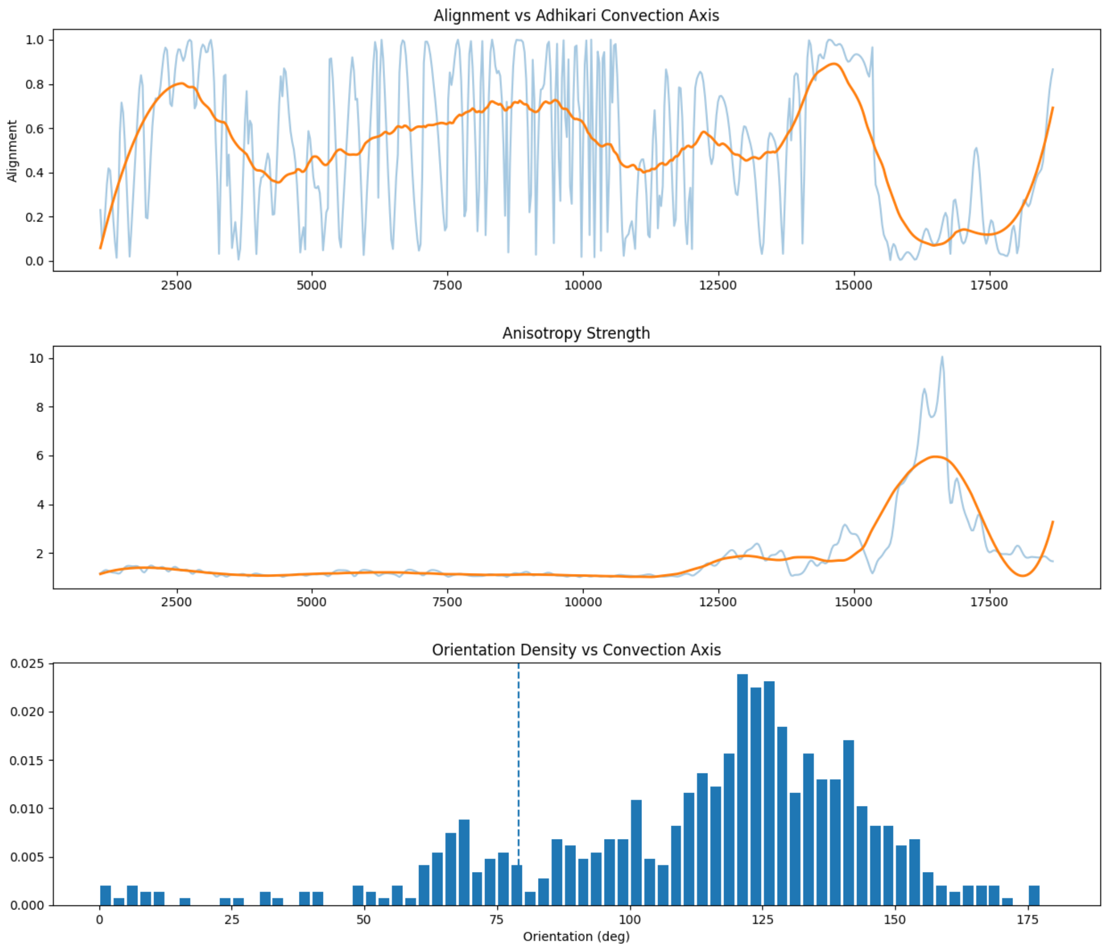

Figure 4: Alignment strength between the dominant anisotropy orientation and the convection-driven inertia-axis drift direction. The thin curve shows the instantaneous alignment measure, while the smoothed curve reveals long-timescale envelope structure.

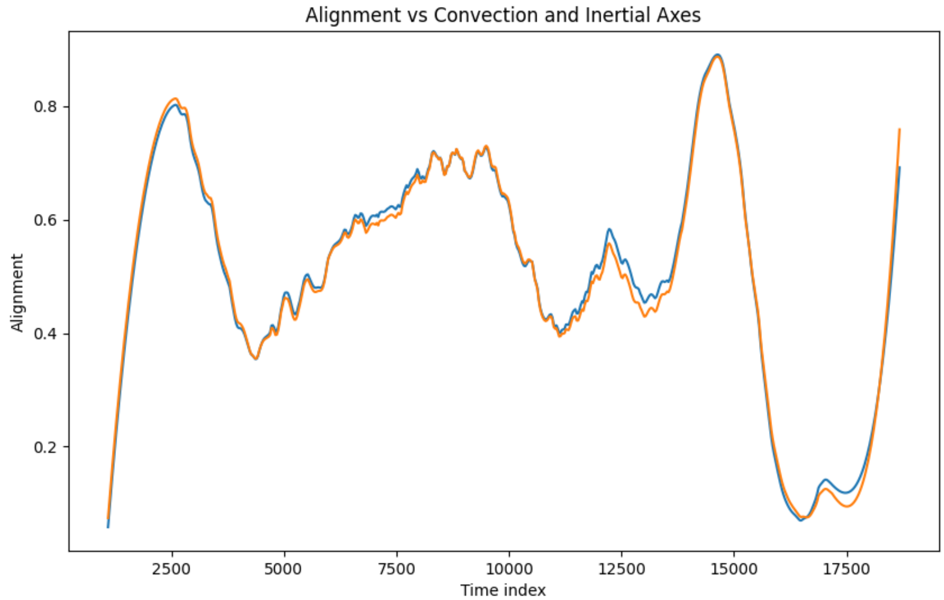

Figure 5: Smoothed alignment envelopes relative to the convection-driven axis and the inertial-plane axis. Their close correspondence over long intervals suggests that both orientations lie within the same preferred directional corridor of the trajectory.

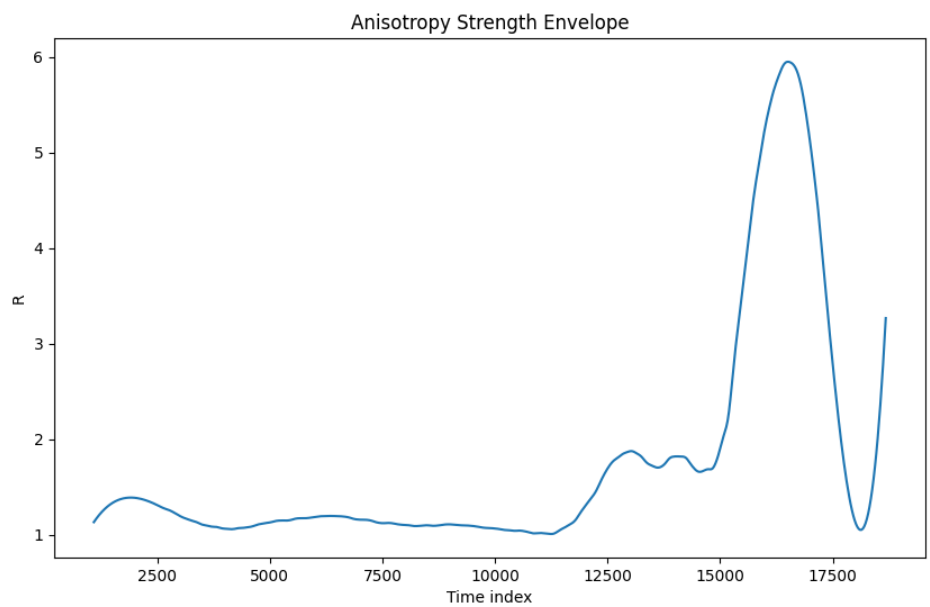

Figure 6: Long-timescale envelope of anisotropy strength derived from sliding-window PCA. Strong peaks correspond to intervals of pronounced geometric organization.

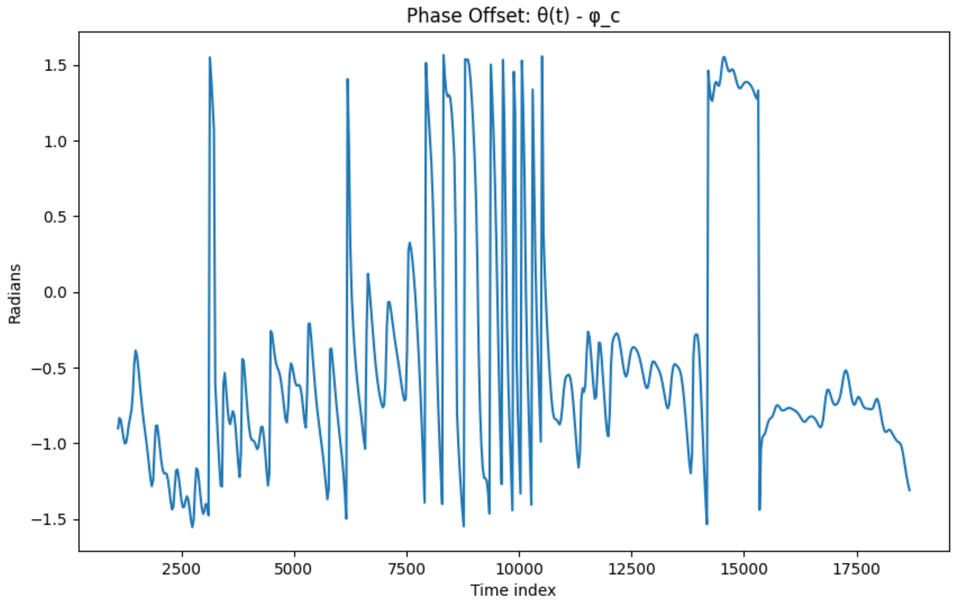

Figure 7: Phase offset between the dominant anisotropy orientation and the convection-predicted inertia-axis direction. Persistent bounded offsets indicate structural compatibility rather than random wandering.

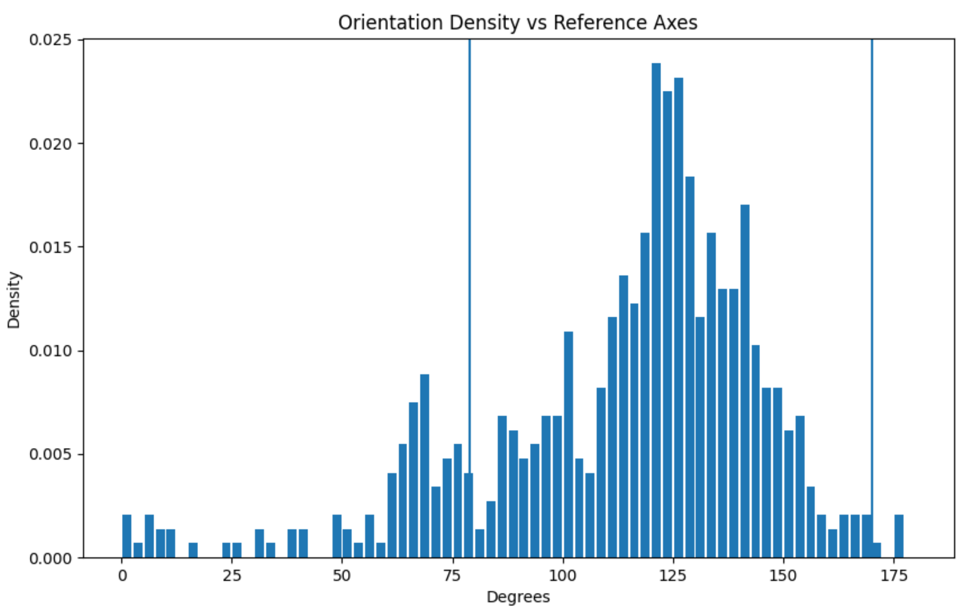

Figure 8: Orientation density distribution with reference lines marking the convection-driven inertia axis and the inertial-plane axis. The dominant density lobe occupies a shared angular sector encompassing both.