

Thesis Abstract

Decadal climate variability (DCV) modulates regional temperature and precipitation on multi-year to multidecadal timescales. These timescales bridge the gap between initial-value seasonal forecasting and boundary-forced century-scale projections. The skill of near-term climate prediction depends critically on how faithfully climate models represent the leading modes of DCV. It also depends on how those modes and their teleconnections respond to anthropogenic forcing. Furthermore, we must understand how much of their variability can be predicted once models are initialised from observations. This regional hydroclimate information has well-documented societal impacts. Despite this importance, the leading DCV modes have not been evaluated systematically across the current generation of models with respect to all of these dimensions simultaneously. The absolute limits of their predictability remain poorly quantified. The role of competing external forcings in setting those limits is also unclear. This thesis addresses these gaps through an integrated, end-to-end analysis of two dynamically distinct modes. These are the Pacific Decadal Oscillation (PDO) and the Tropical Atlantic SST Gradient (TAG), evaluated alongside their global precipitation teleconnections.

This work is built on the Coupled Model Intercomparison Project Phase 6 (CMIP6) multi-model ensemble (MME). It utilises the uninitialised historical and piControl simulations. It also incorporates the four Shared Socioeconomic Pathway scenarios, namely SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. For initialised predictions, the hindcasts of the Decadal Climate Prediction Project are used, including both DCP-P-A and the DCP-P-C volcanic experiments. The model output is evaluated against the Extended Reconstructed Sea Surface Temperature version 5 (ERSSTv5) and the Global Precipitation Climatology Centre (GPCC) observational references. A consistent analytical framework is applied across the thesis. Spatial structures are evaluated using Empirical Orthogonal Function and Maximum Covariance Analysis. Objective patterns are assessed via normalised Taylor diagrams. Time-frequency behaviour is examined using continuous Morlet wavelet power spectra and wavelet coherence. Intrinsic predictability is quantified through the Nonlinear Local Lyapunov Exponent (NLLE) framework. Finally, initialised skill is evaluated with a hierarchy of deterministic and probabilistic verification metrics alongside a deep-learning recalibration model.

Within this framework, the thesis pursues five core objectives. The first objective is to examine the DCV modes and their global teleconnections in CMIP6 models. The second is to explore the changes in these teleconnections under warming scenarios. The third objective characterises the predictability and prediction skill of the DCV modes and teleconnections. This is done globally and over regions of high societal exposure, such as the densely populated monsoon regions. The fourth objective examines the role of external forcing in the predictability of DCV and its impacts. The final objective explores ways of improving the prediction of the DCV modes from the DCP-P hindcasts.

The first results chapter establishes the historical fidelity of the modes. The CMIP6 MME successfully reproduces the canonical horseshoe geometry of the PDO. It also captures the cross-equatorial dipole structure of the TAG. These are evaluated together with the principal loci of their precipitation teleconnections. This includes the ENSO-modulated Walker circulation response in the Pacific and the ITCZ-mediated wind-evaporation-SST response in the Atlantic. The normalised Taylor diagrams confirm that ensemble averaging suppresses unforced noise. Consequently, the MME attains the highest spatial pattern correlation of any ensemble member for both the SST and precipitation fields. The wavelet analyses demonstrate that the models capture the dominant low-frequency pacing of each mode. This pacing is multidecadal for the PDO and decadal for the TAG. However, the amplitude of the precipitation teleconnection is systematically attenuated. This finding is a clear manifestation of the signal-to-noise paradox. The wavelet coherence analysis localises this attenuation in the time-frequency plane. It shows that the two modes communicate with the atmosphere through distinct frequency channels. The MME consistently underestimates the peak coupling in both basins. The NLE analysis quantifies the intrinsic predictability limits. The observed PDO retains an oceanic memory of approximately eleven years. The associated precipitation teleconnection saturates much earlier. This reveals a basin-dependent atmospheric ceiling on the predictability of the rainfall response. In the Pacific, the observed precipitation limit of about eight years falls several years below the oceanic memory. In contrast, the Atlantic precipitation limit lies only marginally below that of the SST gradient. Thus, the atmospheric truncation is pronounced in the Pacific basin but slight in the Atlantic.

The second results chapter examines how anthropogenic forcing reorganises the modes. This analysis uses a normalised difference relative to the unforced piControl baseline, which serves as a spatial signal-to-noise ratio. The forced reorganisation of the SST regression patterns emerges above the internal-variability spread over wide tropical regions. This reorganisation is centred principally in the Indian Ocean, the tropical Atlantic, and the equatorial Pacific. The emergent area scales monotonically with radiative forcing. It transitions from a largely sub-threshold response under strong mitigation to a basin-scale response under the high-emission pathway. The precipitation teleconnections reorganise in a spatially fragmented, land-concentrated manner. This shift moves variance toward the interannual band. Meanwhile, the time-localised SST-precipitation coupling weakens progressively with forcing. Most consequentially, the NLE analysis demonstrates a forced erosion of intrinsic predictability. The unforced control retains the longest memory of any configuration. Conversely, the high-emission scenario displays the shortest memory. Under forcing, the oceanic indices lose memory faster than their precipitation teleconnections. Therefore, the ocean-precipitation predictability gap narrows as emissions rise instead of remaining a fixed property of the system.

The third results chapter assesses the actual prediction skill of the initialised DCP-A hindcasts after lead-time-dependent drift removal. This assessment uses deterministic, probabilistic, and signal-to-noise metrics. The choice of drift climatology is proven to be decisive. One widely used definition annihilates the ensemble-mean anomaly identically. This renders its apparent multi-model skill a machine-precision artefact. A well-defined optimal initialisation frequency emerges for the PDO, at an annual-to-biennial frequency, consistent with its fast, ENSO-residual pacing. The TAG index, by contrast, shows little robust skill at any frequency, its signal skill positive only at the first lead year before falling to the noise floor. For the PDO index, and more broadly in the

regional, seasonally resolved skill of raw land precipitation, a robust dissociation emerges between predictable phase and unpredictable magnitude. Probabilistic discrimination skill persists into the extended lead years over physically coherent regions. These regions concentrate where the established teleconnections fall, including parts of Africa, South America, and monsoon Asia. Annual averaging conceals this localised skill, which remains visible even where amplitude-sensitive deterministic skill fails. The TAG index, by contrast, retains little discriminable phase skill beyond the first lead year. The role of external forcing is isolated through the DCP-P-C volcanic experiments. These experiments reveal a dual response. First, they show a localised, transient thermodynamic reduction of magnitude error. This is confined to the deep-convective tropical continents during boreal winter. Second, they demonstrate a spatially distributed, durable dynamical restructuring of phase skill that overrides the internal modes. These volcanic results are interpreted qualitatively as the targeted response to the Agung, El Chichón, and Pinatubo eruptions. This cautious interpretation acknowledges the limited model and eruption sample, alongside the reduced effective degrees of freedom of the highly autocorrelated decadal series.

The final methodological contribution addresses the core diagnosis that initialised hindcasts retain predictable phase information while attenuating amplitude. It develops a deep-learning framework based on Long Short-Term Memory networks to recalibrate the predicted DCV indices. The framework learns the non-linear relationship between the modelled and observed indices separately at each lead year. It is designed to restore the attenuated coupled signal while preserving the phase structure that dynamical models already capture. This effectively addresses the signal-to-noise deficiency that linear drift correction cannot remedy.

Taken together, the chapters trace a single coherent thread. This narrative covers the attenuation, forced erosion, and partial recovery of decadal predictability. The thesis follows this trajectory from the intrinsic limits set by the climate system, through the consequences of anthropogenic forcing, to a practical non-linear correction strategy. In doing so, the work clarifies the fundamental boundaries of decadal prediction for the PDO and TAG. It also establishes a viable route toward more skillful and actionable regional hydroclimate forecasts. This work provides a quantitative baseline against which future generations of initialized prediction systems can be measured.

Keywords: Decadal Climate Variability; Pacific Decadal Oscillation; Tropical Atlantic SST Gradient; CMIP6; Decadal Climate Prediction Project; decadal prediction; teleconnections; precipitation; signal-to-noise paradox; Nonlinear Local Lyapunov Exponent; wavelet coherence; predictability limits; external forcing; deep learning; LSTM.