Response RC1

The use of ICOADS data wind direction data to document long time variability of the Choco Jet seems to be OK, but the uncertainties in the use of this data in the long term trend analysis starting on the XIX Century may be complicated by uncertainties in this early data, as compared to the NCEP reanalyses. I have marked directly on the PDF version some comments, doubts and questions I have for the authors. I am not sure if with this merging of ICOAS and NCEP reanalyses one is able to study trend, decadal variations or even the stability of interconnection patterns. There is a need for some physical explanations of some of the correlation patterns investigated here, for instance, that correlation between the Choco jet and SST in Nino3.4 months later. Figure 7 needs some indicators of uncertainties in the ICOADS data, because these uncertainties are perhaps higher than those from recent decades from the reanalysis.

Response: Most of the referee concerns are related to the uncertainties of our data and results. We make a somewhat “innovative” use of ICOADS that probably needs additional explanation. As demonstrated by Prieto et al. (2005, Climatic Change, 73, DOI:https://doi.org/10.1007/s10584-005-6956-2), early wind speed observations have some uncertainty related to the fact that these observations were not instrumental (this uncertainty depends on multiple factors such as the evolution of the language, the observer nationality, etc.). In order to avoid this uncertainty, we used directly the raw ICOADS database which contains every individual observation of wind speed and direction separately. We did not use the speed observation in order to design an index exclusively based on wind direction.

We needed to envision a method to aggregate the wind direction data producing an index significantly related with the strength (speed) of the Choco Jet. Our calibration against NCEP/NCAR data for the 1948-2014 confirmed that the CHOCO-D is significantly related with the wind speed at the core of the Choco Jet. The advantage of our approach is that we can compute an index for the Choco Jet since long before anemometers were widely available.

The “instrumental” errors in the original wind directions are unknown, but early wind direction measurements were usually taken making use of a 16 or 32-point compass. They can be corrected for magnetic declination and they are regarded as precise as the equivalent modern ones (Barriopedro et al., 2013, Clim. Dyn, DOI:

https://doi.org/10.1007/s00382-013-1957-8). We assumed that the raw observations were essentially free of error. In this regard, recent research demonstrates that this is a trustworthy assumption, as small changes in historical wind direction contained on ICOADS have been even used to quantify subtle details of the atmospheric circulation, as it is the case of the date of the Indian Summer Monsoon onset (Ordoñez et al, 2016, J. Climate, doi:10.1175/JCLI-D-15-0788.1, 2016).

Notwithstanding, even assuming that the original observations are precise, early observation networks were spatially sparser than today's, and for years prior to the 1930's one is forced to compute the CHOCO-D from a relatively small sample of measurements. Incidentally, the number of observations does have an effect on the index uncertainty. Because of this, we developed a method to estimate this uncertainty as the expected standard deviation of the CHOCO-D index as a function of the number of observations available each month. Typical uncertainties of the CHOCO-D index range between +/- 15% (end of the 19th Century) and +/- 6% (late 20th century) (see Figure 4 of our original manuscript). These concepts were included in our original manuscript, but we will clarify them in the revised version. In particular we will expand our explanation of the characteristics of the observations, the procedure to compute the uncertainty of the CHOCO-D and the interpretation of the error-bars in Figure 7.

Regarding the merging of ICOADS and NCEP reanalyses commented by the referee, it is worth noting that our index has been exclusively computed from ICOADS wind direction observations. NCEP/NCAR data are uniquely used to calibrate the index, but both databases are never mixed. This characteristic of our method was probably not clear in our original manuscript, since both referees have expressed comparable concerns about this issue. In our revised manuscript we will explicitly incorporate a discussion on this topic, making particular emphasis on the homogeneity of our index. It is the use of ICOADS as our single data source, what makes the CHOCO-D particularly adequate to estimate long term trends and changes in correlations.

Finally, it is suggested that the explanation of the relation between El Niño and the CHOCO-D should be improved. This point has also been raised by referee #2. In essence, the Choco Jet can be seen as the final stretch of a low level wind current that starts in the Southern Hemisphere trade wind belt. North of the equator, the change in the sign of the Coriolis term, deflects the current to the east, entering northern South America at 5ºN as a low level westerly jet. Concerning the relation with ENSO, the weakening of the trade winds characteristic of a developing El Niño event is accompanied by a subsequent decrease in the trades and thus in the Choco Jet. Therefore, positive SST anomalies associated with an El Niño event (Niño3.4>0) are concurrent to weak Choco jets (standardised CHOCO-D index<0) and the negative correlation we found in Figure 9 was expected. We consider important, as suggested, to clarify this point in the revised paper and further stress the novelty of our result (the stability of the relation for long periods). Additionally, new in-phase and out of phase correlations will be added in this point in response to the concerns expressed by referee #2 further improving the ENSO-Choco Jet section (please see also our response to the last question of the referee below)

Minor and major comments are included directly in the PDF version of the paper.

Response: A number of the comments included in the supplementary material (annotated manuscript) have to do with the origin of the data or the uncertainty and physical meaning of the ENSO/Choco Jet relation. They have been partly answered in the previous paragraphs. Other comments are formal corrections/considerations/erratum that can be easily implemented in the revised paper (we thank the referee for his/her detailed review). In the following lines, we respond to other considerations included in the supplementary material not yet fully answered:

Page 3, line 19. To the best of our knowledge, the first work explicitly referring to the “Choco Jet” as such, was published by Poveda and Mesa (1999). We will add this precision and the corresponding reference in the revised paper.

Page 3, lines 20 and 23: The Choco Jet modulates the moisture transport from the Pacific into large parts of Central America and northern South America. In some areas, the resulting precipitation can exceed 10,000 mm per year. Characterising the long term variability of the system responsible of the moisture transport toward one of rainiest places on Earth is quite relevant from a climatological point of view. This idea will be stressed in our revised version.

Page 3, line 27 and page 4, line 24: Most of the raw wind force observations were codified using the Beaufort scale. However this was not always the case. It was frequent the use of not standard language or the inclusion of modifiers which are hard (uncertain) to convert into numbers. This is why we decided to develop an index based only on wind direction. Of course, we lose some information, but the one we maintain is free of the uncertainty associated to the observational procedure. In our revised text we will clarify this concept by expanding our description of the data source.

Page 4, line 30. The CHOCO-D index is not sensitive to changes in the percentage in the order of +/- 15%. We will change our phrase *“...proves that the CHOCO-D index is scarcely sensitive to changes in the percentage…”* to “*…shows that variations in this optimal percentage of up to +/- 15% produces only minor changes in the resulting CHOCO-D…”*

Page 5, line 5: That's correct, the double maxima is related with the meridional migration of the ITCZ. In the revised version we will change our introduction to incorporate a complete explanation of the climatology of the region in which we will explicitly include the relation of the jet with the ITCZ.

Page 6, line 7: Positive and negative phases of the CHOCO-D are defined as months with a CHOCO-D index below/above one standard deviation of its average value for the 1901-2013 period. We will clarify this definition in the revised text.

Page 6, line 24: We meant "eastern Pacific" instead of "Pacific". We'll correct it in the revised version.

Page 7, line 1: We checked the possible relations of the CHOCO-D with NAO, AMO, PDO and ENSO. We only found consistent correlations for the latter, so we decided to limit our discussion to the link between ENSO and the Choco Jet.

Page 7, line 20: In response to the "veracity" of the climate shift that shows the CHOCO-D around the 1930s, this is an extremely difficult issue to judge. We would need comparable reconstructions at monthly resolution to compare with. For the moment, the only independent observational series that we could use to test our finding is the precipitation. As shown in figure 8 of our original manuscript, we found, at least, a change in precipitation consistent with the shift we found in the CHOCO-D. However, this comparison is also problematic. First because the precipitation associated to the Choco Jet it is estimated to be around 30% of the total precipitation (Duran-Quesada et al 2010, J. Geophys. Res., 115, doi: 10.1029/2009JD012455), so any shift in the Choco jet would be only responsible of a part of the total precipitation variability. Second, because precipitation series in the first decade of the 20th century in northern South America are quite scarce. However, for the first time, there is a continuous series of the strength of the Choco Jet lasting more than a century, and we considered interesting to include a short discussion on this topic. We hope this could trigger new research.

Page 9 line 9: The main implication of being able to construct an index for the Choco Jet without using the wind speed is the possibility of quantifying the variability of this system for years prior to the mid-20th Century in a homogeneous form. This is probably the central point of our research.

Page 9 line 24: We do not mix reanalysis and ICOADS data. We exclusively use ICOADS to generate our index. Reanalysis is only used to calibrate the new CHOCO-D index for the 1948-2014 period. In this regard, we are pretty sure about the homogeneity of our series. However, the CHOCO-D has some uncertainty related to the number of observations, as previously indicated. This uncertainty is discussed in the original manuscript, but in Figure 7 it is not completely clear the relevance of the error-bars. We will enhance the presentation of this uncertainty in the revised version.

Page 9, line 34: This is a relevant point. In our work, the stability of the teleconnection patterns is evaluated without using reanalysed datasets. Both El Niño3.4 and CHOCO-D series are instrumental and independent. Although both series have some uncertainty, they are quite adequate to analyse changes in the ENSO-Choco Jet relation at decadal scale. This idea will be clarified in the revised paper.

Page 23 (Figure 9 caption): We concur. Our original Figure 9 is probably not clear enough and the implications for the ENSO-Choco Jet relationship can be improved. We have performed a more complete analysis (including other lagged correlations) that completes our discussion (Figure 1 below). In summary we have computed the following correlations: El Niño index (JJA and DJF+1) vs. CHOCO-D (JJA); and El Niño index (JJA and SON) vs. CHOCO-D (SON). We found that a weak jet in JJA tends to be followed by SST increases (El Niño conditions) the following winter and that these negative correlations are also found for the in-phase JJA series. The relevant result here is that these relations have been remarkably stable along the 20th century. On the other hand, we found that a weak jet during SON is also typically concurrent to in-phase warmer SSTs, while warm SSTs during JJA tend to be followed by a weaker jet. For this extended analysis we have found that the stability of the relations involving the SON-averaged CHOCO-D has changed along the 20th century, being clearly weaker prior to the 1930s. This finding is probably related to the shift from negative to positive anomalies around the 1930s we found for the September and October CHOCO-D series (see Figure 7 of our original manuscript). We consider these results quite relevant for stimulating future research, so we will include this discussion in the revised paper, replacing Figure 9 with the new Figure 1 (below).

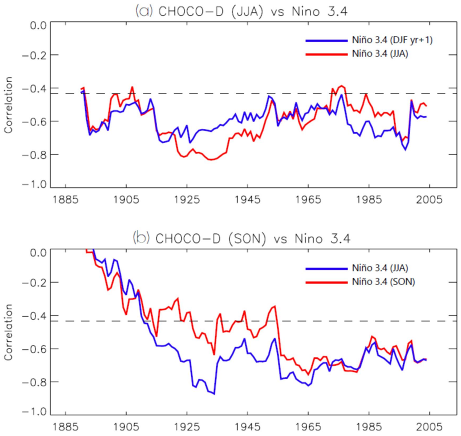

Figure 1. 21-yr running Pearson's correlation coefficient between CHOCO-D and El Niño3-4 for in-phase and lagged cases.

Response RC2

General Comment

I commend the authors for their interest in this relevant and singular feature (westerlies!) within the low-level atmospheric circulation over the tropical far eastern Pacific. In particular, I find it very relevant their objective of tracking the Choco jet since the 19th Century using historical wind observations, by introducing and computing the so-called CHOCO-D index. That said, I think that the manuscript is far from being ready for publication in Earth Syst. Dynam., and that major and minor comments need to be dealt with in detail in the revised version.

Response: We thank Dr. Poveda for his constructive approach to this review. Please see below our detailed response to major and minor comments.

Major Comments:

1. The Choco low-level jet (LJJ) was introduced in the literature as one of the mechanisms that contribute to explain the existence of one of the rainiest regions on Earth over the Pacific coast of Colombia (Poveda et al., 1998; Poveda & Mesa, 1999a, 1999b,2000). In particular, the locality of Lloró witnesses mean annual rainfall rates on the order or 13,000 mm, with years such as 1974 with 26,000 mm. Such world-record breaking rainfall intensity would not be possible were if not for the large amounts of moisture transported by the Choco jet into the Colombian Pacific coast. The original Choco Jet was defined at the region between 2N-8N and 80W [77W-82W], either using the averaged horizontal zonal wind velocities or the transport of moisture by the zonal winds (Poveda et al., 2006, Rueda and Poveda, 2006) at 925 hPa, the vertical location of its core, as it is constrained between 1000 and 850 hPa. As referred to by the authors, more recent studies have shown that the Chocó Jet is an important mechanism of the Central American isthmus weather and climate. Within that geographical region, the Choco Jet satisfies all the criteria mentioned by Stensrud (1996) to identify a low-level jet.

Response: We agree. The relevance of this jet for the moisture transport to Central America and northern South America is unquestionable. Remarkably, some of the characteristics mentioned by Stensrud as typical of Low Level jets and found in the Choco Jet (maximum wind velocities between 900 and 1000 hPa, shallow baroclinicity, significant horizontal shear, etc.) make it quite challenging to envision a method intended to quantify the Choco Jet intensity by relying solely on the distribution of the wind direction taken at the surface level. We must admit that at the beginning of the work, we were also quite skeptical about this possibility but as our work progressed we realized that it was possible and that the signal we found in the spatial distribution of the wind direction was significantly related to the intensity of the wind at the core of the Choco Jet. Later we will clarify the basis of this relationship.

2. Also, the geographical region associated with the original Choco Jet allowed to differentiate it from the activity of the Caribbean LLJ, at the time referred to as the San Andres LLJ (Poveda and Mesa, 1999a, 2000) given that it crosses over the San Andres archipelago in the Colombian Caribbean. Figures 1 and 2 show, respectively, the distribution of the zonal and meridional components of the horizontal winds at 925 hPa over the far eastern Pacific, northwestern South America and the southwestern Caribbean Sea. It can be seen that that the region is crossed by the westerly and easterly winds of both jets (Figure 1), but also by meridional winds associated with both jets (Figure2). Furthermore, the original Choco Jet was also constrained vertically, given that the westerly wind flow was evident from 1000 to 850 hPa, but also to differentiate its dynamics from the mid-tropospheric jet (700-600 hPa) (Hastenrath,1991, 1999; Poveda and Mesa, 1999a, 1999b, 2000) which is also seen in Figures 3 to 6.

Response: In fact, it is the existence of the San Andres LLJ what allowed to develop an index for the Choco Jet by using solely wind direction observations. This is precisely the reason why we need data along a large range of latitudes (4N to 15N) to obtain a meaningful signal. Please, see our reply to question #4 for details.

3. This previous introduction was deem necessary to point out one of the major concerns with the manuscript, regarding the region defined for the newly introduced CHOCO-D index: the area [4 N-15 N; 120W-84 W] plus the area [4N-9 N; 84W-77.5W]. Such region mixes up regions influenced by the opposite seasonal dynamics of both the Choco and the Caribbean LLJs. In particular, during December-January-February (DJF), the easterly Caribbean LLJ crosses the Mesoamerican isthmus, and three distinct wind jets form across the major gaps of the Central American mountain range in the Gulfs of Tehuantepec, Papagayo, and Panama (Chelton et al.,2000; Xie et al., 2005; Serra et al., 2010; Poveda et al., 2014).

Response: When using an index only relying in wind direction (directional index) to characterize 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 other words, 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, simply because the wind direction is scarcely variable there. In this area, the variability of the jet is optimally captured by changes in the wind force, but this is not our approach. Instead, we want to build a series based solely on wind direction and longer than those currently available. This viewpoint has been extensively applied with success (see Garcia Herrera et al

2018, WIRES Clim. Change. DOI: 10.1002/wcc.544, and references therein) because the use of indices based on wind direction has several advantages when looking at long term variability (temporal homogeneity, instrumental character even for the oldest records…). As can be seen in the examples shown in García-Herrera et al (2018), the area selected is always wider than the core of the phenomenon that we want to characterize. This is an extremely relevant issue and a number of concerns of Dr. Poveda are related to it. This will be clarified in the new version of the manuscript. In our reply to the following question (#4) we develop a complete discussion on this topic.

4. Therefore, I think it is a mistake to state that the Choco Jet constitutes a monsoonal circulation. What is really going on is a “tug of war” between two different LLJs acting over the proposed region through the seasonal cycle. As defined originally, the Choco Jet does not reverse once a year as evidenced in Figures 1 and 2. Furthermore, Figures3 to 6 show the vertical distribution of the zonal winds at 80W between 5S and15N, using data from four different reanalysis: NCEP/NCAR, ERA-Interim, MERRA2,and 20th Century V2c Reanalysis. All of them confirm that the original Choco Jet maintains its westerly direction and a very well-defined seasonal variability. Therefore, we are not in the presence of a monsoonal circulation but of two different LLJs acting over the region simultaneously. The situation is even more complex, given that during the DJF season the Caribbean jet, after crossing over the Panama Gulf gets merged with the Choco Jet and then inland over western Colombia (Poveda and Mesa, 1999a;2000; Sakamoto et al., 2011; Poveda et al., 2001, 2006, 2014).

Response: We concur with Dr. Poveda in this point. The Choco jet is not, by any way, a monsoonal circulation and in this sense we think that our original introduction section, developed in terms of monsoons can led to this misinterpretation.

The reason why we approached the development of the CHOCO-D index in this way was that our methodology was originally conceived to quantify monsoons (see Gallego et al. 2015. Q. J. R. Meteorol. Soc. DOI:10.1002/qj.2601 or García-Herrera et al. 2018 for example). During the course of our work on monsoonal systems, we performed a general feasibility analysis intended to locate the areas best suited to develop directional indices with ICOADS data. The one affected by the Choco Jet immediately arose as a promising area of study (see figure 1 of our original manuscript). We focused our introduction on this general feasibility analysis.

We agree that this introduction can be misleading. Consequently, the new version of the introduction will be focused on the climatology of the region and more specifically in the description of the two LLJ mentioned by Dr. Poveda. 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, as Dr. Poveda points out (see comment #3).

In essence, in order to find out which jet is winning the “tug of war” mentioned by the reviewer by using solely the changes in the wind direction, it is necessary to observe the entire “arena” where the jets are “fighting”. To illustrate this, we have chosen the years 1997 and 2010 where the average u-wind at 925hPa at 5N and 80W is low and high respectively (weak/strong Choco jet according to its original definition, see also Figure 3 of the original manuscript). During years of weak Choco jet (Figure 1.a in this document) 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. In the zonal wind height-latitude cross sections at 80N (Figure 1.b) the Choco jet is apparent at 925 hPa (although still noticeable and precisely centered at 5ºN as Dr. Poveda indicates). At 90W the easterlies are clearly dominant (Figure 1.c). On the contrary, during strong Choco Jet years, such as 2010, the jet shows its canonical structure in the 80W cross section (Figure 2.b), with its core still centered at 925hPa and 5N. However, during these episodes, the westerlies are still clearly seen well westward 80W (Figure 2.c). At the surface level these westerlies can reach the 15N latitude (the northern limit of our study area). The wind structure over our study region (Figure 2.a) shows the extension of the area with predominant westerly component in relation with our study area.

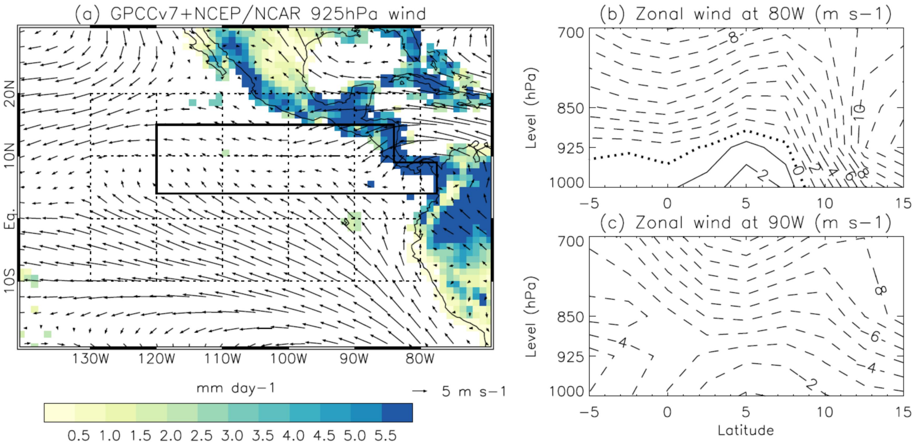

Figure 1. (a) NCEP/NCAR wind vector at 925 hPa for August 1997. The area where the CHOCO-D is defined is indicated by the black box. (b) Cross section of the zonal wind from 5S to 15N at 80W,. b) Cross section of the zonal wind from 5S to 15N at 90W. In (b) and (c), positive/negative (westerly/easterly) zonal wind is indicated by continuous/dashed contours.

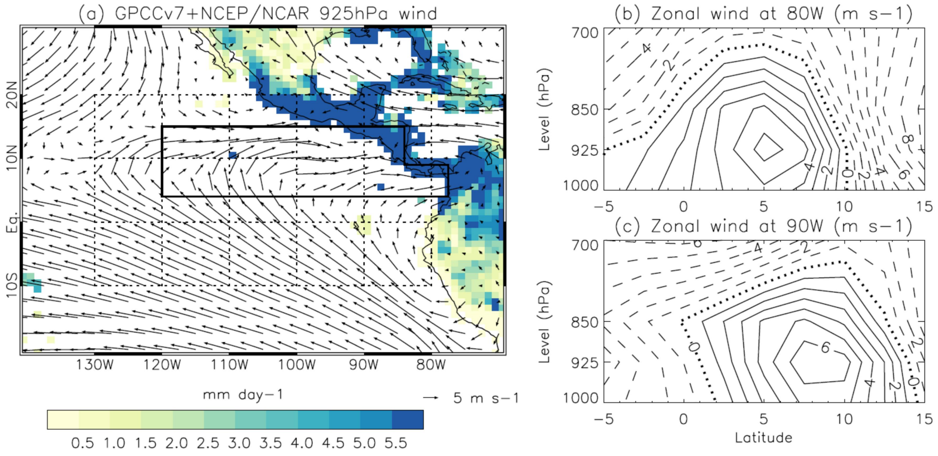

Figure 2. (a) NCEP/NCAR wind vector at 925 hPa for August 2010. The area where the CHOCO-D is defined is indicated by the black box. (b) Cross section of the zonal wind from 5S to 15N at 80W,. b) Cross section of the zonal wind from 5S to 15N at 90W. In (b) and (c), positive/negative (westerly/easterly) zonal wind is indicated by continuous/dashed contours.

From figures 1 and 2, it is evident that the core of the Choco jet is always centered at 5ºN and its latitude is scarcely dependent on the jet strength (as pointed out by the referee). In this sense, any index for the Choco Jet based on the wind speed should be centered at 5N and 80W as Dr. Poveda indicates, 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 (something not evident that will be stressed in our revised version). As any climate proxy, the CHOCO-D index has pros and cons, being the main "pro" the possibility of computing the index for long periods (wind direction was measured with great precision since the pre-instrumental era) and the main "con" (as for any proxy) that it is not perfectly correlated with the wind speed at the core of the Choco Jet (as our correlations of Figure 4 ranging between +0.36 to +0.69 reveal). This discussion will be explicitly included in our revised paper.

5. Besides the mentioned shortcomings of the chosen region, the definition of the CHOCO-D index is based upon criteria defined by the NCEP/NCAR reanalysis. Figures3 to 6 show that the different reanalysis capture the seasonal cycle of the Choco Jet, albeit with different core velocities, range of extent of peak velocities, and zonal wind velocities at 850 hPa (top of the Choco LLJ), also shown in Table 1.

Response: In the definition of our CHOCO-D index, the NCEP/NCAR reanalysis is only used as a “calibrator” i.e. we select the optimal percentage of observations necessary to consider a day as one “with prevalent wind blowing from the south west” as that maximizing the correlation of our directional index (CHOCO-D) and the “classical” index based on wind velocity (from NCEP/NCAR). In this sense, we only make use of the year-to-year variability and the precise value of the wind speed at the jet-core is not quite relevant for this correlation. We preferred performing the calibration with NCEP/NCAR in order to do it for a period as large as possible (1948-2014). ERA interim or MERRA-2 limit the calibration period to 1979-2014 or 1980-2014 respectively. This will be explicitly stated in the revised manuscript.

6. Also, I find it confusing to discuss the dynamics involved from a summer-winter perspective, given its very equatorial setting. The area proposed for the new CHOCO-D index also mixes up regions whose annual rainfall regime is bi-modal (as per the passage of the Intertropical Convergence Zone), and unimodal as per their location on the northern hemisphere.

Response: In our study area bi-modal and unimodal precipitation regimes can be found, but this is not relevant for the index definition. Our original introduction based on monsoons can lead to think that we make use of the changes in the seasonal (summer/winter) precipitation to define our area and/or to calibrate the index. However, this is not the case. The area is chosen as that allowing to capture the changes in the Choco Jet through the westerlies/easterlies relationship (see our reply to question #4). So our study area is only dependent on the winds climatology. This is also valid for the calibration, which exclusively relies on the correlation with the zonal wind speed between 5N and 7.5N. We expect that our new introduction will clarify these issues.

7. Lines 18-19. “In the case of precipitation, monsoonal areas are usually demarcated as those where the local summer minus winter precipitation rate exceeds 2 mm day-1.” Comment: Again, the consideration of summer and winter precipitation is misleading here, since this area contains regions exhibiting a bi-modal annual cycle of rain allowing to the meridional oscillation of the ITCZ, passing twice per year over this region, but also regions with uni-modal annual cycle of rainfall.

Response: We concur. However this does not interfere with our index definition nor with our interpretation of the results (see reply to question #6). This will be addressed by rewriting the introduction and abandoning the unnecessary summer/winter perspective given there.

8. Lines 28-29: “...it is necessary to identify regions where the monsoonal wind reversal found at the 850 hPa level is also found at the surface.” Comment: This is not the case of the Choco Jet as shown in the mentioned reanalysis.

Response: Again this is just the result of focusing our introduction in terms of monsoons. Most monsoonal indices are defined at the 850 hPa level and that was the level we used in our initial feasibility study (Figure 1 of our original manuscript). However after our introduction section, we do not use the 850 hPa wind anymore and we do not use any variable at this level for subsequent results. In fact we only use the zonal wind at 925 hPa, -at the core of the Choco jet- to calibrate the CHOCO-D index (see Figure 3 in our original manuscript). This issue will be addressed by rewriting the introduction, avoiding any reference to monsoons. Any reference to the wind at 850 hPa is then unnecessary and it will be removed from the text.

9. Line 32: “...in a 2.5_ x 2.5 grid where the last release of the ICOADS database currently has two or more wind direction observations per month for the summer months for at least 90 years in the 1900-2014 period. ”Comment: Such spatial resolution seems too gross to perform detailed analyses of this LLJ.

Response: This paragraph also belongs to our feasibility analysis originally included in the introduction (see reply to question #4). In order to compute a directional index with reasonable uncertainty, it is necessary to have a minimum of 50 to100 raw observations per month (see Figure 4 of our original manuscript representing the uncertainty of a directional index in our study area as a function of the number of data). For our entire study area, this roughly corresponds to the specified data density. However, although the output of this feasibility analysis inspired our study, it is not necessary in the manuscript because the finally chosen region is not based on this analysis (see our reply to question #4). In consequence, the referred phrase, as part of the original introduction, will be eliminated from the revised text.

10. Lines 13-14, p. 3. “CHorro del Occidente COlombiano” (Western Colombian Jet) and as the place name “Chocó”, one of the Colombia’s regions most affected by this wind reversal. ”Comment: There is no wind reversal in the Choco Jet as shown by the different reanalyses.

Response: Again, this phrase is related with our original approach in terms of monsoons. Our feasibility algorithm detected that in a large area of the equatorial Pacific, the winds typically reverses between January and July, which is one of the classical criteria to define monsoonal areas (see Figure 3 below). However, as Dr. Poveda points out, this does not imply that the Choco jet reverses (at its core 80ºW 5ºN, 925 hPa). As with the rest of our original approach in terms of monsoons, this phrase will be eliminated. In our revised text it will be clearly stated that while the Choco Jet core does not reverse the change in the relation of the westerlies/easterlies winds in our extended area can be considered a "proxy" of the jet core strength.

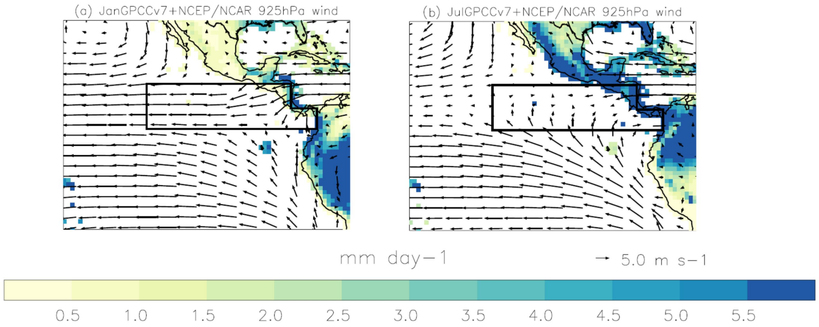

Figure 3. 1981-2010 averaged NCEP/NCAR wind vector at 925 hPa for (a) January and (b) July. The area where the CHOCO-D is defined is indicated by the black box. Shading shows the corresponding GPCCv7 precipitation.

11. Lines 14-16. Between May and November, the winter wind regime characterized by predominant north-easterly winds in this part of the world is replaced by south westerlies at low levels". Comment: Again, it does not seem appropriate to talk about winter wind regime over this tropical region, since the winds are quite different during MAM, when the ITCZ is heading in a northward direction, while in SON the ITCZ is heading in a southward direction.

Response: This is a relevant precision. In the revised text, the references to winter/summer regime will be substituted by a discussion in terms of the seasonal migration of the ITCZ.

12. Lines 17-18. "... and it has a profound impact on the western coast, from Costa Rica to northern Colombia, which, as a result, are among the rainiest places on earth(Poveda et al., 2014)."Comment: This is quite true. Perhaps the community needs to be aware that this world record breaking rainy region has been recognized in the literature since long: Murphy(1939), Schmidt (1952), Trojer (1958), Arnett and Steadman (1970), Snow (1976, p.371), Meisner and Arkin (1987), Eslava (1993, 1994), Janowiak et al. (1994), Poveda and Mesa (1999a, 2000), Jaramillo et al. (2017), King et al. (2017), among others.

Response: We concur. Unfortunately, the climate community is still not fully aware of the singular precipitation regime of this part of the world. We will emphasize this fact in our revised version adding the provided references.

13. Lines 27-29, p. 4: “This percentage was set as the one maximizing the average correlation between June and October for the 1948-2014 period with the NCEP/NCAR monthly zonal wind at 925 hPa averaged over the area [5N-7.5N; 90W-80W],which is considered a good representation of strength of the Choco jet core (Poveda and Mesa, 2000)”.Comment: Again, restricting analysis to June-October is misleading since the Choco Jet is permanent (although seasonally-variable) throughout the year.

Response: Our directional index is not capable of characterizing the Choco Jet in some months. The CHOCO-D index is statistically related with the Choco jet strength (wind velocity at its core) only between May and November with a maximum correlation in August. During the rest of the year, the winds in the selected area at the surface level blow mainly from the east (see for example Figure 3 in our response to comment #10 for the case of January). For these months our index is close to zero. In the revised version, we will include a specific paragraph explaining this limitation.

14. Figure 3 caption. “Numbers over the CHOCO-D values indicates the monthly correlation between both series for the 1948-2014 period. ”Comment: The mean annual cycle of the new proposed index shows easterly (negative) winds from January to April, which is not the case for the original definition. No wonder why the lack of correlation between the newly proposed index and the original one.

Response: As stated in the original figure caption, in this figure we compare the CHOCO-D with the NCEP/NCAR 925 hPa u winds averaged over the region [5N-7.5N; 90W-80W]. In this region, the area-averaged zonal wind is slightly negative from January to April as our original figure 3 shows.

As Dr. Poveda points out, this is not the case for the area where the Choco jet was originally defined [2N-8N and 80W] (see comment #1). In Figure 4 (below) we show a figure equivalent to our original Figure 3.a but for [2N-8N; 80W]. In this case, limiting the longitude to 80W, the easterly winds are noticeable smaller and they only appear for February and March. When the area is restricted to the grid point 80W 5N at 925 hPa there are not easterly winds along the entire year (not shown).

Notwithstanding, we prefer to maintain our original figure, this does not affect the interpretation nor the significance of our results (correlations in Figure 4 shown here are comparable to those on Figure 3 of the original paper) but the original figure makes easier to discuss the changes in wind direction in terms of the migration of the ITCZ. Notwithstanding, we will explicitly indicate in the paper that the core of the Choco Jet shows westerlies along the entire year and that the negative values found in Figure 3 are consequence of the extended area.

In relation with the absence of correlation between the CHOCO-D and the averaged zonal velocity from December to April, it can be easily explained by the characteristics of our index. As the CHOCO-D is defined as the % of westerly winds in the selected area, our index is essentially zero from December to April. (see for example the wind distribution for January in Figure 3.a in this document) so by correlating the CHOCO-D with any other series, we are correlating the latter with a series mostly composed by “zeroes”. As stated in our reply to question #13 the impossibility of characterizing the wind variability these months is a limitation of our index and it will be explicitly discussed in our revised version.

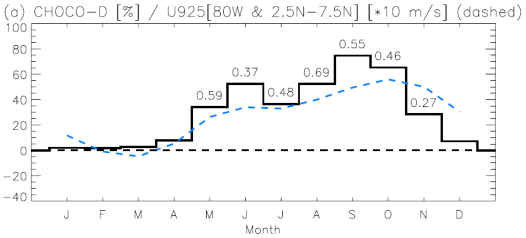

Figure 4. Monthly averages (1948-2014) of the NCEP-NCAR zonal wind at 925 hPa averaged over [5N-7.5N; 80W] (blue dashed line) and monthly averages of the CHOCO-D index for the same period in % of days in a month with prevailing wind flowing from the southwest (black line). Numbers over the CHOCO-D values 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. This figure should be compared with Figure 3.a of our original manuscript.

15. Also Fig 3 caption: “... 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 [5N-7.5N; 90W-80W] (blue dashed line).”Comment: Again, June-October is not completely appropriate to judge the newly proposed index.

Response: As explained in our reply to question #13, the CHOCO-D is only related with the jet’s strength from May to November. For computing annual averages we also discarded the months in the limits (May and November). 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. Of course, the benefit of our approach is that we can compute an index based on actual observations since the late 19th century. We think that this characteristic fully justifies the interest of the new index, even considering its limitations. We will add a discussion on this issue in the new version of the manuscript.

16. Lines 12-13, p.5: “These values indicate that the CHOCO-D captures a significant part of the variability of the zonal winds at the core of the Choco jet. ”Comment: Please quantify correlation among these two series and p value.

Response: This correlation is r=+0.59 (p<0.01). We will add this information to the revised figure 3.b.

17. Line 23, p.5: "...as a function of N between May and November is shown in Fig. 4 for the period 1971-2010."Comment: Again. May-November is not an appropriate period for this Equatorial region, since it contains winds from two different LLJs exhibiting opposite directions depending on the month of the year.

Response: As detailed in our reply to question #4, we need these two different LLJs over the region to construct an index based on wind direction. What we found is that between May and November, the relationship between the westerlies (Choco) and the easterlies (CLLJ) in our study area is significantly correlated with the strength of the Choco Jet, as measured by the zonal wind at the jet core. This correlation is only significant between May and November. Between December and April, the predominance of the easterlies in our extended area is too large (see for example Figure 3.a in our reply to comment #10) to capture any variability related with the Choco Jet. As commented in our reply to comment #13, this is a limitation of our approach that will be explicitly discussed in the revised version.

18. Lines 14-15, p. 6: "The connection of these rainfall anomalies with the moisture advection has been assessed by computing the vertically integrated moisture transport through the 1000-700 hPa levels and the corresponding moisture convergence (Fig.6)."Comment: The original westerly Choco jet is confined between 1000 and 850 hPa as shown in Figures 3 to 6. Above 850 hPa the winds are clearly easterlies, and therefore the 1000-700 hPa layer contains winds from opposite directions.

Response: Thank you for noting this; limiting the integration to the 1000-850 hPa layer allows a more precise estimation of the specific contribution of the Choco Jet to the moisture advection. We have redone the figure with these new limits (see Figure 5 below).This figure will substitute our original Figure 6. These new results are quite similar to the original ones, but the anomalies in the moisture convergence (shading) are now more clearly centered at 5N latitude. This is especially evident in August, the month in which the CHOCO-D is best correlated to the wind anomalies between 2.5N-7.5N and 80W (see our response to question #14). We think this reinforces the usefulness of our index.

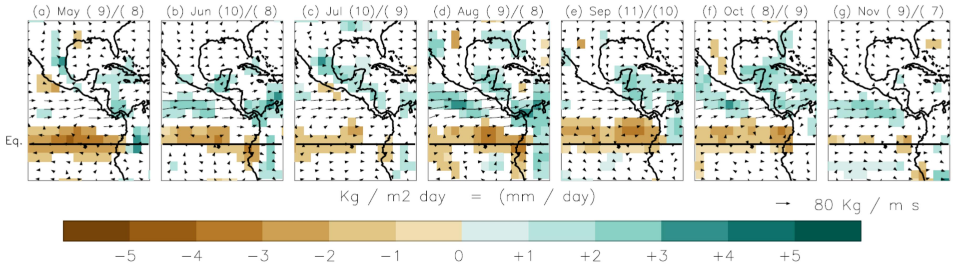

Figure 5 1000-850 hPa vertically integrated moisture transport (arrows, scale at the lower-right corner) and moisture convergence (shaded areas) differences between CHOCO-D +/- 0.75 standard deviations years for the 1979-2014 period and NCEP/NCAR reanalysis data. Only moisture convergence differences significant at p<0.05 are represented. The number of CHOCO-D positive/negative cases used to compute the anomalies are indicated in brackets.

19. Lines 24 and 25, p. 7: “Ultimately the Choco jet originates in the southerly trade winds, making it strongly dependent on the meridional SST gradient along the Eastern Equatorial Pacific (Martinez et al., 2003).”Comment: Please acknowledge that this explanation was originally introduced by Poveda and Mesa (1999a, 2000), and has been further discussed by Poveda et al.(2001, 2006 and 2014).

Response: This is again a relevant issue, as this scheme is quite related to the possibility of characterizing the Choco Jet by measuring changes in a large area of the Eastern Equatorial Pacific. We will emphasize this explanation and will acknowledge the suggested references in the revised paper.

20. Last line, p. 7 and first line p. 8: “Figure 9 shows the correlation of the CHOCO-D index between July and September and the following El Niño3.4 index (December to February of the following year) for variable timescales. ”Comment: I find it difficult to understand why the authors estimate seasonal lagged correlations between the newly proposed CHOCO-D index and the following El Niño3.4index. It would make much more physical sense to estimate the simultaneous and lagged (El Niño index leading, instead of lagging) seasonal correlations among ElNiño3.4 index and the CHOCO-D index. Another point worth commenting is the selection of the seasons. I suggest estimating the simultaneous and lagged correlations for the following cases: El Niño index (JJA) vs. CHOCO-D (JJA), El Niño index (JJA) vs. CHOCO-D (SON), El Niño index (SON) vs. CHOCO-D (SON), El Niño index (SON) vs. CHOCO-D (DJF, year +1), and El Niño index (DJF, year +1) vs. CHOCO-D (DJF, year+1).

Response: There are three different issues about this question:

First, with regard to the election of the seasons, we concur with Dr. Poveda, using the standard season definition (DJF, MAM, JJA and SON) eases comparison with existent literature, so we have changed our season's definition as suggested.

Second, due to the limitations of our index, the CHOCO-D does not produces reliable estimations of the jet strength between December and April (see our reply to question #13), so unfortunately we cannot perform useful correlations for the suggested cases involving CHOCO-D(DJF).

Third, in our original manuscript, we decided to present the lagged correlation (CHOCO-D leading ElNiño3.4) because we were interested in the relation between a weakening of the jet during a developing phase of El Niño. We found that there is a strong correlation between a weak Choco Jet during summer and the existence of El Niño conditions the following winter. However, as recommended, being both the ENSO cycle and the Choco-jet long lived climatic features, it is also quite interesting to test the suggested correlations (El Niño index (JJA) vs. CHOCO-D (JJA), El Niño index (SON) vs. CHOCO-D (SON)) and the lagged El Niño index (JJA) vs. CHOCO-D (SON). We have computed these cases (see Figure 6 below. Figure 6.a (blue line) corresponds to our original analysis, where a weak jet in JJA tends to be followed by SST increases (El Niño conditions) the following winter. Additionally, Figure 6.a (red line) also shows that these negative correlations are also found for the in-phase JJA series. The relevant result here is that these relations have been remarkably stable along the 20th century. On the other hand, Figure 6.b shows that, according to our series, a weak jet during SON is also typically concurrent to with in-phase warmer SSTs (Figure 6.b, red line), while warm SSTs during JJA tend to be followed by a weaker jet (Figure 6.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 1930s. We have not currently an explanation for this finding, but it is probably related to the shift from negative to positive anomalies around the 1920s-1930s discussed for the September and October CHOCO-D series (see Figure 7 of our original manuscript). We consider these results quite relevant for stimulating future research in the area, so we will include this discussion in the revised paper. Former figure 9 of the manuscript will be replaced by Figure 6 of this document.

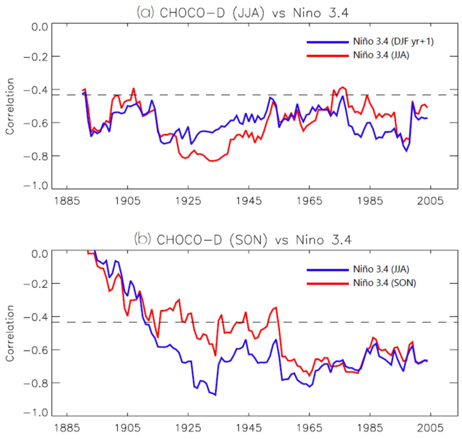

Figure 6. 21-yr running Pearson's correlation coefficient between CHOCO-D and El Niño3-4 for in-phase and lagged cases.

21. Lines 18-19, p.8: "This is because the exceptionally large latitude range where the monsoon-like changes in the wind direction can be related to the Choco jet. "Comment: This is one of the problems of the manuscript. Changes in the wind direction are not solely related to the Choco Jet, but to the dynamics of the Caribbean LLJ over such a wide region.

Response: As commented in previous replies, this is probably the central issue raised by Dr. Poveda. We expect that by changing the introduction (eliminating our feasibility analysis in terms of monsoons), 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. This new approach will clarify at the same time the questions relative to the study area and the presence of two different LLJs and the questions relative to the inadequacy of discussing in summer/winter terms.

22. Lines 7-8, p.9: "This structure explains the excellent response of the CHOCO-D to the seasonal march of the Choco jet." Comment: This seems to be an overstatement as per results shown in Figure 3a.

Response: 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.

Minor Comments:

1. Line 23, p.6: Change pacific for Pacific.2. Line 28, p. 7: “In this way, a year with weak (strong) jet tends to be followed by ElNiño (La Niña) conditions.”Comment: For the sake of clarity, I suggest rephrasing this sentence as: In fact, the transport of moisture by the jet is weakened during El Niño events, and enhanced during La Niña events (e.g. Figure 9 of Poveda et al., 2006).

Response: We concur and we will include this rephrasing in our revised text.

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 ~~demonstrate that the methodology recently developed to quantify the strength of monsoonal circulations by using~~ on historical wind direction observations ~~can be applied~~ to ~~compute~~ quantify ~~a new index for~~ the intensity of the Choco jet. This is a low-level westerly jet ~~observed from May to November~~ ~~whose~~with its core ~~is~~ 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 ~~of~~ for up to 30% of the total precipitation in these areas. We have been able to produce an index ~~for~~ 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, ~~with has diminished~~decreasing (~~increased~~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 quantification of the moisture transport in the atmosphere requires a precise knowledge of the atmospheric motion (i.e. the wind field) and the three-dimensional distribution of water vapour (Gimeno, 2014). As global reanalysed datasets have become widely available and high resolution models have been applied to track the origin of atmospheric water (Sthol and James, 2004), a lot of research has addressed this topic. As a result, the recent variability of the moisture transport in the atmosphere is nowadays relatively well understood (Gimeno et al., 2012). Unfortunately, most of these works are limited to the second part of the 20th century (Marengo et al., 2004; Gimeno et al., 2012) or even to years after 1979, mainly because of the large uncertainties in the knowledge of the specific humidity before the satellite era, hampering the analysis of the long term moisture transport variability.~~

~~During the last years, it has been possible to assess 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 sailing ships since the end of the 17th century. 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 meteorological observations are nowadays incorporated into the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) database (Freeman et al., 2016). In its most recent release ICOADS holds over 456 million individual marine reports, covering the period 1662-2014.~~

The Northern Hemisphere eastern equatorial Pacific is an ~~ath~~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 ~~two~~ 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 ~~jet~~ 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·s^{-1}) and maximum in October-November (6 to 7 m·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·s^{-1} is observed at 15ºN and 925 hPa. ~~This maximum~~It corresponds to the Caribbean Low-Level Jet (CLLJ) (Amador, 1998; Poveda and Mesa, 1999; Poveda et al., 2006; Wang,

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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·s^{-1} (October) and a maximum of 14 m·s^{-1} in July, with a secondary maximum in December and January (12 m·s^{-1}).

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While the location of the core of both jets is rather constant at ~~intra-annual and~~ 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). ~~By the~~Westward of 90ºW ~~longitude (and westward)~~ the prevalence of the easterly component is absolute, even at the surface ~~level~~. 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~~s~~ 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 ~~level,~~ the westerlies can reach the 14ºN latitude.

~~Directional indices have resulted excellent tools to quantify the moisture transport associated to monsoons because in these regions, the changes in precipitation are directly related to a seasonal wind reversal. Wind and precipitation changes are profoundly related and they are dynamically consistent through the "Gill pattern" (Gill, 1980), but they are not necessarily the same (Wang et al., 2014). Monsoonal areas based on wind changes are usually defined as those where the local summer westerly minus winter easterly at 850 hPa exceeds 50% of the annual mean zonal wind speed. The local summer/winter denotes May to September/November to March for the Northern Hemisphere and vice versa for the Southern Hemisphere (Wang et al., 2014). Figure 1.a shows the areas meeting this criterion based on zonal wind data from the NCEP/NCAR reanalysis data (Kalnay et al., 1996). In the case of precipitation, monsoonal areas are usually demarcated as those where the~~

~~local summer minus winter precipitation rate exceeds 2 mm day^{-1}. Additionally, to distinguish between monsoon climate and arid/semiarid or Mediterranean climates and furthermore, to discriminate from equatorial perennial rainfall regimes, it is also required that the local summer precipitation exceeds 55% of the annual total areas (Conroy and Overpeck, 2011; Hsu et al., 2011; Wang et al., 2014). Figure 1.b shows these areas based on the CPC Merged Analysis of Precipitation (Xie and Arkin, 1997).~~

~~The intersection between the areas in Figs. 1.a and 1.b should be optimal for computing monsoonal directional indices based on wind changes highly representative of the moisture transport associated to a monsoon. However historical wind measurements were taken at the surface level, not at 850 hPa, and of course, they are only available along the ships' routes, so it is necessary to identify regions where the monsoonal wind reversal found at the 850 hPa level is also found at the surface. In this regard, Fig. 1.c shows the areas where local summer westerly minus winter easterly wind at the 0.995 sigma level exceeds 100% of the annual mean zonal wind speed. This is an analogous criterion as that used for the wind at 850 hPa but with a larger threshold in order to account for the greater wind variability at the near surface level. Additionally, Fig. 1.d shows the areas (in a 2.5º x 2.5º grid) where the last release of the ICOADS database currently has two or more wind direction observations per month for the summer months for at least 90 years in the 1900-2014 period. This is the minimum density of data considered necessary to build a meaningful directional index at monthly scale over the area typically used to compute dynamical indices for a monsoon, spanning around 20º in longitude and 10º in latitude (Li and Zeng, 2002; Gallego et al., 2015).~~

~~The regions where the four previous conditions are simultaneously met are shown in Fig. 1.e and they can be considered as those where building dynamical indices for monsoon-like systems highly related to precipitation (based on historical data from ICOADS) is possible. Directional indices have already been developed for the obvious cases, i.e. the West African Monsoon (area centred at 8º N-20º W), the Indian Monsoon (15º N - 75º E), the Australian Summer Monsoon (10º S -120º E) or the Western North Pacific Summer Monsoon (15º N – 120º E) (Gallego et al., 2015; Ordoñez et al., 2016; Gallego et al., 2017; Vega et al., 2018 respectively). Interestingly, this general analysis identifies some other areas with monsoon-like behaviour in the Indian Ocean, north of Madagascar and a large area in the eastern tropical Pacific between 120º W and 80º W, extending between around 4º N and 15º N. Although both the wind and the precipitation in the latter region show a monsoon-like behaviour, this system is not a monsoon, but a low-level westerly jet known as the Choco 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 regions most affected by this wind reversal. Between May and November, the winter wind regime characterized by predominant north-easterly winds in this part of the world is replaced by south westerlies at low levels. The consequent change in the moisture transport from the Pacific into the continent affects millions of people (Arias et al., 2015) and it has a profound impact on the western coast, from Costa Rica to northern Colombia, which, as a result, are among the rainiest places on earth (Poveda et al., 2014).~~

Due to its relevance to the pluviometry of large areas, ~~Q~~quantifying the variability of ~~this system~~the Choco jet is ~~therefore~~ of great importance. ~~and currently~~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 ~~, limiting its availability to the second part of the 20th Century~~ (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 ~~In view~~warm season poses an interesting possibility: the development of an ~~of the potential of this region evidenced by Fig. 1.e, we have developed a new directional~~ 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 ~~T~~this method provides an extension of ~~adds~~ almost one~~a~~ century to the current available indices of this jet~~system~~.

2 The CHOCO-D index

a. Index definition

Con formato: Título 3

~~A complete description of the concept of directional indices can be found in Barriopedro et al. (2014) and Gallego et al. (2015) and only a brief introduction is given here.~~ Directional indices ~~These 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 ~~Wind direction has been measured~~

~~essentially in the same way since the early times of sailing, not needing any conversion beyond referring the observation to the geographic north. In fact, wind direction can be regarded as an instrumental measurement independently of the period and in consequence, directional indices can be considered instrumental ones.~~

~~For this work, raw wind direction measurements have been taken from the ICOADS database in its 3.0 release (Freeman et al., 2017). 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 ~~in which~~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.~~, covering all of the outlined region over the eastern tropical Pacific in Fig.~~ Figure 4 ~~1.e. Figure 2~~ 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. ~~2~~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~~2~~ shows the ~~resulting~~ 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. ~~At~~ 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 ~~final years~~end of the 1950's~~ decade~~. 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 9º~~-~~N) 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 ~~selected~~ 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 b~~f~~lowing 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 ~~period with the NCEP/NCAR monthly zonal wind at 925 hPa averaged over the area [5º N-7.5 ºN; 90º W-80º W]~~with the calibration series~~, which is considered a good representation of strength of the Choco jet core (Poveda and Mesa, 2000)~~. 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~~the CHOCO-D index is scarcely sensitive to changes in the percentage used for its definition~~. 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 ~~the NCEP-NCAR zonal wind at 925 hPa averaged over the area [5º N-7.5º N; 90º W-80º W] for the 1948 and 2014 period is~~ displayed in Fig. 5~~3~~.a for the 1948-2014 period ~~(dashed blue line)~~. ~~As expected~~The calibration series (dashed blue line) shows that~~,~~ the region from 90ºW to 80ºW ~~area~~ 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. T~~by the positive values of the average zonal wind, which it is characterized byt~~he two characteristic relative maxima in June and October are also found. T~~T~~he CHOCO-D index based exclusively on ICOADS wind direction observations (black line) closely mimics ~~this~~ 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~~3~~.a also shows the monthly correlations between the ~~averaged NCEP/NCAR zonal wind at 925 hPa~~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~~3~~.b. These values indicate that the CHOCO-D captures a significant part of the variability of the zonal winds at the ~~core~~ latitude of the Choco jet.

b. Assessment of the CHOCO-D index uncertainty

Con formato: Título 3

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. ~~4~~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. ~~4~~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 ~~(Wang et al., 2006)~~ through the ~~Caribbean Low-Level Jet~~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 ~~importance~~ relevance of the Pacific source is captured by the CHOCO-D. Figure 7~~clearly evidenced in Fig. 5, which~~ 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·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-~~700~~ 850 hPa levels and the corresponding moisture convergence (Fig. ~~6~~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. ~~5~~7 and 8~~6~~ is remarkable. As expected, large CHOCO-D values appear related to an enhanced moisture transport (~~of~~ anomalies of up to 100 kg · m^{-1} · 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~~5~~.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~~7~~). 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~~7~~). 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~~7~~, 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. ~~8~~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, ~~which~~ with changes in the total precipitation in the order of +/- 2 mm · day^{-1}.

4.2 Relationship with ENSO

As stated in the introduction, ~~Uultimately~~ the Choco jet is ultimately ~~originates~~ 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 encompasse~~d~~s 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), ~~- which~~ then declin~~e~~sing ~~up~~ to the subsequent summer (year +1). The ~~. A d~~diminished temperature gradient between the Peruvian Coast ~~(El Niño 1+2 area)~~ and the Panama Bight / northern Colombian western coast around 5º N during the course of ~~the developing phase of~~ an El Niño event is accompanied by ~~weaker trades and therefore,~~ a weaker Choco jet (Poveda et al., 2001). ~~In this way, a year with weak (strong) jet tends to be followed by El Niño (La Niña) conditions.~~ The profound link between this meridional SST gradient and the precipitation in western Colombia through ~~the~~ changes in the Choco jet has been documented for the second part of the 20th 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 ~~the~~ 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 20th 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~~. indicating~~ 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 ~~to~~ 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.

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~~Figure 9 shows the correlation of the CHOCO-D index between July and September and the following El Niño3.4 index (December to February of the following year) for variable timescales. Some fluctuations in the absolute magnitude of the~~

~~correlation are evident at short timescales, but for windows over 30 years, our results indicate that the correlation between the Choco jet and the ENSO has remained negative and relatively stable since the late years of the 19th century for the core of the jet season. This same result is 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).~~

5 ~~Discussion~~ Summary and ~~conclusions~~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 ~~have made~~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 ~~computed~~ estimated through an ~~reliable~~ index starting in the 1850's decade by using in-situ wind direction measurement contained in ICOADS ~~and the methodologies recently developed to quantify monsoonal circulations~~. To the best of ~~Up to~~ our knowledge, this is the first time that ~~it has been possible to construct~~ a quantitative instrumental climate index over the eastern tropical Pacific has been built for such a ~~large~~ long period.

~~This is because the exceptionally large latitude range where the monsoon-like changes in the wind direction can be related to the Choco jet.~~ This reconstruction has been possible because~~,~~ the signature of the Choco jet variability in the distribution of the wind direction at the surface ~~level~~ is sought in a large area ~~in which~~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 ~~level~~ 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 ~~values~~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 F~~o~~ig. 5.b). However during these months, this relation is significant, peaking in May and August, -with ~~and in some cases reach~~ correlations above $r=+0.68$ ($p<0,01$) ~~as it is the case of May and August~~. Additionally, we have found that the ~~Although it had been widely shown in literature that the latitude of the Choco jet core is usually restricted to the 5º N-7º N range and it is maximum at 80ºW-90ºW (Poveda and Mesa, 2000; Sierra et al., 2017) we found that the optimal area for computing an index based solely on wind direction measurements at the surface level for this jet goes from 4º N to 15º N and extends from 120º W to 80º W. Over such a large area, the cumulative number of observations taken by ships, especially those sailing along the coast, resulted large enough to compute a meaningful index.~~

~~The reason beyond this fortunate circumstance is the profound link between the location of the Intertropical Convergence Zone (ITCZ) and the Choco jet (Waliser and Sommerville, 1994; Sierra et al., 2017). Forced by the north-south orientation of the South American coastland and the predominant position of the ITCZ north of the Equator between April and November, the southerly trade winds over the eastern Pacific cross the Equator acquiring a predominant westerly direction and entering the continent with maximum zonal velocity around the 5º N to 7º N latitude characteristic of the Choco jet core (Poveda and Mesa, 2000; Sakamoto et al., 2011; Arias et al., 2015). During the boreal winter, 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). In this way, in this part of the world, the ITCZ separates the domain of winds with westward/eastward component always in the same hemisphere and its migration is the ultimate reason of the seasonal wind reversal observed in the tropical eastward Pacific and consequently its characterization as a “monsoonal” area by wind-based criteria (see Figs. 1.a and 1.c). Recently, Wodzicki and Rapp (2016) showed that the central latitude of the eastern Pacific ITCZ ranges between 4ºN and 10-12ºN. So, along the year, the ITCZ displaces between these limits, modifying the relation between the areas affected by winds with westward/eastward components and therefore the relative number of wind observations with wind blowing from the southwest inside the area where the CHOCO-D index is defined. This structure explains the excellent response of the CHOCO-D to the seasonal march of the Choco jet. Additionally, we also found that, even not including the wind velocity, the CHOCO-D is highly correlated with the indices currently used to measure this jet based on spatial averages of the zonal component of the wind.~~

~~As a consequence, 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~~We have found that since at least 1880~~, the Choco jet has experienced ~~large~~ changes at decadal scales at least since 1880. ~~These~~ 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 ~~this average~~it from 1910 ~~and~~ 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. ~~7~~9).

~~Finally, s~~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 ~~quite~~ 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 tha~~n~~t the relation between the Choco jet strength during JJA and ~~and~~ the ~~ENSO~~ 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).

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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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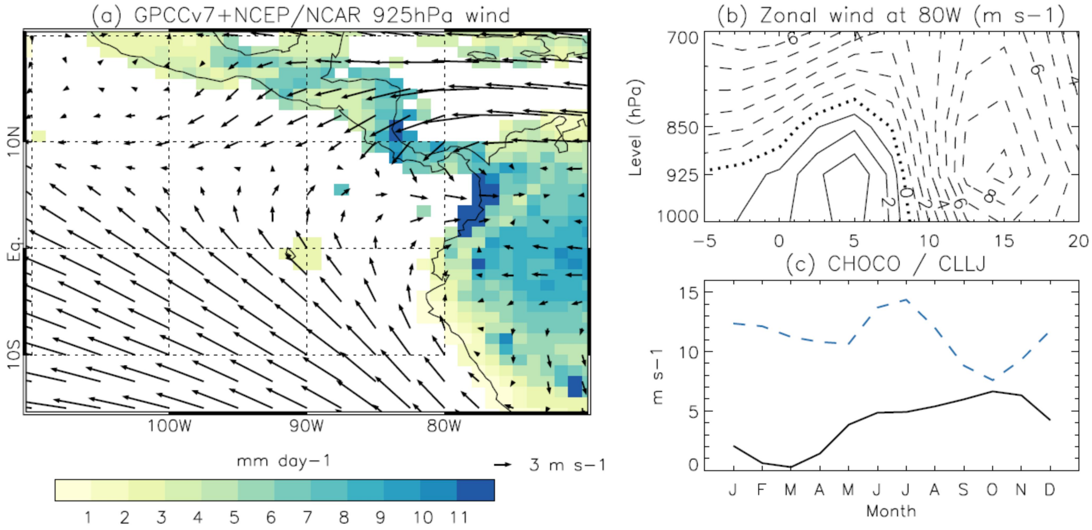


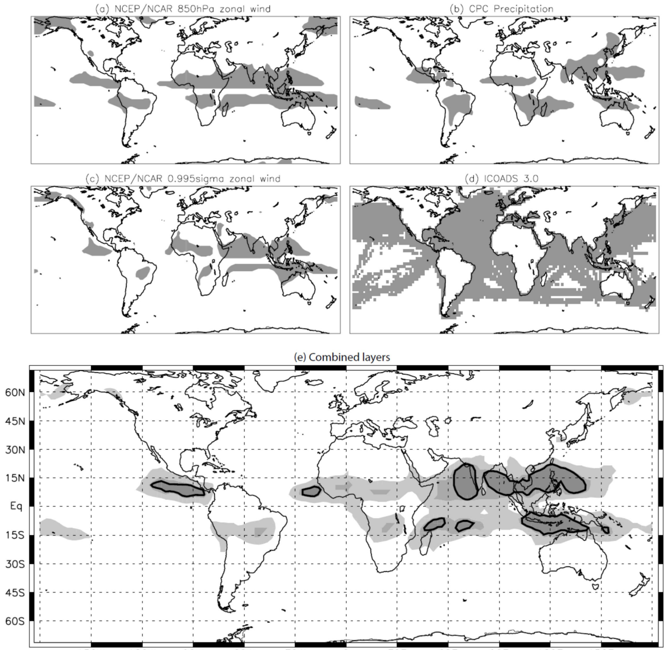


Figure 1: (a) Average NCEP/NCAR wind vector at 925 hPa for the period 1981-2010 shading shows the corresponding average GPCCv7 precipitation. (b) 1981-2010 average cross section of the zonal wind from 5S to 20N at 80W. Positive/negative

(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).~~(a) Monsoonal areas according with a wind criteria at 850 hPa, (b) monsoonal areas according with a precipitation criteria, (c) Monsoonal areas according with a wind criteria at the near surface level, (d) Areas in which the ICOADS database has adequate coverage to build a directional index since 1900 and (e) Areas where two or more (light grey), three or more (darker grey) and all four (darkest grey and outlined) of the criteria selected do define a monsoonal area feasible to be quantified using ICOADS data are simultaneously met.~~

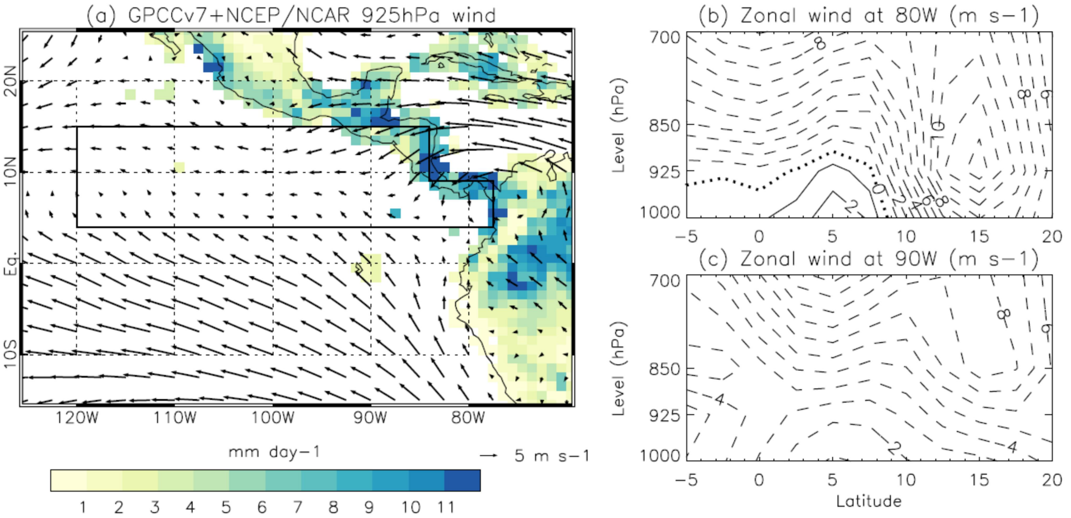


Figure 2: (a) NCEP/NCAR wind vector at 925 hPa for August 1997. The black box indicates the area ~~in which~~where the index developed in this paper is defined. (b) Cross section of the zonal wind from 5S to 20N at 80W, (c) Cross section of the zonal wind from 5S to 20N at 90W. In (b) and (c), positive/negative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

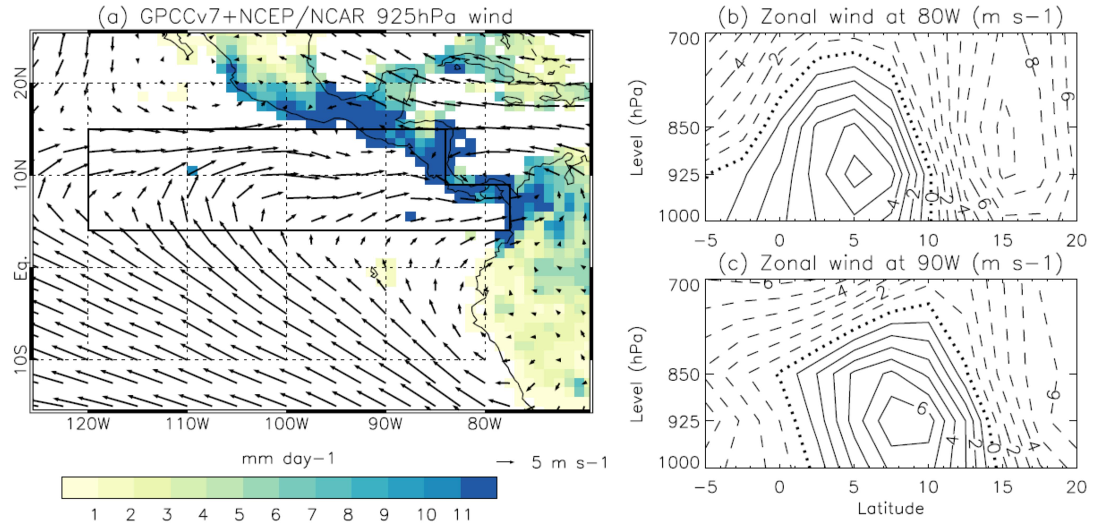


Figure 3: a) NCEP/NCAR wind vector at 925 hPa for August 2010. The black box indicates the area ~~in which~~where the index developed in this paper is defined. (b) Cross section of the zonal wind from 5S to 20N at 80W, (c) Cross section of the zonal wind from 5S to 20N at 90W. In (b) and (c), positive/negative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

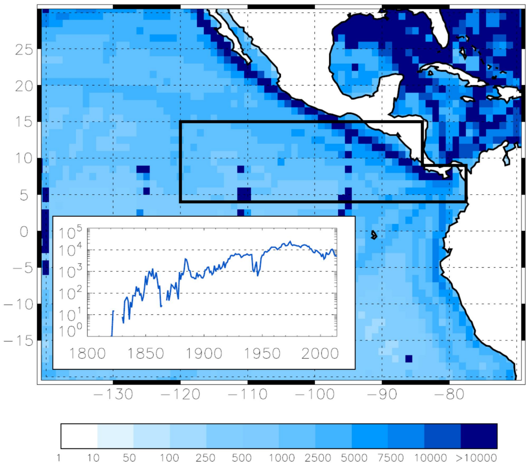
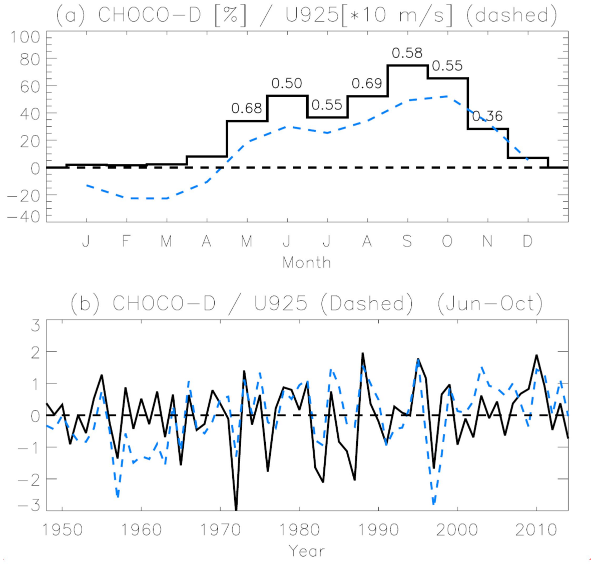


Figure 4~~2~~: Number of wind direction observations in a 1x1 grid (May to November) and the 1800-2014 period available in ICOADS 3.0. Black contour indicates the area selected to compute the CHOCO-D index [4ºN-15ºN ; 120ºW-80ºW]. The graph at the bottom-left shows the time evolution of the cumulative number of wind direction observations inside the selected domain not considering data taken at moored buoys (note the logarithmic y-scale).


(a) CHOCO−D [%] / U925[*10 m/s] (dashed)
100
80
60
40
20
0
−20
−40
0.68
0.50
0.55
0.69
0.58
0.55
0.36
J F M A M J J A S O N D
Month
(b) CHOCO−D / U925 (Dashed) (Jun−Oct)
3
2
1
0
−1
−2
−3
1950 1960 1970 1980 1990 2000 2010
Year

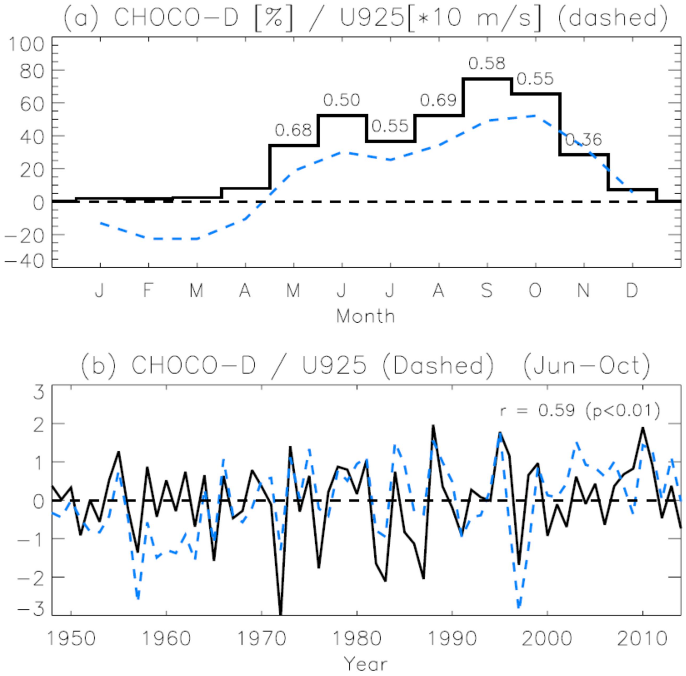

(a) CHOCO−D [%] / U925[*10 m/s] (dashed)
100
80
60
40
20
0
−20
−40
0.68
0.50
0.55
0.69
0.58
0.55
0.36
J F M A M J J A S O N D
Month
(b) CHOCO−D / U925 (Dashed) (Jun−Oct)
r = 0.59 (p<0.01)
3
2
1
0
−1
−2
−3
1950 1960 1970 1980 1990 2000 2010
Year

Figure 5~~3~~: (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 * $m \cdot s^{-1}$ 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).

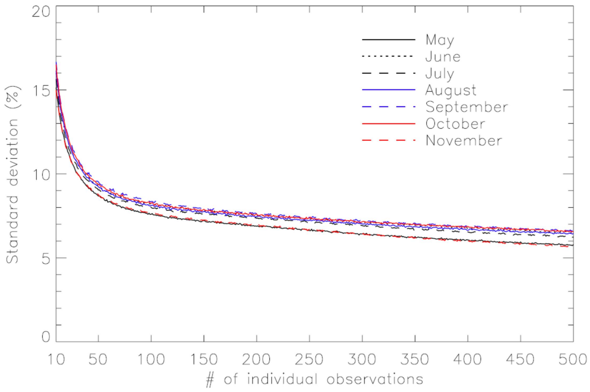


Figure 64: Expected dispersion (in %) of the CHOCO-D as a function of the number of wind direction observations used to compute it (x-axis) for May to November.

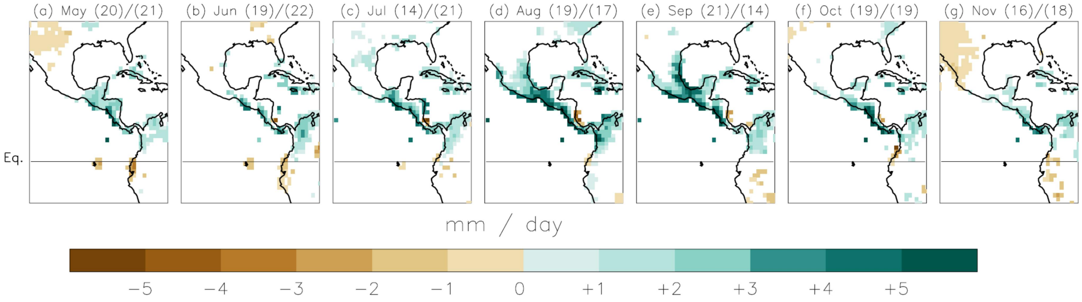


Figure 7~~5~~: GPCC Precipitation differences between months with CHOCO-D over +/- 1 standard deviation for the 1901-2013 period (number of +1/-1 cases are indicated in brackets). Only areas with precipitation differences statistically significant at $p<0.05$ are represented.

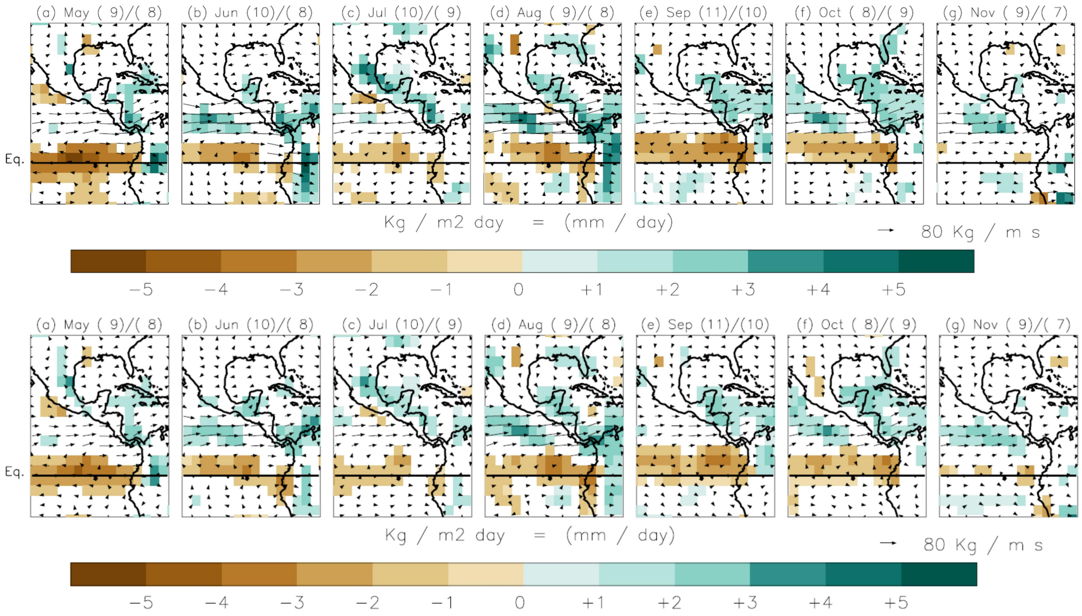


Figure 8~~6~~: 1000-85~~70~~0 hPa vertically integrated moisture transport (arrows, scale at the lower-right corner) and moisture convergence (shaded areas) differences between CHOCO-D +/- 0.75 standard deviations years for the 1979-2014 period and NCEP/NCAR reanalysis data. Only moisture convergence 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.

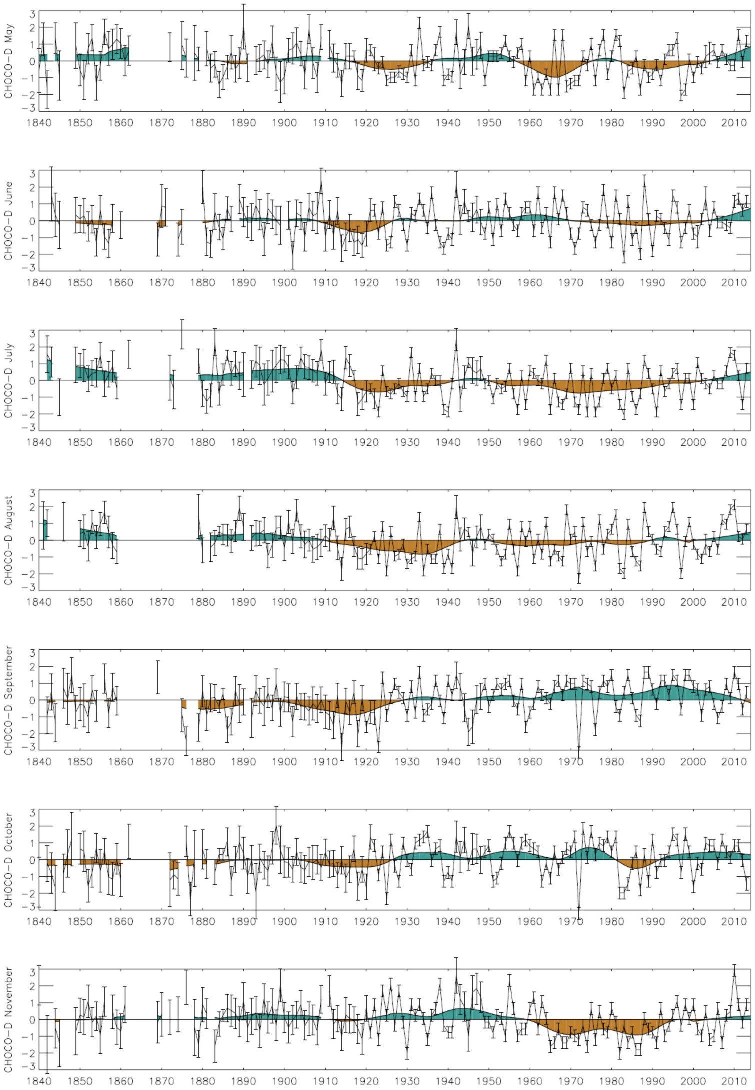


Figure ~~7~~9: Standardized CHOCO-D for May to November between 1840 and 2014. Error bars indicate the expected standard deviation based on the number of observations available each year in ICOADS 3.0 (see text for details). Shaded smoothed curve is computed as a robust locally weighted regression with a 31-year window (Cleveland, 1979).

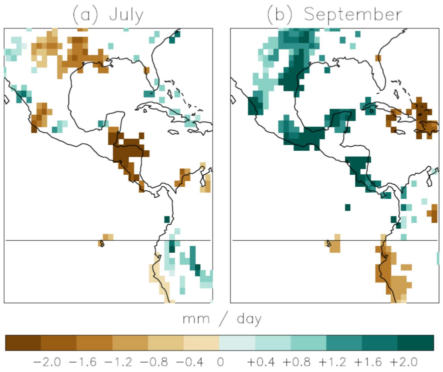
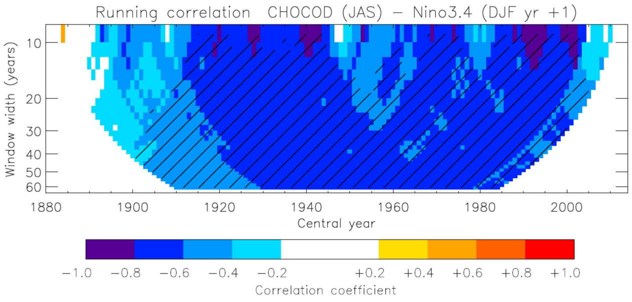
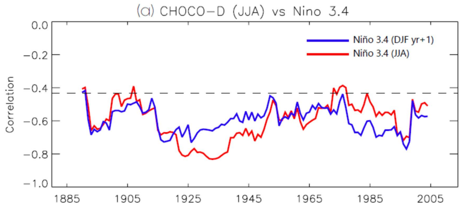


Figure 108: GPCC precipitation differences between the 11-year period 1965-1975 and 1901-1911 for a) July and b) September. Only differences at $p<0.05$ are displayed.





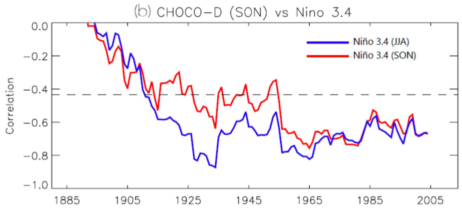


Figure 119: (a) 21-yr running Pearson's correlation coefficient between CHOCO-D (JJA) and El Niño3.4 in Phase (JJA, red line) and the following boreal winter (DJF yr+1, blue line). (b) 21-yr running Pearson's correlation coefficient between CHOCO-D (SON) and El Niño3.4 the previous boreal summer (JJA, blue) and in phase (SON, red line). Dotted line indicates ~~Running Pearson's correlation coefficient for variable window width (y-axis) between the July-August-September average CHOCO-D and the El Niño3.4 index averaged for December-January(year+1)-February(year+1). Hatched areas indicates~~ statistically significant correlation at $p<0.05$.