Examining the impact of multiple climate forcings on simulating Southern Hemisphere Seasonal Climate Variability

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Outline

- Seamless Climate Prediction framework context at the CSIR South Africa.
- Research question and seasonal forecast experimental designs used.
- Summary of key findings on:
  - Seasonal climate predictability in relation to the role of changes in sea-ice and SST forcing.
  - Couple interactions ENSO, ITCZ and its characteristics
  - Process orientated attributions.
- Identified areas of further research and development.

Research Questions

Phase 1:

- What are the influences of SIC and SST forcings and atmosphere-ocean-sea-ice coupled interaction on the Southern Hemisphere leadings modes of climate variability and recent changes?

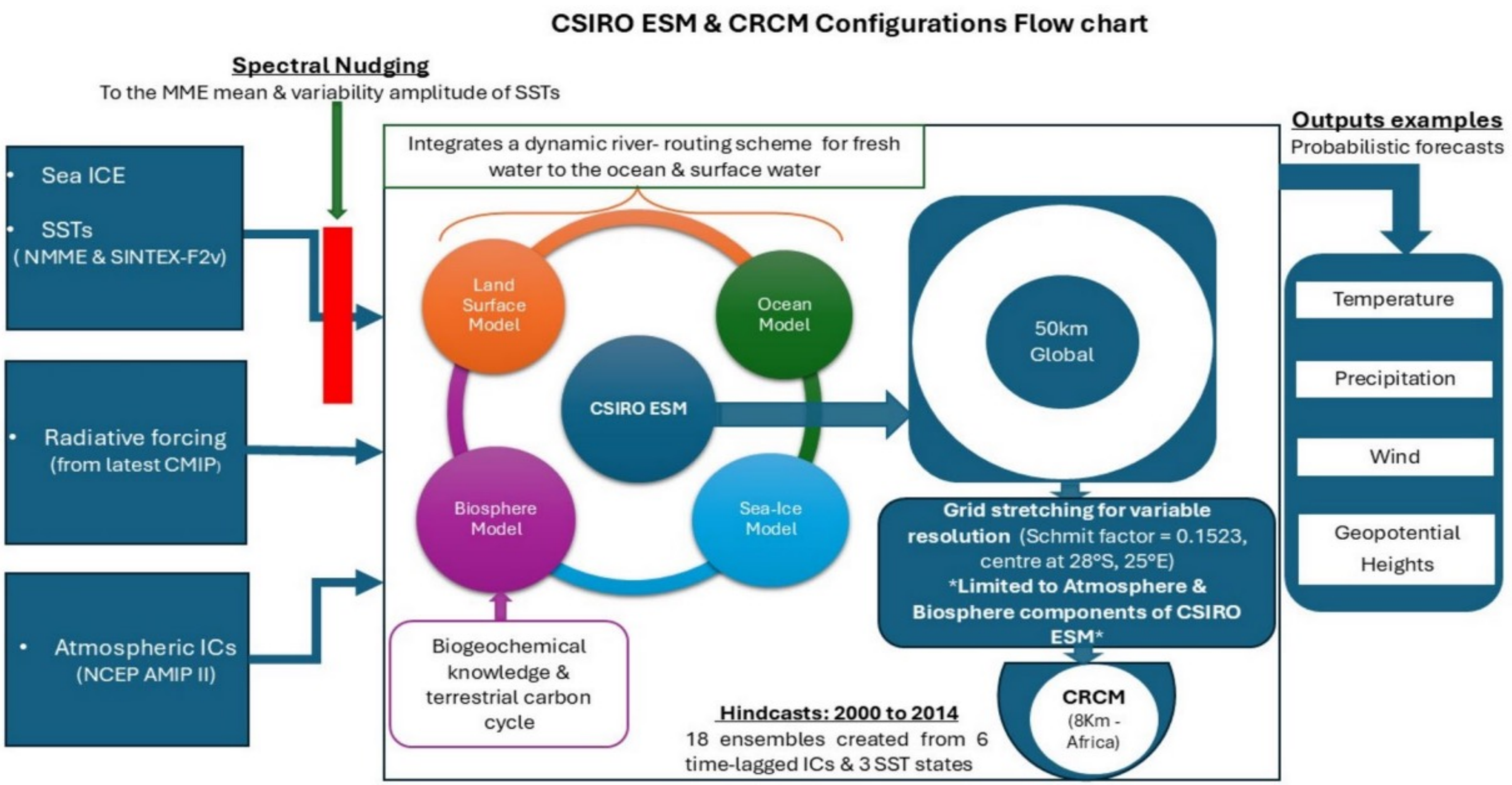
Phase 2:

- What are the transition of the ITCZ position in response to North vs South differential heating gradients? and what is the co-variability of seasonal ENSO signal with the ITCZ over Africa?
- How does CCAM ECM seasonal prediction represent the seasonal migration of the ITCZ, Hadley cell and subtropical jet in relation to ENSO?

CCAM seasonal forecasting experiment key features

- CCAM evolved to the level of ESM of intermediate complexity following:
  - The ocean model, in turn, feeds information to the atmospheric model with SST and Sea-ice model
  - The approach is based on the reversibly staggered grid, which possesses excellent dispersive properties for modelling the geophysical fluid dynamics of both the atmosphere and the ocean.
- The ESM experiment is conducted, resembling, to a large extent, the standard CMIP5 models configured for comparison with observations (Taylor et al. 2012).
  - The model includes a prognostic aerosols scheme due to Mitchell et al (1995),
  - which can be applied consistently with the emission inventories and radiative forcing specifications of the CMIP5.

CCAM dynamical seasonal prediction downscaling model set-up



Ramotubei et al., (**2025**)

Simulation forcing data

	Inputs	Collaborating Intuitions/ Projects
Initial conditions and boundary forcings	• Atmospheric Initial states reanalysis • Sea Surface temperatures (SSTs) • Sea Ice • CMIP5 Emissions	• National Centers for Environmental Predictions (NCEP), Department of Energy (DOE) Atmospheric Model Intercomparison Project (AMIP) II Reanalysis (R2). • University of Pretoria & North American Multi-Model Ensemble(NMME) • Syntax F2 Japan Agency for Marine-Earth Science and Technology (JAMSTEC) • CMIP5

Description of model experiments strategies and their configurations

Phase 1: Sensitivity experiments

Exp ID	Description
ESM	Interactively couple's atmosphere, ocean, biosphere and cryosphere; nudged to time-varying AMIP SSTs and SICs
AMIP	Standard AMIP style simulation; interactively couples atmosphere and biosphere; forced with nudged time-varying AMIP and SICs
SICclim	As *AMIP* except forced with and nudged with AMIP SIC climatology
SSTclim	As *AMIP* except forced with and nudged to AMIP SST climatology

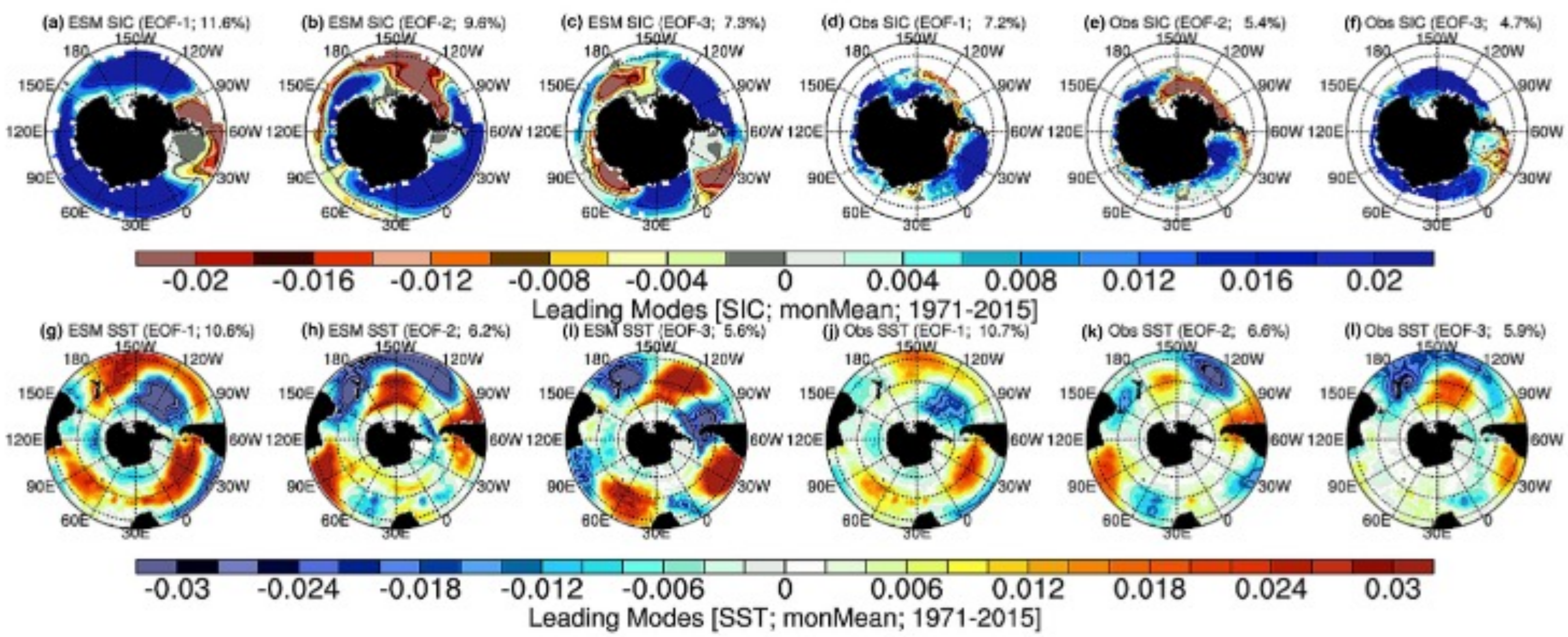
Resolution: C48 quasi-uniform horizontal resolution (approx. 200 km) is used

Phase 2: experimental seasonal forecast simulation system process-based evaluation

ESM: All experiments use AMIP sea-surface-temperatures (SSTs) and sea-ice concentrations (SICs) provided through CMIP5 as lower boundary forcing or nudging.

Resolution: About global 50km horizontal resolution (using C192) and further downscaled to 8km over Africa.

Simulated leading modes of the SH SIC and SST

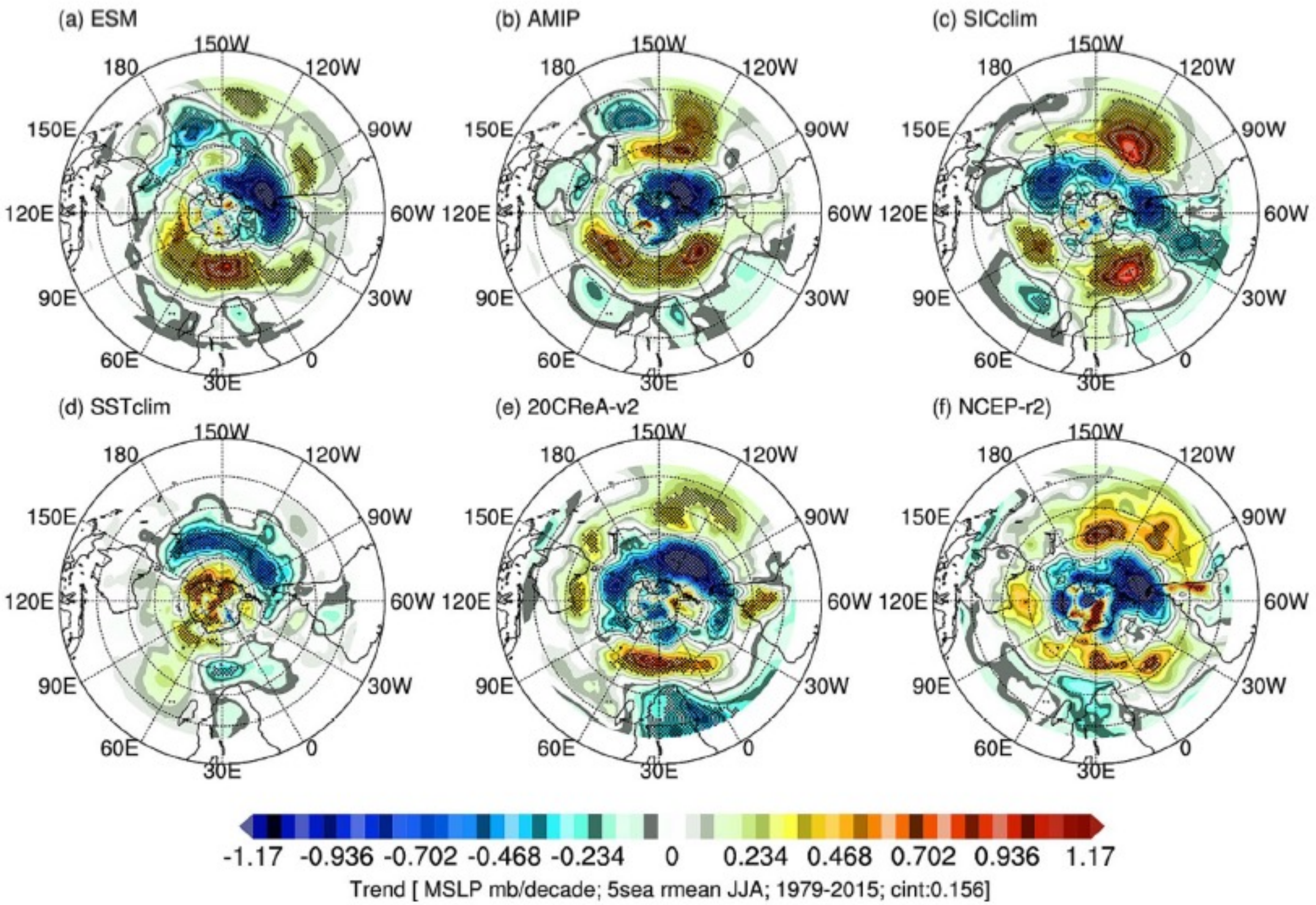


Simulated and observed first three leading SH SIC (upper panel) and SST (lower panel) modes of variability based on the (rotated) EOF analysis using detrended monthly anomaly of each field as input. Also shown in the title of each plot is the EOF mode rank along with its variance explained (%).

Background from: [Examining the impact of multiple climate forcings on simulated Southern Hemisphere climate variability] (A Beraki et al., 2020)

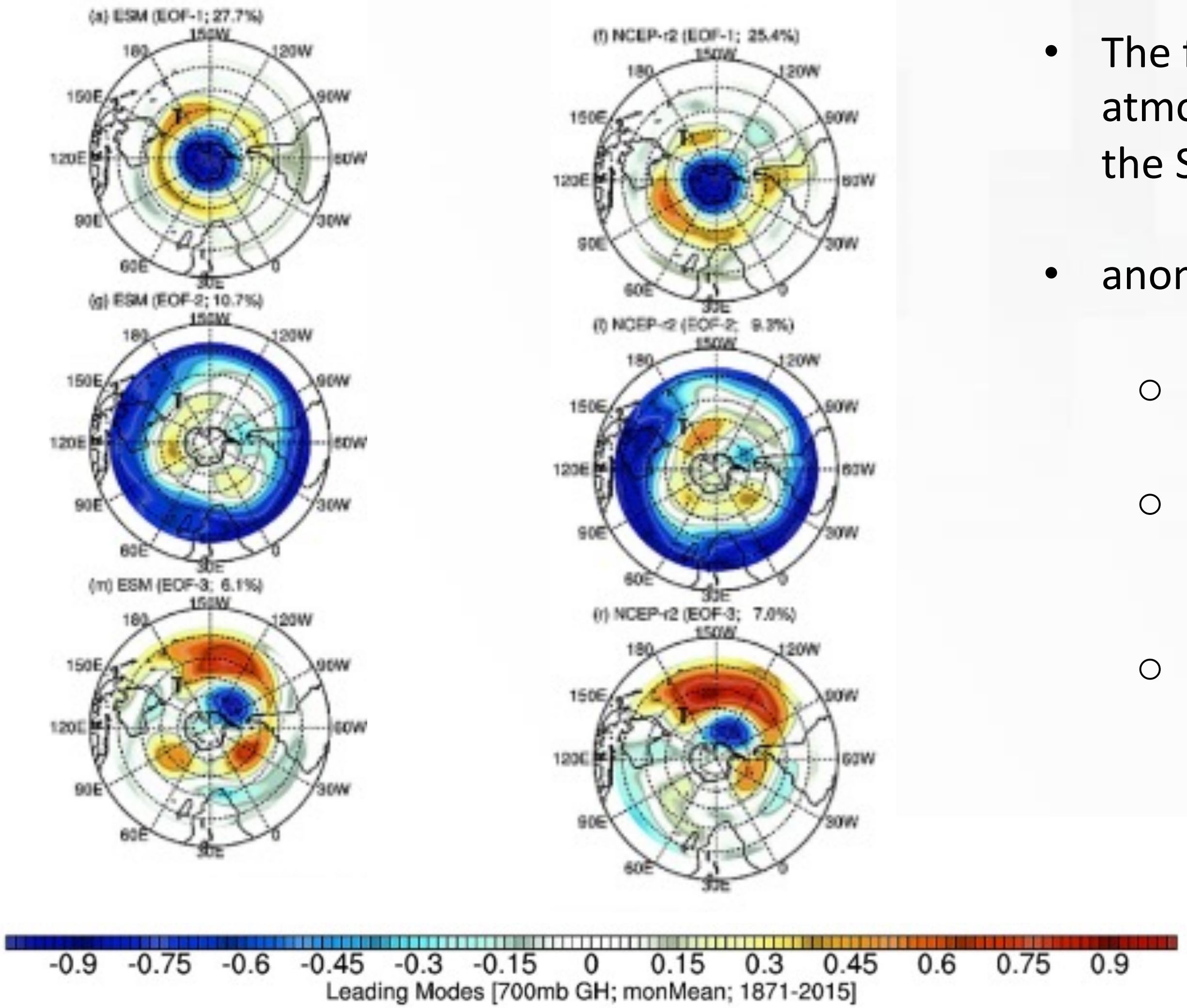
- Sea Ice variability, leading mode reveals the dipole-like sea–ice pattern
- The first sea–ice dominant mode explains 11.5% of variability and 7.2% (observation)
- The other modes of observation more or less display a similar pattern with a slight zonal shift in orientation
- Model manifests two troughs over the Ross Sea and the southern Indian Ocean
- off the coast of Antarctica, which is not present in the observed mode
- **Dipole structure suggests an important physical process associated with sea ice.**

Mean sea level pressure sensitivity: comparing differences in temporal trends across experiments.



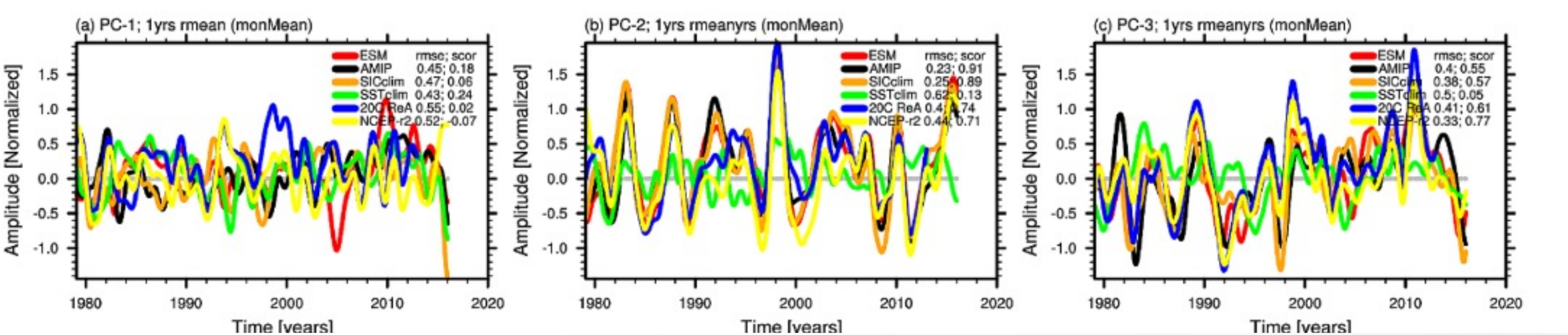
- In figure (C) trend we can see a signature of surface deepening of the polar vortex and pacific mid-latitude anticyclones relative to other experiments.
- Similar upper-level trend analysis allows interrogation of changes in upper air circulation in response.

Southern Hemisphere atmosphere variability (GH anomalies leading rotated EOFs)



- The first mode represents the dominant atmospheric variability, commonly referred to as the SAM or the Antarctic Oscillation (AAO).
- anomalous SAM is **known** to affect:
  - the westerly circumpolar flow,
  - further influences the circulation, temperature distribution,
  - mixed layer depth and Heat capacity in the ocean through the Ekman pumping effect.

Southern Hemisphere atmosphere variability CCAM sensitivity experiment (The leading principal components (PCs) of SH 700 mb GH)



- The time evolution of the SAM is chaotic and follows **a random trajectory** (across the simulations) at the interannual timescale. Suggesting that multiple feedback mechanisms arising from the coupled interactions noticeably modulate the time-evolution of the SAM.

- For **Second and Third Modes,** the other leading modes exhibit a high degree of consistency except in the SSTclim scenario, which tends to oscillate quite differently. This noticeable sensitivity emphasises the importance of (notably tropical) ocean temperature forcing, irrespective of timescales.

- **Second and Third Modes,** the SIC climatological forcing (SICclim) is indistinguishable (or predominantly localised) from the ESM and AMIP experiments, suggesting that sea–ice forcing does not seem to play a significant role in driving these modes of climate variability or influencing a hemispheric-wide atmospheric response

Phase2: Simulation of the ITCZ during austral summer seasons and ENSO phases over Africa: application of an RCM derived from stretched grid ESM

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CRCM process-based evaluation and benchmarking experiment

Objective:

- Explore CRCM and ESM ability to track:
    - ITCZ position and location of Hudley Cell position hence ability of the model to simulate atmospheric energy balance between North and Southern Hemisphere.
    - Multi-level (1,00hPa to 100hPa) steam function (Ψ) and subtropical Jet steam (STJ)

at different lead times and anomalous ENSO phases.

Rational:

- Literature suggest that In Southern Africa, ITCZ position is like to Southern Africa rainfall variability
- A recent study Randriatsara at al., (2022) uncovered that onset and offset of the Southern African seasonal rainfall are affected by position of ITCZ.

CRCM process-based evaluation and benchmarking experiment

Reference data sets:

- Climate Hazards Group Infrared Precipitation with Stations version 2 (CHIRPS2.0) data at (0.05° × 0.05°) grid resolution (Funk et al., 2015).

- The (0.25 × 0.25°) European Centre for Medium-Range Weather Forecasts (ECMWF) fifth generation reanalysis (ERA5; Hersbach et al., 2020).

- Climate Research Unit gridded Time Series version 4 (CRU TS v4; Harris et al., 2020) at (0.5° × 0.5° grid).

Selection of ENSO years:

- Seasonal Oceanic seasonal Oceanic Niño Index (ONI) in the Niño 3.4 ocean region was used to identify the El-Niño and La-Niña phases.

- year is confirmed to be an El-Niño/La-Niña year provided the phase remains active in three of the four (NDJ, DJF, JFM, and FMA) rolling seasons

Experiment Initialization:

- CSIRO ESM & CRCM are initialized in November and run for 6 months,

Forecast Evaluation: Tracking of the ITCZ position

Models:

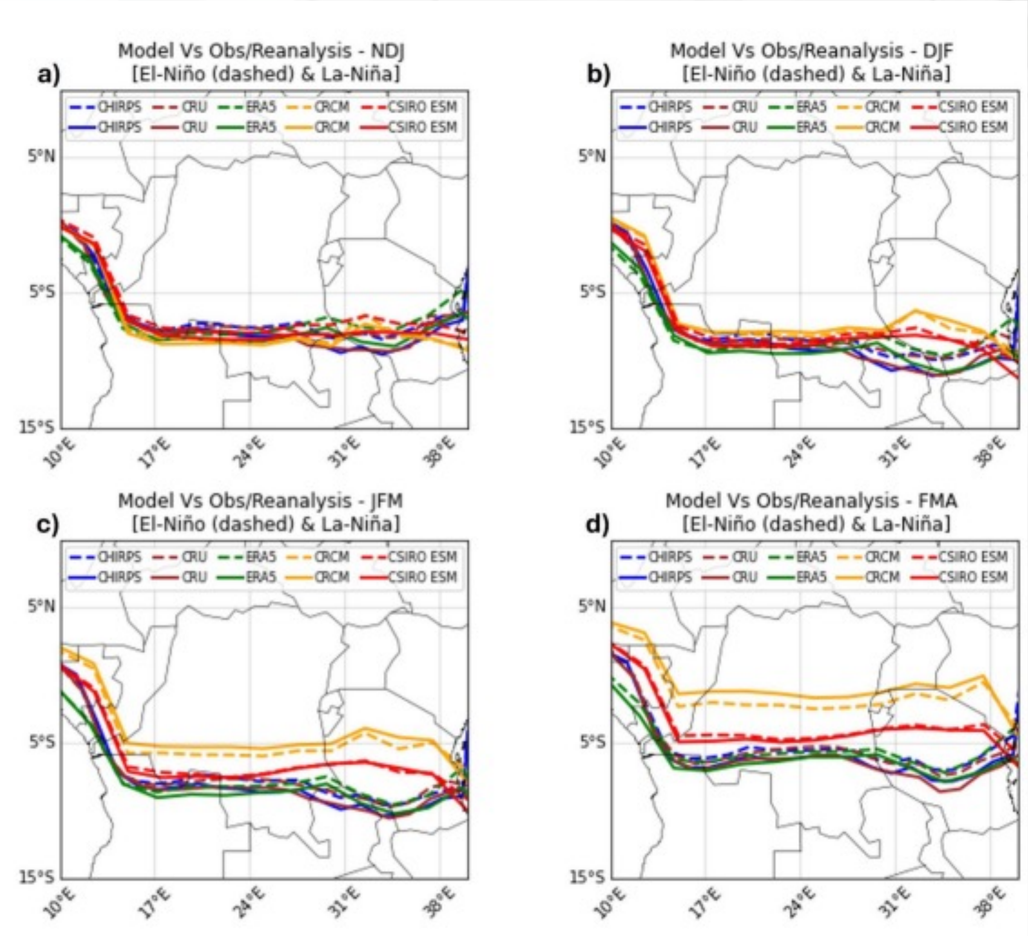
- CSIRO ESM and CRCM for period 2000-2014

Region:

- 10° E–40° E area

Quantification method:

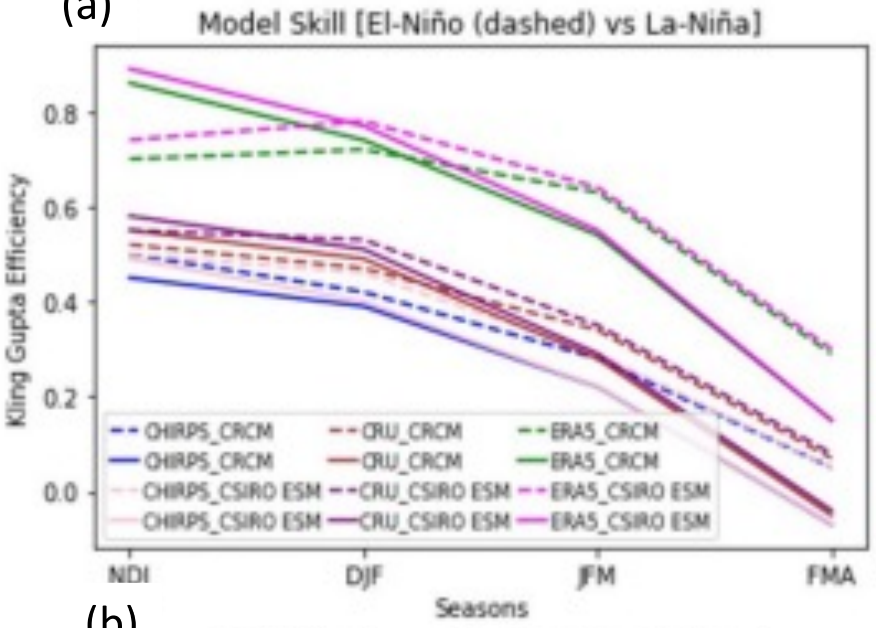
- The *centroid method* was used for the identification of the spatial and zonal positions of the ITCZ. CSIRO ESM and CRCM consist .



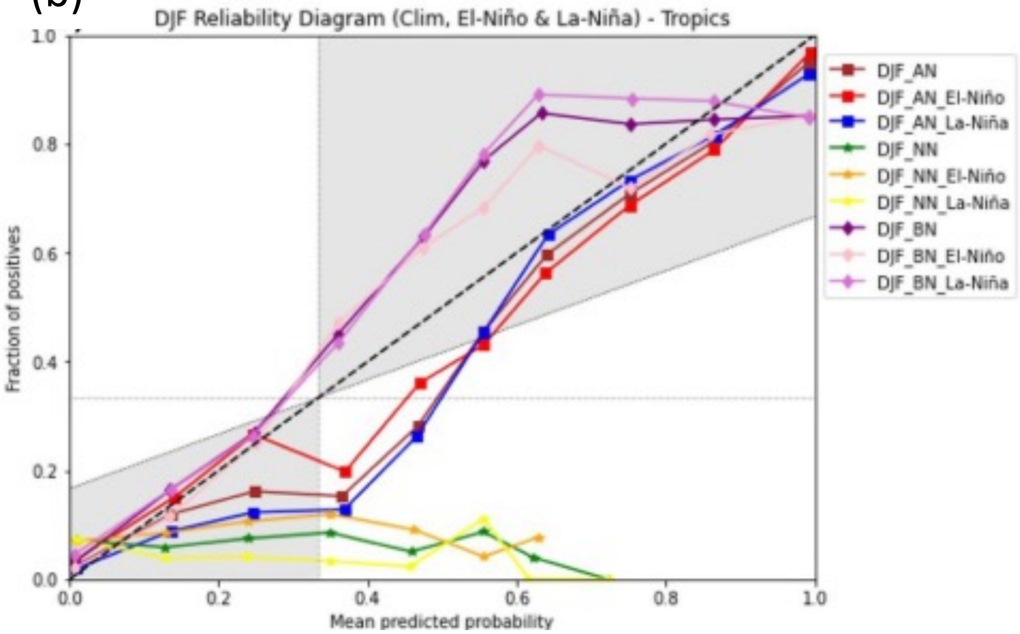
- CSIRO ESM and CRCM consistently track the seasonally migrating spatial position of the ITCZ in line with both the observations and reanalysis data during the El-Niño/La-Niña ENSO.
- When maximum precipitation is used ITCZ is found to be 1 ° South of that found using centroid method.

Forecast Skill Evaluation: Probabilistic forecast

(a)



(b)



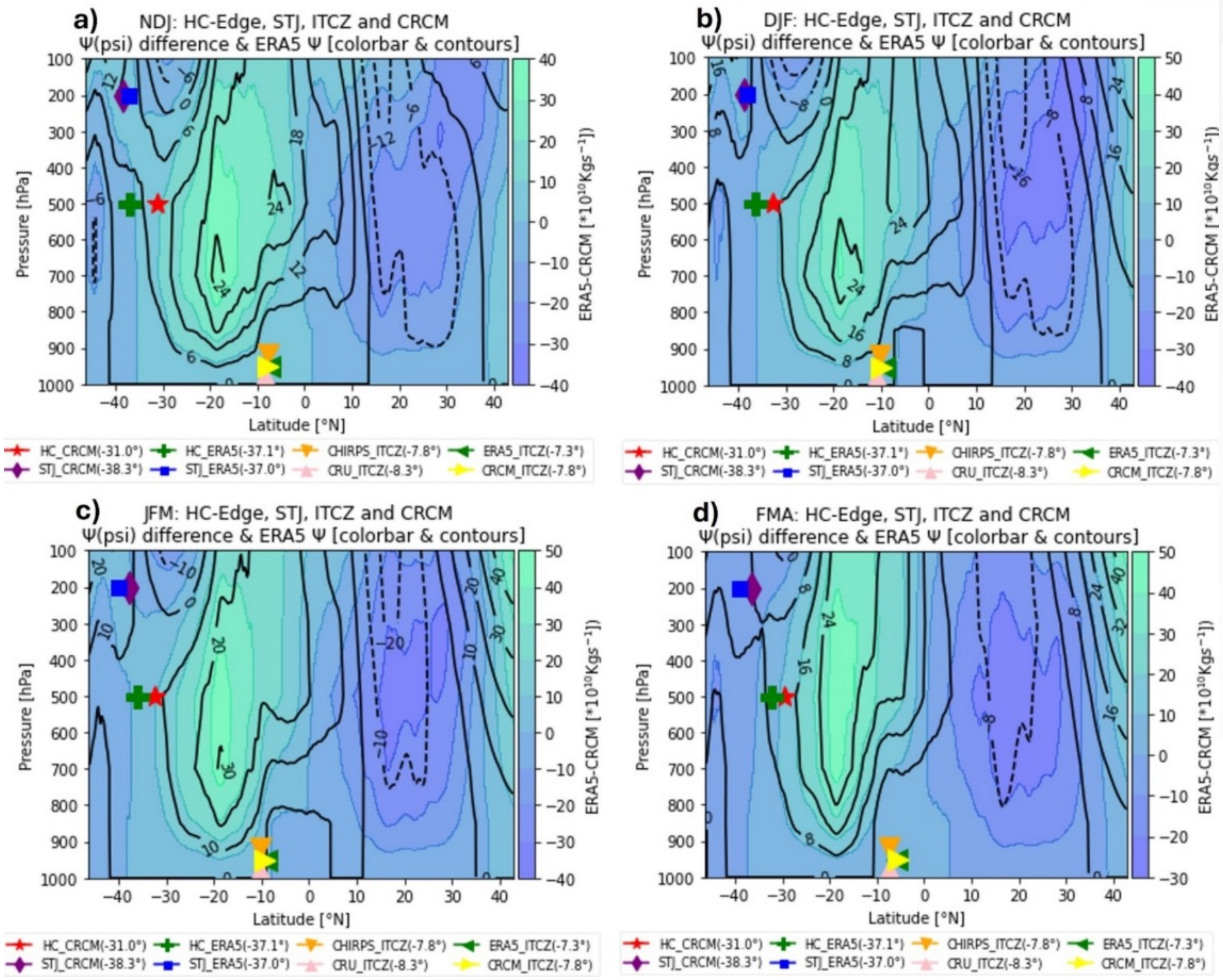
- When it comes to model skill
  - KGF reflects that there is skill for both CSIRO ESM and RCM.
  - The dynamical downscaling process does not demonstrate an added value over the tropical region looking at the KGE.
  - The both CSRO ESM and RCM skill during the La-Nina is higher that than or El-Nino.
  - CRCM is skillful and reliable for certain AN and BN while being over-confident for AN and BL normal events while having low confidence for some frequently observed AN and BN seasonal precipitation categories during El-Niño and La-Niña, respectively for Lead-1.

Forecast evaluation: Spatial correlations

	Model and datasets correlations during El-Niño and La-Niña					
	CRCM (CSIRO ESM) Vs. CRU		CRCM (CSIRO ESM) Vs. CHIRPS		CRCM (CSIRO ESM) Vs. ERA5	
	El-Niño	La-Niña	El-Niño	La-Niña	El-Niño	La-Niña
NDJ	0.48 (0.58)	0.51 (0.59)	0.54 (0.52)	0.51 (0.50)	0.80 (0.87)	0.87 (0.91)
DJF	0.44 (0.54)	0.50 (0.55)	0.46 (0.47)	0.48 (0.46)	0.82 (0.90)	0.85 (0.91)
JFM	0.39 (0.44)	0.42 (0.45)	0.40 (0.39)	0.41 (0.39)	0.89 (0.92)	0.85 (0.92)
FMA	0.39 (0.40)	0.39 (0.41)	0.39 (0.37)	0.40 (0.37)	0.88 (0.91)	0.88 (0.92)
Mean	0.43 (0.49)	0.46 (0.50)	0.45 (0.44)	0.45 (0.43)	0.85 (0.90)	0.86 (0.92)
Min	0.39 (0.40)	0.39 (0.41)	0.39 (0.37)	0.40 (0.37)	0.80 (0.87)	0.85 (0.91)
Max	0.48 (0.58)	0.51 (0.59)	0.54 (0.52)	0.51 (0.50)	0.89 (0.92)	0.88 (0.92)

- Table show a marginally better spatial correlation between CSIRO ESM and CRU/ERA5
- Comparable correlations exist between CRCM/CSIRO ESM and CHIRPS observations.
- This implies that CSIRO ESM performs better than CRCM against the low-resolution verifying datasets while both
- CSIRO ESM and CRCM are highly correlated with ERA5.

Process based model evaluation: Hadley cell, the regional subtropical jet stream, and multi-level stream function



The climatological differences (prior to phase correction) between ERA5 and CRCM (ERA5-CRCM)

Climatological Latitude (in brackets) during NDJ - FMA seasons **for**.

I) the descending edge of the HC-Edge,

- HC_CRCM,
- HC_ERA

II) ITICZ position:

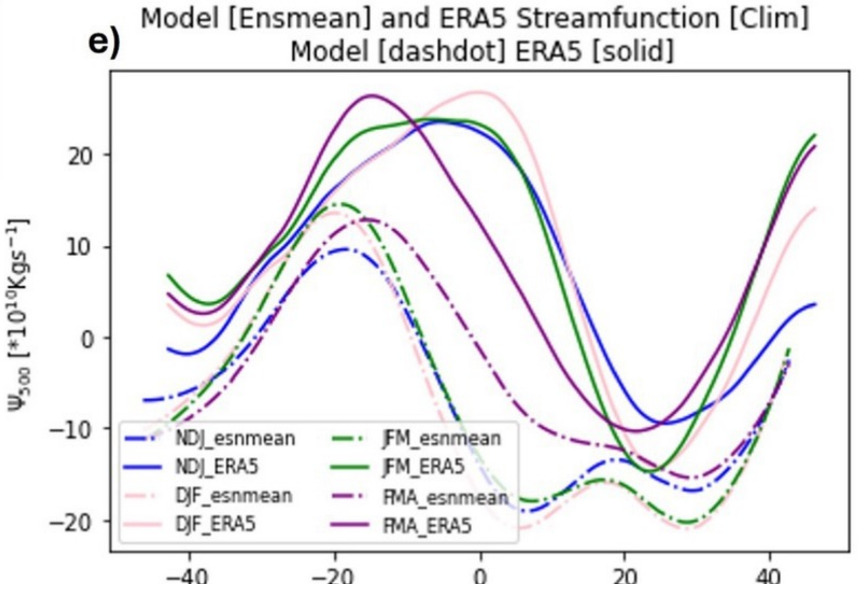
- CRCM_ITCZ
- ERA5_ITCZ
- CHIRPS_ITCZ
- CRU_ITCZ

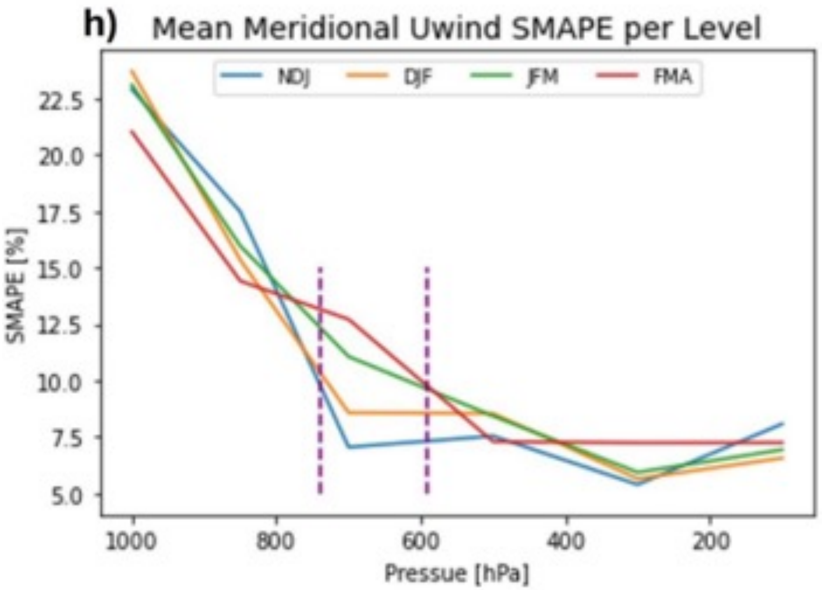
III) subtropical jet stream (STJ)

- STJ_CRCM,
- STJ_ERA5,

Contour contours stream function (Ψ) the stream function differences (ERA5 minus CRCM) as the in $*10^{10}$ Kgs^{-1}.

ENSO seasonal variability of subtropical Jetstream: Model limitations

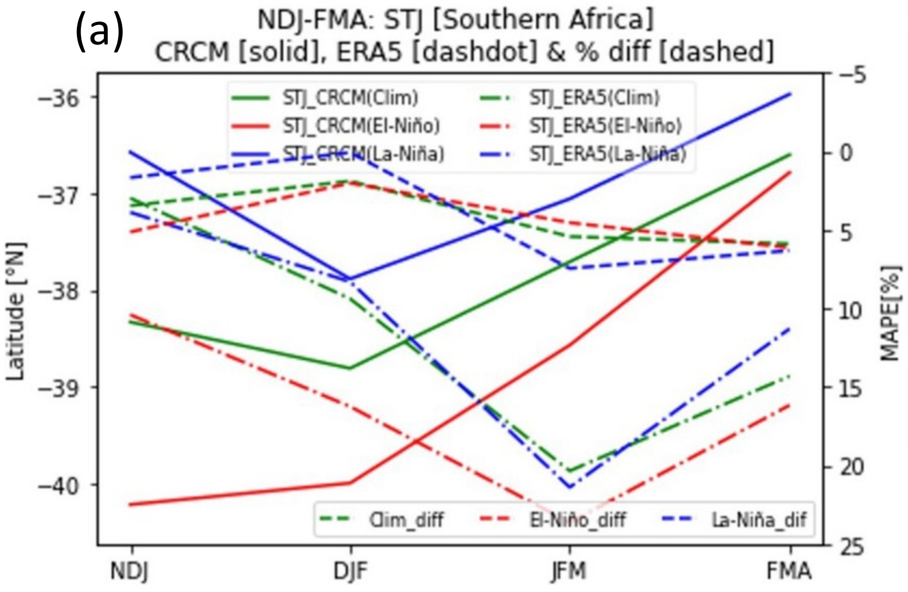




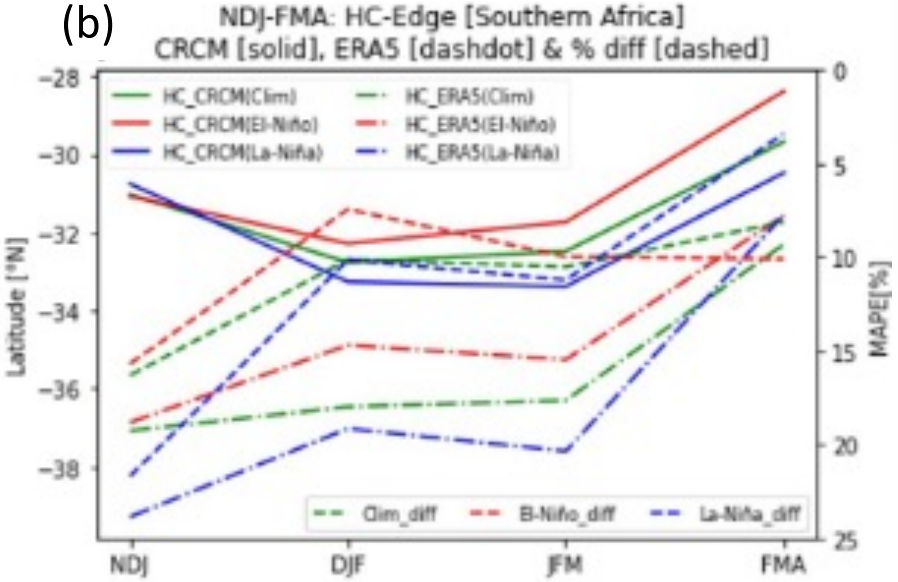
- Steam function phase error
- Dynamic error growth affecting all parameters including wind. For wind the errors are seemingly more pronounced at certain pressure levels.

ENSO seasonal variability of subtropical Jetstream and Hutley cell edge

(a)



(b)



- We found that the STJ latitude shifts poleward during El-Niño
- while it shifts equatorward during La-Niña over the southern hemisphere and Africa.
- In comparison, the model performs better in identifying the STJ latitude Figure (a) than it does in identifying the edge of the HC Figure (a).

Conclusion and recommendations

Feedback to the SAM:

- Chances in seasonal climate variability associated with the sea-ice forcing is likely restricted to the sea-ice-air interface and impact on atmospheric circulation is likely localized.
- Sensitivity to degradation of SST forcing is reflective of potential of the model of use in understanding sea-air coupling over the polar and mid-latitude regions.
- The model is sensitive to the seasonal migration of the ITCZ however, with a satisfactory position of the HC descending edge and mass stream function.
- The benefit of dynamical downscaling to 8km is outwight by dynamic error growth with increasing lead times.
- Model process diagnostics at seasonal time scales could greatly benefit interpretation of skill or lack.

Key references

Beraki, A.F., Morioka, Y., Engelbrecht, F.A. et al. Examining the impact of multiple climate forcings on simulated Southern Hemisphere climate variability. Clim Dyn 54, 4775–4792 (**2020**). https://doi.org/10.1007/s00382-020-05253-y

Ramotubei TS, Landman WA, Mateyisi MJ, Nangombe SS and Beraki AF (**2025**) Simulation of the African ITCZ during austral summer seasons and ENSO phases: application of an RCM derived from stretched grid ESM. *Front. Clim*. 7:1504756. doi: 10.3389/fclim.2025.1504756

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