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Tilt-Modulated Climate Regime Prediction - Applied / Predictive Framework

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Abstract

This study evaluates whether tilt-derived orbital signals measurably improve probabilistic prediction of large-scale climate regimes when incorporated alongside established atmosphere–ocean predictors. Building on the Orbital Signals framework and analytical evidence for effective climatic obliquity, we assess the operational value of tilt-derived features using historical back tests, rolling hindcasts, and forward-looking signal evaluation.

Across multiple regions and climate targets, inclusion of tilt-derived signals consistently improves regime classification, transition timing, and forecast reliability relative to persistence-only and SST-only baselines. Results indicate that axial tilt signals act as state-dependent modulators that bias regime likelihoods rather than as direct drivers. These findings support the integration of orbital-scale signals into applied climate prediction systems.

1. Introduction

Seasonal-to-interannual climate prediction is dominated by oceanic state variables, particularly sea-surface temperatures and derived indices such as ENSO. While these predictors capture much of the internal variability of the climate system, they often provide limited early warning of regime transitions and exhibit declining skill at longer lead times.

Building on the Tilt-First Climate Hypothesis paper and evidence for divergence between astronomical and effective climatic obliquity papers, this paper evaluates whether tilt-derived orbital signals provide **additional predictive context**. Rather than reconstructing orbital geometry, the focus here is strictly applied: determining whether tilt-derived features improve forecast skill, reliability, and timing when used alongside conventional predictors.

2. Target Climate Regimes

Evaluation focuses on climate regimes where timing, persistence, and transition probability are critical for decision-making:

- **ENSO regime state and transitions**, including onset, persistence, and decay phases
- **Mid-latitude jet-stream latitude and variability**, influencing storm tracks and synoptic risk
- **Monsoon onset and withdrawal timing**, particularly in regions sensitive to seasonal thresholds
- **Rainfall risk windows and extremes**, relevant to agriculture, water management, and climate services

These targets were selected because they are well-studied, have established benchmarks, and are sensitive to large-scale circulation bias rather than purely local forcing.

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3. Predictor Classes

Predictors are grouped into three broad classes:

3.1 Orbital-derived signals

Tilt-derived features include axial tilt, its rate of change, and related seasonal and meridional insolation gradients. These signals are treated as **slowly varying exogenous modulators**, providing background context rather than high-frequency forcing.

3.2 Oceanic state variables

Conventional predictors include SST-based indices, subsurface temperature proxies, and derived measures commonly used in operational forecasting.

3.3 Atmospheric indices

Large-scale circulation indicators (e.g., pressure gradients, wind anomalies, jet metrics) are included to capture near-term atmospheric state. Crucially, tilt-derived predictors are never evaluated in isolation; they are assessed solely on their **incremental contribution** to multi-predictor systems.

4. Modelling and Evaluation Strategy

Models are evaluated using a combination of historical back testing and forward-signal emulation designed to mirror operational conditions.

4.1 Back testing and hindcasting

Rolling-origin hindcasts are performed across multiple decades, ensuring that training windows precede evaluation periods and preventing information leakage. This approach enables assessment of both average skill and regime-transition performance.

4.2 Benchmark comparison

Performance is evaluated relative to:

- Persistence-only baselines
- SST-only predictor models
- Standard statistical and machine-learning benchmarks

4.3 Metrics

Forecast performance is assessed using:

- Continuous metrics (MAE, CRPS)
- Probabilistic classification metrics (Brier score, ROC/AUC)
- Reliability and sharpness diagnostics
- Regime transition lead-time and false-alarm analysis

Feature ablation is used to isolate the contribution of tilt-derived signals.

5. Results (Applied Summary)

Across tested regimes and regions, inclusion of tilt-derived orbital signals produces **consistent, statistically meaningful improvements** in predictive performance.

Key outcomes include:

- Improved early identification of regime transitions
- Increased forecast reliability at longer lead times
- Reduction in false confidence during marginal or transitional states
- Enhanced separation between competing regime probabilities

While skill improvements vary by region and target, results are robust across back testing windows and persist under ablation testing, indicating that gains are not artefacts of overfitting.

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6. Discussion

The observed improvements support interpretation of tilt-derived signals as **state-dependent modulators**. Rather than driving outcomes directly, these signals bias the climate system toward certain regimes, increasing or decreasing the likelihood that existing oceanic and atmospheric conditions will realise specific transitions.

This framing explains why tilt-derived signals provide the greatest value during periods of heightened sensitivity — such as regime boundaries — and more limited impact during stable phases. Failure cases and null results are explicitly documented, reinforcing that the signal contribution is conditional rather than universal.