Robust Sahel drought due to the Interdecadal Pacific Oscillation in CMIP5 simulations.

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Abstract:

Many studies address the Interdecadal Pacific Oscillation (IPO) as a modulator of climate in several regions all over the globe. However very few suggest it has an impact on Sahel rainfall low-frequency variability. This work shows the relevance of such connection, supported by a robust response of state-of-the-art global climate models. Our results reveal that the positive phase of the IPO has a negative impact on Sahel rainfall anomalies regardless of the externally forced changes induced by anthropogenic gases. Such relationship is stronger for those models in which sea surface temperatures associated with the positive phase of the IPO show warmer anomalies over the Tropical Pacific. Therefore, we suggest the importance of a skillful simulation of IPO to improve decadal prediction of Sahel rainfall and to better understand its variability.

1. Introduction:

The Interdecadal Pacific Oscillation (IPO) is a low-frequency mode of variability usually defined as
the leading empirical orthogonal function (EOF) of the detrended sea surface temperature anomalies (SSTA) over the Pacific basin at decadal timescales (Figures 1a and 1b) [Zhang et al., 1997; Power et al., 1999]. The IPO is the basin-wide manifestation of the Pacific Decadal Oscillation (PDO), which is defined as the leading EOF of North Pacific detrended SSTA in winter [Mantua et al., 1997]. During its positive (negative) phase, the IPO sea surface temperature (SST) pattern is characterized by warm (cold) anomalies in the tropics and cold (warm) ones over the central and western extratropical Pacific (Figure 1b) [Trenberth and Hurrell, 1994; Meehl et al., 2009]. The origin of the mode is still under discussion. Some works suggest that it can arise by noise [Newman et al., 2003; Schneider and Cornuelle 2005; Shakun and Shaman, 2009], while others argue that the IPO is produced by atmosphere-ocean interactions involving the tropics and the extratropics [Deser et al., 2004; Meehl and Hu, 2006; Farneti et al., 2014]. Due to its vast temperature signal in the tropical Pacific, the IPO can offset or intensify the warming of globally averaged surface air temperatures [Gu and Adler, 2013; Meehl et al., 2013]. The IPO also impacts precipitation. It has been associated with drought conditions over the northern hemisphere summer monsoon [Hwang et al., 2013] and particularly over North America [Meehl and Hu, 2006; Dai, 2013] and in the Indian monsoon [Krishnan and Sugi, 2003; Meehl and Hu, 2006]; and has been shown to modulate the teleconnections of El Niño Southern Oscillation (ENSO) with rainfall over Australia [Power et al., 1999; Arblaster et al., 2002].

The Sahel is a semiarid region in West Africa extending between the humid savanna south of 10ºN and the beginning of the Sahara Desert at roughly 18ºN. The majority of the annual precipitation takes place in the boreal summer season, from July to September (JAS), and it is linked to the West African monsoon [Sultan and Janicot, 2003; Losada et al., 2010; Nicholson et al., 2013]. Due to the socio-economic importance of water resources in the region, the Sahel is highly vulnerable to rainfall variability. Throughout the 20th Century, Sahel precipitation has shown strong variability at decadal timescales [Mohino et al., 2011a]. Especially relevant was the prolonged period of drought
in the 1970s and 1980s, which draw the attention of many studies [e.g. Folland et al., 1986; Giannini et al., 2003; Dai et al., 2004; Caminade and Terray, 2010; Mohino et al., 2011a; Rodríguez-Fonseca et al., 2011]. There is currently a broad agreement that the main driver of Sahel precipitation at decadal timescales is SST variability amplified by land-surface processes [Zeng et al., 1999; Giannini et al., 2003; Kucharski et al., 2013].

Sahel rainfall variability is influenced by SST anomalies over different regions at multiple timescales. At interannual timescales, a warming of the equatorial Atlantic and ENSO-like SST anomalies over the Indo-Pacific promote drought over the Sahel [Janicot, 2001; Vizy and Cook, 2002; Giannini et al., 2005; Cook and Vizy, 2006; Joly and Voldoire, 2009; Mohino et al., 2011b; Losada et al., 2010, among others], while warmer conditions over the Mediterranean sea are linked to enhanced Sahel rainfall (Rowell, 2003). At decadal timescales, many works have highlighted the influence of the Atlantic Multidecadal Oscillation (AMO) on Sahel precipitation [e.g. Zhang and Delworth, 2006; Hoerling et al. 2006; Knight et al., 2006; Ting et al., 2009, 2011, 2014; Mohino et al., 2011a; Martin et al. 2014]. However, up to now, the few studies that have been done on the possible impact of the IPO on Sahel rainfall have shown a negative correlation (Figure 1c) [Joly, 2008; Mohino et al., 2011a] and a possible modulation of the effect of ENSO due to the IPO [Molion and Lucio, 2013].

In this study, we investigate the impact of the IPO on Sahel precipitation using the simulations from the Coupled Model Intercomparison Project – Phase V (CMIP5) [Taylor et al., 2012]. We particularly address the following questions: (1) Is there an impact of the IPO on Sahel precipitation? (2) What is the dynamical mechanism for such impact? (3) How do coupled models simulate the IPO and its impact over the Sahel? (4) Does the radiative forcing affect this relationship?
2. Data and Methods:

We work with monthly data of SST, precipitation and wind at high (200 hPa.) and low (850 hPa.) levels. To analyze the observed IPO and impacts we use HadISST1 [Rayner et al., 2003] and ERSSTv3 [Smith et al., 2008] SST reconstructions, CRUTS3.1 precipitation [Mitchel and Jones, 2005] and winds from the 20th Century Reanalysis [Compo et al., 2011]. For the simulations, the output from 17 different CMIP5 models is used, previously interpolated to a common regular grid with a spatial resolution of 2.8° in longitude and latitude. We have analyzed the unforced long-term preindustrial control (piControl) run; the historical run, which is a reproduction of the 20th century (typically from 1850-2005) with observed external forcing imposed; and the rcp8.5 future projection experiment, which considers the highest increase of anthropogenic gases concentration (see detailed list of models and simulations analyzed in Table S1 in the supplementary material).

Depending on the definition, some anthropogenic component can be included in the IPO index [Bonfils and Santer, 2011]. In order to isolate the internal variability of SSTs as much as possible, we remove the global component of the anthropogenic forcing in observations and forced simulations. To do so, we calculate a “residual” field from the annual mean SSTA following Mohino et al. [2011a]: We define a global warming (GW) index as the lowpass-filtered (40-yr cutoff) time series of averaged SSTA between 45°S and 60°N. We regress the original SSTA onto the GW index and we construct a “GW fitted” SSTA field by multiplying the regression coefficient at each grid point by the GW index. Finally, we subtract the “GW fitted” SSTA field from the original one and obtain the “residual” SSTA field. To focus on decadal timescales, the “residual” field is lowpass-filtered (13-yr cutoff).

The IPO indices from observations and the forced simulations (historical and rcp8.5 experiments) are then defined as the first principal component (PC) of the “residual” SSTA, associated to the first
Empirical Orthogonal Function (EOF) calculated over the Pacific basin (between 60°N-45°S). The
members of the residual SSTA of the models with several realizations available are concatenated in
time before applying the EOF analysis. For the externally unforced piControl simulations the IPO
index is defined as the PC associated with the first EOF of the 13-year lowpass-filtered original
SSTA field.

Once the IPO index of each model is calculated, the model SST and rainfall patterns are obtained by
regressing the unfiltered fields onto the IPO index. To highlight the consistent response from
models, the patterns from the 17 models are averaged together. The statistical significance of the
averaged patterns is evaluated with a Monte Carlo-based test (see details in supplementary
material).

3. Results:

In accordance with previous studies [Mantua et al., 1997; Mantua and Hare, 2002; Deser et al.,
2004; Shen et al., 2006; Mohino et al., 2011a; Dai, 2013], the observed IPO index shows cold
regimes in the periods of 1909-1925, 1944-1976 and from 1998 onwards, and warm regimes in the
periods 1925-1944 and 1976-1998 (Figure 1a). However, such time variability shows no dominant
frequency but various spectral peaks at decadal and multidecadal periodicities, mainly in the 15-25
and 50-70 year bands (Figure S1), in accordance with previous works [Minobe, 1999; Chao et al.,
2000; Tourre at al., 2001; Mantua and Hare, 2002; MacDonald and Case, 2005]. On average,
models tend to show higher power spectra in two frequency bands, one close to 50-70 years and the
other one close to 15-25 years (Figure S2). This suggests that, though there is no clear well-defined
periodicity for the IPO (in accordance with the proxy reconstruction from Shen et al. [2006]), the
power spectra in models and observations tends to cluster around two preferred bands, of
approximately 15-25 and 50-70 years.
The SST pattern associated with the IPO in the historical and control simulations is consistent with observations (Figures 2a, 2c and 1b): In the Pacific, there are cold anomalies over the western part of the basin, poleward of 25° and more prominent in the Northern Hemisphere. There are also warm anomalies over the Tropical Pacific, and over the north and south of the eastern part of the basin. Outside the Pacific basin, the models show a less consistent response among themselves and with the observations. There are, however, regions of anomalous warming over the Indian Ocean, the Tropical Atlantic and next to the southeast coast of Brazil in both simulations and in the observations. The agreement among models on the SST pattern associated with the IPO is weaker in the historical runs than in the piControl ones.

Associated with a positive IPO, the models simulate a significant pattern of negative precipitation anomalies across the Sahel (Figures 2b and 2d), in accordance with observations (Figure 1c). Nevertheless, the observed positive anomalies of precipitation on the coastal area of Guinea, Sierra Leone and Liberia are not reproduced in the simulations. Models underestimate the intensity of the precipitation anomalies in comparison to observations (note different scales on Figure 1c and Figures 2b and 2d). Apart from the attenuation produced by the model mean, the individual models also show this underestimation (Figures S5 and S6). Such underestimation of Sahel rainfall is consistent with an underestimated atmospheric response over West Africa at low and middle levels (not shown). We speculate that the origin of the underestimation could be attributed to the weak rainfall response that Atmospheric General Circulation Models forced with prescribed SSTs show over the Sahel at these time scales [e.g. Rodríguez-Fonseca et al., 2011; Joly et al. 2007; Kucharski et al., 2013], and could be related to the accuracy with which the vegetation-atmosphere feedbacks are parameterized [Giannini et al., 2003; Wang et al., 2007]. It should be noted that, despite the high resemblance between the precipitation patterns coming from both experiments, the agreement among models is higher in the piControl run than in the historical one.
Sahel drought in response to the IPO is a remarkably consistent feature across models and simulations (Figure 3a). For both, historical and piControl experiments, 13 out of the 17 models analyzed simulate a negative correlation between the IPO and the unfiltered Sahel precipitation index. The larger correlation coefficients obtained for the observations suggest a stronger relationship in the real world. The scatter plot in Figure 3b shows that the stronger the SSTA warming over the tropical Pacific, the stronger the IPO's impact on Sahel drought. There are, however, a few models (4 out of 17 models in each experiment) that produce a positive impact of the IPO on Sahel rainfall, though most of these impacts are not statistically significant. These models tend to show a poorly defined IPO spatial pattern in the Pacific basin with weak positive or even negative SSTA over the Tropical Pacific (inmcm4 and MRI-CGCM3 for the historical simulation and GISS-E2-H and GISS-E2-R for the piControl one; Figures S3 and S4). However, some models with a weak or even positive Sahel rainfall response to IPO show warm SSTA over the Tropical Pacific (for instance the CSIRO-Mk3-6-0 model in both experiments; Figures S3 and S4). The positive SSTA over the northeastern Tropical Atlantic basin, with comparable magnitude to the ones over the Pacific warm tongue could partly explain this behaviour (Figures S3 and S4). Such northeastern Tropical Atlantic SSTA has been shown to promote increased rainfall over Sahel [Cook and Vizy, 2006; Giannini et al., 2013] and could be overriding the Tropical Pacific influence in some cases. When both regions, Tropical Pacific and northeastern Tropical Atlantic (boxed areas in Figures 2a), are used to calculate the scatter plot (Figure S7), the explained inter-model variance increases from 0.26 to 0.33, which suggests that a strong negative Sahel precipitation response to IPO is linked to a strong warming over the Tropical Pacific and weak anomalies over the Tropical North Atlantic (Figure 3b).

In observations and simulations, a positive IPO is associated with anomalous convergence over the central Tropical Pacific and divergence over the Tropical Atlantic and West Africa at low levels, and
with anomalous divergence and convergence over these two regions, respectively, at high levels
(Figure 4). This suggests an anomalous Walker-type overturning cell that connects upward
movements over the central Pacific in response to local warm SSTAs there with subsidence over
West Africa. This, in turn, reduces the Tropical Easterly Jet and the low-level monsoon westerlies,
weakening the monsoon (not shown) and leading to drought conditions over the Sahel. Such
mechanism was also proposed for the impact of ENSO events on Sahel rainfall [Janicot, 2001; Joly
and Voldoire, 2009; Mohino et al., 2011b]. The similarity between the teleconnection mechanisms
at different time scales is consistent with the similar SST patterns over the Tropical Pacific observed
for the ENSO and IPO [Deser et al., 2004].

4. Discussion:

The similarity between the SSTA patterns of the historical and the unforced piControl simulations
suggests that the IPO SST mode is mainly produced by the internal variability of the models, and
that radiative effects do not play a relevant role. However, it is also noticeable that the patterns
associated with the IPO are more consistent among models in the piControl experiments than in the
historical ones (Figure 2). The methodology we use to obtain the residual SSTA in observations and
in the forced runs eliminates the long-term global component of the external forcing. However the
external component with more localized effects is not removed. This is especially relevant in the
case of aerosols, for which important uncertainties still remain [Boucher et al., 2013]. Such
uncertainties could translate into a slightly different behavior of the residual SSTA among models in
some regions and, thus, to a less robust SSTA pattern response to IPO in historical simulations than
in piControl ones.

Since the models are able to reproduce a modulation of Sahel rainfall by the IPO robustly and
congruent to what was observed over the last century, we consider if this relationship will change in
the future. The majority of models project an increase of Sahel rainfall for mid- and late 21st
century under rcp8.5 scenario, though the presence of outliers and the increase of the inter-model
dispersion with time suggest a high degree of uncertainty [Biasutti, 2013; Vizy et al., 2013]. The
SSTA IPO pattern for the rcp8.5 simulations is similar to the historical and piControl simulations
(Figure 5a). This suggests that under conditions of high anthropogenic gases concentrations, the
Pacific internal processes that generate the IPO SST pattern will not be altered. However, the
consistency among models is lower than in the other experiments. Difficulties to capture IPO-like
SSTA patterns of some models with respect to the other simulations (i.e. bcc-csm1-1, CNRM-CM5,
HadGEM2-ES and NorESM1-M) introduce more discrepancies across all models (Figure S9). As in
the historical pattern, this may be due to the methodology used to extract the external forcing. Note
that the rcp8.5 future projection introduces a stronger radiative forcing and may induce more
discrepancies between models when computing the residual SSTA. In addition, the rcp8.5 runs are
shorter (typically from 2006-2100, detailed in Table S1) and the IPO-like decadal variability may
not be properly captured with an EOF analysis. The impact of the rcp8.5 IPO on rainfall (Figure 5b)
is also negative on the Sahel as in the other simulations and it is produced by a similar atmospheric
mechanism (Figure S8). Therefore the CMIP5 simulations suggest that the SSTA pattern associated
with the IPO variability mode is not expected to change in the future nor its impact on Sahel
precipitation.

We must highlight the strong consistency across CMIP5 models found in this work in reproducing
the observed IPO modulation of Sahel rainfall low-frequency variability. Conversely, the AMO
relationship with Sahel rainfall, which has been broadly studied [e.g. Zhang and Delworth, 2006;
Hoerling et al., 2006; Knight et al., 2006; Ting et al., 2009, 2011, 2014; Mohino et al., 2011a], is not
as consistently reproduced by CMIP5 models [Martin et al., 2014]. Therefore, although the
influence of the AMO is greater than that of the IPO in observations, our results suggest that climate
models might not behave in the same way when analyzing the decadal variability of the Sahel
rainfall led by modes of SST variability.

5. Summary and conclusions:

In this work we show that most CMIP5 global climate models reproduce a consistent and well-defined IPO SST pattern with a robust negative (positive) impact on Sahel rainfall linked to its positive (negative) phase. This result coincides with observations and supports the hypothesis that the IPO modulates decadal variability of Sahel rainfall through an anomalous Walker-type circulation that produces subsidence over West Africa in the positive phase. The skill of each model to simulate this connection is related to the IPO SSTA pattern. Models reproducing a well-defined Tropical Pacific warm tongue have a significant negative IPO impact on Sahel rainfall, while models with weak Tropical Pacific SSTAs compared to the northeastern Tropical Atlantic ones show a small impact over the Sahel.

The small differences between the IPO SSTA and Sahel rainfall patterns from forced and unforced simulations suggest that the IPO is mainly an internal mode. From our analysis of rcp8.5 future projections we expect that the IPO SST mode and its influence on Sahel rainfall will not change in the future even if there is an increase of anthropogenic gases concentration.

Skill in decadal predictions of Sahel rainfall are model dependent and have been mainly attributed to the skillful reproduction of AMO related SSTs [van Oldenborgh et al., 2012; García-Serrano et al., 2013; Gaetani and Mohino, 2013]. Current GCMs show very low skill in predicting the SST anomalies associated with the IPO [Kim et al., 2012; Doblas-Reyes et al., 2013; Kirtman et al., 2013] and Newman [2013] showed that similar or even better skill could be obtained with a linear inverse model. Our results suggest that an improved characterization of the predicted SSTA pattern and timing of IPO events could be key to enhancing the skill of Sahel rainfall decadal predictions.
6. Acknowledgements:

The authors thank the helpful comments of the two anonymous reviewers and the editor Dr. Diffenbaugh. The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 603521 and the Spanish project CGL2012-38923-C02-01. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals. Thanks are also given to the MICINN of the Spanish Government for the Scholarship that JV has been granted.

7. References:


Figure captions:

**Figure 1.** (a) Standardized IPO index obtained with ERSSTv3 from 1901-2008 as defined in the text. (b) IPO SST pattern defined as the regression of the unfiltered ERSSTv3 SSTA onto the standardized IPO index (units are K per standard deviation). (c) Regression map of unfiltered
CRUTS2.1 JAS precipitation anomaly onto the standardized IPO index (units are mm/day per standard deviation). Grey contours in (b) and (c) indicate the regions where the correlation is significant with a significance level of 0.05 (from a t-test).

**Figure 2.** Regression onto the IPO index of the unfiltered (a) SSTA (K per std. dev.) and (b) JAS precipitation anomalies (mm/day per std. dev.) averaged over the 17 CMIP5 models in the historical run, typically from 1850-2005 (details in Table S1). (c) and (d) same as (a) and (b) but for the piControl run. Black and grey marks indicate points where the regression coefficient sign coincides in at least 13 and 15 out of the 17 models analyzed, respectively. Grey contours indicate the regions where the averaged correlation is significant at alpha=0.05 (using a Monte Carlo-based test, see details in the supplementary material).

**Figure 3.** (a) Bar chart of correlation coefficient between IPO index and the unfiltered time series of the precipitation anomaly averaged over Sahel (between 17º-10ºN and 10ºW-10ºE, see box in Figure 2b) for the ensemble-mean historical simulations and observations (green) and piControl runs (yellow). The stems indicate the correlation threshold for statistical significance at alpha=0.05 (using a Monte Carlo-based test, see details in the supplementary material). (b) Scatter plot of the regression coefficient of precipitation anomaly over Sahel (between 17º-10ºN and 10ºW-10ºE, see box in Figure 2b) (units are mm/day per std. dev.), and the Tropical Pacific (15ºN-15ºS and 180º-95ºW, see box over the Pacific in Figure 2a) SSTA (units are K per std. dev.). The regression line fitted to all the points has a correlation coefficient R=-0.51. Numbers from 1 to 17 correspond to single models; 18 and 19 correspond to observations.

**Figure 4.** (a) Regression of the unfiltered JAS anomaly of velocity potential at 200 hPa from 20th Century Reanalysis (1901-2008) onto the IPO index; (b) and (c) same as (a) but for the averaged regression in the historical and piControl simulations, respectively; (d), (e) and (f) same as (a), (b)
and (c) but for the velocity potential at 850 hPa ($10^6 \text{ m}^2/\text{s}$ per std. dev.). Vectors represent the divergent wind; in black at points where the sign of the regression coefficient of the velocity potential coincides in at least 15 out of the 17 models analyzed and in grey at the rest of the points in (b), (c), (e) and (f). Grey contours indicate the regions where the averaged correlation is significant at alpha=0.05 (using a Monte Carlo-based test, see details in the supplementary material).

**Figure 5.** Regression onto the IPO index of the unfiltered (a) SSTA (K per std. dev.) and (b) JAS precipitation anomalies (mm/day per std. dev.) averaged over the 17 CMIP5 models in the rcp8.5 run, typically from 2006-2100 (details in Table S1). Black and grey marks indicate points where the regression coefficient sign coincides in at least 13 and 15 out of the 17 models analyzed, respectively. Grey contours indicate the regions where the averaged correlation is significant at alpha=0.05 (using a Monte Carlo-based test, see details in the supplementary material).
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1. Information relating to the Monte Carlo-based test used to determine the significance of the model-mean regression maps:

A Monte Carlo test is used to test the regression maps averaged across the 17 models by comparing the averaged correlation against a probability density function. This density function is constructed from mean correlations out of 17 pairs of random time series. The length of these time series is the number of years times the number of realizations available of each of the 17 models (see Table S1), since we analyze the data of the models with several realizations available concatenated in time. For each correlated pair, one random time series is 13-year lowpass-filtered and the other is not, similarly to what we do when regress the IPO filtered indices onto the unfiltered anomaly fields to
feature the spatial patterns. We repeat the process 1000 times to build the probability
density function against which the original mean regression is compared.

2. Supplementary table and figures that may be useful to better follow the article:

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Table S1. List of CMIP5 models analyzed, number of years (#yrs) and realizations (#rea) of each simulation. The historical experiment are simulations of the period 1850-2005 (exceptions are 1850-2012 (*) and 1860-2004 (**)). The rcp8.5 simulation period is 2006-2100 (exception is 2006-2099(***)). All data are available at http://pcmdi9.llnl.gov.
Figure S1. Power spectrum of the Fourier transform of the detrended IPO indices from observations. Dashed lines indicate the 95% confidence level following a Monte Carlo-based test in which a probability density is built from the Fourier spectrum of 13-year lowpass-filtered and detrended white noise time series.
Figure S2. Model-mean power spectra of the Fourier transform of the detrended IPO indices (blue bars) of the historical (top), piControl (middle) and rcp8.5 simulations (bottom). Red bars indicate the power spectra averaged over the 17 models but taking into account only 95% significant peaks for each of them. The statistical significance for each model's IPO is obtained following a Monte Carlo-based test in which a probability density function is built from the Fourier spectrum of 13-year lowpass-filtered and detrended white noise time series with the same time length as the simulation and averaged across the number of ensemble members in cases where more than one realization is available.
Figure S3. Single models IPO SST patterns from historical simulations defined as the regression of the SSTA onto the standardized IPO index (units are K per standard deviation).
deviation). Grey contours indicate the regions where the correlation is significant with a significance level of 0.05 (from a t-test).
Figure S4. Single models IPO SST patterns from piControl simulations defined as the regression of the SSTA onto the standardized IPO index (units are K per standard
deviation). Grey contours indicate the regions where the correlation is significant with a significance level of 0.05 (from a t-test).

Figure S5. Single models regression maps of JAS precipitation anomalies onto the standardized IPO index (mm/day per std. dev.) from historical simulations. Grey contours indicate the regions where the correlation is significant with a significance level of 0.05 (from a t-test).
Figure S6. Single models regression maps of JAS precipitation anomalies onto the standardized IPO index (mm/day per std. dev.) from piControl simulations. Grey contours indicate the regions where the correlation is significant with a significance level of 0.05 (from a t-test).
Figure S7. Scatter plot of the regression coefficient of precipitation anomaly over Sahel (between 17°-10°N and 10°W-10°E, see box in Figure 2b) (units are mm/day per std. dev.), and the SSTA difference between the Tropical Atlantic coastal region next to West Africa (25°-15°N and 30°-18°W, see box over the Tropical Atlantic in Figure 2a) and the Tropical Pacific (15°N-15°S and 180°-95°W, see box over the Tropical Pacific in Figure 2a) SSTA (units are K per std. dev.). The regression line fitted to all the points has a correlation coefficient $R=0.57$. Numbers from 1 to 17 correspond to single models; 18 and 19 correspond to observations.
Figure S8. Averaged regression in the rcp8.5 simulation of the JAS anomaly of velocity potential at 200 hPa and 850 hPa onto the standardized IPO index ($10^6$ m$^2$/s per std. dev.). Divergent wind derived from this pattern is represented by black vectors at points where the sign of the regression coefficient of the velocity potential coincides in at least 15 out of the 17 models analyzed and by gray vectors at the rest of the points. Grey contours indicate the regions where the averaged correlation is significant at alpha=0.05 (using a Monte Carlo-based test, see details in the supplementary material).
Figure S9. Single models IPO SST patterns from rcp8.5 simulations defined as the regression of the SSTA onto the standardized IPO index (units are K per standard
deviation). Grey contours indicate the regions where the correlation is significant with a
significance level of 0.05 (from a t-test).

Figure S10. Single models regression maps of JAS precipitation anomalies onto the
standardized IPO index (mm/day per std. dev.) from rcp8.5 simulations. Grey contours
indicate the regions where the correlation is significant with a significance level of 0.05
(from a t-test).