



Explaining the Modulation of Forced Precipitation Changes with Internal Variability Storylines: The case of decadal Sahel Precipitation Changes

Julius Mex¹, Julia Mindlin¹, and Marlene Kretschmer¹

¹Leipzig Institute for Meteorology, Leipzig University, Leipzig, Germany

Correspondence: Julius Mex (julius.mex@uni-leipzig.de)

Abstract. Decadal Sahel rainfall is strongly influenced by internal climate variability, which can substantially modulate anthropogenically forced changes, particularly in the near- and mid-term. Yet, the complexity and inherent randomness of internal variability make it difficult to interpret, communicate and integrate into decision-relevant climate information. Here, we develop internal variability storylines of Sahel summertime precipitation using a large model ensemble. We identify the Atlantic Multidecadal Variability (AMV) and Pacific Decadal Variability (PDV) as two key oceanic drivers of decadal Sahel rainfall variability that act through distinct atmospheric mechanisms: AMV-related sea surface temperature changes are consistent with changes in the Atlantic inter-hemispheric temperature gradient, shifting the meridional position of the Intertropical Convergence Zone (ITCZ) and associated monsoon circulation, whereas positive PDV increases tropospheric stability and subsidence over the Sahel, suppressing convection. By conditioning on the combined phases of AMV and PDV, we construct physically coherent climate storylines that illuminate how decadal internal variability can organise tropical circulation and Sahel precipitation anomalies. Their effects reinforce most strongly in out-of-phase configurations, with AMV+/PDV- producing a wet Sahel, and AMV-/PDV+ a dry Sahel, while in-phase states show weak responses. These combined influences are captured by the North Atlantic Relative Index (NARI), which combines thermodynamic and dynamic impacts of oceanic forcings on the Sahel. A positive NARI corresponds to AMV+/PDV-, whereas a negative NARI is associated with AMV-/PDV+, with NARI explaining 37% of Total Sahel precipitation variability. Understanding the pathways of oceanic drivers reveals how they modulate the forced response: around mid-century, opposing storylines can more than double or cancel forced regional precipitation changes. Overall, our results demonstrate how internal variability storylines can extract physically grounded decadal climate information from large ensembles, providing a framework complementary to initialised predictions for regional climate information.

1 Introduction

Precipitation in the Sahel region is highly seasonal with most rainfall occurring in the months from July to September as a result of the West African Monsoon (WAM, Sultan and Janicot (2003)). A majority of the 300 Million inhabitants of the semiarid region are reliant on rain-fed agriculture (Tomalka et al., 2021); consequently, changes in the timing, intensity and spatial distribution of monsoon rainfall has major societal impacts through altering water availability, agricultural production



25 and food security (Sultan and Gaetani, 2016). Providing actionable climate information about the possible evolution of Sahel rainfall in the coming decades is thus a major scientific challenge (Nissan et al., 2019).

Sahelian precipitation has shown significant decadal variability over the last century (Mohino et al., 2011a), with a significant drought period in the 1970 and 1980s, followed by a partial rainfall recovery (Giannini et al., 2003; Rodríguez-Fonseca et al., 2011; Giannini and Kaplan, 2019). While external forcing such as greenhouse gases and aerosols are important in understanding these changes (Held et al., 2005; Dong and Sutton, 2015; Nnamchi and Fiedler, 2026), subsequent studies based on observations, idealised model simulations as well as fully coupled general circulation models have produced an emergent consensus that Sahel decadal variations are strongly influenced by slow-varying oceanic variability in the Atlantic, Indian and Pacific Ocean (Pomposi et al., 2016; Villamayor and Mohino, 2015; Monerie et al., 2019; Mohino et al., 2011b; Zhang and Delworth, 2006).

35 On decadal timescales, internal variability can amplify, attenuate or temporarily reverse the effect of anthropogenic climate change (Deser et al., 2012; Maher et al., 2020; Kosaka and Xie, 2013) and its effect is especially pronounced for dynamically driven variables such as precipitation, which depend on changes in the atmospheric circulation (Lehner et al., 2020). Uncertainty in climate predictions for the near-term (next 20 years) is dominated by internal variability, whereas model and scenario uncertainty become dominant at the end of the century as it has been highlighted for Sahel precipitation by Lehner et al. (2020).
40 Given its sensitivity to oceanic variability, the Sahel has been considered a region where near-term information can be extracted from initialised decadal predictions, which combine external forcing with observed initial conditions to constrain the phase of internal variability. Significant skill has been reported for predictions of Sahel rainfall in an initialised single-model (Sheen et al., 2017), as well as in multi-model hindcasts (Smith et al., 2019). However, this regional skill is much larger for thermodynamics than for dynamic variables; critically, initialization shows an improvement in skill for precipitation but a reduction for
45 sea-level pressure (Smith et al., 2019); furthermore. This discrepancy indicates a poorly constrained atmospheric circulation and points to a deeper challenge: decadal hindcast skill offers only limited insight into atmospheric mechanics and thus limited confidence in whether the forced response will be attenuated or amplified by internal variability. To better assess near-term climate risks therefore requires approaches that complement initialized predictions by integrating process understanding and exploring a physically plausible and coherent range of outcomes (Findell et al.).

50 The challenge of understanding coherent and plausible outcomes - rather than offering a statistical description of simulations - also arises in long-term climate projections issued with multi-model climate ensembles. To tackle this, Zappa and Shepherd (2017) have proposed the ‘storyline’ framework, a conditional framing of the Earth’s systems evolution, focusing on physical plausibility. This approach has found increasing application to move away from multi-model ensemble means as best estimates of forced climate changes and investigate the causes of model uncertainty at regional scales in the long term (Zappa and
55 Shepherd, 2017; Mindlin et al., 2020; Monerie et al., 2023; Ghosh and Shepherd, 2023; Levine et al., 2024). For instance, Monerie et al. (2023) have shown that the uncertainty in the forced response in Sahel precipitation can be explained in terms of North Atlantic and Mediterranean SST evolutions, and opposing storylines of driver responses show a substantially different trend pattern with opposite sign in the total precipitation trend. This framing of regional climate changes, observed through



the prism of climate storylines, has already been used to guide decision on model selection based on emergent constraints and physical arguments (Cardoso et al., 2026; Graff et al., 2026).

To apply the conditional approach of storylines for near-term information, i.e., for timescales dominated by unforced climate variability, Liné et al. (2024) proposed constructing *internal variability storylines*. In their work, using a single model large ensemble, they show how large-scale features such as the North Atlantic Oscillation and the Atlantic Meridional Overturning Circulation drive wintertime atmospheric variability over Northern Europe that significantly modulate anthropogenically-forced warming in the coming decades.

In this study, we extend the framework of internal variability storylines to understand how forced changes are modulated by remote drivers over the course of the century. We apply this approach to linking spread in Sahel precipitation projections to their oceanic drivers. We use the 100-member Community Earth System Model Version 2 Large Ensemble (CESM2-LE; Danabasoglu et al. (2020)), which provides a robust sampling of internal variability throughout the twenty-first century. To understand how remote drivers jointly organise the atmospheric circulation and precipitation response when they reinforce or oppose one another, we address the following scientific questions:

1. What are the drivers of Sahel summertime precipitation variability on decadal timescales?
2. How does their joint influence impact the atmospheric circulation and the precipitation response?
3. How does internal variability modulate the forced response in the near- and long-term?

In Section 2 we present the data and methods used, before presenting the results addressing the abovementioned research questions in Section 3, which are further discussed in Section 4.

2 Data and Methods

2.1 Data

We use simulations from the Community Earth System Model Version 2 (CESM2; Danabasoglu et al. (2020)), namely the preindustrial control (piControl) simulation and the 100-member CESM2 Large Ensemble forced under SSP3–7.0 conditions (Rodgers et al., 2021). For the piControl simulation, to remove model drift, the first 100 years are excluded, leaving 1100 years for analysis; all fields are linearly de-trended following the approach of Zappa et al. (2021). Anomalies are computed relative to the full-period monthly climatology. The piControl data are used to characterize the model’s internal variability in the absence of external forcing. We use the SSP3–7.0 simulations to investigate how different realizations of internal variability modulate Sahel forced precipitation changes. Here, the forced response is computed as changes in the ensemble mean relative to a 2015–2024 baseline and internal variability is isolated by removing the ensemble mean at every time step.

All analyses are performed using decadal averages. The piControl simulation is divided into 110 non-overlapping 10-year periods, while for SSP3–7.0, 10-year centered running means are computed for each ensemble member and year. Spatial averages are weighted by grid cell area. Following Monerie et al. (2023), Sahel precipitation is separated into a western



(20°W–5°W and 10°N–20°N) and a central (5°W–20°E and 10°N–20°N) region to account for longitudinal heterogeneity in the precipitation changes. The ‘Western Sahel’ and the ‘Central Sahel’ index are defined as precipitation over the respective boxes, with their joint region being denoted ‘Total Sahel’, as in Monerie et al. (2023). We focus on summertime precipitation, defined as the seasonal average over the months July to September (JAS). Large-scale oceanic and atmospheric drivers are characterized using established indices based on spatial averages of annual sea surface temperatures (SSTs). Pacific Decadal Variability (PDV) is represented by the Tripole Index (TPI; Henley et al. (2015)), and Atlantic Multidecadal Variability (AMV) follows Trenberth and Shea (Trenberth and Shea, 2006); the regions used to compute AMV and PDV are also indicated in Fig. 1. The North Atlantic Relative Index (NARI; Giannini et al. (2013)) is defined as the difference between annual SST anomalies averaged over the North Atlantic (10°–40°N, 75°W–15°W) and the global tropical (20°S–20°N), shown in Fig. 5a. Circulation diagnostics are computed from summertime (JAS) anomalies in zonal (u), meridional (v), and vertical (ω) winds. Where applicable, circulation averages are computed to be representative for the Total Sahel region, i.e. meridional averages over 10°–20°N and zonal averages over 20°W–20°E.

2.2 Methods

To construct internal variability storylines, we consider the four quadrants of the AMV-PDV phase space. The data inside of the central 20% covariance ellipse is excluded as the neutral phase; for each phase-combination, we then compute the average across all decadal anomalies, as represented for AMV and PDV by the colored points in Fig. 3 for piControl. The same process is applied for projections under the SSP3-7.0 scenario for all time steps independently. To quantify the modulation of the storylines of the forced response, it is added back to each storyline. In contrast to Liné et al. (2024), we divide the phase space at zero along both standardized indices, thereby preserving the physical interpretation of positive and negative AMV and PDV phases at the expense of equal sample sizes among storylines. A one-way analysis of variance (ANOVA; von Storch and Zwiers (1999)) is used to quantify the extent to which the AMV–PDV storyline classification organizes decadal Sahel precipitation variability. Total precipitation variance is partitioned into variance between the four storylines and residual variance within storylines. The fraction of variance explained by storyline (η^2) is used as a measure of the precipitation variability captured by the classification.

3 Results

3.1 Drivers of Decadal Summertime Variability

Previous studies have shown that multidecadal Sahel rainfall variability is related to slowly varying SST anomalies in the Atlantic and Pacific. In particular, an interhemispheric temperature gradient in the Atlantic, that is, a warmer North Atlantic relative to the tropics or Southern Hemisphere has been shown to favor a northward displacement of the tropical rain belt and wetter Sahel conditions. This finding has been confirmed on decadal timescales in terms of the Atlantic Multidecadal Variability through reanalysis, idealised and atmosphere-only model and global coupled model analysis (Martin et al., 2014; Mohino



et al., 2011a, 2024; Monerie et al., 2023, 2019; Rodríguez-Fonseca et al., 2011). The regression of decadal summertime (JAS) anomalies of precipitation and SSTs in CESM2 piControl confirms the importance of the meridional temperature gradient in the Atlantic, with positive regression coefficients over the tropical to subtropical North Atlantic and the Mediterranean and negative anomalies over the tropical South Atlantic and equatorial Atlantic (Fig. 1a). This pattern is amplified for the
125 Regression of Western Sahel rainfall; for the Central Sahel it shows the same pattern but to a lesser intensity (Fig.S1). The regression coefficients of summertime decadal anomalies of SST on the AMV index (Fig. 1b) have a global pattern correlation of $r = 0.30$ with the precipitation-SST regression map (Fig. 1a), and captures the interhemispheric SST gradient in the Atlantic. The Pacific component, exhibiting a broad, triangular pattern extending from the eastern tropical Pacific along the American coastlines toward the central and western tropical Pacific is likewise in agreement with previous work identifying an influence
130 of Pacific variability on Sahel rainfall. While this teleconnection is commonly discussed on interannual timescales in relation to the El-Nino Southern Oscillation (ENSO) (Cai et al., 2025; Rodríguez-Fonseca et al., 2015; Martín-Gómez et al., 2022), Pacific Decadal Variability (PDV) and Interdecadal Pacific Oscillation (IPO)-like patterns have also been shown to affect Sahel rainfall, with positive IPO-like phases favouring drier Sahel conditions (Joshi et al., 2022; Mohino et al., 2011a, b; Pomposi et al., 2016; Rodríguez-Fonseca et al., 2011; Villamayor and Mohino, 2015). In particular the tropical SST anomalies of
135 the IPO have been argued to play the dominant mechanistic role, by altering tropical overturning circulation and enhancing subsidence over the Sahel, suppressing convection and rainfall (Mohino et al., 2011a). The pattern correlation between the precipitation-SST regression and the SST anomaly pattern corresponding to the PDV (Fig. 1c, displayed for negative loading for comparability to Fig. 1a) is $r = -0.45$, showing the broad triangular cooling in the east Pacific.

The regression analysis further reveals a dipole-like signal in the Indian Ocean (Fig. 1a); however, we do not retain it as an
140 additional driver for further analysis. This does not imply that Indian Ocean SSTs are dynamically irrelevant for Sahel rainfall. Rather, in the present decadal framework, the Indian Ocean variability is not sufficiently independent from the selected Pacific driver: the PDV associated pattern shows a dipole structure over the Indian Ocean and indeed, the decadal Indian Ocean Dipole (IOD) index, defined as in Saji et al. (1999) is strongly correlated with PDV (at $r = 0.61$), while the IOD's regression pattern (not shown) is only moderately correlated with the Sahel precipitation-associated SST pattern as shown in Fig. 1a ($r = 0.17$).

145 The correlation between AMV and PDV is $r = -0.26$, implying that approximately 7% of their variability is not independent. This is expected from physical arguments of interbasin teleconnections (Meehl et al., 2021; O'Reilly et al., 2023) and comparable to results from CMIP5, CMIP6 and observations (Xu et al., 2025).

Overall the regression analysis presented in Fig. 1a indicates that decadal Sahel rainfall variability in CESM2 is associated with large-scale SST reorganizations rather than with a single adjacent ocean basin. AMV and PDV are two physically
150 interpretable, established and largely independent modes of decadal SST variability, which explain the key features of the SST-driven signal.

3.2 The atmospheric circulation and Sahel precipitation response to AMV and PDV

We next investigate the atmospheric mechanisms through which the selected AMV and PDV drivers affect Sahel precipitation. Figure 2 shows the regression of decadal summer circulation and precipitation anomalies on AMV and PDV in piControl

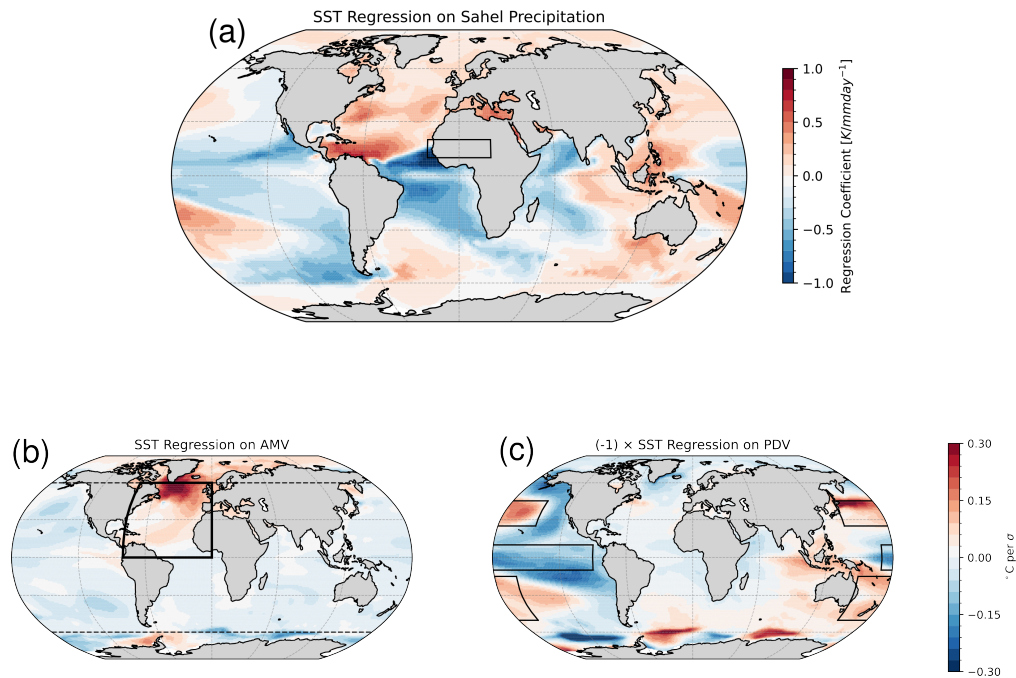


Figure 1. Remote Oceanic Drivers of Sahel Summertime Precipitation a) Regression coefficients [K day mm^{-1}] between decadal means of JAS sea surface temperatures (SST) and decadal means of JAS precipitation for the total Sahel in piControl. b) Decadal means of JAS SST regressed on decadal AMV and c) and on decadal PDV, multiplied by (-1) for visual comparability with a).

around the Sahel region. A positive AMV phase is associated with a coherent organisation of the meridional circulation (Fig. 2a-c): The ascending branches of the Hadley Cell are shifted northward as indicated by the dipole of vertical velocity anomalies, so that the deep convective cell between 10°N and 20°N and the shallow convective cell are strengthened (Fig. 2a). Zonally, the signal is the strongest over the Atlantic Ocean and western Sahel from 30°W to 0° , with ocean-land differences in the response of the shallow convective cell (Fig. 2b). This response is consistent with the warming of the North Atlantic, which characterises a positive AMV phase (Fig. 1b), and the resultant increased interhemispheric temperature contrast, which favours a northwards shift of the ITCZ, as also reported in observational and modelling studies (Sheen et al., 2017; Monerie et al., 2019; Rodríguez-Fonseca et al., 2015). The resultant precipitation response (Fig. 2c) follows the circulation anomaly and is most pronounced in the Western Sahel (20°W to 5°W). The stronger precipitation response over the ocean in Fig. 2c suggests that the SST variability is particularly effective in driving precipitation variability in the coastal part of the monsoon system, where low-level moisture transport and regional convergence can directly increase moist static energy, affecting convective instability and rainfall. Regression of sea-level pressure confirms the results from the vertical cross-sections (Fig. S2a), as do previous findings (Mohino et al., 2011a; Monerie et al., 2019).

Compared to AMV, the effect of the PDV has a more homogenous imprint on the atmospheric circulation and is associated with anomalous subsidence across most of the climatological ITCZ latitude band (Fig. 2d). In line with upper level convergence,



170 shown by velocity-potential regressions (Fig. S2d) and visible as southerly and easterly horizontal wind anomalies around 250hPa, positive PDV states show subsidence motion between 5°N and 20°N (Fig. 2d) and from 30°W to 30°E (Fig. 2e) and, contrary to AMV, no shift of the meridionally overturning circulation. The main exception is the shallow circulation at around 17°N which shows indications of a northward displacement (Fig. 2 d). Overall the regression suggests that PDV primarily modifies the vertical structure and stability of convection over West Africa, rather than shifting the full monsoon circulation meridionally. This interpretation is consistent with previous work viewing Pacific impacts on Sahel rainfall as mediated by large-scale tropical energetics and atmospheric stability, with Pacific SST anomalies increasing tropospheric stability over West Africa and suppressing deep convection (Cai et al., 2025; Neelin et al.; Pomposi et al., 2016). In the precipitation response signal, PDV is associated with reduced summer rainfall across the Sahel, consistent with anomalous subsidence and increased stability over the Sahelian rain belt. This drying response, spatially coherent with the atmospheric circulation modulation, agrees with previous studies linking positive PDV-like conditions to reduced Sahel rainfall on decadal timescales (Mohino et al., 2024; Monerie et al., 2019).

In summary, our results are consistent with previous studies and indicate that AMV acts primarily through a meridional temperature-gradient and ITCZ-shifting pathway, whereas PDV influences precipitation mainly through a stability and subsidence pathway over the Sahelian rain belt. Importantly, these established mechanisms are overall captured by CESM2, supporting its use for investigating how decadal ocean variability shapes Sahel precipitation variability.

3.3 Internal variability storylines of Decadal Sahel Precipitation

Whereas the previous section considered the drivers separately, here we examine how AMV and PDV jointly organize atmospheric circulation and precipitation anomalies over the Sahel through the use of internal variability storylines. The construction of the storylines is done by averaging over the anomalies of decadal means in each of the four quadrants in the AMV-PDV phase space (see 2) and Fig. 3). Each storyline consists of roughly 20 decadal means [16, 29, 19, 24 (starting top right, going anticlockwise), 22 in neutral.]

The strongest circulation anomalies occur in the out-of-phase storylines: In AMV+/PDV- (bottom right quadrant in Fig. 3, green frame in Fig. 4, the meridional circulation shows a northward displacement and strengthening of the northern ascending branch (10°N–20°N, Fig. 4d). This signal is coherent in the zonal cross sections, with the strongest ascending motion near the prime meridian. Over the Atlantic ocean, convection extends through the entire depth of the troposphere, while the lower-tropospheric response over land is more mixed, as a result of the northwards shift of the shallow convective cell (Fig. 4g). The AMV-/PDV+ storyline (top left quadrant, brown frame) shows opposite patterns: the monsoon circulation weakens overall as well as shifts southward (Fig. 4a), and anomalous subsidence dominates over the Sahelian rain belt (Fig. 4a, e). These two out-of-phase storylines therefore represent the constructive combination of the individual driver effects of AMV and PDV and the alignment of PDV-related subsidence and the AMV-caused circulation shift, resulting in an overall suppressed (enhanced) convection over the Sahel region in the AMV-/PDV+ (AMV+/PDV-) storyline. This circulation modulation can also be regarded dynamically through changes in sea level pressure and low-level winds, showing the strongest wind anomalies in the out-of-phase storylines at 15 N°, in line with a northwards shift of the ITCZ (Fig. S4b,d). Equally, the upper level velocity potential

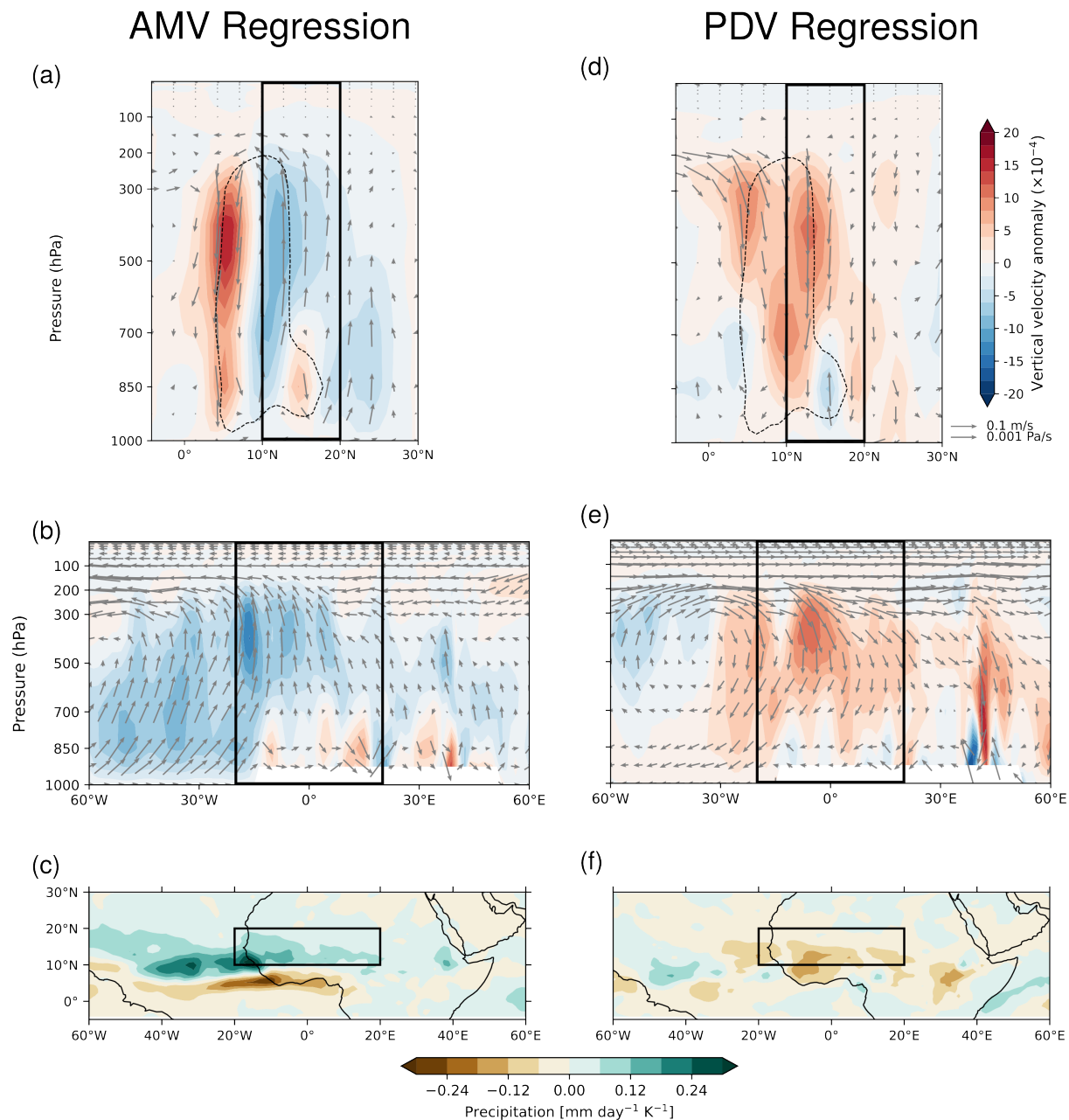


Figure 2. Mechanisms of Sahel Rainfall Modulation **a)** Regression coefficients between decadal means of summer (JAS) vertical velocity (shading) and meridional velocity (vectors) averaged between 20°W and 20°E (black box in **b**), and decadal means of AMV. Dashed contours denote the climatological summertime circulation at $\omega = -0.03 \text{ Pa/s}$. **b)** Vertical velocity (shading) and zonal velocity (vectors) averaged between 10°N and 20°N (black box in **a**) regressed against decadal means of AMV. **c)** Regression coefficients of decadal means of JAS Precipitation on decadal means of AMV. **d-f)** Same as **a-c)** but for PDV instead of AMV.

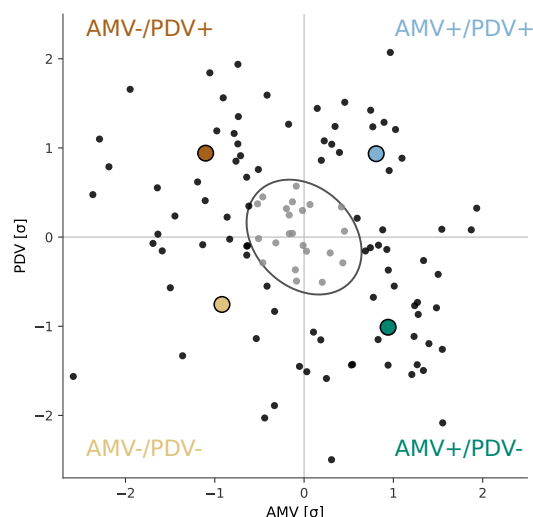


Figure 3. Storylines of Physical Coherent Changes Phase-space of standardised AMV and PDV for piControl decadal means (black dots). The grey dots are part of the neutral phase, which is excluded; storylines are grouped by quadrants and colored dots denote the respective sub-ensemble mean. Members per phase: 16, 29, 19, 24 (starting top right, going anticlockwise), 22 in neutral.

patterns and divergent winds indicate increased convergence (divergence) in the AMV-/PDV+ (AMV+/PDV-) storylines (Fig. S4e,h)

The in-phase storylines show weaker and more asymmetric circulation responses: In AMV+/PDV+ (top right quadrant in Fig. 3, blue frame Fig. 4), the meridional circulation shows a slight southward shift and a strong overall weakening of convection (Fig. 4b), with the strongest anomalies between the equator and 10°N. In the zonal cross section, the response is convective over the ocean but mixed over land, with weak subsidence over parts of the continental sector (Fig. 4f). The AMV-/PDV- storyline (bottom left quadrant, yellow frame) is not symmetric in pattern to AMV+/PDV+, but instead, it primarily shows a displacement of the circulation rather than a coherent strengthening or weakening (Fig. 4c).

This asymmetry in the circulation response to AMV phases under different PDV phases suggests that PDV does not act linearly across its positive and negative phases. Rather, a positive PDV appears to act as a stability constraint on Sahel convection with convection over the Sahel being inhibited, even when AMV is positive (Fig. 4b). In contrast, negative PDV appears to relax this constraint but does not by itself imply enhanced continental convection (Fig. 4c). Consequently, differences between an AMV- and AMV+ storyline are more pronounced in circulation if PDV is negative (Fig. S3). This behavior is consistent with an “upped-ante mechanism”, in which PDV increases the tropospheric temperature and thus the moist static energy threshold for deep convection to occur (Neelin et al.; Giannini et al., 2013).

The precipitation response spatially aligns with the circulation anomalies. As a result of the joint organisation of atmospheric circulation, the out-of-phase storylines produce the strongest Sahel rainfall signals, with wet anomalies in decreased subsidence and northwards displaced ITCZ modulated AMV+/PDV- storyline and dry anomalies in the opposing AMV-/PDV+



storyline. In both cases, the largest anomalies occur just west of the zero meridian, consistent with the location of the strongest vertical-motion response in the circulation cross sections, but show the same sign throughout the Sahel region. Just as the circulation anomalies, the precipitation signal is stronger over land than over ocean. This is even more the case for the in-phase storylines, where continental Sahel anomalies remain weak and less spatially coherent, with land anomalies being restricted nearly exclusively to coastal areas. As explained by the asymmetry in the circulation response, we also find an asymmetry in the precipitation signal of the in-phase storylines and a larger sensitivity to AMV changes under a negative PDV state (Fig. S3c,d).

3.4 The North Atlantic Relative Index (NARI) as a storyline mediator

In the previous section we have shown that the out-of-phase combinations of AMV and PDV leads to constructive effects over the Sahel region and results in the symmetrically opposing, pronounced precipitation anomalies. We next assess how their combined effect can be represented by a single index, namely the North Atlantic Relative Index (NARI). This index has been introduced by Giannini et al. (2013), defined as the difference between the tropical North Atlantic (10–40°N, 75–15°W) and global tropical (20°S–20°N) mean sea surface temperature anomalies (see boxes in Fig. 5a),

$$NARI = SST_{NATL} - SST_{Tropical} \quad (1)$$

A positive North Atlantic term captures the regional energetic and moisture supply favorable to a northward displacement of the ITCZ, while the tropical-mean term approximates the free-tropospheric temperature constraint on Sahel convection (Neelin et al.; Giannini et al., 2013). In this context, Sahel rainfall has been shown to be enhanced when the North Atlantic warms relative to the tropical mean (high NARI), but suppressed when tropical warming increases stability over West Africa (low NARI). We here test how NARI serves as a reduced representation of the AMV-PDV storylines.

NARI's predictive power for decadal Sahel precipitation variability captures the influence of the North Atlantic and the Pacific. This is apparent in its SST regression pattern (Fig. 5a), showing cross-equatorial temperature gradient in the Atlantic and the PDV-like triangular cool waters in the Pacific. Accordingly, much of the AMV and PDV variability is captured by NARI. Figure 5b) shows the AMV-PDV phase space, with the scatters colored by NARI value indicating a strong relationship. Fitting a multiple linear regression model ($\hat{NARI} = 0.58\hat{AMV} - 0.54\hat{PDV} + \epsilon$) in CESM2 piControl, we find that 79% of decadal NARI variability is explained by the two drivers (Fig. 5b). The high-impact out-of-phase AMV+/PDV- and AMV-/PDV+ storylines occupy the high- and low-NARI ends of the phase space, respectively, while the in-phase storylines lie closer to intermediate NARI values. NARI thus provides a compact representation of the oceanic variability along the out-of-phase storyline axis, spanning from AMV+/PDV- to AMV-/PDV+.

Consistent with this, we find the NARI index in the CESM2 piControl simulations to be strongly positively correlated with total Sahel precipitation ($r=0.60$, $p<0.01$). Thus, this single relative-SST index explains about 37% of the decadal variance in total Sahel precipitation (Fig. 5c). Notably, this value is close to the maximum SST-driven decadal variability signal in CESM2 for the Sahel as found by Noyelle et al. using ridge regression with global SST patterns as inputs.

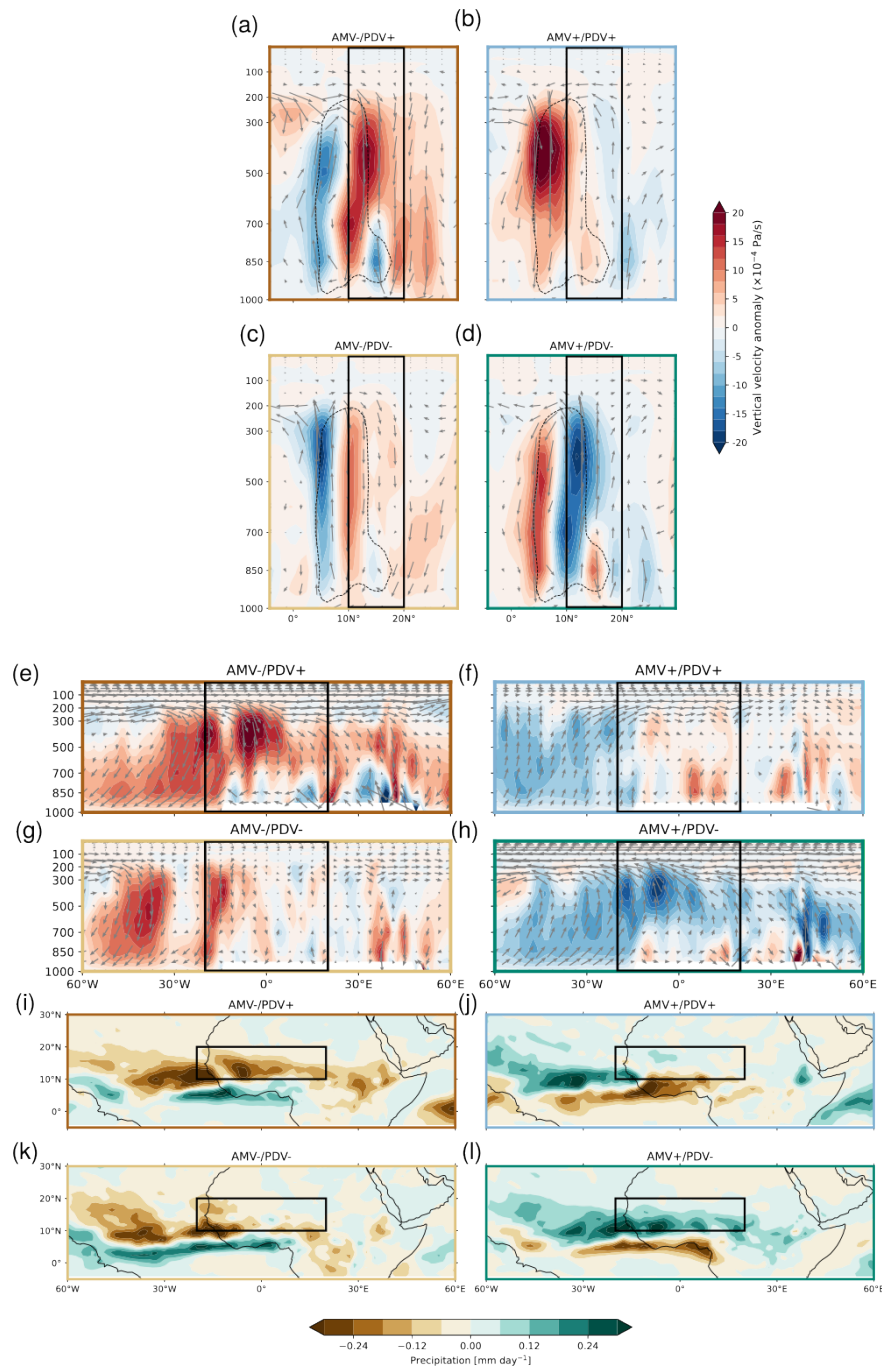


Figure 4. Storylines of Physical Coherent Changes **a-d)** Anomalies of vertical motion (shading) and meridional and vertical winds (vectors) averaged from 10°N to 20°N for each storyline. Dashed contours denote the climatological summertime circulation at $\omega = -0.03 \text{ Pa/s}$. **e-h)** As in a) for vertical and zonal winds between 20°W and 20°E. **i-l)** Anomalies of precipitation for each storyline.

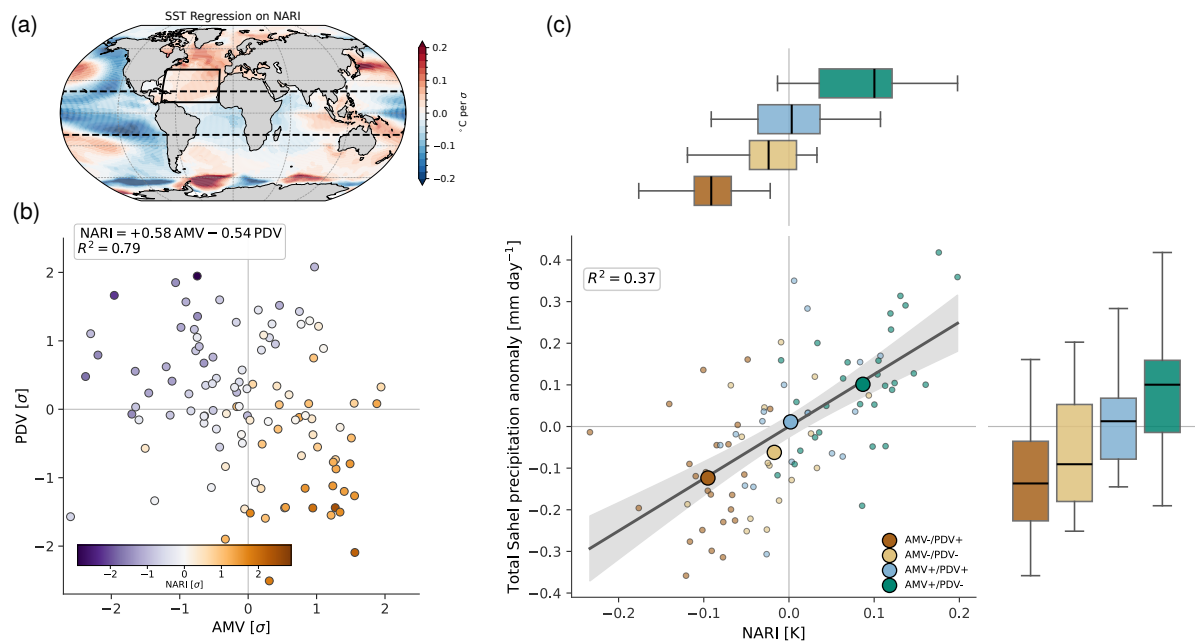


Figure 5. North Atlantic Relative Index (NARI) as a mediator of AMV–PDV variability and its link to Sahel precipitation. **a)** Decadal summertime SST regressed on decadal NARI anomalies in piControl. Boxes denote the averaging regions for the computation of NARI. **b)** NARI (shading; [K]) in standardised phase space. **c)** Total Sahel precipitation anomaly (mm day^{-1}) as a function of NARI. The solid line shows the least-squares linear fit, with shading indicating the 95% confidence interval ($R^2 = 0.37$, $p < 0.01$). Points are colored by storyline, with filled markers indicating the corresponding IVS means. Distribution of NARI (top) and precipitation anomalies (right for each storyline with boxes (whiskers) denoting the 50% (100%) range and black lines the medians.

The box and whiskers plots in Fig. 5c further show the organization of the oceanic state (represented by NARI) and the Sahel precipitation response by the storyline partitioning. The storyline distributions separate more clearly in NARI (marginals on top) than in precipitation itself (marginals on the right). An analysis of variance indicates that the AMV/PDV storyline classification explains about 61% of NARI variance, compared with about 24% of total Sahel precipitation variance. This difference is expected as the storylines separation is performed by oceanic drivers, and therefore constrains the large-scale SST-based NARI more tightly than the regional precipitation response.

NARI thus provides a compact representation of the oceanic variability along the out-of-phase storyline axis, spanning from AMV+/PDV- to AMV-/PDV+. Its approximately linear relationship with Sahel precipitation, supported by the physical mechanisms described above, links this oceanic variability directly to the regional precipitation response and therefore provides a useful one-dimensional framework for investigating precipitation storylines across the full range of these oceanic states.



3.5 Modulation of Forced Changes by Internal Variability Storylines

265 Based on the piControl experiment, which is free of external forcing, we have established that it is the out-of-phase AMV-PDV storylines which are most relevant for decadal NARI variability and consequently precipitation variability in the Sahel. In this section we assess their potential to modulate the near-term forced precipitation response by utilising the 100-member SSP3–7.0 scenario. A causal network analysis (Fig. S5) shows the consistency of the effect strength between oceanic drivers, mediator and precipitation in piControl and SSP3–7.0, which supports the use of piControl-derived internal-variability storylines to interpret future precipitation change modulation in SSP3–7.0 and NARI as a one-dimensional storyline index, conceptually comparable to the storyline index in model uncertainty story lines (Zappa and Shepherd, 2017; Mindlin et al., 2020).

Figure 6a shows the forced Sahel precipitation changes (solid line), computed as the CESM2 ensemble-mean standardised summer decadal precipitation change based on SSP3–7.0 forcing with respect to a present climate baseline (2015–2035), as well as the standardised NARI ensemble mean forced response, which well explains the precipitation trend with a correlation coefficient of $r = 0.96$ ($R^2 = 0.92$). In the Western Sahel, the precipitation declines throughout the century, with the correlation with NARI being close to unity ($R^2 = 0.99$, Fig. S7). The initially slower response in Total Sahel Precipitation is a result of the transient wetting trend in the central Sahel (see Fig. S8). Throughout the century, Sahel precipitation shows pronounced decadal variability, which we show by plotting the projected Sahel precipitation changes of all 100 ensemble member, alongside the ensemble mean (Fig. 6b). Indeed, internal variability determines the sign of decadal anomalies in the near- and mid-term (Fig. 6c). Only at the end of the century the forced response is so dominant, that the chances of experiencing positive decadal precipitation anomalies vanish (Fig. 6d). The colors of the members' decadal average precipitation changes indicate the respective decadal NARI changes. High NARI values (purple) are associated with above ensemble mean precipitation changes, while low NARI values (orange) are linked to below average precipitation changes. This stresses that NARI not only explains the forced response (Figure 6a) but also remains effective in representing ensemble precipitation variability throughout the century, with a time averaged correlation coefficient of 0.58 over the century, consistent with piControl (Fig. S6).

The modulation of the forced response by NARI is exemplified for the Mid-Term and the End-of-Century in Fig. 6c) and d), respectively: In the mid-term, the forced response is close to zero and NARI variability explains about half of the total Sahel precipitation variability ($R^2 = 0.49$). For the end of century, the forced Sahel drying dominates, with NARI explaining only about a third of the variance ($R^2 = 0.28$). Using NARI as a storyline index to target the extreme driver combinations, we construct dry and wet storylines as the top and bottom quintile of the NARI distribution. The NARI-constructed storylines are largely equivalent to the out-of-phase AMV/PDV storylines, being roughly the same size with $\sim 2/3$ of the members being equal and the resultant mean values and spatial patterns nearly indiscernible. The storylines well separate the Total Sahel Precipitation response, with almost no overlap in their distributions (Fig. 6c) and mean precipitation anomaly of $-0.22 \text{ mm day}^{-1}$ and $+0.15 \text{ mm day}^{-1}$ for the dry and wet storylines.

295 Figure 7 highlights the spatial heterogeneity of the modulation of forced response in the mid-term: The forced response exhibits a pronounced zonal dipole, with drying over the western Sahel and wetting over the central Sahel (Fig. 7a). This drying pattern in the Western Sahel is more than doubled in the low NARI (AMV-/PDV+) storyline (+119%), while it is nearly

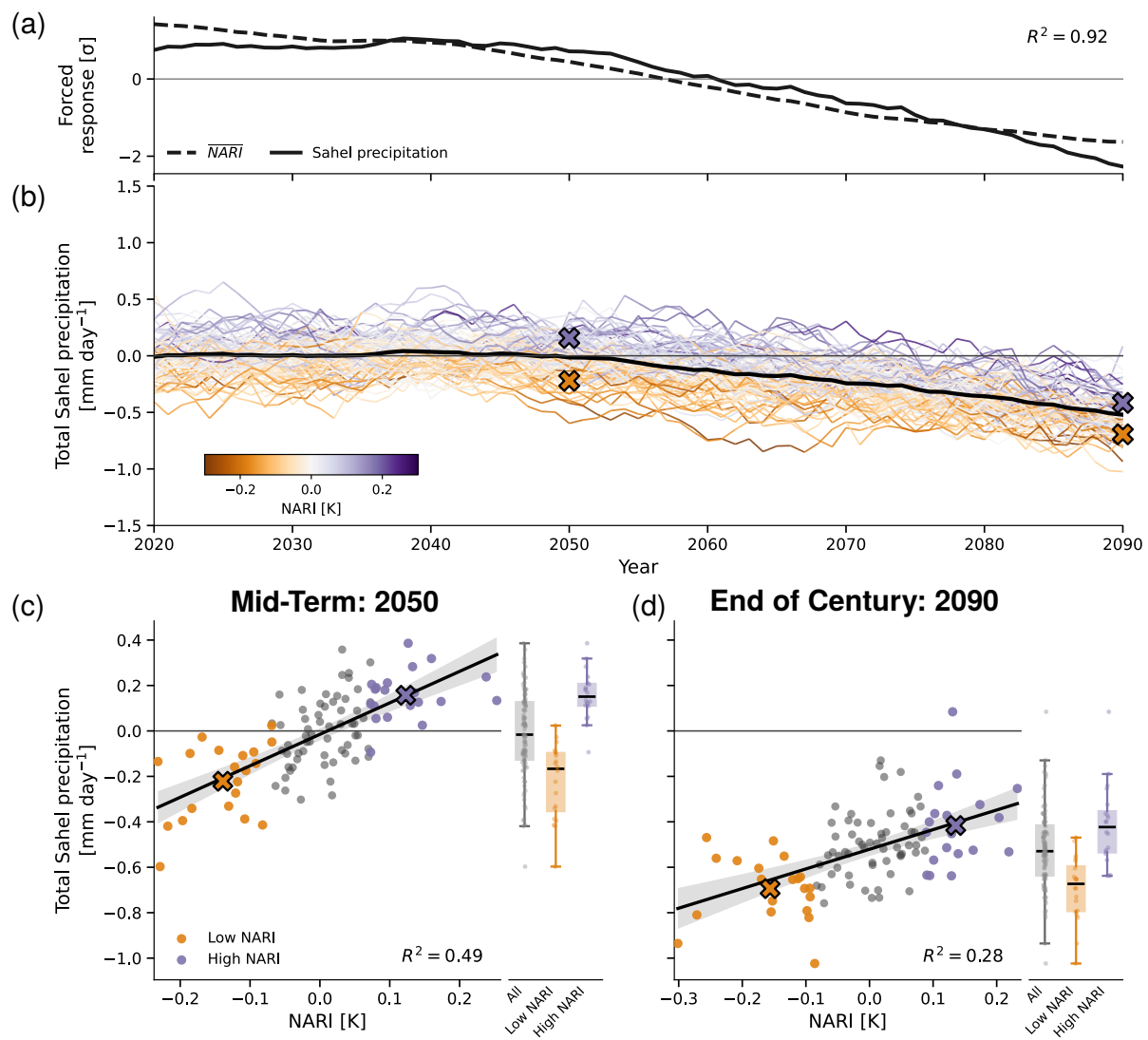


Figure 6. Modulation of the Total Sahel Forced Response by NARI over time. **a)** Ensemble mean of JAS decadal precipitation changes over the Total Sahel (solid line) and ensemble mean of decadal NARI ($\overline{NARI}$, $r = 0.96$). **b)** Ensemble mean of decadal precipitation (solid line) and all members, colored by decadal NARI anomaly value. **c)** NARI anomalies and Total Sahel precipitation for the mid-term (2050) and their regression as in Fig. 5b) ($r = 0.7$). Precipitation distribution of the storylines of low and high NARI show to the right. Crosses denote the means of each storyline and their position in b) is indicated. **d)** As in c) for the End of century (2090, $r = 0.52$).

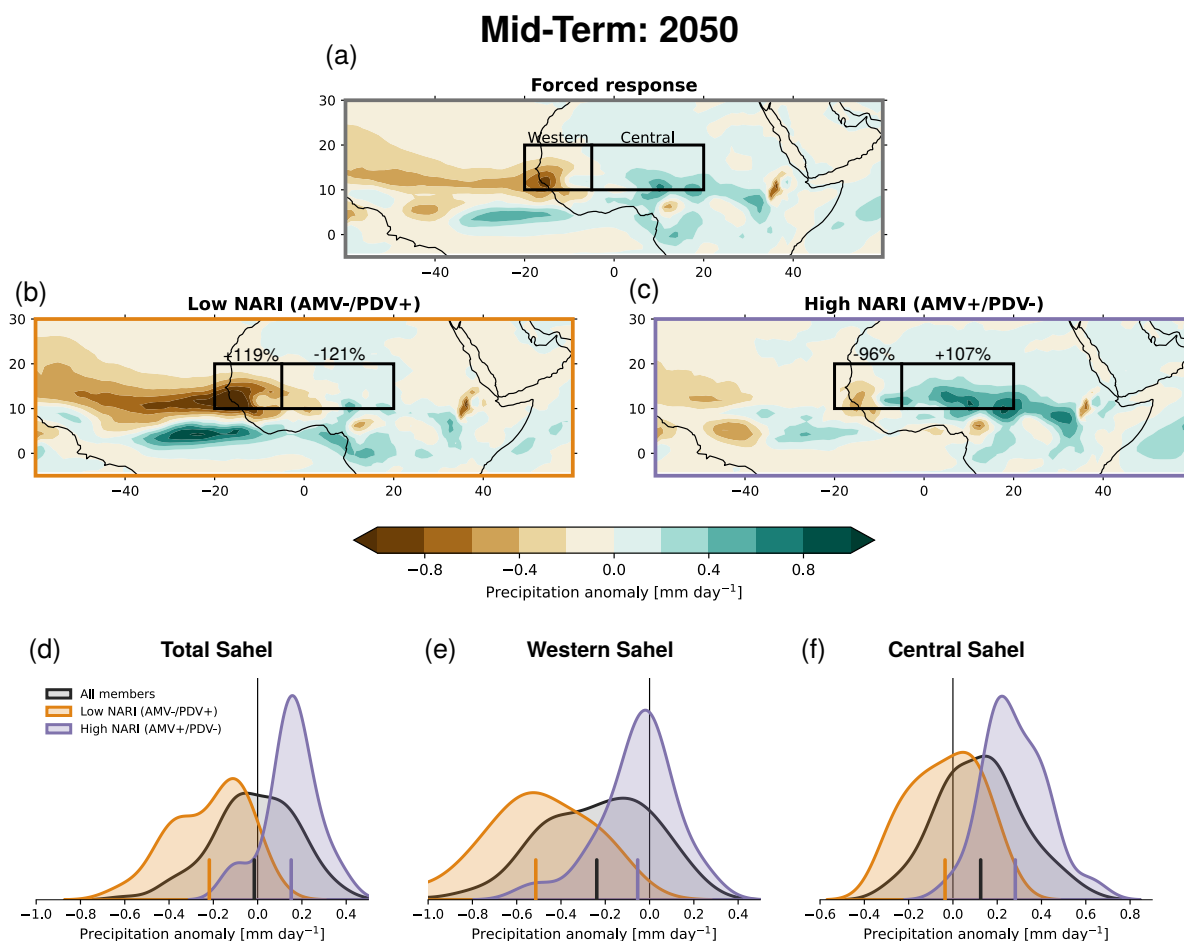


Figure 7. Modulation of mid-term (2050) Sahel precipitation change by AMV–PDV storylines. a) CESM2 ensemble-mean JAS decadal precipitation change for 2050 relative to a 2015–2035 climatology. Plausible JAS precipitation changes conditioned on NARI storylines for 2050 relative to 2015–2035: b) low-NARI storyline (AMV-/PDV+) and c) high-NARI storyline (AMV+/PDV-). Percentages in b) and c) over the boxes denote changes relative to the forced response for each storyline for the Western and Central Sahel. d) Total Sahel precipitation distribution kernel density estimates for the total ensemble (black) as well as the Low NARI (AMV-/PDV+) and High NARI (AMV+/PDV-) storylines. Short vertical lines indicate the mean. As in d) for the e) Western Sahel and f) Central Sahel.



completely nullified in the wetting storyline (-96%), see Fig. 7b,c and e. The transient wetting in the Central Sahel is equally strongly affected, showing a reverse of the sign when conditioned on low NARI (-121%, Fig. 7b, f) and is more than twice as large in high NARI (AMV+/PDV-) storyline (+107%, Fig. 7c, f). At the end of the century, the forced response of Total Sahel precipitation is strongly negative ($-0.51 \text{ mm day}^{-1}$), following the negative trend of the NARI ensemble mean; at this point, internal variability storylines still modulate the forced response overall (Fig. 6d) as well as on subregional scales (+/-16% for the Western Sahel, +/-47% for the Central Sahel, Fig. S9), however the forced response dominates.

In summary, internal variability strongly modulates the forced precipitation response, and this modulation can be described by internal variability storylines. This is most pronounced in the near- and mid-term where they separate positive from negative anomalies for the Total Sahel and highlight internal variabilities potential to double (or cancel out) the forced response for the regions of the Western and Central Sahel.

4 Discussion

The here identified impact of the individual drivers and their modulation of the atmospheric circulation is consistent with previous studies of decadal precipitation variability in the Sahel. The AMV-induced interhemispheric temperature gradient drives a displacement of the ITCZ, as shown with other fully coupled models (Mohino et al., 2011b; Martin et al., 2014; Monerie et al., 2019, 2023; Joshi et al., 2022; Rodríguez-Fonseca et al., 2011) idealised model experiments (Mohino et al., 2011a) and observational studies (Mohino et al., 2011b; Joshi et al., 2022). The PDV-related tropical teleconnections and Sahel-wide drying are likewise consistent with previous studies (Villamayor and Mohino, 2015; Pomposi et al., 2016; Joshi et al., 2022; Rodríguez-Fonseca et al., 2011; Cai et al., 2025). Our study extends these findings by studying the joint effect on the atmospheric circulation and precipitation response. While AMV and PDV influence Sahel rainfall through dynamically distinct pathways, the largest decadal anomalies in circulation and thus precipitation arise in their out-of-phase configuration, as shown schematically in Fig. 8: In the PDV+/AMV- storyline, deep convection in the Pacific increases the tropospheric temperature and thus stability over the African continent, enhancing subsidence (Fig. 8a), while cool waters in the North Atlantic lead to a southwards displacement of the ascending branch of the Hadley Cell. The combined effect of these atmospheric changes is a Sahel-wide drying. The opposite occurs in the PDV-/AMV+ storyline, where a warmer North Atlantic shifts the ITCZ northwards, while the decreased stability allows for more convection over the Sahel (Fig. 8b). This joint perspective is consistent with Joshi et al. (2022), who identified a global interdecadal SST variability pattern in observational products that resembles the AMV+/PDV- state and produces strongest wetting over the Sahel. The circulation anomalies in the out-of-phase storylines are furthermore in line with Sheen et al. (2017) who identified differences in atmospheric states between multi-year dry and wet periods over the Sahel. In our study, we combined these elements into one physically coherent framework linking remote drivers, joint circulation responses, precipitation anomalies and the modulation of the forced response to provide a physically based interpretation of variability and change in a large ensemble of simulations.

In the in-phase storylines, the circulation effects partially cancel each other, resulting in insignificant precipitation responses over the Sahel. It is noteworthy, that the atmospheric anomalies in the AMV+/PDV+ storyline are not simply the opposite of

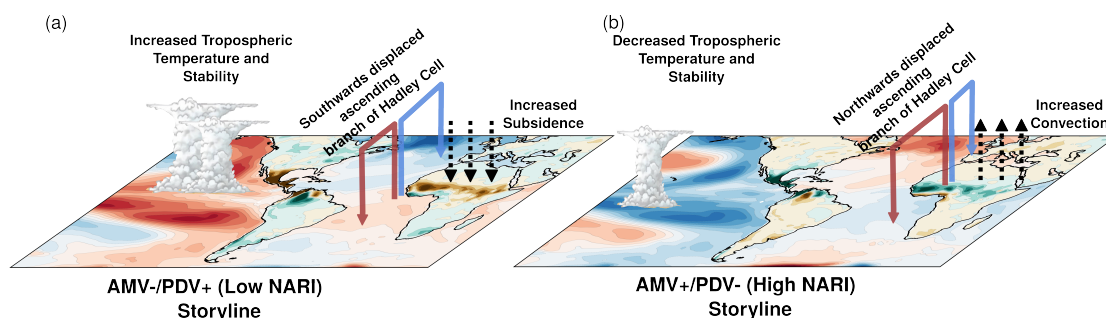


Figure 8. Schematic of Mechanism of Sahel Rainfall Modulation. Decadal summertime anomalies of SST and land precipitation in the piControl Storylines of **a)** PDV+/AMV- and **b)** PDV-/AMV+. Black arrows represent the Hadley Cell and the meridional shift of its ascending, convective branch; clouds represent deep convection warming the troposphere and grey arrows the anomalies of subsidence/ascent resulting from the increased/decreased stability.

the AMV-/PDV- one, which is interpreted as an upped-ante threshold behaviour imposed through tropospheric stability by the PDV. In line with this interpretation, the influence of AMV on circulation changes is larger under a negative PDV state (Fig. S3).

The impactful out-of-phase driver combinations project onto the North Atlantic Relative Index (NARI): AMV and PDV jointly explain 79% of NARI variability. Through its North Atlantic term, NARI represents the impact of regional energetic and moisture contributions and the larger-scale conditions to shift the ITCZ, while its tropical part represents the free-tropospheric stability constraint; NARI thus combines the two main physical pathways by which the drivers impact Sahel precipitation and explains nearly 40% of its variability. The modulation of future, forced changes is thus discussed in terms of NARI-conditioned states: throughout the century NARI correlates robustly with precipitation and effectively separates dry from wet decades in the near- and mid-term (Fig. 6 and 7); towards the end of the century, the forced response begins to dominate, although substantial regional modulation remains (Fig. S7, S8, S9).

Stemming from a single-model study, the results presented depend on the realism of the model. Two potential model biases arise: first, the representation of the drivers themselves, and second, the representation of their teleconnections to Sahel precipitation. For the representation of PDV, CESM2 provides a comparatively strong basis. ? rank CESM2 as the second-best CMIP6 model for PDV representation, based on pattern correlation, decadal power spectral density, and the ratio of tropical to extratropical variability. It is also the best-ranking large ensemble in the assessment of the Multi Model Large Ensemble Archive (MMLEAv2) Maher et al. (2025), suggesting that CESM2 provides an overall credible representation of PDV within both CMIP6 and MMLEAv2. The representation of AMV is more uncertain. CMIP5 and CMIP6 models tend to perform poorly in representing both the spatial pattern and amplitude of AMV when it is defined through Empirical Orthogonal Function (EFO)-based methods (Maher et al., 2025), and CESM2 performs only moderately well in both respects. In this study, we use a box-based definition of AMV, which enforces SST anomalies in the relevant North Atlantic regions, but at the cost of not necessarily capturing the dominant mode of Atlantic variability in this model. This choice therefore prioritizes physical inter-



pretability and consistency with the hypothesized Sahel teleconnection over an EOF-based representation of maximum Atlantic variance. Additional uncertainty arises from the teleconnections themselves. Across models, there is substantial discrepancy in the strength of SST–hydroclimate teleconnections and, in the case of PDV, even in the sign of the Sahel precipitation response (?). At the same time, observational evaluation is difficult. The reliable observational record is short (Sun et al., 2018), and the twentieth-century Sahel rainfall record is strongly affected by aerosol forcing (Biasutti and Giannini, 2006; Herman et al., 2020; Ackerley et al., 2011). This makes it challenging to isolate internally generated hydroclimatic teleconnections from forced variability. Overall, there are indications that the fraction of Sahel precipitation variability explainable by oceanic drivers may be underestimated in CESM2. Noyelle et al. show that the full SST field explains roughly 30% of decadal Sahel precipitation variability, which is similar to the variance explained in our SST-based storyline framework. However, they further show that CESM2 lacks substantial year-to-year memory in the Sahel precipitation system, in contrast to observations. This points to missing land–atmosphere feedbacks, or to resolution-dependent ocean–atmosphere interaction processes, that may contribute to the residual variability not being captured by SST-based drivers (Koster et al., 2004; Czaja et al., 2019). Lastly, the near-term precipitation forced response pattern over the Sahel is complex and model-dependent, reflecting the combined effects of greenhouse-gas and aerosol forcing and their influence on regional and remote circulation and SST patterns. The forced response in CESM2 shows a distinct dipole pattern which is model dependent (Monerie et al., 2020b) and has been linked to the evolution of Atlantic and Mediterranean surface temperatures (Monerie et al., 2020b, a, 2025), which strongly affect the regional monsoon response. The central Sahel wetting should also be interpreted as a near- to mid-term transient response, influenced by aerosol-related recovery (e.g., Herman et al. (2020); Ndiaye et al. (2022); Nnamchi and Fiedler (2026) and the fast atmospheric adjustment to increasing CO_2 (Bony et al., 2013).

Our methodological approach builds on the internal-variability storylines developed by Line et al (Liné et al., 2024) for European climate using oceanic and atmospheric drivers in the North Atlantic . We utilise this approach, combined with a process-based selection of drivers, in our investigating of the modulating atmospheric mechanisms and their impact on Sahel precipitation. In the exploration of future changes, we extend the idea by considering NARI (Giannini et al., 2013) as a near-complete mediator of AMV and PDV influence on Sahel participation. NARI, thus, serves as a storyline index and allows the interaction between internal variability and the time-evolving forced response to be investigated throughout the century. In our study, we selected the drivers with a priority on mechanistic understanding; alternatively, one could utilise statistical methods to optimise the signal in the target variable, such as principal component analysis or Variational Autoencoders (Spuler et al., 2025). To extend the findings of this study to observations and predictions, it is necessary to better understand how the representation of the drivers and their teleconnections affects internal-variability storylines across models. The framework developed here provides a basis for such extensions. The physical interpretation of the AMV–PDV storylines and their reduction to NARI offer concrete diagnostics for model evaluation and multi-model comparison. This is even more important as the forced Sahel precipitation response remains divergent across models (Monerie et al., 2023). We propose to combine storylines of forced-response model uncertainty with multi-model storylines of internal variability to ultimately address model uncertainty and internal variability in the evolution of future regional climate change.



Our results offer a concrete avenue for addressing the limitations of decadal predictions and the noteworthy lower and less consistent skill for precipitation and circulation than for temperature (Smith et al., 2019). Robust circulation and precipitation skill may depend on correctly capturing the joint phases of both AMV and PDV, rather than either driver in isolation. Hindcast evaluation could thus directly assess whether a system is able to reproduce the observed AMV-PDV phase relationship or the evolution of NARI.

More fundamentally, however, we view the storyline approach as a conceptually distinct form of near-term climate information, complementing rather than competing with initialised prediction. Instead of aiming for a single best estimate of the coming decades, storylines characterise the physically plausible bounds of their outcomes on the basis of established atmospheric mechanisms — reframing the question from "what will happen" to "what could plausibly happen, and why." This approach also offers a physical basis for ensemble-member selection in downscaling and impact studies, as has already been done for model-uncertainty storylines (Cardoso et al., 2026; Graff et al., 2026): members representing the relevant storylines can be specifically chosen to characterise a larger range of plausible Sahel precipitation outcomes at higher resolution where computational cost is limited. This can help bridging the gap between the production and use of climate information (Rodrigues and Shepherd, 2022), allowing adaptation planning to proceed on physically interpretable grounds even where initialised predictions cannot yet offer confident, spatially coherent skill.

5 Conclusion

This study demonstrates that decadal Sahel precipitation variability in the 100-member large ensemble CESM2 is not an unstructured residual around the forced response or due to atmospheric internal variability alone; instead, it is organised by remote oceanic drivers. AMV and PDV are established modes of low-frequency oceanic variability which project onto the SST patterns associated with Sahel rainfall variability at decadal timescales, and affect Sahel precipitation through physically distinct pathways. AMV primarily acts through a meridional temperature gradient mechanism, shifting the ITCZ northwards during its positive phase. A positive PDV, in contrast, is associated with increased atmospheric stability and therefore anomalous subsidence over the Sahelian rain belt. When considered jointly, the largest effect on circulation anomaly occurs under a positive AMV (northwards shift of deep convection)/negative PDV (reduced stability) storyline, resulting in a wet Sahel and vice-versa for the opposing combination. The storyline partitioning consistently organizes both atmospheric circulation and precipitation variability and the out-of-phase combinations with the largest influences can be projected on the North Atlantic Relative Index (NARI), which explains 37% of total Sahel precipitation variance. Applying this partitioning to the CESM2 Large Ensemble under SSP3–7.0 forcing, we find that up to the middle of the century, the storylines substantially modulate the forced response and can double or cancel forced precipitation changes in the Sahel. While the use of Internal Variability Storylines as a communication tool for plausible future changes is thus most relevant for the near- and mid-term future, their influence on the forced response persists across timescales. Our results support the use of internal-variability storylines as a physically interpretable framework for near- to mid-term Sahel rainfall uncertainty, complementing initialised predictions to improve actionable climate information at the regional scale.



420 *Code and data availability.* The CESM2 pre-industrial control simulation is available through the Earth System Grid Federation (ESGF), LLNL node. The CESM2 Large Ensemble (CESM2-LE) data are available at <https://www.cesm.ucar.edu/community-projects/lens2>. All code used to reproduce the figures in this study is available on GitHub at https://github.com/juliusMex/Sahel_IVS.

425 *Author contributions.* All authors contributed to the study design, interpretation of results, and writing of the manuscript. Mex performed the formal analysis and wrote the original draft.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. M.K. acknowledges funding from the Horizon Europe project EXPECT (Towards an Integrated Capability to Explain and Predict Regional Climate Changes), Grant Agreement No. 101137656. M.K. and J.Mindlin further acknowledge the Horizon Europe
430 project FUTURA (Future Climate, Impact and Emission Pathways and Infrastructure: Informing Risk, Transitions and Responses for Assessment and Society) Grant Agreement No. 101295156 and J.Mindlin acknowledges funding from the European Union's Horizon 2025 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 101199503. J.Mex acknowledges support from the German Academic Scholarship Foundation. We acknowledge the CESM2 development team for producing and making available the model simulations used in this study. The authors thank Alessandra Giannini, Christophe Cassou, Juliette Mignot, and Paul-Arthur Monerie for
435 helpful discussions.



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