The climate in the mid and high latitudes is influenced by the Southern Hemisphere (SH) jet, primarily due to its association with storm track and low-pressure systems. The jet itself is subject to influence from the El Niño Southern Oscillation (ENSO) during the early austral summer. Furthermore, ENSO exerts an impact on the Southern Hemispheric stratospheric polar vortex (SPV), which in turn impacts the jet's behaviour. This interaction is visually depicted by the causal network illustrated in Figure 1. For this report, our objective is to quantify both the direct and indirect causal effects of ENSO on the jet. Additionally, we also aim to carefully examine the temporal fluctuations of these causal effects.

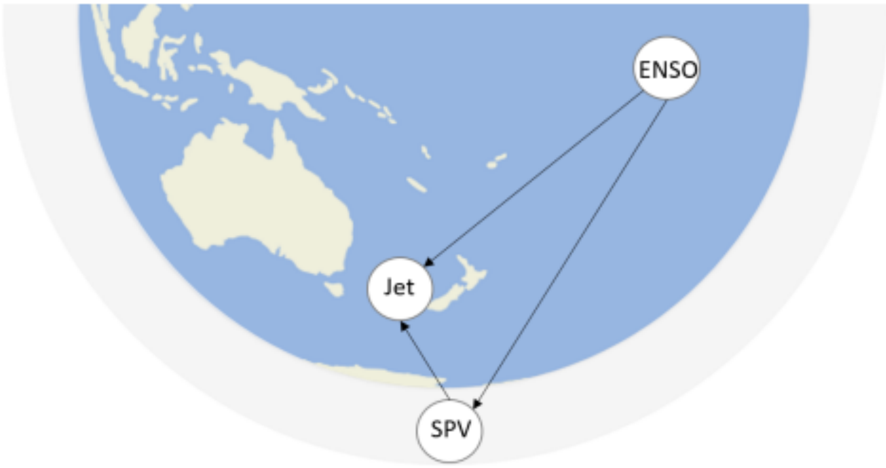


Figure 1: Directed acyclic graph (DAG) showing the direct influence of ENSO on the Jet (tropospheric pathway) and indirect influence via SPV (stratospheric pathway)

The three datasets used for our analysis are obtained from the National Centers for Environmental Prediction (NCEP) reanalysis provided by the National Oceanic and Atmospheric Administration (NOAA)[1][2]. These datasets cover the period from 1950 to 2018. The year 2002 is excluded from the analysis due to its representation of the Sudden Stratospheric Warming on record in the Southern Hemisphere. Consequently, any data corresponding to this particular year is considered an outlier. Each year's data is linked to the October to December (OND) mean for all variables in each dataset, resulting in each year being represented by a single value.

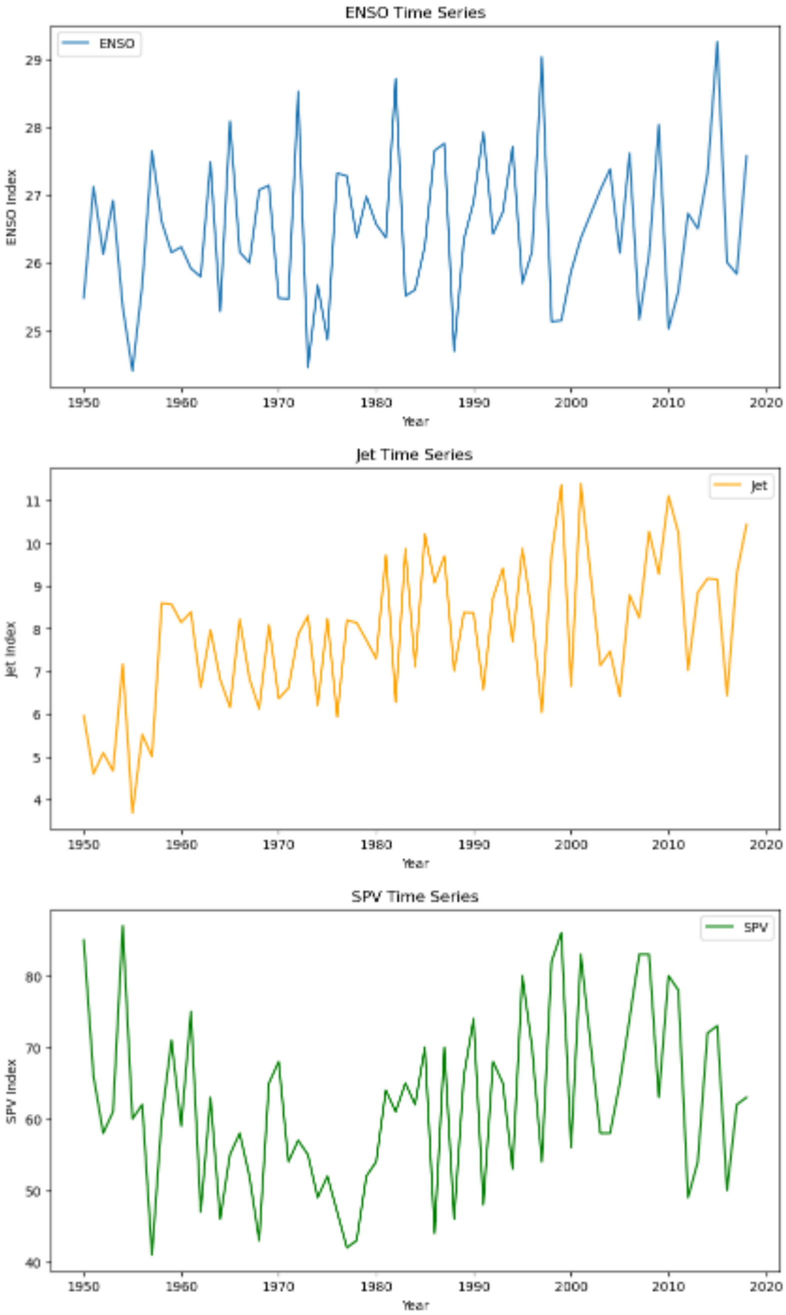
The first dataset contains data for the El Niño 3.4 index (ENSO), expressed in units of degrees Celsius (°C). The second dataset contains data for the jet index (Jet), expressed in meters per second (m/s). It represents the zonal-mean zonal wind data averaged between 55°-65°S at 850 hPa. The third dataset contains data for the Southern Hemispheric polar vortex (SPV) index, computed as the last day in spring when the 5-days moving average zonal-mean zonal-wind, at 60ºS and 50hPA, falls below the 10 m/s threshold. The SPV index is expressed as the number of days following the 1st of October of each season.

1) We explored the datasets by plotting the time series for each dataset (Figure 2) and also provided summary statistics (Table 1). This approach can aid us in understanding the interannual variability for the ENSO, Jet, and SPV indexes.

Table 1: Summary statistics for the ENSO, Jet, and SPV indexes. The ENSO index is measured in degrees Celsius (°C), the Jet index is expressed in meters per second (m/s), and the SPV index unit is expressed in days. The data is sourced

	Mean	Std Deviation	Min	Max	Median	1st Quartile	3rd Quartile
ENSO	26.49	1.09	24.41	29.25	26.35	25.67	27.29
Jet	7.85	1.70	3.69	11.39	8.11	6.60	9.10
SPV	62.04	12.13	41.00	87.00	61.50	53.75	70.00

from the National Centers for Environmental Prediction (NCEP) reanalysis provided by the National Oceanic and Atmospheric Administration (NOAA) and covers the period from 1950 to 2018.[1][2]



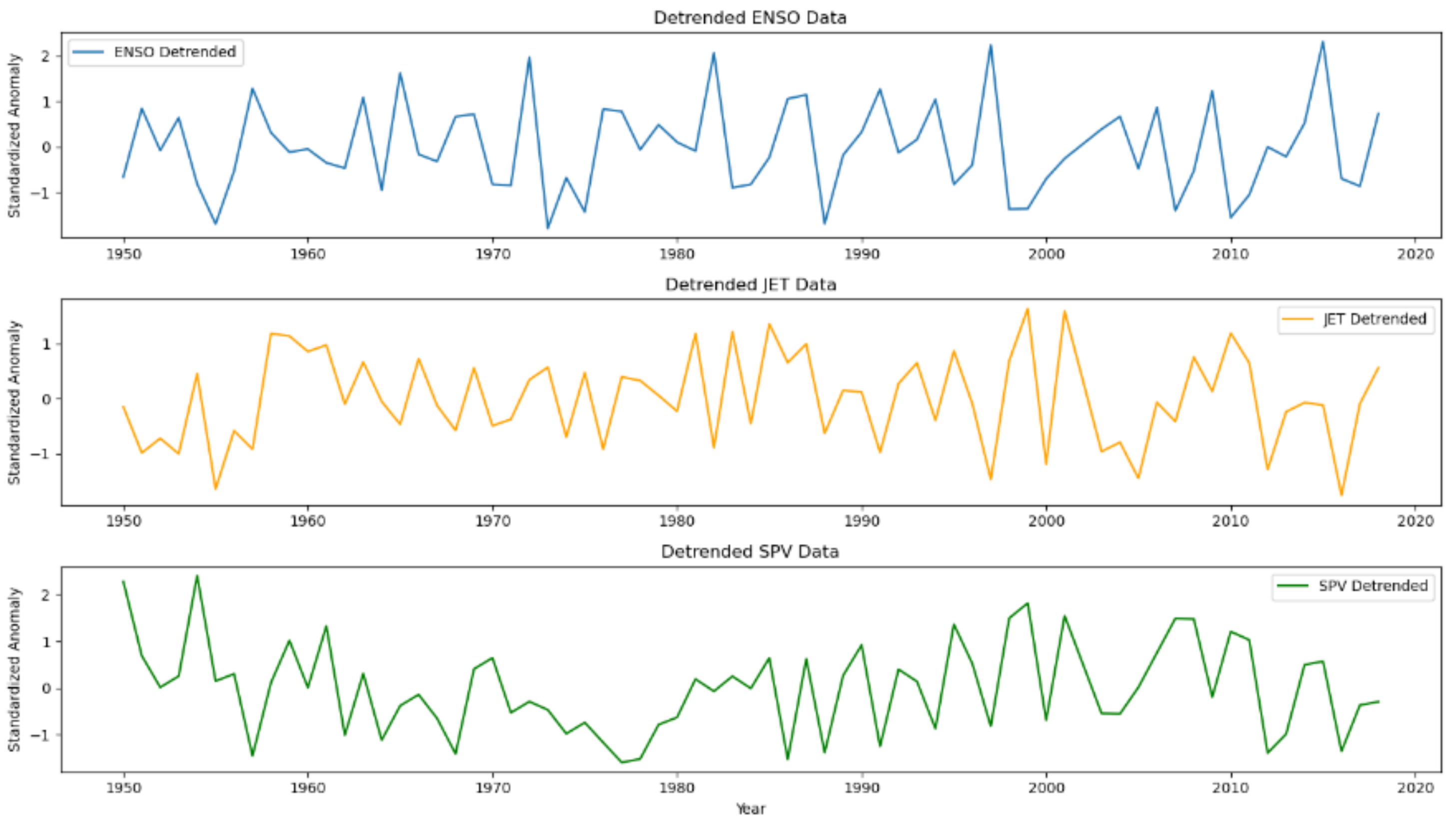
Figures 2(a)-(c)(top to bottom)**:** ENSO Time Series, Southern Hemisphere Jet Stream Time Series and Stratospheric Polar Vortex Time Series. The datasets cover the period from 1950 to 2018.

The time-series depicted in Figures 2(a)-(c) provide a visual insight into the interannual variability of the ENSO, Jet, and SPV indexes. Each graph reveals distinct fluctuations over the observed period, reflecting the dynamic nature of these climatic phenomena. As shown in Table 1, the mean values for the datasets are equal to 26.49°C for ENSO, 7.85m/s for the Jet stream, and 62.04 days for the SPV index. These figures provide a baseline understanding of the central tendencies across the respective datasets.

Furthermore, Table 1 provides insight into the standard deviation for each index. The ENSO index demonstrates a relatively lower standard deviation of 1.09°C, suggesting comparatively less variability in interannual mean values within this dataset. Conversely, the Jet stream index exhibits a moderate standard deviation of 1.7m/s, indicating a greater degree of variability compared to the ENSO index data. Interestingly, the SPV index displays the highest standard deviation at 12.13 days, underscoring significant variability in its interannual mean values.

These observations not only deepen our understanding of the climatic dynamics captured by the datasets but also emphasise the diverse degrees of variability inherent in these key atmospheric indices. Such insights are crucial for elucidating the complex interactions and potential impacts of these climatic phenomena on regional and global climate patterns.

2) After detrending and standardising the time series, we proceed with further analysis on the datasets. We generate plots illustrating the standardised time series for the ENSO, Jet, and SPV indexes. Each index has been detrended and standardised to achieve a mean of 0 and a standard deviation of 1.



Figures 3(a)-(c)(top to bottom): Detrended and Standardised ENSO Time Series, Southern Hemisphere Jet Stream Time Series and Stratospheric Polar Vortex Time Series. Each index has been detrended and standardised to achieve a mean of 0 and a standard deviation of 1. The datasets cover the period from 1950-2018.

This adjustment emphasises the variability of the three indexes relative to their mean state over the period from 1950 to 2018. The detrended and standardised time series are presented in Figure 3(a)-(c). By standardising the time series, we effectively remove the long-term trends and highlight the fluctuations around the mean.

The normalisation process involves the following steps for each time series. First, we subtract the mean value of the time series from each data point. Then, we divide each data point by the standard deviation of the time series. This process standardises the data, making it centered around zero with a standard deviation of 1. This allows us to better discern patterns and anomalies in the data, providing valuable insights into the interannual variability of these climatic indices. This procedure can also be useful for various statistical analyses and machine learning algorithms, as it helps in comparing the different datasets or features on a similar scale.

3) We parametrise the causal network assuming the variables are linearly dependent. We obtain the link coefficients for our causal network by calculating the Pearson-correlation coefficients between our standardised and detrended values of the ENSO, Jet, and SPV indexes. We calculate the respective p-values to provide a measure for the uncertainty and present the findings in Table 2.

Link	**Pearson correlation coefficient**	**P-value**
Jet & SPV	0.47	0.00
SPV & ENSO	-0.27	0.03
ENSO & Jet	-0.17	0.16

Table 2: Table presenting the link coefficients and their corresponding p-values between the ENSO, SPV and Jet indexes for the period 1950-2018 (overall period).

The correlation coefficient for the Jet and SPV is 0.47, which is the strongest correlation observed in Table 2, highlighting a significant direct interaction between the two variables. The corresponding p-value is 0 indicating that the observed association is highly statistically significant, suggesting strong evidence against the null hypothesis. This typically means there is a very low probability that the observed association would have occurred by chance alone, if we assume that the null hypothesis is true. This result indicates a strong positive relationship between Jet stream and SPV.

The link coefficient for the ENSO and SPV is calculated as -0.27. This indicates a weak to moderate inverse relationship between ENSO and SPV. This could imply that higher ENSO index values tend to be associated with an earlier breakdown of the SPV. The p-value of 0.03 indicates that there is statistically significant evidence to reject the null hypothesis at the conventional alpha level of 0.05. This means there's a low probability that the observed association would have occurred by chance if we assume that the null hypothesis is true, suggesting a meaningful association or effect in the study.

We calculated the link coefficient for the ENSO and Jet as -0.17. This value indicates a weak inverse relationship between the ENSO and Jet. This value suggests that, on average, higher ENSO index values are associated with lower Jet index values although the relationship is not the strongest. The p-value of 0.16 also indicates that there is insufficient statistical evidence to reject the null hypothesis at the conventional significance levels (0.05). This suggests that the observed association is reasonably likely under the null hypothesis, implying a lack of strong evidence for a significant effect or association.

The relationships between ENSO with Jet and SPV, although inverse, are weaker. The difference in magnitude of the uncertainties/p-values for the calculated link coefficients reflect the variability inherent in the datasets used to estimate the effects.

4) For the next part of the analysis, we quantified the direct causal effects of ENSO on the Jet. We used the standardised, de-trended datasets from part 3 for our linear regression models. Based on rules of causal inference, the effect of ENSO on the Jet can be assessed by examining the coefficient obtained from a linear regression model. In this model, the Jet serves as the response variable, with ENSO as the predictor variable, while controlling for the SPV.

The direct causal effect of ENSO on the Jet, as determined by the regression analysis, is quantified as approximately -0.042. This implies that, while controlling for the effect of the SPV, a one-standard-deviation increase in the ENSO index correlates with a decrease of 0.04 standard deviations in the Jet index. This effect is direct and does not involve the mediation of the SPV breakdown index.

This procedure is justified by the rules of causal inference because it isolates the effects of ENSO on the Jet in our model by controlling for other variables, such as the SPV, that could potentially influence the relationship. By holding the SPV constant in the analysis, we can accurately assess the direct impact of ENSO on the Jet, minimising the potential confounding effects of other factors.

5) Quantifying the indirect causal effect of ENSO on the Jet through the SPV involves understanding the role of SPV as a mediator in the relationship between ENSO and the Jet stream. To quantify the indirect causal effect of ENSO on the Jet via the SPV, we consider the linear causal effect of ENSO on the SPV(denoted as ‘a’) and the linear causal effect of the SPV on the Jet(denoted as ‘b’). The indirect causal effect of ENSO on the Jet can then be represented as the product of the two effects (a*b).

The linear causal effect of ENSO on the SPV can be assessed by examining the coefficient obtained from a linear regression model, where the SPV serves as the response variable and ENSO as the predictor variable, while also controlling for the Jet. The analysis yields a coefficient of approximately -0.19 for the effect of ENSO on the SPV index. This result indicates that, even when accounting for the influence of the Jet, a one-standard-deviation increase in the ENSO index is associated with a 0.19 standard deviation decrease in the SPV index.

The linear causal effect of the SPV on the Jet, is assessed by examining the coefficient obtained from a regression model, where the Jet acts as the response variable and the SPV as the predictor variable, while also controlling for ENSO. This approach, which incorporates ENSO as a control variable, yields a coefficient of approximately 0.39 for the effect of SPV on the Jet Stream index. Investigating the effect of the mediator, the SPV, in the model, allows us to examine for potential confounding effects. This approach possibly enables a clearer interpretation of ENSO’s influence on the Jet.

Using these results, we calculate the indirect causal effect of ENSO on the Jet, mediated through the SPV, as approximately -0.074. This value is derived by multiplying the linear causal effect of ENSO on the SPV (-0.19) by the effect of the SPV on the Jet (0.39). This calculation of the indirect effect suggests that ENSO's influence on the Jet, mediated through the stratospheric pathway, leads to a decrease in the Jet Index.

This result, compared to the direct causal effect of -0.04, indicates that the indirect pathway, mediated through the SPV, plays a more substantial role in the relationship between ENSO and the Jet, dominating the direct pathway. This highlights the importance of considering mediating factors, like the SPV to fully understand complex dynamics, such as the those between ENSO and the Jet stream.

These calculations are justified within the framework of causal inference by explicitly considering the mediation effect of the SPV in the relationship between ENSO and the Jet stream. By accounting for the indirect pathway through which ENSO influences the Jet Stream, our model offers a comprehensive view of the causal mechanisms at play.

6) The total causal effect of ENSO on the Jet can be derived by summing the direct and indirect causal effects. In parts 4 and 5, we calculated the direct causal effect of ENSO on the Jet (tropospheric pathway) as approximately -0.04, and the indirect effect (stratospheric, mediated by the SPV) through the SPV as approximately -0.07. The total causal effect combines these two influences to reflect the overall impact of ENSO on the Jet and we therefore obtain a value of -0.11 for the total causal effect of ENSO on Jet.

Alternatively, to derive this coefficient using an alternative estimate, we can model the Jet directly as a function of ENSO using a linear regression, without controlling for the SPV. This method could inherently capture both direct and indirect effects without explicitly modelling the mediation process. We assessed a value for the total causal effect using this method.

We examined the coefficient obtained from a linear regression model, where the Jet serves as the response variable and ENSO as the predictor variable, while not controlling for the SPV. The total causal effect of ENSO on the Jet, as determined by the regression analysis, is quantified as approximately -0.14.However, it's worth noting that this alternative approach does not provide detailed insights into how much of the effect is mediated through the SPV or acting directly from ENSO to Jet.

7) Based on our framework for the causal network and the pathways involved, we focused on the causal relationships during the period ranging from 1978 to 1998. This period is chosen as we expect to observe a stronger than average correlation between ENSO and the Jet Stream for this period. By narrowing our analysis to fit this timeframe, we aim to compare the individual pathways' influence on the relationship between ENSO and Jet during this timeframe with our original analysis.

We repeated our analysis for part 3, focussing on the periods from 1978 to 1998. Our findings are presented in Table 3. The reanalysis reveals that the the direct effect of ENSO on Jet has a correlation coefficient of approximately -0.45 with a p-value of 0.04. This indicates a more substantial negative impact during this period compared to the overall analysis.

This may suggest that the direct influence of ENSO on the Jet index was more pronounced and negative during these years. The p-value of 0.04 suggests that there is statistically significant evidence to reject the null hypothesis at the conventional alpha level of 0.05.

Table 3: Table presenting the correlation coefficients and their corresponding p-values between the ENSO, SPV and Jet indexes for the period 1978-1998.

Index	Pearson correlation coefficient	P-value
Jet vs SPV	0.623	0.00
SPV vs ENSO	-0.368	0.10
ENSO vs Jet	-0.45	0.04

A p-value of 0.04 indicates a low probability that the observed results occurred by chance if we assume the null hypothesis is true. This suggests a meaningful association or effect in the data being analysed. In other words, the statistically significant p-value strengthens our confidence in the observed negative impact of ENSO on the Jet index during the specified period.

This finding highlights the dynamic nature of the relationship between ENSO and the Jet stream, with variations observed across different time periods. The stronger negative impact observed between 1978-1998 may indicate potential shifts in atmospheric circulation patterns or other climatic phenomena during these years, influencing both ENSO and the Jet stream. Further investigation into the underlying mechanisms driving this enhanced negative influence during this period could provide insights into climate variability and its impacts for the region.

The correlation coefficient for ENSO's effect on the SPV during this period is approximately -0.368, indicating a stronger negative relationship between ENSO and the SPV compared to the overall analysis. This suggests that ENSO's impact on the timing of the stratospheric polar vortex breakdown was more significant during this time. However, the p-value of 0.1 indicates that there is not enough statistical evidence to reject the null hypothesis at the conventional significance level of 0.05. This suggests that the observed results could reasonably occur under the null hypothesis, implying a lack of strong evidence for a statistically significant effect or association. While the correlation coefficient suggests a stronger negative relationship between ENSO and the SPV during the specified period, the non-significant p-value warrants caution in interpreting this result as statistically significant. Further analysis may be needed to better understand the nature and significance of the relationship between ENSO and the SPV during this timeframe.

Using our analysis from part 4, we obtain a value of -0.26 for the direct causal effect of ENSO on the Jet, for the period between 1978 and 1998. Using our analysis from part 5, we find that the indirect causal effect of ENSO on the Jet, mediated through the SPV, is quantified as approximately -0.06. This value for the indirect causal effect is derived by multiplying the linear causal effect of ENSO on the SPV (controlling for Jet), calculated as -0.01, with the linear causal effect of the SPV on the Jet (controlling for ENSO), calculated as 0.59. Subsequently, the total causal effect for ENSO on the Jet between 1978 to 1998 is calculated as the sum of the direct causal effect and the indirect causal effect of ENSO on the Jet for this period, resulting in -0.32, using the method described in part 6.

Comparing the results from part 7 with the analysis for the overall period, it appears that the direct causal effect of ENSO on the Jet was stronger during the 1978-1998 period compared to the indirect causal effect, which is lower for the same period. The direct pathway could therefore be considered responsible for the increase in the correlation. The significant negative direct effect (-0.26) observed during this period suggests an increased influence of the tropospheric pathway, in contrast to the general analysis where the indirect (stratospheric) pathway had a more substantial role.

Conclusion

This comprehensive analysis provides a thorough understanding of the causal mechanisms by which ENSO influences the Jet index in the Southern Hemisphere, and demonstrates the variability in these causal mechanisms across different timeframes.

The findings suggest that the heightened correlation between ENSO and Jet observed during 1978-1998 may be primarily attributed to the enhanced direct (tropospheric) influence of ENSO on the Jet, rather than the indirect (stratospheric) pathway. This observation challenges the conclusions drawn in part 5 regarding the dominant pathway during the overall period, indicating that the relative significance of the tropospheric and stratospheric pathways can fluctuate across different time periods.

The heightened effect observed during 1978-1998 signifies an intensified influence of ENSO on the Jet stream dynamics at the tropospheric level, potentially driven by fluctuations in atmospheric circulation patterns or other climatic factors unique to this period. Understanding the underlying mechanisms behind this enhanced interaction among ENSO, the SPV, and the Jet stream during specific timeframes can yield valuable insights into the dynamics of the atmospheric circulation system and its response to climate variability.

Thus, this analysis contributes to a more nuanced understanding of the dynamic interactions between ENSO and the Jet stream, as well as their implications for regional and global climate patterns. By studying the causal networks influencing these climatic phenomena, we can identify biases in our predictions. Overall, our findings underscore the importance of accounting for temporal variability when examining the relationship between ENSO and the Jet stream.

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