



From 20,000 Years Ago to Near Present Climate Classification of North America

RESEARCH PAPER

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ABSTRACT

Climate classification allows an efficient encapsulation of climate data into climate units. For North America and most of Central America during 20, 14, 13, 11, 10, 7, 5, and 1 thousand years ago (ka) and recent years, I applied a Köppen-Trewartha classification system, but with dry classes subsumed under primary thermal classes to preserve information. The boreal and polar classes decreased from a combined 70% of area during 20 ka until reaching 42% of area at 7 ka, after which the area remained relatively stable. Conversely, the subtropical and temperate classes increased from 25% of area until reaching 53% of area at 7 ka, with slight increase of the tropical class. The combined dry subclasses increased from 7.5% to 15% of area, primarily in the subtropical and temperate classes, displaying unique trends over time. Based on ordination, the classes since 5 ka are similar; the 1950 interval is most similar to 1 and 5 ka and the intervals of 1600 and 1800 are most similar. The climate classes and transitions generally corresponded with major vegetation distributions. Visually, political boundaries appeared to parallel climate classes, which might indicate the influence of long-standing ecological differences on human land use and settlement. A future research need is identifying the influence of climate on directing settlement and political boundary establishment.

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KEYWORDS:

biomes; ecosystems; forest; historical; Köppen-Trewartha; landscape memory; Last Glacial Maximum

TO CITE THIS ARTICLE:

Hanberry, BB. 2022. From 20,000 Years Ago to Near Present Climate Classification of North America. *Open Quaternary*, 8: 11, pp. 1–11. DOI: <https://doi.org/10.5334/oq.116>

INTRODUCTION

Modeled climate data of the past can complement climate reconstructions and inform parallel (paleo) historical research. To compress climate data, climate classification systems convey temperature, precipitation, and separation between wet and dry climates into comprehensible ecological units. Guetter and Kutzbach (1990) may have been the first to use simulated climate of the past in a Köppen (1884) climate classification system, for 18 thousand years ago (ka) to the present at 3000-year intervals and at 126 ka, the previous interglacial period. They acknowledged the problems intrinsic to extremely coarse spatial resolution of 4 degrees latitude by 7.5 degrees longitude for a climate simulation with identified deficiencies in temperature and precipitation patterns. At 18 ka, 45% of land surface had climate classifications different from the present; 30% of land surface never changed in climate classification from the present, with core areas that encompassed the Amazon Basin, the northern Sahara, and Australia.

General circulation models have improved with time and spatial resolution has become finer since early research. Yoo and Rohli (2016) and Willmes et al. (2017) developed global Köppen-Geiger climate maps of the Last Glacial Maximum of 21 ka, 6 ka, and the present, which were the available time slices. Zhang et al. (2012) generate climate classifications for Asia 50 million years ago.

New paleoclimate data sets continue to become operational, and one is the TraCE-21000 simulation (He et al. 2010; He et al. 2013), a 22,000-year transient simulation generated from the Community Climate System Model (Liu et al. 2009). The Community Climate System Model was forced by prescribed trends in orbital parameters, ice sheet extent and height, sea level, greenhouse gases, and meltwater pulses to the North Atlantic. Both the TraCE-21000 simulation and the Community Climate System Model temperature progressions were able to simulate major features of the deglacial paleoclimate reconstructions in Greenland and the Antarctic (Liu et al. 2009; He et al. 2013). Using climate data from the simulations, Lorenz et al. (2016a, b) published decadal averages of monthly data from 21 ka to the 1900s for North America after spatially downscaling through bilinear interpolation to 0.5° resolution. To debias the variables, Lorenz et al. (2016a, b) used the standard change factor approach to calculate the difference between modeled climate and present observed climate followed by applying the change factor to the models (Wilby et al. 2004).

In addition to climate data, climate classifications have changed over time. Köppen (1884) developed the first and most widely used climate classification for primary thermal classes of tropical, temperate, cold, and polar classes and an arid class, all of which

have additional subclasses (Belda 2014). Trewartha (1968) modified the Köppen thermal classifications into tropical, subtropical, temperate, boreal, and polar primary classes, with a 0°C coldest month isotherm between the subtropical and temperate classes instead of -3°C coldest month isotherm between temperate and cold classes (Belda 2014). The 0°C isotherm has a better foundation ecologically, as for example, growing degree days typically are calculated with either a base of 0°C or 5°C. Bailey (1995) separated the temperate class into warm and hot summer subclasses for North America.

Slight modification of the climate classification will increase the information contained in the climate classes, at least by region (Guetter & Kutzbach 1990). Primarily, thermal information is lost by grouping all dry climates together into an arid class, rather than dividing the primary thermal class into dry subclasses. When the thermal class information is discarded, it is not possible to measure change in thermal classes over time. Secondly, large boreal and polar extents occur in North America, but the classification system does not subdivide each of these classes. Although not very populated, these areas have received close attention for rapid warming response to climate change. Thus, the number of months at 5°C, a critical temperature for plant and insect growth, creates an equal and useful split. Additionally, some subclasses have low abundance in North America, such as the tropical rainforest subclass, and it may be helpful to condense the number of less abundant subclasses to preserve the value of rapid visual assimilation, despite loss of precipitation or temperature information.

My objective was to assess changing climate classifications from 20,000 years ago to the recent past (1950–1989) for North America. I focused on intervals of 1950–1989 (hereafter 1950), 1850–1899 (1850), 1800–1849 (1800), 1600–1699 (1600), 950–1049 (1000), and two-hundred-year intervals centered on 5, 7, 10, 11, 13, 14, and 20 thousand years ago. The interval between 1800–1899 is a time of recent dryness and cold, with historical accounts of tree increases and expansion, while 1600–1699 is a period of Euro-American exploration and initial settlement of North America. The interval around 1000 is part of the Medieval Warm Period and by about 5 to 7 ka, analogous ecosystems to current ecosystems established (Delcourt & Delcourt 1993; Dyke 2005). The interval between 10 to 14 ka was a time of rapid change from warming during the Bølling-Allerød (approximately 14.6 to 12.9 ka) to cooling during the Younger Dryas (12.9 to 11.7 ka), and 20 ka was during the Last Glacial Maximum (He et al. 2010). Formally, research questions were (1) did thermal class area become relatively stable, (2) have dry subclasses remained stable, and (3) what was the class similarity of the time intervals? I additionally compared the climate classes to pollen reconstructions because climate classes generally accord with optimal thermal

ranges of dominant vegetation, although vegetation response lags behind climate (Denk et al. 2013).

METHODS

For climate data, I extracted monthly minimum temperature, maximum temperature, and total precipitation from Lorenz et al. (2016a, b) for the twelve time intervals: 1950–1989, 1850–1899, 1800–1849, 1600–1699, 950–1049, and two hundred-year intervals centered on 5, 7, 10, 11, 13, 14, and 20 ka. Monthly mean temperature was calculated as the mean of the monthly minimum and maximum temperatures and then I calculated number of months above different temperature thresholds. I summed mean monthly total precipitation to determine mean annual precipitation and also determined arid classes using Patton's (1962) boundaries of arid climates, defined as $R = 2.3T - 0.64Pw + 41$, where Pw is percentage of annual precipitation during six winter or cooler months and T is mean annual temperature.

Although I followed the climate classification rules from Bailey (1995) and Belda (2014), I made a few

small revisions (Table 1; Figure 1). Instead of removing thermal classes for arid classes, all thermal classes were retained and subclasses for thermal classes were defined by aridity. Due to large extents of boreal and polar classes in North America, I used the number of months $\geq 5^\circ\text{C}$ to subdivide each class. To validate this subdivision, I compared the class subdivisions to the North American Land Change Monitoring System 2005 North American land cover (Commission for Environmental Cooperation 2022). The last modification was a combination of rare subclasses, which may be abundant globally but not in North America, with the primary thermal class.

After visualization, I clipped the climate classes to current land area and projected to North America Albers equal conic area in order to summarize by area. I performed a non-metric multidimensional scaling ordination of the class percentage of area for each time interval with the Bray-Curtis distance, which allows display of (dis)similarity (Minchin 1987; Goslee and Urban 2007; R Core Team 2021). Additionally, to examine stability over time, I determined mean value by class of minimum and maximum temperature and total precipitation.

CLIMATE CLASSES	LETTER	RULESET
<i>Tropical</i>	A	all months $\geq 18^\circ\text{C}$
Tropical dry	ADr	mean annual precipitation $< (2.3T - 0.64Pw + 41)^a$
Subtropical	C	8–12 months $\geq 10^\circ\text{C}$
Subtropical steppe	CS	mean annual precipitation $< 0.5 \cdot (2.3T - 0.64Pw + 41)^a$
Subtropical desert	CD	mean annual precipitation $\geq 0.5 \cdot (2.3T - 0.64Pw + 41)^a$
<i>Temperate</i>	D	4–7 months $\geq 10^\circ\text{C}$
Temperate hot	Dca	warmest month $\geq 22^\circ\text{C}$
Temperate hot dry	DcaDr	mean annual precipitation $< (2.3T - 0.64Pw + 41)^a$
Temperate warm dry	Dcb	coldest month $< 0^\circ\text{C}$, warmest month $< 22^\circ\text{C}$
Temperate warm dry	DcbDr	mean annual precipitation $< (2.3T - 0.64Pw + 41)^a$
<i>Boreal</i>	E	1–3 months $\geq 10^\circ\text{C}$
Boreal cold	Ey	5–12 months $\geq 5^\circ\text{C}$
Boreal cold dry	EyDr	mean annual precipitation $< (2.3T - 0.64Pw + 41)^a$
Boreal coldest	Ez	0–4 months $\geq 5^\circ\text{C}$
Boreal coldest dry	EzDr	mean annual precipitation $< (2.3T - 0.64Pw + 41)^a$
<i>Polar</i>	F	all months $< 10^\circ\text{C}$
Polar cold	Fy	2–12 months $\geq 5^\circ\text{C}$
Polar cold dry	FyDr	mean annual precipitation $< (2.3T - 0.64Pw + 41)^a$
Polar coldest	Fz	0–1 months $\geq 5^\circ\text{C}$
Polar coldest dry	FzDr	mean annual precipitation $< (2.3T - 0.64Pw + 41)^a$

Table 1 Climate classes for North America, with revision to keep thermal classes for arid classes and subdivide large boreal and polar extents.

^a T = mean annual temperature, Pw = % annual precipitation in six winter months.

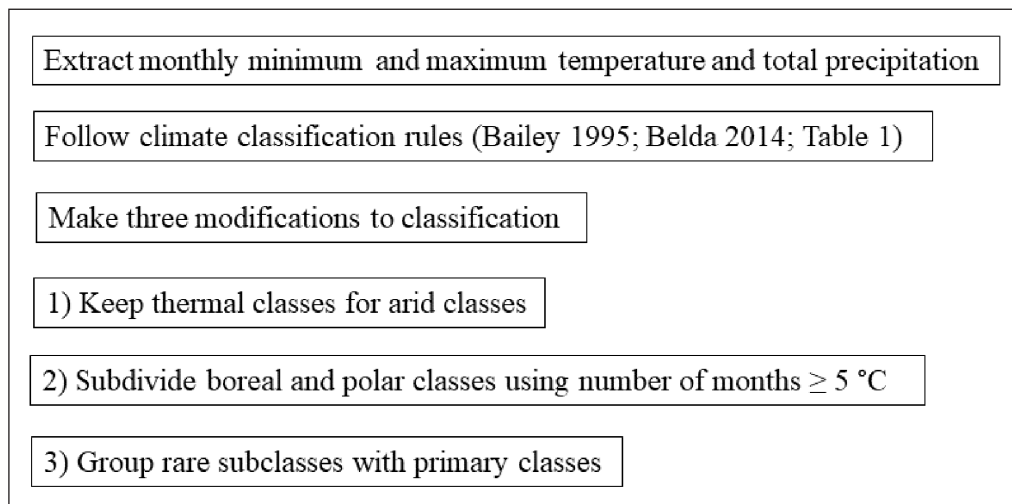


Figure 1 Workflow, with minor modifications to climate classification.

CLASS	MIXED FOREST	WETLAND	TEMPERATE OR SUB-POLAR ECOSYSTEMS	SUB-POLAR TAIGA NEEDLELEAF FOREST	SUB-POLAR OR POLAR LICHEN-MOSS	BARREN, SNOW, AND ICE
Ey	16.6	8.4	67.0	5.0	0.8	2.1
Ez	7.4	4.7	45.9	11.8	26.4	3.7
Fy	0.8	0.9	11.7	1.1	64.6	20.9
Fz	0.0	0.3	0.5	0.0	29.4	69.7

Table 2 Land cover (percentage) of the boreal cold (Ey), boreal coldest (Ez), polar cold (Fy), and polar coldest (Fz) climate classes.

RESULTS

Subdivision of the large extents of boreal and polar classes in North America resulted in very different vegetation in each subclass, according to the 2005 North American land cover (Commission for Environmental Cooperation 2022; Table 2). The boreal cold (Ey) subclass predominantly consisted of temperate or sub-polar ecosystems (67%) with <1% sub-polar or polar lichen-moss, whereas the boreal coldest (Ez) contained 46% temperate or sub-polar ecosystems with progression to 26% sub-polar or polar lichen-moss. The polar cold (Fy) subclass primarily consisted of sub-polar or polar lichen-moss (65%) with progression to 21% barren, snow, and ice cover, whereas the polar coldest (Fz) was largely (70%) barren, snow, and ice cover.

Steady change occurred in the climate classes between 20 ka and 14 ka, followed by rapid change between 14 ka and 10 ka, then modest change (Figures 2 and 3). An ordination of (dis)similarity based on ecological distance of the climate class proportions indicated that the selected time intervals between 20 ka and 5 ka were relatively dissimilar, spaced evenly, and directionally distant driven by the percentage of coldest polar class (Figure 4). Recent time intervals since 5 ka are similar, based on tight clustering. The 1950 interval is

most similar to 1 and 5 ka and the intervals of 1600 and 1800 are most similar.

The boreal and polar E and F classes decreased from a combined 70% of all area during 20 ka to 42% of area during 7 ka, the Mid-Holocene Warm Period. Then the boreal and polar area increased steadily but slightly to 46% during 1850 (the Little Ice Age), before decreasing to 41% during 1950 (Figure 5A, B). The subtropical and temperate C and D classes increased from a combined 25% of all area at 20 ka until reaching 53% of area at 7 ka, decreased steadily but slightly to 48% of area during 1850, and increased to 53% of area during 1950. The tropical A class increased steadily but slightly from 4.3% to 6% in area.

Similarly, the dry subclasses combined (from all thermal classes and subclasses) increased steadily from 7.5% of total area during 20 ka to 15% of total area during 1950 (Figure 5A, B). The subtropical C (desert and steppe) and temperate hot Dca dry classes reached 3.4% to 4.8% of total area and the temperate warm Dcb dry class reached 2.8% of area, whereas the other climate dry classes reached <0.6% of total area in the dry subclass. The dry subclasses with greatest area exhibited unique trends. While dry area in the subtropical desert class increased over time to 3.4%, dry area in the subtropical steppe class attained 4.4% during 1 ka

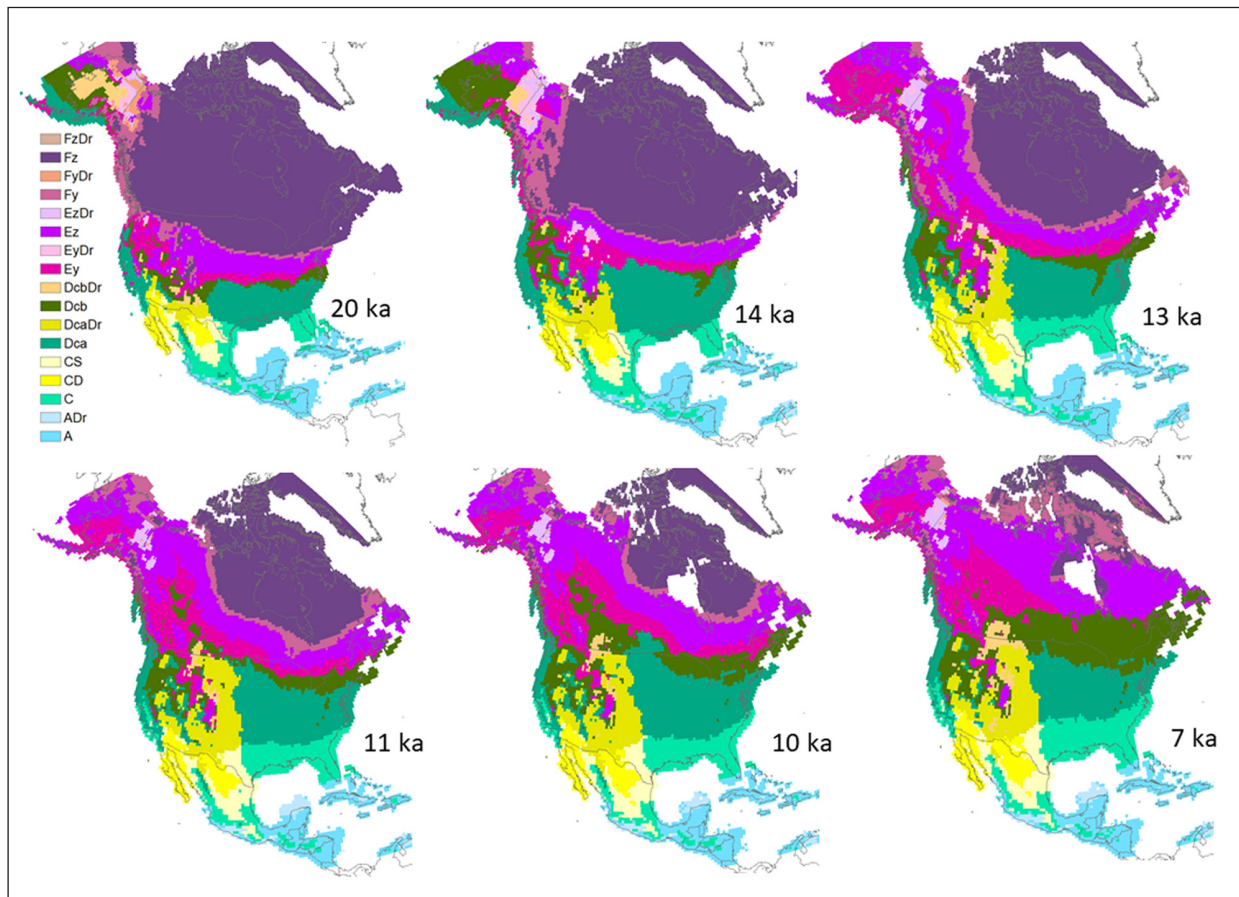


Figure 2 Climate classes during 20 ka to 7 ka. For the legend the main thermal classes are A = Tropical, C = Subtropical, Dca = Hot Continental, Dcb = Warm Continental, E = Boreal, F = Polar (see Table 1).

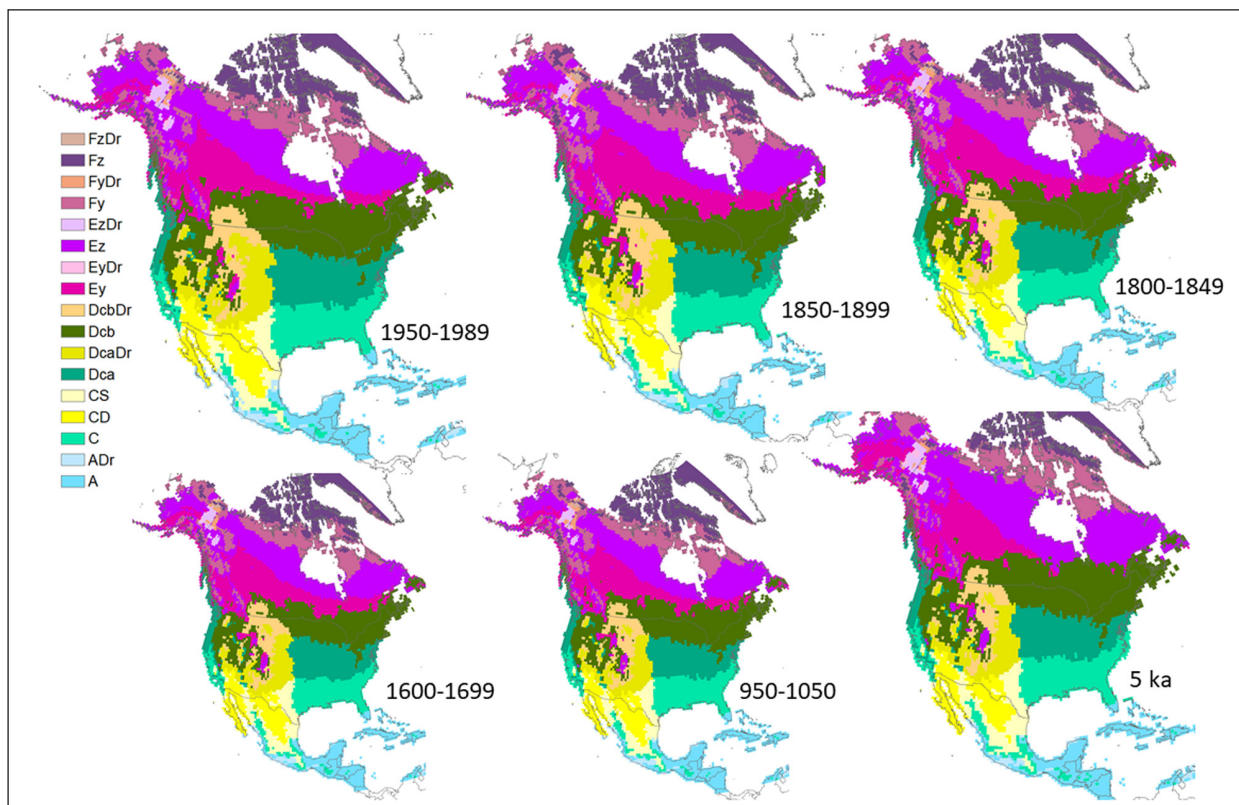


Figure 3 Climate classes during 5 ka to 1950–1989. For the legend the main thermal classes are A = Tropical, C = Subtropical, Dca = Hot Continental, Dcb = Warm Continental, E = Boreal, F = Polar (see Table 1).

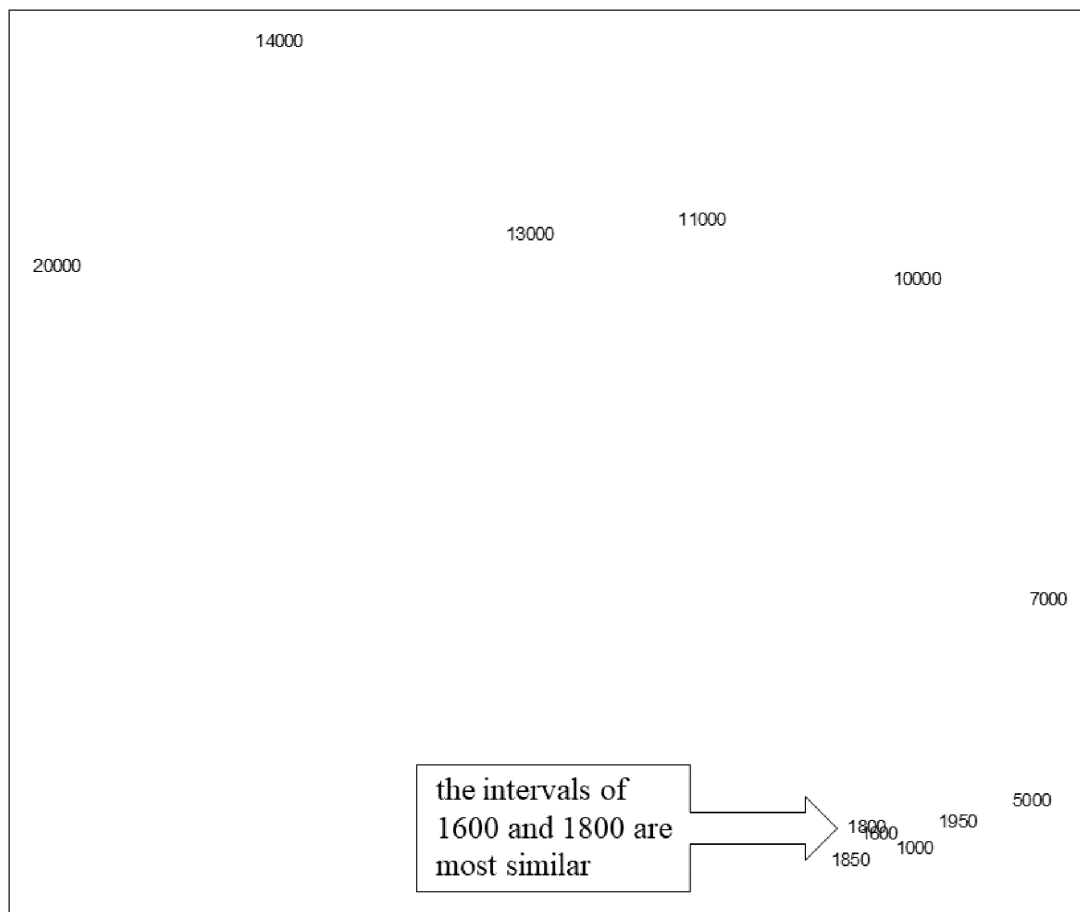


Figure 4 Ordination of climate classes.

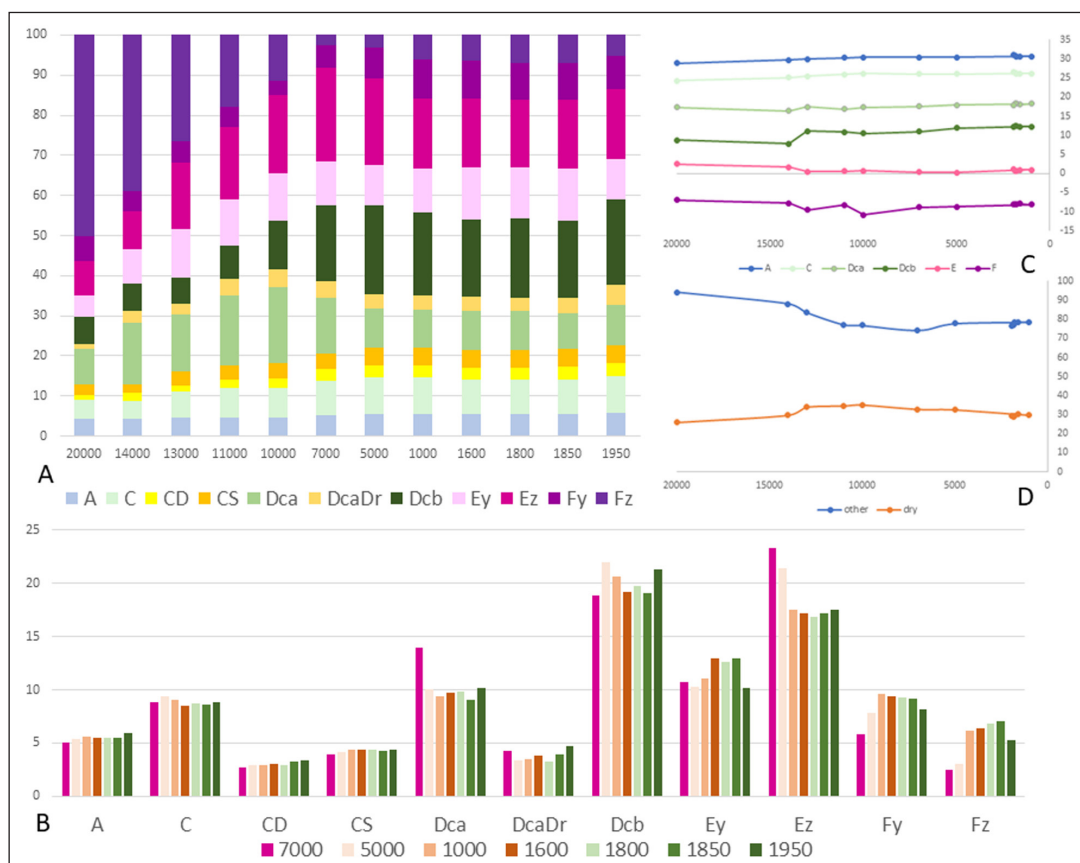


Figure 5 Change in climate classes over time (**A, B**) and change in minimum temperature and precipitation over time by classes (**C, D**).

(the Medieval Warm Period) and during 1950. Dry area in the temperate hot Dca class declined after reaching 4.3% during 7 ka (the Mid-Holocene Warm Period), but then achieved a maximum of 4.8% during 1950. Dry area reached 2.8% in the temperate warm Dcb during 1850, the Little Ice Age, and then declined. Temperature and precipitation remained relatively consistent over time for the thermal classes and the dry subclasses (Figure 5C, D).

DISCUSSION

The climate classifications illustrated climate change over time, from a cooler climate at 20 ka dominated by boreal and polar classes to rapid change following abrupt warming at the onset of the Bølling-Allerød circa 14.6 ka (He et al. 2010). By 7 ka, the climate classes appeared similar to recent climate classes, and according to ordination, climate classes of 5 ka were very similar to climate classes of 1950 to 1989. While boreal and polar classes decreased in area, the subtropical and temperate classes increased from a combined 25% of area to 53% of area by 7 ka, similar to current extent. The tropical class increased slightly. Overall, dry subclasses increased steadily in area from 7.5% during 20 ka to 15% during 1950, answering the question of whether dry subclasses have remained stable. Dry subclasses have the greatest area in the subtropical and temperate classes, each of which demonstrated unique trends in dry area over time. Maps at the time steps of 20 ka and 7 ka appeared to resemble maps displayed in Yoo and Rohli (2016) and Willmes et al. (2017) of global Köppen-Geiger classification at 21 ka and 6 ka, despite different spatial extents, resolutions, and classes. The climate classes from simulated climate of 1950 to 1989 were comparable to climate classes from daily near-surface gridded data during 1981–2010, albeit at different resolutions; observational data were applied to inform the debiasing and downscaling process that standardizes the simulations (Supplementary file 1: Figure 1; Lorenz et al. 2016a, b; Hanberry & Fraser 2019).

Modifications to the climate classification, while slight, were beneficial, particularly to measure warming since the Last Glacial Maximum. By retaining the thermal class information with a dry subclass, it was possible to track change over time both directly in the thermal classes and also the dry area within each thermal class. Specifically, the subtropical and temperate classes contained $\geq 80\%$ of the dry area and the subtropical and temperate classes and dry subclasses increased over time. If classification of dry subclasses discarded the subtropical and temperate class information, then it would appear that the subtropical and temperate classes did not increase as much in extent, nor would the thermal classes of developing dry areas be as evident.

Another modification was subdivision of the large boreal and polar extents, which covered 70% of total area during 20 ka and about 40% of area during the 1950 interval. Each of the boreal and polar subclasses encompassed at least the same area as the tropical class, if not much greater, and were more dynamic than the stable, slightly increasing tropical class. The subdivisions consisted of unique vegetation, progressing from a boreal subclass consisting of 67% temperate or sub-polar ecosystems with $<1\%$ sub-polar or polar lichen-moss, to a boreal subclass of 46% temperate or sub-polar ecosystems with 26% sub-polar or polar lichen-moss, to a polar subclass of 65% sub-polar or polar lichen-moss and 21% barren, snow, and ice cover, to a polar subclass of 70% barren, snow, and ice cover. By subdividing these classes, better detection of climate change is possible. Specifically, recent warming during the 1950 interval shifted the polar subclasses to the coldest boreal class and the cold boreal class to the temperate warm class. If the warming trajectory follows the climate classes of 5 ka and 7 ka, then the two boreal subclasses will both gain in area in the future due to continued decreases in the polar subclasses.

Climate classes can translate into similar spatiotemporal assimilation of major vegetation types (Denk et al. 2013). Climate classes during 20 ka overall corresponded with pollen reconstructions circa 28 ka to 15 ka, an interval with consistent vegetation patterns as reviewed by Delcourt and Delcourt (1987, 1993) and Dyke (2005). The Laurentide Ice Sheet extended as far south as 39°N latitude, and the polar zone mostly followed the ice sheet (Figure 6, Batchelor et al. 2020). Boreal forest, similar in composition to modern boreal forest, occurred south of the Laurentide ice to approximately 34°N, whereas the boreal and temperate warm climate classes ended at about 35°N for this dataset set during 20 ka. Boreal forests contained temperate tree species and likewise, temperate forests had boreal elements, with less spatial separation than modern associations (Delcourt & Delcourt 1993; Dyke 2005). In Alaska during 20 ka to 14 ka, a large extent was dry and another extent appeared to be suitable for tundra or a unique steppe tundra, which had no modern analogue but matches reconstructions (Delcourt & Delcourt 1993; Dyke 2005). However, in simulations, after 14 ka a part of this region cooled from temperate to boreal classes, which is relatively consistent with maximum temperatures at 12 ka indicated by pollen reconstructions (Viau et al. 2008).

Transition in climate classes also coincided with shifts in physiological tolerances of dominant plant species. Latitudinal and altitudinal ranges are constrained by the tradeoff in traits between survival of freezing and faster growth and reproduction, that is, where plant species can compete well. Between 15 ka and 6 ka, warming and consequent retreat of the ice sheet resulted in widespread changes in climate and vegetation, resulting

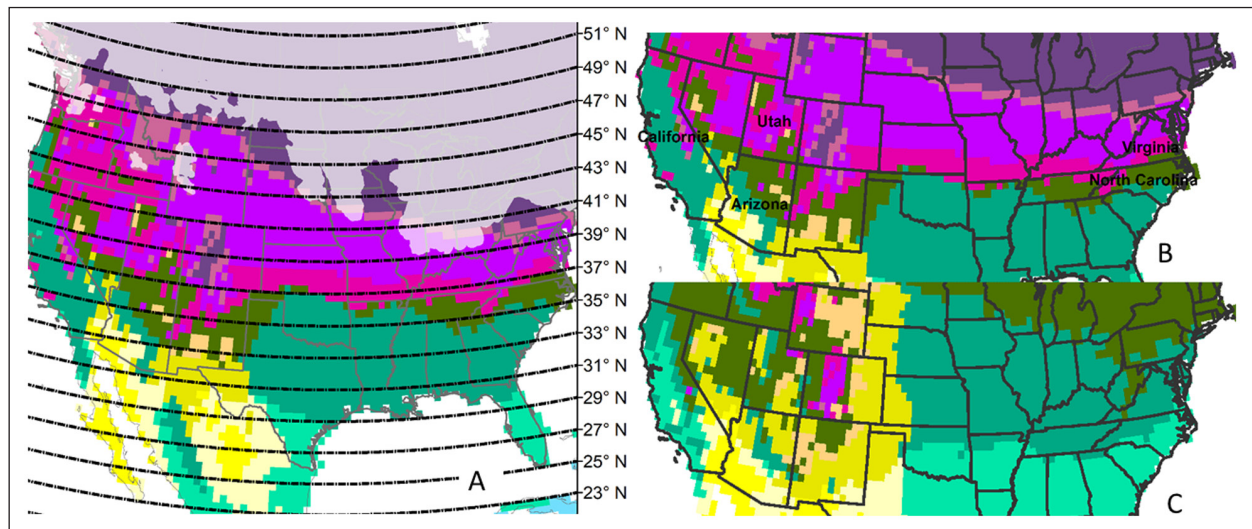


Figure 6 Approximate extent of the Laurentide ice sheet about 26.5 ka (A; transparent layer over the polar class; Batchelor et al. 2020) and general resemblance between climate class distributions and eastern United States state boundaries, which followed latitudinal lines until curving poleward in the western United States, at 20 ka (B) and 1600–1699 (C).

in current ecosystems. Biomes shifted northward and toward ice margins at rates of 100 to 200 m per year (Dyke 2005).

Spruces (primarily *Picea glauca*, *P. mariana*) are an indicator genus of boreal forests and shifted with temperature at mean late Quaternary rates of 14.1 km per century (Delcourt & Delcourt 1987). However, spruces were limited in their window of optimal tolerance, with a slowly receding ice sheet to the north and faster-growing tree species competing in the southern range, causing population disruption in some locations (Delcourt & Delcourt 1987, 1993). In the northeastern United States, pines (particularly *Pinus banksiana*, *P. resinosa*) form distinctive forests within the southern boreal forest matrix (e.g., Hanberry and Dey 2019) and migrated northward at a mean rate of 13.5 km per century (Delcourt & Delcourt 1987). In the central eastern United States, oaks (e.g., *Quercus alba*) were the foundation genus and equally, oak-pine (*P. echinata*) were the foundation genera in the northern southeastern United States (e.g., Hanberry et al. 2019); oaks migrated at 12.6 km per century (Delcourt & Delcourt 1987). Pines, which dominated with oak in the northern southeastern USA and were the foundation species (*P. palustris*) of the southeastern USA, expanded at an average rate of 8.1 km per century (Delcourt & Delcourt 1987).

Grasslands were established in central North America by 10 ka (Delcourt & Delcourt 1993). Grassland vegetation is not matched with a climate classification type in North America (Hanberry and Fraser 2019). Climate as a barrier between forests and grasslands may be an artificial ecological concept in grasslands that are not designated as arid climate by climate classification systems, which classically use relationships between precipitation and temperature (Shin et al. 2012; Belda 2014), or different aridity indices that incorporate the relationship between precipitation and evapotranspiration. Instead, wind

speed as an index of fire disturbance bound grasslands in North America (Hanberry 2021).

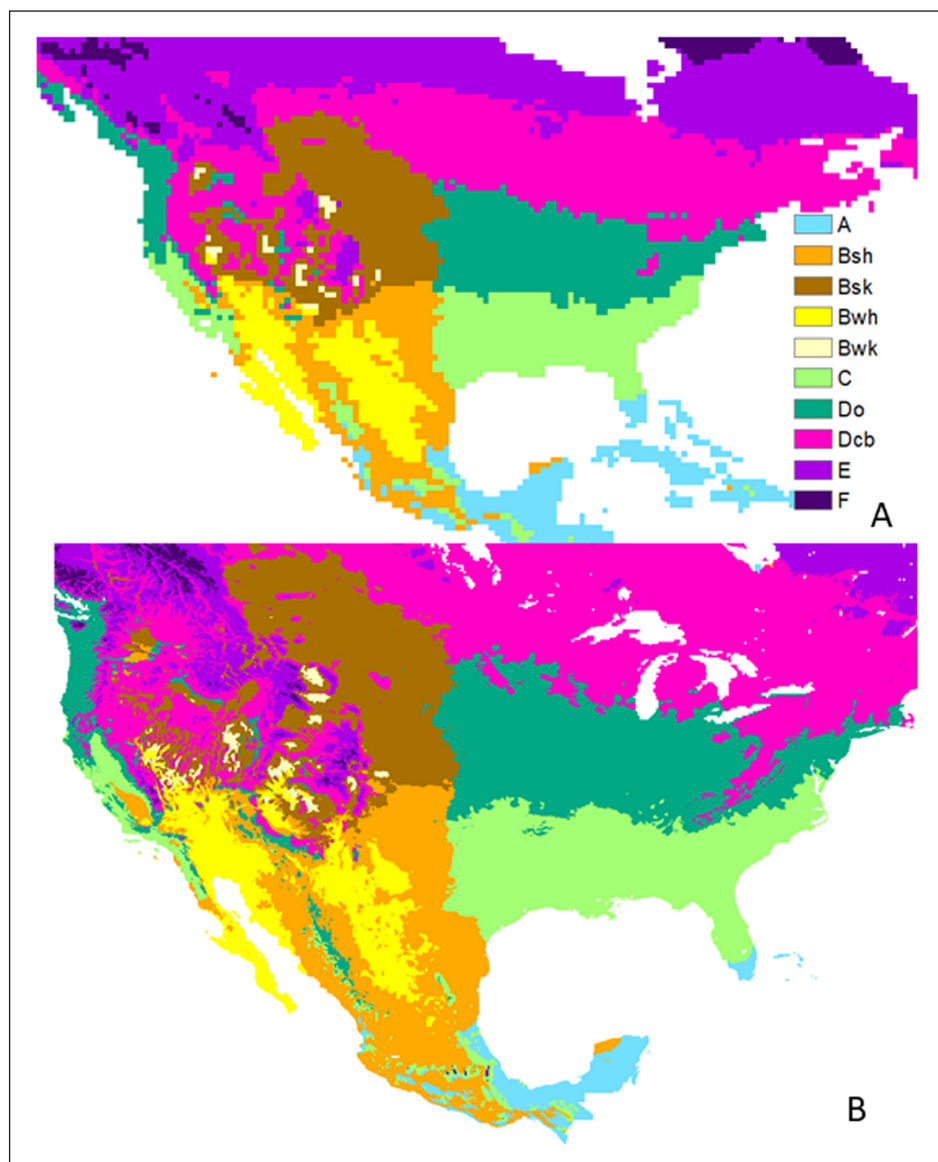
Complex climate class and topographic patterning occur in the western United States, with corresponding vegetation that developed after retreat of the boreal climate (Delcourt & Delcourt 1993; Dyke 2005). Shrublands, dominated by sagebrush, expanded over time, commonly replacing subalpine forest (Dyke 2005); arid deserts and shrublands currently are widespread, largely due to orographic effects on precipitation. In wetter locations, typically alpine tundra dominates high elevations, subalpine forests of spruce and fir at the next elevational band, and woodlands at lower elevations, with elevational shifts upwards over time. A Mediterranean climate with chaparral and woodlands is present along the southern Pacific Coast with rain forest along the northern Pacific Coast.

Although speculative, political boundary lines also appeared to reflect climate class boundaries; that is, climatic boundaries might have influenced state boundaries (Figure 6). Generally, both climate classes and eastern United States state boundaries followed latitudinal lines until curving poleward in the western USA. Specifically, the boreal extent during 20 ka ended at the 36°30' north latitude line that runs along state borders from the border between Virginia and North Carolina at the Atlantic coast to the border between Utah and Arizona and encompassing most of Nevada. The border of Nevada and California mostly followed the boreal extent as well, as California primarily was in the temperate hot class until slowly becoming subtropical. This political boundary along the boreal extent also is similar to the boundary between the temperate and subtropical classes of recent times. It is possible that there was an ecological influence, such as ecosystem, soil differences, or growing degree days, in setting the Royal Colonial Boundary of 1665 followed by the Missouri Compromise. The most heavily populated

districts of Carolina remained south of the boundary, after the boundary was adjusted north from the 36th parallel (Norris 2006). Euro-American settlers often preferred to farm the land that was previously occupied by native humans, who may have responded to long-standing ecological differences at climate and ecosystem boundaries (Coughlan & Nelson 2018). Evocative terms such as ‘landscape memory,’ ‘land use legacy,’ and ‘inheritance’ describe the interaction between land and humans and the continuance of human influence and disturbance (Coughlin & Nelson 2018). Certainly, other datasets, time intervals, or variations in classification may result in climate classes that do not fall as clearly at state boundaries but likely will suggest the same latitudinal to curving pattern that indicates some relationship that may be established by additional research into historical archives.

CONCLUSIONS

Climate classes allow useful visualization of temperature, precipitation, and aridity and change across space and time. For example, current climate classes are similar to 1 ka and 5 ka. With retention of thermal class information for arid climate classes, it became measurable that percentage area of dry classes was greatest in the subtropical and temperate hot classes, with increases over time, and thermal class area has remained relatively stable since 7 ka. In North America, the climate classes and transitions overall corresponded with major vegetation distributions during the past 20,000 years, with rapid change between 14 ka and 7 ka. Determining whether political boundary lines follow climate boundaries is a topic for future research.



Supplemental figure 1 Comparison of conventional climate classes from the 1950 to 1989 climate data used in this paper to daily near-surface gridded data during 1981 to 2010. For the legend: A = Tropical, C = Subtropical and Mediterranean, Do (Dca) = Hot Continental, Dcb = Warm Continental, E = Boreal, F = Polar, Bwh = Subtropical desert, Bsh = Subtropical steppe, Bwk = Temperate desert, Bsk = Temperate steppe.

DATA ACCESSIBILITY STATEMENTS

The repository location for climate classes is <https://doi.org/10.5281/zenodo.6608773>, hosted at zenodo.com.

ACKNOWLEDGEMENTS

I thank the reviewers for their time and comments. This research was supported by the USDA Forest Service, Rocky Mountain Research Station. The findings and conclusions in this publication are those of the author and should not be construed to represent any official USDA or U.S. Government determination or policy.

COMPETING INTERESTS

The author has no competing interests to declare.

AUTHOR CONTRIBUTIONS

BBH completed all authorship tasks.

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TO CITE THIS ARTICLE:

Hanberry, BB. 2022. From 20,000 Years Ago to Near Present Climate Classification of North America. *Open Quaternary*, 8: 11, pp.1–11. DOI: <https://doi.org/10.5334/oq.116>

Submitted: 17 April 2022 **Accepted:** 25 July 2022 **Published:** 03 August 2022

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