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The delayed oscillator model for climate variability: A review and an application to the Atlantic meridional mode

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Abstract: Understanding climate variability in the tropical Pacific and Atlantic oceans is a considerable challenge for climate scientists. Interannual to decadal climate variability is dominated in these regions by the El Niño-Southern Oscillation (ENSO), the North Atlantic Oscillation, the tropical Atlantic zonal and meridional modes. These climatic modes are mainly driven by competing positive and negative feedback processes that involve ocean-atmosphere interactions. The delayed oscillator, a conceptual model that include these processes, has been developed to explain the cyclic nature of ENSO in the Pacific Ocean. We review its successful applications in the Atlantic Ocean and present our own application of this model to the tropical Atlantic meridional mode. After identifying key climatic variables and main feedbacks involved, we estimate model parameters and find that the delayed oscillator model can explain the main periodicity of this climatic mode.

Keywords: Climate variability, El Niño, Atlantic zonal and meridional modes, conceptual models

1 INTRODUCTION

Understanding climate variability in the tropical Pacific and Atlantic oceans is a considerable challenge for climate scientists. El Niño-Southern Oscillation (ENSO) is the dominant mode of interannual climate variability at global scale and periodically affects the tropical Pacific and beyond. The strong El Niño that developed in 2015 certainly contributed to the new annual world heat record (Tollefson 2016). Our understanding of ENSO really began with the results of Bjerknes (1969). He first recognized that the growth of an El Niño event, previously known as an oceanic phenomenon, is in fact due to a positive feedback mechanism resulting from ocean–atmosphere interactions in the equatorial Pacific. Specifically, during El Niño, a positive sea surface temperature (SST) anomaly initially appears in the eastern equatorial Pacific, reducing the SST gradient along the equator. SST and atmospheric pressure at sea level are strongly coupled in the tropical ocean. As a result, the equatorial easterly trade winds weaken (interannual changes of these winds were previously known as the Southern Oscillation), which reinforce the original SST anomaly—a positive feedback mechanism collectively known as the Bjerknes positive feedback. Unlike the tropical Pacific, interannual climate variability in the tropical Atlantic is characterized by two distinct modes: the zonal or equatorial mode, which is the Atlantic counterpart to the Pacific ENSO, and the Atlantic meridional mode , which has no Pacific counterpart (Xie & Carton, 2004). The Atlantic meridional mode (Figure 2) is characterized by an anomalous south-north gradient of SST centered near the latitude of the thermal equator (~5°N). Associated surface wind anomalies are directed toward the warmer hemisphere, resulting in a meridional displacement of the rain-producing intertropical convergence zone (ITCZ).

Using a general circulation model, Chang et al. (2001) have conducted a detailed investigation on the potential importance of ocean–atmosphere interaction in the tropical Atlantic and identified positive feedbacks that drive the two climatic modes. The zonal mode is controlled by the dynamical feedback between zonal winds, thermocline (the frontier between warm surface waters and cold deep waters) depth and SST, i.e. the same Bjerknes feedback operating in the Pacific. The meridional mode is dominated by dynamical and thermodynamical feedbacks between meridional winds, latent heat flux associated with evaporation, and SST. There are two physical distinctions between the tropical Atlantic zonal and meridional modes of interannual variability. First, mechanisms are different: the zonal mode is driven by ocean dynamics, whereas the Atlantic meridional mode is thought to be primarily driven by air-sea heat fluxes and therefore thermodynamic in nature. Second, the modes have a different seasonality: the zonal mode is strongest in boreal summer, whereas the Atlantic meridional mode peaks in boreal spring (Chang et al., 2000; Keenlyside and Latif, 2007). To interpret observations of climate variability and explore the dynamics of climatic modes such as ENSO in the Pacific Ocean and the equatorial and meridional tropical Atlantic modes, linear or nonlinear forced or coupled models are commonly used. But the more complex the model, the more it is difficult to identify dominant processes, unless carefully-designed and time-consuming sensitivity experiments are done. Another way to proceed is to develop conceptual models based on a reduced set of equations representing key processes that affect key variables in key regions, whose parameterization rely on more complex models and observations. Conceptual models allow to isolate the key processes giving rise to the interannual modes without interfering with other processes included in the coupled ocean-atmosphere general circulation models and also avoid the need for large-scale computing resources normally associated with the sophisticated models.

For example, the first mechanical explanation of the El Niño phenomenon was the build-up theory of Wyrtki (1975). According to this theory, an accumulation of warm waters in the western part of the basin, pushed by the trade winds, precedes El Niño, when trade winds weaken, and allow the warm waters to extend eastward. However, this theory does not explain the transition from warm to cold events or vice versa which makes the quasi oscillatory nature of the phenomenon. The delayed oscillator model of Suarez and Schopf (1988) was the first conceptual model to provide an explanation for the quasi oscillatory nature of ENSO, through equatorial wave dynamics. This conceptual framework has also been used to understand the zonal displacement of the western equatorial Pacific warm pool (Clarke et al., 2000). The recharge oscillator of Jin (1997) is another conceptual model for ENSO that put forward the heat recharge and discharge of the whole equatorial band through meridional heat transport. Recently, the delayed oscillator and the recharge oscillator could be applied to the tropical Atlantic Zonal mode (Jansen, et al., 2009). The delayed oscillator formulation was also used to understand the quasi-periodic multi-decadal variability of the North Atlantic Oscillation, one of the dominant modes of atmospheric circulation variability in the northern hemisphere (Sun et al., 2015).

In this paper we will review the development and application of the delayed oscillator conceptual model and propose a new application of this theory in the Atlantic domain. The remainder of the paper is organized as follows: The formulation of the model and its scheme that captures the essential physics of the coupled oscillation of ENSO is described in Section 2. In Section 3 we present applications of the delayed oscillator to Atlantic climatic modes: the Atlantic zonal mode, the North Atlantic Oscillation, and our own application of the delayed oscillator to the Atlantic meridional mode. Finally, a summary and perspectives is presented in Section 4.

2 Formulation of the model and its scheme for ENSO

The delayed oscillator model is a simple model, firstly proposed by Suarez and Schopf (1988) in order to capture the main mechanisms of ENSO, and later used by other authors to explain the results of many general and intermediate models (Jansen, et al. 2009, Graham et al 2015, Sun et al., 2015). This model is sketched in Figure 1 and relies on the existence of a strong positive feedback in the coupled ocean-atmosphere system and on some unspecified nonlinear mechanism invoked to limit the growth of unstable perturbations. Its key element is the inclusion of the effects of equatorially trapped oceanic waves propagating in a closed basin through a time delayed term.

The strongest air-sea coupling takes place in the central region of the equatorial Pacific ocean. Using a linear model, Suarez and Schopf (1988) found that the feedback arises from the coupling of the tropical ocean and atmosphere: an initial ocean surface warming result in atmospheric heating and wind responses that drive ocean currents so as to enhance the original perturbation. The grow rate of this feedback in the model depends on the sensitivity of the atmospheric heating to SST and the sensitivity of SST to resulting wind anomalies. Both sensitivities are strong in the central equatorial Pacific. This local positive feedback can be written as:

$$\frac{d}{dt}T(t) = aT(t) \tag{1}$$

where T, the amplitude of the growing disturbance, represents the SST anomalies in the central region of the equator. The term on the right represents the positive feedback mechanisms from air-sea coupling that generate an instability with the parameter **a** its grow rate. The solution of the equation (1) gives an exponential growth mode for T, which is contrary to the oscillatory nature of ENSO. As such a mode amplifies from an assumed equilibrium state, nonlinear effects appear and will come to limit this growth. The two obvious candidates for this damping are heat transport processes in the ocean and moist processes in the atmosphere (Suarez and Schopf, 1988). The former is the dominant effect in Cane and Zebiak (1985), although the details of the process are not clear. Partly because of this uncertainty, and partly to keep things as simple as possible, the nonlinear form assumed is:

$$\frac{d}{dt}T(t) = aT(t) - \varepsilon T^3(t) \tag{2}$$

The second term represents the negative feedback mechanisms that limit perturbation growth through nonlinearity in the system. To explain the quasi-oscillatory nature of ENSO, Suarez and Schopf (1988) assume that all variations in the western part of the basin are an uncoupled response emanating from the coupled action in the central part of the basin. They propose a negative feedback to explain the transition from El Niño event to neutral state or La Niña event and vice versa. This feedback is represented as follows: The wind anomalies induced by a positive SST perturbation generate oceanic Rossby waves that decrease thermocline depth. These waves propagate westward from the coupled region, and on reaching the western boundary, reflect into eastward propagating equatorial Kelvin waves. During this transit to the western boundary, information carried by the signals is "hidden" from the coupled problem. Upon returning to the central/eastern portion of the basin where the mean thermocline is relatively shallow, the thermocline gets shallower which tends to decrease SST. We may then think of these signals "reentering" the coupled problem after a time delay equal to their transit time τ. This adds a new term to the equation that has now an oscillatory solution:

$$\frac{d}{dt}T(t) = aT(t) - \varepsilon T^3(t) - \beta T(t-\tau) \tag{3}$$

Figure 1 summarizes the delayed oscillator process and can be described as follows: Positive SST anomalies in the equatorial eastern Pacific cause westerly wind anomalies in the equatorial center (1) that generate eastward Kelvin waves (2), which act to increase the positive SST anomalies. The westerly wind anomalies also generate oceanic equatorial Rossby waves (3), which propagate westward and reflect from the western boundary as equatorial Kelvin waves (4). By reaching the eastern part of the basin a few months later and since the thermocline anomalies for the reflected Kelvin waves (4) have an opposite sign to those of the directly forced Kelvin waves (2), they provide a negative feedback for the coupled system to oscillate.

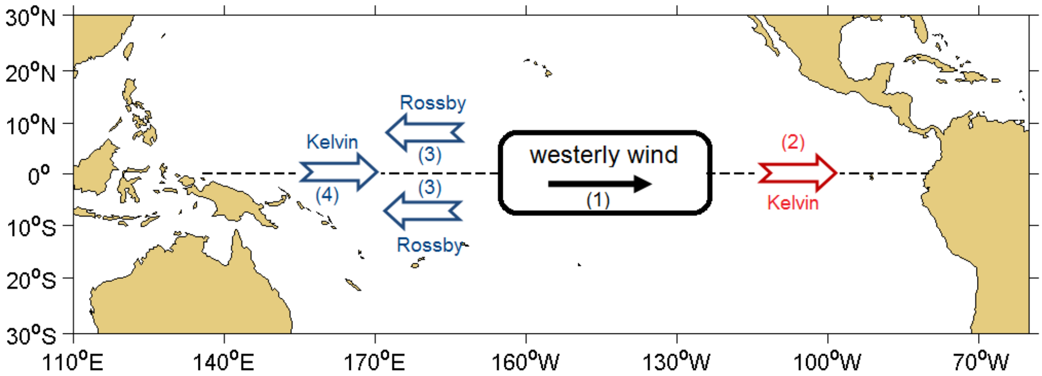

Figure 1- Schematic representation of the delayed oscillator model for ENSO

3 Applications of the delayed oscillator in the Atlantic Ocean

While the Pacific Ocean climate variability is essentially dominated by ENSO, the Atlantic Ocean is under the influence of three major climatic modes: the North Atlantic Oscillation (NAO), the tropical Atlantic zonal and meridional modes. In this section, we show that the delayed oscillator model described in the previous section can be applied to these different modes.

3.1 Atlantic zonal mode

The zonal mode is an interannual climate mode in the Atlantic Ocean similar to ENSO in the Pacific, where a wind anomaly causes a SST anomaly in the eastern basin. This SST anomaly is mainly concentrated in the Gulf of Guinea, in particular in the ATL3 box (Figure 2). Keenlyside et al. (2007) and Jansen et al. (2009) showed that this mode can be explained by the recharge–discharge oscillator model. In this model, the positive feedback is identical to that described above for the ENSO, which allows for the growth of an initial perturbation via atmosphere-ocean interaction but the negative feedback is due to a recharge or discharge of the equatorial heat content. The warm phase of this Atlantic mode, similar to an El Niño event in the Pacific, is preceded by a warm water recharge of the equatorial band, in agreement with the build-up theory of Wyrtki (1975). On the contrary, currents driven by the westerly wind anomaly during the warm phase discharge the equatorial band, which leads to an anomalously shallow equatorial thermocline, that can trigger a cold SST anomaly in the eastern part of the basin and an associated easterly wind anomaly. The recharge–discharge oscillator has the same mathematical formulation as the delayed oscillator under special assumptions and both are included in the unified oscillator model developed by Wang et al. (2001).

3.2 North Atlantic Oscillation

In the North Atlantic Ocean, atmospheric variability is dominated by the North Atlantic Oscillation (NAO), a sea level pressure anomaly seesaw between the subtropical Atlantic high and the Arctic low pressure centers with a dominant 60-year period (Sun et al., 2015) that affects European climate. The main oceanic feature is the Atlantic Meridional Overturning Circulation (AMOC), characterized by a surface northward flow (the Gulf Stream) of warm, salty waters that progressively get colder as they move northward, until they plunge due to their increased density and feed a deep southward flow of cold waters. Recently, Sun et al. (2015) showed that, once again, the delayed oscillator model can explain the main mechanisms responsible for the multi-decadal NAO period by interactions between the NAO and AMOC. The positive and negative feedback processes involved are described as follows: The positive NAO phase (increased mean pressure gradient) strengthens the AMOC, with a delayed effect due to the large inertia associated with slow oceanic processes; this enhanced AMOC induces later, due to slow oceanic adjustment, a SST pattern with warming in the northern North Atlantic and cooling in the southern part, which leads to an atmospheric response that resembles the negative NAO phase. Subsequently the oscillation proceeds, but in the opposite sense.

3.3 A new delayed oscillator for Atlantic meridional mode

In this section, a new delayed oscillator model is derived to highlight the key physical processes responsible for the interannual oscillations of the Atlantic meridional mode, defined in section 1 as an inter-hemispheric SST gradient in the tropical Atlantic. Our model is also based on competing positive and negative feedbacks, like the tropical Pacific delayed oscillator model, but these feedbacks have different physics. The positive feedback involves wind, evaporation and SST interaction (Chang et al. 2001; Vimont 2010), while heat transport by meridional currents has been proposed as the negative feedback (Chang 1997).

Firstly, we focus on SST and identify key regions in each hemisphere (see the boxes in Figure 2) where this variable strongly interacts with atmosphere. This interaction is estimated by linear regression between the different climate variables likely to evolve in phase and play a role in the meridional mode : meridional wind and SST gradient, local wind and heat flux, local heat flux and SST. Based on the regions where coupling arises, we choose a northern hemisphere box at (5°N-12°N, 35°W-25°W) and a southern hemisphere box at (5°S-12°S, 20°W-10°W).

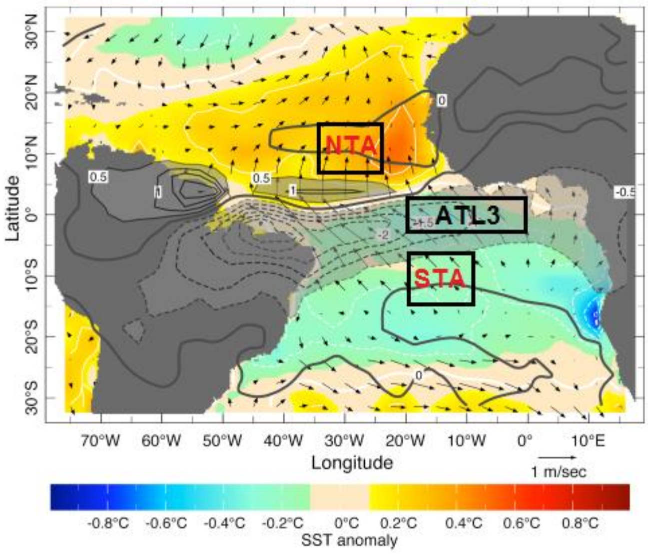

Figure 2- Illustration of the warm phase of the Atlantic meridional mode. SST anomalies are represented in color (see scale), the contours represent the anomalies of precipitation and the arrows are the surface wind anomalies. The boxes NTA (North Tropical Atlantic) , STA (South Tropical Atlantic) and ATL3 (Atlantic 3) represent respectively the box considered for the north hemisphere, the south hemisphere and the Atlantic zonal mode (Kushnir et al. 2003).

Secondly, we identify feedback loops that relate SST variations in the chosen boxes and can explain the oscillation of the meridional mode. The proposed cycle is summarized in figure 3 and can be described as follows: An initial warming anomaly that affects SST in the northern tropical Atlantic (NTA) box (T_N) increases the temperature gradient T_N-T_S (arrow 1). The increased gradient causes an intensification of northward meridional winds in the south of the mean position of the Inter-Tropical Convergence Zone (ITCZ), corresponding to a northward displacement of the ITCZ (arrow 2). This intensification of the wind increases evaporation (latent heat flux), which cools SST in the southern tropical Atlantic (STA) box (T_S), south of the mean position of the ITCZ (arrow 3). This cooling in the STA box therefore reinforces the anomalous meridional temperature gradient (arrow 4) initiated by warming in the north, which in turn can strengthen the wind. This is the positive feedback for the meridional mode. As the mean surface currents are westward around 10°S (South Equatorial Current), northward along the southern American coast (North Brazil Current) and eastward around 10°N (North Equatorial Counter-Current), the cold anomaly in the STA box can be transported (this process is known as advection) toward the NTA box (arrow 6), with a delay due to the slow speed of the meridional mean current. This advection can then offset the initial warming anomaly of T_N and reverse it to cooling, which can reduce the temperature gradient (arrow 7) and weaken the intensity of the northward wind. Relaxation of the wind would result in a reduction of latent heat flux and a subsequent warming of T_S. This is the negative feedback for the meridional mode.

The equation that summarizes the whole process can have the same mathematical formulation as the delayed differential equation (3). It could explain the meridional oscillation of the coupled system between warm and cold temperature anomalies in the STA and NTA boxes. Here, we define the meridional mode index by the difference between the monthly anomalous SST in the northern and southern boxes :$T = T_N - T_S$. With this choice, positive values of the index (T) correspond to a SST dipole pattern that is positive in the north and negative in the south, and vice versa.

The physical processes incorporated in this model are represented as follows:

$+\alpha T(t)$: is the positive feedback on the meridional gradient of temperature (T) that involves wind and evaporation. The limit to this feedback is made through the nonlinear damping term $-\varepsilon T^3(t)$. It represents the limitation of the temperature T_N growth by atmospheric convection associated with the ITCZ.

$-\beta T(t-\tau)$: This term represents the delayed negative feedback due to advection processes suggested in the schematic model (Figure 3) with the lag τ. This lag approximately corresponds to the time it would take for the mean currents to transport a temperature anomaly from the STA to the NTA box. It is approximately estimated as the distance of the pathway previously identified between the two boxes divided by the mean current velocity.

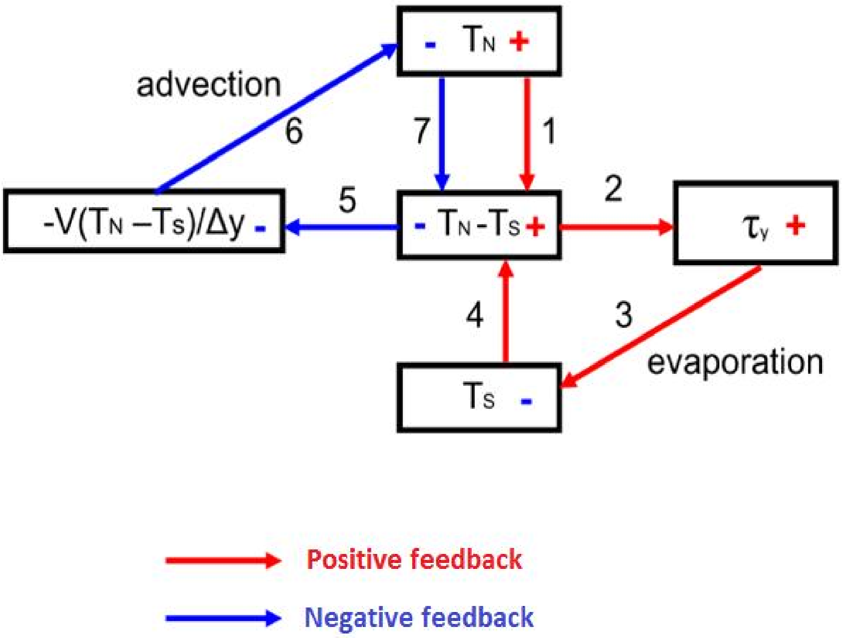

Figure 3 - Schematic model. T_N is the anomaly temperature in the box NTA and T_S the anomaly temperature in the box STA.

The oscillatory model proposed for the meridional mode is solved numerically with a set of estimated parameters. The parameter $\alpha = 0.27 \pm 0.03$ is the positive feedback due to coupling between wind, evaporation and SST previously described. This coupling is obtained by a local linear regression between the normalized latent heat flux and SST in a climate reanalysis of the Global Ocean Data Assimilation System developed at National Centers for Environmental Prediction. The delay time τ is estimated at 4 months. Using an iterative optimization method that aims to maximize the correlation between the model and the observed meridional mode index, the remaining parameters of the model are estimated as: $\varepsilon = 0.20$ and $\beta = 0.13$. The statistical properties of the numerical solution can then be evaluated in order to validate the model skills. For this, we conduct a spectral analysis of model outputs compared to that observed. This analysis reveals that the meridional mode oscillation has a main peak with a 16 months period and a secondary peak with a period of about 5 years (Figure 4). The model output is a regular oscillation that reproduces the main 16 month period. We therefore conclude that the meridional mode resulted from the superposition of a self-sustained oscillation mechanism of high frequency and another low frequency oscillation mechanism which remains to be identified

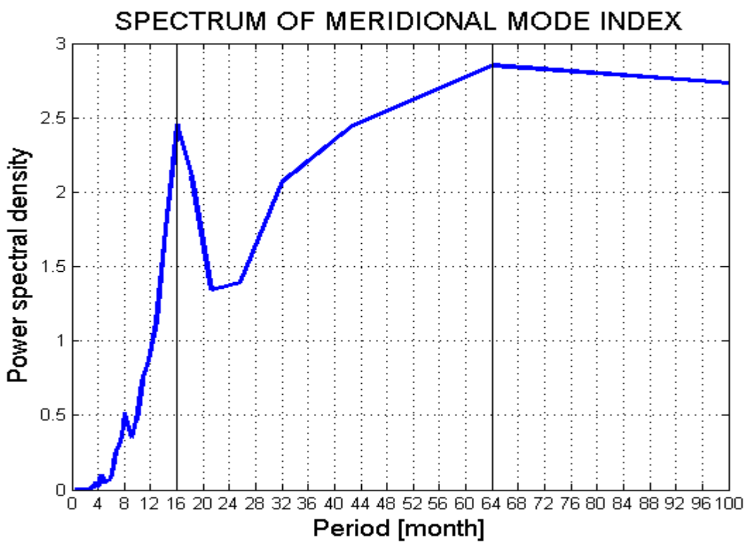

Figure 4- Spectral analysis of the meridional mode index using the observed data

4 CONCLUSIONS

In this study, we show that climate variability in the Pacific and Atlantic oceans can partly be described by a simple conceptual model known as the delayed oscillator that was developed to understand the cyclic nature of ENSO. It was subsequently applied to the NAO and the Atlantic zonal mode. We show that the key element to apply this delayed oscillator model to climatic modes is to identify and quantify the main positive and negative feedback processes that are responsible for variability of these modes. When correctly parameterized, the delayed oscillator can show if processes suspected to drive climatic modes are indeed consistent with observed periodicity of the modes. We applied the delayed oscillator to the tropical Atlantic meridional mode, assuming that this mode grows due to a wind-evaporation-SST interaction and that the negative feedback, which allows oscillation, is due to slow heat transport by the mean currents. Once the parameters of the model are fit to observations, it reproduces the main 16 month observed periodicity of the mode, demonstrating that the suggested processes are likely dominant.

However, interannual climatic modes are irregular oscillations and do not reduce to a single spectral peak. The tropical Atlantic meridional mode shows a secondary 5 year period in addition to the main 16 month period. Multiple peaks may result from interaction between time scales and between climatic modes, which could still be investigated within the conceptual model framework. In further work, the perspectives are multiple. Compared to the Pacific Ocean, the Atlantic Ocean is characterized by much larger seasonal variations. A seasonal modulation of the coupling coefficients could be taken into account in our oscillatory model, following the methodology of Jansen et al (2009), which could improve performance. Interaction between climatic modes have been suggested, for example ENSO and the NAO are thought to influence the Atlantic meridional mode (Chang et al., 2001), and the Atlantic meridional mode could also affect the zonal mode through different processes (Luebbecke 2013). These interactions and their effect on the respective spectra of the different modes could be investigated by coupling several delayed oscillators. Finally, for climatic modes that are not well reproduced in coupled climate models, oscillator models could be valuable tools for studying how, depending on the expected evolution of coupling coefficients in the various future climate scenarios, interannual climate variability might evolve in the future.

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