Response to Dr. Poveda

Introduction

In successive, blue text indicates the authors' response to Dr. Poveda 2nd revision of the manuscript "Tracking the Choco jet since the 19th Century by using historical wind direction measurements" by Gallego et al. (including this brief intro).

After the first review, we strongly felt that most of the issues raised by both referees contributed to improve the original manuscript. We did the major revision required and we addressed all the concerns raised. We really feel that the revised version is significantly clearer that the initial submission and at the same time, it incorporates the physical basis of our index (which was probably not clear in our first version). In particular, Dr. Poveda's comments on the unnecessary references to monsoons and the necessity of including the physical basis of our index were quite useful and so we acknowledged Dr. Poveda's contributions in our previous response.

We would like to express our astonishment when we read Dr. Poveda´s 2nd revision (included in this document as black text). To our surprise, we felt as if none of our changes had been considered by him in this second round. Most of the concerns raised by Dr Poveda are exactly the same as those in his first revision. In our opinion they are not applicable to the revised version any longer.

Therefore, we think that the revised version does not require further changes, since the concerns raised by Dr Poveda had already been addressed in the first round. In the following responses we explain the reasons beyond this decision. Please, note that all our replies are done with due respect and they only imply disagreement in scientific terms.

The authors' responses to my previous comments and the revised version of the manuscript both keep ignoring my point that the proposed index CHOCO-D is erroneous and misleading to track the Choco jet. The Choco jet was discovered and introduced in the literature two decades ago (Poveda and Mesa, 1999; 2000), as a low-level jet acting on a well-defined geographical (3-D) setting, and having a very precise physical definition: a year-long westerly low-level jet, with a clear-cut annual cycle, which satisfies all the criteria put forward by Stensrud (1996) for low-level jets. As such, the Choco jet has been extensively studied by many authors since (see Yepes et al., 2019). The large latitude range that the authors chose to define the newly proposed index is under the action of the Choco jet and the Caribbean low-level jet, another very-well defined circulation mechanism acting over the Caribbean, Central America and the far eastern Pacific, also exhibiting a clear-cut annual cycle (Magaña et al., 1999: Poveda and Mesa, 1999; Wang, 2007; Muñoz et al., 2008; Cook and Vizy, 2010, etc.). The newly proposed CHOCO-D index does not exhibit a steady westerly flow, but a regime of seasonally varying westerly and easterly winds owing to the crashing dynamics ("tug of war", as per my original review) of the Choco and Caribbean low-level jets over the far eastern north tropical Pacific. With all due respect, the proposed new index contaminates the dynamics of the Choco jet with that of the Caribbean jet, and does not make historical or physical sense. As it has been defined, the proposed index introduces unnecessary confusion in the study and understanding of the region's weather and climate. I kindly urge the authors to refrain referring to the newly proposed index as an index of the Choco jet.

At the most, it is an index for the tug of war between the Choco and the Caribbean jets. Therefore, I strongly recommend to change the title of the paper, and all the sections accordingly. What the authors built is not an index of the Choco jet but of the tug of war between the Choco and the Caribbean (CHOCAR, which by the way means to crash, in Spanish). As such, the authors need to justify the need and the relevance of such phenomenon to support the need for creating such an index. Therefore, the manuscript demands major revisions.

In relation with the area of study:

Along all his review, one of the main concerns of Dr. Poveda is related to the area of study. So in this first response we detail the physical fundament of our election.

Directional indices such as the one we propose cannot be interpreted in the same way as "traditional" circulation indices based on changes in zonal wind. Directional indices are a kind of "proxy" indices. Directional indices do not necessarily rely on changes in the wind direction in the same region where the "core" of the phenomenon occurs. They usually take advantage of large-scale structures that are significantly related with the phenomenon object of study.

As it is said in our revised introduction, the weakening of the trades associated to positive SST anomalies in the eastern tropical Pacific results in a weaker Choco jet (Poveda et al. 2001). On its part, the SST interaction with the Caribbean Low Level Jet (CLLJ) is dependent on the season. As demonstrated by Wang (2007), during the boreal winter, a weak/strong CLLJ implies warm/cold SST anomalies in the tropical Pacific (exactly as in the case of the Choco jet). In this way, during the boreal winter, warm/cold SST anomalies are associated both to weaker/stronger Choco jet and CLLJ. Therefore, in winter the distribution of wind directions is not a good proxy of the strength of the Choco jet because both jets respond to SST changes in the same sense and the spatial distribution of the wind direction field in our study area shows little variability.

On the contrary, during the boreal summer, a strong (weak) CLLJ is associated with warm (cold) SST anomalies (Wang, 2007). Therefore, the modulation of the SST anomalies over the CLLJ and the Choco jet is opposite during this season. This configuration results in a significant change in the distribution of the wind direction field in a large area. In particular, we found optimal the areas delimited by the boundaries [4º N-15º N ; 120º W-84º W] plus [4º N-9º N; 84º W-77.5º W] (i.e. the areas we selected for the Choco-D).

To illustrate this effect, we decided to include in the revised manuscript two new figures (Figures 2 and 3). We think both of them, graphically demonstrate the opposite relationship of both jets in summer and the adequacy of selecting the persistence of the SW winds in the selected area to track the strength of the Choco jet.

So our method has solid and physically consistent foundations and, in addition, we explain why we can use the CHOCO-D from May to November but not between December and April.

Notwithstanding, we still consider the CHOCO-D a kind of proxy (for the reason raised by Dr. Poveda i.e. that our study area is not located over the core of the Choco jet). Despite having solid foundations, we subsequently followed the standard procedure to "validate" any proxy:

1. Comparison with validated indices for a calibration period. We did this calibration against the average wind speed at the core of the Choco jet. This is the "classical" index used to quantify the Choco jet strength (see our Figure 5). We found significant correlations between our new index and previous literature. Beyond the correlation values, our Figure 5.b clearly shows that the variability of our index closely mimics that of the zonal wind at 925hPa and corresponding to the Choco jet.
2. Assessment of the climate anomalies related to extremes on the new index using independent datasets. We performed an analysis of the moisture transport and precipitation for opposite values of the CHOCO-D and the results are entirely consistent with the expected anomalies should the CHOCO-D be a good proxy of the Choco jet strength (see Figures 7 and 8 of the revised manuscript).

We believe that the evidences now included in the paper clearly proof the goodness of the CHOCO-D and we do not fully understand the extreme concerns raised by Dr. Poveda related to our study area. In particular we strongly disagree with the use of the terms "erroneous" or "contaminated" to describe our index. To say that the CHOCO-D is "erroneous" or "contaminated" because the latitude range of the analysed area is not centred at the Choco jet core would be comparable to say that an El Niño reconstruction is "erroneous" or "contaminated" because it is based on data taken far from the equatorial Pacific. There are abundant examples of proxy indices defined for areas far away of the region directly affected by a climatic system (Liu et al., 2017; Li et al., 2013, etc.). Indices are useful or not useful depending on their representativeness to the phenomena object of study. Our CHOCO-D index is significantly related to the Choco jet variability both from the physical and statistical points of view, and, in both senses, useful and valid.

In relation with the Stensrud's criteria

Regarding the referee's concern about the necessity of "satisfy all the criteria put forward by Stensrud", this very same concern was raised in his first review.

We would like to stress that our definition does not contradicts any of these criteria. Anyway, as result of this concern, we included in our revised version a general explanation of the structure of the Choco jet (see our Figure 1) and its interannual variability in relation with the wind distribution (Figures 2 and 3). Our index is compatible with this structure. We think that including a deeper discussion about the Stensrud's criteria is unnecessary and completely out of the scope of a paper presenting a climate reconstruction of a well-known system. There is abundant published bibliography dealing with the dynamical structure of the Choco-jet, these works are cited in our revised version. In fact, the physical sense of our index is in part, based on them.

Summarising, in our view, we demonstrate, beyond reasonable doubt, that the changes in the wind distribution in our study area and measured by the persistence of the winds blowing from the SW are related to the changes in:

a) zonal wind at the core of the Choco jet.
b) changes in moisture advection from the tropical Pacific into Central America and Northern South America, and,
c) changes in precipitation from the tropical Pacific into Central America and Northern South America.

In the following replies we expand some of the concepts here outlined.

I also find fundamental problems in the authors responses to my original review, discussed next:

Response to comment No. 3: “When using an index only relying in wind direction (directional index) to characterise a jet, it is critical to define it in an area larger than that where the core of the jet is located. Otherwise it would be impossible to obtain a climatic signal related to the jet’s variability.” In this case, the authors must provide evidences to prove that the proposed index does comply with the requirements defined by Stensrud (1996). Moreover, as I previously mentioned it does not make physical sense to define a low-level-jet using a large latitudinal extent that is subject to the dynamics of two different low-level jets. Also, the second statement is incorrect. It is precisely because of the very well-defined setting of the historical Choco Jet that it is possible to obtain a climatic signal related to the jet variability, at diurnal, seasonal, intra-seasonal, annual and inter-annual timescales. Otherwise, the authors are mixing different phenomena and creating unnecessary confusion.

The dynamical structure on a wind system usually offers a good starting point to conceive an index. For example the afore mentioned Stensrud’s requirements are, among others, (a) that low level jets have maximum wind velocity at low levels, (b) they are typically associated with strong ocean-land temperature gradients (c) they have considerable vertical and horizontal wind shear, etc. (for a comprehensive list see Stensrud, 1996). One can choose among these characteristics (not necessarily all of them) to try to find a representative index.

For example, the classical index for the Choco jet is based on the first characteristic (the wind speed at low levels). However, this classical –and useful- definition does not make use of other of the Stensrud’s requirements. For example, the existence of large ocean-land temperature gradients is not explicitly included in the definition. Of course, this fact does not invalidate the classical index.

This reasoning is applicable to our CHOCO-D (or to any other) index. Not including features characteristic of a system do not invalidate an index.

From our previous experience (Barriopedro et al. 2014; Gallego et al. 2015; Ordoñez et al. 2016; Gallego et al 2017; Vega et al. 2018; García-Herrera et al. 2018; Gómez-Delgado et al. 2019), we suspected that it could be possible to find some area where the changes in wind direction persistence could be related to the wind speed at the core of the Choco jet. In the case of the Choco jet, the tug-of-war established during the warm season in response to SST changes is precisely the foundation of our method (see our first response). Finding a relation between the wind speed at one point and the wind direction persistence in a different one, does not contradict any of the Stensrud’s requirements. As previously argued (see first revision), directional indices are not applicable to the jet core region, where variability of the wind direction should be minimum and the signal-to-noise ratio, higher than in the selected area.

Response to comment No. 3: “if a directional index is defined for a region where the jet is permanently located as suggested (in this case the vicinity of 5ºN and 80ºW at 925 hPa), we would find no changes in the wind direction associated to the jet’s variability”. I do not understand why the authors keep arguing that there is the need to define the Choco jet in terms of a wind reversal. As historically defined, the all year-round westerly Choco jet does exhibit a clear-cut behaviour at diurnal, annual and inter-annual time scales. The so-called variability in the wind direction of the newly proposed index is solely due to the contamination with the dynamics of the Caribbean jet, and not a reversal of the Choco Jet.

We do not understand why it is said that “the authors keep arguing that there is the need to define the Choco jet in terms of a wind reversal”. It can be clearly seen in our revised version that we do not define the CHOCO-D in terms of wind reversal at all. We establish a relation between the frequency of the SW winds in an area and the wind speed in other area and we use the former as a “proxy” for the latter. Along all the procedure, we do not assume any wind reversal. And in our results, we do not find any wind reversal. In fact, in the revised text it is explicitly said that: “*Minimum velocities at this jet core are found in February-March (below 1 m·s-1) and maximum in October-November (6 to 7 m·s-1)*”, please note the positive values of the zonal wind in all cases.

In our opinion, there is no reason to claim that our index is “contaminated” simply because we use the relation between the CLLJ and the Choco jet to define it. We tested our index and it has a strong and significant response to the Choco jet, so it can be considered a proxy of the Choco jet strength

Response to comment No. 3: “Instead, we want to build a series based solely on wind direction and longer than those currently available.” This objective is quite different than building an index of the Choco jet. Again, what the authors built is not an index of the Choco jet but of the tug of war between the Choco and Caribbean low-level jets.

That’s correct. And then, we demonstrate that the variability of the spatial distribution of the winds resulting from this tug of war is significantly related to the wind speed at the core of the Choco jet (i.e. the classical index used to quantify the strength of the Choco jet) during the warm season.

We also demonstrate that the moisture advection and precipitation anomalies during extremes of our index are compatible with the changes in the Choco jet. In this sense, we feel that we are legitimated to claim that our index can be used to track the variability of the Choco jet.

Response to comment No. 4: “The Choco jet is not, by any way, a monsoonal circulation.” Yes, indeed. Although by the definition of the newly proposed index, it becomes a monsoonal (once-a-year) circulation, which contradicts the historical and physical definition of the Choco jet.

Again we disagree with Dr Poveda’s comment. Our index measures the number of days in a month with prevailing wind from the SW direction. This is the persistence of the SW winds in the area. And we demonstrate that this persistence is related to the wind speed at the core of the Choco jet.

Our index cannot measure any wind reversal, because it only takes into account the winds coming from the SW direction (more or less frequent) and it does not contradict the physical definition of a low level jet as the definition of a low level jet does not include any requirement on the persistence of the wind direction.

Concerning the historical reasons, we do not feel that they should be appealed to define a new index

Response to comment 4: "This will also allow us to justify the necessity of using the large area [4N-15N; 120W-84W] plus the area [4N-9N;84W-77.5W] where the influence of both jets is mixed,…" Again, it is incorrect and confusing to introduce a new definition of the Choco jet by mixing winds from two jets. The original Choco jet does not get reversed during the annual cycle, unlike the newly proposed one. So, the authors completely change the physical interpretation, dynamics and effects.

At the risk of being repetitive, we think that an index is useful/not useful depending on the sensibility of the index to the changes in the systems intended to be analysed. From previous responses it is clear that we found that the CHOCO-D is significantly related to the wind speed at the core of the Choco jet and in consequence, it is legitimate to use the index as a measurement of the Choco jet strength.

We also want to further stress that we do not claim, at any moment, that the "jet is reversed". Our definition of the CHOCO-D does not make use of any "wind" reversal. In fact, it is clearly established that the CHOCO-D is based on the changes in the frequency of the SW in the analysed region. We do not use any other direction, so it is impossible that the CHOCO-D quantify any wind reversal.

In fact, in several parts of the paper we mention that the Choco jet shows positive zonal velocity along the year, as the referee points out. In our revised version we explicitly included the seasonal evolution in our Figure 1.c and discussed it, mentioning explicitly the constant westward wind. We even discuss the limitations of the CHOCO-D index based on this premise. In consequence we do not feel that we introduce any "incorrect" or "confusing" concept.

Response to comment 4: "the CLLJ is clearly "winning" and easterlies dominate the selected area from 4N to 15N, while the weak westerlies associated with the Choco Jet are restricted to the 5N 80W vicinity." It is misleading to trying to justify the proposed Choco jet index using a single month of a single year, in particular during the occurrence of extreme phases of ENSO (Yepes et al., 2019). Figure 1a of the responses document illustrates the winds during August 1997, just in the middle of one of one of the strongest El Niño events ever recorded. As such it is normal to witness an enhanced Caribbean jet and a weakened Choco jet, and therefore the Caribbean winning the tug of war over the Choco jet, moreover at 90W, as shown in Fig 1(c). A similar deficiency-limitation can be pointed out in the case of Figure 2, since it depicts the winds at 925 hPa during a strong La Niña event (August 2010), and therefore the predominance of the Choco jet over the Caribbean jet. This cherry-picking of months and ENSO events are inadequate and misleading to justify the climatological features of the newly proposed index for the Choco jet.

As the Choco-jet and the ENSO cycle are so profoundly related (Poveda and Mesa, 2000), strong anomalies in the Choco jet strength are usually coincident with warm/cold ENSO events. So it was foreseeable that a good example of strong/weak Choco jet is coincident with cold/warm ENSO events. This is of course, the case of our Figures 2 and 3 as the referee indicates.

We would like to point out, however, that neither the months nor the years were selected by the "cherry-picking" method as suggested. August was selected because it is the month with the most consistent relation between our index and the classical one (see our figure 5) and this is because August is the core of the boreal warm season, when the opposite character of the behaviour of the Choco jet and the CLLJ should be more evident (see our first response). The years were selected because they show one of the clearest views of the fundament of our method. As our method is based on the opposite response of the CLLJ and the Choco jet to SST anomalies, obviously the best examples are those occurring under the most extreme SST anomalies. However, selecting the best example for presenting an explanation is completely legitimate as far as the "best case" is representative of a general behaviour. And this is the case. We tested other months and years and we obtained essentially the same results (see figures 1 and 2 of this document). So we feel that our description is representative of the general behaviour of the wind field in our study area.

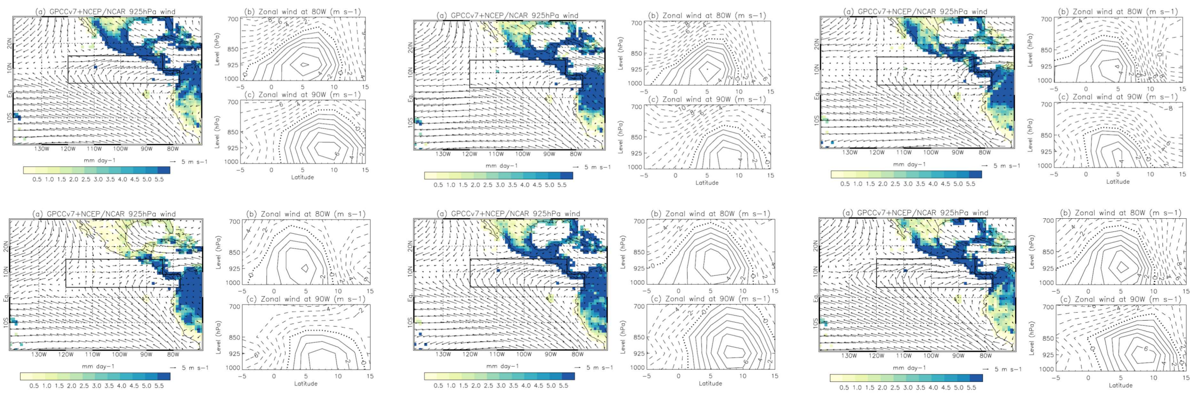

Figure 1. Some examples of the wind distribution in our study area during cases of strong Choco jet (intended to be compared with Figure 2 in our paper). From left to right and from up to down: August 1995, June 1988, August 2009, May 2011, September 1999, August 2010. Note how in all cases, strong zonal winds at 5ºN 80ºW 925hPa (core of the Choco jet) implies a northward-displaced CLLJ and a larger frequency on SW at the surface level in our study area and in consequence a large CHOCO-D as measured by the persistence of SW winds as seen from in-situ ICOADS wind direction measurements.

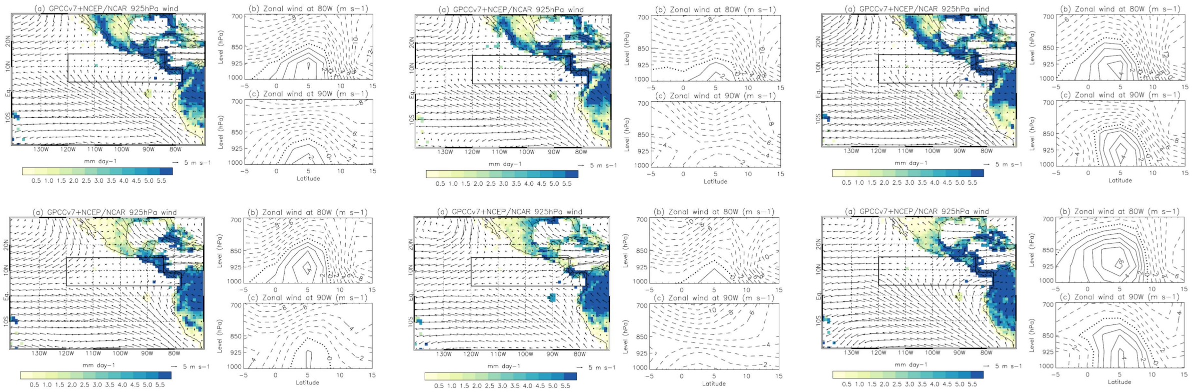

Figure 2. As figure 1, but for weak Chocho jet cases

Response to comment 4: "… but this would not be effective for an index based on wind direction such as ours, as the wind direction scarcely varies at this location. What we have found is that by using an extended area, the changes in the relation of westward/eastward winds are a good "proxy" of the strength of the Choco jet at its core" Again, the historical definition of the Choco jet was justified by the presence of steady (all year long) westerly winds flowing from the Pacific Ocean towards inland Colombia, and showing a clear-cut annual cycle associated with the spatial gradient between air temperatures over western continental Colombia and SSTs over the Nino 1+2 region. The newly proposed index turns out to mix the dynamics of two different jets, and causes confusion in the interpretation and analysis of diverse land-ocean-atmospheric mechanisms operating at the region. Therefore, I strongly disagree that the enlarged area used to define this new index provides an adequate "proxy" of the Choco jet. It is precisely due to the reversal of the winds with the annual cycle, when taken over such a large area, that the newly proposed index does not make historical of physical sense, beyond the correlations between the Choco jet index and the CHOCO-D index. My concern is about the physics and dynamics and not about statistics.

It is acceptable to say that constructing a proxy in terms of a simple correlation is not satisfactory, and it would be desirable to have a proxy based on a premise with physical sense. We think that this is the case with the CHOCO-D. The physical fundaments of our method are explicitly included in the paper (please, see our first response in this document).

In this sense, we disagree with the affirmation that our proxy is correlated with the core of the Choco jet because of "the reversal of the winds with the annual cycle, when taken over such a large area". This is equivalent to affirm that the correlation between the CHOCO-D and the wind at the core of the Choco jet is the result of the coupling of the seasonal cycle of the wind at the core of the Choco jet and the seasonal migration of the CLLJ over our study area. However this is not the case, as we performed the correlation on a monthly basis (i.e. we correlated the zonal wind with the CHOCO-D each month independently) and this procedure filters the seasonal effect. For example, when we found a large CHOCO-D index in August, we also found larger than average zonal winds at 925hPa, 5ºN 80ºW, and this link does not depend on the seasonal migrations of the jets, as we are always looking at a fixed month. The same argument is applicable from May to November (see the examples in Figures 1 and 2 of this document).

We do not think that “The newly proposed index turns out to mix the dynamics of two different jets, and causes”. As the referee has pointed out along his review, the CLLJ and the Choco jet are not independent entities (the “tug of war” issue) and we make use of this relationship, and the different responses of these jets to SST anomalies in summer to infer the strength of one of them. In our view, this is not equivalent to “mixing” the dynamics of the two jets.

Response to comment 10. “the winds typically reverses between January and July, which is one of the classical criteria to define monsoonal areas”. Again, the winds of the Choco jet do not get reversed. The problem is the selected region, where two different jets are acting at the same time, and by taking averages of the winds of both jets, the authors find an spurious reversal resulting from the mixing of both mechanisms, thus confusing the dynamics of two different phenomena/mechanisms as a single physical phenomenon.

This comment could make some sense with the first version of the manuscript, but we do not feel it makes sense any longer with the second version of the paper. In our original version, we explained our methodology in terms of monsoonal circulations (although this was only done as an introduction to the methodology). And in his first revision, Dr. Poveda indicated that this introduction can lead to confusion, as the Choco jet is not a monsoon and it does not get reversed. We completely agreed with that observation, and already did major changes to our original paper in order to clarify the dynamics of the wind circulation in the area. We wrote a completely new introduction and discussion that provide an overview of the two jets operating in the area and the physical mechanism that is the basis of our index (see our first response). This physical link (which is explicitly described in paragraph 3 of our revised paper) is based on the joint dynamics of the CLLJ and the Choco jet extensively described in published literature and we think it provides a very consistent basis to our method.

Additionally, we would like to stress that:

1. <u>In our revised paper there is not a single mention to any monsoonal system</u> (apart of saying that directional indices have been applied to monsoonal circulations in previous works).
2. <u>It is not said at any point of the text that the Choco jet gets reversed</u>.
3. <u>The CHOCO-D index is not based on any kind of “wind reversal”</u>.

So in this point we strongly disagree in the referee’s affirmations that the authors “find a spurious reversal resulting from the mixing of both mechanisms” (<u>we do not find any reversal</u>) and that in consequence we “confuse the dynamics of two different phenomena”.

Response to comment 13: “Our directional index is not capable of characterizing the Choco Jet in some months.” Indeed! This is precisely the main problem of the newly proposed index (inadequate region, mixing of dynamics), thus creating confusion in the scientific literature.

As any reconstruction/proxy, the CHOCO-D has limitations. We explicitly recognised them and we provide a physical explanation for such limitations in our paper, so we do not believe that they create confusion as claimed.

We strongly feel that the CHOCO-D constitutes a useful index. It provides an estimation of the Choco jet strength from May to November, it is consistent with precipitation anomalies for all these months, which also happen to be the months when the Choco jet is stronger along the year (see our Figure 1.c).

Response to comment 14: "As the CHOCO-D is defined as the % of westerly winds in the selected area, our index is essentially zero from December to April." This points out the limitations and shortcomings of the newly proposed index. Owing to the enlarged region used to define the proposed index, and that there are no westerly winds from December to April within such region, the index is useless almost half of the year. Therefore, what would be the value of the proposed index to represent the Choco jet?

We disagree on this point as well. From our point of view, having an index for a relevant climatic system that works more than half of the year and covers more than a century is usually considered extremely valuable in climatology.

Response to comment 15. "So although it is true that June-October is not ideal to analyze the dynamic of the Choco- jet, it is the best that can be achieved with a directional index." Indeed! The authors recognize one of the limitations of the proposed index. The problem is that Choco jet is defined as permanent (westerly) jet, and not as a directional (reversed once-a-year) circulation feature. Again, the confusion results from the proposed enlarged region under the dynamics of two distinct low-level jets.

In our opinion, recognising a limitation of a new methodology does not invalidate it.

As we already stated in previous responses, we do not affirm at any part of the paper that the Choco jet suffer a reversal, nor our index is based on this premise either. In our revised version it is explicitly said that (second paragraph of the introduction) "*Minimum velocities at this jet core are found in February-March (below 1 m·s-1) and maximum in October-November (6 to 7 m·s-1)*."

Response to comment 15. "the benefit of our approach is that we can compute an index based on actual observations since the late 19th century." This argument hardly applies, given the aforementioned shortcomings and limitations of the proposed new index in historical and physical terms. What would be the usefulness of such an index? On the other hand, it would valuable if the authors can produce a better historical record of the (properly defined) Chocó jet.

From our previous responses, it is clear that the CHOCO-D is representative of the wind speed variability at the core of the Choco jet between May and November. Being based on the only meteorological measurements available in this part of the world since the late 19^{th} century, it offers a unique opportunity to analyse the long-term changes of this important system. Regarding the suggestion that a better record could be produced, we think that with the currently available data, the CHOCO-D is the optimal choice.

Response to comment 20. “the CHOCO-D does not produces reliable estimations of the jet strength between December and April (see our reply to question #13),…” Quite true! The newly proposed index does not provide reliable information about the Choco jet during almost half (5/12) of the year!

That’s true. The CHOCO-D does not provide information during 5/12 of the year and the reason is justified in paragraph 3 of our manuscript (see also our first reply in this document). However, this could also been said as “the CHOCO-D provide information for 7/12 of the year”. Based on the following facts this information is also, reliable.

1. Significant correlations with the classic Choco jet index between May and November (Figure 5 of the manuscript).
2. Consistent anomalies with the moisture transport during strong/weak CHOCO-D index (Figure 8).
3. Consistent precipitation anomalies based on independent data (GPCC, our Figure 7). This consistency is independently found every month, so it is not related to seasonality.
4. Consistent moisture transport anomalies during phases of predominantly low and predominantly high CHOCO-D as see in the filtered evolution (our figures 9 and 10).

Response to comment 21. “it should be clear the necessity of considering an area where both the Choco Jet and the Caribbean LLJ are included in order to compute a directional index.” With all due respect, I disagree based upon my previous comments on the inadequacy to define the new index using an enlarged region, which is under the dynamics of two different low-level jets.

As we have already expressed in previous replies, our index is based on the interaction of both jets, which in our opinion, as discussed here and in the manuscript, allows to track the interannual variability of the Choco jet strength. And, again, the CHOCO-D index physical impacts are consistent with those described for the classical CHOCO index.

Response to comment 22. “Maybe we were a little bit enthusiastic. In the revised version we will substitute “excellent response” by “significant relationship” and we will explicitly indicate that this relation is restricted to the May-November period.” Again, I disagree. They differ almost half (5/12) of the year!

The CHOCO-D agrees with the wind speed variability 7/12 of the year, and that is exactly what we say in our response to comment 22 acknowledging that “this relation is restricted to the May-November period”. We also think that the reason why our index works from May to November is clearly discussed and justified in the manuscript (as already said in our previous responses).

References

Cook, K.H. and E.K. Vizy, 2010: Hydrodynamics of the Caribbean low-level jet and its relationship to precipitation. J. Climate, 23, 1477–1494.

Magaña, V., J. Amador, and S. Medina, 1999: The midsummer drought over Mexico and Central America. J. Climate, 12, 1577–1588.

Muñoz, E., A. J. Busalacchi, S. Nigam, and A. Ruiz-Barradas, 2008: Winter and summer structure of the Caribbean low-level jet. J. Climate, 21, 1260–1276.

Poveda, G., and O.J. Mesa, 1999: La Corriente de Chorro Superficial del Oeste ("del CHOCÓ") y otras dos corrientes de chorro atmosféricas sobre Colombia: Climatología y Variabilidad durante las fases del ENSO. Revista de la Academia Colombiana de Ciencias Exactas, Físicas y Naturales, Vol. 23, No. 89, 517-528.

Stensrud, D.J., Importance of low-level jets to climate: A review, J. Climate, 9, 1698-1711, 1996.

Wang, C., 2007: Variability of the Caribbean low-level jet and its relations to climate. Climate Dyn., 29, 411–422

Yepes, J., G. Poveda, J.F. Mejía, L. Moreno, and C. Rueda (2019): CHOCO-JEX: A Research Experiment Focused on the CHOCO Low-level Jet over the Far Eastern Pacific and Western Colombia. Bull. Amer. Meteor. Soc. In the press. https://doi.org/10.1175/BAMS-D-18-0045.1

References

Barriopedro, D., Gallego, D., Alvarez-Castro, M. C., Garcia-Herrera, R., Wheeler, D., Peña-Ortiz, C., and Barbosa, S. M.: Witnessing North Atlantic westerlies variability from ship's logbooks (1685-2008), Clim. Dynam., 43, 939–955. doi:10.1007/s00382-013-1957-8, 2014.

Gallego, D., Ordóñez, P., Ribera, P., Peña-Ortiz, C., and García-Herrera, R.: An instrumental index of the West African Monsoon back to the 19th century, Q. J. Roy. Meteor. Soc., 141, 3166-3176, doi: 10.1002/qj.2601, 2015.

Gallego D. García-Herrera R., Peña-Ortiz C. and Ribera P. 'The steady increase of the Australian Summer Monsoon in the last 200 years'. Scientific Reports, 7, Article number: 16166. doi: 10.1038/s41598-017-16414-1, 2017.

Garcia-Herrera, R., Barriopedro, D., Gallego, D., Mellado-Cano, J., Wheeler, D., Wilkinson, C.: Understanding weather and climate of the last 300 years from ship's logbooks, WIREs Clim. Change, e544, doi:10.1002/wcc.544, 2018.

Gomez-Delgado, FdP., Gallego, D., Peña-Ortiz, C., Vega, I., Ribera, P., García-Herrera, R.: Long term variability of the northerly winds over the Eastern Mediterranean as seen from historical wind observations, Glob. Planet. Change, 172, 355-364, doi: https://doi.org/10.1016/j.gloplacha.2018.10.008, 2019.

Li, J. et al. El Niño modulations over the past seven centuries. Nat. Clim. Change 3, 822–826 (2013). doi: 10.1038/nclimate1936

Liu, Y. et al. Recent enhancement of central Pacific El Nino variability relative to last eight centuries. Nat. Commun. 8, 15386 (2017). doi: 10.1038/ncomms15386.

Poveda G. and Mesa O. J.: On the existence of Lloró (the rainiest locality on Earth): Enhanced ocean-land-atmosphere interaction by a low-level jet. Geophys. Res. Lett., 27, 1675-1678, doi:https://doi.org/10.1029/1999GL006091, 2000.

Ordóñez P, Gallego, D., Ribera, P., Peña-Ortiz, C., García-Herrera. R. 'Tracking the Indian Summer Monsoon onset back to the pre-instrumental period'. J. Climate, 29 (22), 8115-8127, doi: 10.1175/JCLI-D-15-0788.1, 2016.

Vega I., Gallego D., Ribera P., Gómez-Delgado FdP., García-Herrera R., and Peña-Ortiz C.: Reconstructing the Western North Pacific Summer Monsoon since the late 19th century, J. Climate, 31, 355-368, doi:10.1175/JCLI-D-17-0336.1, 2018.

Wang, C.: Variability of the Caribbean Low-Level Jet and its relations to climate, Clim. Dyn., 29, 411-422, https://doi.org/10.1007/s00382-007-0243-z, 2007

Tracking the Choco jet since the 19th Century by using historical wind direction measurements

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Abstract. In this paper, we develop an instrumental index based on historical wind direction observations to quantify the intensity of the Choco jet. This is a low-level westerly jet with its core located at 5º N and 80º W that modulates the moisture transport from the Pacific into large areas of Central America and northern South America. The Choco jet is profoundly related to the dynamics of the Intertropical Convergence Zone in the eastern equatorial Pacific and it is responsible for up to 30% of the total precipitation in these areas. We have been able to produce an index of this jet starting in the 19th century, adding almost a century of data to previous comparable indices. Our results indicate that the seasonal distribution of the precipitation in Central America has changed along the 20th century as a response to the changes in the Choco jet, decreasing (increasing) its strength in July (September). Additionally, we have found that in general, the relationship between the Choco jet and the El Niño / Southern Oscillation has been remarkably stable along the entire 20th century, a finding particularly significant because the stability of this relation is usually the basis of the hydrologic reconstructions in northern South America.

1 Introduction

The Northern Hemisphere eastern equatorial Pacific is an interesting area from a climatological point of view. It is affected by two different low level jets whose interaction determines the moisture transport towards wide regions of Central America and northern South America, generating huge amounts of precipitation and affecting the living of millions of people (Arias et al., 2015). In the eastern equatorial Pacific, the Intertropical Convergence Zone (ITCZ) is predominantly located in the Northern Hemisphere (Wodzicki and Rapp, 2016). In this region, the Southern Hemisphere trade winds cross the Equator and the change in the sign of the Coriolis term, facilitated by the coast orientation and the land-sea temperature gradients, deflects the trades to the east, entering northern South America at 5ºN as a low level westerly jet, whose core is located at the 925 hPa level (Fig. 1.a) introducing huge amounts of moisture into the continent (Poveda and Mesa, 1999, 2000). This jet was first described by Poveda and Mesa (1999) who named it as the Chocó Jet, the name standing both as an acronym from "CHorro del Occidente COlombiano" (Western Colombian Jet) and as the place name "Chocó", one of the Colombia's departments most affected by the moisture advection from the Pacific related to this jet (Poveda and Mesa, 1999, 2000). In some localities such as Lloró (5º30'N, 76º32'W), the large amounts of moisture transported from the Pacific into the Colombian coast results in average rainfall ranging from 8,000 to 13,000 mm, making this region one of the rainiest in the world (Murphy, 1939; Trojer, 1958; Arnett and Steadman, 1970; Meisner and Arkin, 1987; Janowiak et al., 1994; Poveda and Mesa, 2000; Poveda et al., 2011; Jaramillo et al., 2017; King et al., 2017). At 80ºW, the cross section of the zonal wind from 5ºS to 20ºN (Fig. 1.b) shows the distinctive characteristics of this system, a jet core located at 925 hPa and 5ºN confined to the lower troposphere, with westerlies restricted to altitudes below 850 hPa. Although the location of the core is almost constant throughout the year (Poveda and Mesa, 2000; Sakamoto et al., 2011; Sierra et al., 2018), its intensity has a strong seasonal cycle (Fig. 1.c, black line). Minimum velocities at this jet core are found in February-March (below 1 $m \cdot s^{-1}$) and maximum in October-November (6 to 7 $m \cdot s^{-1}$). From May and up to December, the jet is quite active and its relation with the ITCZ seasonal migration is evidenced by the presence of two relative maxima in June and October (Fig. 1.c).

In Fig. 1.b a maximum of easterly zonal winds around 10 $m \cdot s^{-1}$ is observed at 15ºN and 925 hPa. It corresponds to the Caribbean Low-Level Jet (CLLJ) (Amador, 1998; Poveda and Mesa, 1999; Poveda et al., 2006; Wang, 2007). This jet also shows a marked seasonal variation. The absolute value of the zonal wind at 15ºN, 75ºW and 925 hPa constitutes a good measure of the intensity of this jet (Figure 1.c, dashed blue line). At the core of the CLLJ the absolute value of the wind speed varies between a minimum around 7 $m \cdot s^{-1}$ (October) and a maximum of 14 $m \cdot s^{-1}$ in July, with a secondary maximum in December and January (12 $m \cdot s^{-1}$).

While the location of the core of both jets is rather constant at inter-annual scales, their relative strength is quite variable, and strongly dependent upon the SST in the tropical Pacific. This dependence is different in each case. Ultimately, the Choco jet is originated in the Southern Hemisphere trades; so, the weakening of the trades associated to positive SST anomalies in the eastern tropical Pacific (El Niño conditions) results in a weaker Choco jet (Poveda et al. 2001). On the other hand, the dependence of the CLLJ with the SST anomalies is season dependent. As demonstrated by Wang (2007), during the boreal winter, a weak (strong) CLLJ corresponds to warm (cold) SST anomalies in the tropical Pacific. On the contrary, during the boreal summer a strong (weak) CLLJ is associated with warm (cold) SST anomalies. In this way, during the boreal winter, warm (cold) SST anomalies are associated both to weaker (stronger) Choco jet and CLLJ. In summer, the modulation of the SST over both jets is opposite. Warm (cold) SST anomalies are associated to weak (strong) Choco jets but strong (weak) CLLJs. This divergent behaviour results in a major signature on the distribution of the westerlies / easterlies noticeable at the surface level and over a large area of the eastern tropical north Pacific. As an example, Fig. 2 shows the average winds during August 1997, a month with high positive SST anomalies over the tropical Pacific. The pressure-latitude cross-section of the zonal wind at 80ºW (Fig. 2.b) shows the consequent weak Choco jet (although still existent and centred at 5ºN) and an enhanced CLLJ. It is clearly evidenced that during these episodes, easterlies dominate a large area in the tropical north Pacific (outlined area in Fig. 2.a). Westward of 90ºW the prevalence of the easterly component is absolute, even at the surface. On the contrary, in August, 2010 (Fig. 3), a month of strong SST negative anomalies in the eastern equatorial Pacific, the enhanced Choco jet is quite evident (Fig. 3.b) and most interesting, in these cases, the westerlies (predominantly south-westerlies) dominate a wide area of the tropical Pacific (outlined area in Fig. 3.a). Remarkably, the cross-section of the zonal wind at 90ºW (Fig. 3.c) shows that at the surface the westerlies can reach the 14ºN latitude.

Due to its relevance to the pluviometry of large areas, quantifying the variability of the Choco jet is of great importance. Currently, the index used to measure the Choco jet strength is based on the changes in the zonal wind speed at the core of this jet, and it relies on reanalysis products (Poveda and Mesa, 2000). Precipitation series in the area directly affected by the jet are also severely limited in time and they are not adequate to build longer indices (Carmona and Poveda, 2014). The large changes in the distribution of the easterlies / westerlies over a broad area associated to strong / weak Choco jets during the boreal warm season poses an interesting possibility: the development of an index for the Choco jet by using exclusively wind direction measurements.

In this regard, during the last years, it has been possible to quantify the interannual variability of the moisture advected to landmasses by designing indices based solely on wind direction over some key areas (Garcia-Herrera et al., 2018 and references therein). The main advantage of these so-called "directional indices" is that by design, they only require the knowledge of the wind direction, a variable that has been routinely measured aboard ships since the end of the 17th century and avoid the uncertainties associated to the measurement of the wind speed for early times (Prieto et al., 2005; Gallego et al., 2007). As a result of several data recovery projects (García-Herrera et al., 2005; Allan et al., 2011; Wilkinson et al., 2011 among others), millions of these early wind observations are nowadays incorporated into the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) database (Freeman et al., 2017). In its most recent release ICOADS holds over 456 million individual marine reports, covering the period 1662-2014. The objective of this paper is to develop a new index representative of the Choco jet strength by using exclusively the raw wind direction measurement currently incorporated in ICOADS. As we will show below this method provides an extension of almost one century to the current available indices of this jet.

2 The CHOCO-D index

a. Index definition

Directional indices are based solely on daily observations of wind direction and are usually defined as the monthly frequency of wind direction coming from a given range of angles. For a directional index to be representative, the climatological feature intended to be quantified must have a noticeable signature on the wind direction over a wide area at the surface level. We selected the area [4º N-15º N ; 120º W-84º W] plus the area [4º N-9º N; 84º W-77.5º W] (outlined area in Figs. 2.a and 3.a) as those where the change in the distribution of easterlies / westerlies is most dependent on the relative strength of the two low level jets active in the region. Figure 4 shows the selected domain, while shading shows the 1800-2014 cumulative density of ICOADS observations in a 1ºx1º grid between May and November. The darkest gridpoints noticeable in the equatorial Pacific in Fig. 4 correspond to data taken by moored buoys, which in this region started operating in June 1986. Some of these buoys are inside the selected domain and due to their fixed location, far from the most usual ship's routes, and their high temporal resolution, they became the dominant source of data since the 1990s in the selected domain. In order to maintain the homogeneity in the geographical distribution of the observed data into the domain, we did not consider data taken by moored buoys.

The graph at the bottom-left corner in Fig. 4 shows the temporal evolution in the number of the available wind direction observations inside the selected area between May and November. Unfortunately, for the first half of the 19th Century ICOADS has a very poor coverage in the Pacific (typically below 100 observations between May and November). Around 1850 there is an increase in the data coverage and, for some years, up to around 1000 observations can be found. However, the number of observations diminishes again below 100 per year between 1860 and the final decade of the 19th Century. From the beginning of the 20th Century onwards, the number of observations is typically well over 1000 per year (with the exception of the World War II period) rising to more than 10000 after the end of the 1950's. It is noteworthy that a large number of observations correspond to the routes following the coast, with a large contribution of the route from North America to the Panama Canal since its opening in the late 1910's. In fact, the latitude of the Panama Canal (around 9ºN) was the southernmost latitude reached for most of the ships aimed to the Caribbean Sea.

As a calibration series, we selected the NCEP/NCAR monthly zonal wind at 925 hPa averaged over the area [5º N-7.5 ºN; 90º W-80º W] (Kalnay et al., 1996) as this database allows performing the calibration since 1948. Although the original Choco jet index was defined exclusively at 80ºW (Poveda and Mesa, 2000), we chose an extended region from 90ºW to 80ºW to calibrate our index series to take into account for the presence of westerlies as westward as 90ºW in episodes of enhanced Choco jet (See Fig. 3.c). Inside the area outlined in Fig. 4.a, we computed the so called CHOCO-D index (Choco - Directional index) as the percentage of days per month with prevalent wind blowing from the southwest (observed wind direction ranging between 180 to 270 degrees from the true north). Following the methodology of Barriopedro et al. (2014) we considered a day as "a day with prevalent wind flowing from the southwest" when at least 37% of the wind observations in the selected area for a given day reported this wind direction. This percentage was set as the one maximizing the average correlation between June and October for the 1948-2014 with the calibration series. It must be stressed that a sensitivity test (not shown) proves that variations in this optimal percentage of up to +/- 15% produces only minor changes in the resulting CHOCO-D. A minimum of 10 days represented in a month was required to compute the index (Barriopedro et al., 2014).

The seasonal cycle of both the CHOCO-D index (black line) and the calibration series (dashed blue line) are displayed in Fig. 5.a for the 1948-2014 period. The calibration series (dashed blue line) shows that the region from 90ºW to 80ºW is dominated by weak north easterly winds between January and March, but this regime has already changed to a westward one by April and the westward component characteristic of the Choco jet is clearly evidenced between May and November. The two characteristic relative maxima in June and October are also found. The CHOCO-D index based exclusively on ICOADS wind direction observations (black line) closely mimics the seasonal march of the calibration series, with percentages of westerly days close to zero up to April, and higher values between May and November. Two relative maxima are found as well in June and September. A relative minimum is observed in July, coincident with the well-known midsummer drought in Central America (Small et al., 2007; Duran-Quesada et al., 2017). Figure 5.a also shows the monthly correlations between the calibration series and the CHOCO-D index for the concurrent 1948-2014 period. For all the active jet season, correlations are positive and significant, with a maximum value of +0.69 ($p<0.01$) for August and always above +0.50 ($p<0.01$) from May to October. With the exception of some years around 1960, the close agreement between the temporal series of the CHOCO-D index and the 925 hPa zonal wind for the (June-October average) is shown in Fig. 5.b. These values indicate that the CHOCO-D captures a significant part of the variability of the zonal winds at the latitude of the Choco jet.

b. Assessment of the CHOCO-D index uncertainty

As shown by Gallego et al. (2015), directional indices suffer from a certain uncertainty derived from the fact that the wind direction in the chosen sector is represented by a limited number of point observations. Consequently, it is related to the number of data used to compute the index. In this case, the region encompasses around 5,000,000 km^2. The inherent spatial variability of the wind inside this huge region and the finite number of available measurements in a given month is translated as dispersion in a particular realization of the index based on a finite sample of data. To estimate the expected uncertainty as a function of the number of available measurements, we computed 1000 'degraded' CHOCO-D indices constructed from N randomly selected wind observations inside the selected area with N ranging between 10 and 500. For each N, the 1000 degraded CHOCO-D are expected to be different because they are computed from a different set of observations. The average standard deviation of these 1000 series as a function of N between May and November is shown in Fig. 6 for the period 1971-2010. This particular period was selected in order to have a large-enough pool of wind observation in ICOADS to select a random sample of at least 500 observations. The results are scarcely dependent on the month and, as expected, the largest standard deviations are found for N=10 (around 16%) in all cases. This value rapidly decreases as N increases. For N=50 observations, the standard deviation is below 10% and, for N over 400, the standard deviation is almost stable around 6% to 7%. The fact that the standard deviation does not tend to cero as N increases reflects the inherent spatial variability of the wind inside the large region considered. We took the standard deviation shown in Fig. 6 as a conservative dispersion measure for the final CHOCO-D index. It must be pointed out that this dispersion measure is purely empirical, depends on the region and it should be only interpreted as the expected standard deviation of a CHOCO-D value computed from a particular set of wind direction measurements and not as a confidence interval in a statistical sense.

3 Relation between the CHOCO-D and the moisture transport

Traditionally, it has been considered that the Caribbean Sea was the main moisture supplier for Central America and northern South America through the CLLJ (Wang et al., 2006). However, the importance of the transport from the Pacific source by the Choco jet has been recently highlighted and it is estimated that the moisture advected from this ocean can contribute up to 30% of the total precipitation in areas of the western coast of Central America (Duran-Quesada et al., 2010; Duran-Quesada et al., 2017). The relevance of the Pacific source is captured by the CHOCO-D. Figure 7 shows the difference between precipitation composites for months with CHOCO-D above and below one standard deviation of its average value for the 1901-2013 period ("positive" and "negative" Choco jet phases in successive) covered by the Global Precipitation Climatology Centre (v7) dataset (Becker et al., 2013). The precipitation changes associated to opposite anomalies of the CHOCO-D index extend over large areas of southern Mexico, Central America and spread southward into northern Colombia. The largest positive precipitation anomalies are found between July and September, when the Choco jet is fully developed, and they are especially noticeable in the western coast of Central America from Guatemala to Panama, where precipitation anomalies exceed 5 $mm \cdot day^{-1}$ during positive phases of the CHOCO-D in relation to the negative ones. The connection of these rainfall anomalies with the moisture advection has been assessed by computing the vertically integrated moisture transport through the 1000-850 hPa levels and the corresponding moisture convergence (Fig. 8). We limited the latter analysis to the 1979-2014 period because of the large uncertainties in the vertical distribution of the specific humidity in the NCEP/NCAR reanalysis over the equatorial Pacific prior to the satellite era. In order to attain a large enough number of cases for this shorter period, we relaxed the threshold for including positive/negative phases by considering the years above/below 0.75 standard deviation of the CHOCO-D index. Despite the different periods considered and the lower spatial resolution of the reanalysis, the agreement between Figs. 7 and 8 is remarkable. As expected, large CHOCO-D values appear related to an enhanced moisture transport (anomalies of up to 100 $kg \cdot m^{-1} \cdot s^{-1}$) from the Pacific into Central America in a latitude band extending from around 4º N to 15º N. The higher values of moisture convergence related to this enhanced transport are located over Panama and the pacific coast of Colombia, westward of the Cordillera Central. It is also interesting to note that the Pacific is a relevant moisture source for the Caribbean as well. Over this area, large values of moisture convergence occur, originating significant changes in the precipitation of the Greater Antilles, especially in Jamaica and large areas of Cuba (see Fig. 7.d for example).

4 Temporal evolution of the CHOCO-D index

4.1 Interannual and decadal variability

The exceptional time coverage of ICOADS allows building an almost continuous monthly record of the CHOCO-D index starting in the 1880s and for some years between 1850 and 1860 (Fig. 9). The series indicates that the Choco jet is rather variable at interannual scale but the most prominent feature of the time evolution is a marked interdecadal variability, which is evident for all months (smoothed coloured curves in Fig. 9). This longer-term variability is quite dependent on the considered month. In general, the period 1880-1910 was characterized by stronger than average jets from May to August and also in November, while weaker than average jets are found in September and October. The subsequent three decades (1910-1940) show a general tendency to lower than average jets (except in November) which is quite evident in August. After the 1940s, the long term anomalies became even most dependent on the month. In May, the CHOCO-D shows an alternating behaviour at near decadal periods, while in June the index oscillates around average. In July and August the CHOCO-D was mostly below its low term average up to the 1990s, while in September and October it was above it up to the end of the series (2014), with a short period (1981-1990) of weak jets in October. November shows a long period of quite weak jets from 1960 to the late 1990s followed by a recovery to near-average values since the first years of the 21th century.

The strong dependence of the CHOCO-D behaviour on the month suggests that the seasonal distribution of the precipitation associated with the Pacific moisture source could be modulated by these long term changes in the Choco jet. Accounting for no more that 30% of the total precipitation in the area (Duran-Quesada et al., 2010), the changes in the total precipitation associated with the variability of the Choco jet are necessarily moderate, but yet discernible in cases of large opposite jet anomalies. For example, according to Fig. 9, the period 1901-1911 was characterized by a persistent strong jet in July and a relatively weak one in September. The contrary situation is observed in the 1965-1975, with a very weak jet in July and a strong one in September. When the GPCC difference in precipitation between the 11-year periods 1965-1975 and 1911-1901 is computed (Fig. 10), it is found that in July (September), the period 1965-1975 was significantly drier (wetter) than the 1911-1901 in large parts of Central America and northern Colombia, with changes in the total precipitation in the order of +/- 2 mm · day^{-1}.

4.2 Relationship with ENSO

As stated in the introduction, the Choco jet is ultimately originated in the southerly trade winds, making it strongly dependent on the meridional SST gradient along the Eastern Equatorial Pacific (Martinez et al., 2003) and therefore on the ENSO. Typically the ENSO cycle encompasses two calendar years. A warm event (El Niño) tends to begin during the boreal spring (year 0), developing increasing SST anomalies peaking the following winter (year +1), then declining to the subsequent summer (year +1). The diminished temperature gradient between the Peruvian Coast and the Panama Bight /

northern Colombian western coast around 5º N during the course of an El Niño event is accompanied by a weaker Choco jet (Poveda et al., 2001). The profound link between this meridional SST gradient and the precipitation in western Colombia through changes in the Choco jet has been documented for the second part of the 20^{th} Century by Poveda and Mesa (2000) and Poveda et al. (2001) and it has been subsequently assumed as the basis for the reconstruction of the climate in the area since the last glaciation (Martinez et al., 2003). The long series of the CHOCO-D index allows to assess the stability of this relationship between the Choco jet and the ENSO at secular scale for the first time.

Figure 11 shows that as expected, the correlation between El Niño3.4 index and the CHOCO-D has been mostly negative through the entire 20^{th} century for the in phase (JJA, Figure 3.a red line) and the lagged cases (CHOCO-D(JJA) leading El Niño3.4 (DJF yr+1)). This indicates that a weak jet in JJA tends to be followed by SST increases (El Niño conditions) the following winter. Some fluctuations in the absolute magnitude of the correlation are found, but Fig. 11.a shows that these relations have been remarkably stable along the 20th century. On the other hand, Fig. 11.b shows that, according to our series, a weak jet during SON is also typically concurrent with in-phase warmer SSTs (Fig. 11.b, red line), while warm SSTs during JJA tend to be followed by a weaker jet (Fig. 11.b blue line). Interestingly, the intensity of these relations involving the SON averaged CHOCO-D has changed along the 20th century, being clearly weaker prior to the 1920s.

5 Summary and discussion

During the last years, a number of studies have dealt with climate reconstructions based on historical wind direction measurements (see Garcia-Herrera et al., 2018 for a recent review). However, due to the low number of historical meteorological records over the eastern Pacific, most of these works correspond to reconstructions over the North Atlantic or the Indian Oceans. The few exceptions considering the Pacific are limited to the study of the climatic implications in the changes in the duration of a particular shipping route (Garcia et al., 2001), focus on the westernmost north Pacific (Vega et al., 2018) or make use of indirect approaches, by estimating the climate in the tropical Pacific through the use present-time teleconnections patterns using data taken at other oceanic basins (e.g. Barrett et al., 2017a; Barrett et al., 2017b). In this work, we have found that the strength of the Choco jet can be estimated through an index starting in the 1850's decade by using in-situ wind direction measurement contained in ICOADS. To the best of our knowledge, this is the first time that a quantitative instrumental climate index over the eastern tropical Pacific has been built for such a long period.

This reconstruction has been possible because the signature of the Choco jet variability in the distribution of the wind direction at the surface is sought in a large area where the aggregated number of observations available in ICOADS is currently enough for computing a meaningful index. As graphically described by Poveda (2018), in the tropical eastern Pacific, the wind field configuration is the result of a "tug of war" between two low level jets blowing from opposite directions: the CLLJ blowing from the Caribbean into the Pacific and the Choco jet originated in the Southern Hemisphere trade winds belt and recurving to the east as it crosses the equator (Poveda et al., 2001, 2006 and 2014). While the location of the core of both jets is almost stationary (Poveda and Mesa, 2000; Sakamoto et al., 2011; Sierra et al., 2018), their relative strength is quite dependent on the SST anomalies over the equatorial Pacific. During the Northern Hemisphere warm season, the modulation of the SST anomalies over both jets is opposite (Wang, 2007), and this results in a significant change in the distribution of the westerlies / easterlies in a large oceanic area. In this way during years of strong Choco jet, at the surface the westerlies can reach the 15ºN latitude limit even as westward as 120ºW, while in years of weak Choco jet, the westerlies are restricted to the 80ºW longitude. We found that, the proportion of days with wind blowing from the southwest in the areas [4º N-15º N ; 120º W-84º W] plus [4º N-9º N; 84º W-77.5º W] are significantly related to the relative strength of the Choco jet as measured by the average wind speed at its core.

It must be pointed out that our index has some caveats. On one hand, the strength of the Choco jet is not exclusively dependent on the relative strengths of the CLLJ and the Choco jet, as it is implicitly assumed in our approach. In fact, the strength of the Choco jet is partly dependent on the CLLJ dynamics. From the Caribbean, the CLLJ divides in two branches, one passes through Central America toward the Pacific (the one entering our study area), but the other one crosses the Panama Isthmus and then merges with the Choco jet (see Fig. 1.a), enhancing it (Poveda et al., 2014). On the other hand, the Choco jet suffers from positive feedbacks not necessarily related to the CLLJ, as the Choco jet core is enhanced by the latent heat released as it enters the continent generating precipitation (Velasco and Fritsch, 1987; Poveda and Mesa, 2000). Additionally, while the Choco jet is present in the region through the whole year, our index can be only computed between May and November. Between December and April, the southward migration of the ITCZ allows the north-easterly Northern Hemisphere trade winds to blow as southward as 4º N (Wodzicki and Rapp, 2016) and during these months easterlies are essentially dominant in our study area, and the CHOCO-D index is near zero regardless of the strength of the Choco jet.

These limitations explain both the absence of estimations of the Choco jet strength between December and April and the moderate correlation between the CHOCO-D and the Choco jet strength for the rest of the year ($r=+0.59$ $p<0.01$ for the May-October average, see Fig. 5.b). However during these months, this relation is significant, peaking in May and August, with correlations above $r=+0.68$ ($p<0,01$). Additionally, we have found that the CHOCO-D is strongly representative of the moisture advection from the Pacific into Central America and northern South America and, therefore, of a significant part of the precipitation in this area related to the moisture transported from the Pacific.

According to the CHOCO-D record, the Choco jet has experienced changes at decadal scales at least since 1880. They are quite dependent on the month. Interestingly the July series shows a tendency to be above its long term average value from 1840 to 1910 and below it from 1910 to 1990. September exhibits an opposite behaviour, being below average up to the 1920s and above it since that decade on. As the reversal in the trends for July and September occurred at the beginning of the

20th Century, the evaluation of the consequent changes in independent precipitation records are rather uncertain because of the low number of precipitation data in this part of the world during the first two decades of the 20th Century (Becker et al., 2013). Notwithstanding, the analysis of the GPCC dataset suggest that along the 20th century, there was a discernible change in the seasonal distribution of the precipitation related with the intra-annual variability of the Choco jet. Finally, it is worth mentioning that Carmona and Poveda (2014) found an increasing trend in the precipitation of the Pacific coast of Colombia starting in the last decades of the 20th century. Our results support this finding, as the strength of the Choco jet has been steadily increasing for May, June, July and August since the last years of the 20th century (Fig. 9).

Since their conception, one of the main applications of directional indices has been the analysis of the stability of teleconnection patterns (Gomez-Delgado et al., 2019). For instance, directional indices have been used to prove that the relation between the strength of the West African monsoon and the ENSO or the Atlantic Multidecadal Oscillation have been unstable (Gallego et al., 2015). Similarly, instabilities have been described in the relation between the ENSO and the strength of the Western North Pacific Summer monsoon (Vega et al., 2018). On the contrary, we have found that the relation between the Choco jet strength during JJA and the El Niño3.4 index (JJA and DJF yr+1) has been remarkably stable at least since the 1880s. This is particularly relevant because the stability of this relation is usually the basis of the hydrologic reconstruction or prediction in northern South America (Gutiérrez and Dracup, 2001; Prange et al., 2010; Córdoba-Machado et al., 2015). However, our results suggest that the intensity of these relations involving the SON averaged CHOCO-D has changed along the 20th century, being clearly weaker prior to the 1930s. We have not currently an explanation for this finding and it must be considered cautiously as the uncertainty of the CHOCO-D during this early period is the largest (Fig. 9), but it could be related to the shift from negative to positive anomalies around the 1920s-1930s discussed for the September and October CHOCO-D series (see Fig. 9). The results are also found when the ENSO cycle is represented by the Southern Oscillation Index (Ropelewski and Jones, 1987) based on sea level pressure instrumental measurements (not shown).

In this paper, we present a new example of how climate indices based exclusively on wind direction measurements over the ocean have a large potential to attain a better understanding of the long term climate variability, in this case in the eastern equatorial Pacific, a region with scarce inland observational records. The low level circulation in this region is dominated by the Choco jet, driving a large amount of moisture toward Central America and northern South America, which as a result is one of the rainiest areas in the world. With the data currently available on ICOADS, it has been possible to assess the long term variability of this jet since the late 19th century and some years of the 1850s decade, revealing a complex but significant variability at multidecadal scales. However, there are still some important gaps in the data coverage such as the World War II period or the years between 1860 and 1880, while prior to the 1920s, the low number of available observations results in uncertainties of the CHOCO-D index around 15%. We expect the results of this research will stimulate future efforts in data rescue aimed to improve the data coverage in this part of the world for years prior to the 1920s.

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References

Allan, R., Brohan, P., Compo, G. P., Stone, R., Luterbacher, J., and Brönnimann, S.: The International Atmospheric Circulation Reconstructions over the Earth (ACRE) Initiative, Bull. Amer. Meteor. Soc., 92, 1421–1425, doi:10.1175/2011BAMS3218.1, 2011.

Amador, J. A.: A climatic feature of the tropical Americas: The trade wind easterly jet. Top. Meteor. Oceanogr. 5,91–102, 1998.

Arias P. A., Martínez, J. A., and Vieira, S. C.: Moisture sources to the 2010–2012 anomalous wet season in northern South America, Clim. Dynam., 45, 2861–2884, doi:https://doi.org/10.1007/s00382-015-2511-7, 2015.

Arnett, A. B. and Steadman, C. R.: Low-level wind flow over eastern Panama and northwestern Colombia, ESSA Technical Memorandum ERLTM-ARL 26, U. S. Department of Commerce, Environmental Science Services. Administration Research Laboratories, Air Resources Lab., Silver Spring, Maryland, 73 pp., 1970.

Barrett, H. G., Jones, J. M., and Bigg, G. R.: Reconstructing El Niño Southern Oscillation using data from ships' logbooks, 1815–1854. Part I: methodology and evaluation, Clim. Dynam., 50, 845–862, doi:https://doi.org/10.1007/s00382-017-3644-7, 2017a.

Barrett, H. G., Jones, J. M., and Bigg, G. R.: Reconstructing El Niño Southern Oscillation using data from ships' logbooks, 1815–1854. Part II: Comparisons with existing ENSO reconstructions and implications for reconstructing ENSO diversity, Clim. Dynam., 50, 3131–3152, doi:https://doi.org/10.1007/s00382-017-3797-4, 2017b.

Barriopedro, D., Gallego, D., Alvarez-Castro, M. C., Garcia-Herrera, R., Wheeler, D., Peña-Ortiz, C., and Barbosa, S. M.: Witnessing North Atlantic westerlies variability from ship's logbooks (1685-2008), Clim. Dynam., 43, 939–955. doi:10.1007/s00382-013-1957-8, 2014.

Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Schamm, K., Schneider, U., and Ziese, M.: A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present, Earth Syst. Sci. Data, 5, 71-99, doi:10.5194/essd-5-71-2013, 2013.

Carmona A. and Poveda G.: Detection of long-term trends in monthly hydro-climatic series of Colombia through Empirical Mode Decomposition, Climatic Change, 123, 301-313, doi:10.1007/s10584-013-1046-3, 2014.

Cleveland W. S.: Robust locally weighted regression and smoothing scatterplots. J. Am. Stat. Assoc, 74, 829-836, doi:10.1080/01621459.1979.10481038, 1979.

Córdoba-Machado, S., Palomino-Lemus, R., Gámiz-Fortis, S. R., Castro-Díez, Y., and Esteban-Parra, M. J.: Influence of tropical Pacific SST on seasonal precipitation in Colombia: prediction using El Niño and El Niño Modoki, Clim. Dynam., 44, 1293–1310, doi:https://doi.org/10.1007/s00382-014-2232-3, 2015.

Durán-Quesada, A. M., Gimeno, L., Amador, J. A., and Nieto, R.: Moisture sources for Central America: Identification of moisture sources using a Lagrangian analysis technique, J. Geophys. Res., 115, D05103, doi: 10.1029/2009JD012455, 2010.

Durán-Quesada, A. M., Gimeno, L., and Amador, J.: Role of moisture transport for Central American precipitation, Earth Syst. Dynam., 8, 147-161, doi: https://doi.org/10.5194/esd-8-147-2017, 2017.

Freeman, E., Woodruff, S. D., Worley, S. J., Lubker, S. J., Kent, E. C., Angel, W. E., Berry, D. I., Brohan, P., Eastman, R., Gates, L., Gloeden, W., Ji, Z., Lawrimore, J., Rayner, N. A., Rosenhagen, G., and Smith, S. R.: ICOADS Release 3.0: A major update to the historical marine climate record. Int. J. Climatol. (CLIMAR-IV Special Issue), 37, 2211-2237, doi:10.1002/joc.4775, 2017.

Gallego, D., García-Herrera, R., Calvo, N., and Ribera, P.: A new meteorological record for Cadiz (Spain) 1806-1854. J. Geophys. Res., 112, D12108, doi:10.1029/2007JD008517, 2007.

Gallego, D., Ordóñez, P., Ribera, P., Peña-Ortiz, C., and García-Herrera, R.: An instrumental index of the West African Monsoon back to the 19th century, Q. J. Roy. Meteor. Soc., 141, 3166-3176, doi: 10.1002/qj.2601, 2015.

Garcia, R. R., Díaz, H. F., García-Herrera, R., Eischeid, J., Prieto, M. R., Hernández, E., Gimeno, L., Durán, F. R., and Bascary, A. M.: Atmospheric Circulation Changes in the Tropical Pacific Inferred from the Voyages of the Manila Galleons in the Sixteenth–Eighteenth Centuries, Bull. Amer. Meteor. Soc., 82, 2435–2456, doi:https://doi.org/10.1175/1520-0477(2001)082<2435:ACCITT>2.3.CO;2, 2001.

García-Herrera, R., Können, G. P., Wheeler, D. A., Prieto, M. R., Jones, P. D., and Koek F. B.: CLIWOC: a climatological database for the World's Oceans 1750–1854, Climatic Change, 73, 1–12, doi:10.1007/s10584-005-6952-6, 2005.

Garcia-Herrera, R., Barriopedro, D., Gallego, D., Mellado-Cano, J., Wheeler, D., Wilkinson, C.: Understanding weather and climate of the last 300 years from ship's logbooks, WIREs Clim. Change, e544, doi:10.1002/wcc.544, 2018.

Gomez-Delgado, FdP., Gallego, D., Peña-Ortiz, C., Vega, I., Ribera, P., García-Herrera, R.: Long term variability of the northerly winds over the Eastern Mediterranean as seen from historical wind observations, Glob. Planet. Change, 172, 355-364, doi: https://doi.org/10.1016/j.gloplacha.2018.10.008, 2019.

Gutiérrez, F. and Dracup, J. A.: An analysis of the feasibility of long-range streamflow forecasting for Colombia using El Niño–Southern Oscillation indicators, J. Hydrol., 246, 181-196, doi:https://doi.org/10.1016/S0022-1694(01)00373-0, 2001.

Janowiak, J. E., Arkin, P. A., and Morrissey, M.: An examination of the diurnal cycle in oceanic tropical rainfall using satellite and in situ data, Mon. Wea. Rev., 122, 2296-2311, doi: https://doi.org/10.1175/1520-0493(1994)122<2296:AEOTDC>2.0.CO;2, 1994.

Jaramillo, L., Poveda, G., and Mejía, J. F.: Mesoscale convective systems and other precipitation features over the tropical Americas and surrounding seas as seen by TRMM, Int. J. Climatol, 37,380-397, doi:10.1002/joc.5009, 2017.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R., and Joseph, D.: The NCEP/NCAR 40-Year Reanalysis Project, Bull. Amer. Meteor. Soc., 77, 437–471, doi: 10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2., 1996.

King, M. J., Wheeler, M. C., and Lane, T. P.: Mechanisms Linking Global 5-Day Waves to Tropical Convection. J. Atmos. Sci., 74, 3679–3702, https://doi.org/10.1175/JAS-D-17-0101.1, 2017.

Martínez, I., Keigwin, L., Barrows, T. T., Yokoyama, Y., and Southon, J.: La Niña-like conditions in the eastern equatorial Pacific and a stronger Choco jet in the northern Andes during the last glaciation, Paleoceanography, 18, 1033, doi:10.1029/2002PA000877, 2, 2003

Meisner, B. N., and Arkin, P. A.: Spatial and annual variations in the diurnal cycle of large-scale tropical convective clouds and precipitation, Mon. Wea. Rev., 115, 2009-2032, doi: https://doi.org/10.1175/1520-0493(1987)115<2009:SAAVIT>2.0.CO;2 1987.

Murphy, R. C.: The Littoral of Pacific Colombia and Ecuador, Geographical Review, 29, 1-33, doi:10.2307/210063, 1939.

Poveda G. and Mesa O. J.: La Corriente de Chorro superficial del Oeste (“del Chocó”) y otras dos corrientes de chorro en Colombia: Climatología y variabilidad durante las fases de ENSO. Rev. Acad. Colom. Cien., 23, 517-528, 1999. (in Spanish).

Poveda G. and Mesa O. J.: On the existence of Lloró (the rainiest locality on Earth): Enhanced ocean-land-atmosphere interaction by a low-level jet. Geophys. Res. Lett., 27, 1675-1678, doi:https://doi.org/10.1029/1999GL006091, 2000.

Poveda, G., Jaramillo, A., Gil, M. M., Quiceno, N., and Mantilla, R. I.: Seasonally in ENSO-related precipitation, river discharges, soil moisture, and vegetation index in Colombia, Water Resour. Res., 37, 2169–2178, doi:10.1029/2000WR900395, 2001.

Poveda, G., Waylen, P. R., and Pulwarty, R. S.: Annual and interannual variability of the present climate in northern South America and southern Mesoamerica, Palaeogeogr. Palaeoclimatol. Palaeoecol., 234, 3–27, doi: https://doi.org/10.1016/j.palaeo.2005.10.031, 2006.

Poveda, G., Alvarez, D. M., and Rueda, O. A.: Hydro-climatic variability over the Andes of Colombia associated with ENSO: a review of climatic processes and their impact on one of the Earth’s most important biodiversity hotspots, Clim. Dyn., 36, 2233-2249, doi: https://doi.org/10.1007/s00382-010-0931-y, 2011.

Poveda, G., Jaramillo, L., and Vallejo, L. F.: Seasonal precipitation patterns along pathways of South American low-level jets and aerial rivers, Water Resour. Res., 50, 98–118, doi:10.1002/2013WR014087, 2014.

Poveda, G.: Interactive comment on “Tracking the Choco jet since the 19th Century by using historical wind direction measurements”, Earth Syst. Dynam. Discuss., doi:https://doi.org/10.5194/esd-2018-54-RC2, 2018.

Prange, M., Steph, S., Schulz, M., and Keigwin, L. D.: Inferring moisture transport across Central America: Can modern analogs of climate variability help reconcile paleosalinity records?, Quaternary Sci. Rev., 29, 1317-1321, doi:https://doi.org/10.1016/j.quascirev.2010.02.029, 2010.

Prieto, M.R., Gallego, D., García-Herrera, R., and Calvo, N.: Deriving wind force terms from nautical reports through content analysis. The Spanish and French cases, Clim. Change, 73, 37–55,doi:https://doi.org/10.1007/s10584-005-6956-2, 2005.

Ropelewski, C. F. and Jones, P. D.: An extension of the Tahiti-Darwin Southern Oscillation Index. Mon. Weather Rev., 115, 2161-2165, doi:https://doi.org/10.1175/1520-0493(1987)115<2161:AEOTTS>2.0.CO;2, 1987.

Sakamoto M. S., Ambrizzi, T., and Poveda, G.: Moisture sources and life cycle of convective systems over Western Colombia, Adv. Meteorol., Article ID 890759, 11 pages, doi:https://doi.org/10.1155/2011/890759, 2011.

Sierra, J. P., Arias, P. A., Vieira, S. C., and Agudelo, J.: How well do CMIP5 models simulate the low-level jet in western Colombia?, Clim. Dynam., 51, 2247–2265, doi:https://doi.org/10.1007/s00382-017-4010-5, 2018.

Small, R. J., de Szoeke, S. P., and Xie, S.: The Central American Midsummer Drought: Regional Aspects and Large-Scale Forcing, J. Climate, 20, 4853–4873, doi:https://doi.org/10.1175/JCLI4261.1, 2007.

Trojer, H.: Meteorología y climatología de la vertiente del Pacífico colombiano, Rev. Acad. Colomb. Cienc. Ex. Fis. Nat., 10, 199-219, 1958 (in Spanish).

Vega I., Gallego D., Ribera P., Gómez-Delgado FdP., García-Herrera R., and Peña-Ortiz C.: Reconstructing the Western North Pacific Summer Monsoon since the late 19th century, J. Climate, 31, 355-368, doi:10.1175/JCLI-D-17-0336.1, 2018.

Velasco, I. and Fritsch, J. M.: Mesoscale convective complexes in the Americas, J. Geophys. Res., 92, 9591–9613, doi: https://doi.org/10.1029/JD092iD08p09591, 1987.

Wang, C., Enfield, D. B., Lee, S., and Landsea, C. W.: Influences of the Atlantic Warm Pool on Western Hemisphere Summer Rainfall and Atlantic Hurricanes, J. Climate, 19, 3011–3028, doi:https://doi.org/10.1175/JCLI3770.1, 2006.

Wang, C.: Variability of the Caribbean Low-Level Jet and its relations to climate, Clim. Dyn., 29, 411-422, https://doi.org/10.1007/s00382-007-0243-z, 2007

Wilkinson, C., Woodruff, S. D., Brohan, P., Claesson, S., Freeman, E., Koek, F., Lubker, S. J., Marzin, C., and Wheeler, D.: Recovery of logbooks and international marine data: the RECLAIM project, Int. J. Climatol., 31, 968–979. doi:10.1002/joc.2102, 2011.

Wodzicki, K. R. and Rapp, A. D.: Long-term characterization of the Pacific ITCZ using TRMM, GPCP, and ERA-Interim, J. Geophys. Res. Atmos., 121, 3153–3170, doi:10.1002/2015JD024458, 2016.

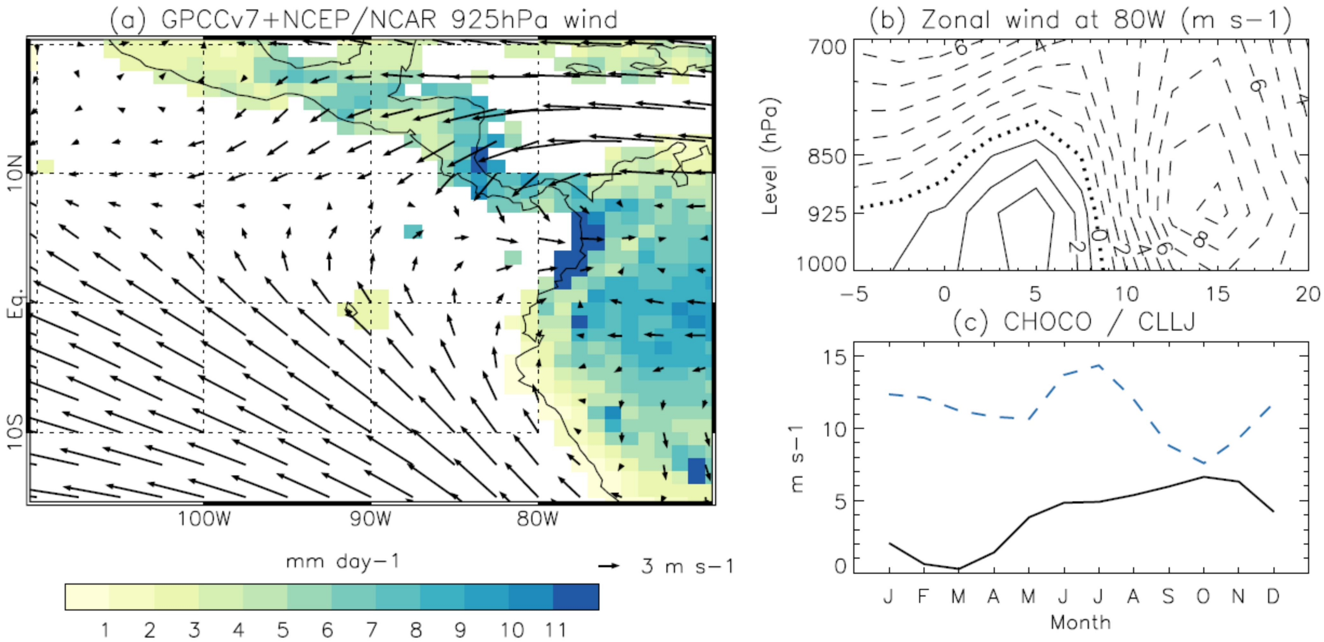

Figure 1: (a) Average NCEP/NCAR wind vector at 925 hPa for the period 1981-2010 shading shows the corresponding average GPCCv7 precipitation. (b) 1981-2010 average cross section of the zonal wind from 5S to 20N at 80W. Positive/negative (westerly/easterly) zonal wind is indicated by continuous/dashed contours. (c) 1981-2010 average monthly evolution of the zonal wind at 5N 80W and 925 hPa (CHOCO, black line) and zonal wind (changed of sign) at 15N 75W and 925 hPa (CLLJ, blue dashed line).

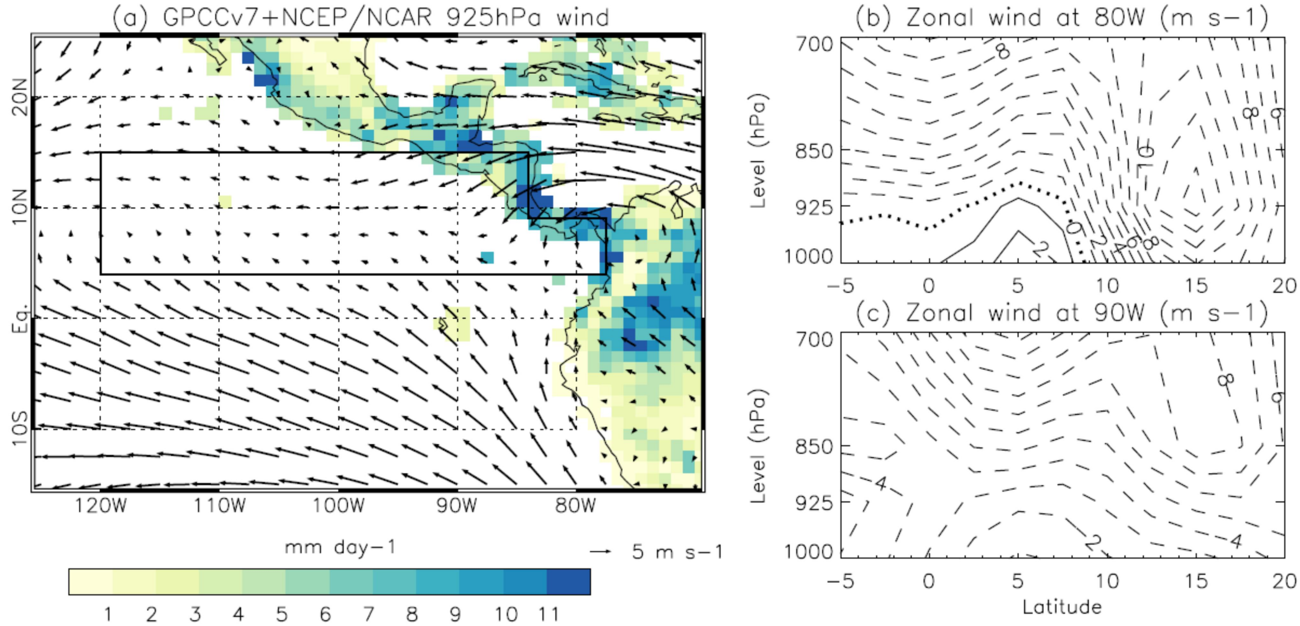

Figure 2: (a) NCEP/NCAR wind vector at 925 hPa for August 1997. The black box indicates the area where the index developed in this paper is defined. (b) Cross section of the zonal wind from 5S to 20N at 80W, (c) Cross section of the zonal wind from 5S to 20N at 90W. In (b) and (c), positive/negative (westerly/easterly) zonal wind is indicated by continuous/dashed contours.

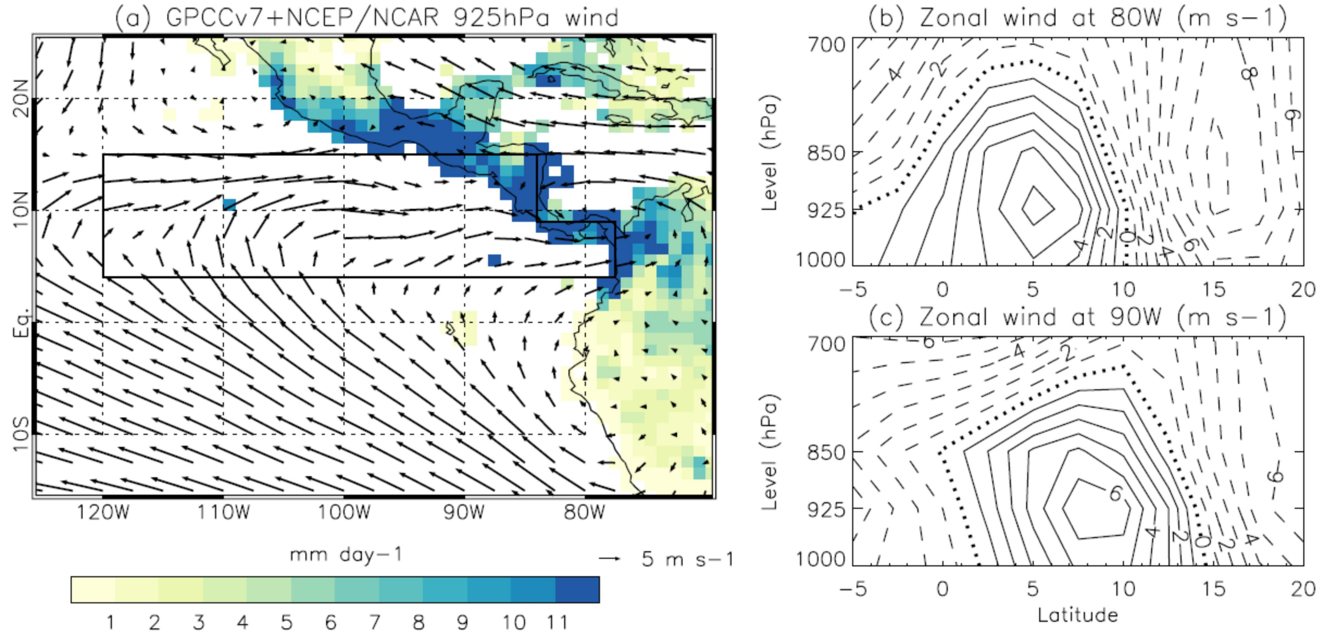

Figure 3: a) NCEP/NCAR wind vector at 925 hPa for August 2010. The black box indicates the area where the index developed in this paper is defined. (b) Cross section of the zonal wind from 5S to 20N at 80W, (c) Cross section of the zonal wind from 5S to 20N at 90W. In (b) and (c), positive/negative (westerly/easterly) zonal wind is indicated by continuous/dashed contours..

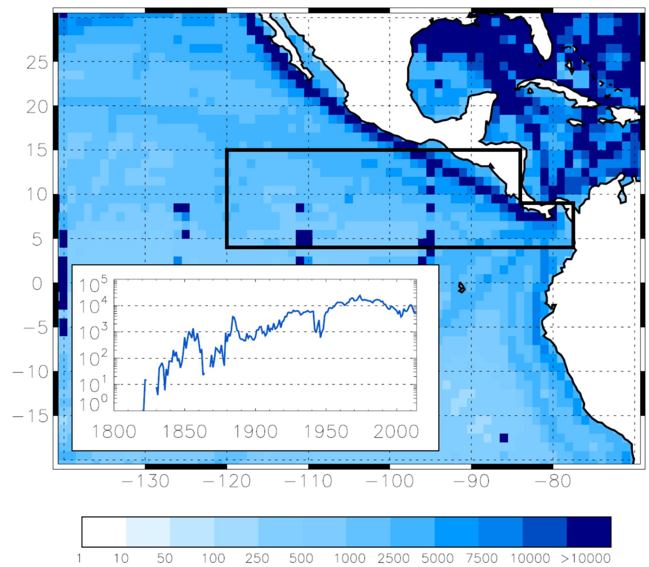

Figure 4: Number of wind direction observations in a 1x1 grid (May to November) and the 1800-2014 period available in ICOADS 3.0. Black contour indicates the area selected to compute the CHOCO-D index [4ºN-15ºN ; 120ºW-80ºW]. The graph at the bottom-left shows the time evolution of the cumulative number of wind direction observations inside the selected domain not considering data taken at moored buoys (note the logarithmic y-scale).

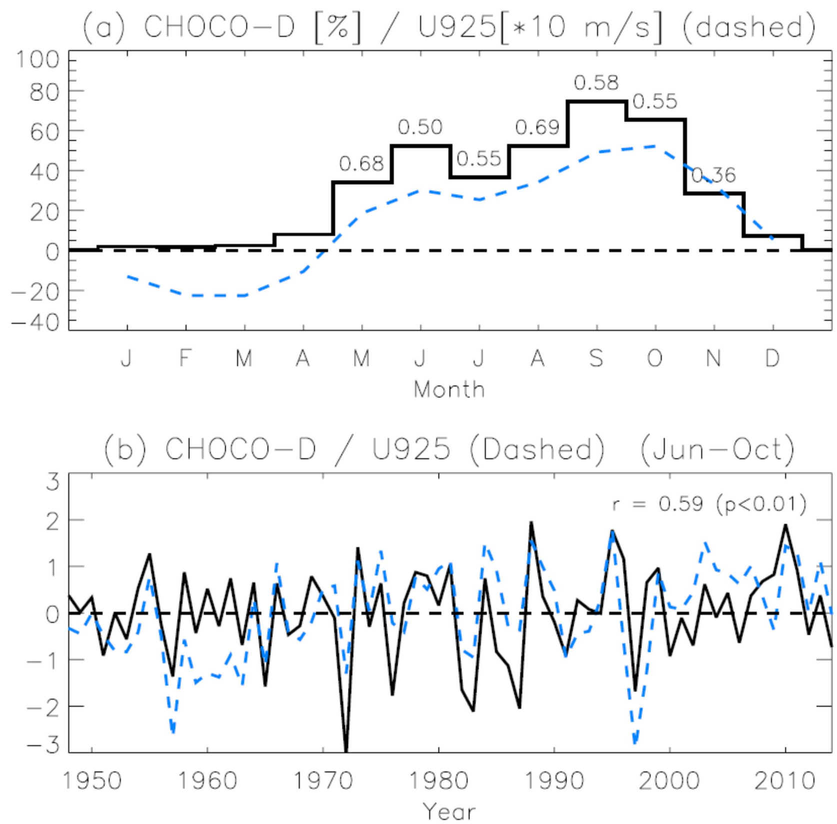

Figure 5: (a) Monthly averages (1948-2014) of the NCEP-NCAR zonal wind at 925 hPa averaged over the [5º N-7.5º N; 90º W-80º W] area (blue dashed line) and monthly averages of the CHOCO-D index for the same period in % of days in a month with prevailing wind flowing from the southwest (black line). Numbers over the CHOCO-D values indicates the monthly correlation between both series for the 1948-2014 period. Only correlations statistically significant ($p<0.01$) are displayed. Note the scale of the wind is expressed as 10 * m·s^{-1} to ease comparison. (b) Standardized temporal series (June to October average) of the CHOCO-D index and the NCEP-NCAR zonal wind at 925 hPa averaged over the [5º N-7.5º N; 90º W-80º W] (blue dashed line).

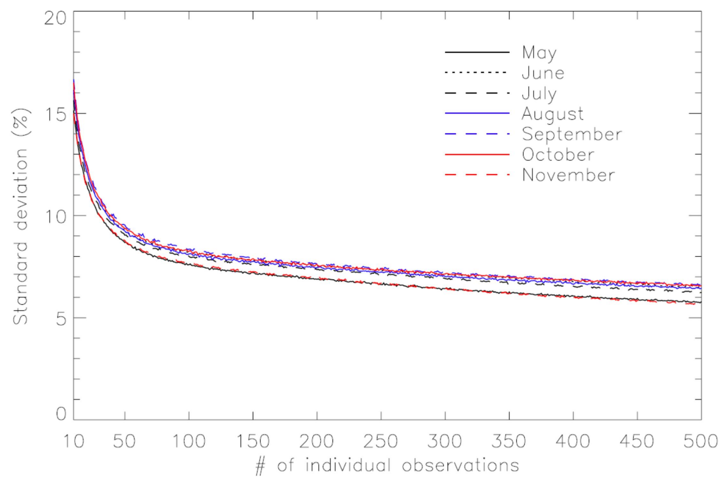

Figure 6: Expected dispersion (in %) of the CHOCO-D as a function of the number of wind direction observations used to compute it (x-axis) for May to November.

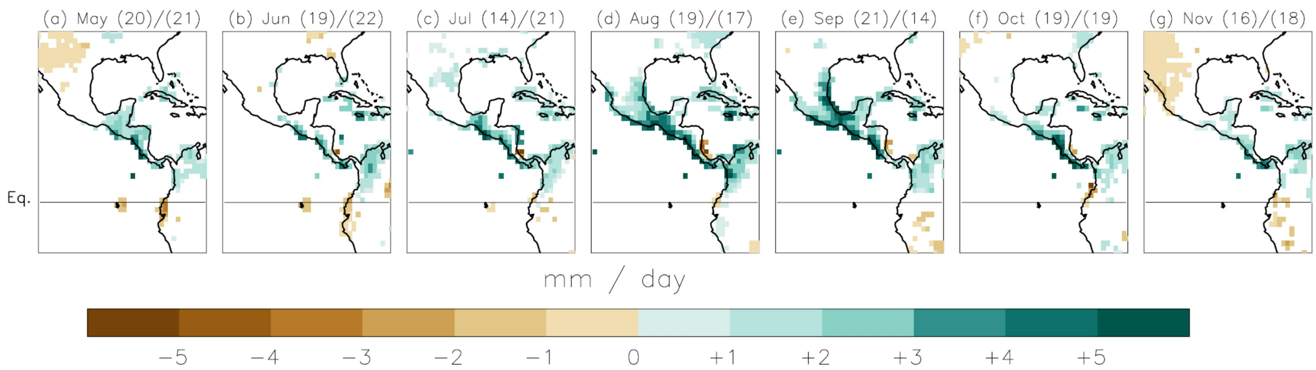

Figure 7: GPCC Precipitation differences between months with CHOCO-D over +/- 1 standard deviation for the 1901-2013 period (number of +1/-1 cases are indicated in brackets). Only areas with precipitation differences statistically significant at p<0.05 are represented.

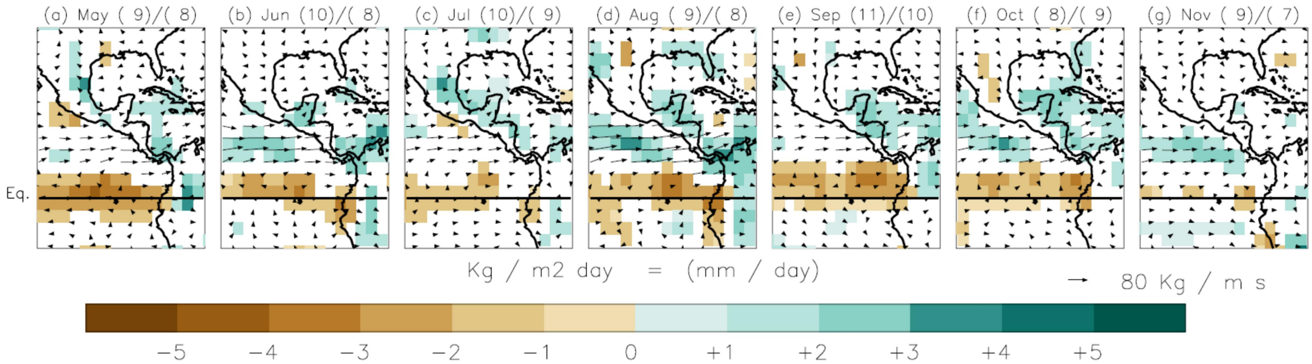

Figure 8: 1000-850 hPa vertically integrated moisture transport (arrows, scale at the lower-right corner) and moisture convergence (shaded areas) differences between CHOCO-D +/- 0.75 standard deviations years for the 1979-2014 period and NCEP/NCAR reanalysis data. Only moisture convergence differences significant at p<0.05 are represented. The number of CHOCO-D positive/negative cases used to compute the anomalies are indicated in brackets.

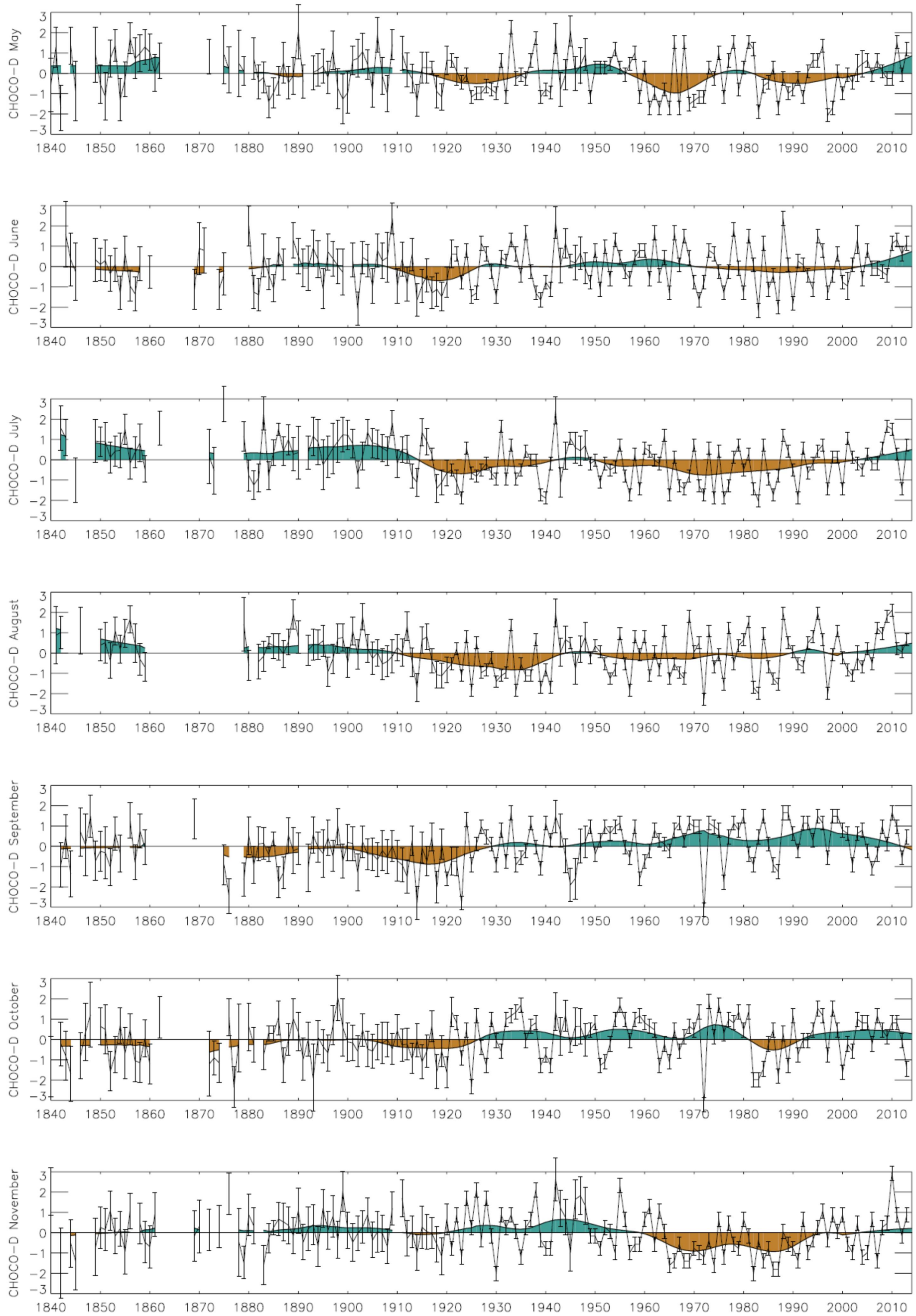

Figure 9: Standardized CHOCO-D for May to November between 1840 and 2014. Error bars indicate the expected standard deviation based on the number of observations available each year in ICOADS 3.0 (see text for details). Shaded smoothed curve is computed as a robust locally weighted regression with a 31-year window (Cleveland, 1979).

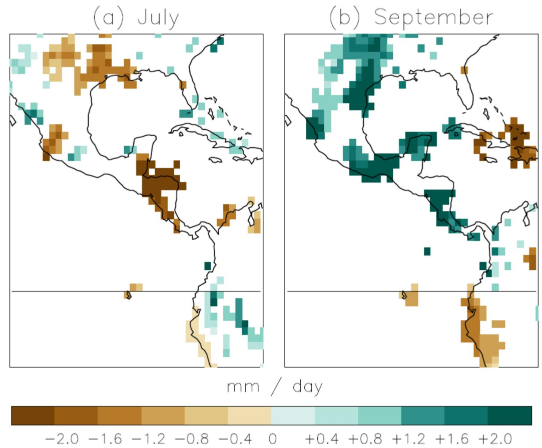

Figure 10: GPCC precipitation differences between the 11-year period 1965-1975 and 1901-1911 for a) July and b) September. Only differences at $p<0.05$ are displayed.

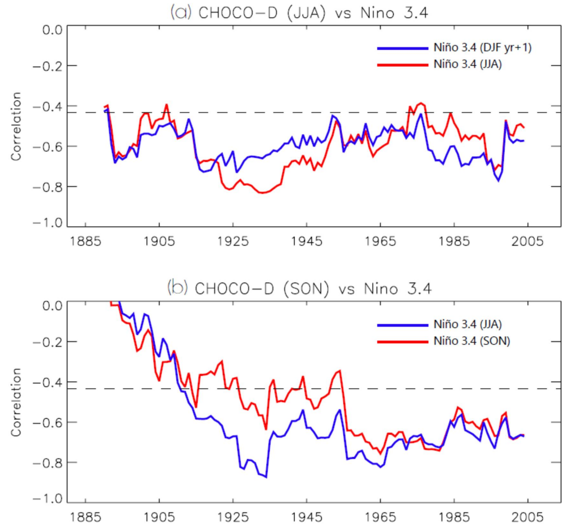

Figure 11: (a) 21-yr running Pearson's correlation coefficient between CHOCO-D (JJA) and El Niño3.4 in Phase (JJA, red line) and the following boreal winter (DJF yr+1, blue line). (b) 21-yr running Pearson's correlation coefficient between CHOCO-D (SON) and El Niño3.4 the previous boreal summer (JJA, blue) and in phase (SON, red line). Dotted line indicates statistically significant correlation at $p<0.05$.