Reviewer #1 (Robert Jnglin Wills)

I find this to be an interesting paper and the conclusions can largely be supported by the work presented. Overall this is a substantial contribution and the needed revisions are minor. Nice work.

We thank the reviewer for the careful revision of the manuscript and appreciate the positive feedback and the helpful comments and suggestions.

My only major concern is with the discussion of the links to the AMO. The AMO is generally associated with a center of action in the North Atlantic subpolar gyre (e.g., O'Reilly et al. 2016, Wills et al. 2019, and references therein), which shows no clear anomaly in either of the resented composites. To the extent that the Atlantic temperature anomalies are there at all, they (Fig. 4c) look more like NAO-coupled variability of the ocean gyre circulation (i.e., warming in the Gulf Stream and GIN seas, but cooling in between; Curry and McCartney 2001, Eden and Jung 2001, Sun et al. 2015, Wills et al. 2019). Since these anomalies are weak anyway, I would limit your discussion of connections to the AMO, instead saying something like "there appear to be differences in Atlantic temperatures between the two drought types, and that this could be related to modes of Atlantic multi-decadal variability such as the AMO or the NAO-coupled variability of the gyre circulation, as discussed in the literature". Note that I've included a lot of Atlantic multidecadal variability literature here because of my own interest in that part of the story, and in case it is useful, but I don't actually think it is necessary to go into/reference all of it in this manuscript.

We agree with the reviewer and have included the suggested phrase in our revised manuscript:
"There appear to be differences in Atlantic temperatures between the two drought types (Fig. 4), which could be related to modes of Atlantic multi-decadal variability such as the AMO or the NAO-coupled variability of the gyre circulation as discussed in the literature (i.e., warming in the Gulf Stream and Greenland, Iceland and Norwegian Seas (GIN) seas, but cooling in between; Curry and McCartney, 2001; Eden and Jung, 2001; Sun et al., 2015; Wills et al., 2019)."

Scientific questions/issues:

17 droughts is a small number of degrees of freedom to be computing clusters from. Could you quantify what you mean by "most conclusive clustering result" or give some metric of how this clustering depends upon sampling? Furthermore, you then explain a principal component analysis based approach and this left me confused as to which method you were using. Are you using two separate methods to characterize the droughts? Do they get the same answer?

A sample size of 17 droughts is admittedly small and quite sensitive to the number of clusters or generally the sampled area. We thus tried many different settings of the clustering by changing the cluster numbers, the chosen spatial and temporal domain as well as the clustering approach itself. We found that limiting the clustering to two instead of three clusters resulted in the more evident classification of the 17 droughts and is furthermore consistent with the literature (*e.g.*, Fye et al., 2003). In that process, we also decided to exclude the turn-of-the-century drought from the clustering because of its inherently different spatial signal compared to the other 16 droughts in our sample.
In terms of the clustering method: We tested two different clustering approaches: k-means clustering and ward clustering, both of which have their strengths and weaknesses. While both methods resulted in an almost identical classification of the droughts, they disagreed on the class affiliation of one drought. Therefore, we chose to combine the two clustering methods and make use of the method's strengths to more accurately define the right cluster for the remaining drought (page 6, l. 14-15): "Ward hierarchical clustering was used to determine the cluster centers, which were then used as a starting point for the

k-means clustering.”). The combined approach of ward and k-means results in the identical drought affiliation as the ward method (Supplementary Figure S3 and S4), pointing to the robustness of the clustering.

In the revised version we mention that clustering is sensitive to the cluster numbers, the chosen spatial and temporal domain as well as the clustering approach itself. We note that limiting the cluster number to two results in a robust classification that is furthermore consistent with Fye et al. (2003).

With regards to your methodology of “each drought period was first expressed relative to a reference period that comprised 5 years before and 5 years after the drought period”, have you compared this to the simpler approach of using anomalies from the long-term mean? It seems that this would be a simple check and I would hope it doesn’t make a huge difference.

This is a good point, thank you. We did compare the ±5 years composites approach to other approaches for the case of SLP. Figure 1 shows the comparison of the drought type composites and differences between our ±5yrs approach (a,c,e) and anomalies from the long-term mean over the entire period (1604-2003) (b,d,f). Both approaches show qualitatively similar patterns and point towards their robustness. We added a sentence on that to the revised paper and the figure to the Supplementary material. However, using a common climatology is not a good option for variables that have strong centennial trends such as T2m and GPH. For these variables, spurious signals may appear as our drought sample is small and the two types of droughts are not equally distributed over time, so they will be aliased by global warming trends. A long term trend would have to be subtracted, raising numerous other questions as to what trend should be chosen and how it should be fitted. We believe that the ±5yr composite approach is much more suitable to capture the differences between the drought and non-drought periods in a satisfactory manner.

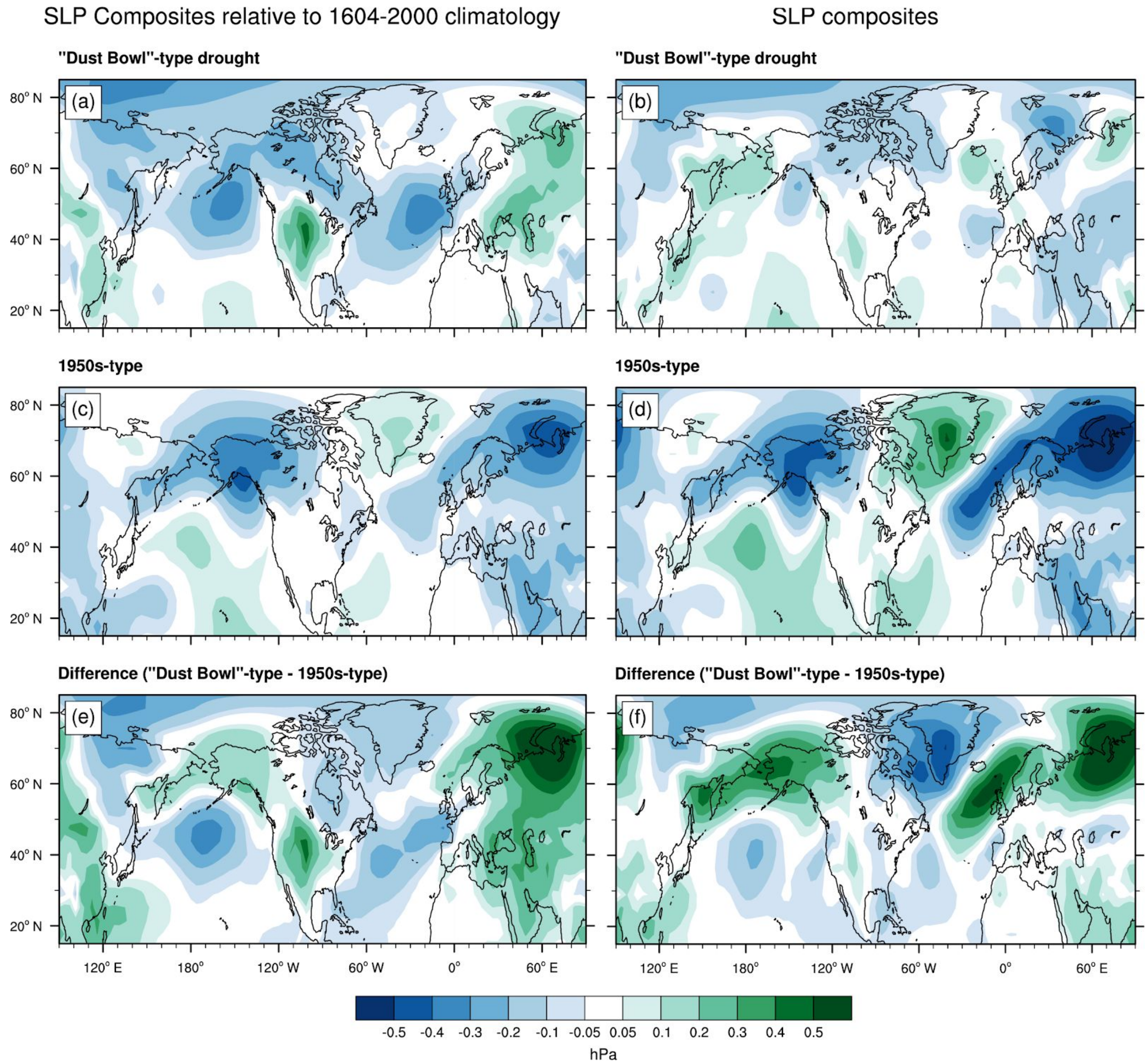


Figure 1 | SLP composites relative to the 1604-2003 long-term mean **(a,c,e)** and the composites relative to the 5yrs periods prior and after the drought **(b,d,f)**. The top row depicts the SLP composites of the "Dust Bowl"-type droughts, the middle row the 1950s-type droughts and the bottom row the difference between the two drought types.

Do you have an explanation why the SLP anomalies tend to be weaker / less significant than the GPH anomalies? Physically this would arise if the circulation anomalies were baroclinic (consistent with a shift of the subtropical jet in the longitude band of Pacific/North America), but I am not sure the EKF400 reanalysis can be trusted to that great of a degree. Could it possible be reconstructing less of the SLP variance than it does the GPH variance? Are the differences in anomaly amplitude actually quantitatively different? It may be helpful to rescale the SLP colorbar and to consider my following comment.

That is an interesting comment. We suspect that this might be due to the fact that the 500hPa field includes more of the temperature signal and thus performs statistically slightly better.
In the revised manuscript we improved the GPH and SLP colorbars to make the differences in the anomaly amplitude better visible.

Why do your GPH figures seem to have a mean over the plotted domain that is less than zero? This could be due to variability in the Southern Hemisphere that is not relevant here. Could you remove this so that the plots are easier to parse?

Well spotted. N-S asymmetries can play a role, but one has to keep in mind, that our approach is not mass conserving (applicable for SLP).

How is the 95% significance level computed for the figures? In particular, how are you computing the number of temporal degrees of freedom? It would be helpful to state this in the caption.

This is mentioned in the method section but we added it to the captions as well. All significant tests are based on a non-parametric Wilcoxon-Mann-Whitney test.

Please check that there are no major differences between a composite of SST and the T2M composite shown. No need to show it, but it would be good to check this and state whether there are any significant differences.

We compared the T2m fields with the SST fields that were used as input variables for the model. Figure 2 shows the comparison. It can be seen that over the ocean, there exists very little difference between the T2m (a-c) and the SST from the model input (d-f). We therefore conclude that the use of T2m is justified also over the ocean. We included at statement thereof in the revised manuscript.

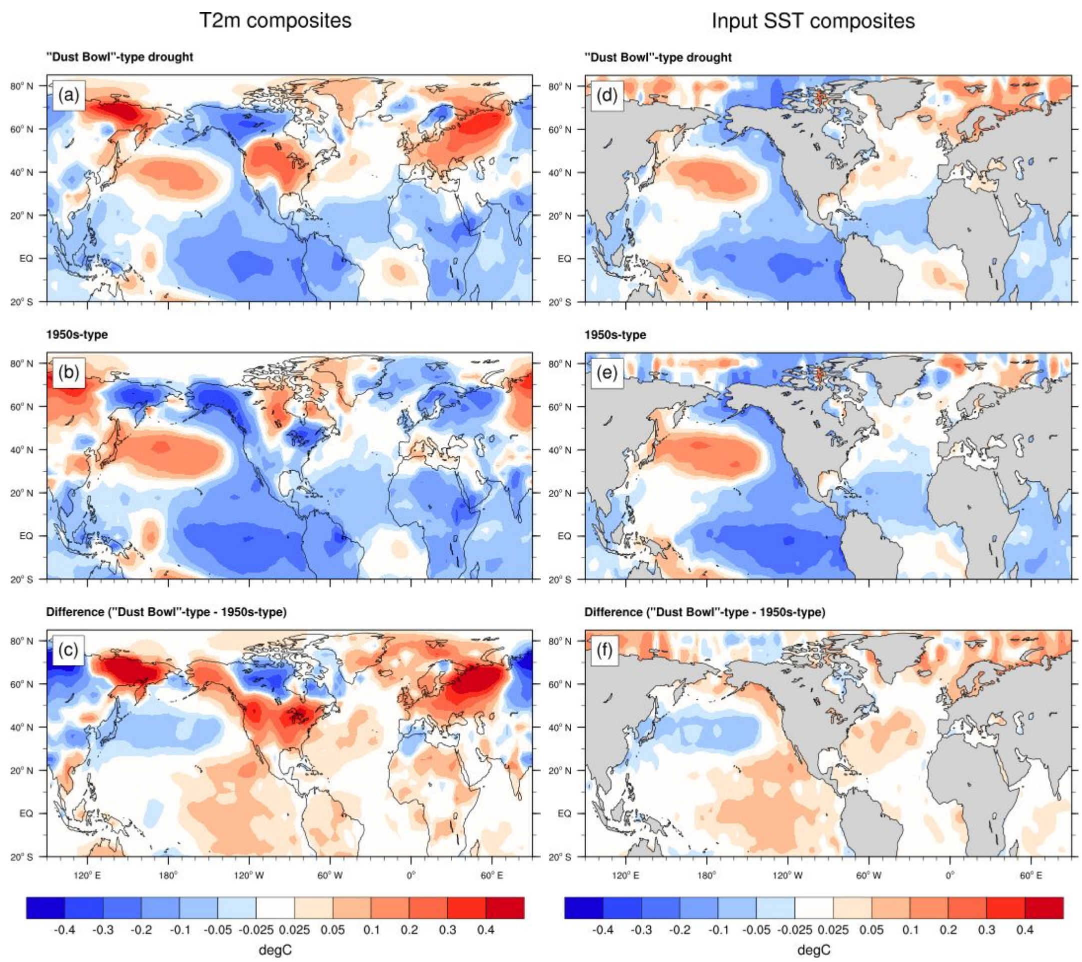


Figure 2 | Composites of T2m **(a-c)** and the SSTs that were used as model input **(d-f)**. The top row depicts the temperature composites of the "Dust Bowl"-type droughts, middle row the 1950s-type droughts and the bottom row the difference between the two drought types.

I don't fully agree with your interpretation of Fig. 4. There are not particularly stronger or more significant ocean T2M anomalies in the North Atlantic than the North Pacific. Given the larger influence of tropical SST anomalies on the atmospheric circulation (e.g., Kushnir et al. 2001), the different atmospheric anomalies are just as likely to result from the tropical Pacific or tropical Atlantic temperature anomalies, *even though those anomalies are smaller and not significant. You state multiple times in the discussion that the warmer North Atlantic (while not significant) could explain this or that atmospheric change, but I don't think these results make a strong case for that, especially not for any role of the AMO, which should have larger-scale coherent warm anomalies focused in the subpolar gyre (such as those seen in Fig. 5). It may be helpful to consider Ruprich-Robert et al. 2017, which looks at the differing impacts between the tropical and extratropical component of "AMO" anomalies in a climate model.*

In the revised version we limited our discussion on the connections between droughts and the AMO. Instead we point towards the differences in Atlantic temperatures between the two drought types that are potentially related to different modes of Atlantic multi-decadal variability.

Could you extend the latitude range of your T2M plot over the equator? Any SST anomalies in the 0-20° S latitude range could still have a large impact on the atmospheric circulation in the Northern Hemisphere.

We extended the T2m composite fields to 20°South in the revised manuscript to get a more comprehensive view.

Technical corrections:

Thank you for pointing out typos/wording problems. We corrected the following in the revised version.

- *Page 1, Line 14 typo: "show" should be "shows"*
- *Page 2, Line 13: typo, extraneous "of" after behind*
- *Page 3, Line 18 typo: "or" instead of "of"*
- *Page 4, Line 25-25: I think "opposed to decadal variability" is not the correct word choice for what you are saying. Should be "compared to decadal variability" instead.*
- *Page 6, Line 8: missing word(s) between La Niña and El Niño*
- *Page 6, Line 17 typo: "at in"*
- *May not Mai*
- *Mid-19th not mit-19th*
- *Page 6, Line 17: former and latter are both singular, and you should use "exhibits" with them, not "exhibit"*
- *Page 8, Line 27: "turn-of-the-century drought" not "turn of the century"*
- *Page 1, Line 16-17: positive and negative anomalies in what index?*

  We specified here: positive and negative **GPH** anomalies.

- *Page 2, Line 4-6: the words "most relevant" are not very precise, consider rephrasing*

  Agreed, we used "alarming" instead.

- *Page 2, Line 11: Is "moisture interpretation" a vocabulary word I am not aware of, or is this simply a wording problem where you should have said "are mostly restricted to interpretations as temperature and moisture"?*

  This is a wording problem, we used your suggestion instead.

- *Consider referencing Enfield et al. 2001 as well for the Atlantic SST influence on multi-decadal drought.*

  Good idea, we added Enfield et al. 2001 in the revised version.

- *Your abstract had me wondering why only summer SST/SLP/GPH is relevant. If you say you are looking at summer drought, then it would become clear why, and you then don't even need to say that it is summer SST/SLP/GPH.*

  Elegant, we added "summer" in the abstract to clarify that we are focussing on multi-annual droughts during summer.

- *Page 4, Line 6: please state how/why the ensemble members differ*

  We specified the sentence as follows in the revised manuscript to clarify how the 30 ensemble members in EKF400 differ:
  "EKF400 is a global, monthly, three-dimensional reconstruction based on an off-line assimilation of early instrumental data, documentary data, and proxies (tree ring width, late wood density) into an initial condition ensemble of 30 global model simulations using an Ensemble Kalman Filter technique. "

- *Page 6, Line 9/10: twice you say "three" where I think you mean "two"*

  Yes, that is a mistake, we corrected this to "two" in the revised version.

- *Page 8, Lines 19-20: the second half of this sentence needs to be reworded, this word order (especially with contribute at the end) does not work in English.*

  Agreed, we reworded this sentence in the revised manuscript to "Again, both Atlantic and Pacific might contribute. In particular, a negative PDO/La Niña like pattern over the Pacific has been shown to conduce to tropical expansion (Allen et al., 2014). Moreover, Atlantic SSTs were demonstrated to play a role in the form of a positive (negative) AMO for a poleward (equatorward) shift of the jet (Brönnimann et al., 2015)."

- *First sentence of conclusions: please add that this is the first time this has been studied in a climate reconstruction, because there have of course been model-based studies*

  Yes, that's a good point. We added this specification in our revised conclusion.

Reviewer #2 (Anonymous Referee)

Burgdorf and colleagues, motivated to better understand drought forcing in North America, use the LBDA and EKF400 datasets to relate multi-year droughts in North America (via LBDA) to their synoptic circulation drivers (via EKF400) over a sufficiently long record to make robust claims.
The authors rely on clustering analysis of multiyear drought events (5-yr running mean on the standardized PDSI values) to identify their prevailing spatial patterns. They find two dominant modes of soil moisture anomalies (consistent with previous findings), and building on work, are then positioned to link those patterns to their atmospheric drivers via the EKF400 data assimilation product. They find (generally consistent with the previous literature) that particular configurations of ocean-atmosphere variability select for different drought types.
Overall the paper appears to be in a position to make a nice contribution. I have a few larger comments and some minor ones the authors might find helpful in a revision.

We thank the reviewer for the positive feedback and constructive comments and suggestions. In the following, we will take a stance on them.

Major comments
1. How does the spatial domain presented (page 5, line 4) influence the clustering of the drought events and thus the spatial patterns presented? Presumably the clustering is quite sensitive to the domain selection and its odd that Figs. 1 and 5a use a constrained North American domain to show the drought patterns, while the rest of the analysis puts North America more fully in perspective. The LBDA v1 on which the central analysis is based, encompasses all of North America, so I wonder why the authors chose to constrain their analysis in such a way, particularly given their emphasis on both pattern identification (which is likely domain-sensitive) and synoptic scale circulation on such drought events. I recognize the authors' point at page 3, line 31 about version 2 being more limited spatially. But since the 20th C. drought is dropped from the central analysis, why not expand the domain to encompass all of NA, or at the least, all of CONUS (as in Fye et al.)?

That is a legitimate point we focused on for a considerable amount of time. We first looked at the first version of the NADA (Cook et al., 2004, 2008) and compared the droughts resulting from our detection method with the droughts found by Fye et al. (2003) who used an earlier version of the PDSI (Cook et al., 1996, 1999). In these first examinations, we looked at the entire domain (all of North America) and ended up with a very similar set of droughts. We then looked at the droughts in the even more advanced version the LBDAv1 (Cook et al., 2010) which again showed an almost identical drought catalog, affirming the robustness of our approach. Since all multi-annual droughts we found mainly affect the Great Plains and the Southwest, we tested the idea of subsetting our domain to even better capture the spatial signal of droughts in this particular drought-prone area. In doing so, our detection method revealed in addition to the pervious drought catalog, further multi-annual drought periods that are very prominent in the relevant domain but remain disguised when looking at entire North America.
So while we argue that the development and subsistence of droughts in North America are driven by large scale circulation, we recognized that their spatial signature is more limited to particular regions in central and western North America which calls for a more regional vantage point in terms of the detection and classification of droughts. We ended up choosing a domain that includes, beside the Great Plains and the Southwest, prominent drought regions in the Mississippi Valley, Northern Mexico, and the southern Canadian Great Plains. It however excludes the East Coast and the tropical South as well as Alaska and most of Canada.
We added an explanation as to why we chose that particular spatial domain for the detection of the multi-annual droughts.

*2. I wonder about the comparison of EKF400 anomalies to the LBDA anomalies: do they share the same standardization intervals? I *believe* the LBDA is standardized relative to the instrumental period of 1931-90 (could be wrong here), and then the authors here take the 5-year running mean to define a drought event (plus a spatial scale threshold). The GPH analysis is just relative to +/- 5 years centered on the drought. I wonder if the atmospheric fields should first be centered to the same interval as the LBDA and then those EKF400 anomalies can be composited with the +/- 5 year approach. This may make some more consistent GPH, T2M, and SLP patterns emerge.*

This suggestion, as we understand it, affects the results only insofar as standardisation is involved (centering to 1931-90 and then re-centering to +/-5 years cancels out), but this is a valid point. Standardisation emphasises the signal in the tropics and suppresses the high-latitude signal. Figure 1 with standardised anomalies (b,d,f) shows exactly that. However, to some extent this information is already included in the figure, namely in the form of the stippling of significant differences, which depends on the signal-to-noise ratio.

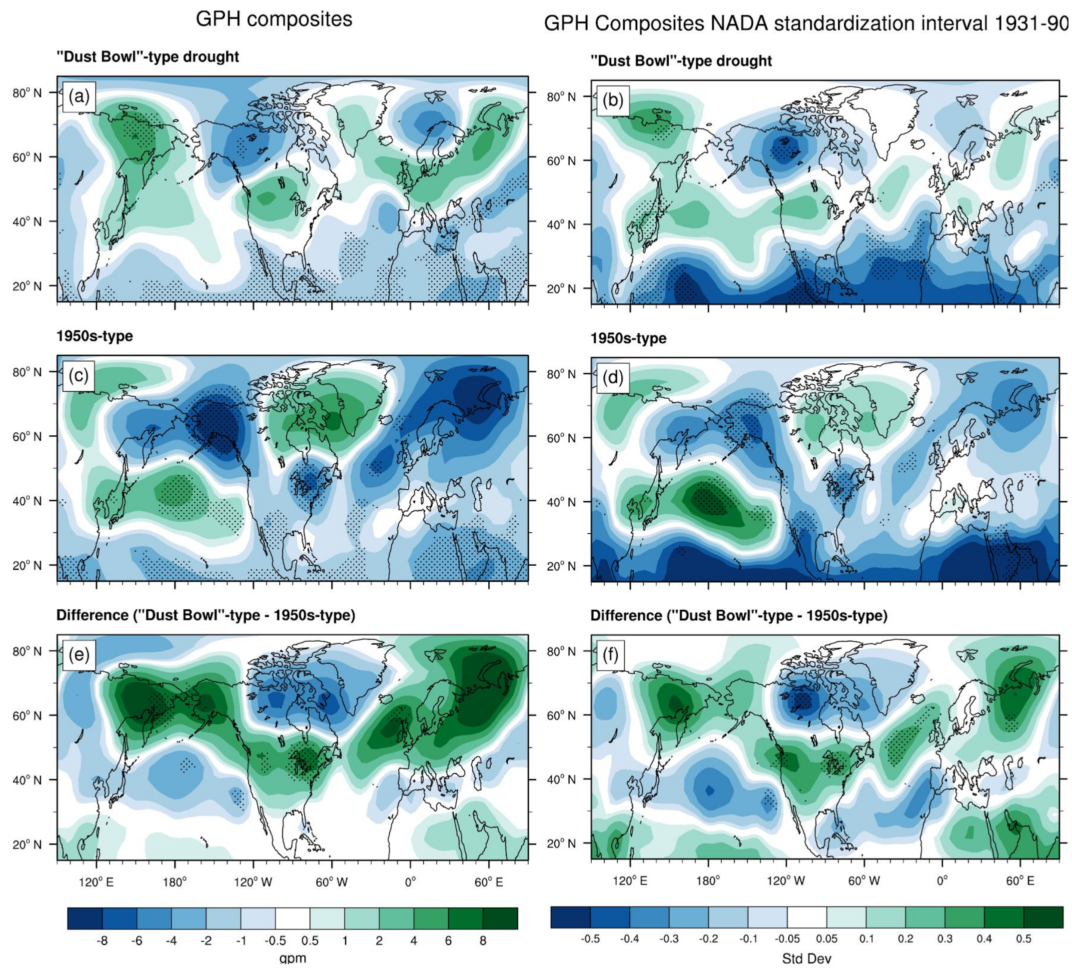


Figure 1 | GPH composites (±5yrs) based on our initial method (version A) **(a,c,e)** and GPH composites centered on the standardization interval (1931-90) prior to calculating the ±5yrs composites (version B) **(b,d,f)**. The top row depicts the GPH composites of the “Dust Bowl”-type droughts, the middle row the 1950s-type droughts and the bottom row the difference between the two drought types.

3. Are the EKF400 T2M data representative of ocean skin temperatures? Certainly SSTs and T2M should share the same variations over climate timescales, but some kind of validation of that, or just using SSTs over ocean basins would be more sound for making claims about oceanic forcing.

We compared the T2m fields with the SST fields that were used as input variables for the model. Figure 2 shows the comparison. It can be seen that over the ocean, there exists very little difference between the T2m (a-c) and the SSTs from the model input (d-f). We therefore conclude that the use of T2m is justified also over the ocean. We included a statement thereof in the revised manuscript.

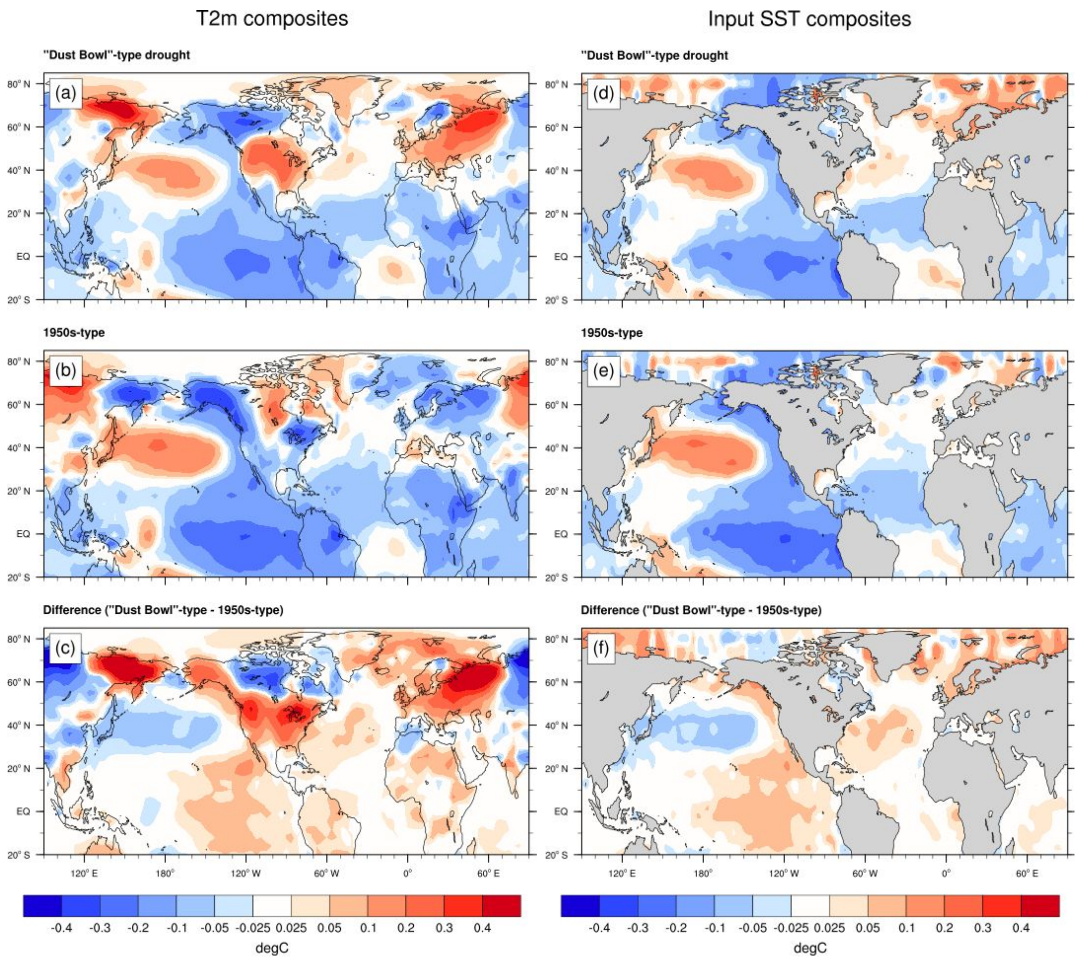
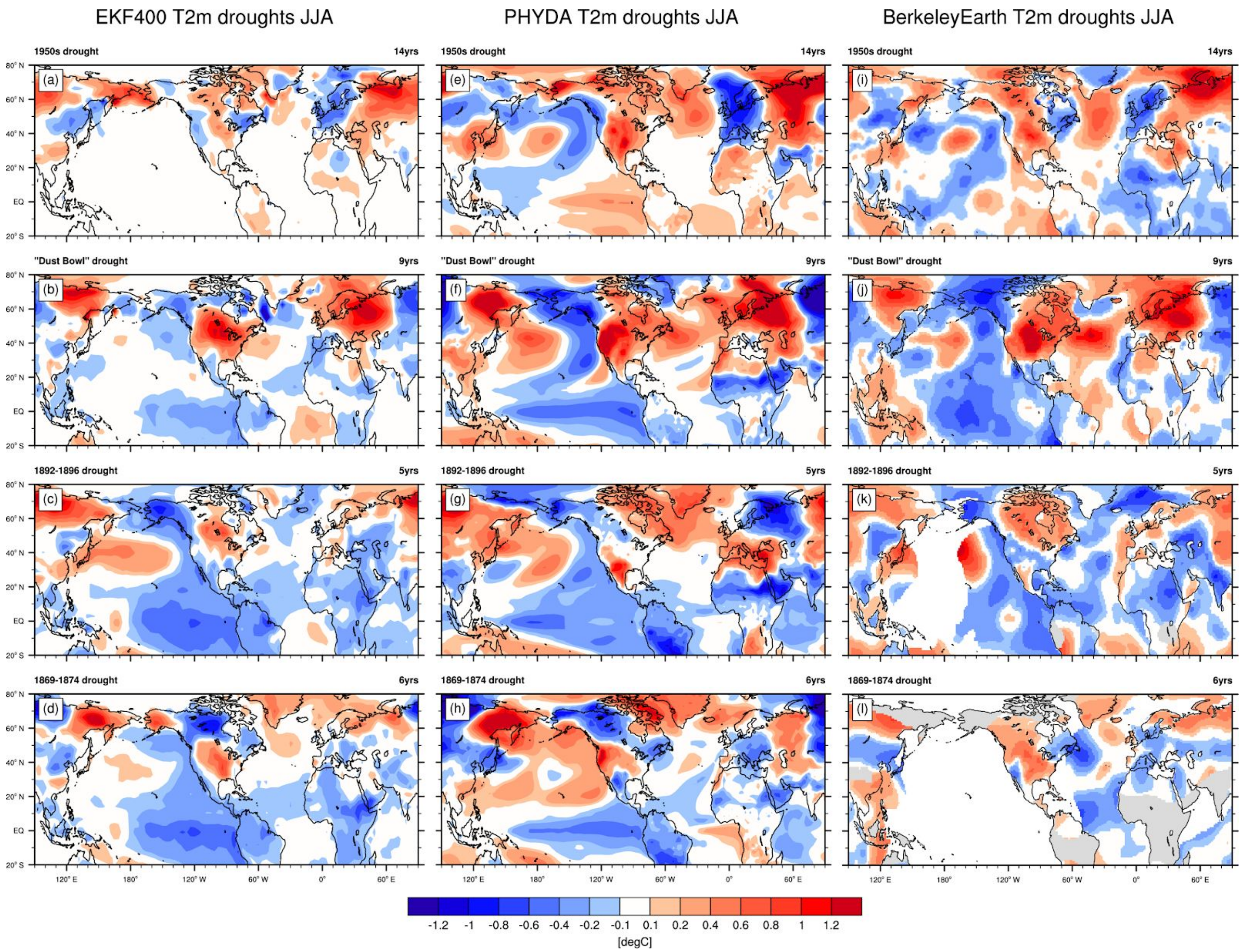


Figure 2 | Composites of T2m **(a-c)** and the SSTs that were used as model input **(d-f)**. The top row depicts the temperature composites of the "Dust Bowl"-type droughts, middle row the 1950s-type droughts and the bottom row the difference between the two drought types.

4. It strikes me as a pretty large missed opportunity to not also leverage the PHYDA in this work as a check on EKF400 results, given the uncertainties in the latter that the authors concede (e.g., page 6, line 33) and the authors' search for robustness. As I understand it, EKF400 simulations are forced with SST reconstructions that use a number of the same proxies that are also then used in the data assimilation process itself, which seems potentially problematic. The authors' ability to make robust claims about wave trains, jet positions, and SSTs would be greatly enhanced if there is consistency across more than one atmospheric reconstruction, which is now publicly available.

Thank you for the suggestion. PHYDA does not allow interpretations of atmospheric circulation, but the reviewer is right that consistency across products should be checked. We therefore added a figure to the supplementary material (see Figure 3 below) that shows a comparison of temperature composites (±5yrs) of the latest four drought periods in the EKF400 (a-d), the PHYDA (e-h) and furthermore in BerkeleyEarth (i-l), 20CRv2c (m-p) and HadCRUT4.6 (q-t). It can be seen that there are both similarities and differences among the different products. EKF400 is slightly closer to the observations over the landmasses than PHYDA. This can be expected since instrumental temperature data is assimilated. However, also PHYDA, that solely assimilates natural proxies (tree rings, corals, sclerosponges, ice cores, speleothems, lake sediments and marine sediment) corresponds well with the observations. For example over the Arctic and South East Asia PHYDA performs better than EKF400. PHYDA does assimilate data here whereas EKF400 does not. Both PHYDA and EKF400 as well as 20CRv2c have difficulties over tropical Africa and South America where very little proxies/inst. measurements are available and thus assimilated. The comparison of the two paleo reconstructions (EKF400, PHYDA) is a great opportunity for future work. However, within the scope of this paper we will focus on the EKF400 analysis since we have, besides T2m, atmospheric variables (GPH and SLP) available to analyse the atmospheric circulation patterns contributing/driving the different multi-annual droughts in the U.S.



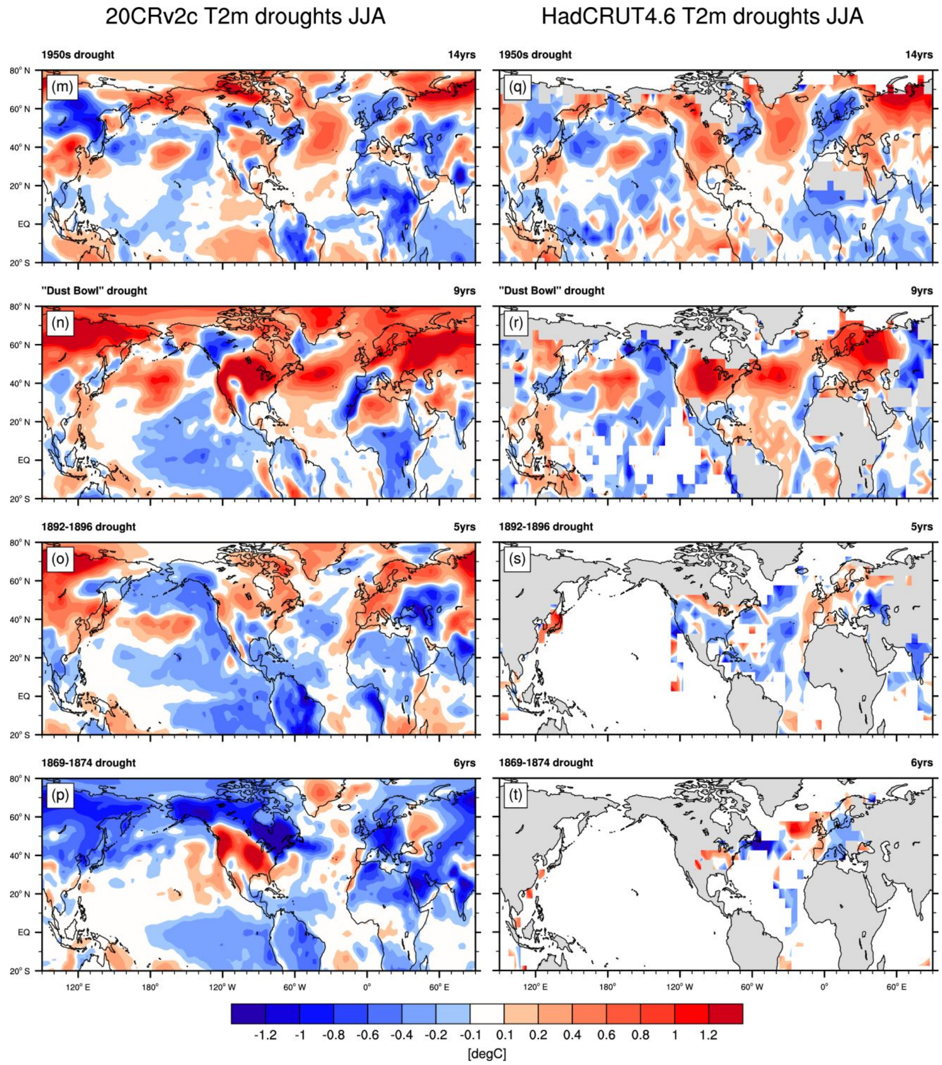


Figure 3 | Temperature composites in five different datasets for the latest four droughts, the 1950s droughts (top row), the "Dust Bowl" drought (second row), the 1892-1996 drought (third row) and the 1869-1874 drought (bottom row). The T2m of the two palaeo reconstructions EKF400 **(a-d)** and PHYDA **(e-h)** are shown as well as the surface air temperature from the observational products Berkeley Earth **(i-l)** and HadCRUT6.4 **(q-t)** and additionally, the T2m from the 20CRv2c reanalysis **(m-p)**.

5. Updating the Fye et al. paper seems to be a central motivation in this work and there are places where contrasts are drawn between the findings here and those in Fye, which is interesting, but it would be great to have the reasons for those differences explained or hypothesized about a bit more.

A possible hypothesis for the slightly different drought catalogue in Fye at al., 2003 and our study is the fact that they 1. use a different, less sophisticated version of PDSI reconstruction, 2. use a different drought detection metric and 3. use the entire domain over the contiguous U.S. Given these methodological differences, it is rather remarkable how similar the results are, pointing to their robustness.

6. Finally, the outlier pattern associated with the most recent drought is really quite compelling as the authors suggest this one is anomalous based on their pattern clustering. Are there any droughts in the original two clusters (Dust Bowl and 1950s) that look somewhat like the modern drought? Some more validation of that finding would be really great. Could it be a methodological artifact due to its being in version 2 and not 1, and the need to put v2 (PMDI) on equal footing with v1 (PDSI)? It might be easier to drop this from the paper and do a more rigorous treatment of it in a separate analysis.

There is one drought (1652-1656) in our catalog of 16 droughts that somewhat resembles the turn-of-the-century drought. It also features the unique (among the other droughts in our catalog) spatial pattern with a diagonal divide between dry anomalies along the entire Westcoast and Southwest and wet anomalies (!) in the north-eastern Great Plain stretching down south along the Mississippi Valley. We added plots of all the individual multi-annual droughts as a new supplementary figure so droughts can be looked at individually. Figure 4 shows correlation plots of the turn-of-the-century drought vs. the "Dust Bowl"-type droughts (A) and the turn-of-the-century drought vs. 1950s-type droughts (B). It indicates how different the turn-of-the-century drought is compared to the two drought types. We don't think that the very distinct spatial signature of the turn-of-the-century drought is an artifact caused by the calibration of the LBDAv2 to fit the LBDAv1. Theses differences are only minor and would not explain the very different spatial pattern featuring the 21th-century drought.

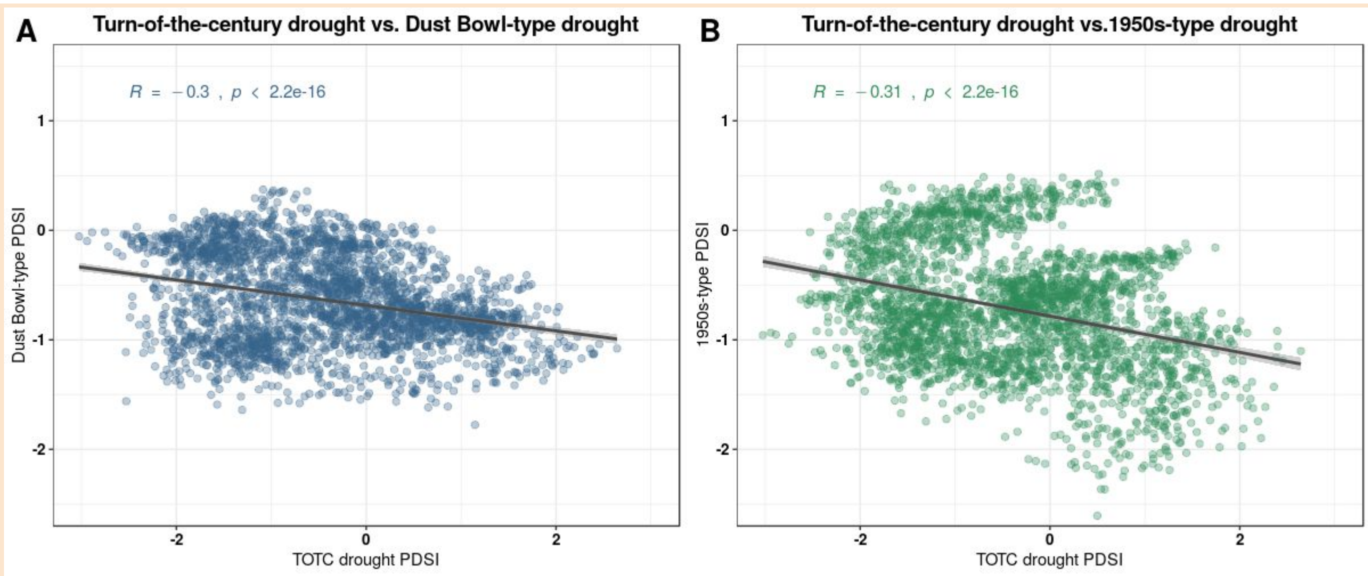


Figure 4 | Correlations (pearson) between the turn-of-the-century drought and the "Dust Bowl"-type drought **A** and between the turn-of-the-century drought and the 1950s-type drought respectively **B.** Each point depicts a gridbox.

Minor comments

Thank you for the suggestions and for pointing out typos/wording problems. We corrected the following in the revised version.

- *P2, L27: You cite internal variability here; a recent Cook et al. 2018 paper ("Revisiting the Leading Drivers of Pacific Coastal Drought Variability in the Contiguous United States," Journal of Climate) shows that there are numerous ocean-atmosphere configurations that can give rise to the same drought pattern in the West Coast of North America.*
  Thank you, we added that reference to the revised manuscript and pointed out the combined influence of atmospheric variability and forced ocean low-frequency variability.

- *P5, L5: is the PDSI < -1 consistent with Fye?*
  Yes. However, Fye et al. used a different approach for drought detection (they are identifying decadal moisture regimes).

- *P5, L10: point to the Supplemental Figures here?*
  Thank you, that is a good idea, we did point to the supplement figure at this point in the revised version.

- *P6, L9: You discuss two drought types, but in this and the subsequent sentences you reference three.*
  That is a mistake that we corrected in the revised version.
- *Online it's fine, but in a print out, Fig. 2's color bar is difficult to discern.*
  Thank you for pointing that out, we adjusted the color bars of all figures in the revised version.
- *P6, L29: Are these statistical tests on the patterns of droughts or the jet positions? As written it's not clear. (Seems like it should be on the jet positions.)*
  They are on the jet position. We formulated this more clearly in the revised version.
- *the quotes around "Dust Bowl" and such are upside-down(?); usage of e.g. requires a parenthetical, etc.; please just check the manuscript for the typos throughout.*
  Thank you for pointing out these typos, we did correct them and checked for further typos in the revised manuscript.

Two types of North American droughts related to different atmospheric circulation patterns.

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Abstract. Proxy-based studies suggest that the southwestern USA is affected by two types of summer drought, often termed „Dust Bowl““Dust Bowl”--type droughts and 1950s--type droughts. The spatial drought patterns of the two types are distinct. It has been suggested that they are related to different circulation characteristics, but lack of observation-based data has precluded further studies. In this paper, we analyze multi-annual summer droughts in North America since 1600 in tree-ring based drought reconstructions and in a global, monthly 3-dimensional reconstruction of the atmosphere. Using cluster analysis of drought indices, we confirm the two main drought types and find a similar catalog of events as previous studies. These two main types of droughts are then analyzed with respect to sea-surface2-meter temperatures (SSTT2m), sea-level pressure (SLP),, and 500 hPa geopotential height (GPH) in summer. 1950s-type droughts are related to a stronger wave-train over the Pacific-North American sector than „Dust Bowl““Dust Bowl”--type droughts, whereas the latter showsshow the imprint of a poleward shifted jet and establishment of a Great Plains ridge. The 500 hPa GPH patterns of the two types differ significantly not only over the contiguous United States and Canada but also over the North Atlantic and the Pacific. „Dust Bowl““Dust Bowl”--type droughts are associated with positive GPH anomalies, while 1950s-type droughts exhibit strong negative GPH anomalies. In comparison with 1950s-type droughts, the „Dust Bowl““Dust Bowl”--type droughts are characterized by higher SSTs in the North Atlantic. Results suggest that atmospheric circulation and SST characteristics not only over the Pacific but also over the extratropical North Atlantic affect the spatial pattern of North American droughts.

1 Introduction

Since the turn of the 21st century, prolonged drought events have afflicted large parts of North America, predominantly the southwestern United States (hereafter Southwest) (Seager, 2007; Weiss et al., 2009; Cayan et al., 2010; Seager and Vecchi, 2010; Seager and Hoerling, 2014). In recent years, exceptionally severe droughts struck California (Griffin and Anchukaitis, 2014; Seager et al., 2014a, 2015), the Great Plains (Hoerling et al., 2012, 2014; Livneh and Hoerling, 2016) as well as the Texas-Northern Mexican region (Seager et al., 2014b). However, drought conditions are a regular feature of the climate in the western United States and have repeatedly affected the region in the past (*e.g.,* Cook et al., 2007; Seager et al., 2009). A particularly strong multi-annual drought event in the instrumental record period was the decadal-scale "Dust Bowl" drought, which coincided with the Great Depression and had tremendous economic and social effects (Worster, 1979). Proxy-data provide evidence that even longer and more severe drought periods, so-called "megadroughts", have occurred in the past (*e.g.,* Woodhouse and Overpeck, 1998; Cook et al., 2007, 2010, 2016; Stahle et al., 2007). Severe droughts in the paleoclimate record include decadal to multidecadal droughts during medieval times (~AD 900-1300), characterized by not only persistent aridity but also increased temperatures over western North America (Woodhouse and Overpeck, 1998; Cook et al., 2004; Woodhouse et al., 2010).

In light of greenhouse gas-induced global warming, this temperature-drought relationship (with the concurrence of increasing aridity and rising temperatures) is most relevanalarmingt t and climate model simulations suggest a possible increase in drought frequency and duration in the 21st century (Seager et al., 2007; Cayan et al., 2010; Seager and Vecchi, 2010; Dai, 2013; Cook et al., 2014a, 2015, 2018a2018; Ault et al., 2016). In order to be able to cope with the challenges associated with the projected increase in aridity and thus drought risk in the future, it is important to better understand the dynamics behind multi-annual drought events in the western United States. Since severe multi-annual droughts are limited in the era of observation-based climate data, analyses have to be extended into the reconstruction era. Reconstructions based on proxy data, however, are mostly restricted to interpretations as surface temperature and moisturesurface temperature and moisture interpretation. Here we analyze past drought periods in 3-dimensional reconstruction that is based on data assimilation.

During the last decade, considerable progress was achieved in isolating the mechanisms behind of multi-annual droughts in the western U.S.. Both proxy-based studies (Woodhouse and Overpeck, 1998; McCabe et al., 2004; Routson et al., 2016) and model simulations suggest that oceanic forcing by both the Pacific and to lesser degree the Atlantic acts as a trigger (*e.g.,* Schubert et al., 2004a; b, 2009; Seager, 2007; Cook et al., 2008; Kushnir et al., 2010; Seager et al., 2015; Baek et al., 2019). In particular, a cool Pacific and a warm Atlantic, especially in their tropical regions, are conducive to droughts such as the 1930s „Dust Bowl"“"Dust Bowl" drought, demonstrating a combined impact of both ocean basins (McCabe et al., 2004; Schubert et al., 2004b, 2009; Feng et al., 2008; Kushnir et al., 2010). However, the roles of individual ocean basins remain less clear. For the period of instrumental SST observations after 1856, a persistent La Niña-type SST pattern during all prolonged droughts is found as well as a cold Indian Ocean during most of them (Seager et al., 2005; Herweijer et al., 2006; Seager, 2007). The contribution of the Atlantic Ocean is shown to be only minor. In contrast, Nigam et al. (2011) find a key role of the Atlantic SST in their observation-based analysis of 20th century drought and wet periods in the Great Plains. A significant influence of North Atlantic SSTs variations on multi-decadal droughts in the continental U.S. is also found by Enfield et al. (2001). While the general setting of a cool Pacific and warm Atlantic is generally overall sufficient to produce drought conditions in AMIP-type model simulations, strong droughts require further mechanisms such as a land-surface feedback or the effect of dust (see Schubert et al., 2004b; Cook et al., 2008, 2009, 2013, 2014b). Furthermore, studies have ~~also~~ shown that droughts are strongly influenced by internal atmospheric variability of the climate system unrelated to oceanic forcings or a combination thereof (*e.g.,* Hoerling et al., 2009; Seager and Hoerling, 2014; Cook et al., 2018b; Baek et al., 2019)~~)~~.

Considering this complex interplay of oceanic forcings, internal atmospheric variability as well as feedback mechanisms, it is apparent that not all North American droughts are alike. Fye et al. (2003) analyzed tree-ring based multi-annual drought reconstructions and found two different types of drought based on their spatial pattern: ~~„Dust Bowl“~~“Dust Bowl”-~~-~~type droughts and 1950s-type droughts. These distinct spatial patterns possibly suggest different underlying dynamics of the atmospheric circulation leading to prolonged drought events. Woodhouse et al. (2009) analyzed two types of drought with respect to associated 500 hPa geopotential height fields and found evidence for both tropical and extratropical influences. Their study was based on severe single-year droughts and restricted to the 1949-2003 period. Further, they focused on atmospheric circulation during December through March to represent conditions of the cold season. Analyzing a large sample of droughts with respect to upper-level atmospheric circulation was not hitherto possible and thus only droughts in the instrumental record period have so far been analyzed, mostly focusing on the ~~„Dust Bowl“~~“Dust Bowl” drought. Hemispheric and global upper-level fields were reconstructed by Griesser et al. (2010) back to 1881 and used to study upper-level circulation during the ~~„Dust Bowl“~~“Dust Bowl” drought (Brönnimann et al., 2009, 2012), but not a larger set of droughts. The ~~„~~“~~„~~Twentieth Century Reanalysis”~~“~~ (Compo et al., 2011) now extends back to 1851 and was used to study, *e.g.,* the heat waves associated with the ~~„Dust Bowl“~~“Dust Bowl” drought (Cowan et al., 2017) or the Atlantic imprint on droughts in the USA (Nigam et al., 2011). Here we follow up on this work and further analyze the two types of multi-annual drought suggested by Fye et al. (2003) in a new monthly global 3-dimensional reconstruction back to 1600 (Franke et al., 2017), which allows focusing on atmospheric circulation. We analyze the imprint of the two types of drought in different fields and find that they differ significantly in their imprint over the contiguous United States and the extratropical North Atlantic.

The paper is organized as follows. Section 2 describes the data sets used (reconstructions and reanalyses) as well as the methods. Analyses of droughts during the past 400 years are presented in Section 3. Additionally, we analyze the most recent drought, namely 2000-2015, that was excluded from previous statistical analyses. In Section 4 we discuss the results in the light of possible oceanic forcing. Finally, conclusions are drawn in Section 5.

2 Data and Methods

2.1 Data sets used

Droughts in our study are addressed using the Living Blended Drought Atlas version 1 (LBDAv1) (Cook et al., 2010). This data set is an updated version of~~for~~ the North American Drought Atlas (NADA) (Cook et al., 1996, 1999, 2004) and provides annual values of the summer (June-August, JJA) Palmer Drought Severity index (PDSI) for the past two millennia based on tree ring reconstructions. The reconstruction includes 1845 tree ring chronologies and covers the North American continent at a spatial resolution of 0.5°x0.5° degree latitude. This allows for a regionally better characterization of drought variability compared to the NADA. The LBDAv1 is highly consistent with the global hydroclimate reconstruction (PHYDA) that reconstructs the PDSI at ~2° resolution, based on a multi-proxy approach (Steiger et al., 2018). The comparison of PDSI fields from the LBDAv1 and PHYDA confirmed the very good agreement of the two PDSI products. Because no significant differences exist between the two data sets over the southwestern U.S., we decided to use the LBDA due to its higher resolution and in order to stay consistent with the work of Fye et al. (2003).

For comparison with Fye et al. (2003) and due to the availability of the reconstruction data set EKF400 (see below) we restricted the analysis to the post-1600 period for PDSI and atmospheric circulation. In order to include droughts in the 21st century we used the Palmer Modified Drought index (PMDI) from the Living Blended Drought Atlas version 2 (LBDAv2) (Cook et al., 2010). While the LBDAv1 ends in 2005, the LBDAv2 is updated until 2017. It is based on the LBDAv1 (Cook et al., 2010) and calculates a PMDI by recalibrating the PDSI using GHCN 5km instrumental data and a Kernel Density Distribution Method. The LBDAv2 is furthermore limited to the contiguous U.S. compared to North America in the LBDAv1 which is why version 2 is only used for the 21st century drought. This latest drought, ca. 2000-2015, is too recent to be statistically analyzed according to our definitions (see below) but is briefly addressed as a separate event. To ensure a consistent drought detection metric we had to scale the LBDAv2 (PMDI) to the LBDAv1(PDSI) (see below).

To address fields of atmospheric circulation we analyzed 500 hPa geopotential height (GPH), sea-level pressure (SLP), and air temperature 2 meters above ground (T2m) as well as circulation indices from the EKF400 data set (Franke et al., 2017). T2m and sea surface temperature (SST) from the model input are almost identical which justifies the use of T2m also over the ocean. EKF400 is a global, monthly, three-dimensional reconstruction based on an off-line assimilation of early instrumental data, documentary data, and proxies (tree ring width, late wood density) into an initial condition ensemble of 30 global model simulations using an Ensemble Kalman Filter technique. The data set is given at a resolution of 4° and covers the period 1603-2004. The model is constrained, among other forcings, with annual sea-surface temperature reconstructions from Mann et al. (2009), to which we have added intra-annual, ENSO-related variability (see Bhend et al. (2012), for a method description). In this study, we analyze the ensemble mean. While the PHYDA data set offers reconstructed global T2m fields for the boreal growing season June through August (JJA) at a ~2° resolution it does not include further atmospheric variables. We therefore limit our analysis of the atmospheric circulation contributing to long-term summer droughts to the EKF400 reconstruction. However, we offer a comparison of surface temperature composites for the four most recent drought periods in EKF400, PHYDA and furthermore in Berkeley Earth (Rohde et al., 2013a, 2013b), HadCRUT4.6 (Morice et al., 2012) as well as 20CRv2c (Compo et al., 2011) in the supplement (Supplement Figure S7). The reconstructions are generally in good agreement with the observations, but some differences remain.

In order to analyze drought dynamics of droughts in the 21st century we use the ERA-Interim reanalysis at a 2° lat x 2° spatial resolution (Dee et al., 2011), which is updated to the present.

The circulation indices analyzed are the Pacific North American (PNA) pattern (Wallace and Gutzler, 1981) and), the latitude of the zonal mean subtropical jet over North America (i.e., the latitude of the maximum zonal mean zonal wind speed at 200 hPa as in, see Brönnimann et al. (, 2015), but restricted to 120° W to 60° W).) and the Atlantic Multidecadal Oscillation (AMO) index (Enfield et al., 2001) from the model forcing data. For the PNA index, monthly anomaly time series were standardized based on the 1901-2000 reference period. All analyses are performed using the ensemble mean of 30 members as well as using the "Best Member", i.e., choosing for each warm season the member that best reproduces a global set of 34 high-quality tree-ring width chronologies (Brönnimann, 2015). The best member minimizes the cost function Eq. (1):

$$J(\boldsymbol{x}) = (\mathbf{y} - H[\mathbf{x}])^T \, \mathbf{R}^{-1} \, (\mathbf{y} - H[\mathbf{x}]) \,, \qquad (1) \quad (1)$$

with $\boldsymbol{y}$ denoting the tree ring width, $H[\boldsymbol{x}]$ is the tree ring width as modeled by the VS lite tree ring model (Breitenmoser et al., 2014) and $\boldsymbol{R}$ the corresponding error covariance matrix determined from using instrumental data in the 20th century (see Breitenmoser et al., 2014, for details). In contrast to the ensemble mean, whose variance decreases back in time, the best member has a stable variance over time.

Note that the SSTs used to drive the model that formed the basis of the assimilation exhibit suppressed interannual as opposed compared to decadal variability (Franke et al., 2013). For instance, indices of El Niño and of the Pacific Decadal Oscillation (PDO) are very similar. Since the focus of this paper is on multi-annual drought, defined by means of a 5-yr filter (see below), the suppression of interannual variability does not markedly affect our results (given the similarity between El Niño and PDO indices in the SSTs underlying our assimilation, we refer to a „"„negative PDO/La Niña" in this paper).

2.2 Methods

Our starting point is the paper by Fye et al., (2003), which was based on a previous version of a PDSI reconstruction with a 2° lat × 3° spatial resolution, derived from 426 tree-ring chronologies (Cook et al., 1996, 1999). We first reproduced their analysis using the LBDAv1 (Cook et al., 2010) which has improved areal coverage and spatial resolution. The agreement between the two data sets was generally good, clear deviations were found for some of the drought periods, pointing to the need for re-classifying the drought events using LBDAv1.

All multi-annual droughts found in our preliminary analysis as well as documented by Fye et al. (2003) primarily affect the Great Plains and the Southwest. For that reason, we decided to subset our domain in order to even better capture the spatial signal of droughts in this particular drought-prone area. In doing so, our detection method revealed, in addition to the pervious drought catalog, further multi-annual drought periods that are very prominent in the relevant domain but remain disguised when looking at entire North America. We thus concentrated our drought classification on the region 22°-52°N and 130°-85°E, a domain that includes, beside the Great Plains and the Southwest, prominent drought regions in the Mississippi Valley, Northern Mexico, and the southern Canadian Great Plains. It however excludes the East Coast and the tropical South as well as Alaska and most of Canada.

Since the spatial signature of the „Dust Bowl"-type drought and 1950s-type drought mostly affects the Southwest and the Great Plains, we concentrated our drought classification on the region 22°-52°N and 130°-85°E. For the definition of drought periods, we proceeded in the following way: First, an index for the surface area affected by drought (PDSI < -1) (following Fye et al., 2003) for every time step (summer) was calculated. The index was then filtered with a 5-yr moving average, as the focus is on multi-year droughts. Years with >33% of surface area affected by drought were then selected. These years are considered "drought years". Five or more drought years in succession are defined as drought periods. Single years with a smaller percentage than 33% in-between continuous drought years are included in the drought period. This resulted in a list of 17 drought periods for the period 1600-2005, which is displayed in Table 1 (see Supplementary Table S1).

In a next step, the spatial patterns of the drought periods were clustered. The clustering was based on the fields of time-averaged PDSI per drought period in LBDAv1. The individual drought periods were weighted with the square root of their length in years, furthermore, grid cells were area weighted. Clustering was performed with a combined approach of ward hierarchical clustering and *k*-means clustering. Ward hierarchical clustering was used to determine the cluster centers, which were then used as a starting point for the *k*-means clustering. The sample size of 17 drought periods is quite sensitive to the cluster numbers, the chosen spatial and temporal domain as well as the clustering approach itself. Limiting the clustering to two clusters resulted in a robust classification of the droughts and is furthermore consistent with the literature (e.g., Fye et al., 2003) (see Supplementary Figure S1 and S2 for the PDSI pattern of the individual droughts). In terms of the clustering method, we chose The most conclusive clustering result was achieved with two clusters. Clustering was performed with a combined approach of ward hierarchical clustering and *k*-means clustering. Ward hierarchical clustering was used to determine the cluster centers, which were then used as a starting point for the *k*-means clustering (see Supplementary Figure S3 and S4). With this combined method, the resulting clustering affiliations for the droughts are identical to the ward hierarchical clustering, pointing to the robustness of the clustering.

The "Turn of the centuryturn-of-the-century" drought was excluded from the clustering analysis due to limited data availability (LBDAv1 only covers the years up to 2005, whereas drought conditions in the southwestern U.S. continued into the 2010s). Using LBDAv2, which ends 2017 (due to the different areal extent and spatial resolution, the dataset had to be fitted to the LBDA using regression), our definition detects a drought from 2000 to 2015.

Interestingly, its spatial pattern correlates negatively with both drought types which indicates that it is potentially characteristic of an alternative drought type (Supplementary Figure S5). We therefore excluded the most recent drought, henceforth called 21st century drought, from the clustering and statistical analyses and instead analyzed it independently.

For the analysis of climate fields, each drought period was first expressed relative to a reference period that comprised 5 years before and 5 years after the drought period. Then we calculated composites for the types of drought events for different seasons. In the following, we focus on the summer-mean (JJA) fields of 500 hPa GPH, SLP, and T2m. We did compare the ±5 years composites approach to the simpler approach of using anomalies from the long-term mean, which resulteds in qualitatively similar patterns for the case of SLP (Supplementary Figure S6). However, using a common climatology is not a good option for variables that have strong centennial trends such as T2m and GPH. For these variables, spurious signals may appear as our drought sample is small and the two types of droughts are not equally distributed over time, so they will be aliased by global warming trends.

The anomalies of the individual composites as well as their differencesThe anomalies of the individual composites as well as their difference were tested using a non-parametric Wilcoxon-Mann-Whitney test.

3 Results

Plotting the first two principal components of the PDSI during the drought periods well separates two distinct clusters, explaining 23.3% and 17.2% of the total variance respectively (Supplementary Figure Fig. S42). A comparison with Fye et al. (2003) reveals, that our approach tends to depict more drought periods than theirs, but 11 (perhaps 12) out of our 16 periods can be attributed to corresponding periods in Fye et al. (2003), though the length differs (see Table S1). Among these 11 (12) droughts, eight (nine) were classified in the same cluster as in Fye et al. (2003) if we term our first cluster „Dust Bowl"“"Dust Bowl"--type droughts and our second cluster 1950s-type droughts (see Table S1). We therefore kept that nomenclature. Fye et al. (2003) use a different clustering method which could explain part of the difference in the classification. We find four (five) drought periods that are not classified by Fye et al. (2003) whereas they find two droughts that our analysis does not capture. Out of the 11 (12) drought periods, three are assigned to opposite clusters in our study compared to Fye et al. (2003): We found the 1772-1776 and the 1869-1874 droughts to be "Dust Bowl"-type droughts while Fye et al. (2003) depict them as 1950s-type droughts. In their study, however, the duration of these two droughts is double in length compared to ours, which could serve as an explanation as to the different classification. The third drought that is classified differently is the „"„Civil War Drought"" of the 1850s and 1860s where the duration of the drought is coincident in both two studies apart from one year. It appears that the drought changes its character within the drought period from La Niña to El Niño condition which could possibly explain this discrepancy. There are three major differences between our study and Fye et al. (2003): First, Fye et al. (2003) use the first version of gridded summer PDSI reconstruction (Cook et al., 1996, 1999) which is a less sophisticated version of the LBDAv1. Second, we use a different drought detection metric and third, they use the entire domain over the contiguous U.S. whereas we focus on a subsetted drought-prone domain. Given the methodological differences between Fye et al. (2003) and our study, it is remarkable how similar both drought catalog and clustering results are, pointing to their robustness.

Figure 1 shows averaged PDSI values of three two clustered drought types (a-c). There are distinct differences visible between the three two types of drought. While both the „Dust Bowl"“"Dust Bowl"--type and 1950s-type affect the midwestern and southwestern United States, „Dust Bowl"“"Dust Bowl"--type droughts stretch far into the Pacific NorthwestNorth West, whereas 1950s-type droughts stretch down into Mexico. The difference between the „Dust Bowl"“"Dust Bowl"--type and 1950s-type (9 and 7 droughts, respectively) shows that these two features are statistically significant (Fig.1 c). A clear NW-SE dipole arises.

In order to investigate potential differences in atmospheric circulation associated with the different spatial pattern of the two drought types, we performed a composite analysis in EKF400, namely in the 500 hPa GPH, SLP and T2m anomaly fields.

The results for boreal summer (Fig. 2) show that "Dust Bowl"“-type and 1950s-type droughts are markedly different particularly at in 500 hPa GPH (Fig. 2 a,c,e). Only the former exhibitsexhibit a clear „"„Great Plains ridge" "(see Namias, 1982) (a), whereas the 1950s-type drought displays negative anomalies over large parts of North America (c). The difference field shows a band of positive anomalies stretching from Alaska, the Pacific Northwest across the continent and the Atlantic towards Northern Europe and Scandinavia (e). Over Alaska, the Northwest, the Great Lake Region and over the northern Atlantic, the differences are statistically significant. Moreover, there are significant positive anomalies in the extratropical Pacific.

Both types of droughts have a less strong SLP imprint (Fig. 2 b,d,f). The signal resembles the 500 hPa GPH fields especially north of 50°N. Significant differences between the two drought types are located across Alaska and the central northern Pacific.

In order to address the circulation on a global scale, we also analyzed the position of the zonal mean subtropical jet at 200 hPa (maximum of zonal mean zonal wind, see Brönnimann et al., 2015) for the two drought types both in the ensemble mean and the best member (Fig. 3). -"Dust Bowl"-type droughts are associated with anomalous northward shift of the jet over North America while during 1950s-type droughts the jet is shifted slightly further south relative to the preceding and following 5-year period. According to a heteroscedastic t-test, the differences in the jet position between the two drought types are significant (p = 0.014013) for the ensemble mean (for the best member analysis, p = 0.03210).

Summer droughts in the United States are often associated with precipitation deficits in winter and spring (*e.g.,* Weiss et al., 2009). While we performed our analysis for preceding winter (December-January-February) and spring (March-April-Mayi) seasons as well, we do not include the results here. This is because, over North America, EKF400 is based on mostly tree ring proxy-data until the midt-19th century. Therefore, outside of the growing season, the reconstruction basically reflects an atmospheric model simulation.

The composites for T2m reveal that both types of events are clearly accompanied by a negative PDO/La Niña signature in the Pacific (Fig. 4), where cool surface temperatures along the western coast of North America in a horseshoe shaped pattern surround a core of warmer surface waters in the central North Pacific. However, larger differences appear over the contiguous USA as well as over the Atlantic.“ “ “Dust Bowl“ ”-“ type droughts are 0.1-0.5 °C warmer over the USA and southern Canada than 1950s-type droughts (relative to their corresponding references), with largest differences in the Great Lakes region and the Pacific Northwest. Over central and northern Canada, on the other hand, 1950s-type droughts are markedly warmer (0.1 – 0.4°C) compared to “Dust Bowl“ ”-“ type droughts. The temperature differences between the two drought events are not significant over the Pacific though the negative PDO is less pronounced for „Dust Bowl““Dust Bowl” cases. In contrast, the signal over the Atlantic differs between the two drought types. „Dust Bowl““Dust Bowl”--type droughts exhibit positive anomalies in the extratropical North Atlantic (the region of the North Atlantic current) and significantly warmer temperatures in the Barents Sea. Note that 5 years preceding and following the drought periods were used as a reference. In the presence of slowly varying SSTs, this means that part of the signature of low-frequency modes such as the AMO might be missing (see discussion).

The latest multi-annual drought we include in the composite analyses is the 1950s drought. As mentioned before, the 21st century drought from 2000-2015 classified based on the LBDAv2 was excluded from previous analyses since its pattern correlated negatively with the two drought types.

Figure 5a shows the spatial pattern (PMDI) of the 21st century drought. The drought pattern is characterized by a pronounced dipole consisting of drought conditions in the West, especially the Southwest and wet conditions over the Midwest.

In 500 hPa GPH (Fig. 5b5c) and SLP (Fig. 54d) the 21st century drought exhibits strong positive anomalies in high latitudes and over Greenland and in contrast, strong negative anomalies over the northeastern Atlantic. These large-scale composite patterns differ strongly from the composites of the „Dust Bowl““Dust Bowl”--type and 1950s-type drought, nevertheless the dipole Greenland - northeastern Atlantic resembles the 1950s-type drought. The T2m composite (Fig. 5d5b) shows a negative PDO/La Niña signature and in the Pacific, however, also a warm equatorial Pacific e.g. an El Niño signature. In the far north, more precisely over Greenland and the Arctic Archipelago, the turn of the centuryturn-of-the-century drought is characterized by a strong warming signal (0.2 – 1.5°C). While the GPH and SLP fields if anything, resemble the 1950s-type drought, the surface temperature field with above normal temperatures in the western U.S. corresponds with the „Dust Bowl““Dust Bowl”--type.

4 Discussion

Droughts in the USA have been shown to be closely linked to SST anomalies (*e.g.,* Hoerling, 2003; McCabe et al., 2004; Schubert et al., 2004b; a; Seager, 2007). Both types of drought exhibit generally negative SST anomalies over the tropical Pacific similar to a negative PDO/La Niña mode. This is consistent with the above-mentioned studies. However, not all La Niña-type (or negative PDO) events lead to drought, the pronounced 1972-1975 event did not, for instance (*e.g.,* Seager and Hoerling, 2014). Pu et al. (2016) argue that the drought development in La Niña years requires anomalous warming over the tropical North Atlantic in spring. Nigam et al. (2011) find that a positive phase of the AMO favors droughts in North America. In fact, their 500 hPa GPH pattern for positive AMO phases in summer is very similar to the anomalies found for the „Dust Bowl"“"Dust Bowl" –drought (Brönnimann et al., 2012). However, the SST differences (Fig.4) are not significant over the Atlantic in our analysis. There appear to be differences in Atlantic temperatures between the two drought types (Fig. 4), which could be related to modes of Atlantic multi-decadal variability such as the AMO or the NAO-coupled variability of the gyre circulation as discussed in the literature (i.e., warming in the Gulf Stream and Greenland, Iceland and Norwegian Seas (GIN) seas, but cooling in between; Curry and McCartney, 2001; Eden and Jung, 2001; Sun et al., 2015; Wills et al., 2019).

Differences between the two drought types appear most significantly in the 500 hPa GPH composites. The pattern for 1950s-type droughts exhibits a clear wave pattern, which however does not project well onto the PNA pattern, which is usuallyf defined for winter only. The pattern for „Dust Bowl"“"Dust Bowl"–-type droughts is more zonally symmetric and the wave imprint is weaker. At the same time, a poleward shift of the subtropical jet is found. Upper-air observations and reconstructions for the "Dust Bowl" "Dust Bowl“ drought indicate a poleward-shifted jet over North America (Brönnimann et al., 2009) and the development of a „"„Great Plains ridge"“ (Namias, 1982). The composite of all the "Dust Bowl"-type droughts corresponds well with these findings.

The wave-pattern in 500 hPa GPH over the North Pacific for 1950s-type droughts might be an indication that the relation to Pacific SSTs is stronger. Both types of drought are related to a negative PNA index in the preceding winter and spring period (not shown). There has been some debate as to what extent SST variability modes such as ENSO modify the mode itself or merely excite a „"„fixed"“ pattern (Straus and Shukla, 2002), but a negative PNA index is expected in La Niña winters. Skillful reconstruction of 500 hPa GPH in winter would be necessary to decide whether the difference between the two drought types only emerges in spring and summer or already in the preceding winter. The results of Woodhouse et al. (2009) suggest the latter.

The poleward shift of the jet, in thea zonal average, has also been shown to be related to SSTs (Staten et al., 2018). Again, both Atlantic and Pacific might contribute. In particular, a negative PDO/La Niña like pattern over the Pacific has been shown to contribute conduce to tropical expansion (Allen et al., 2014)). Moreover, – but also the Atlantic SSTs were demonstrated to play a role in the form of a positive (negative) AMO for a poleward (equatorward) shift of the zonal mean jet- or negative for an equatorward shift contribute (Brönnimann et al., 2015). It is thus not surprising that „Dust Bowl““Dust Bowl”--type droughts, with a warmer North Atlantic, have a more poleward shifted jet, although SST differencesdifference in the North Atlantic are not significant.

In all, this suggests that the two patterns of North American drought emerge from slightly different combinations of Atlantic and Pacific influences that operate via a Pacific wave train and a poleward shift of the jet, respectively. Atmospheric circulation and SSTs over both ocean basins, the Pacific and the North Atlantic, shape drought development in North America.

Seager (2007) analyzed the turn of the centuryturn-of-the-century drought (1998-2004) and argued that it started with strong La Niña conditions (1998/99, which is not yet part of our drought definition due to the 5-yr moving average), which that subsequently weakened and gave rise to a second phase (after 2002) with even slight El Niño conditions. Seager (2007) noted that the turn of the centuryturn-of-the-century might not yet be over. It did indeed persist and was predominantly characterized by La Niña conditions interrupted by weak El Niño phases. It ultimately ended with the strong El Niño of 2015/16.

Our analysis shows that the 21st century drought exhibited a markedly different spatial pattern that can be attributed to neither the „Dust Bowl““Dust Bowl”-- nor the 1950s-type drought. While drought conditions in the last two decades have been studied extensively, the focus has been on specific regions and exceptionally severe events like the 2011-2014 California Drought (Griffin and Anchukaitis, 2014; Seager et al., 2014a, 2015). Here we analyze the atmospheric circulation in summer (JJA) from 2000-2015 and find a distinct pattern in both the 500 hPa height and SLP fields. Recent drought events often are found to be associated and amplified with anomalously warm temperatures (e.g., (Griffin and Anchukaitis, 2014). The surface temperature fields show warmer than usual temperatures in the U.S. Southwest as well as a strong warming signal over Arctic Archipelago, Greenland and the northern Atlantic.

Here, we have demonstrated that both the spatial pattern and atmospheric circulation of the 21st century drought differ considerably compared to 16 multi-annual drought periods in the past five centuries. This highlights the likelihood of global warming contributing to the complex drought dynamics, not only amplifying drought duration and severity (Seager and Vecchi, 2010; Woodhouse et al., 2010; Cook et al., 2015, 2018a) but possibly changing the character of droughts in the future.

5 Conclusion

The new global 3-dimensional climate reconstruction EKF400 allows for the first time to study atmospheric circulation during a sufficiently large number of prolonged dry spells in a climate reconstruction. We find two distinct drought types over North America, that differ with respect to atmospheric circulation and SSTs. While the 1950s-type droughts exhibit a wave-train pattern over the Pacific North American sector, the „Dust Bowl““Dust Bowl”--type droughts show the imprint of a poleward shifted jet and a „“„Great Plains ridge“. SSTs exhibit a negative PDO/La Niña-like pattern in the Pacific for both types, but slightly stronger for 1950s-type drought whereas the „Dust

~~Bowl~~"Dust Bowl"-type droughts show a stronger warming of the Atlantic. Differences in SSTs (which are not significant) and differences in atmospheric circulation (which are significant) are consistent with each other and with the literature.

Results suggest that atmospheric circulation and SSTs characteristics over both the Pacific and the extratropical North Atlantic affect the spatial pattern of North American droughts, leading to two main drought types. Given the possible increase of droughts in a future climate, deepening our understanding of drought mechanisms in North America is important. Further refined reconstruction of past climate hydroclimate could help.

Data sets

EKF400

Franke, J., Brönnimann, S., Bhend, J. & Brugnara, Y. World Data Center for Climate at Deutsches Klimarechenzentrum. http://dx.doi.org/10.1594/WDCC/EKF400_v1 (2017).

ERA-Interim

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N. and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. R. Meteorol. Soc., 137(656), 553–597, doi:10.1002/qj.828, 2011.

LBDAv1, LBDAv2

Cook, E. R., Seager, R., Heim, R. R., Vose, R. S., Herweijer, C. and Woodhouse, C. A.: Megadroughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context, J. Quat. Sci., 25(1), 48–61, doi:10.1002/jqs.1303, 2010.

PHYDA

Steiger, N. J., Smerdon, J. E., Cook, E. R. and Cook, B. I.: A reconstruction of global hydroclimate and dynamical variables over the Common Era, Sci. Data, 5, 1–15, doi:10.1038/sdata.2018.86, 2018.

Steiger, N.J. Zenodo https://doi.org/10.5281/zenodo.1154913 (2018).

20CRv2c

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M. C., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, Ø., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D. and Worley, S. J.: The Twentieth Century Reanalysis Project, Q. J. R. Meteorol. Soc., 137(654), 1–28, doi:10.1002/qj.776, 2011.

Berkeley Earth

Rohde, R., A. Muller, R., Jacobsen, R., Muller, E. and Wickham, C.: A New Estimate of the Average Earth Surface Land Temperature Spanning 1753 to 2011, Geoinformatics Geostatistics An Overv., 01(01), 1–7, doi:10.4172/2327-4581.1000101, 2013a.

Rohde, R., Muller, R., Jacobsen, R., Perlmutter, S. and Mosher, S.: Berkeley Earth Temperature Averaging Process, Geoinformatics Geostatistics An Overv., 01(02), 1–13, doi:10.4172/2327-4581.1000103, 2013b.

HadCRUT4.6

Morice, C. P., Kennedy, J. J., Rayner, N. A. and Jones, P. D.: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set, J. Geophys. Res. Atmos., 117(8), D08101, doi:10.1029/2011JD017187, 2012.

Code

Clustering is performed with the following R packages: *hclust{stats}* and *kmeans{stats}*.

The R code for the subtropical jet position is published as supplement to Brönnimann et al. (2015).

Author contribution

SB had the initial idea for this paper. A-MB performed most of the analysis and figure designs with contribution of SB. JF provided the reanalysis data and assisted with interpreting the results. A-MB and SB drafted the manuscript in consultation with JF. All authors provided critical feedback and helped shape the manuscript.

Competing interests

There are no competing interests present.

Acknowledgements

This work was supported by the Swiss National Science Foundation (project 162668 RE-USE) and EU project 787574 (ERC Grant PALAEO-RA).

References

Allen, R. J., Norris, J. R. and Kovilakam, M.: Influence of anthropogenic aerosols and the Pacific Decadal Oscillation on tropical belt width, Nat. Geosci., 7(4), 270–274, doi:10.1038/ngeo2091, 2014.

Ault, T. R., Mankin, J. S., Cook, B. I. and Smerdon, J. E.: Relative impacts of mitigation, temperature, and precipitation on 21st-century megadrought risk in the American Southwest, Sci. Adv., 2(10), 1–9, doi:10.1126/sciadv.1600873, 2016.

Baek, S. H., Smerdon, J. E., Seager, R., Williams, A. P. and Cook, B. I.: Pacific Ocean Forcing and Atmospheric Variability Are the Dominant Causes of Spatially Widespread Droughts in the Contiguous United States, J. Geophys. Res. Atmos., 124(5), 2507–2524, doi:10.1029/2018JD029219, 2019.

Bhend, J., Franke, J., Folini, D., Wild, M. and Brönnimann, S.: An ensemble-based approach to climate reconstructions, Clim. Past, 8(3), 963–976, doi:10.5194/cp-8-963-2012, 2012.

Booth, B. B. B., Dunstone, N. J., Halloran, P. R., Andrews, T. and Bellouin, N.: Aerosols implicated as a prime driver of twentieth-century North Atlantic climate variability, Nature, 484(7393), 228–232, doi:10.1038/nature10946, 2012.

Breitenmoser, P., Brönnimann, S. and Frank, D.: Forward modelling of tree-ring width and comparison with a global network of tree-ring chronologies, Clim. Past, 10(2), 437–449, doi:10.5194/cp-10-437-2014, 2014.

Brönnimann, S.: Climatic Changes Since 1700, Springer International Publishing., 2015.

Brönnimann, S., Stickler, A., Griesser, T., Ewen, T., Grant, A. N., Fischer, A. M., Schraner, M., Peter, T., Rozanov, E. and Ross, T.: Exceptional atmospheric circulation during the "Dust Bowl," Geophys. Res. Lett., 36(8), L08802, doi:10.1029/2009GL037612, 2009.

Brönnimann, S., Griesser, T. and Stickler, A.: A gridded monthly upper-air data set from 1918 to 1957, Clim. Dyn., 38(3–4), 475–493, doi:10.1007/s00382-010-0940-x, 2012.

Brönnimann, S., Fischer, A. M., Rozanov, E., Poli, P., Compo, G. P. and Sardeshmukh, P. D.: Southward shift of the northern tropical belt from 1945 to 1980, Nat. Geosci., 8(12), 969–974, doi:10.1038/ngeo2568, 2015.

Cayan, D. R., Das, T., Pierce, D. W., Barnett, T. P., Tyree, M. and Gershunov, A.: Future dryness in the southwest US and the hydrology of the early 21st century drought, Proc. Natl. Acad. Sci., 107(50), 21271–21276, doi:10.1073/pnas.0912391107, 2010.

Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Matsui, N., Allan, R. J., Yin, X., Gleason, B. E., Vose, R. S., Rutledge, G., Bessemoulin, P., Brönnimann, S., Brunet, M., Crouthamel, R. I., Grant, A. N., Groisman, P. Y., Jones, P. D., Kruk, M. C., Kruger, A. C., Marshall, G. J., Maugeri, M., Mok, H. Y., Nordli, Ø., Ross, T. F., Trigo, R. M., Wang, X. L., Woodruff, S. D. and Worley, S. J.: The Twentieth Century Reanalysis Project, Q. J. R. Meteorol. Soc., 137(654), 1–28, doi:10.1002/qj.776, 2011.

Cook, B. I., Miller, R. L. and Seager, R.: Dust and sea surface temperature forcing of the 1930s "Dust Bowl" drought, Geophys. Res. Lett., 35(8), L08710, doi:10.1029/2008GL033486, 2008.

Cook, B. I., Miller, R. L. and Seager, R.: Amplification of the North American "Dust Bowl" drought through human-induced land degradation, Proc. Natl. Acad. Sci., 106(13), 4997–5001, doi:10.1073/pnas.0810200106, 2009.

Cook, B. I., Seager, R., Miller, R. L. and Mason, J. A.: Intensification of North American Megadroughts through Surface and Dust Aerosol Forcing*, J. Clim., 26(13), 4414–4430, doi:10.1175/JCLI-D-12-00022.1, 2013.

Cook, B. I., Smerdon, J. E., Seager, R. and Coats, S.: Global warming and 21stcentury drying, Clim. Dyn., 43(9–10), 2607–2627, doi:10.1007/s00382-014-2075-y, 2014a.

Cook, B. I., Seager, R. and Smerdon, J. E.: The worst North American drought year of the last millennium: 1934, Geophys. Res. Lett., 41(20), 7298–7305, doi:10.1002/2014GL061661, 2014b.

Cook, B. I., Ault, T. R. and Smerdon, J. E.: Unprecedented 21st century drought risk in the American Southwest and Central Plains, Sci. Adv., 1(1), e1400082, doi:10.1126/sciadv.1400082, 2015.

Cook, B. I., Cook, E. R., Smerdon, J. E., Seager, R., Williams, A. P., Coats, S., Stahle, D. W. and Díaz, J. V.: North American megadroughts in the Common Era: Reconstructions and simulations, Wiley Interdiscip. Rev. Clim. Chang., 7(3), 411–432, doi:10.1002/wcc.394, 2016.

Cook, B. I., Mankin, J. S. and Anchukaitis, K. J.: Climate Change and Drought: From Past to Future, Curr. Clim. Chang. Reports, 4(2), 164–179, doi:10.1007/s40641-018-0093-2, 2018a.

Cook, B. I., Park Williams, A., Mankin, J. S., Seager, R., Smerdon, J. E. and Singh, D.: Revisiting the leading drivers of Pacific coastal drought variability in the contiguous United States, J. Clim., 31(1), 25–43, doi:10.1175/JCLI-D-17-0172.1, 2018b.

Cook, E. R., Meko, D. M., Stahle, D. W. and Cleaveland, M. K.: Tree-ring reconstructions of past drought across the conterminous United States: tests of a regression method and calibration/verification results, in Proceedings of the International Conference, Radiocarbon, edited by J. S. Dean, D. M. Meko, and T. W. Swetnam, pp. 155–169, Tuscon., 1996.

Cook, E. R., Meko, D. M., Stahle, D. W. and Cleaveland, M. K.: Drought reconstructions for the continental United States, J. Clim., 12(4), 1145–1163, doi:10.1175/1520-0442(1999)012<1145:DRFTCU>2.0.CO;2, 1999.

Cook, E. R., Woodhouse, C. A., Eakin, C. M., Meko, D. M. and Stahle, D. W.: Long-Term Aridity Changes in the Western United States, Science (80-.)., 306(5698), 1015–1018, doi:10.1126/science.1102586, 2004.

Cook, E. R., Seager, R., Cane, M. A. and Stahle, D. W.: North American drought: Reconstructions, causes, and consequences, Earth-Science Rev., 81(1–2), 93–134, doi:10.1016/j.earscirev.2006.12.002, 2007.

Cook, E. R., Seager, R., Heim, R. R., Vose, R. S., Herweijer, C. and Woodhouse, C. A.: Megadroughts in North America: placing IPCC projections of hydroclimatic change in a long-term palaeoclimate context, J. Quat. Sci., 25(1), 48–61, doi:10.1002/jqs.1303, 2010.

Cowan, T., Hegerl, G. C., Colfescu, I., Bollasina, M., Purich, A. and Boschat, G.: Factors contributing to record-breaking heat waves over the great plains during the 1930s Dust Bowl, J. Clim., 30(7), 2437–2461, doi:10.1175/JCLI-D-16-0436.1, 2017.

Curry, R. G. and McCartney, M. S.: Ocean Gyre Circulation Changes Associated with the North Atlantic Oscillation*, J. Phys. Oceanogr., 31(12), 3374–3400, doi:10.1175/1520-0485(2001)031<3374:OGCCAW>2.0.CO;2, 2001.

Dai, A.: Increasing drought under global warming in observations and models, Nat. Clim. Chang., 3(1), 52–58, doi:10.1038/nclimate1633, 2013.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N. and Vitart, F.: The ERA-Interim reanalysis: configuration and performance of the data assimilation system, Q. J. R. Meteorol. Soc., 137(656), 553–597, doi:10.1002/qj.828, 2011.

Eden, C. and Jung, T.: North Atlantic Interdecadal Variability: Oceanic Response to the North Atlantic Oscillation (1865–1997), J. Clim., 14(5), 676–691, doi:10.1175/1520-0442(2001)014<0676:NAIVOR>2.0.CO;2, 2001.

Enfield, D. B., Mestas-Nuñez, A. M. and Trimble, P. J.: The Atlantic Multidecadal Oscillation and its relation to rainfall and river flows in the continental U.S., Geophys. Res. Lett., 28(10), 2077–2080, doi:10.1029/2000GL012745, 2001.

Feng, S., Oglesby, R. J., Rowe, C. M., Loope, D. B. and Hu, Q.: Atlantic and Pacific SST influences of medieval drought in North America simulated by the Community Atmospheric Model, J. Geophys. Res. Atmos., 113(11), doi:10.1029/2007JD009347, 2008.

Franke, J., Frank, D., Raible, C. C., Esper, J. and Brönnimann, S.: Spectral biases in tree-ring climate proxies, Nat. Clim. Chang., 3(4), 360–364, doi:10.1038/nclimate1816, 2013.

Franke, J., Brönnimann, S., Bhend, J. and Brugnara, Y.: A monthly global paleo-reanalysis of the atmosphere from 1600 to 2005 for studying past climatic variations, Sci. Data, 4, 1–19, doi:10.1038/sdata.2017.76, 2017.

Fye, F. K., Stahle, D. W. and Cook, E. R.: Paleoclimatic analogs to twentieth-century moisture regimes across the United States, Bull. Am. Meteorol. Soc., 84(7), 901–909+872, doi:10.1175/BAMS-84-7-901, 2003.

Griesser, T., Brönnimann, S., Grant, A., Ewen, T., Stickler, A. and Comeaux, J.: Reconstruction of global monthly upper-level temperature and geopotential height fields back to 1880, J. Clim., doi:10.1175/2010JCLI3056.1, 2010.

Griffin, D. and Anchukaitis, K. J.: How unusual is the 2012-2014 California drought?, Geophys. Res. Lett., 41(24), 9017–9023, doi:10.1002/2014GL062433, 2014.

Herweijer, C., Seager, R. and Cook, E. R.: North American droughts of the mid to late nineteenth century: A history, simulation and implication for Mediaeval drought, Holocene, 16(2), 159–171, doi:10.1191/0959683606hl917rp, 2006.

Hoerling, M., Quan, X. W. and Eischeidi, J.: Distinct causes for two principal U.S. droughts of the 20th century, Geophys. Res. Lett., 36(19), 1–6, doi:10.1029/2009GL039860, 2009.

Hoerling, M. P.: The Perfect Ocean for Drought, Science (80-.)., 299(5607), 691–694, doi:10.1126/science.1079053, 2003.

Hoerling, M. P., Eischeid, J. K., Quan, X. W., Diaz, H. F., Webb, R. S., Dole, R. M. and Easterling, D. R.: Is a transition to semipermanent drought conditions imminent in the U.S. great plains?, J. Clim., 25(24), 8380–8386, doi:10.1175/JCLI-D-12-00449.1, 2012.

Hoerling, M. P., Eischeid, J., Kumar, A., Leung, R., Mariotti, A., Mo, K., Schubert, S. D. and Seager, R.: Causes and predictability of the 2012 great plains drought, Bull. Am. Meteorol. Soc., 95(2), 269–282, doi:10.1175/BAMS-D-13-00055.1, 2014.

Kushnir, Y., Seager, R., Ting, M., Naik, N. and Nakamura, J.: Mechanisms of Tropical Atlantic SST Influence on North American Precipitation Variability*, J. Clim., 23(21), 5610–5628, doi:10.1175/2010JCLI3172.1, 2010.

Livneh, B. and Hoerling, M. P.: The Physics of Drought in the U.S. Central Great Plains, J. Clim., 29(18), 6783–6804, doi:10.1175/JCLI-D-15-0697.1, 2016.

Mann, M. E., Woodruff, J. D., Donnelly, J. P. and Zhang, Z.: Atlantic hurricanes and climate over the past 1,500 years, Nature, 460(7257), 880–883, doi:10.1038/nature08219, 2009.

McCabe, G. J., Palecki, M. A. and Betancourt, J. L.: Pacific and Atlantic Ocean influences on multidecadal drought frequency in the United States, Proc. Natl. Acad. Sci., 101(12), 4136–4141, doi:10.1073/pnas.0306738101, 2004.

Morice, C. P., Kennedy, J. J., Rayner, N. A. and Jones, P. D.: Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set, J. Geophys. Res. Atmos., 117(8), D08101, doi:10.1029/2011JD017187, 2012.

Namias, J.: Anatomy of Great Plains Protracted Heat Waves (especially the 1980 U.S. summer drought), Mon. Weather Rev., 110(7), 824–838, doi:10.1175/1520-0493(1982)110<0824:AOGPPH>2.0.CO;2, 1982.

Nigam, S., Guan, B. and Ruiz-Barradas, A.: Key role of the Atlantic Multidecadal Oscillation in 20th century drought and wet periods over the Great Plains, Geophys. Res. Lett., 38(16), n/a-n/a, doi:10.1029/2011GL048650, 2011.

Pu, B., Fu, R., Dickinson, R. E. and Fernando, D. N.: Why do summer droughts in the Southern Great Plains occur in some La Niña years but not others?, J. Geophys. Res. Atmos., 121(3), 1120–1137, doi:10.1002/2015JD023508, 2016.

Rimbu, N., Lohmann, G. and Ionita, M.: Interannual to multidecadal Euro-Atlantic blocking variability during winter and its relationship with extreme low temperatures in Europe, J. Geophys. Res. Atmos., 119(24), 13,621-13,636, doi:10.1002/2014JD021983, 2014.

Rohde, R., A. Muller, R., Jacobsen, R., Muller, E. and Wickham, C.: A New Estimate of the Average Earth Surface Land Temperature Spanning 1753 to 2011, Geoinformatics Geostatistics An Overv., 01(01), 1–7, doi:10.4172/2327-4581.1000101, 2013a.

Rohde, R., Muller, R., Jacobsen, R., Perlmutter, S. and Mosher, S.: Berkeley Earth Temperature Averaging Process, Geoinformatics Geostatistics An Overv., 01(02), 1–13, doi:10.4172/2327-4581.1000103, 2013b.

Routson, C. C., Woodhouse, C. A., Overpeck, J. T., Betancourt, J. L. and McKay, N. P.: Teleconnected ocean forcing of Western North American droughts and pluvials during the last millennium, Quat. Sci. Rev., 146, 238–250, doi:10.1016/j.quascirev.2016.06.017, 2016.

Schubert, S., Gutzler, D., Wang, H., Dai, A., Delworth, T., Deser, C., Findell, K., Fu, R., Higgins, W., Hoerling, M., Kirtman, B., Koster, R., Kumar, A., Legler, D., Lettenmaier, D., Lyon, B., Magana, V., Mo, K., Nigam, S., Pegion, P., Phillips, A., Pulwarty, R., Rind, D., Ruiz-Barradas, A., Schemm, J., Seager, R., Stewart, R., Suarez, M., Syktus, J., Ting, M., Wang, C., Weaver, S. and Zeng, N.: A U.S. CLIVAR Project to Assess and Compare the Responses of Global Climate Models to Drought-Related SST Forcing Patterns: Overview and Results, J. Clim., 22(19), 5251–5272, doi:10.1175/2009JCLI3060.1, 2009.

Schubert, S. D., Suarez, M. J., Pegion, P. J., Koster, R. D. and Bacmeister, J. T.: Causes of Long-Term Drought in the U.S. Great Plains, J. Clim., 17(3), 485–503, doi:10.1175/1520-0442(2004)017<0485:COLDIT>2.0.CO;2, 2004a.

Schubert, S. D., Suarez, M. J., Pegion, P. J., Koster, R. D. and Bacmeister, J. T.: On the Cause of the 1930s Dust Bowl, Science (80-.)., 303(5665), 1855–1859, doi:10.1126/science.1095048, 2004b.

Seager, R.: The Turn of the Century North American Drought: Global Context, Dynamics, and Past Analogs*, J. Clim., 20(22), 5527–5552, doi:10.1175/2007JCLI1529.1, 2007.

Seager, R. and Hoerling, M. P.: Atmosphere and ocean origins of North American droughts, J. Clim., 27(12), 4581–4606, doi:10.1175/JCLI-D-13-00329.1, 2014.

Seager, R. and Vecchi, G. A.: Greenhouse warming and the 21st century hydroclimate of southwestern North America, Proc. Natl. Acad. Sci., 107(50), 21277–21282, doi:10.1073/pnas.0910856107, 2010.

Seager, R., Kushnir, Y., Herweijer, C., Naik, N. and Velez, J.: Modeling of Tropical Forcing of Persistent Droughts and Pluvials over Western North America: 1856–2000*, J. Clim., 18(19), 4065–4088, doi:10.1175/JCLI3522.1, 2005.

Seager, R., Ting, M., Held, I., Kushnir, Y., Lu, J., Vecchi, G., Huang, H.-P., Harnik, N., Leetmaa, A., Lau, N.-C., Li, C., Velez, J. and Naik, N.: Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America, Science (80-.)., 316(5828), 1181–1184, doi:10.1126/science.1139601, 2007.

Seager, R., Tzanova, A. and Nakamura, J.: Drought in the Southeastern United States: Causes, variability over the last millennium, and the potential for future hydroclimate change, J. Clim., 22(19), 5021–5045, doi:10.1175/2009JCLI2683.1, 2009.

Seager, R., Hoerling, M. P., Schubert, S. D., Wang, H., Lyon, B. and Nakamura, J.: Causes and Predictability of the 2011-14. California Drought Assessment Report., 2014a.

Seager, R., Goddard, L., Nakamura, J., Henderson, N. and Lee, D. E.: Dynamical Causes of the 2010/11 Texas–Northern Mexico Drought, J. Hydrometeorol., 15(1), 39–68, doi:10.1175/JHM-D-13-024.1, 2014b.

Seager, R., Hoerling, M. P., Schubert, S. D., Wang, H., Lyon, B., Kumar, A., Nakamura, J. and Henderson, N.: Causes of the 2011-14 California drought, J. Clim., 28(18), 6997–7024, doi:10.1175/JCLI-D-14-00860.1, 2015.

Stahle, D. W., Fye, F. K., Cook, E. R. and Griffin, R. D.: Tree-ring reconstructed megadroughts over North America since a.d. 1300, Clim. Change, 83(1–2), 133–149, doi:10.1007/s10584-006-9171-x, 2007.

Staten, P. W., Lu, J., Grise, K. M., Davis, S. M. and Birner, T.: Re-examining tropical expansion, Nat. Clim. Chang., 8(9), 768–775, doi:10.1038/s41558-018-0246-2, 2018.

Steiger, N. J., Smerdon, J. E., Cook, E. R. and Cook, B. I.: A reconstruction of global hydroclimate and dynamical variables over the Common Era, Sci. Data, 5, 1–15, doi:10.1038/sdata.2018.86, 2018.

Straus, D. M. and Shukla, J.: Does ENSO Force the PNA?, J. Clim., 15(17), 2340–2358, doi:10.1175/1520-0442(2002)015<2340:DEFTP>2.0.CO;2, 2002.

Sun, C., Li, J. and Jin, F.-F.: A delayed oscillator model for the quasi-periodic multidecadal variability of the NAO, Clim. Dyn., 45(7–8), 2083–2099, doi:10.1007/s00382-014-2459-z, 2015.

Wallace, J. M. and Gutzler, D. S.: Teleconnections in the Geopotential Height Field during the Northern Hemisphere Winter, Mon. Weather Rev., 109(4), 784–812, doi:10.1175/1520-0493(1981)109<0784:TITGHF>2.0.CO;2, 1981.

Weiss, J. L., Castro, C. L. and Overpeck, J. T.: Distinguishing pronounced droughts in the southwestern united states: Seasonality and effects of warmer temperatures, J. Clim., 22(22), 5918–5932, doi:10.1175/2009JCLI2905.1, 2009.

Wills, R. C. J., Armour, K. C., Battisti, D. S. and Hartmann, D. L.: Ocean–Atmosphere Dynamical Coupling Fundamental to the Atlantic Multidecadal Oscillation, J. Clim., 32(1), 251–272, doi:10.1175/JCLI-D-18-0269.1, 2019.

Woodhouse, C. A. and Overpeck, J. T.: 2000 Years of Drought Variability in the Central United States, Bull. Am. Meteorol. Soc., 79(12), 2693–2714, doi:10.1175/1520-0477(1998)079<2693:YODVIT>2.0.CO;2, 1998.

Woodhouse, C. A., Russell, J. L. and Cook, E. R.: Two Modes of North American Drought from Instrumental and Paleoclimatic Data*, J. Clim., 22(16), 4336–4347, doi:10.1175/2009JCLI2705.1, 2009.

Woodhouse, C. A., Meko, D. M., MacDonald, G. M., Stahle, D. W. and Cook, E. R.: A 1,200-year perspective of 21st century drought in southwestern North America, Proc. Natl. Acad. Sci., 107(50), 21283–21288, doi:10.1073/pnas.0911197107, 2010.

Worster, D.: Dust Bowl: The Southern Plains in the 1930s, Oxford University Press, Oxford., 1979.

Figures

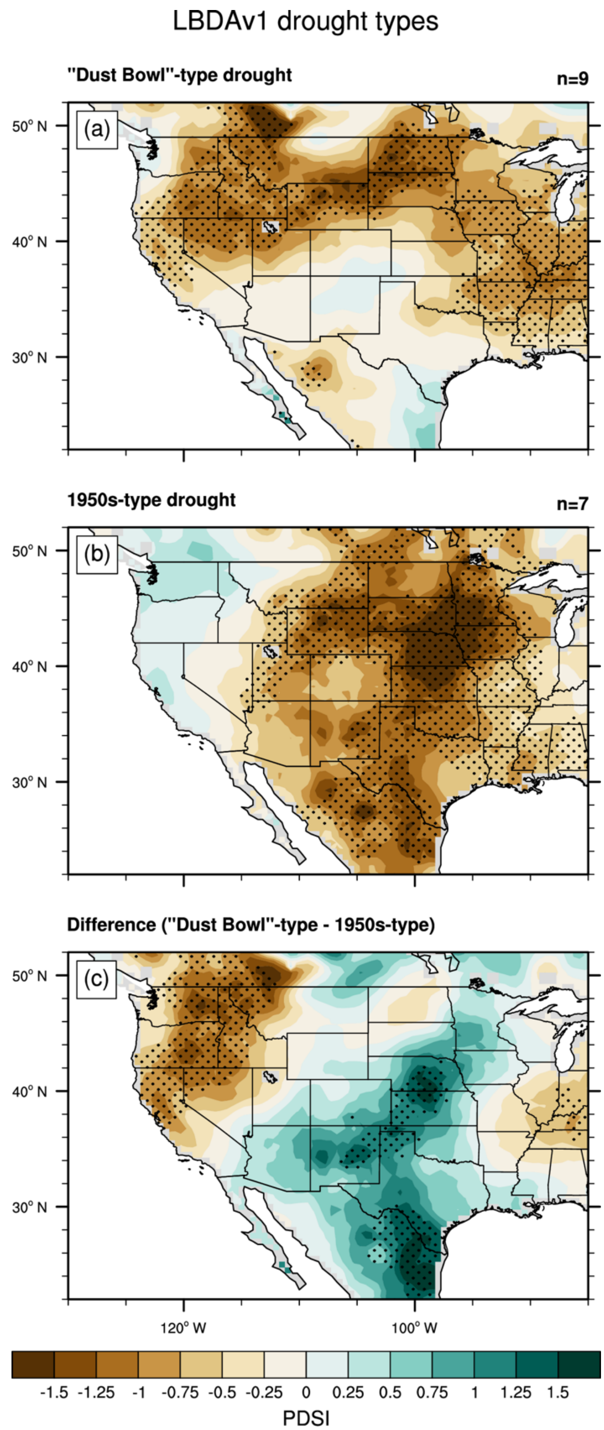

Figure 1: Averaged PDSI values from LBDAv1 for ~~„Dust Bowl“~~“Dust Bowl”-~~-~~type droughts (a) and 1950s-type droughts (b) since 1600. The difference between “Dust Bowl”- and 1950s-type is shown in (c). Stippling indicates significance at the 95% level based on a non-parametric Wilcoxon-Mann-Whitney test.~~.~~

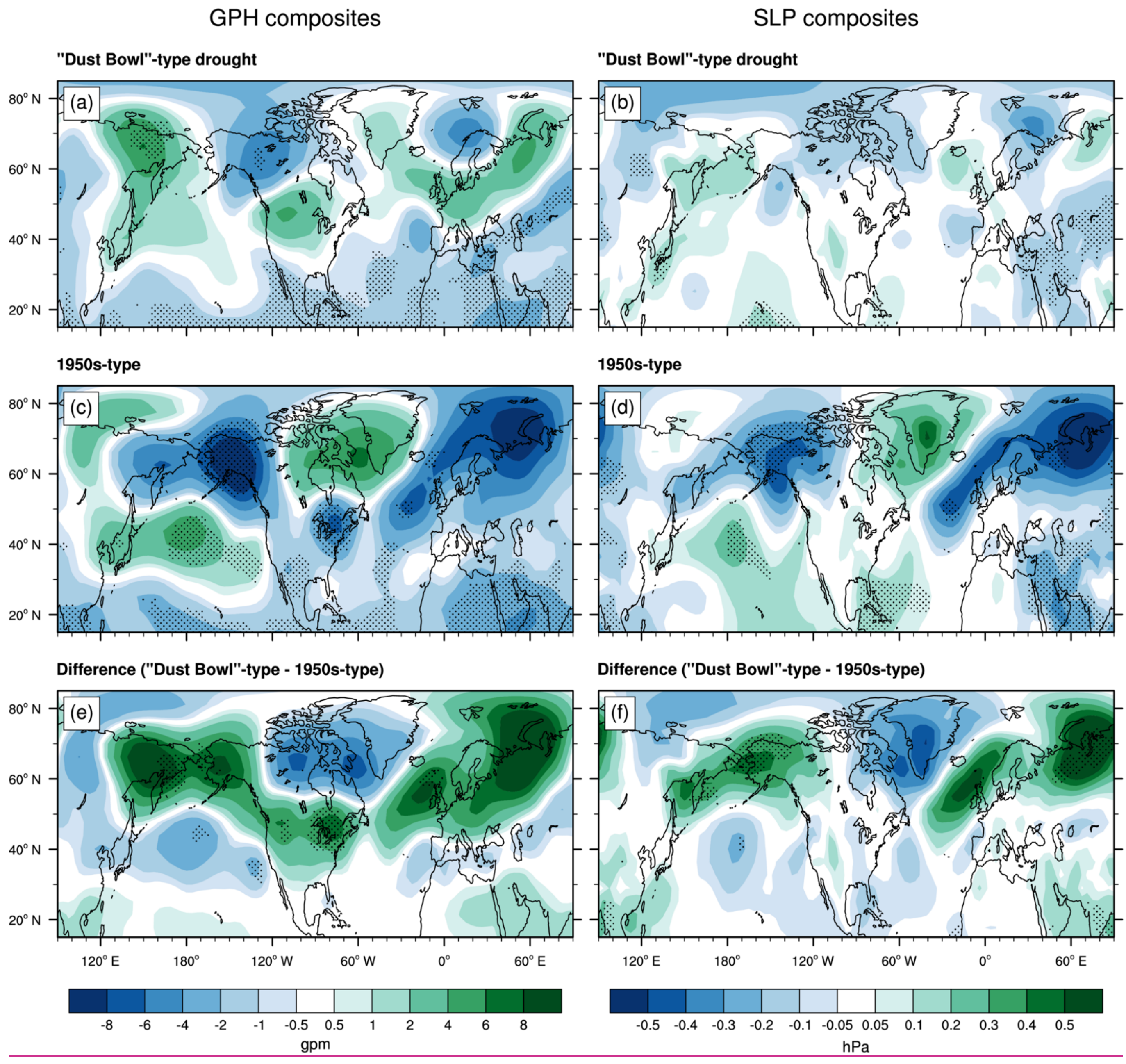

Figure 2: Composites of 500 hPa geopotential height anomalies (left column) and sea-level pressure anomalies (right column) from EKF400 for ~~„Dust Bowl“~~“Dust Bowl”-–type droughts (top row), 1950s-type droughts (middle row) and their difference (bottom row). Stippling indicates significance ($p<0.05$) based on a non-parametric Wilcoxon-Mann-Whitney test.

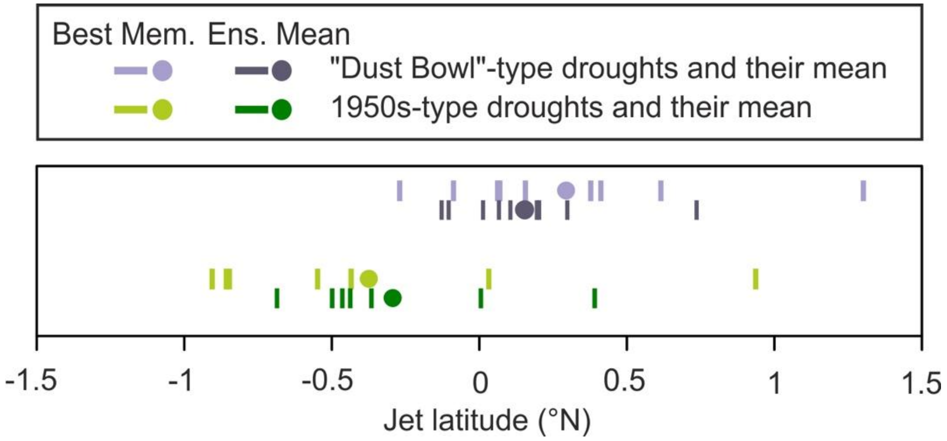

Figure 3: Changes in the position of the subtropical jet over North America for "Dust Bowl"- type droughts (purple) and 1950s-type droughts (green). Anomalies are relative to the preceding and following 5-year period of the drought. ~~are~~ Lines indicate individual drought periods, the circle indicates the drought-type mean.

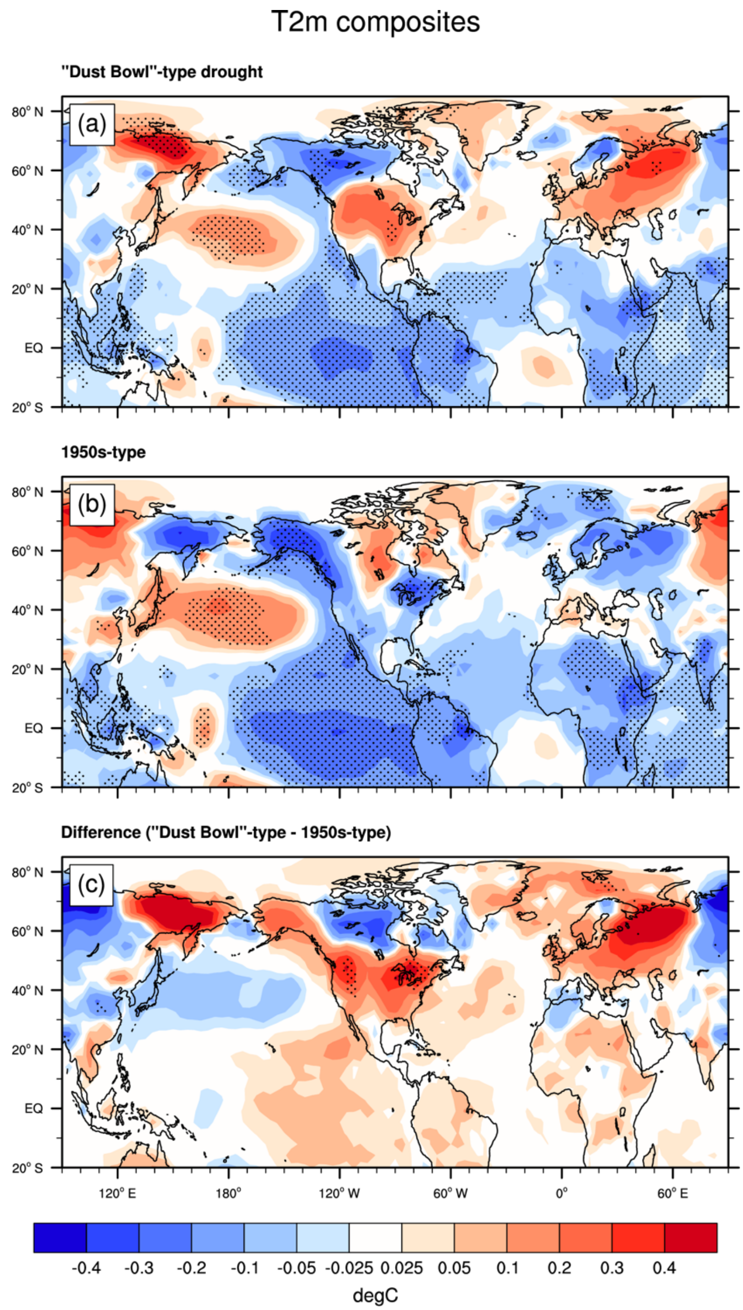

Figure 4: Composites of ~~surface~~ 2-meter~~air~~ temperature from EKF400 for ~~„Dust Bowl“~~“Dust Bowl”-~~-~~type ~~(a)~~ droughts (a), 1950s-type droughts (b) and their difference (c). Stippling indicates significance ($p<0.05$) based on a non-parametric Wilcoxon-Mann-Whitney test.

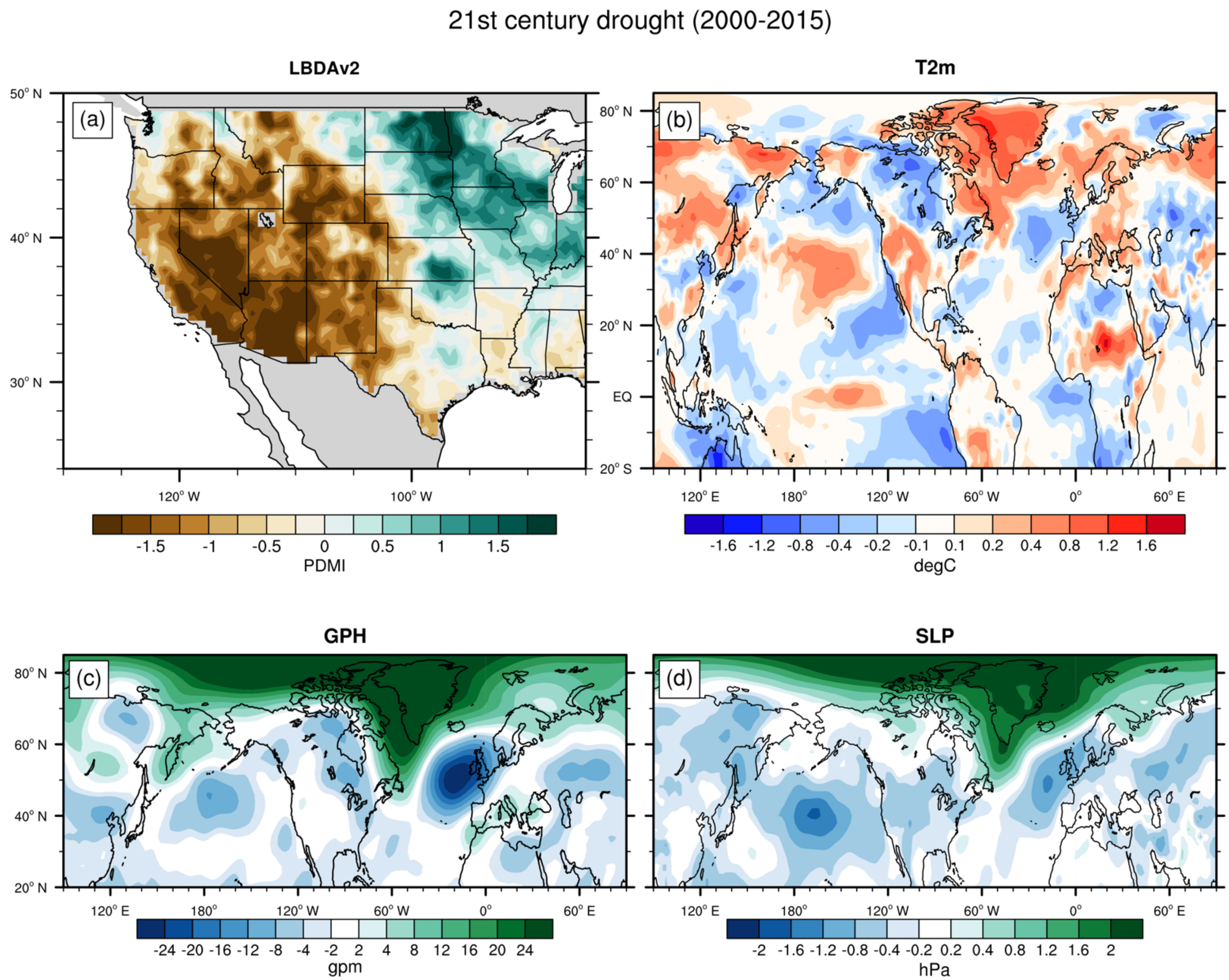

Figure 5: The 21st century drought (2000-2015) in the PMDI of the LBDAv2 (a), composites relative to the preceding 5-year period and the following 3-year period (only 2016-2018 available) of 2-meter temperature (T2m) (b), – of 500 hPa geopotential height (GPH) (b)(bc) and,, sea-level pressure (SLP) (d) and air temperature (T2m) (c) fromfrom the ERA-Interim reanalysis.

Tables

Table 1: Drought periods since 1600 based on clustering with LBDAv1, drought duration and attribution to cluster.

#	LBDA Drought Periods	$N_{\text{drought years}}$	Clustering
17	2000 – 2005	5	–
16	1952 – 1965	14	1950s-type
15	1931 – 1939	9	"Dust Bowl"-type
14	1892 – 1896	5	1950s-type
13	1869 – 1874	6	"Dust Bowl"-type
12	1855 – 1866	12	1950s-type
11	1817 – 1824	8	1950s-type
10	1783– 1791	9	1950s-type
9	1772– 1776	5	"Dust Bowl"-type
8	1753 – 1758	6	"Dust Bowl"-type
7	1734 – 1743	10	1950s-type
6	1716 – 1720	5	"Dust Bowl"-type
5	1703 – 1710	8	"Dust Bowl"-type
4	1663 – 1671	9	1950s-type
3	1652 – 1656	5	"Dust Bowl"-type
2	1644 – 1648	5	"Dust Bowl"-type
1	1624 – 1634	11	"Dust Bowl"-type