frontiers in Earth Science

BRIEF RESEARCH REPORT
published: 11 December 2018
doi: 10.3389/feart.2018.00227

Droughts Over Amazonia in 2005, 2010, and 2015: A Cloud Cover Perspective

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Amazon forests experienced recent severe droughts in an anomalous short period induced by different mechanisms and had different length periods and spatial patterns. Droughts of 2005 and 2010 were attributed to anomalous Sea Surface Temperature (SST) over the Tropical North Atlantic (TNA) during the dry season, but the 2010 drought was more severe and remained for a longer period because it was also induced in late 2009 by a moderate to strong El Niño (EN). Drought in 2015 led to unprecedented warming and extreme soil moisture deficits over some regions, and it was attributed to a very strong EN. Several studies analyzed these drought events regarding different climatic factors such as anomalies in SST, vegetation, temperature, precipitation, soil moisture deficits, solar radiation, etc. However, we have not identified a complete analysis of total cloud cover (TCC) over Amazonia during these drought events in the context of long-term trends and past strong EN events. This brief report aims to present a preliminary analysis of anomalies in TCC over Amazon using reanalysis data with a focus on the last recent drought events into a long-term context. Results show a significant decreasing trend ($p < 0.05$) for TCC over southern Amazonia during the dry season (around −2% per decade), in contrast to the significant increasing trend found over northern Amazonia during this season and the significant widespread increasing trend during the wet season (between +2 and +4% per decade). Correlation analysis between SST and TCC anomalies is also indicative of the different West-East and North-South patterns linked to EN events or drought episodes driven by TNA warm anomalies.

Keywords: cloud cover, Amazonia, reanalysis, El Niño, drought, trends

OPEN ACCESS

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Specialty section:
This article was submitted to Interdisciplinary Climate Studies, a section of the journal Frontiers in Earth Science

Received: *10 September 2018*
Accepted: *27 November 2018*
Published: *11 December 2018*

Citation:
Jimenez JC, Libonati R and Peres LF (2018) Droughts Over Amazonia in 2005, 2010, and 2015: A Cloud Cover Perspective. Front. Earth Sci. 6:227. doi: 10.3389/feart.2018.00227

INTRODUCTION

Amazon rainforest ecosystem, which presents typical wet conditions, are experiencing recurrent, persistent and large-scale rainfall deficit over the last decades. During the early years of the twenty-first century, a large portion of Amazon rainforest has experienced three of the most severe droughts in its climate record of the last 100 years (Jiménez-Muñoz et al., 2016; Marengo and Espinoza, 2016; Panisset et al., 2018). The so-called mega-droughts occurred in 2005, 2010, and 2015 induced by large-scale atmospheric mechanisms associated to the interactions with warm sea surface temperature (SST) from Atlantic and Pacific oceans (Coelho et al., 2012). The 2005 and 2010 droughts conditions in western and southern Amazonia are attributed to the Atlantic Multidecadal Oscillation (AMO) inducing the contraction of the northeast trade winds and moisture flux from the warming Tropical North Atlantic (TNA) SST (Zeng et al., 2008; Marengo and Espinoza, 2016).

The 2010 drought was more severe and remained for a more extended period because it was also induced in late 2009 by a moderate to strong positive El Niño southern Oscillation (ENSO) (Marengo et al., 2011). More recently, one of the strongest El-Niño ever record was responsible for the widespread drought conditions in eastern and southern Amazonia (Jiménez-Muñoz et al., 2016; Panisset et al., 2018). This recent EN event occurred under an underlying global warming trend, resulting in the highest warming level observed in the last decades (Jimenez et al., 2018).

Physical climate mechanisms behind the different drought episodes were different, so the resulting spatial patterns of drought severity were also different for each event. Warm SST temperatures over the tropical Pacific (EN events) induce changes in the atmospheric circulation which are different to the changes induced by warm SST temperatures over the tropical Atlantic. Even in the case of EN events, impacts of the atmospheric circulation are different because warm anomalies can be focussed in the Central Pacific (CP) or the Eastern Pacific (EP). Roughly, drought events linked to anomalous warm SST temperatures over the TNA show a characteristic North-South gradient, with wet conditions over the northern Amazonia and dry conditions over southern Amazonia (Marengo et al., 2008; Lewis et al., 2011). In contrast, drought episodes linked to EN events show a West-East (or more properly, a Southwest-Northeast) gradient, with dry conditions over northeastern Amazonia (Malhi et al., 2008). Combination of warm CP, EP, and TNA warm anomalies also induce drought over almost the entire Amazon region. In the case of the last strong EN event in 2015-16, extreme drought severity focused on northeastern Amazonia linked to strong warm CP anomalies (Jiménez-Muñoz et al., 2016; Jimenez et al., 2018).

All these recent studies assessing cause and impacts of the three mega-droughts over Amazonia have focused on measures of precipitation, temperature, soil moisture, vegetation, and radiation. However, they mostly ignored the effects of cloud cover on drought patterns, although such work is critical to understand the hydrological cycle and its associated feedbacks. Accordingly, our current understanding of the coupling between cloud cover and droughts during the last extreme droughts in the Amazon rainforest remains lacking, except a recent work by using remote sensing data (Martins et al., 2018). However, the study period in that work was limited to 2000–2015, which jeopardizes a significant trend analysis and the comparison against previous drought episodes during very strong EN events in 1982/83 and 1997/98. Spatial patterns and trends in cloud cover in Amazonia were also analyzed by Butt et al. (2009). However, the cloud cover dataset used in that study was limited to 1984–2006 and the recent droughts in 2010 and 2015 were not included, as well as the strong EN event in 1982–83.

Our work aims to fill this gap by using a reanalysis dataset to analyze the spatial and temporal patterns of cloud cover during the last four decades (1980–2016), focusing on twenty-first century mega-droughts which recently occurred in the Amazon region and also on strong EN events in 1982–83 and 1997–98.

METHODS

For the study presented in this brief report, we selected the Total Cloud Cover (TCC) product generated by the ECMWF ERA-Interim reanalysis (Dee et al., 2011). The performance of this TCC product is discussed in the **Supplementary Material**.

Because we are interested in the relative comparison between drought events, we computed TCC monthly absolute anomalies, as well as TCC standardized anomalies, for the reference period 1981–2010. Monthly values were averaged for the four quarters January-February-March (JFM), April-May-June (AMJ), July-August-September (JAS), and October-November-December (OND), as well as for the whole year (January to December) to compute yearly means. Trend analysis was performed through the Mann-Kendall non-parametric test, using Sen's method for the computation of the trend (slope) value. Oceanic indices based on SST anomalies over EN regions (3, 4, and 3.4) and over the TNA region were also used for linear correlation analysis between SST and TCC anomalies. Oceanic indices were extracted from 'The state of the ocean climate' initiative (http://stateoftheocean.osmc.noaa.gov). Linear correlation analysis was applied with a lag of one season, so that SST anomalies for one season were correlated to TCC anomalies for the next season. Trend and correlation analysis was applied to the time period 1980–2016.

The study area (mainly Amazon rainforests) was delimited by selecting the Evergreen Broadleaf Forest class included in the MODIS Land Cover Product. The study area was also divided into four quarters to differentiate between northwestern (NW), northeastern (NE), southwestern (SW) and southeastern (SE) Amazonia (see **Supplementary Figure 1**). The climatological mean of TCC for each region and season is presented in **Supplementary Figure 2**.

RESULTS

Spatial patterns of TCC standardized (STD) anomalies are presented in **Figure 1** for the periods 2004/05, 2009/10, and 2015/16. STD anomaly maps for years 1982/83 and 1997/98 are also included for comparison to the most recent strong EN events. Results are presented for season OND of the 1 year and season JFM of the 2 year, where EN event is being developed and reaches the peak (typically in December or January), as well as season AMJ of the 2 year, where EN is vanishing, and season JAS of the 2 year, used in other studies as a reference period for the dry season. Absolute anomaly maps are not discussed in this report, but they are provided in **Supplementary Figure 3** for reference. Details on percentage of area affected by TCC declines are included in **Supplementary Figure 4**.

Visual inspection of maps presented in **Figure 1** indicates that widespread negative TCC STD anomalies were only observed during ENs 1982–83 and 1997–98, in particular for JFM and AMJ seasons in 1983, and for OND season in 1997 and JFM season in 1998. In contrast, widespread declines in TCC were not observed in the last recent drought episodes during 2004–05, 2009–10, and 2015–16. In these cases, negative and significant TCC STD anomalies were only observed over particular regions

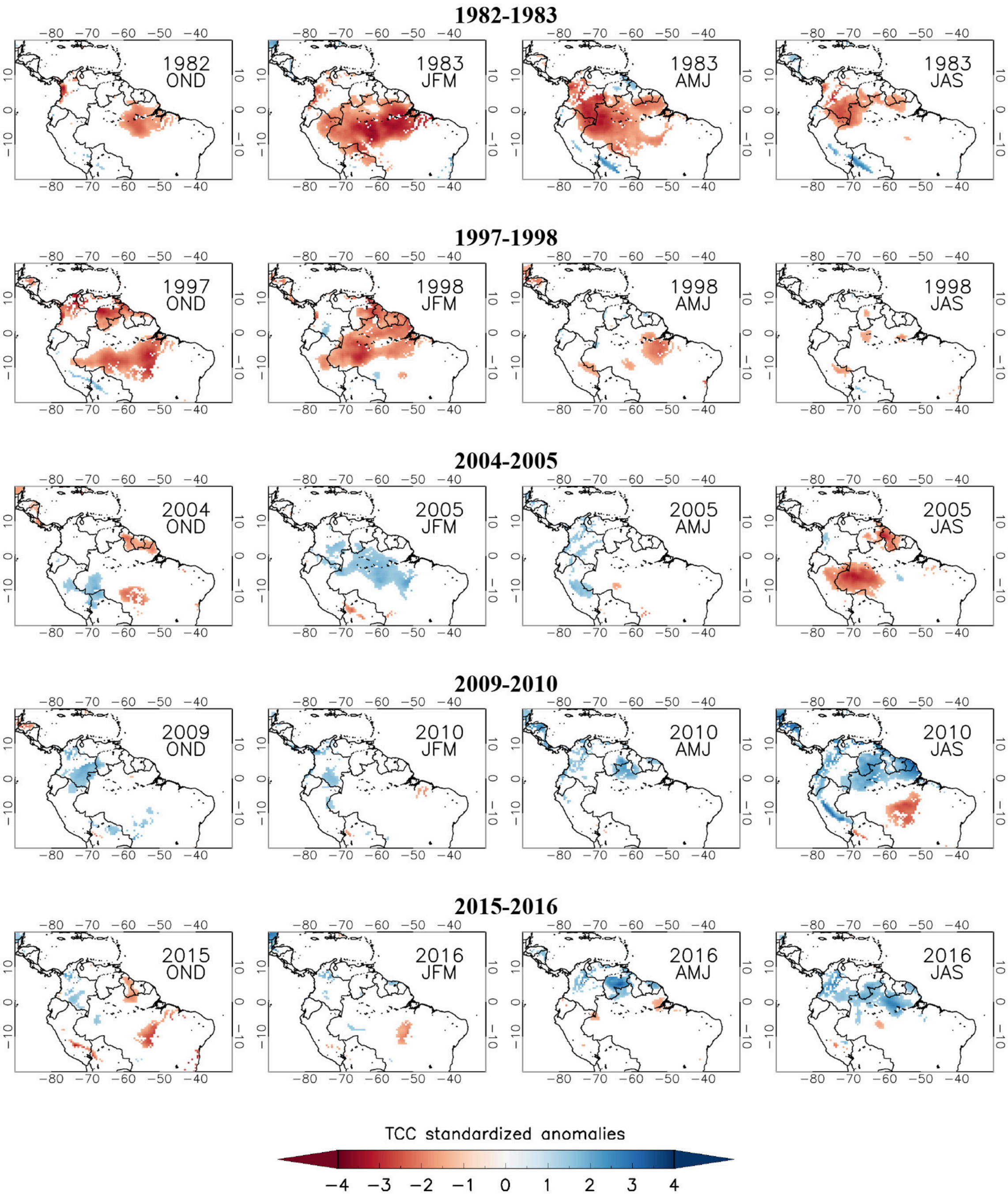

FIGURE 1 | Total cloud cover standardized anomalies over Amazonia for strong EN events in 1982–83, 1997–98, and 2015–16, as well as for moderate EN events in 2004–05 and 2009–10. For each event, standardized anomalies for the OND season of the first year are presented, and standardized anomalies for seasons JFM, AMJ and JAS of the second year, are presented. Total cloud cover product was extracted from the ERA-Interim reanalysis resampled at 0.5° × 0.5°. The reference period to compute the anomalies was 1981–2010. Results are only shown over pixels classified as Evergreen Broadleaf Forest and pixels with standardized anomalies higher than 1.28, equivalent to a confidence level of 80% ($\alpha = 0.2$).

for some seasons and years, namely, OND-2004, JAS-2005, JAS-2010, OND-2015, and JFM-2016. Negative TCC STD anomalies were focussed on northeastern Amazonia during OND season in 2004 and 2015. The dry season (JAS) in 2005 was characterized by two regions with TCC declines over northeastern Amazonia and southwestern Amazonia, whereas during the dry season in 2010 the TCC decline was observed over southeastern Amazonia.

In terms of percentage of area over the entire study region affected by negative STD anomalies (**Supplementary Figure 4**) at 1 sigma level (STDanom < -1), the highest values were obtained in January both in years 1983 and 1998 (around 70 and 60% of the study area, respectively). The highest extreme levels of TCC decline were observed in January-1983 (20% of the study area) and December-1997 (near to 10% of the study area). TCC declines at 1 sigma level were also evidenced in August 2005, 2010, and 2016, with values of area of around 35, 35, and 25%, respectively. A peak on the TCC decline was also observed in December 2015, with an affected area of around 30%. The highest extreme levels of TCC decline during the last three drought episodes were obtained in 2016 (January and July, with area values between 5 and 10%). The analysis of results over the different sub-regions (**Supplementary Figure 4**) provided the highest extreme levels of TCC declines over NE Amazon in 2005, SE Amazon in 2010, and SE Amazon in 2016.

TCC yearly anomalies over Amazonia were examined in a long-term context (1980–2016) through the temporal series presented in **Figure 2A**. The 80s is characterized by predominant negative TCC anomalies, whereas from 2000 to present TCC anomalies were mostly positive, leading to an overall increasing trend. This figure also evidences some differences between sub-regions, as was observed in the previous analysis of the area affected by TCC declines.

Spatial patterns of TCC trends are presented in **Figure 2B**, which corroborates the overall increasing trend over all regions and seasons, except the dry season (JAS), where an increasing trend was observed over northern Amazonia, and decreasing trend was observed over southeastern Amazonia. Values of trends at a monthly level for the four sub-regions are detailed in **Supplementary Table 1**. The highest positive (and statistically significant) anomalies were obtained over the NE region in February and March (around +4% per decade). NW and SW regions show statistically significant increasing trends for all the months (between +2 and +4% per decade), except for August over the SW region, with a non-statistically significant negative trend. The SE region is also characterized by a positive TCC trend, but it is the only region providing a statistically significant negative trend in August (around −2% per decade). A negative trend was also observed in July over this region, but it was not statistically significant.

The correlation analysis presented in **Figure 2C** illustrates the different contribution of SST anomalies over EN and TNA to the spatial patterns of TCC anomalies. EN regions induce a widespread TCC decline during JFM and AMJ seasons, with a TCC decline focused over northeastern Amazonia during JAS and OND seasons, partly extended to southeastern Amazonia during the OND season. The different contribution of EP (EN3) and CP (EN4) SST anomalies is observed in the JFM season. EP anomalies induce widespread TCC declines (northeastern, central, and southwestern Amazonia), whereas CP anomalies are linked to TCC declines over northeastern Amazonia. In the case of the TNA SST anomalies, a significant negative correlation was only observed during the JAS season over southern Amazonia.

DISCUSSION AND CONCLUSIONS

TCC anomalies over Amazon forests were analyzed using a particular reanalysis dataset (ERA-interim) for the period 1980–2016, with focus on the recent drought events in 2005, 2010, and 2015, and previous strong EN events such as those occurred in 1982–83 and 1997–98.

Spatial patterns of standardized TCC anomalies (**Figure 1**) revealed a widespread TCC decline during EN events in 1983 and 1998 (JFM season), with an affected area exceeding 50% of the entire study region. This widespread TCC decline was not observed in the last recent drought episodes in 2005, 2010, and 2015, but focused over northeastern Amazonia in OND-2004, JAS-2005, and OND-2015, over southwestern Amazonia in JAS-2005, and over southeastern Amazonia in JAS-2010 and OND-2015. Overall, significant TCC increases were observed over central Amazonia in JFM-2005 and northern Amazonia in JAS-2010 and JAS-2016. These spatial patterns (see also **Supplementary Figure 3**) roughly evidence three different dominant patterns: widespread TCC decline over the entire region, and transitions from North to South or from Northeastern to Southeastern. This result is consistent with the different modes of drought over Amazonia reported by Lima and AghaKouchak (2017).

The analysis of TCC trends (**Figures 2A,B**, and **Supplementary Table 1**) over Amazon forests shows an enhancement in TCC in the north and a decreasing in the south during the dry-period (JAS). The TCC during austral winter (JAS) over the southeastern Amazon from 1981 to 2016, decreased by −0.6 % per decade, with August providing a decreasing trend of −2.1 % per decade ($p < 0.05$). This result is consistent with previous findings suggesting more (less) moisture in the north (south) (Gloor et al., 2013). An increase in TCC seasonality with a decreasing trend during the dry season and an increasing trend during the wet season was also identified by a previous study (Butt et al., 2009), although their study period was limited to 1984–2006.

Southern Amazonia, and particularly southeastern Amazonia, includes the arc of deforestation, and it is the driest region along the Amazon Basin, particularly vulnerable to ENSO and AMO variability (Yoon and Zeng, 2010; Andreoli et al., 2016) and drought-induced feedbacks (Ribeiro et al., 2018; Staal et al., 2018). During recent decades, southern Amazon presents high levels of fire and deforestation activity (Chen et al., 2013), associated with forest conversion into agriculture and pasture, selective logging and forest fragmentation (Lapola et al., 2014; Ometto et al., 2016; Venter et al., 2016). The observed reduction in cloud cover over the region is probably correlated with forest loss, and land use changes occurred in southern Amazon (Bala et al., 2007; Malhi et al., 2008). The altered land cover may modulate the contribution of southern Amazon forest as a source of moisture for other regions of the rainforest, due to the reduction of tree transpiration (Staal et al., 2018). The present-day dry season over southern Amazonia is induced by changes in surface roughness due to forest loss occurred over the last three decades (Khanna et al., 2017). Furthermore, the deforestation-induced fire biomass burning

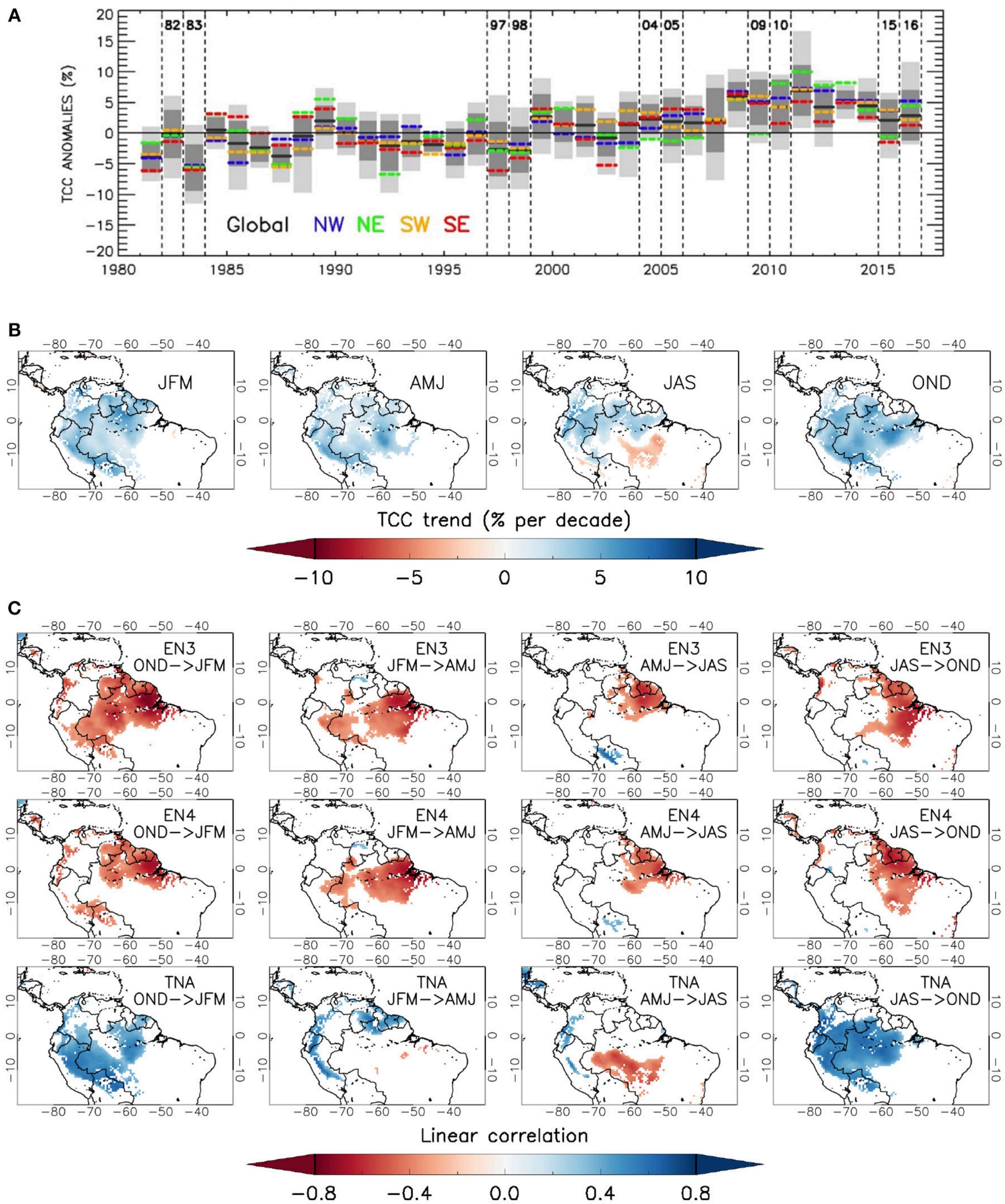

FIGURE 2 | (A) Temporal series of total cloud cover yearly anomalies over Amazonia for the period 1980-2016 over the four regions (NW, NE, SW, SE). Yearly anomalies for the whole Amazon Basin (Global) are included as gray boxes. Black line indicates the mean value, dark gray the $\pm$ 1 σ interval, and light gray the total range (maximum and minimum values). **(B)** Spatial patterns of trends (in percentage per decade) in total cloud cover over Amazonia for the four seasons JFM, AMJ, JAS, and OND. Only pixels with a statistical significance $p < 0.05$ are displayed. **(C)** Linear correlation coefficient between sea surface temperature anomalies over El Niño regions 3 and 4 (EN3, EN4) and Tropical North Atlantic (TNA), and total cloud cover anomalies. Only pixels with $p < 0.05$ are displayed. Correlation analysis was applied to seasonal SST and TCC anomalies with a lag of one season (SST anomalies for one particular season and TCC anomalies for the next season).

during the dry-period over the region also impact into aerosol loading, influencing the formation of cloud, and precipitation (Gu et al., 2017; Andreae et al., 2018).

Even in the absence of climate-deforestation feedbacks, recent studies reported that the hydrological cycle in the Amazon region has been intensified since the 1990s (Gloor et al., 2013).

Changes in energy and water cycles in the southern and eastern portions of the Amazon Basin which are probably beyond natural variability were also suggested (Davidson et al., 2012). The observed reduction in TCC is in accordance to the increase in both frequency and intensity of drought events mainly in the southern Amazon region (Salazar et al., 2007) under a global warming scenario (Malhi et al., 2008). The cause for such a dryness is related to the transport of humidity from the North Atlantic ocean to South America particularly in the southern Amazon during the dry-season (Marengo et al., 2011). The correlation analysis presented in **Figure 2C** evidences the different impact of warm SST anomalies over the CP (EN4 region), EP (EN3 region), and TNA regions on TCC. EN3 region is linked to widespread TCC declines, whereas the impact of EN4 region may be limited to the northeastern region for the JFM season. The impact of both EN regions on the TCC for the other seasons is similar. TNA is clearly linked to TCC declines over southern Amazonia during the dry (JAS) season.

This is a preliminary analysis presented in a brief report style that requires further research in order to assess the differences in TCC between other reanalysis datasets and remote sensing based products, as well to include other indicators (e.g., solar radiation) to better understand the processes behind the development of Amazonian droughts.

AUTHOR CONTRIBUTIONS

JJ and RL conceived and designed the study. JJ and LP carried out the statistical analysis. JJ, RL, and LP contribute to the writing of the manuscript.

ACKNOWLEDGMENTS

RL and LP were supported by Serrapilheira Institute (grant number Serra-1708-15159, process 3633).

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2018.00227/full#supplementary-material

REFERENCES

Andreae, M. O., Afchine, A., Albrecht, R., Amorim Holanda, B., Artaxo, P., Barbosa, H. M. J., et al. (2018). Aerosol characteristics and particle production in the upper troposphere over the Amazon Basin. *Atmos. Chem. Phys.* 18, 921–961. doi: 10.5194/acp-18-921-2018

Andreoli, R. V., Oliveira, S. S., Kayano, M. T., Viegas, J., Souza, R. A. F., Candido, L. A., et al. (2016). The influence of different El Niño types on the South American rainfall. *Int. J. Climatol.* 37, 1374–1390. doi: 10.1002/joc.4783

Bala, G., Caldeira, K., Wickett, M., Phillips, T. J., Lobell, D. B., Delire, C., et al. (2007). Combined climate and carbon-cycle effects of large-scale deforestation. *Proc. Natl. Acad. Sci. U.S.A.* 104, 6550–6555. doi: 10.1073/pnas.0608998104

Butt, N., New, M., Lizcano, G., and Malhi, Y. (2009). Spatial patterns and recent trends in cloud fraction and cloud-related diffuse radiation in Amazonia. *J. Geophys. Res. Atmos.* 114, 1–9. doi: 10.1029/2009JD012217

Chen, Y., Morton, D. C., Jin, Y., Collatz, G. J., Kasibhatla, P. S., van der Werf, G. R., et al. (2013). Long-term trends and interannual variability of forest, savanna and agricultural fires in South America. *Carbon Manag.* 4, 617–638. doi: 10.4155/cmt.13.61

Coelho, C. A. S., Cavalcanti, I. A. F., Costa, S., Freitas, S. R., Ito, E. R., Luz, G., et al. (2012). Climate diagnostics of three major drought events in the Amazon and illustrations of their seasonal precipitation predictions. *Meteorol. Appl.* 19, 237–255. doi: 10.1002/met.1324

Davidson, E. A., de Araújo, A. C., Artaxo, P., Balch, J. K., Brown, I. F., et al. (2012). The Amazon basin in transition. *Nature* 481, 321–328. doi: 10.1038/nature10717

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.* 137, 553–597. doi: 10.1002/qj.828

Gloor, M., Brienen, R. J. W., Galbraith, D., Feldpausch, T. R., Schöngart, J., Guyot, J. L., et al. (2013). Intensification of the Amazon hydrological cycle over the last two decades. *Geophys. Res. Lett.* 40, 1729–1733. doi: 10.1002/grl.50377

Gu, Y., Liou, K. N., Jiang, J. H., Fu, R., Lu, S., and Xue, Y. (2017). A GCM investigation of impact of aerosols on the precipitation in Amazon during the dry to wet transition. *Clim. Dyn.* 48, 2393–2404. doi: 10.1007/s00382-016-3211-7

Jimenez, J. C., Barichivich, J., Mattar, C., Takahashi, K., Sobrino, A., and Malhi, Y. (2018). Spatio-temporal patterns of thermal anomalies and drought over tropical forests driven by recent extreme climatic anomalies. *Philos. Trans. R. Soc. B.* 373:20170300. doi: 10.1098/rstb.2017.0300

Jiménez-Muñoz, J. C., Mattar, C., Barichivich, J., Santamaría-Artigas, A., Takahashi, K., Malhi, Y., et al. (2016). Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015–2016. *Sci. Rep.* 6:33130. doi: 10.1038/srep33130

Khanna, J., Medvigy, D., Fueglistaler, S., and Walko, R. (2017). Regional dry-season climate changes due to three decades of Amazonian deforestation. *Nat. Clim. Chang.* 7, 200–204. doi: 10.1038/nclimate3226

Lapola, D. M., Martinelli, L. A., Peres, C. A., Ometto, J. P. H. B., Ferreira, M. E., Nobre, C. A., et al. (2014). Pervasive transition of the Brazilian land-use system. *Nat. Clim. Chang.* 4, 27–35. doi: 10.1038/nclimate2056

Lewis, S. L., Brando, P. M., Phillips, O. L., van der Heijden, G. M. F., and Nepstad, D. (2011). The 2010 Amazon drought. *Science* 331:554. doi: 10.1126/science.1200807

Lima, C. H. R., and AghaKouchak, A. (2017). Droughts in amazonia: spatiotemporal variability, teleconnections, and seasonal predictions. *Water Resour. Res.* 53, 10824–10840. doi: 10.1002/2016WR020086

Malhi, Y., Roberts, J. T., Betts, R. A., Killeen, T. J., Li, W., and Nobre, C. A. (2008). Climate change, deforestation, and the fate of the Amazon. *Science* 319, 169–172. doi: 10.1126/science.1146961

Marengo, J. A., and Espinoza, J. C. (2016). Extreme seasonal droughts and floods in amazonia: causes, trends and impacts. *Int. J. Climatol.* 36, 1033–1050. doi: 10.1002/joc.4420

Marengo, J. A., Nobre, C. A., Tomasella, J., Oyama, M. D., Sampaio de Oliveira, G., De Oliveira, R., et al. (2008). The drought of Amazonia in 2005. *J. Clim.* 21, 495–516. doi: 10.1175/2007JCLI1600.1

Marengo, J. A., Tomasella, J., Alves, L. M., Soares, W. R., and Rodriguez, D. A. (2011). The drought of 2010 in the context of historical droughts in the Amazon region. *Geophys. Res. Lett.* 38, 1–5. doi: 10.1029/2011GL047436

Martins, V. S., Novo, E. M. L. M., Lyapustin, A., Aragão, L. E. O. C., Freitas, S. R., and Barbosa, C. C. F. (2018). Seasonal and interannual assessment of cloud cover and atmospheric constituents across the Amazon (2000–2015): Insights for remote sensing and climate analysis. *ISPRS J. Photogramm. Remote Sens.* 145, 309–327. doi: 10.1016/j.isprsjprs.2018.05.013

Ometto, J. P., Sousa-Neto, E. R., and Tejada, G. (2016). "Land use, land cover and land use change in the Brazilian Amazon (1960–2013)," in *Interactions Between Biosphere, Atmosphere and Human Land Use in the Amazon Basin. Ecological*

Studies, eds L. Nagy, B. Forsberg, and P. Artaxo (Berlin; Heidelberg: Springer), 369–383. doi: 10.1007/978-3-662-49902-3_15

Panisset, J. S., Libonati, R., Gouveia, C. M. P., Machado-Silva, F., França, D. A., França, J. R. A., et al. (2018). Contrasting patterns of most extreme drought episodes of 2005, 2010 and 2015 in the Amazon Basin. *Int. J. Climatol.* 38, 1096–1104. doi: 10.1002/joc.5224.

Ribeiro, I. O., Andreoli, R. V., Kayano, M. T., de Sousa, T. R., Medeiros, A. S., Guimarães, P. C., et al. (2018). Impact of the biomass burning on methane variability during dry years in the Amazon measured from an aircraft and the AIRS sensor. *Sci. Total Environ.* 624, 509–516. doi: 10.1016/j.scitotenv.2017.12.147

Salazar, L. F., Nobre, C. A., and Oyama, M. D. (2007). Climate change consequences on the biome distribution in tropical South America. *Geophys. Res. Lett.* 34:L09708. doi: 10.1029/2007GL029695

Staal, A., Tuinenburg, O. A., Bosmans, J. H. C., Holmgren, M., van Nes, E. H., Scheffer, M., et al. (2018). Forest-rainfall cascades buffer against drought across the Amazon. *Nat. Clim. Chang.* 8, 539–543. doi: 10.1038/s41558-018-0177-y

Venter, O., Sanderson, E. W., Magrach, A., Allan, J. R., Beher, J., Jones, K. R., et al. (2016). Sixteen years of change in the global terrestrial human footprint and implications for biodiversity conservation. *Nat. Commun.* 7:12558. doi: 10.1038/ncomms12558

Yoon, J. H., and Zeng, N. (2010). An Atlantic influence on Amazon rainfall. *Clim. Dyn.* 34, 249–264. doi: 10.1007/s00382-009-0551-6

Zeng, N., Yoon, J.-H., Marengo, J., a, Subramaniam, A., Nobre, C. A., Mariotti, A., et al. (2008). Causes and impacts of the 2005 Amazon drought. *Environ. Res. Lett.* 3:014002. doi: 10.1088/1748-9326/3/1/014002

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.