CLIMATE CLASSIFICATION FOR THE EARTH'S OCEANIC AREAS USING THE KÖPPEN SYSTEM

by

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Abstract

The objective of this thesis is classify climate for the Earth's ocean areas. The classification task is accomplished in part by using monthly average sea surface temperature and precipitation data from 1980-2008. Coast-to-coast coverage of the needed data were obtained from the reanalysis product produced by the National Centers for Environmental Prediction and the National Center for Atmospheric Research. Köppen's classification scheme was implemented in the ArcGIS suite of software, which was used to analyze and display all of the classified map products. Russell's 'climatic years' concept was used and separate classifications were produce for each year of available data. Findings indicate that the oceans are very different from land areas when it comes to the location and extent of varying climate types. Some main findings include the idea that A, C, and E climates dominate the geography of the oceans and that there are zero continental, or D, climates. Also, the Southern Oscillation plays an important part in tropical ocean dynamics and climate, but summarizing twenty nine years of mapped patterns into a summary product removes any major effect from yearly climate system anomalies. A key finding is an argument that supports the establishment of a unique Southern Ocean surrounding Antarctica. There are polar, ET and EF, climate subtypes surrounding both the Arctic and Antarctic poles, but only the north has the well established Arctic Ocean. Oceanic E climate areas are more pronounced in the Southern Hemisphere with circumpolar rings around the Antarctic continent. Classification results support the idea of a Southern Ocean based on the spatial pattern of climate types and in view of the fact that that the climate of the Southern Ocean area is so different from the temperate, or C, climate and its subtypes. This research is important for many reasons, the primary being that climate classification helps us better understand the world around us. It is difficult to see change in the environment without first knowing what the state of the system used to be. Classification will also help depict the changes that have happened, when these shifts in climate occurred, and with that information we can better predict what the future will hold.

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Acknowledgements

I wish to take this opportunity to express my gratitude to my advisor Dr. John Harrington Jr. for introducing me to the world of climatology and how important it truly is to our planet. Also for taking the time for all those office visits and e-mails to guide me along the correct path, but giving me enough freedom to figure it out for myself. Thanks also to Dr. Shawn Hutchinson who helped greatly with the GIScience portion of the thesis. I greatly appreciate all the running back and forth between 164B, 164H, and GISSAL, also the time to answer countless questions about ModelBuilder troubles. Also, thanks to Tom, Robert, Jimmy, and the John's for getting me through those long hours in the GIS lab and late nights at home. Lastly, I would like to give special thanks my wife Kimberly for her patience and understanding while I was on campus running countless models early on, but especially for when I was up until all hours of the night writing like there was no tomorrow. I know it was very tough because she was forced into all of the responsibilities at home. One of the things I appreciate most is taking care of Charles at night so I could squeeze in a couple hours of sleep before work the next morning. I appreciate everything you for me and without you this thesis would not be close to as good as I feel it has turned out. Thank you.

Preface

This thesis is based upon data for 1980 through 2008 that were obtained from the Earth Systems Research Laboratory located in Boulder, Colorado as well as the National Snow and Ice Data Center which is located in Boulder as well, but on the University of Colorado campus. It is submitted as partial fulfillment of the requirements for a Master of Arts Degree from Kansas State University. It has been carried out from August 2009 through May 2011. The advisor on the project has been Dr. John Harrington Jr. and the thesis research has been done solely by the author; most of the text, however, is based on the research of others, and I have done my best to provide references to these sources. Writing this thesis has been challenging, but in the process of writing I feel I have learned much about climatology and climate classification in general. I have dealt with large amounts of data and refined it the best way possible so that the final product met the standards I have set for myself as well as hopefully achieving the expectations of my professors and peers.

Chapter 1 - Introduction

Climate is an important characteristic of the Earth's surface and grouping the wide variety of climate conditions into a small number of distinct categories is a challenge. When creating classes of climate, there are many aspects of the environment that can be considered. One of the top concerns is choosing the meteorological data types to use. Using satellite and meteorological model derived estimates of surface conditions as the primary inputs to the classification, this thesis provides an analysis of the climates of oceanic areas where meteorological observations are in general quite sparse.

There has been little work done in the classifying of ocean climates even though oceans comprise around 70% of the Earth's surface. Existing climate classification systems (e.g., Köppen and Thornthwaite) were developed for land areas with an attempt to match the climate classes to major terrestrial biomes. Research findings from oceanographers and climate scientists indicate that there are important physical and biological regions in the oceans and that these areas do indeed have distinct climatic conditions. Knowing even basic facts about how water and land each effect climate demonstrates that there is a clear difference in the climate over the oceans compared to that of the land. Land based climate classification systems that try to include an oceanic element may not give oceans enough credit in showing how different the two surface types are.

An important early step was to consider which classification system to use. An empirical taxonomic approach, based on the decades of research done by the Russian, Wladimir Köppen, was used. Köppen was a geographer, botanist, and climatologist. In constructing his classification scheme, meteorological elements important to of all of these interrelated fields were used. He is considered to be a leader in climate classification simply for the fact that since 1918 no one has created any classification scheme that even comes close to replacing his system for introductory discussion of global climate types.

Monthly sea surface temperature (SST) and precipitation are used as inputs to the geographic information system (GIS) model that creates the yearly climate maps. Sea ice is also included in this analysis of ocean climate areas because of how important ice cover is to ocean-atmosphere interaction. The sea ice data are not directly incorporated into the Köppen climate classification system, but analysis of the mapped patterns of ice correlate closely with the polar climate subtype, EF.

The El Niño Southern Oscillation (ENSO) is an important internal driver of climate variability not only over the oceans, but across the globe. It is imperative that the climate classification done on an annual basis is able to pick up on these warmer and cooler than average ocean waters in the equatorial Pacific. The more years that are added into creating long-term means for a climate classification the more that averaging process keeps anomalies like El Niño and La Niña from having too much influence on the overall picture. For this analysis of oceanic climates, twenty nine years of data were used, 1980-2008. The reason for this specific span of dates was because it was the largest sample size available that encompassed the three variables, SST, precipitation, and sea ice.

Given that events are like El Niño and La Niña are important temporal variations of the global climate system, this thesis uses a climatic years approach (Russell, 1934) to classifying the oceans. With a climatic years analysis, a separate classification is done for each year of available data. This way summary information about the climate of the oceans is not based on just an average of data for the same location producing one final output; rather individual climate classifications for every year are prepared and summarized to identify consistency and inter-annual variability among the years. Data from every calendar year were analyzed to produce each of these yearly climate maps. From these twenty nine separate maps, a modal filter was applied over the temporal data pulling out the most frequent annual climate subtype for each 0.5 square kilometer (km^2) grid cell. This modal approach provides a final synthesis of the ocean climates.

Other analyses can be done with the individual climate year maps. Examples of other studies that were done are maps of frequencies for each climate subtype, a map of core areas, and of course the contrasting of El Niño and La Niña years. Core areas are simply locations where the climate subtype was the same for every year of the study. If an area was classed as BWh, or the hot desert climate, for all twenty nine years it would be considered a part of the BWh core area. The climate frequency maps are offshoots of core area maps. These maps show the location of every half km^2 cell that was classified a certain climate subtype at least one time throughout the study. These maps are useful because they provide information about the steepness of the gradient of change from one climate class to another. For instance, El Niño and La

Niña cause quite a bit of transition in where the Am, tropical monsoonal, and Af, tropical rain year round, occur. The relatively warm and cool equatorial ocean waters helps dictate how much rainfall occurs in an area. If there is a cool pool of water it could have enough of an impact to cause a month to fall short of the required 60 millimeters (mm) of precipitation to be classified as an Af subtype and instead be an Am.

Geographers are interested, in part, in knowing about the location of varying phenomena on the Earth. Analysis of the geographic patterns of classified features helps geographers see if regions exist. In addition, classification and regionalization help scholars to better understand not only where things exist but may even help in developing ideas about the Earth-system processes that are important in generating the conditions that produce the specific geographic distributions. A major objective of this thesis research is to help advance our understanding of oceanic patterns on Earth by classifying the climate of ocean areas. Given concerns about the rapid pace of global change, a climatic years approach was used. By producing not just one classification, but twenty nine annual classifications, important questions regarding the nature of inter-annual variability can be addressed. As more and better data regarding the surface conditions of oceanic areas are collected in the years to come, geographer-climatologists may be able to detect directional trends in the climate for specific oceanic areas.

Chapter 2 - Literature Review

Importance of Classification

People like to organize information to help them better understand it. A specific way to do this is to put the information in pre-defined categories that help us retain and understand the phenomenon better (Kwasnik, 1999). Classification is basically a systematic arrangement in groups or categories according to established criteria. However, classifications are dynamic and ever changing. Cline (1949, 84), a soil scientist, stated, *"Classification should deal with the knowledge existing at the time. As knowledge changes, the classification must also change."* This holds true today with the vast environmental and social changes going on, including global temperature increases and Arctic sea ice change.

Classifying objects helps us distinguish similar things form the dissimilar ones. For instance, giraffes and elephants have much more in common than one would first think. They could both be classified as large animals and mammals. Also, both are herbivores, from Africa, live in the savanna, have two eyes, tails, and the list could go on and on. Now compare an elephant to a chair. About the only thing analogous between these two is they both have four legs and if the chair is grey, one could say they are the same color. Classifying helps us with these comparisons and distinctions. According to Biederman (1987) we can assign objects into approximately 3,000 basic-level categories. This ability helps us subconsciously to group things together based on their details, but also to separate these groups we create based on important discriminating factors.

Geographers take advantage of a special category of classification based on the spatial location of classed objects. Just as historians group similar items into specific time periods or eras, geographers develop regions to help them understand phenomena. If members of the same class are grouped together in space, then a region (a special type of class) is formed.

Climate

Climate classification is important in helping us understand our world. Hare (1951, 47) stated that:

> *"Climate classification is an essentially geographic technique. It allows the simplification and generalization of the great weight of statistics built up by climatologists. The real purpose of classification is (to) define climatic types in*

statistical terms; in which climate as a geographic factor is to be regarded as having definite and uniform characteristics."

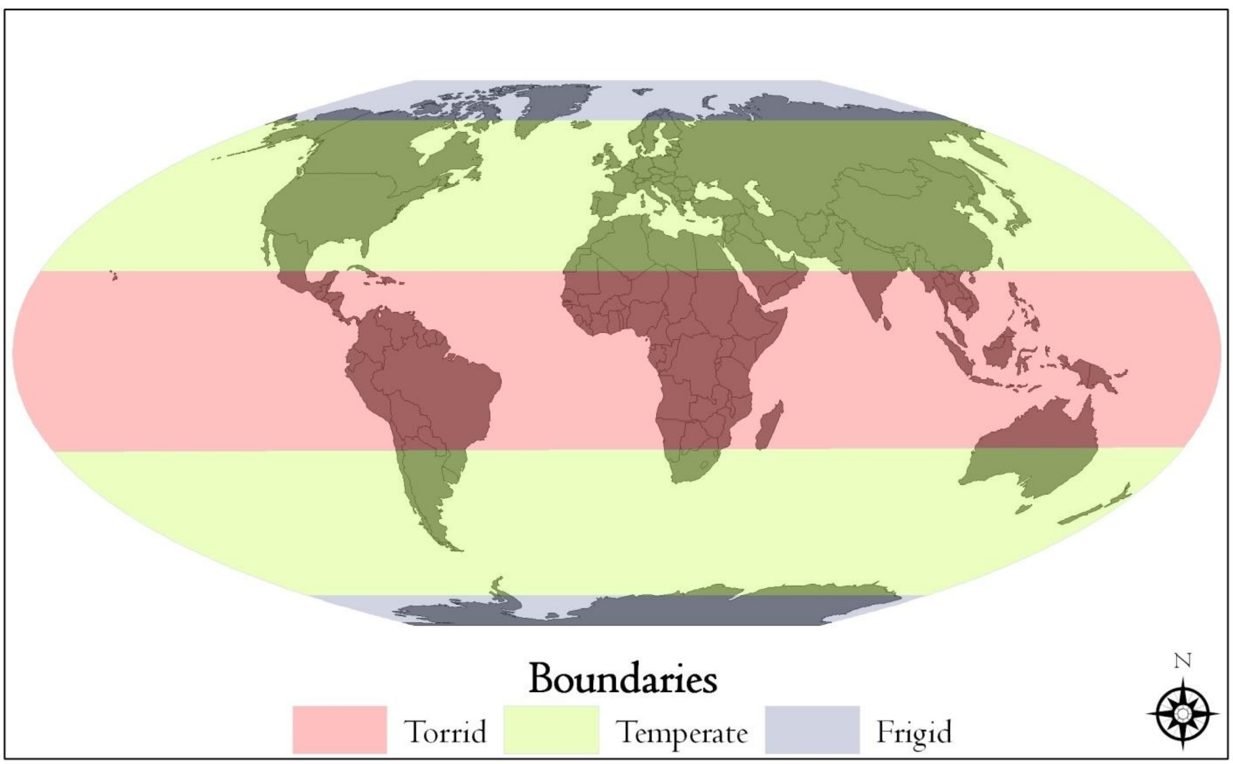
Trying to find patterns in space and/or trends over time in climate can help us figure out the way things are and what may come in the future. If we can predict what climatic changes will take place we can better prepare ourselves for drastic changes that may emerge down the road (Williams *et al.*, 2007).

A History of Climate Classification Systems

Ancient Greek Philosophers

One of the first people to think about climate and long term weather was a Greek by the name of Parmenides (Sanderson, 1999). In the early sixth century BC, he came up with the idea of an Earth divided into three climatic types arranged in five climatic regions or zones (Figure 2.1). An equatorial and tropical zone which featured the torrid boundary, mid-latitude zones in the northern and southern hemispheres with temperate climates, and lastly two polar zones were labeled frigid. Parmenides stated incorrectly that the torrid zone, because of the heat from the

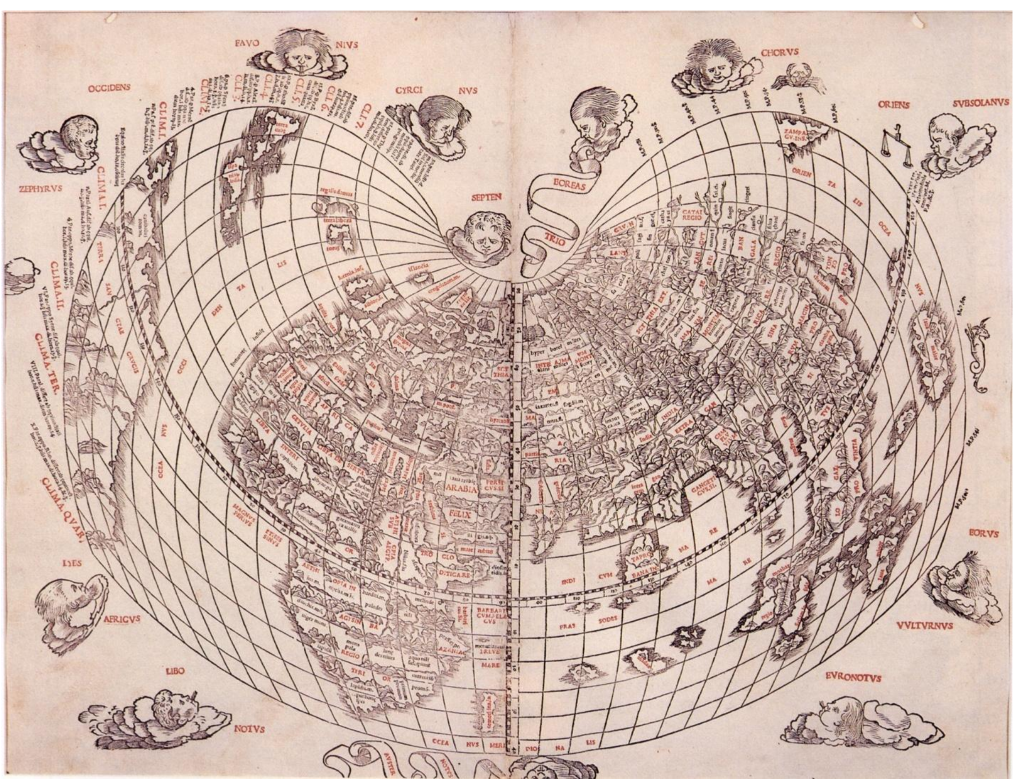
Figure 2.1 Parmenides climate map (6th Century BC) [Source: created by author]



direct rays of the sun, was inhabitable (Harley and Woodward, 1987). The much more well-known Aristotle picked up on this line of thinking and even deduced, however a bit egocentric, that the 'habitable world' was confined to just the temperate zones between the torrid and frigid zones. He stated the torrid and frigid areas were uninhabitable because of excessive heat and cold, and that there must exist a matching temperate belt in the southern hemisphere. The southern temperate zone was definitely habitable, but inaccessible by the Europeans of the time because of the impassable equatorial zone (Thornthwaite, 1961).

Since 350 BC philosophers/logicians have discussed ways in which this intellectual process of generalization and grouping items into classes should be done. Classification is one of the ways to do this. Classification, whether by grouping like objects or by subdivision of the whole, has an obvious application in plant taxonomy, which is simply orderly classification of plants and animals according to their presumed natural relationships (Grigg, 1965). It would not be until 1511, that the Southern Hemisphere would get mapped as a habitable environment (Sanderson, 1999). The Venetian Bernard Sylvanus created the first map that carried this theory out (Figure 2.2). The idea was not from Sylvanus, but from Ptolemy of Alexandria. Ptolemy

Figure 2.2 Sylvanus climate classification (1511) [Source: William Clements Library, University of Michigan]



stated, *"Reason herself asserts that all animals and all plants have a similarity under the same kind of climate and under similar weather conditions, that is, when under the same parallel and situated at the same distance from either pole"* (Ptolemy, 1932, 31-32). The idea of a habitable southern hemisphere was thought of, but stayed buried for almost 1500 years until Renaissance men, like Sylvanus, rediscovered them.

Köppen

Wladimir Köppen was the first person to come up with a complete quantitative climate classification (Kottek *et al.*, 2006). A modification of Köppen's 1918 system is still widely used today (Figure 2.3). Many climate classification efforts developed since then have worked to enhance the Köppen system. Köppen worked on his climate classification for over thirty years. It uses long-term mean monthly precipitation and temperature as inputs. Using thermal limits, precipitation amounts, and precipitation seasonality, Köppen determined climate class boundaries that would match well with the patterns of major biomes on Earth (Table 2.1). Several of the Köppen climate types are further subdivided by precipitation characteristics. When there is no strong seasonality in precipitation, the second letter of the climate class is a lower case f. However, if there is pronounced summer dryness, then the second letter is an 's'

Figure 2.3 Köppen climate classification [Source: Rubel and Kottek, 2010]

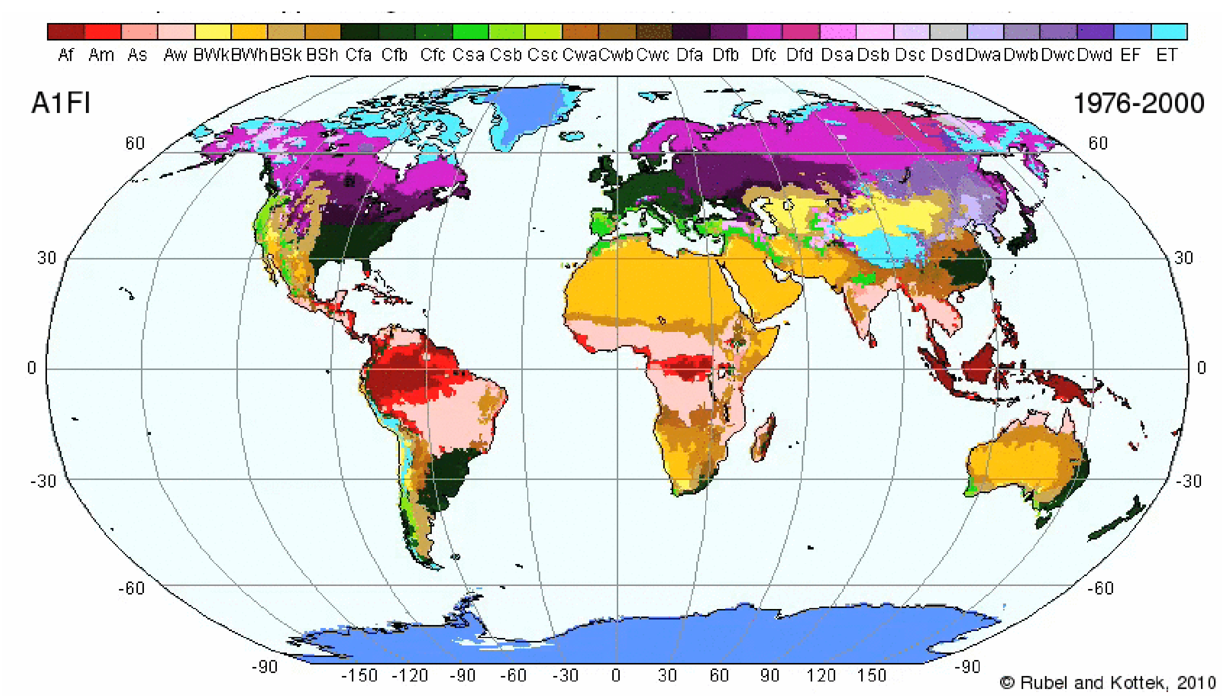


Table 2.1 Köppen's six major climate types [Source: Essenwanger, 2001]

Climate Letter	Description
A	Tropical
B	Arid
C	Temperate
D	Continental
E	Polar
H	Highland

and a climate with unusually dry winter conditions it is given a 'w'. The tropical climate region also has a special option; an 'Am' can be assigned to regions that have the distinctive seasonal precipitation pattern associated with a monsoonal airflow regime.

The Köppen temperate and continental climates have major temperature swings between the high and low sun seasons. To account for these phases, Köppen assigned a third letter of a, b, c, or d to these climates (Table 2.2).

Table 2.2 Köppen subclimates for C and D classes [Source: Essenwanger, 2001]

Climate Letter	Description	Border Rules
a	Hot Summer	Average temperature of the warmest month is > 22˚C
b	Warm Summer	Average temperature of the warmest month is ≤ 22˚C but four or more months average temperatures have to be > 10˚C.
c	Cool Summer	Average temperature of one to four months must be > 10˚C, but the coldest months average temperature must be > 38˚C below zero.
d	Cold Summer	Average temperature of the coldest month must be > 38˚C below zero.

The arid (BW) and semiarid (BS) climates are assigned a third letter like the temperate and continental climates. However there are only two subclasses, 'h' for hot, which means the average annual temperatures is ≥ 18˚C, and 'k' for cool, which means the average annual temperature must be < 18˚C. In some cases, the arid and semiarid climates can have a fourth letter of 's' or 'w' to indicate precipitation seasonality.

For the polar or E climates, there is a second letter possible based on temperature alone. ET is assigned for tundra, which must have the temperature of the warmest month between 10˚ and 0˚C. To be classified as an EF climate, the average temperature of the warmest month must be < 0˚C. Lastly, in highland climate areas altitude impacts physical processes and summary data are different from what they would be if the observations were from a higher or lower elevation. To account for altitudinal effects, places are given an H for their climate type. Essenwanger (2001) provides a good description of the difference among all the major climate types (Table 2.3).

Table 2.3 A listing of Köppen climate classes [Source: Essenwanger, 2001]

Climate Type	Description
Af	Tropical rain forest, hot, rain all seasons
Am	Tropical monsoon, hot, seasonally excessive rainfall
Aw	Tropical savanna, hot, dry season (most locations in winter)
BSh	Tropical steppe, hot, semi-arid
BSk	Mid-latitude steppe, semi-arid, cool or cold
BWh	Tropical desert, hot, arid
BWk	Mid-latitude desert, cool to cold, arid
Cfa	Humid subtropical, moist all season, hot and long summer, mild winter
Cfb	Marine, moist all season, warm summer, mild winter
Cfc	Marine, moist all season, short summer, mild winter
Csa	Interior Mediterranean, mild winter, hot summer, summer dry
Csb	Coastal Mediterranean, mild winter, warm summer, summer dry
Cwa	Subtropical monsoon, mild winter, hot summer, winter dry
Cwb	Tropical upland, mild winter, warm summer, winter dry
Dfa	Humid continental, moist all season, hot summer, cold winter
Dfb	Humid continental, moist all season warm summer, cold winter
Dfc	Subarctic, moist all season, short summer, cold winter
Dfd	Subarctic, moist all season, short summer, severe winter
Dwa	Humid continental, hot summer, cold winter, winter dry
Dwb	Humid continental, warm summer, cold winter, winter dry

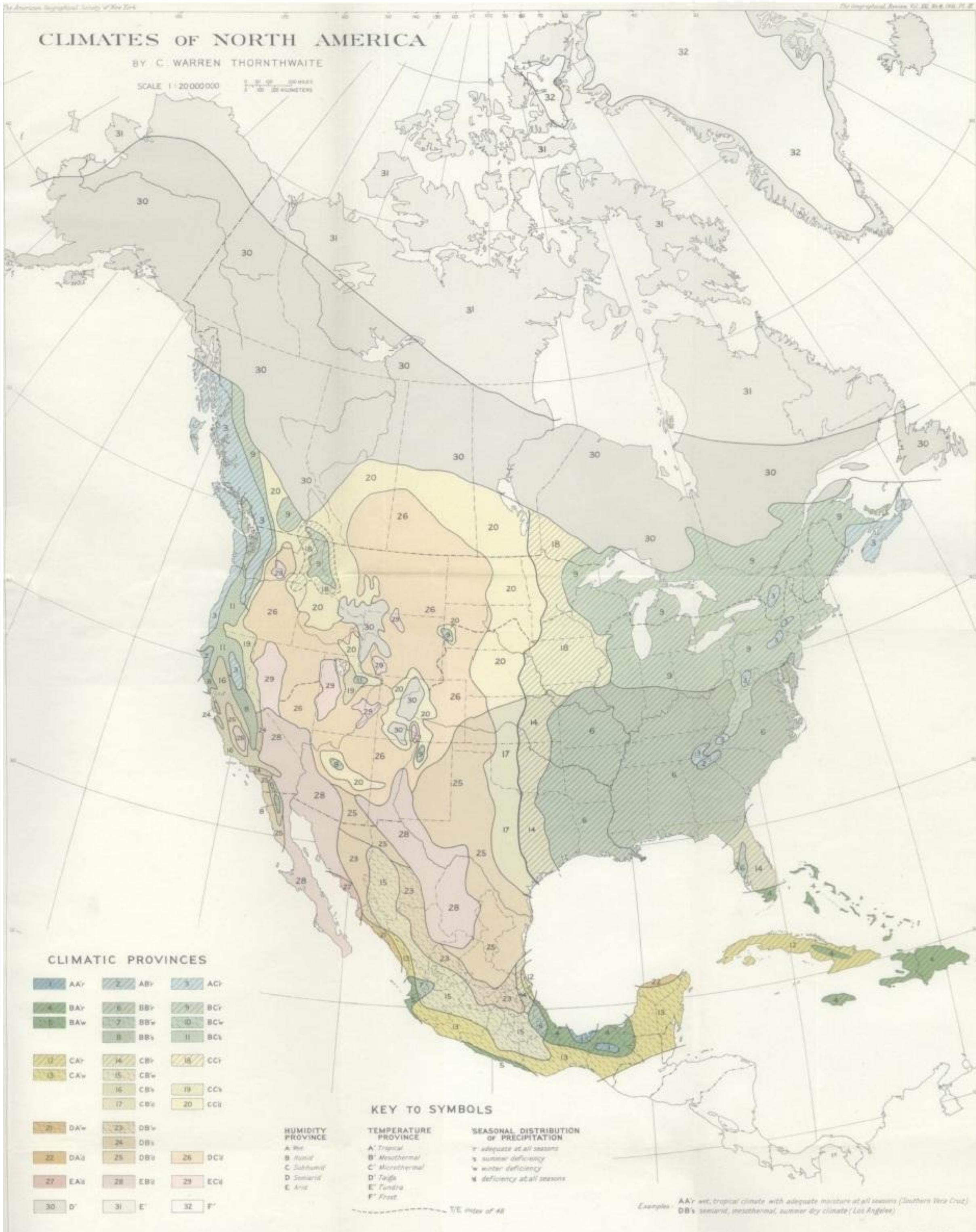
Dwc	Subarctic, short summer, cold winter, winter dry
Dwd	Subarctic, short summer, severe winter, winter dry
ET	Tundra, very short summer
EF	Ice and snow cover all year
H	Highland climate (undifferentiated)

According to Marcus (1979), the Köppen climate classification system is a quintessential example of physical geography today that is also powerful because of its simplicity and intellectual influence. Köppen put his botanical and biological background to work when he created his classification system. Geographic patterns of vegetative growth, or no growth, were a primary determinant for selecting numerical cutoffs for the climate classification scheme. One of the ideas of genius behind Köppen's classification is that the categories are mutually exclusive and that the scheme will work for any place on the planet. Numerical values based on summarizing weather observations are used to determine class membership and justify climate boundaries. *"This may be regarded as Köppen's major contribution to modern climatology, that schemes of classification must rest on an objective, numerical basis"* (Hare 1951, 97). An empirical approach is still the foundation of all major climate classification schemes today. This mindset toward classification approach has held its ground, even with the immense surge of technology over the past one hundred years.

Thornthwaite

Charles Warren Thornthwaite was the father of the water budget approach to climate classification and use of the moisture factor. He criticized Köppen's system for not accounting for this more 'rationale' variable. Thornthwaite stated that the Köppen system was not apt at taking into account evaporation demands and moisture supplies relating to vegetation's needs. Instrumentation, a psychrometer, to measure the evaporation and relative humidity, had come about in the middle of the 19th century. Thornthwaite (1933) took the initiative and created a new climate classification system and produced a worldwide classification map and a North American map (Figure 2.4). His main focus was on potential evaporation (PE). PE is the amount of water that would be evaporated with a continuous water supply present.

Figure 2.4 Thornthwaite climate classification (1942)



Thornthwaite developed his evaporation equation with an understanding of the drivers of plant processes:

$$E = \frac{1.6 \times 10t}{I^b}$$

E - evaporation
t - monthly temperature
I - heat index
b - constant

Thornthwaite then converted the evaporation to a 'thermal efficiency' ratio which he coined potential evaporation.

$$PE = \frac{P}{E}$$

P - monthly precipitation (cm)
E - evaporation, from the above equation (cm)

PE can be considered the energy and water budget of plants and Thornthwaite used these values to create climate boundaries (Table 2.4).

Table 2.4 Thornthwaite climate types (1933)

Region	Humidity Degree	Plants	PE Value
A	Moist	Rainforest	≥ 128
B	Humid	Forest	64-127
C	Subhumid	Grassland	32-63
D	Semi-arid	Steppe	16-31
E	Arid	Little to none	≤ 16

Next Thornthwaite wanted to relate evaporation to temperature and not just use an average monthly temperature like Köppen. To do this he used the following equation to create a temperature efficiency index (I_T):

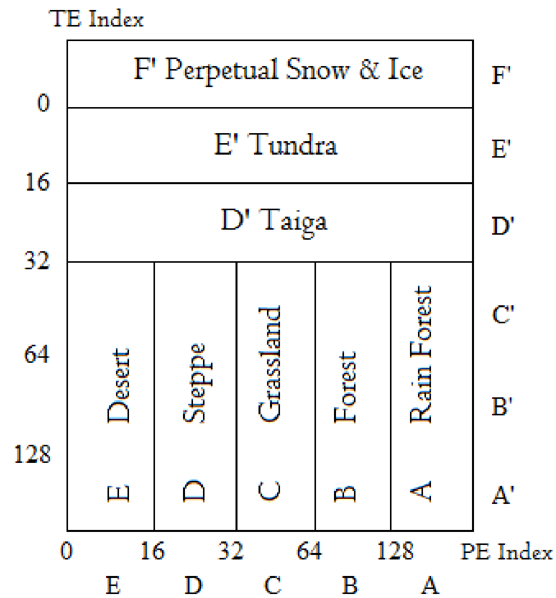
$$I_T = \frac{T}{E}$$

T - temperature
E - evaporation

Then he created temperature index boundaries for each class. The possible major climate types include: tropical, A'; mesothermal, B'; microthermal, C'; taiga, D'; tundra E'; and frost, F' (Figure 2.5). Figure 2.5 is a decision chart that is used to Figure out what climate a specific place is by drawing a point between the intersecting lines of the temperature evaporation (TE) index and PE index.

Lastly a third letter was added to account for adequacy of precipitation across seasons, similar to Köppen's w, s, a, and m subtypes. They include r, adequate all seasons; s, summer deficient; w, winter deficient; d, deficient all seasons. Not every climate class can get each subtype. Each of the three B climates may be divided into r, s, and w, each C climate into r, s, w, and d, and each D climate into s, w, and d. The A climates are always r, and the E climates are always d. (Thornthwaite, 1933).

Figure 2.5 Thornthwaite chart of possible climate types [Source: Essenwanger, 2001]

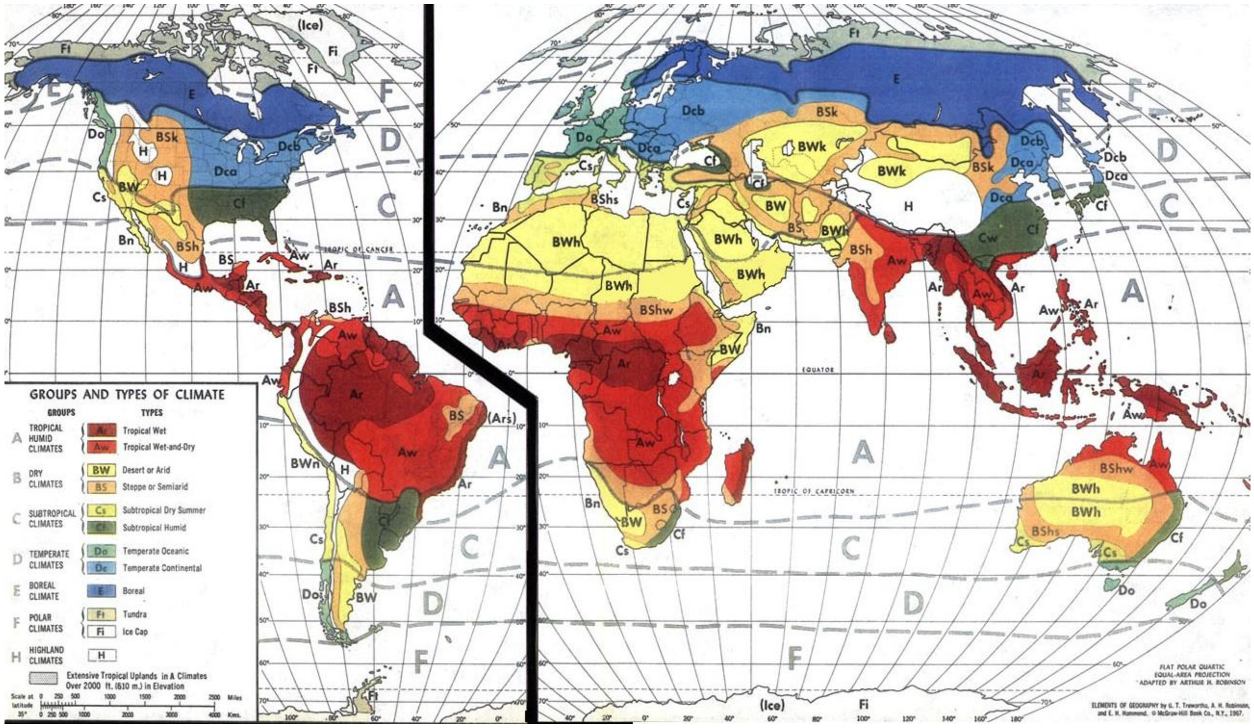


A moisture index is a great way at characterizing climate types in which vegetation will either flourish or perish. One problem with doing these temperature and precipitation indices is that one can theoretically come up with 120 different climate classes/regions using the Thornthwaite system. To combat this he suggested using only thirty two climate zones for classification (Figure 2.4). His classification system is not widely used today, but it was groundbreaking for its time. *"We cannot tell whether a climate is moist or dry by knowing precipitation alone; we must know whether precipitation is greater or less than potential evapotranspiration"* (Thornthwaite, 1948, 55).

Trewartha

Glenn T. Trewartha (1968) created a climate classification system that was a variation of Köppen's but he reduced the number of key climate classes from twenty four to eleven. However, what is relevant to this thesis research is that he created a map of the climate of the oceans (Figure 2.6). Visible in Figure 2.6 is the approach Trewartha took to generally extend land climate types across the oceans. We know today that some of the boundaries drawn here do not make too much sense, but at least he was thinking that climate existed for ocean climates. Trewartha's E climates cover large areas of subpolar continental land, but the extension of this climate type is limited over oceanic areas in the Northern Hemisphere.

Figure 2.6 Trewartha climate classification (1967)



In producing his climate map, Trewartha took into account more than just temperature, precipitation, and evaporation to figure out his climate boundaries. He created a list (Figure 2.7) of 'climate controls' that effect 'climatic elements' and produce different types and varieties of weather and climate (Trewartha, 1967). The water and ocean currents were important to his climate classification.

Figure 2.7 Climate controls [Source: Trewartha, created by author]

Climatic Controls	influence	Climatic Elements
Sun/Latitude		
Land and Water		
Winds and Air Masses	→	Temperature
Altitude	→	Precipitation
Mountain Barriers		Humidity
Semipermanent low & high pressure centers	→	Winds & Air Pressure
Ocean currents		
Storms		

Recent Climate Classification Literature

A search of the journal, Progress in Physical Geography, found no articles that dealt primarily with climate classification during the history of the volume dating back to the first issue in 1977. Articles by Sanderson (1999) and Oliver (1991) tend to be the major exceptions during this period and those articles were primarily reviews of the history of the subject. A recent surge in articles where climatologists have used the Thornthwaite system may be a reflection of the academic training of those who matriculate at the University of Delaware and climatologists may have chosen the subject matter in part to honor Thornthwaite's premier student, John R. Mather (e.g., Grundstein, 2008 and 2009). Other recent examples are of climate studies are a modification to the Thornwaite system (Feddema, 2005) and of the importance of the Thornwaite water balance model (Keim, 2010).

Surface Characteristics of the Oceans

The surface character of the oceans is the theme for this research in climate classification. The oceans regulate weather and climate because oceanic processes greatly influence the Earth's energy, water, and carbon systems. Due to relative size, optical properties, and energy storage properties, oceanic areas absorb much of the solar radiation reaching Earth. The role of the oceans in driving the global atmospheric circulation is critical and large as energy is transferred into the atmosphere as water vapor and then condenses to form precipitation and poleward by ocean currents. Condensation of water evaporated from warm parts of the ocean provides the energy for hurricanes and tropical cyclones. In addition, oceanic areas dominate the Earth's carbon cycle. Half the primary productivity on Earth takes place in the sunlit layers of the ocean and the ocean absorbs roughly half of all carbon dioxide added to the atmosphere (National Marine Educators Association).

Variables

Sea Surface Temperature (SST)

Importance

SST is as important to this classification as air temperature would be to a land based climate classification. Temperature is a main driver of climate so it vital that it be included in as part of the classification scheme. The main difference between an oceanic climate and land climate is temperature (Curry, 1947). Carl Troll (1965) created a table that shows the differences between the hottest month, coldest month, and average annual temperature based on continental land versus land in a close proximity to ocean (Figure 2.8).

Figure 2.8 Ocean versus land temperatures [Source: Troll]

Climates	T_w (°C)	T_c (°C)	A (C°)
Highly oceanic sub-polar (I_4)	5 to 12	−8 to 2	<13
Oceanic boreal (II_1)	10 to 15	−3 to 2	13 to 19
Continental boreal (II_2)	10 to 20	−25 to −3	20 to 40
Highly continental boreal (II_3)	10 to 20	<−25	>40
Highly oceanic cool-temperate (III_1)	<15	2 to 10	<10
Oceanic cool-temperate (III_2)	<20	>2	<16
Sub-oceanic cool-temperate (III_3)	<20	−3 to 2	16 to 25
Sub-continental cool-temperate (III_4)	<20	−13 to −3	20 to 30
Continental cool-temperate (III_5)	15 to 20	−20 to −10	30 to 40
Highly continental cool-temperate (III_6)	>20	−30 to −10	>40

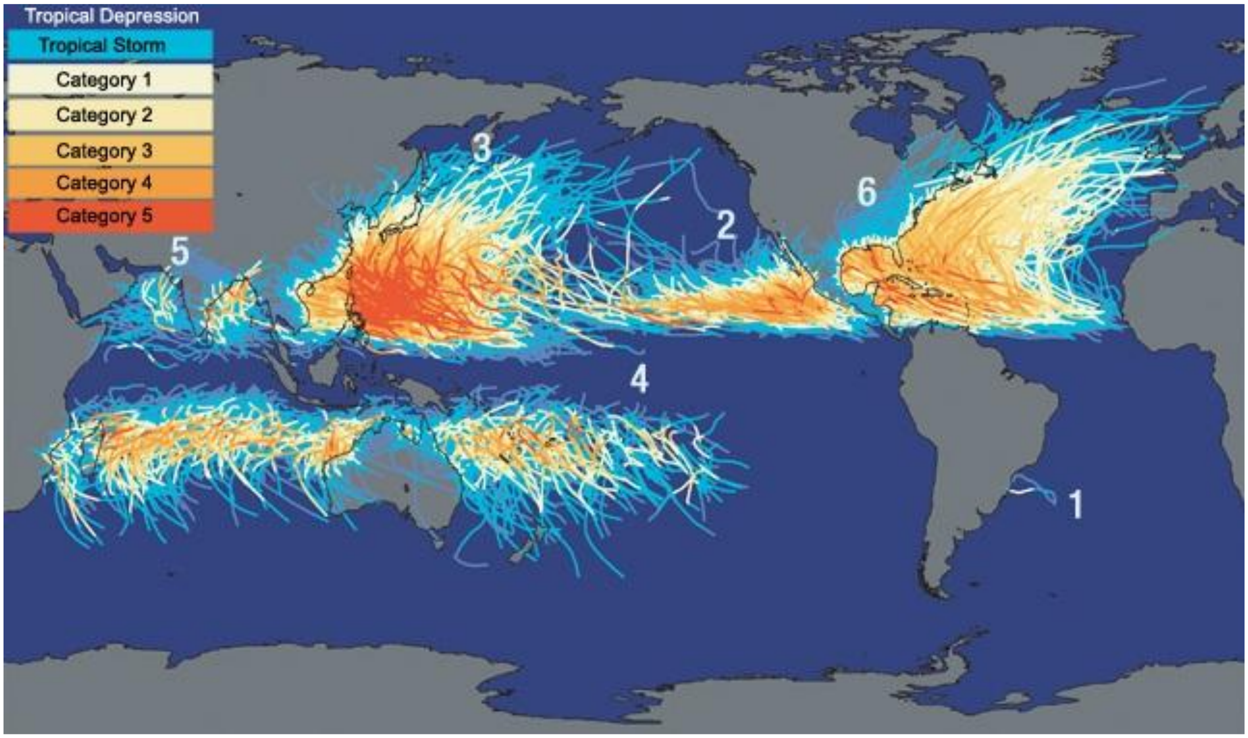
[a] T_w = warmest-month mean temperature; T_c = coldest-month mean temperature; and A = annual temperature range.

Another reason temperature is important to a climate classification is because it helps distinguish deserts and polar areas from one another otherwise they would be classified in the same category due to the low precipitation totals in very cold environments. In classification decision trees, these climates have to be delineated first. The polar climate (E) is figured first since there is close to zero precipitation all year round. This is followed by the arid climates (B) where precipitation begins to further fragment the climate boundaries (Kottek *et al.*, 2006). Temperature is obviously more important to a land based classification system because extreme temperatures can keep plants and animals from thriving in certain areas.

Hurricanes

The oceans play the primary role in the formation of hurricanes/cyclones through energy storage and release (warm SSTs). Areas of warm SSTs provide the input for the power that generates cyclones because the warm surface helps decrease atmospheric stability, which in turn increases the possibility of penetration depth by a vortex (Goldenberg *et al.*, 2001). A local SST value of at least 26.5 °C is required for tropical cyclone development. Also, the higher the SST the more likely a violent tropical storm will be generated (Saunders and Harris, 1997). Figure 2.9 shows where hurricanes have originated over the last 150 years. Many of the hurricanes and tropical storms originate on a seasonal cycle within the area where the intertropical convergence zone (ITCZ) makes maximum pole ward movement.

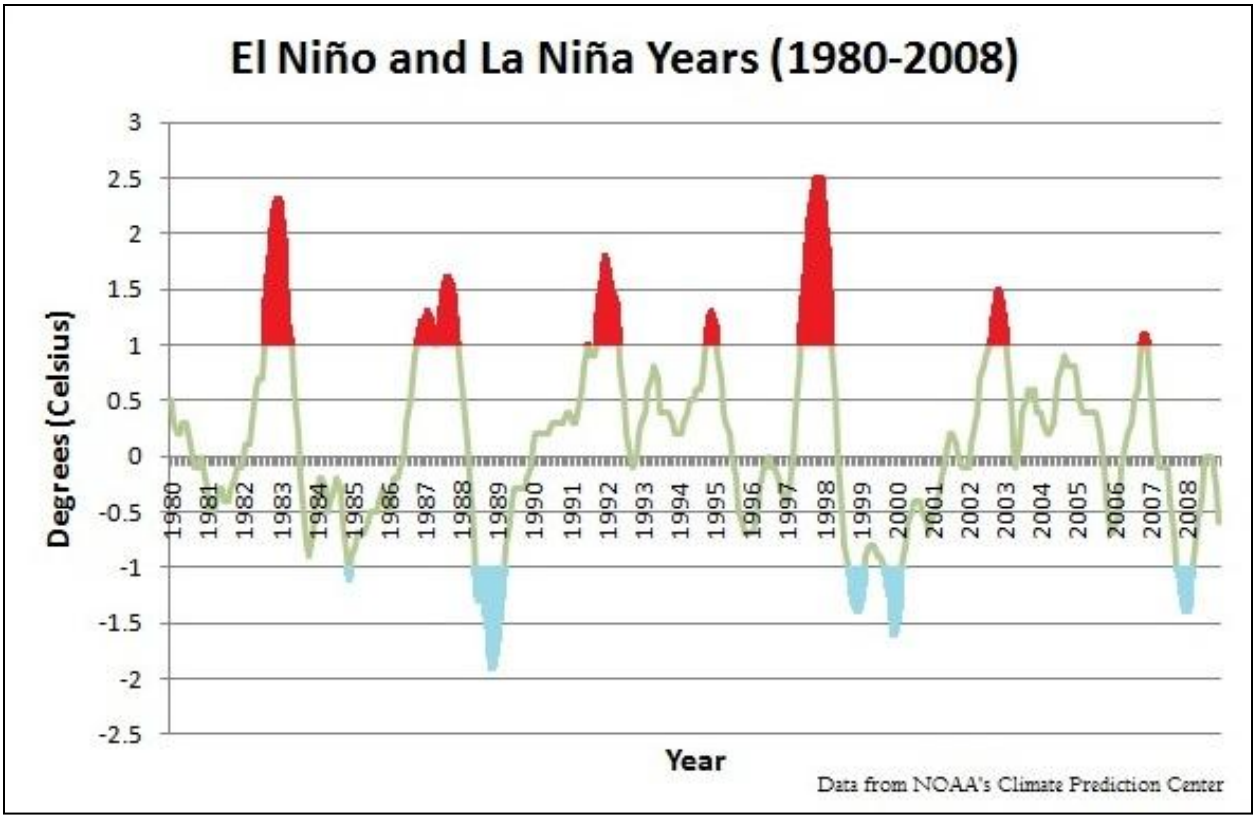
Figure 2.9 Hurricane origin points [Source: Robert Rhode, Discover Magazine 2007]



El Niño and La Niña

El Niños are time periods distinguished by warm ocean temperatures in the eastern equatorial Pacific Ocean which are out of the ordinary. El Niño is an oscillation of the ocean and atmospheric systems in the tropical Pacific which has important consequences for weather around the globe. El Niño has become very recognized in recent years as a dominant source of inter-annual climate variability around the world. These events usually occur irregularly, approximately every two to seven years. The El Niño years in this study that had at least a 1.0°C above average SST during its runtime are: **1982-83**, 1986-88, 1991-92, 1994-95, **1997-98**, 2002-03, and 2006-07. The bolded items are years in which major El Niño events took place. La Niña is the opposite of El Niño; when the eastern equatorial Pacific temperatures are unusually low. The years that were at least a 1.0°C below normal during this study are: 1984-85, 1988-89, **1998-2000**, and 2007-08 (Figure 2.10). The peak of the oscillations are usually around either November or December. It is unknown what causes an El Niño or La Niña, but both effect the climate of the whole planet when they take place.

Figure 2.10 El Niño and La Niña years [Source: Data from NOAA Climate Prediction Center, graph created by author]

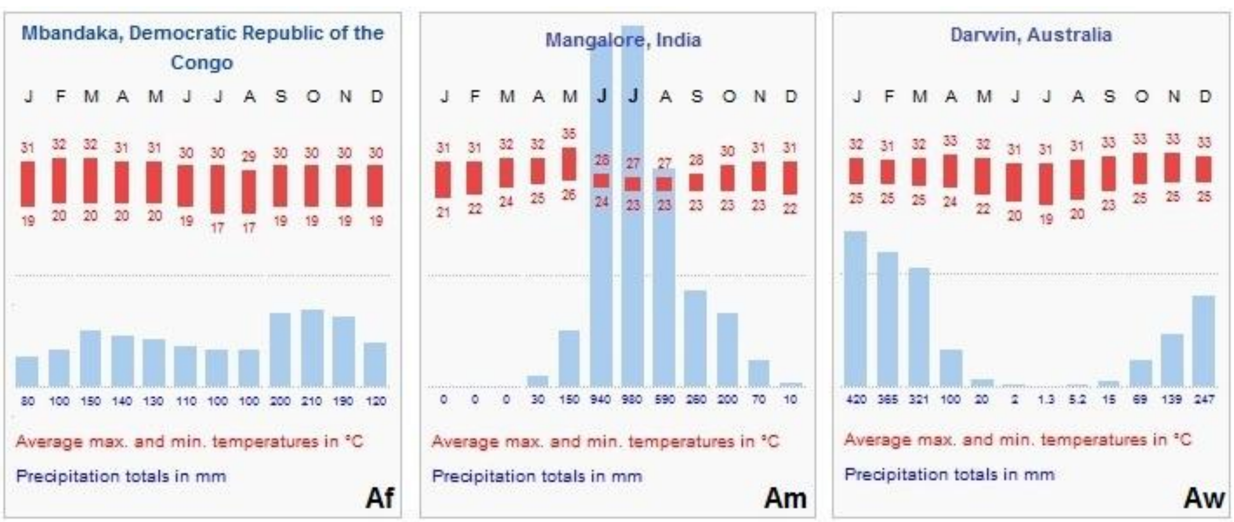


Precipitation

There is a general consensus that the character of precipitation will change as an area's climate changes and therefore it is important to understand its geographical nature. Studying historical precipitation data is vital to climate classification (Lenderink & Van Meijgaard, 2008). To try and quantify climate change scientists investigate climate state variables such as precipitation and temperature (Brutsaert *et al.*, 1998 & Karl *et al.*, 1996). Precipitation is considered as the primary variable in a climate study done by Semenov *et al.* (1997) and they used it in constructing climate change scenarios based on spatial regression downscaling and on the use of a local stochastic weather generator. The other variables used were maximum and minimum temperature and solar radiation which were all 'on a given day conditioned to whether the day is wet or dry' (Semenov *et al.*, 1997). These studies are just a few among countless others that show how important precipitation in to classifying climate.

Precipitation is key in climate classification because it helps divide climate boundaries further than just using temperature would allow. In the Köppen system, the A (tropical) and B (arid) climates are subdivided solely on precipitation. They both have somewhat comparable temperature averages, but their precipitation patterns could not be more dissimilar. Within each main group climates are further subdivided based on precipitation amount as well as seasonality. For instance the tropical climate is divided up into tropical rainy (Af), monsoonal (Am), and wet seasonal (Aw). The thing that differentiates each climate is its specific precipitation levels and timing. The Af subtype (Figure 2.11) is defined by having twelve months of precipitation greater than or equal to 60 mm. The Am subtype (Figure 2.11) is marked by a driest month with rainfall less than 60 mm, but more than 100 - total annual precipitation mm/25. The main characteristic of the Am climate is a dry season coupled with a wet season. Lastly the Aw sub-type (Figure 2.11) is where the driest month still has less than 60 mm of precipitation (otherwise it is classified Af if it as more) and less than 100 − total annual precipitation mm/25 (if it is more than it becomes an Af climate).

Figure 2.11 Climographs [Source: National Climatic Data Center and the Australian Government Bureau of Meteorology]

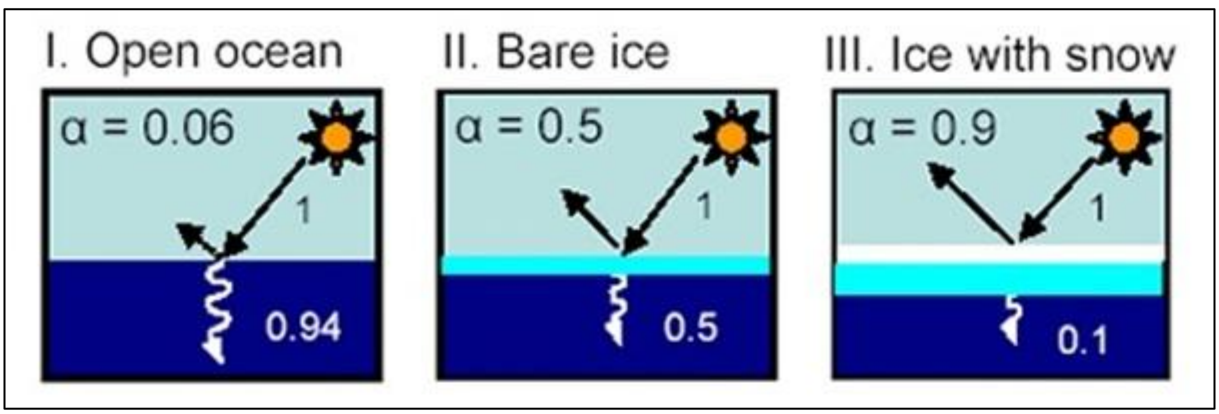


Sea Ice Coverage

Sea ice is found only in remote polar oceans. On average, sea ice covers about 25 million km^2 of the earth which is around 15% of the oceans at a given time (NSIDC). Although sea ice may not directly affect most people on Earth, it is a critical component of our planet because it influences climate, wildlife, and the people who live in the Arctic. It is also an important factor in climate change, especially in the Arctic and Antarctic regions. *"The formation, persistence, and decay of sea ice plays a crucial role in creating distinct physical and chemical habitat conditions and microclimates"* (R. A. Smith, 1999, 577).

A main role that sea ice plays in climate is through the ice-albedo feedback mechanism. It is thought to have a cyclical effect on the planet warming. Instead of the water absorbing the heat from the sun's rays the ice reflects the rays back up. Sea ice cover acts to maintain a low-energy state by creating a high surface albedo (α), bare ice $\alpha = 0.5$, ice with snow cover $\alpha = 0.1$, and open ocean $\alpha = 0.06$ (Figure 2.12). Ice cover limits turbulent heat exchange between the ocean and overlying atmosphere, therefore contributing to each polar heat sink (Nakamura & Oort, 1988).

Figure 2.12 Ocean, ice, and snow albedo [Source: National Snow and Ice Data Center]



Global Change

"About 70 percent of the Earth's surface is water-covered, and the oceans hold about 96.5 percent of all Earth's water" (USGS). People should be concerned about the climate for over two thirds of our planet. Classification can help predict what will happen in a chain of events. For instance, the Intergovernmental Panel on Climate Change (IPCC) findings indicate that the Earth has and is experiencing warming since the late 19^{th} century as well as a positive

(1%) global trend in precipitation over land (Houghton *et al.*, 1995). There is a general sense of concern that recent increases in heavy and prolonged precipitation is attributable in some measure to anthropogenic global warming (Palmer & Räisänen, 2002). This will have an enormous effect on the planet not only from flooding, but also in growing produce. A warmer and wetter climate will lead to drastic changes in agriculture geography and choosing crops suitable for the changing environments.

Another impact of this warming is a rise in global sea level. Nearly one-half of the 6.7 billion people around the world live near the coast and are highly vulnerable to storms and sea level rise. In the United States, coastal populations have doubled over the past fifty years, greatly increasing exposure to risk from storms and sea-level rise (Williams *et al.*, 2009). Vulnerability to sea level rise will continue being a threat to populations in low lying coastal areas. Global sea level is rising and there is evidence the rate is accelerating. Evidence of inundated coastlines, coastal erosion, and other impacts caused by sea level rise can be linked with the increasing atmospheric concentrations of greenhouse gases. Rising sea level poses a major threat to coastal cities, beaches, habitats for flora and fauna, and even whole countries in some situations. How people respond to sea level rise in the coastal zones across the world will have many positive and negative economic and environmental costs.

Causes of Global Sea Level Increase

"Global average sea level rose approximately 1.7 mm per year through the twentieth century. Observations suggest that the rate of global sea level rise may be accelerating" (Williams *et al.*, 2009, 2). This may not seem like too large of a number, but when everything is accumulated over a long period of time it begins to put economic pressure on coastal cities and their residents. An even more alarming statistic is the IPCC projection that global sea level will likely rise between 19 and 59 centimeters (cm) by 2100. It has been proven that global surface temperature has been constantly increasing over the past thirty years and it has no correlation with the sun's energy output (Figure 2.13).Warmer mean temperatures raise sea level by expanding ocean water, melting glaciers, and can increase the rate at which ice sheets discharge ice and water into the ocean. An accumulation of greenhouse gasses (e.g. carbon dioxide) in the atmosphere causes a more pronounced greenhouse effect that correlates with this rise in global temp-

Figure 2.13 Sun's energy output compared to global surface temperature [Source: National Climatic Data Center]

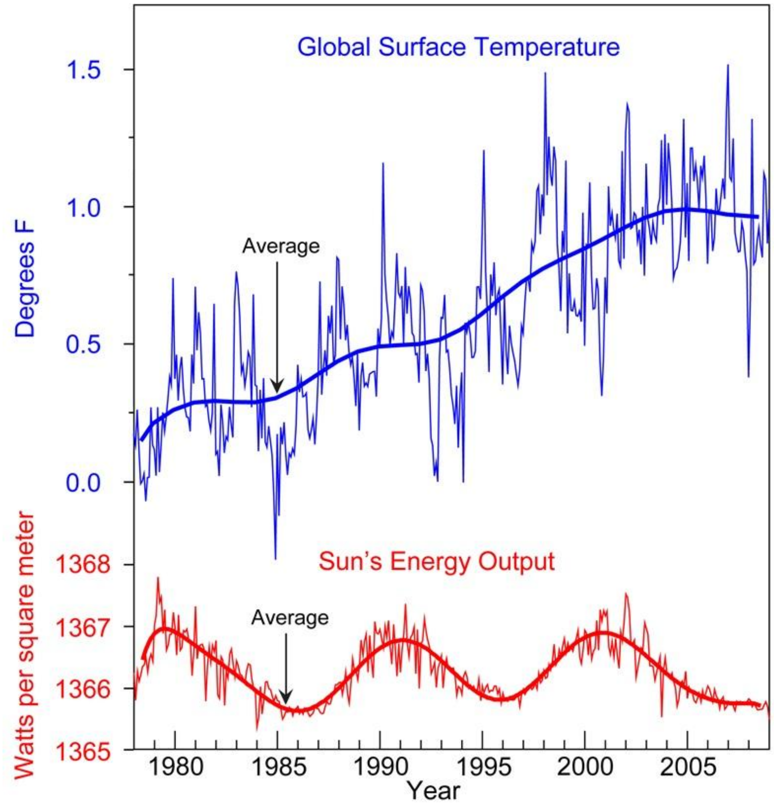
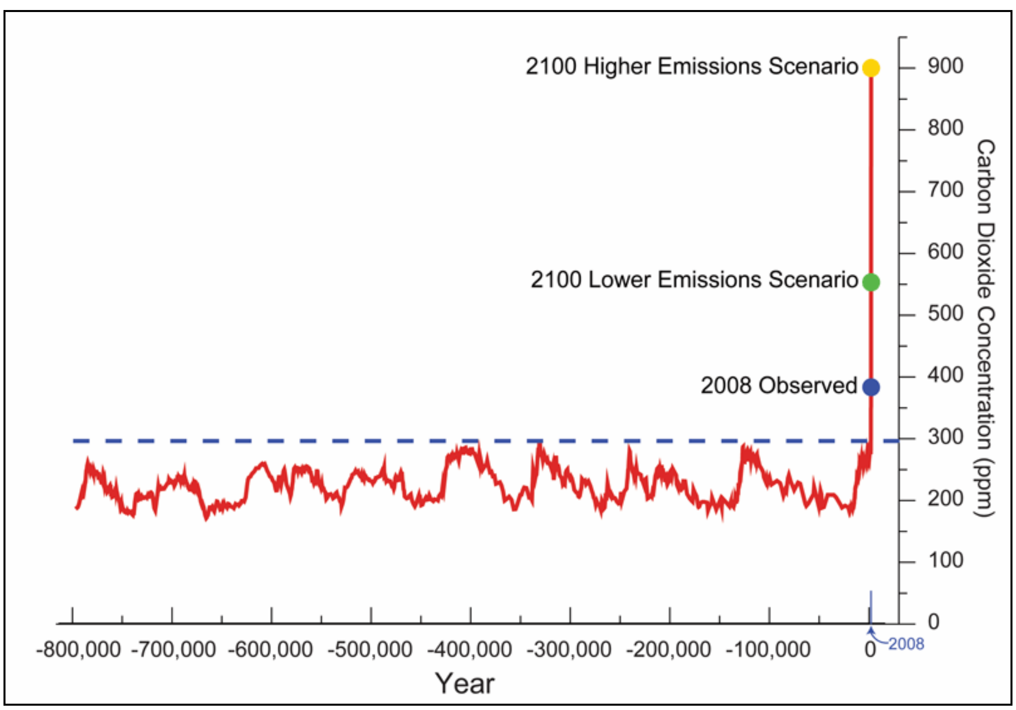
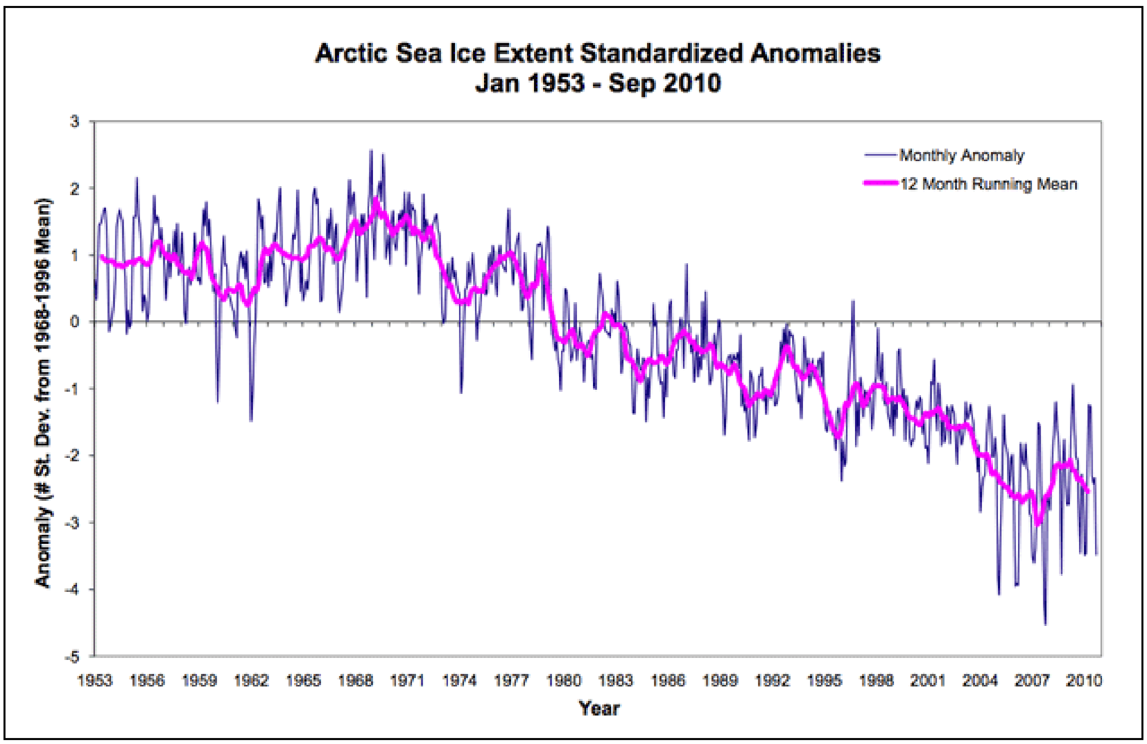


Figure 2.14 Carbon dioxide concentration [Source: National Climatic Data Center]



erature (Figure 2.14). Another result of temperatures increasing is glaciers and ice sheets melting across the planet. The total volume of glaciers on Earth is declining and have been retreating worldwide for at least the last century and the rate of retreat has increased in the past decade. Also the extent of sea ice has declined dramatically since as recent as the 1980's (Figure 2.15). These are just a few pieces of evidence suggesting that sea level change is resulting from anthropogenic forces. Other hard data are ocean surface temperature level is rising, snow cover is retreating, and climate extreme frequencies, such as precipitation, temperature, and storm intensity are on the rise.

Figure 2.15 Passive microwave-derived (SMMR/SSM/I) sea ice extent for the Northern Hemisphere [Source: National Snow and Ice Data Center]



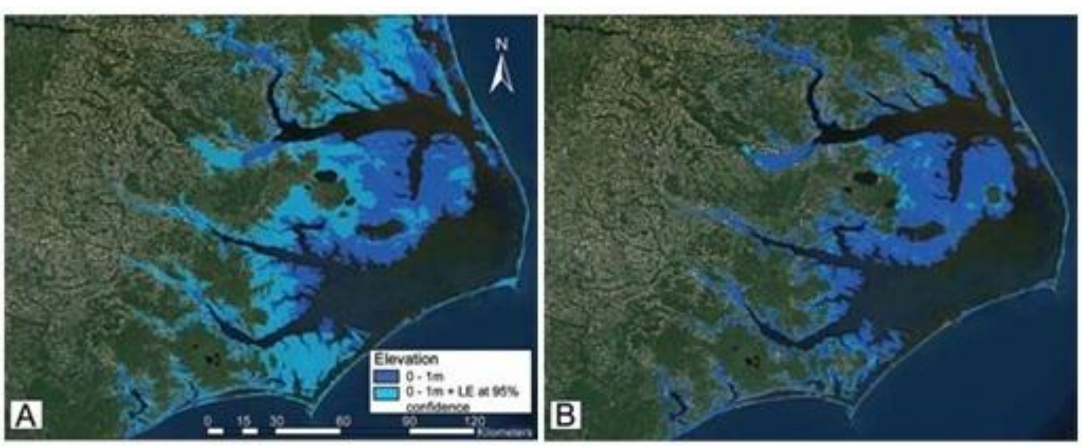
Impacts of Sea Level Rise on Coastal Areas

With sea level rise imminent coastal areas are going to be physically altered with the influx of water. Some of the instant impacts will be land loss and shoreline retreat from erosion and inundation, an increase in the frequency of storm-related flooding, and intrusion of salt water into coastal freshwater aquifers (Cahoon *et al.*, 2009). The responses to sea level change can be complex and complicated. The following is a list that was complied to show how sea level rise can be broadly characterized (Leatherman, 2001; Valiela, 2006; FitzGerald *et al.*, 2008):

- Land loss by inundation of low-lying lands
- Land loss due to erosion
- Barrier island migration, breaching, and segmentation
- Wetland accretion and migration
- Wetland drowning
- Expansion of estuaries
- Saltwater intrusion
- Increased frequency of storm flooding

The two main responses of sea level rise that will physically alter coastal environment are either erosion or inundation of the coastline. Studies have shown that sheltered, low energy coastal areas where sediment influx is minimal and wetlands are absent or are unable to build vertically in response to rising water levels, may be submerged. In these cases, the extent of inundation is controlled by the slope of the land, with a greater degree of inundation occurring in the areas with more gentle gradients (Leatherman, 2001). Inundation will likely occur only if there is an extreme change in sea level rise, say at least one meter (m) per year. If the change occurs more slowly, that will give the waves and currents a chance to physically modify the landscape, such as accumulation if sand in some areas and degradation in others, making the transformation less pronounced. The best way to determine how much inundation will occur is to use elevation data. However, remote sensing instruments can barely record data at a sub-meter resolution therefore measuring the impact across the globe is very difficult. On a larger scale Light Detection and Ranging (LIDAR) data can be used to measure coastlines and is accurate up to 15cm. Figure 2.16 shows the results of the North Carolina mapping comparison.

Figure 2.16 Inundation prediction levels [Source: Gesch]



In Box A the darker blue tint represents the area at or below 1m in elevation, and uncertainty lighter blue tint represents the additional area in the vulnerable zone given the vertical of the input elevation datasets. The more accurate LIDAR data for delineation of the vulnerable zone results in a more certain delineation (B), or in other words the zone of uncertainty is small (Gesch, 2009).

Effects on Animal Habitats

The drastic change of the wildlife's surroundings could be considered the most devastating impact of all relating to sea level rise. Ecosystems and animals in these regions have no way to prepare themselves, unlike humans who can alter their environment around them and fit it to their needs. As evidence of the danger Williams *et al.* (2009, 4) noted that, *"In the mid-Atlantic region acceleration in sea-level rise by two mm per year will cause many wetlands to become stressed; it is likely that most wetlands will not survive acceleration in sea-level rise by seven mm per year."* Sea level is already rising above this rate. Cahoon *et al.* (2009) states it is virtually certain that tidal wetlands already experiencing submergence by sea-level rise and associated high rates of loss will continue to lose area under the influence of future accelerated rates of sea level rise and changes in other climate and environmental drivers. It is also unlikely there will be an overall increase in tidal wetland area on a national scale over the next one hundred years because of current wetland loss rates and the relatively minor accounts of new tidal wetland development.

Wetlands are not the only ecosystem affected by sea level change. Tidal marshes, sea level fens, submerged aquatic vegetation, tidal flats, estuarine beaches, and cliffs will all be altered or impacted by sea level increases. Based on currently available information, it is possible to identify particular groups and even some individual species that appear to be at greatest risk if coastal habitats are degraded or destroyed in response to sea level rise (Shellenbarger et al., 2009, 83).

> *"Degradation and loss of tidal marshes will affect fish and shellfish production in both the marshes themselves and adjacent estuaries. Bird species that are marsh specialist…are particularly at risk. At present, the majority of the Atlantic Coast breeding populations of Forster's tern and laughing gull are considered to be at risk from loss of lagoonal marshes."*

Many marsh islands have already been destroyed or reduced as a result of erosion and flooding related to sea-level raising that has already taken place. Loss of these islands poses a serious threat to bird species of all kinds. Many tidal forest associations may be at risk from sea level rise and a variety of other threats, and are now considered globally imperiled. Loss of tidal flats could lead to increased crowds of foraging birds in remaining areas, resulting in exclusion of many individuals, if alternate foraging areas are unavailable, starvation of excluded individuals may result, ultimately leading to reductions in local bird populations (Shellenbarger *et al.* 2009). Another consequence of tidal flat loss is causing birds to retreat inland to look for food which would result in changes and even destruction of other ecosystems not equipped to meet these bird species needs.

Why We Need to Classify the Climate of the Oceans

Ideas presented in this review of literature on climate classification suggest that classification is an important scholarly activity that helps us to better understand the phenomena we are trying to study. The Köppen system for climate classification is the standard approach and that oceanic areas are important in the function of the Earth system. Given a general lack of maps of the climate of the ocean areas, the objective of this thesis research is to use the Köppen system and generate maps of the climate of the oceans.

Chapter 3 - Data & Methods

Data Sources

The data for sea ice coverage was obtained from the National Snow and Ice Data Center (NSIDC). They have created shapefiles that are available from their File Transfer Protocol (FTP) directory /DATASETS/NOAA/G02135/shapefiles/ at sidads.colorado.edu. The data available for use is from November 1978 to present in both polygons and polylines format. Only polygons from January 1980 - December 2008 were used to be temporally consistent with the SST and precipitation data acquired. This is binary data with either sea ice coverage or no coverage associated with each polygon.

The SST data set was acquired from the Earth System Research Laboratory (ESRL). The data were made available via a network Common Data Form (NetCDF) file downloadable from the following site http://www.esrl.noaa.gov/psd/data/gridded/data.noaa.ersst.html.

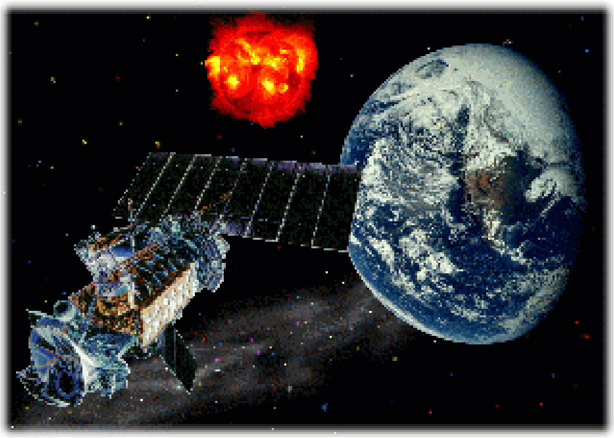
Temporal coverage is in monthly values beginning January 1854, but because of sparse data the analyzed signal is heavily damped before 1880. Again only data from January 1980 to December 2008 were used. The unit of measure is average monthly SST in degrees Celsius.

Precipitation data was also obtained from the ESRL and can be found at the website http://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html. It is in a NetCDF format as well and the temporal resolution is January 1979 to September 2009. Since 2009 was just a partial year, it was decided to use only data through December 2008. The unit of measure is mm per day (mm/day).

Spatial Resolution, Satellites, and Measuring Instruments

The sea ice coverage data is generated from brightness temperature data derived from the Scanning Multichannel Microwave Radiometer (SMMR) located on the Nimbus-7 pathfinder satellite and the Special Sensor Microwave/Imager (SSM/I) mounted on the Defense Meteorological Satellite Program (DMSP) -F8, -F11, and -F13 satellites (Figure 3.1). The spatial resolution is a grid cell size of twenty five km^2. This product is designed to provide a consistent time series of sea ice concentrations (the fraction, or percentage, of ocean area covered by sea ice) spanning the coverage of several passive microwave instruments. To aid in this goal, sea ice algorithm (Comiso, 2008) coefficients are changed to reduce differences in sea ice extent and area as estimated using the SMMR and SSM/I sensors. The data are generated using the National Aeronautics and Space Administration (NASA) Team algorithm developed by the Oceans and Ice Branch, Laboratory for Hydrospheric Processes at NASA Goddard Space Flight Center (Cavalieri *et al.* 2008).

Figure 3.1 DMSP Satellite [Source: National Oceanic and Atmospheric Administration]



The SST data were measured both in situ and by the advanced very high resolution radiometer (AVHRR) located on NOAA's polar orbiting satellite named the Polar Operational Environmental Satellite (POES) (Figure 3.2). The in situ measurements are made by both ships and buoys. The SST was constructed using the most recently available International Comprehensive Ocean-Atmosphere Data Set (ICOADS) SST data and improved statistical methods that allow stable reconstruction using sparse data. The data are given as points on a 2° latitude by 2° longitude grid of the Earth.

The precipitation data were estimated using values obtained by five kinds of satellite estimates, global precipitation index (GPI), outgoing longwave radiation precipitation index (OPI), SSM/I scattering, SSM/I emission, and the microwave sounding unit (MSU). The measuring instruments that acquired the data are mounted on the DMSP satellite. Also, the measurements are supplemented by a blended National Centers for Environmental Prediction (NCEP)/ National Center for Atmospheric Research reanalysis (NCAR) calculation. The spatial resolution of the output data are a 2.5° latitude by 2.5° longitude grid and is not for just the ocean like the SST and sea ice coverage are, but for the whole globe.

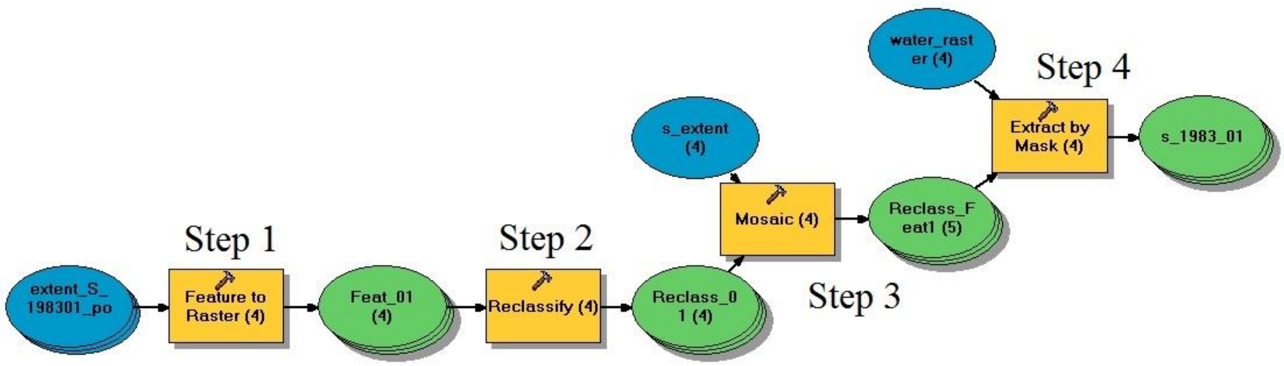
Figure 3.2 POES Satellite [Source: NSIDC]

Data Management

Sea Ice Coverage

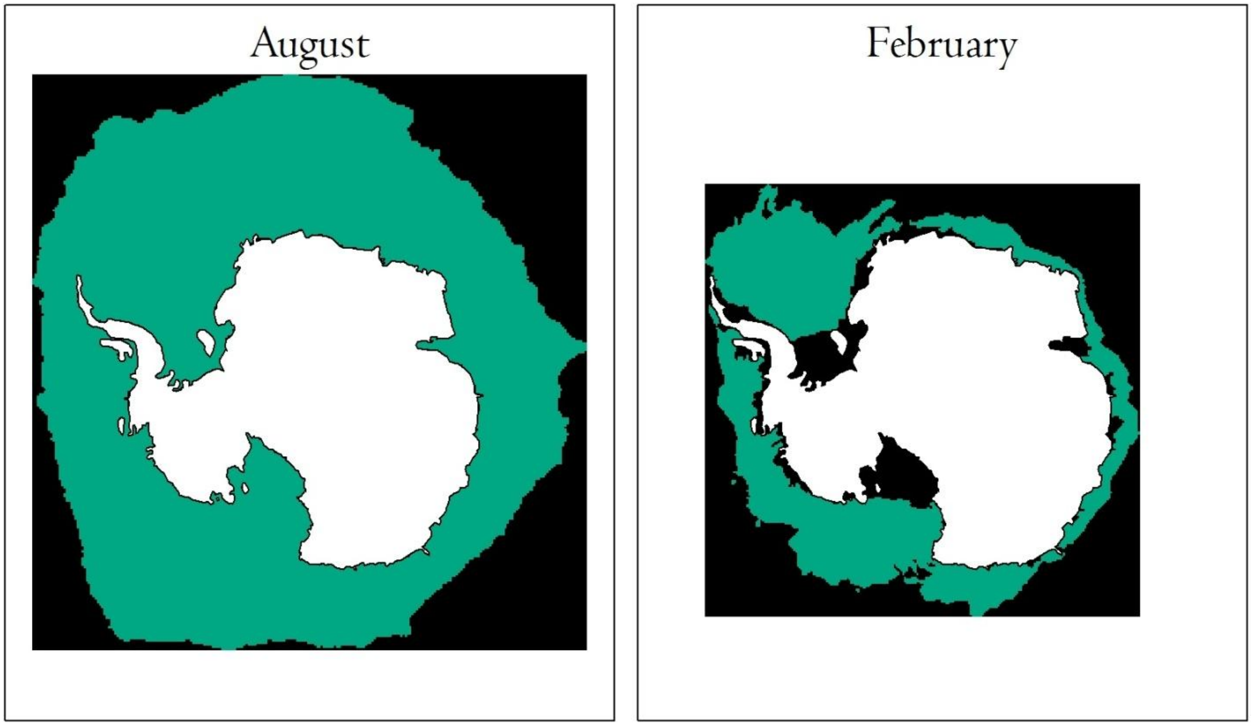
The sea ice coverage was downloaded as an ESRI shapefile. After obtaining the Arctic and Antarctic data for each month there were a number of steps that needed to be executed in order to properly analyze it. The steps (Figure 3.3) are done using ArcGIS ModelBuilder, part of the ArcGIS 9.3 suite. Step 1 converts the data from a shapefile into a raster using the feature to

Figure 3.3 Sea ice data processing model [Source: created by author]



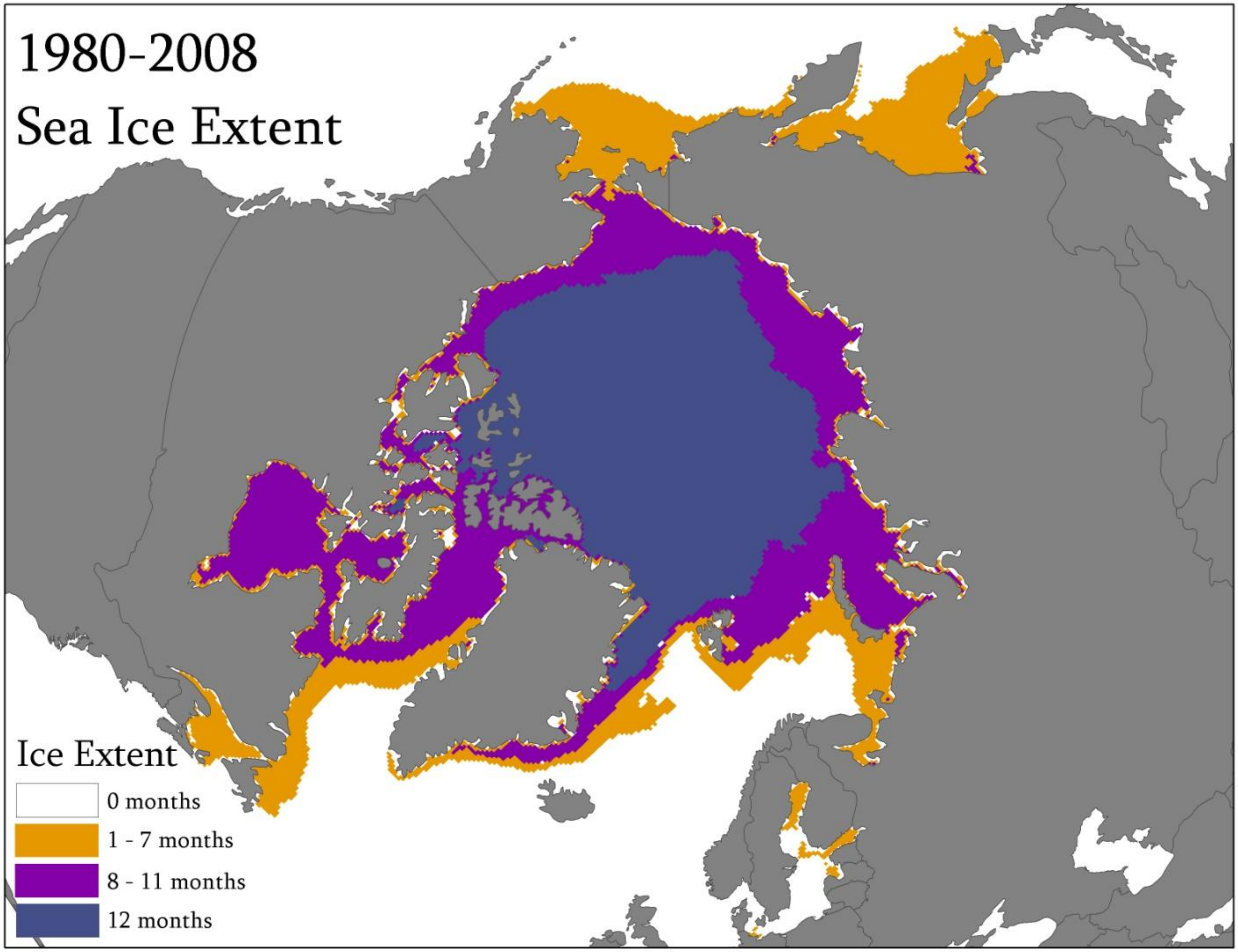
raster tool. Once in raster format the data needs to be reclassified, using the reclassify tool, into ones and zeros which is done in step 2. All the ones are considered ice covered and all the zeros are considered not ice covered. The next step is then to mosaic an extent area to the reclassed raster, step 3. This has to be ran because when the reclassify is done the extent of the new raster only goes as far as the furthest grid cell with a value of one. In the Antarctic the raster extent for August is much further than that of February (Figure 3.4). In a later step when trying to merge months together there are issues with getting data to merge correctly past the month with least ice extent and therefore the mosaic was necessary to add further open ocean extent to the warmer months' rasters. Now that all the rasters have the same boundaries the land is clipped out using the extract by mask tool seen in step 4. Next in the process is to combine all months into their respective ice year. This is done using the raster calculator. Since each raster contained zeros (land/non-ice covered water) and ones (sea ice), the 12 monthly cell values are simply added together creating a new raster with ratio data. If an output cell has a value of 5 it can be inferred that the location contained ice for five of the twelve months of that year. The same process is also done for the Northern Hemisphere totaling 696

Figure 3.4 Antarctic winter (August) versus summer (February) ice extent [Source: created by author]



individual raster maps combined into twenty nine years of Arctic and Antarctic sea ice concentration. After all the maps are made, a reclassification is run on each raster to parcel out the data into a more readable format. The divisions are based on the animals that live in polar habitats and the amount of sea ice needed by the animals that live in that habitat to thrive with. Some of the major animals sea ice requirements are as follows: seals require twelve months of sea ice and polar bears need around 245 days of ice so roughly eight months because the three to four summer months they go ashore to hibernate (Molnar *et al.*, 2010) Humans need eight to ten months of sea ice presence in many western and northern Alaskan coastal communities, for whom it is essential as a buffer against coastal storms. It is also essential to their economic industries such as fishing, marine transportation and offshore resource extraction (ACCAP). Lastly, penguins need at least eight months of sea ice for their chicks to grow up (Wilson *et al.*, 2001). Being that the minimum amount required by any animal to live and thrive is eight months it was chosen as the main break value. The monthly data for the twenty five km^2 grid cells were classified into four categories: 0 (no sea ice), 1-7 (vulnerable zone), 8-11 (adequate zone), and 12 months (stable zone) (Figure 3.5).

Figure 3.5 Arctic sea ice modal map 1980-2008 [Source: created by author]



Sea Surface Temperature

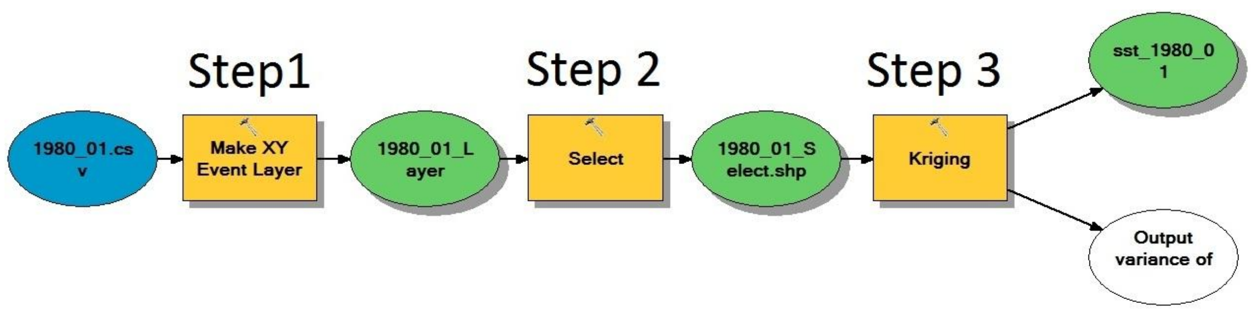
SST data were downloaded as a NetCDF file and then opened with Microsoft Excel using a converter created by Alexander Bruhns called NetCDF4Excel v1.7 (Table 3.1). The first step

Table 3.1 SST data from ESRL [Source: created by author]

A	B	KS	KT	KU	KV	KW
long	lat	200503	200504	200505	200506	200507
144	62	327.67	327.67	327.67	327.67	327.67
144	60	-0.79	-0.42	2.09	7.22	12.80
144	58	-1.41	-0.83	2.00	6.76	12.16
144	56	-1.30	-0.39	1.84	5.90	10.97
144	54	-0.93	0.07	1.91	5.39	10.15
144	52	-0.83	-0.66	2.29	5.52	10.13
144	50	-0.53	0.12	2.84	6.14	10.68
144	48	0.52	1.71	3.50	7.14	11.62
144	46	1.40	2.54	4.36	8.40	12.67

taken was to create an individual excel file with the longitude, latitude, and SST for each month. To do this a macro was created and all 348 files were created using 'year_month' as a naming convention and saved as a comma separated values (.csv) document. This makes the data compatible with ArcGIS and therefore can be entered into an ArcModelBuilder model (Figure 3.6). Step one takes the .csv files that are created and makes a point feature class out of them, along

Figure 3.6 SST data processing model [Source: created by author]



with giving each a spatial reference. For this instance the Geographic Coordinate System World Geodetic System of 1984 (GCS_WGS_1984) is used. Step 2 runs the select tool on the data to gather all of the cell values that contain actual SST data. All the land cells are given a value of 327.67 since there is no way SST can reach this temperature. This can be seen in the top row of table 3.1 where the longitude of 144 and latitude of 62 is in northeastern Russia and the latitudes below fall in the Sea of Okhotsk. The reason these values need to be extracted is because when the kriging is ran and these land cells values are taken into account by the interpolation step it skews the data of all the coastal areas. Figure 3.7 shows what the data looks like if the select tool is not used before the kriging is done. The last step of the model does the kriging interpolation. A local operation taking into account the nine nearest neighbors of each cell was used as well as the exponential version of the kriging operation. The reason this number of neighbors and kriging type was chosen is because the root mean squared error (RMSE) was only 0.045 (Figure 3.8), which means the standardized possible error of any place on the map is only four hundredths of a degree Celsius, and this was the lowest RMSE that could be achieved among the possible kinds of kriging methods available in ArcMap.

Figure 3.7 Coastline kriging error [Source: created by author]

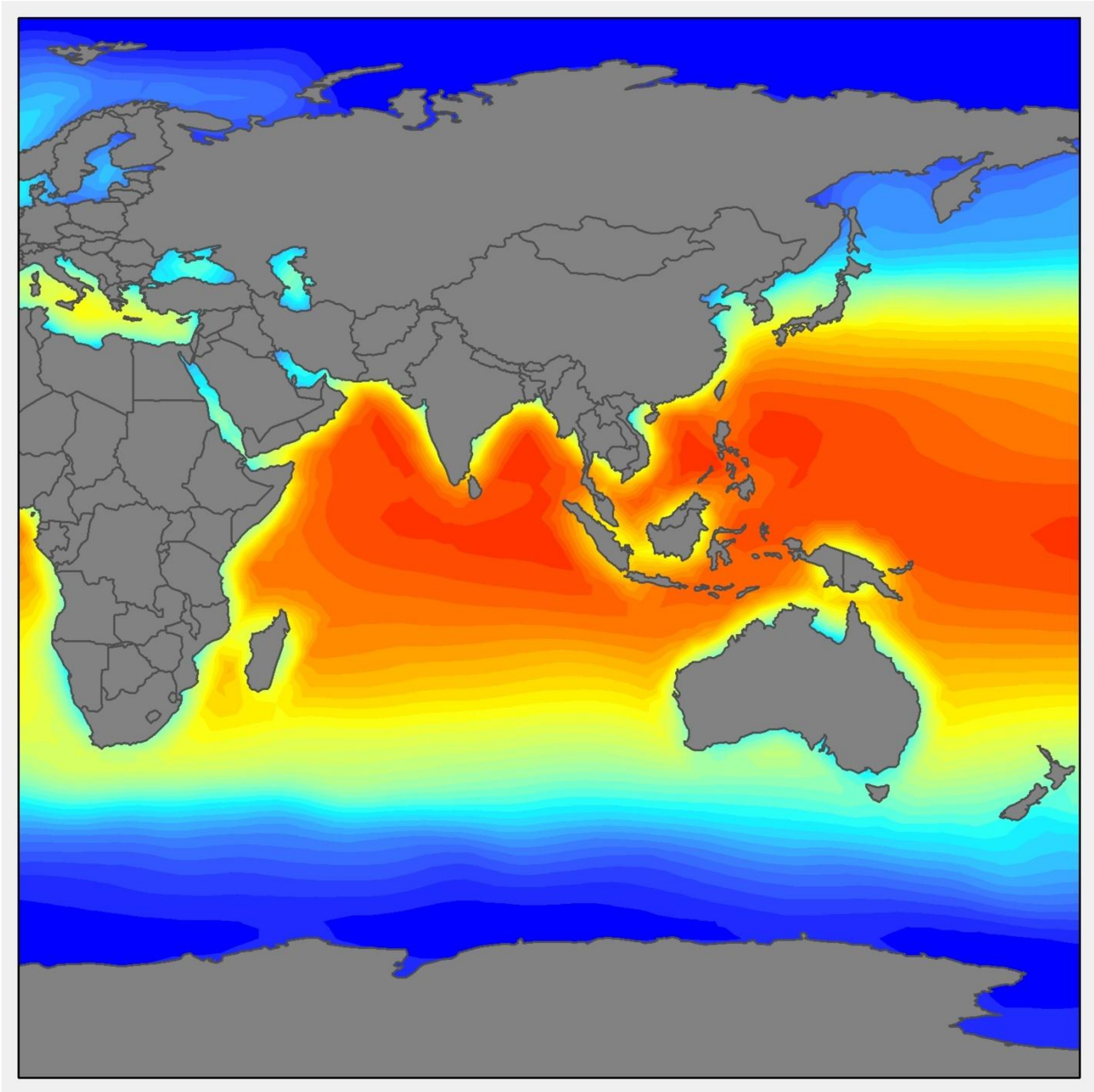
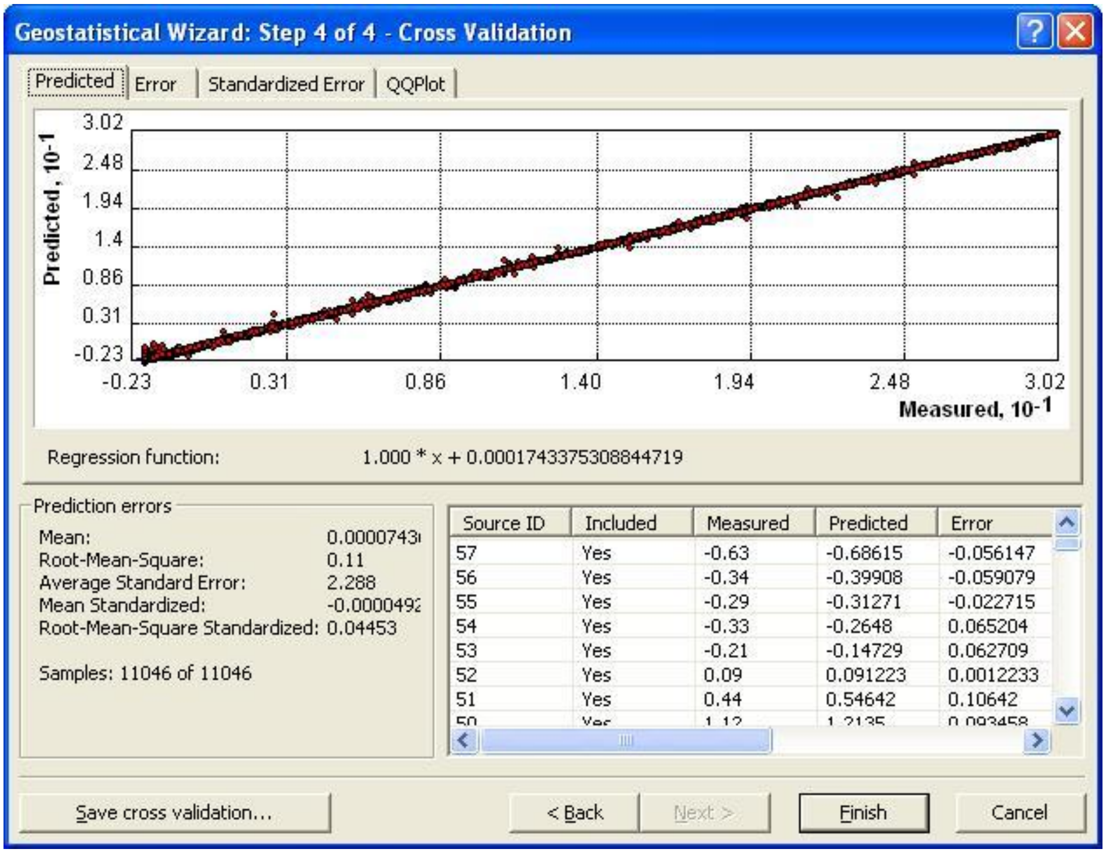


Figure 3.8 RMSE for SST [Source: created by author]



Precipitation

The precipitation data were displayed and analyzed using the same methods as the SST measurements. One of the two differences is the select tool does not need to be used (Figure 3.9). The precipitation data covered the whole Earth and even though the data over the land was used in the kriging interpolation it is not factored into the final model used to create the climate classification map. The other difference is a Gaussian kriging method (Figure 3.10) is used

Figure 3.9 Precipitation model [Source: created by author]

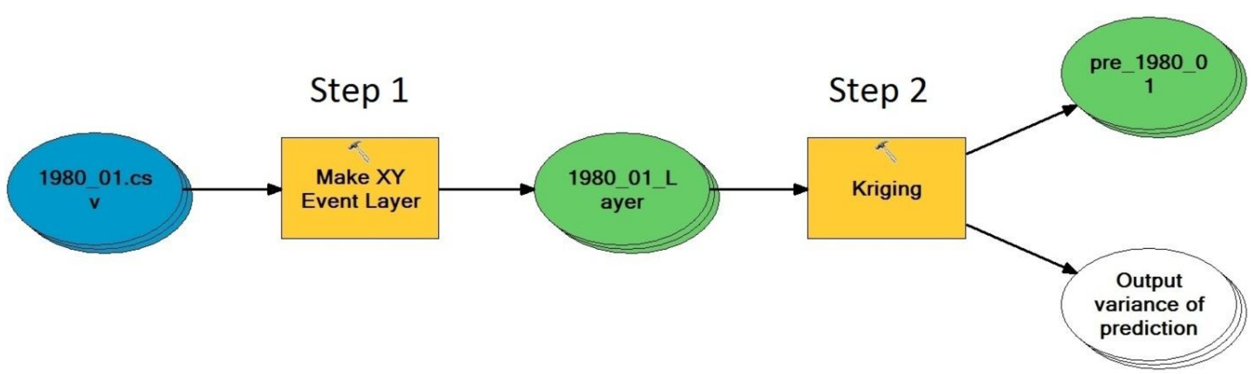
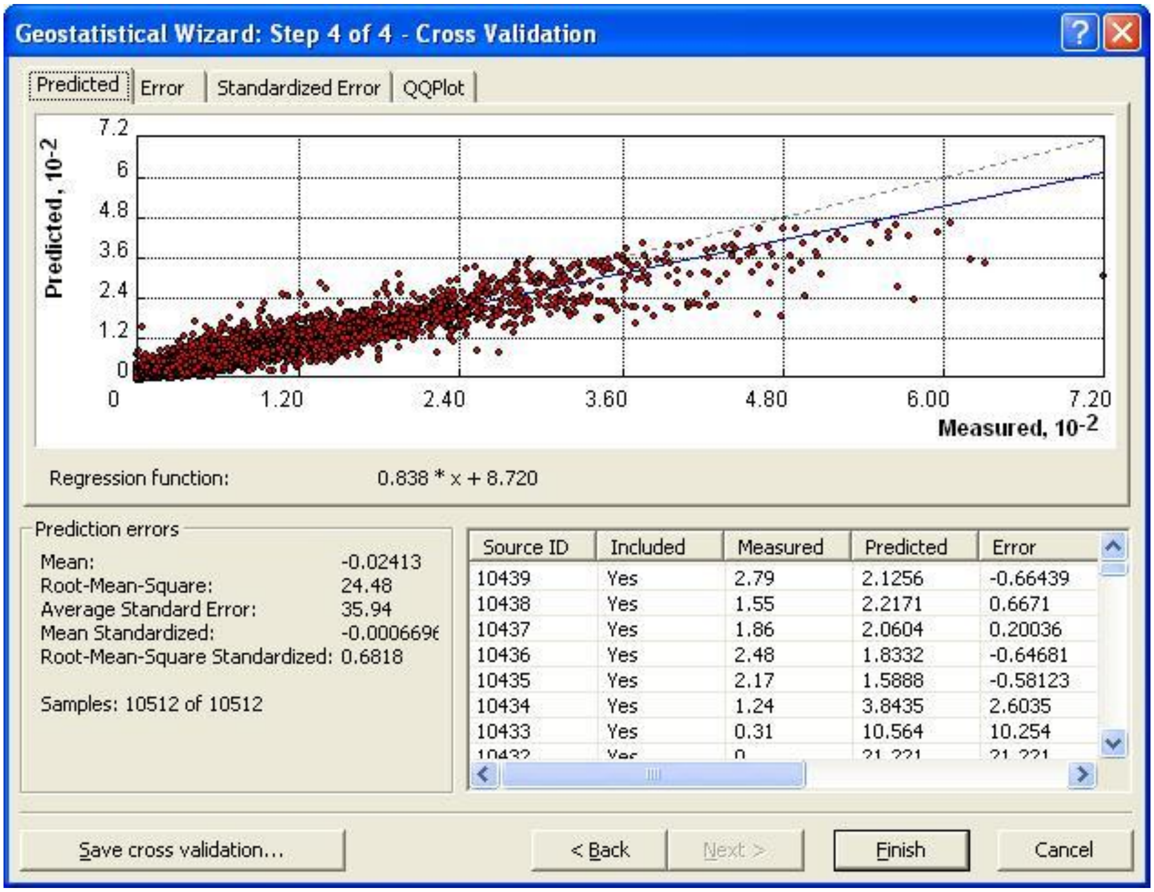


Figure 3.10 RMSE for precipitation [Source: created by author]



instead of an exponential. It still takes into account the nine nearest neighbors of a local calculation, but the best RMSE attainable was from the Gaussian method. It comes out to be 0.68 mm of error which is more than acceptable for the two and a half degree resolution.

The Köppen Model

The Köppen classification system is broken up into six main subgroups: A - tropical, B - arid, C - temperate, D - continental, E - polar, and H - highland. The highland climate will not be included because the ocean is a relatively flat surface and any actual change in sea level height is negligible over thousands of kilometers (km). The continental climate also does not appear because of the temperature requirements needed to fulfill its rules. The ocean does not heat and cool as fast as land can and this is why no D climates materialize in an oceanic classification system. In order to meet the temperature requirements of a continental climate a half km^2 grid cell has to go through at least a 42° Celsius (C) swing from average warmest month to average coldest month. Due to the oceans properties of absorbing and holding heat for long periods of time this fluctuation cannot transpire.

The two main drivers of the Köppen classification system are precipitation and temperature. Individual monthly rasters were input into a model that creates a yearly classification map. The model used to create the classification raster was developed by David Glassett from Brigham Young University. There were a few modifications that had to be accounted for in Glassett's model. First, the calculations in the model had to be converted into Système International (SI) units instead of English. Second, a couple of changes to the A subcategories had to me made. The syntax of the algorithms used is listed in Appendix A and the ArcModelBuilder model can be seen in Figure A.1. The main analysis used in this thesis is to approach the data from a climate years perspective. To do this the data are divided into months and each month from a year was run by the model producing one data set. A total of 29 climate year maps were created from the data and from those maps a modal filter is administered on the twenty nine sets of data to determine a single ocean climate classification for the 1980-2008 time span (Figures C.1 - C.30).

Map Projections

There are three projections used for the map outputs. World maps showing the ocean version of the Goode homolosine projection (Figure 3.11). The homolosine projection is a combination of a homolographic and sinusoidal projection. A homolographic projection reproduces the ratios of areas as they exist on the earth and the sinusoidal shows relative sizes accurately, but distorts shapes and directions. This distortion can be reduced by interrupting the map, which is utilized on all the world maps. Also, the part of the Earth that is cut into is done on land areas so they are more heavily distorted than the oceans, which is perfect for the thesis. Given that this is an equal area projection it is great for visually comparing the sizes of the climate bands. The other two projections are orthographic polar projections of the Arctic and Antarctic regions (Figure 3.12). They both contain a hemispherical limit, but have an advantage of the ability to preserve distances along the latitudes. However, shape and area are sacrificed to maintain distance, particularly when the equatorial latitudes are approached. As sea ice is the item being shown on these maps, and it never matriculated past 50°S or 45°N, this was a great projection to use. Another factor that went into choosing these projections was simply the fact they created the best graphical representation possible of displaying the data.

Figure 3.11 Goode homolosine projection [Source: created by author]

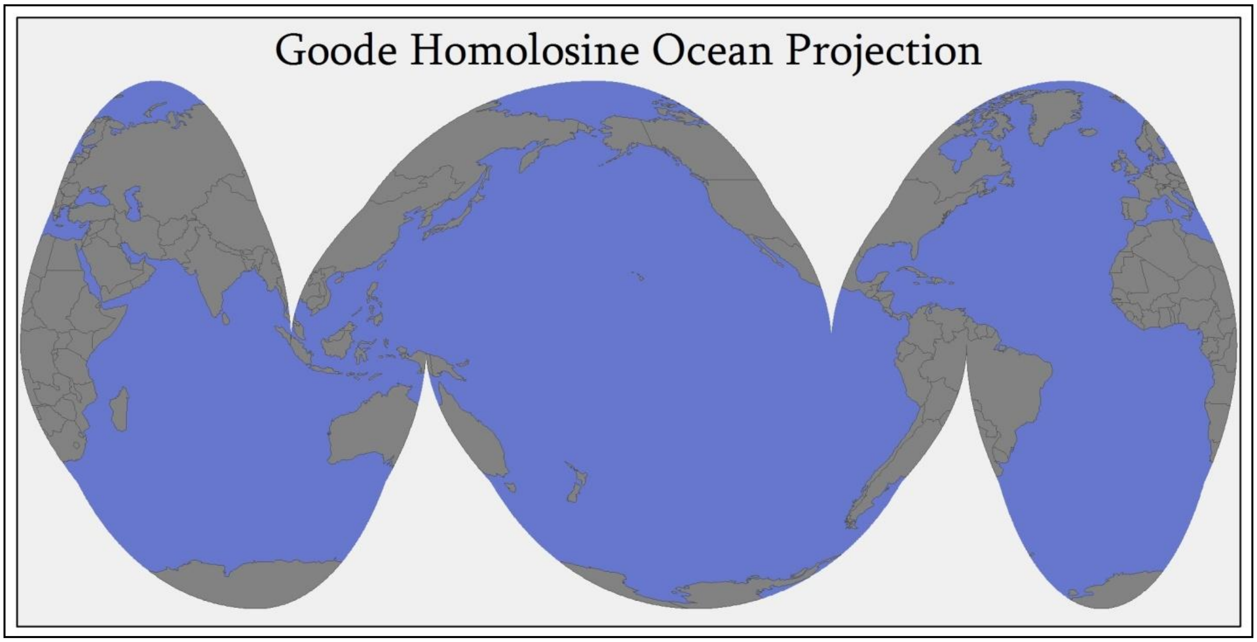
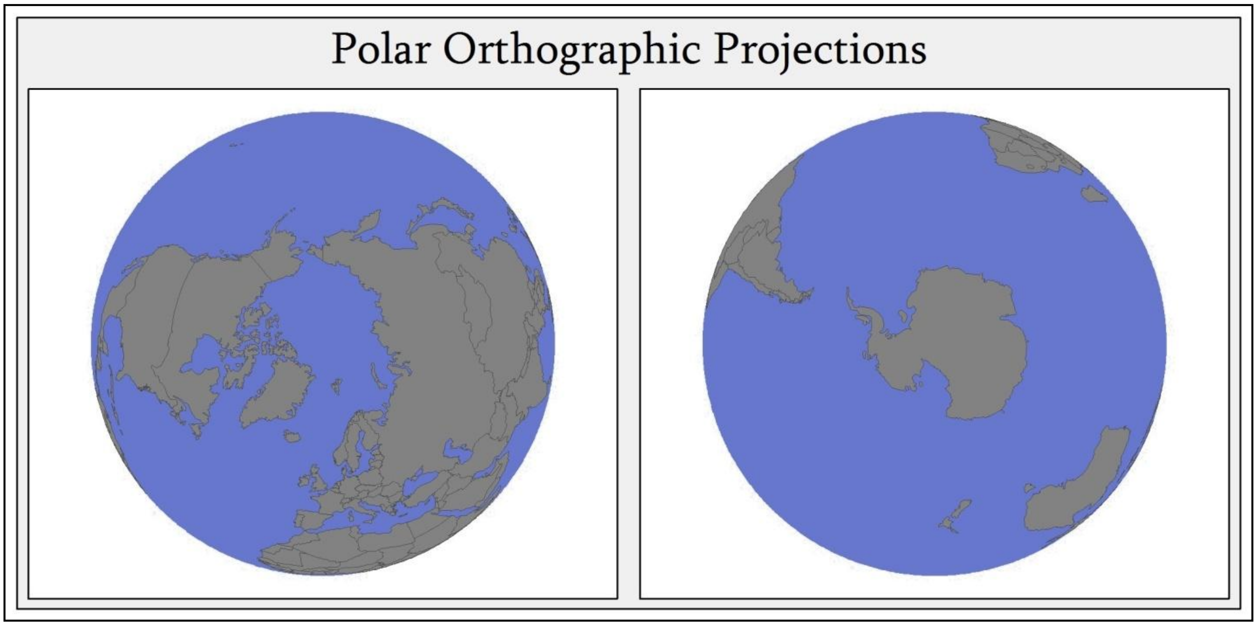


Figure 3.12 Orthographic projections [Source: created by author]



Chapter 4 - Results & Discussion

Climate Years Classification Method

There are many ways to analyze climate related data, but the climate years approach seems to have the most benefit for this thesis. It was chosen for its ability to not only create a final ocean climate map from the twenty nine year analysis, but to compare different years with and against each other as well. For instance, all the years an El Niño or La Niña occurred can have their climate map outputs compared and contrasted.

The modal oceanic climate classification map can be seen in Figure 4.1. There was also an analysis ran on the data to determine the frequency of each climate type occurring in every 5 degree latitude stretch of the ocean (Table 4.1). It can be seen that there is more climate subtypes in the Southern Hemisphere. There are no BSh, BWh, or Cwb climates in the Northern

Figure 4.1 Modal oceanic climate classification product [Source: created by author]

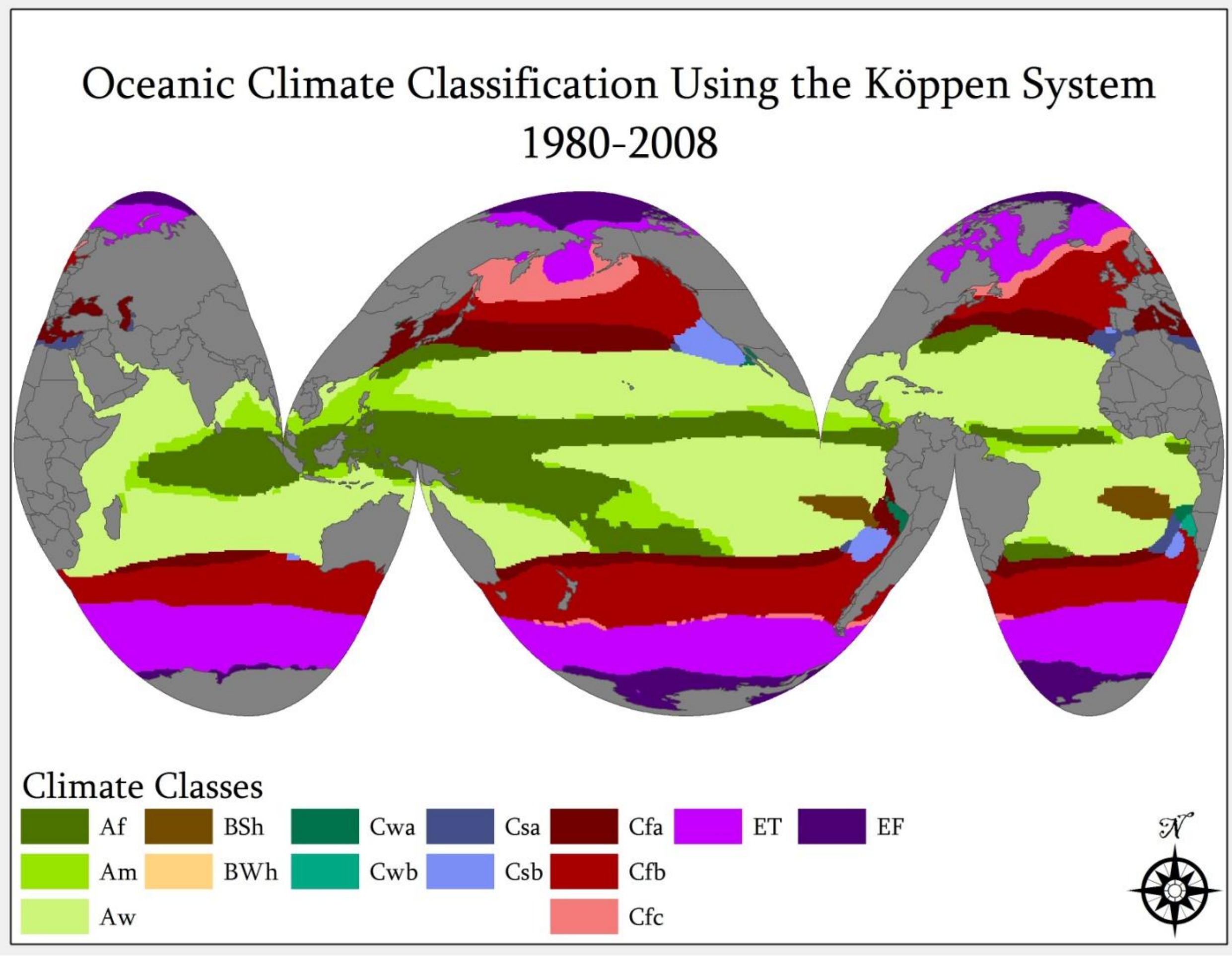


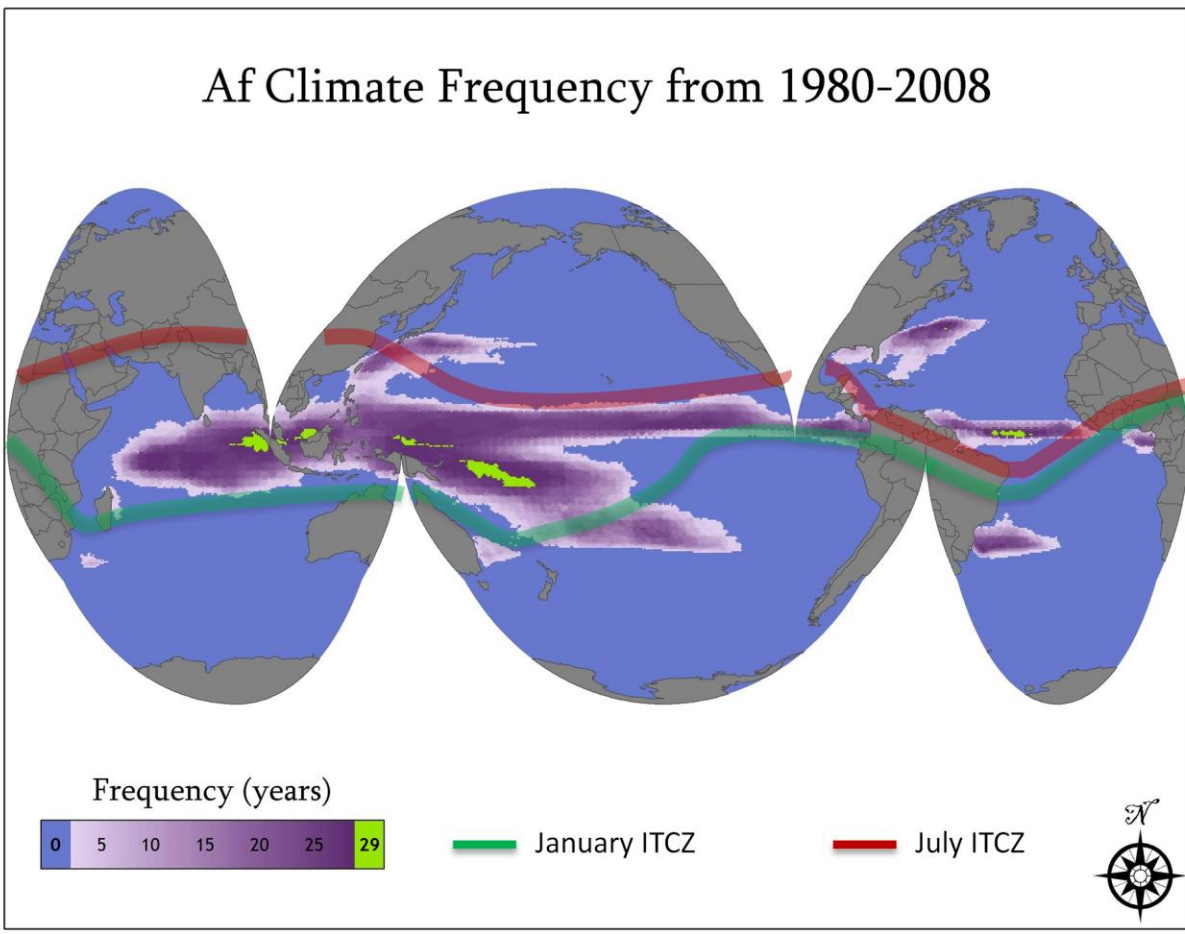
Table 4.1 Oceanic climate frequencies in five degree increments, values are percent of total [Source: created by author]

Latitude	Af	Am	Aw	BSh	BWh	Cwa	Cwb	Csa	Csb	Cfa	Cfb	Cfc	ET	EF
85 to 90	-	-	-	-	-	-	-	-	-	-	-	-	-	100.0
80 to 85	-	-	-	-	-	-	-	-	-	-	-	-	5.6	94.4
75 to 80	-	-	-	-	-	-	-	-	-	-	-	-	46.9	53.1
70 to 75	-	-	-	-	-	-	-	-	-	-	-	0.9	83.1	16.1
65 to 70	-	-	-	-	-	-	-	-	-	-	0.8	15.8	82.6	0.7
60 to 65	-	-	-	-	-	-	-	-	-	-	17.7	22.8	59.5	-
55 to 60	-	-	-	-	-	-	-	-	-	-	34.2	29.0	36.9	-
50 to 55	-	-	-	-	-	-	-	-	-	-	42.7	45.0	12.4	-
45 to 50	-	-	-	-	-	-	-	-	-	3.0	64.5	32.5	-	-
40 to 45	-	-	-	-	-	0.2	-	0.2	0.2	26.3	73.1	-	-	-
35 to 40	5.3	-	1.3	-	-	0.2	-	2.9	5.2	70.1	14.9	-	-	-
30 to 35	14.6	-	25.5	-	-	0.3	-	10.0	9.9	39.7	0.1	-	-	-
25 to 30	8.4	1.2	83.9	-	-	0.8	-	0.1	4.1	1.3	-	-	-	-
20 to 25	1.4	4.6	94.1	-	-	-	-	-	-	-	-	-	-	-
15 to 20	-	9.6	90.4	-	-	-	-	-	-	-	-	-	-	-
10 to 15	14.4	26.6	59.1	-	-	-	-	-	-	-	-	-	-	-
5 to 10	65.7	17.5	16.8	-	-	-	-	-	-	-	-	-	-	-
0 to 5	49.7	7.7	42.6	-	-	-	-	-	-	-	-	-	-	-
0 to -5	36.0	2.9	61.1	-	-	-	-	-	-	-	-	-	-	-
-5 to -10	35.2	6.6	57.5	0.4	-	-	-	-	-	0.3	-	-	-	-
-10 to -15	18.3	8.4	61.6	10.4	0.03	0.3	-	-	-	1.0	-	-	-	-
-15 to -20	5.9	11.3	66.8	10.1	-	3.0	0.4	0.3	-	2.1	-	-	-	-
-20 to -25	11.0	5.3	75.2	0.6	-	0.4	1.3	1.5	2.5	1.6	0.7	-	-	-
-25 to -30	18.4	3.9	60.3	-	-	-	0.1	2.4	6.0	6.2	2.7	-	-	-
-30 to -35	2.2	-	12.2	-	-	-	-	-	1.5	42.9	41.2	-	-	-
-35 to -40	-	-	1.2	-	-	-	-	-	-	2.0	96.9	-	-	-
-40 to -45	-	-	-	-	-	-	-	-	-	-	95.6	-	4.4	-
-45 to -50	-	-	-	-	-	-	-	-	-	-	43.8	4.8	51.3	-
-50 to -55	-	-	-	-	-	-	-	-	-	-	3.2	3.4	93.4	-
-55 to -60	-	-	-	-	-	-	-	-	-	-	-	-	100.0	-
-60 to -65	-	-	-	-	-	-	-	-	-	-	-	-	96.6	3.4
-65 to -70	-	-	-	-	-	-	-	-	-	-	-	-	46.6	53.4
-70 to -75	-	-	-	-	-	-	-	-	-	-	-	-	-	100.0
-75 to -80	-	-	-	-	-	-	-	-	-	-	-	-	2.1	97.9
-80 to -85	-	-	-	-	-	-	-	-	-	-	-	-	-	100.0
-85 to -90	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Latitude	**Af**	**Am**	**Aw**	**BSh**	**BWh**	**Cwa**	**Cwb**	**Csa**	**Csb**	**Cfa**	**Cfb**	**Cfc**	**ET**	**EF**

Hemisphere. It is also interesting how the polar climates dominate to 50 degrees south and extend all the way to 40 degrees whereas in the Northern the polar climates are a majority in only a quarter of the hemisphere. Being there is an Arctic Ocean in the northern hemisphere this data strongly supports the already popular belief for a Southern Ocean surrounding Antarctica.

The subdivision of A climate types provides some interesting patterns. In near equatorial areas, the is a strong spatial correlation between the location of the ITCZ and Af climates (Figure 4.2). Similar to what is found for land areas, there is a tendency for the large areas of Af to have a ring of Am or monsoon climate area prior to the transition to the winter dry or Aw climates. Given the influence of subtropical high pressure centers and the relatively small north to south migration of the ITCZ over the oceans, the global oceanic coverage of Aw climates is large. Interestingly, the poleward transition of Aw climates is not directly into C climate types in the

Figure 4.2 ITCZ and Af relationship [Source: created by author]



western parts of the Pacific and Atlantic ocean basins. At approximately 25° to 40°N and 20° to 35° S latitude there are belts of Af climate (again surrounded by Am) that extend eastward into the ocean basins. As expected, the South Pacific Convergence Zone, which has been described as an extension of the ITCZ with extratropical characteristics, is an area of Af climate that extends southward to the point where it intersects the Cfa climate region to the northeast of New Zealand.

Oceanic B climates are primarily a Southern Hemisphere phenomena with dry climates found primarily where the subsiding Hadley circulation, that creates subtropical cells of higher surface pressure, occurs over cool ocean currents moving equatorward on the east side of the Pacific and Atlantic basins. Areas of BSh climate are more extensive than areas of BWh.

Hemispheric differences are quite pronounced for the oceanic C climates. In both the Northern and Southern Hemispheres, there is a poleward transition from Cfa, through Cfb, to Cfc. In the Southern Hemisphere, the east-west oriented Cfa band is relatively narrow whereas a broad band of Cfb climates tend to dominate the mid-latitudes. Only a very narrow zonally oriented band of Cfc climates exists on the poleward margin of the Cfb belt. In the Northern Hemisphere, the belts of Cfa and Cfb tend to expand in a northerly direction in the eastern parts of the Pacific and Atlantic basins and as a result there are long stretches of the North Pacific and North Atlantic coasts that have offshore Cfb climates. The Cfc climate belt is clearly more pronounced in the Northern Hemisphere. For instance, the climate boundary can get as wide as 2,000 km in the North, but in the Southern Hemisphere the widest it becomes is 350 km.

In subtroptical to mid-latitude areas in the eastern parts of the ocean basins that are cool enough for C climate types, a variety of Cs and Cw climates can be found. The Cw climate areas seem to be poleward extensions of areas with an Aw climate whereas the Cs climates tend to exist within areas of Cf climate in areas where the subtropical high pressure cells extend pole-ward during the warm season.

Climate Frequency and Core Area Zones

Another analysis done on the data set was to find out how often climate types are found in certain locations. Another model was run to reclassify the data of every raster cell and create end values of zero through twenty nine. This was done by assigning a value of zero to all but one climate type for every year. Next, was to take those outputs and using the raster calculator, run a sum calculation on the twenty nine new sets of data. All values of zero means that the climate subtype never occurred once in that raster cell any of the twenty nine years. Figure 4.3 show an example of a climate frequency output. Appendix B shows the climate frequencies for all the climate subtypes in the study.

The next step was to distinguish the core area zones from one another on a single map. Core area zones are the raster cells, after the model was run for all twenty nine years, that contained the exact same climate subtype for every year. Once all the outputs were generated they could be compared and contrasted with one another (Figure 4.4). The arid subtypes seem to be the most sensitive climate type because of the fact none were identified as core area zones. The most stable would have to be the polar climates, especially in the Southern Hemisphere. There is just a slim transition zone in between them and the temperate climate types. The Aw climate subtype dominates the equatorial landscape occurring 15.2% of the time, but the highest percentage goes to the ET subtype emerging a staggering 18.3% of the time. Again, the argument for a Southern Ocean is show here by the consistency of the polar climate subtypes in the Antarctic region. Table 4.2 has a list of the frequency of the other core area climate subtypes.

Table 4.2 Core area rates [Source: created by author]

Climate	**Percentage**	**Area (km^2)**
Af	0.3%	151
Am	0.1%	27
Aw	15.2%	6626
BSh	0%	0
BSk	0%	0
BWh	0%	0
Cwa	0%	0
Cwb	0.01%	4
Cwc	0%	0
Csa	0.01%	3
Csb	0.1%	31
Cfa	1.7%	729
Cfb	11.5%	5044
Cfc	0.6%	251
ET	18.3%	7980
EF	13.9%	6096
Transitional	38.3%	10021

Figure 4.3 Am climate frequency zone [Source: created by author]

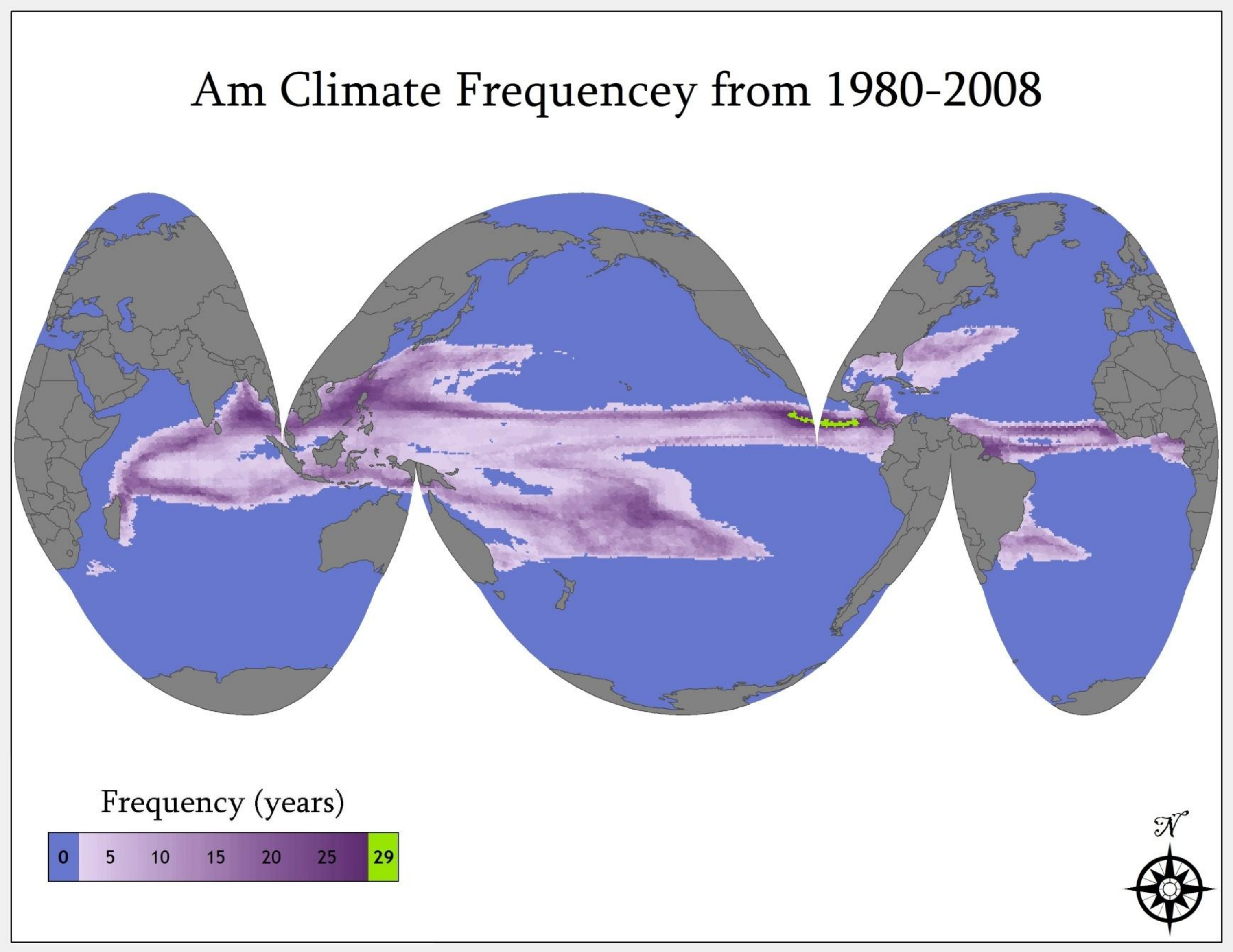
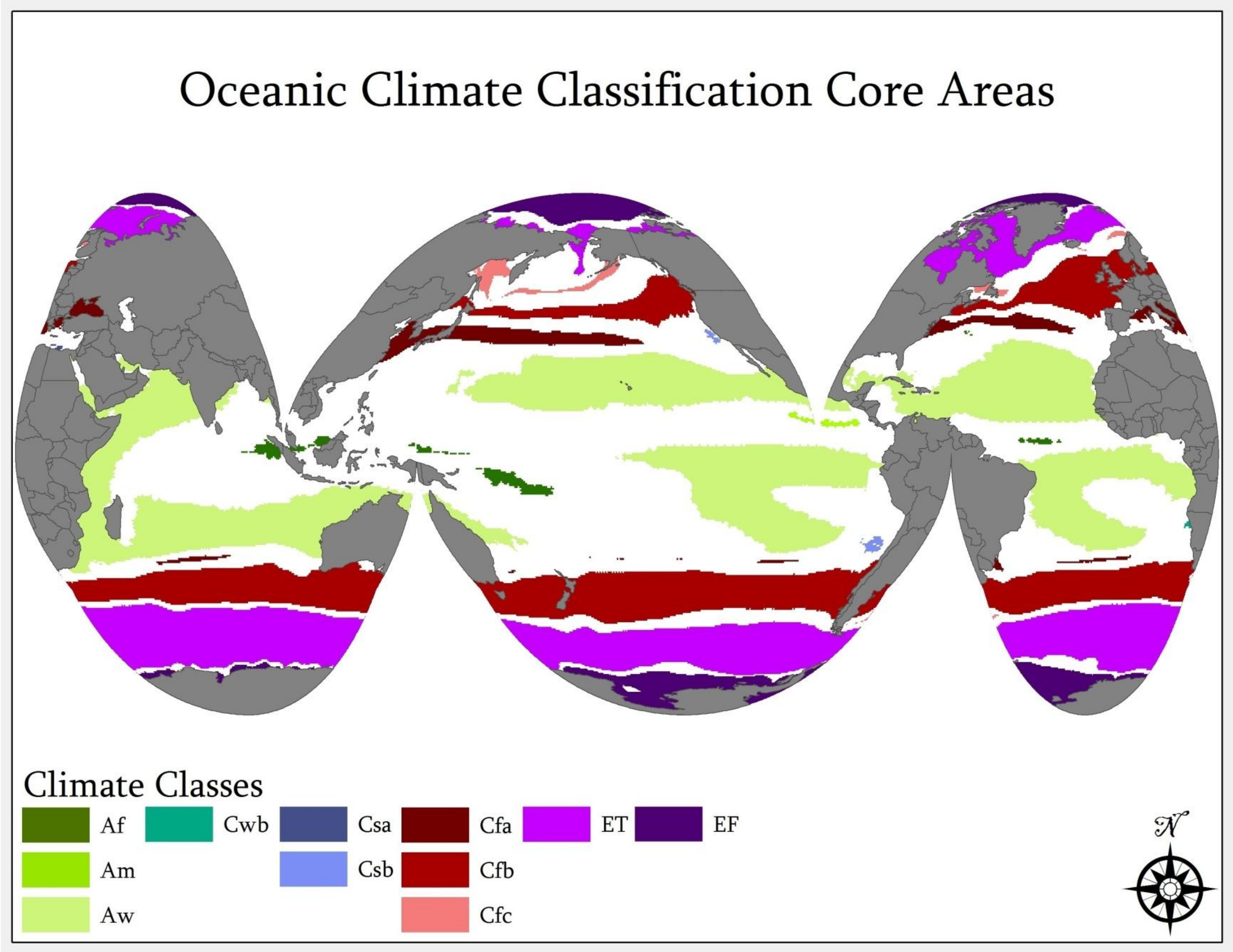


Figure 4.4 Oceanic core area zones [Source: created by author]



El Niño and La Niña

El Niño and La Niña have a profound effect on the climates of the oceans as well as on land. The climate map produced from years in which they occur are very different. Figure 4.6 is a map of what is produced from strong El Niño driven years. There was only one pronounced La Niña year during this study and it was from 1999 through 2000 (Figure 4.7). When comparing the oscillation it can be seen how they each have their own unique effect on the climate system of the tropical Pacific. Given that the SST only fluctuates a plus or minus couple degrees Celsius there is not be a huge discrepancy between El Niño and La Niña years. However, the tropical rainy (Af) and monsoonal subclimates seem to be impacted the most. In the El Niño years the Af climate, which needs at least 60 mm of rain every month to be classified Af, is stretched thin along the equator which indicates a band of year round precipitation here. During La Niña years this band is absent because the cooler waters push the warmer into the Western Pacific warm pool. Also, another consequence of the cooler water pooling along the equator can be seen in the branch of Af subclimate present southeast from Papua New Guinea to just north of New Zealand in the La Niña years. The warmer water causes more convection to occur in this locality which, in turn, initiates rain showers to consistently fall and therefore making a much more substantial Af subclimate develop. When comparing El Niño years this trend seems to hold true because the Papua New Guinea to New Zealand offshoot is very fragmented, especially towards the end of the cycle. Other El Niño years (1982-83, 1986-88, 1991-92, 1994-95, 1998, 2002-03, and 2006-07) along with other La Niña years (1988-89, 1998-2000, and 2007-08) can be seen in Appendix C.

Figure 4.5 1987 El Niño year [Source: created by author]

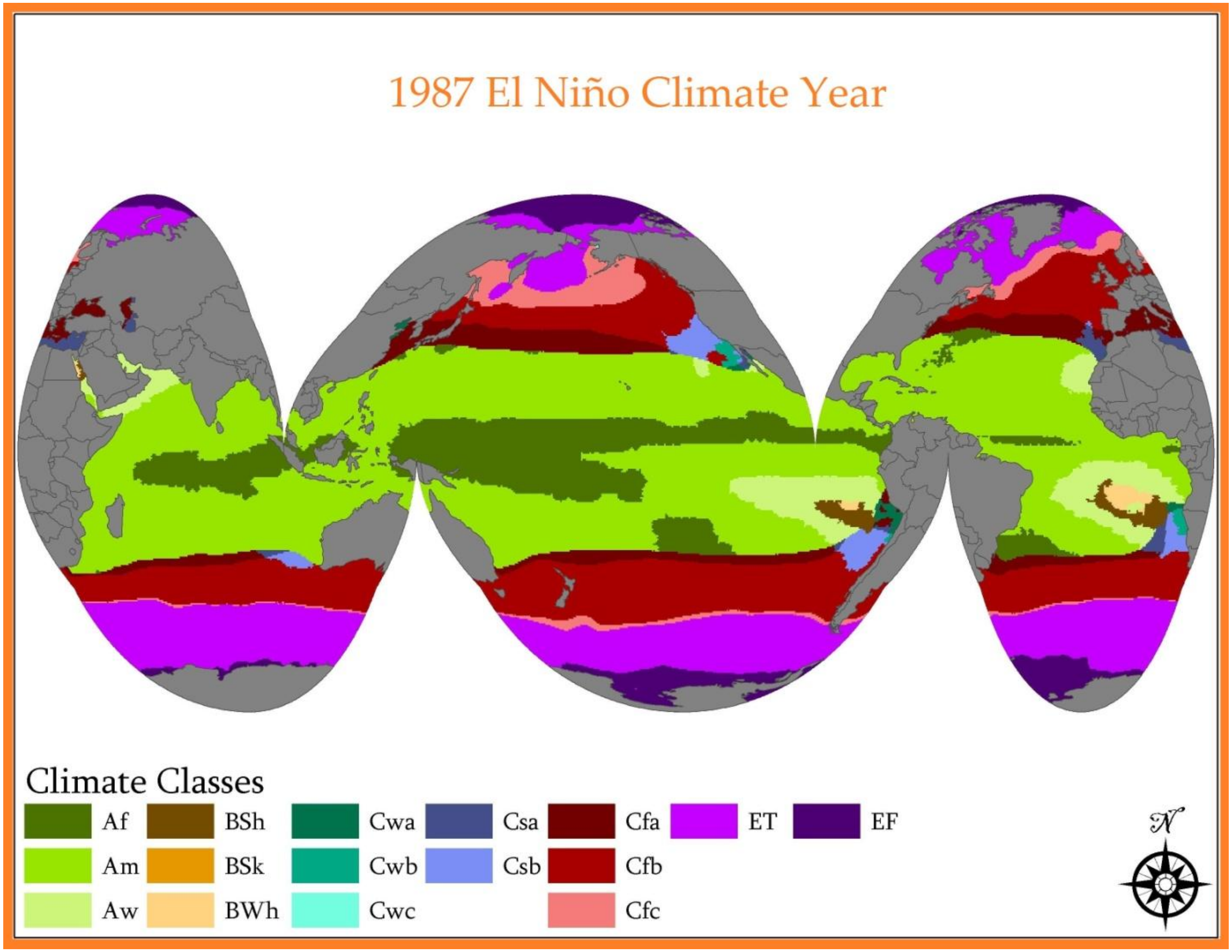
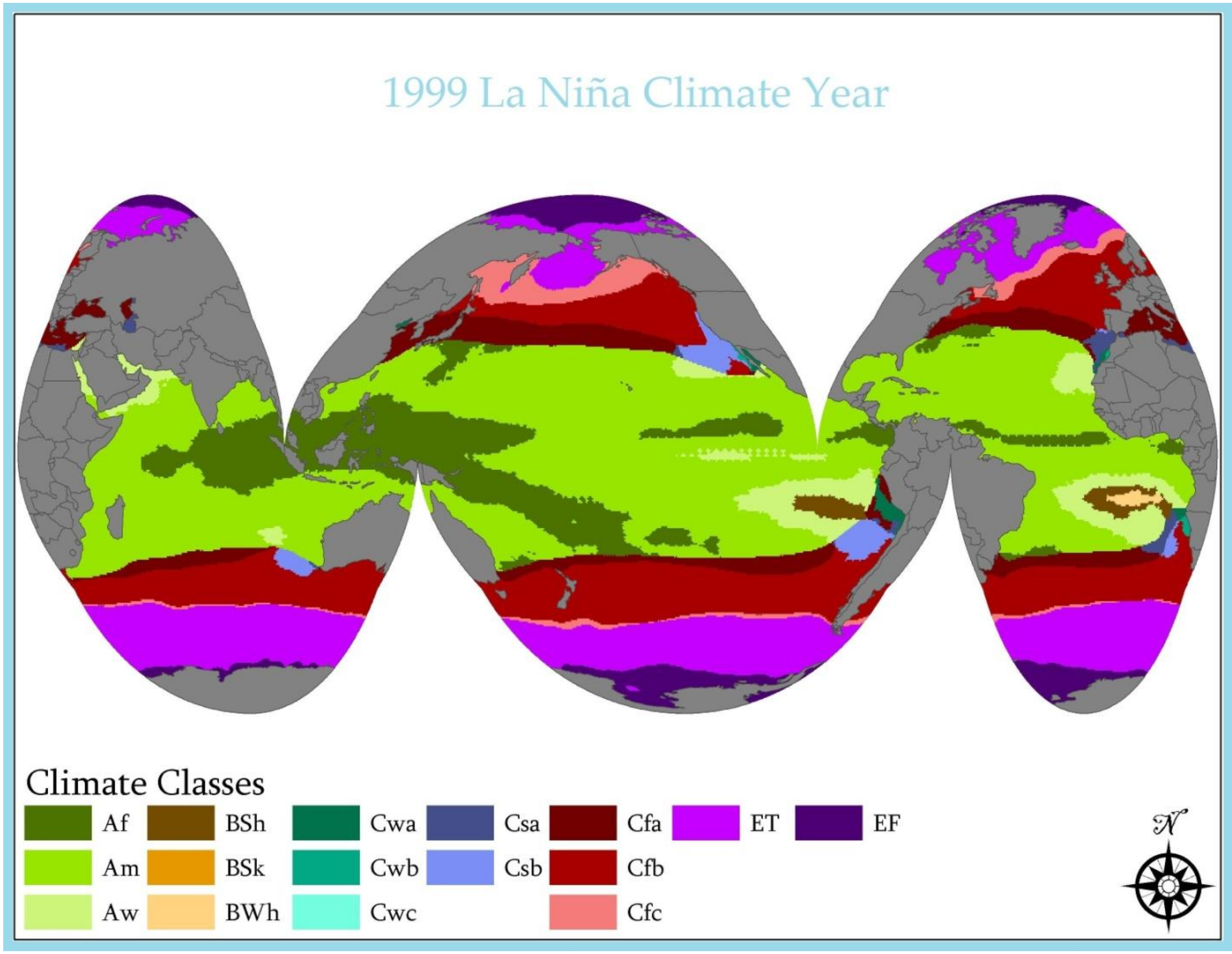


Figure 4.6 1999 La Niña year [Source: created by author]



Individual Climate Years

The main benefit of doing a climate years study is that the individual years are able to be studied amongst one another (Russell, 1934) All of the individual climate year data sets where displayed in the GISystem to facilitate a visual representation of the data and not just using a computer program to find similarities and differences (Appendix C and Figure 4.7). Consistency is the best word to describe what has been going on with regard to ocean climates over the past twenty nine years. All the A, C, and E climates have been extremely steady with regard to transition zones. All have fluctuations within their subclimates, but that is expected since weather is very unpredictable over the short term. However, one significant difference did appear and that is the declining appearance of the arid climates off the western coasts of South America and Africa. The BWh, the hot desert climate, all but disappears after 2000. It appeared in every year but two from 1980-1999, but over the next nine years it only emerged five times and the amount in those five years was less than a tenth of a percent of the total climate subtypes those years. The B climates in general have shrunk greatly, in the 1980s they totaled 0.76% of the sum of all climates, in the 1990's 0.77%, but in the 2000's only 0.66% of the total. A complete list of ocean comparison statistics can be found in Table 4.3.

Figure 4.7 Ocean climate year map example from 1988 [Source: created by author]

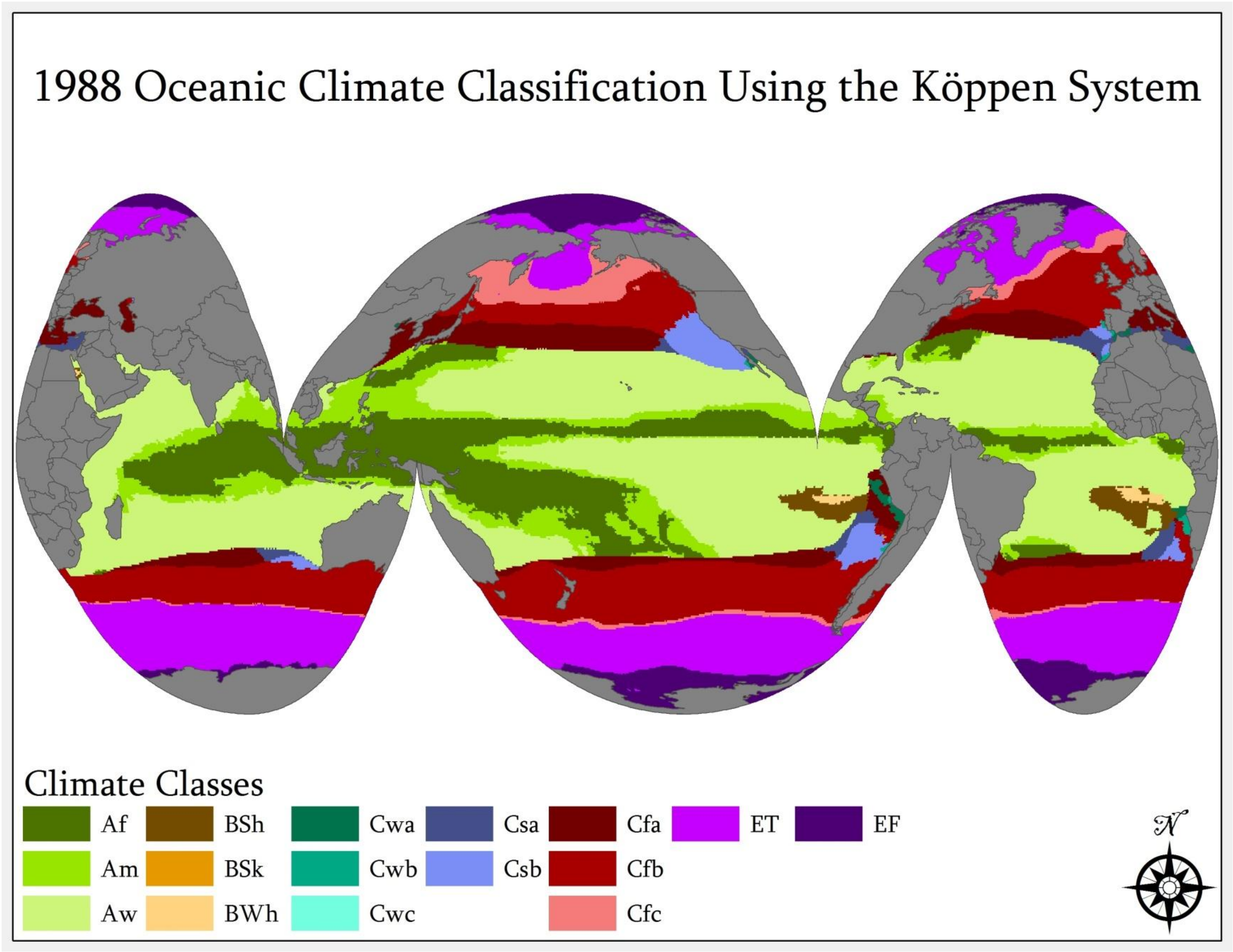


Table 4.3 Ocean climate statistics [Source: created by author]

Climate	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
Af	9.17%	7.99%	7.47%	6.30%	8.74%	8.15%	7.46%	7.05%	8.30%	6.69%
Am	4.43%	5.56%	4.82%	6.74%	5.15%	5.81%	4.81%	4.93%	5.44%	6.36%
Aw	22.30%	22.05%	23.51%	23.10%	22.43%	22.08%	23.80%	24.47%	22.37%	23.56%
BSh	0.83%	0.81%	0.72%	0.53%	0.37%	0.64%	0.32%	0.51%	0.72%	0.54%
BSk	-	-	-	-	-	-	-	-	0.001%	-
BWh	0.03%	0.03%	0.24%	0.03%	0.22%	0.05%	0.32%	0.22%	0.16%	-
Cwa	0.13%	0.17%	0.14%	0.20%	0.16%	0.25%	0.25%	0.19%	0.17%	0.27%
Cwb	0.14%	0.11%	0.08%	0.12%	0.09%	0.11%	0.08%	0.16%	0.08%	0.11%
Cwc	-	-	-	0.02%	0.01%	0.001%	0.02%	0.01%	-	-
Csa	0.56%	0.39%	0.37%	0.46%	0.66%	0.73%	0.57%	0.55%	0.74%	0.51%
Csb	0.40%	0.84%	0.58%	0.70%	0.96%	0.82%	1.03%	0.89%	1.17%	0.93%
Cfa	5.12%	5.72%	4.87%	4.89%	4.85%	4.57%	4.99%	4.43%	4.84%	5.05%
Cfb	15.91%	15.47%	16.08%	15.81%	15.47%	15.62%	15.26%	15.30%	14.85%	15.11%
Cfc	3.60%	3.24%	2.96%	3.35%	3.18%	3.22%	3.33%	3.39%	3.20%	3.24%
ET	21.53%	21.85%	22.52%	22.12%	21.87%	22.22%	21.57%	21.96%	22.06%	21.63%
EF	15.85%	15.77%	15.63%	15.64%	15.84%	15.73%	16.19%	15.92%	15.89%	16.01%

Climate	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Af	7.66%	7.57%	6.99%	8.08%	7.98%	8.54%	8.07%	6.02%	4.88%	7.57%
Am	5.53%	5.02%	5.58%	4.38%	4.98%	4.57%	5.37%	5.13%	5.38%	5.43%
Aw	23.02%	23.45%	23.52%	23.57%	23.21%	23.40%	22.76%	25.60%	26.21%	23.94%
BSh	0.76%	0.76%	0.90%	0.96%	0.64%	0.60%	0.51%	0.62%	0.71%	0.57%
BSk	-	-	-	-	-	-	-	-	0.001%	-
BWh	0.09%	0.01%	0.01%	0.06%	-	0.02%	0.002%	0.05%	0.17%	0.11%
Cwa	0.12%	0.10%	0.11%	0.15%	0.18%	0.17%	0.18%	0.10%	0.11%	0.22%
Cwb	0.06%	0.07%	0.15%	0.20%	0.05%	0.02%	0.04%	0.08%	0.14%	0.06%
Cwc	-	-	0.01%	0.002%	-	-	0.01%	0.01%	0.005%	-
Csa	0.77%	0.58%	0.55%	0.57%	0.40%	0.49%	0.47%	0.30%	0.48%	0.42%
Csb	0.61%	0.94%	0.80%	0.74%	0.86%	0.71%	0.84%	0.68%	0.95%	0.94%
Cfa	4.92%	5.43%	4.74%	4.53%	5.34%	4.87%	5.76%	5.18%	5.05%	5.18%
Cfb	15.63%	15.06%	15.84%	16.06%	15.61%	15.64%	15.26%	15.93%	15.50%	15.10%
Cfc	3.30%	3.28%	2.80%	3.35%	3.04%	3.30%	3.18%	3.35%	3.10%	3.12%
ET	21.85%	22.08%	21.85%	21.78%	21.81%	21.91%	21.19%	21.04%	21.57%	22.14%
EF	15.67%	15.63%	16.13%	15.59%	15.90%	15.77%	16.37%	15.91%	15.74%	15.20%

Climate	2000	2001	2002	2003	2004	2005	2006	2007	2008
Af	8.00%	8.32%	8.49%	8.06%	8.33%	8.74%	7.46%	7.93%	8.09%
Am	5.14%	5.16%	4.72%	4.57%	4.69%	5.03%	4.95%	5.26%	5.25%
Aw	23.87%	23.36%	23.71%	23.71%	23.92%	22.86%	24.32%	23.36%	23.66%
BSh	0.43%	0.60%	0.66%	0.89%	0.47%	0.65%	0.67%	0.60%	0.49%
BSk	-	-	-	-	-	-	-	-	-
BWh	-	-	-	0.06%	0.05%	-	0.02%	0.08%	0.001%
Cwa	0.17%	0.17%	0.14%	0.18%	0.12%	0.26%	0.21%	0.13%	0.26%
Cwb	0.05%	0.05%	0.05%	0.10%	0.09%	0.07%	0.10%	0.05%	0.06%
Cwc	0.01%	0.01%	-	-	0.01%	-	-	0.03%	-
Csa	0.44%	0.57%	0.39%	0.56%	0.52%	0.45%	0.34%	0.64%	0.53%
Csb	0.72%	0.80%	0.86%	0.75%	0.82%	0.84%	0.70%	0.66%	0.87%
Cfa	5.23%	5.41%	5.18%	5.12%	5.15%	5.15%	5.67%	4.99%	5.22%
Cfb	15.41%	15.00%	15.38%	15.64%	15.54%	15.55%	15.15%	15.41%	14.94%
Cfc	3.04%	2.86%	3.09%	3.09%	3.02%	3.25%	3.16%	3.75%	3.52%
ET	21.82%	21.87%	21.61%	21.38%	21.37%	21.36%	21.88%	21.32%	21.19%
EF	15.65%	15.82%	15.74%	15.89%	15.91%	15.78%	15.38%	15.78%	15.91%

Climate	Mean	Standard Deviation	Maximum	Minimum
Af	7.73%	0.90%	9.17%	4.88%
Am	5.18%	0.53%	6.74%	4.38%
Aw	23.49%	0.92%	26.21%	22.05%
BSh	0.64%	0.16%	0.96%	0.32%
BSk	0.001%	0.0004%	0.001%	0%
BWh	0.09%	0.09%	0.32%	0%
Cwa	0.17%	0.05%	0.27%	0.10%
Cwb	0.09%	0.04%	0.20%	0.02%
Cwc	0.01%	0.01%	0.03%	0%
Csa	0.52%	0.12%	0.77%	0.30%
Csb	0.81%	0.15%	1.17%	0.40%
Cfa	5.08%	0.33%	5.76%	4.43%
Cfb	15.47%	0.33%	16.08%	14.85%
Cfc	3.22%	0.20%	3.75%	2.80%
ET	21.74%	0.35%	22.52%	21.04%
EF	15.80%	0.23%	16.37%	15.20%

Sea Ice

Concentration and Extent

It is no secret that the ice at the north pole is starting to retreat. Using March sea ice extent for the Arctic and September for the Antarctic helps create a representation of how sea ice is behaving over the past twenty nine years. These months are used because they are considered to be the high in annual cycles The Arctic sea ice has been steadily declining over the time span whereas the Antarctic has remained steady (Figure 4.8). In most of the years in the 1980's Arctic sea ice was accumulating at least 15.5 million km^2, In the 1990's all but two years failed to reach the 15.5 million km^2 mark, and one of those was 1980. In the last five years none have eclipsed the 15 million km^2. The Antarctic sea ice is much more erratic, but overall consistent with hardly any change at all over the duration. The minimum and maximum sea ice extents actually occur within four years of each other. A list of the exact values for each year can be found in Table 4.4.

Figure 4.8 Arctic and Antarctic sea ice area [Source: created by author]

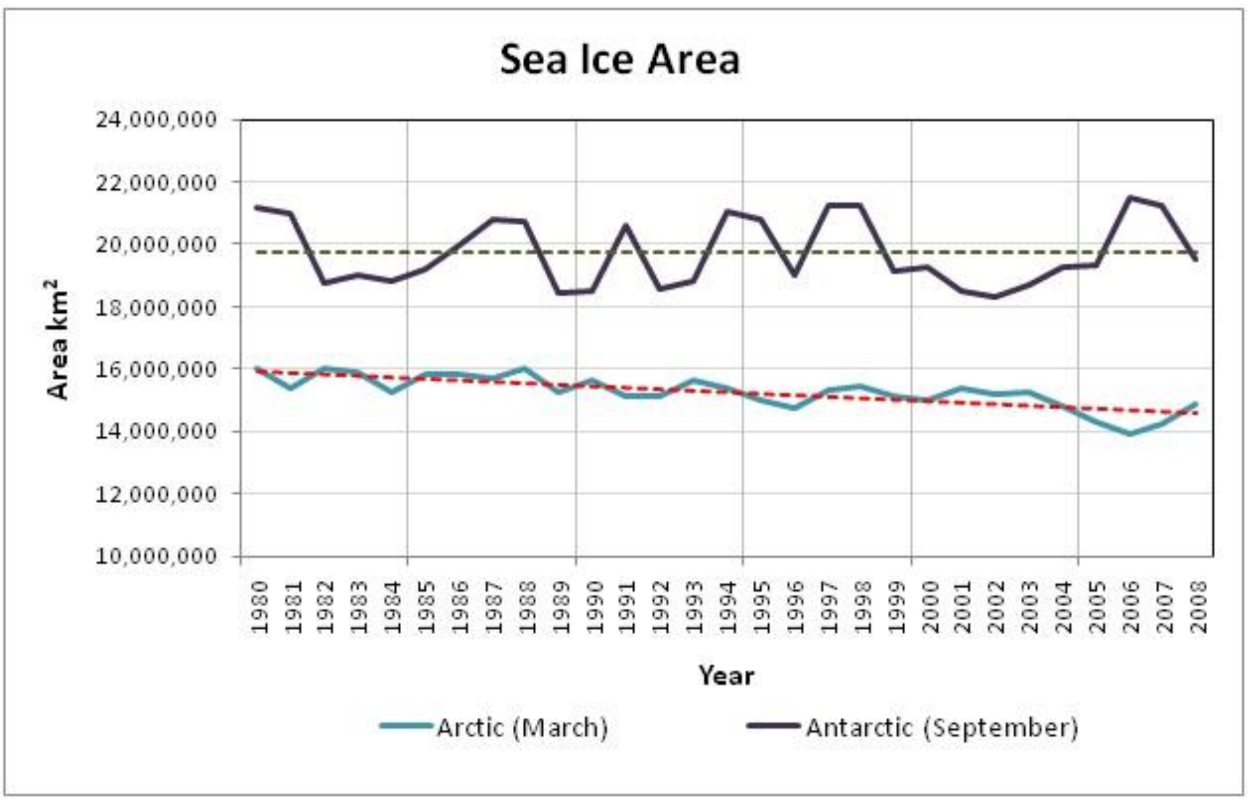


Table 4.4 Sea ice area by year [Source: created by author]

Month & Year	Area km^2	Month & Year	Area km^2
March 1980	16,015,260	September 1980	21,189,078
March 1981	15,399,037	September 1981	20,993,774
March 1982	16,005,886	September 1982	18,754,642
March 1983	15,879,641	September 1983	18,994,004
March 1984	15,272,167	September 1984	18,809,878
March 1985	15,826,206	September 1985	19,183,061
March 1986	15,834,331	September 1986	19,945,386
March 1987	15,732,147	September 1987	20,791,283
March 1988	15,998,699	September 1988	20,706,599
March 1989	15,241,543	September 1989	18,427,467
March 1990	15,666,838	September 1990	18,522,786
March 1991	15,145,610	September 1991	20,600,665
March 1992	15,145,610	September 1992	18,580,897
March 1993	15,655,276	September 1993	18,834,015
March 1994	15,374,663	September 1994	21,020,020
March 1995	15,030,302	September 1995	20,794,093
March 1996	14,744,377	September 1996	18,983,067
March 1997	15,323,415	September 1997	21,213,135
March 1998	15,458,722	September 1998	21,215,011
March 1999	15,125,923	September 1999	19,168,068
March 2000	15,023,115	September 2000	19,280,553
March 2001	15,356,538	September 2001	18,523,639
March 2002	15,199,045	September 2002	18,304,355
March 2003	15,271,854	September 2003	18,723,717
March 2004	14,807,187	September 2004	19,286,189
March 2005	14,334,707	September 2005	19,352,745
March 2006	13,936,286	September 2006	21,462,189
March 2007	14,249,085	September 2007	21,270,319
March 2008	14,906,557	September 2008	19,539,867

Sea Ice Years

The same process that was executed on the precipitation and SST data were also used on the sea ice. A illustrative representation helps give a better depiction than just data and numbers. The data were broken into certain months where sea ice was present, based on animals necessity for them to thrive and survive (Appendix D and Figures 4.9 and 4.10).

Figure 4.9 Antarctic sea ice modal map for 1980-2008 [Source: created by author]

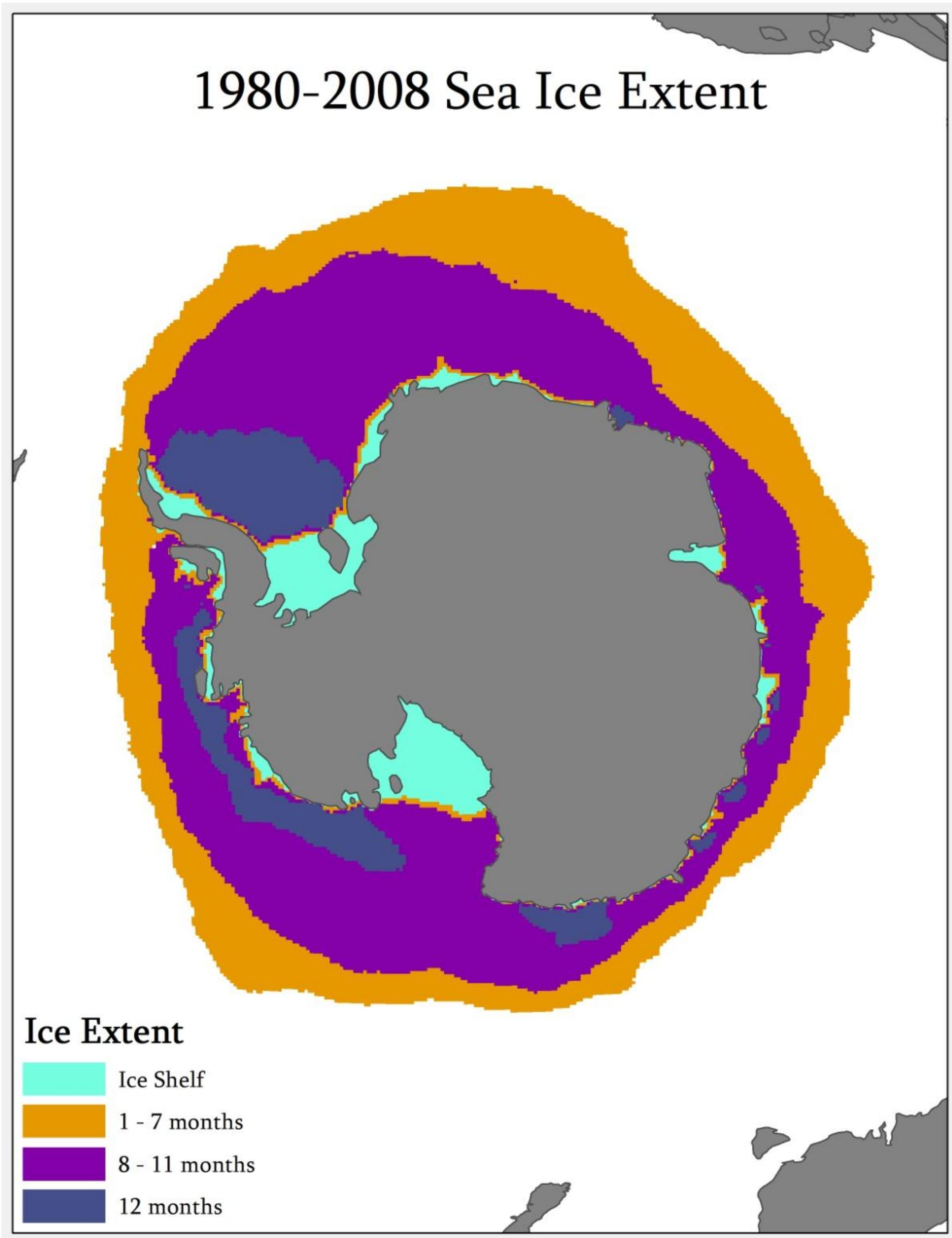
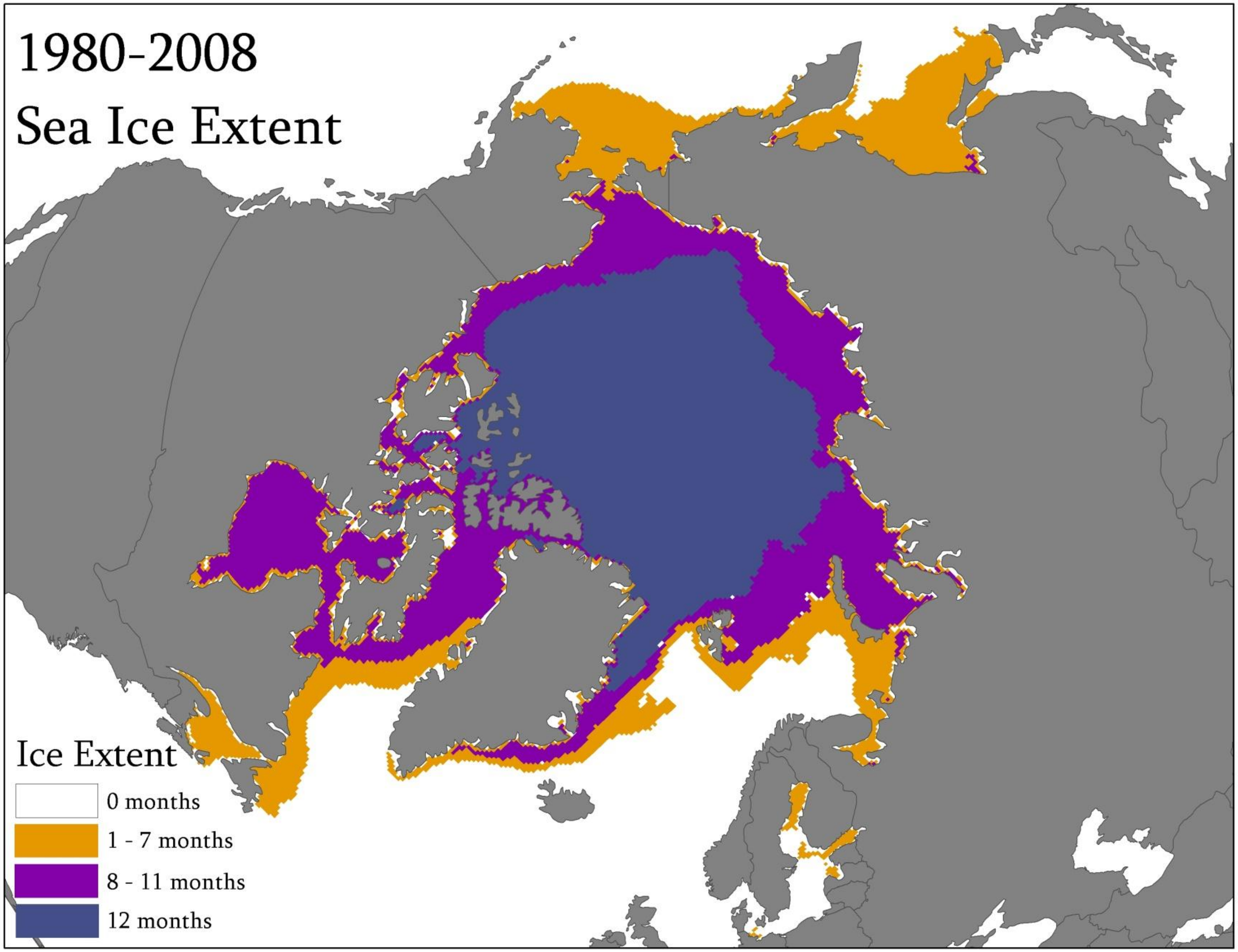


Figure 4.10 Arctic sea ice modal map for 1980-2008 [Source: created by author]

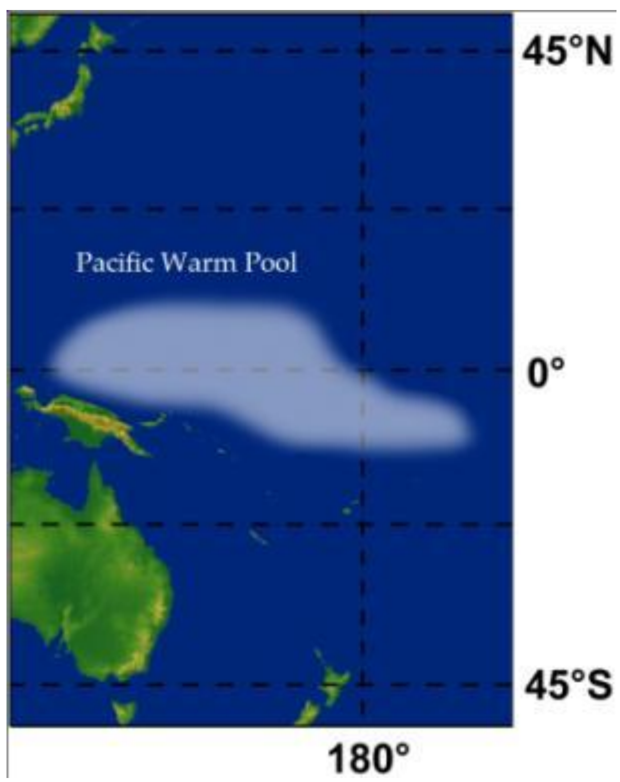


Chapter 5 - Summary

This thesis presents the results of using coast to coast data to classify the climate of the oceans. Input data were from the NCEP NCAR reanalysis. It is believed that this is the first ocean climate classification created based on data. This thesis research used the Köppen classification system. Using strictly statistical data of sea surface temperature and precipitation as inputs to develop the climate boundary locations helped make the classification the best it could be. A climatic years approach was used and separate classifications were produced for each year from 1980 to 2008. Analysis of the outcomes of classification is a process whereby additional understanding can be obtained. It is hoped that the maps and data presented in this thesis will be useful to those working to better understand the workings of the Earth-system. Interactions between climate and the oceans are evident in polar environments with seasonal changes in sea ice extent. Sea ice seasonality was subdivided into 4 classes and annual maps were constructed for both hemispheres.

Significant findings were produced from this climate classification research. First, El Niño and La Niña have a profound effect on the climates over the tropical east Pacific and the Americas and in the research findings climate class changes shows up over other parts of the oceans as well. Trends of cooler and warmer waters flip the climates over the equatorial Pacific between Af (tropical rainy) and Am (tropical monsoonal) in specific regions and the patterns they create are easily recognizable. El Niño creates a linear band of the tropical rainy (Af) climate that coincides with the equator (Figure 4.5), however when a La Niña occurs the warm water is pushed west towards the Papua New Guinea (Figure 4.6). This helps illustrate the

Figure 5.1 Pacific warm pool [Source: National Center for Atmospheric Research and Australian Institute of Marine Science]



relationship between the Af climate and the Pacific warm pool (Figure 5.1) during a La Niña. The warm waters cause convection and an increase in precipitation. The Af climate decision rules pick up on this because there must be at least 60 mm of rain each month to be classified tropical rainy.

Use of a climatic years approach allowed this research effort to generate maps of the core areas (locations that had the same climate class each year) associated with each climate type. The climate classes that occupy the largest areas of the oceans include Aw in tropical latitudes, Cfb in mid-latitudes, and the E climates in polar areas. Clear linkages between the location of the subtropical high pressure cells and annual or seasonally dry oceanic climates exist. West-to-east banding of climatic zones (e.g., Cfb and ET areas in the Southern Hemisphere) is pronounced in the Southern Hemisphere whereas mid- and high-latitude land areas impact the patterns of climate types in the Northern Hemisphere.

Sea ice coverage and extent plays an important role not only for people living close to the poles, but in global climate as well. It was shown that the Antarctic ice seems to be somewhat stable over the last twenty nine years, but the ice surrounding the North Pole is a different story. Sea ice around the Arctic is on a decline due to rising temperatures. The coastline around southern Greenland has been virtually ice free since 1993 and not only is the overall extent declining but the months in which the ice floes begin to form are becoming later in the calendar year. This not only affects the worldwide climate, but creates added pressures to the people and animals living in these Arctic environments. The sea ice data were reclassified into ice months per year to facilitate the ice analyses. Research showed that eight is the magic number when it comes to months of sea ice required for animals to thrive in the frosty ecosystem. This eight-month margin is also in rapid decline and it can be argued that it has more of an influence on the environment than the overall ice extent does since it is directly influencing the animals that live there.

A major argument that has come from this thesis is that climatic areas strongly support the need to have a designated Southern Ocean and many scientists have argued for the official acceptance of this chilly body of water surrounding Antarctica (Hart, 1942; Currie, 1964; Holdgate, 1967; Knox, 1970, 1983, and 1994; Everson, 1977 and 1984; Bengtson, 1978 and 1985; Baker, 1979; Tranter, 1982; Hempel, 1985 and 1987). Knox (1994) describes the important characteristics that argue for a Southern Ocean:

- It is a large system and probably the largest marine ecosystem on the globe.
- It is semi-enclosed, especially in the overlying water masses, and the Polar Front forms a distinct northern boundary
- It is an old system with a long evolutionary history. The main circulation patterns and water mass distributions were established at least 20 million years ago
- Most of the major taxonomic groups are circumpolar in distribution. The principle variations is that of productivity, which is great in certain regions than in others
- The quantitative and qualitative features of the basic processes the Southern Ocean system differ obviously form those of other ocean systems, as demonstrated by the distribution of the dominant herbivore and key spices of the system.

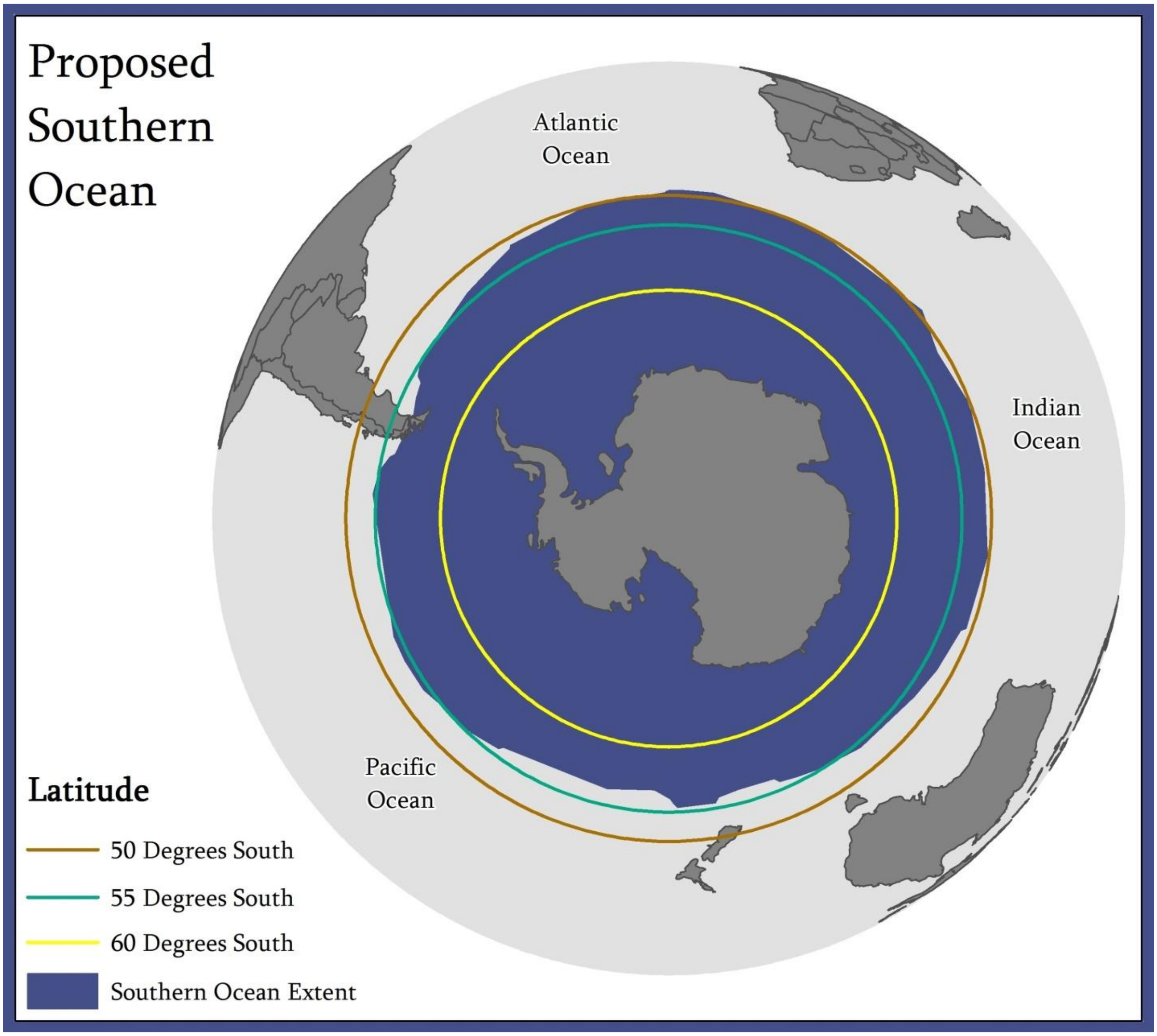
There is no general agreement concerning the northern limit of the Southern Ocean, but biologists consider that it lies at the Antarctic Convergence, the furthest equatorward limit of non-migrating Antarctic species (Knox, 1983). A suggested boundary (between C and E climates) that is designated from this classification is between 50 and 55°S latitude encircling all of Antarctica (Figure 5.2). As the Southern Ocean approaches Cape Horn, the circumpolar symmetry is somewhat offset by influences from land masses.

The total area of the Southern Ocean defined by E climate areas would be just above 44 million km^2, comparatively much larger than the approximate size of the Arctic Ocean at 14 million km^2 (Comiso and Parkinson, 2004). The Polar climate of the Antarctic region is similar to the Arctic, both are well defined with consistent climate boundaries separating them from the temperate climates year after year. However, the polar climates of the Antarctic are over three times larger than the Arctic Ocean itself, so it makes sense that there should be a designated Southern Ocean.

Ice is an important factor in the Antarctic region and only helps strengthen the reasons for designating a Southern Ocean. Sea ice is a complex medium that provides diverse ecological habitats that are key elements of one of the largest and most dynamic ecosystems on Earth (Smith, 1999). It is important to scientists from many different fields such as ecology, biology, geography, geology, oceanography, and even physics because of the way the ice interacts with the surrounding environment. There is a general consensus among scientists of all fields that there already is a designated Southern Ocean, it just is not widely accepted by the general public.

However, it is not because the public are arguing against it, but ignorance. Only a minuscule percent of people will ever physically interact with this environment and that is probably why it

Figure 5.2 Southern Ocean [Source: created by author]



has not gained any ground in the past century. It will take a concerted effort that combines professional and educational organizations, such as *National Geographic* and *The National Council for Geographic Education,* to begin the public acknowledgment that the Southern Ocean is its own distinct entity among the other four oceans

Patterns of geographic phenomena can help increase our knowledge about how a complicated dynamic system such as the Earth works. When relationships are recognized, people can begin to make inferences about what can happen in the future. For instance, when an El Niño is occurring predictions can be drawn about the effects that will take place on regional agriculture and weather over the ensuing months. This is possible today because scientists detected the patterns that have occurred in the past and have learned from that Earth history. A major concern now is with the patterns that may be changing with the warming of the planet. Predictions can be an excellent tool for helping to prevent disasters from occurring in the future, and these predictions are drawn in part because of the detection of relevant patterns. Rubel and Kottek (2010) have created a prediction of the changing patterns of world land climates up to the year 2100 based on a combination of recorded data and future forecasting (Rubel and Kottek, 2010, 135).

> *"Here, we present a series of digital world maps for the extended period 1901-2100 to depict global trends in observed climate and projected climate change scenarios. World maps for the observational period 1901-2002 are based on recent data sets from the Climatic Research Unit (CRU) of the University of East Anglia and the Global Precipitation Climatology Centre (GPCC) at the German Weather Service. World maps for the period 2003-2100 are based on ensemble projections of global climate models provided by the Tyndall Centre for Climate Change Research. The main results comprise an estimation of the shifts of climate zones within the 21st century by considering different IPCC scenarios."*

Chapter 6 - Additional Study

There is always data that can be added to a climate classification to fine-tune it in just the right manner. However, if too much data are added it can become far too complicated with too many classes. Data that could be considered as additions to future research in this subject would be sea level pressure and wind speed and direction. Many studies that have to do with oceans and climates consider these to be top tier variables just below SST and precipitation. If used they could help limit transition zones between major climate types or divide up subclimates based on their data values. Important information could be pulled out of the classification scheme if sea level pressure and wind were added. Another way to improve any classification is to use a longer period of time. When trying assemble data over the ocean areas anything before 1980 is sparse. Satellites that were sent into space to monitor planetary conditions did not start getting launched until the early 1970's. There have been in situ measurements taken for many decades at specific locations or along shipping lanes, but any hope of complete and accurate ocean coverage was basically nonexistent until satellite sensor-based mapping. However, in the future, as spatial resolution of data from satellite sensors becomes even finer, the improvements on a development of a complete ocean climate classification can be outstanding. The data used for this thesis was the finest resolution available for time series used.

Sea ice is extremely important in earth atmosphere interaction and if the sea ice could be incorporated into a classification of ocean surface climates along with the SST and precipitation data that would beneficial. Also, adding complexity to the sea ice measurements would be a great way to get at this relationship. For the Köppen classification there was no option to add ice data because during his time there was no way to observe/measure it. The absolute number one variable in relation to sea ice would have to be albedo. It would be a great measurement to integrate albedo into not only the sea ice data archive, but into 21st Century climate classification system development that is based on process (energy fluxes) rather than outcome (surface temperatures or precipitation).

Creation of a new climate classification system that would incorporate inter-annual variability would be a major advance. Anomalous states of the climate system do not start/stop as the calendar switches from December to January, but we tend to partition the data stream based on our calendar system. In some cases, an El Niño or La Niña event is significant for a period that is shorter or longer than 12 months. Sometimes during one of these periods only six months are warm or cold enough to be considered an El Niño or La Niña. For instance, in 2007-2008 a nine month La Niña occurred from August through April. This is not even a whole year and secondly it had five months in 2007 and only four in 2008. If a classification system was developed to just take months, and disregard the calendar year portion, where the actual SST is indicative of an anomaly value it would be interesting to see the output in terms of climate types and not just SST values. Only in rare cases does an El Niño or La Niña span a whole calendar year. Only in two of the twenty nine years did this take place, 1987 and 1999 (Table 6.1 and Figures 4.5 & 4.6).

Table 6.1 Calendar year El Niño and La Niña [Source: Data from Climate Prediction Center, created by author]

	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	SON	OND	NDJ
1986								0.5	0.7	0.9	1.1	1.2
1987	1.2	1.3	1.2	1.1	1.0	1.2	1.4	1.6	1.6	1.5	1.3	1.1
1988	0.7	0.5										
1998							-0.5	-0.8	-1.0	-1.1	-1.3	-1.4
1999	-1.4	-1.2	-0.9	-0.8	-0.8	-0.8	-0.9	-0.9	-1.0	-1.1	-1.3	-1.6
2000	-1.6	-1.4	-1.0	-0.8	-0.6	-0.5						

When Wladimir Köppen first started out with his classification system in 1898 he only had nine classes (Essenwanger, 2001):

- Tropical rain with dry time in winter and spring with maximum in July/August.
- Tropical rain with double maximum and short maximum in midsummer.
- Tropical rain with maximum in Fall.
- Winter rain, summer dry.
- Spring and early summer rain, also fall and early winter rain, late summer dry.
- All months rain with average precipitation amount or snow cover.
- Main precipitation in winter but also moderate precipitation amounts in summer
- Sparse rain, less than 6 days with precipitation
- All months with precipitation , but less than 15 days with precipitation, with main precipitation in winter.

It was not until 1936 and that Köppen made his final classification *"Handbuch Der Klimatologie Vol. C"* (Handbook of Climatology) which means 38 years were spent until he got the twenty five climate classes just the way he wanted for that time. Köppen made adjustments throughout his career and he would likely want to continue to improve climate classification if he were alive today. He did not have access to all of the modern technologies and the benefits that come with them, such as greatly improved sensors, satellite-based climate measuring tools, and supercomputers to crunch large amounts of data. However, it is believed that Köppen would suggest that there is always room to improve. Therein lies challenge; advance the science of climate classification and try and fit these invisible climate boundaries the best possible way to identify the subtle differences that occur over the oceans.

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Appendix A - The Köppen Model

Model Algorithms

Summer Division Map

“$$rowmap Grid” = $$rowmap

Summer Boolean

“Create Summer Boolean” = con(Summer Division Map < 180, 1, 0)

Total Rainfall

“R” = sum(Precip January, Precip February, Precip March, Precip April, Precip May, Precip June, Precip July, Precip August, Precip September, Precip October, Precip November, Precip December)

Total Precip Wettest

“Rhi” = rank(12, Precip January, Precip February, Precip March, Precip April, Precip May, Precip June, Precip July, Precip August, Precip September, Precip October, Precip November, Precip December)

Total Precip Driest

“Rlo” = rank(1, Precip January, Precip February, Precip March, Precip April, Precip May, Precip June, Precip July, Precip August, Precip September, Precip October, Precip November, Precip December)

Total Precip Summer Six

“Rs” = con(Summer Boolean == 1, sum(Precip October, Precip May, Precip June, Precip July, Precip August, Precip September), sum(Precip April, Precip November, Precip December, Precip January, Precip February, Precip March))

Total Precip Wettest Summer

“Rs-hi” = con(Summer Boolean == 1, rank(6, Precip October, Precip May, Precip June, Precip July, Precip August, Precip September), rank(6, Precip April, Precip November, Precip December, Precip January, Precip February, Precip March))

Total Precip Wettest Winter

“Rw-hi” = con(Summer Boolean == 1, rank(6, Precip April, Precip November, Precip December, Precip January, Precip February, Precip March), rank(6, Precip October, Precip May, Precip June, Precip July, Precip August, Precip September))

Total Precip Driest Summer

“Rs-lo” = con(Summer Boolean == 1, rank(1, Precip October, Precip May, Precip June, Precip July, Precip August, Precip September), rank(1, Precip April, Precip November, Precip December, Precip January, Precip February, Precip March))

Total Precip Driest Winter

“Rw-lo” = con(Summer Boolean == 1, rank(1, Precip April, Precip November, Precip December, Precip January, Precip February, Precip March), rank(1, Precip October, Precip May, Precip June, Precip July, Precip August, Precip September))

Annual Avg Temp

“T” = sum(Temp January, Temp February, Temp March, Temp April, Temp May, Temp June, Temp July, Temp August, Temp September, Temp October, Temp November, Temp December) / 12

Avg Temp Warmest

“Thi” = rank(12, Temp January, Temp February, Temp March, Temp April, Temp May, Temp June, Temp July, Temp August, Temp September, Temp October, Temp November, Temp December)

Avg Temp Coldest

“Tlo” = rank(1, Temp January, Temp February, Temp March, Temp April, Temp May, Temp June, Temp July, Temp August, Temp September, Temp October, Temp November, Temp December)

Over 10C Jan

“Njan” = con(Temp January >= 10, 1, 0)

Over 10C Feb

“Nfeb” = con(Temp February >= 10, 1, 0)

Over 10C Mar

“Nmar” = con(Temp March >= 10, 1, 0)

Over 10C Apr

“Napr” = con(Temp April >= 10, 1, 0)

Over 10C May

“Nmay” = con(Temp May >= 10, 1, 0)

Over 10C June

“Njun” = con(Temp June >= 10, 1, 0)

Over 10C July

“Njul” = con(Temp July >= 10, 1, 0)

Over 10C Aug

“Naug” = con(Temp August >= 10, 1, 0)

Over 10C Sep

“Nsep” = con(Temp September >= 10, 1, 0)

Over 10C October

“Noct” = con(Temp October >= 10, 1, 0)

Over 10C Nov

“Nnov” = con(Temp November >= 10, 1, 0)

Over 10C Dec

“Ndec” = con(Temp December >= 10, 1, 0)

Over 10C

“N10” = sum(Over 10C Jan, Over 10C Feb, Over 10C Mar, Over 10C Apr, Over 10C May, Over 10C June, Over 10C July, Over 10C Aug, Over 10C Sep, Over 10C October, Over 10C Nov, Over 10C Dec)

Pct Summer Rain

“P=Rs/R” = con(Total Annual Rainfall == 0, 0, Total Precip Summer Six / Total Annual Rainfall)

Humid_Arid

“X” = con(Pct Summer Rain <= 0.3, 2 * Annual Avg Temp, Pct Summer Rain >= 0.7, (Annual Avg Temp + 14) * 2, (Annual Avg Temp + 7) * 2)

*Changed to: "X" = con(Pct Summer Rain <= 0.3, .2 * Annual Avg Temp, Pct Summer Rain >= 0.7, (Annual Avg Temp + 2.8) * .2, (Annual Avg Temp + 1.4) * 2)*

ACDE_1 B_0

“R>=X” = con(Total Annual Rainfall >= Humid_Arid, 1, 0)

A

“Not B – Tlo >= 18” = ACDE_1 B_0 == 1 && Avg Temp Coldest >= 18

B

“X > R >= X/2” = con(Humid_Arid > Total Annual Rainfall && Total Annual Rainfall >= Humid_Arid / 2, 1, Total Annual Rainfall < Humid_Arid / 2, 2, 0)

C

“Not B -- 18 > Tlo >= -3 -- Thi >= 10” = ACDE_1 B_0 == 1 && Avg Temp Coldest < 18 && Avg Temp Coldest >= -3 && Avg Temp Warmest >=10

D

“Not B -- Tlo < -3 -- Thi >= 10” = ACDE_1 B_0 == 1 && Avg Temp Coldest < -3 && Avg Temp Warmest >= 10

E

“Not B Thi < 10” = ACDE_1 B_0 == 1 && Avg Temp Warmest <10

As

“A Subcats” = con(A == 1 && Total Precip Driest >= 6, 1, A == 1 && Total Precip Driest < 6 && Total Precip Driest >= 10 - (Total Annual Rainfall / 25), 2, A == 1 && Total Precip Driest < 10 - (Total Annual Rainfall / 25), 3, 0)

Changed to: *"A Subcats" = con(A == 1 && Total Precip Driest >= 60, 1, A == 1 && Total Precip Driest < 60 && Total Precip Driest >= 100 - (Total Annual Rainfall / 25), 2, A == 1 && Total Precip Driest < 100 - (Total Annual Rainfall / 25), 3, 0)*

Bs

“B Subcats” = con(B == 1 && Annual Avg Temp >= 18, 1, B == 1 && Annual Avg Temp < 18, 2, B == 2 && Annual Avg Temp >= 18, 3, B == 2 && Annual Avg Temp < 18, 4, 0)

C Subs w s

“First Sub w_1 s_2” = con(C == 1 && Total Precip Driest < 3 && Total Precip Wettest Summer >= 10 * Total Precip Driest Winter, 1, C == 1 && Total Precip Driest < 3 && Total Precip Wettest Winter >= 3 * Total Precip Driest Summer && Total Precip Wettest Summer < 10 * Total Precip Driest Winter, 2, 0)

C Subs f

“First Sub f_1” = C == 1 && C Subs w s == 0

Cas

“C Sub a” = con(C Subs w s == 1 && Avg Temp Warmest >= 22, 1, C Subs w s == 2 && Avg Temp Warmest >= 22, 2, C Subs f == 1 && Avg Temp Warmest >= 22, 3, 0)

Cbs

“C Sub b” = con(C Subs w s == 1 && Avg Temp Warmest < 22 && Over 10C >= 4, 1, C Subs w s == 2 && Avg Temp Warmest < 22 && Over 10C >= 4, 2, C Subs f == 1 && Avg Temp Warmest < 22 && Over 10C >= 4, 3, 0)

Ccs

“C Sub c” = con(C Subs w s == 1 && Avg Temp Warmest < 22 && 4 > Over 10C && Over 10C >= 1 && Avg Temp Coldest >= -38, 1, C Subs w s == 2 && Avg Temp Warmest < 22 && 4 > Over 10C && Over 10C >= 1 && Avg Temp Coldest >= -38, 2, C Subs f == 1 && Avg Temp Warmest < 22 && 4 > Over 10C && Over 10C >= 1 && Avg Temp Coldest >= -38, 3, 0)

D Subs w s

“D First Sub w_1 s_2” = con(D == 1 && Total Precip Driest < 3 && Total Precip Wettest Summer >= 10 * Total Precip Driest Winter, 1, D == 1 && Total Precip Driest < 3 && Total Precip Wettest Winter >= 3 * Total Precip Driest Summer && Total Precip Wettest Summer < 10 * Total Precip Driest Winter, 2, 0)

D Subs f

“D First Sub f_1” = D == 1 && D Subs w s == 0

Das

“D Sub a” = con(D Subs w s == 1 && Avg Temp Warmest >= 22, 1, D Subs w s == 2 && Avg Temp Warmest >= 22, 2, D Subs f == 1 && Avg Temp Warmest >= 22, 3, 0)

Dbs

“D Sub b” = con(D Subs w s == 1 && Avg Temp Warmest < 22 && Over 10C >= 4, 1, D Subs w s == 2 && Avg Temp Warmest < 22 && Over 10C >= 4, 2, D Subs f == 1 && Avg Temp Warmest < 22 && Over 10C >= 4, 3, 0)

Dcs

“D Sub c” = con(D Subs w s == 1 && Avg Temp Warmest < 22 && 4 > Over 10C >= 1 && Avg Temp Coldest >= -38, 1, D Subs w s == 2 && Avg Temp Warmest < 22 && 4 > Over 10C >= 1 && Avg Temp Coldest >= -38, 2, D Subs f == 1 && Avg Temp Warmest < 22 && 4 > Over 10C >= 1 && Avg Temp Coldest >= -38, 3, 0)

Dds

“D Sub d” = con(D Subs w s == 1 && Avg Temp Warmest < 22 && 4 > Over 10C >= 1 && Avg Temp Coldest < -38, 1, D Subs w s == 2 && Avg Temp Warmest < 22 && 4 > Over 10C >= 1 && Avg Temp Coldest < -38, 2, D Subs f == 1 && Avg Temp Warmest < 22 && 4 > Over 10C >= 1 && Avg Temp Coldest < -38, 3, 0)

Es

“E==1 Thi>=0” = con(E == 1&& Avg Temp Warmest > 0, 1, E == 1 && Avg Temp Warmest <= 0, 2)

Köppen Classification

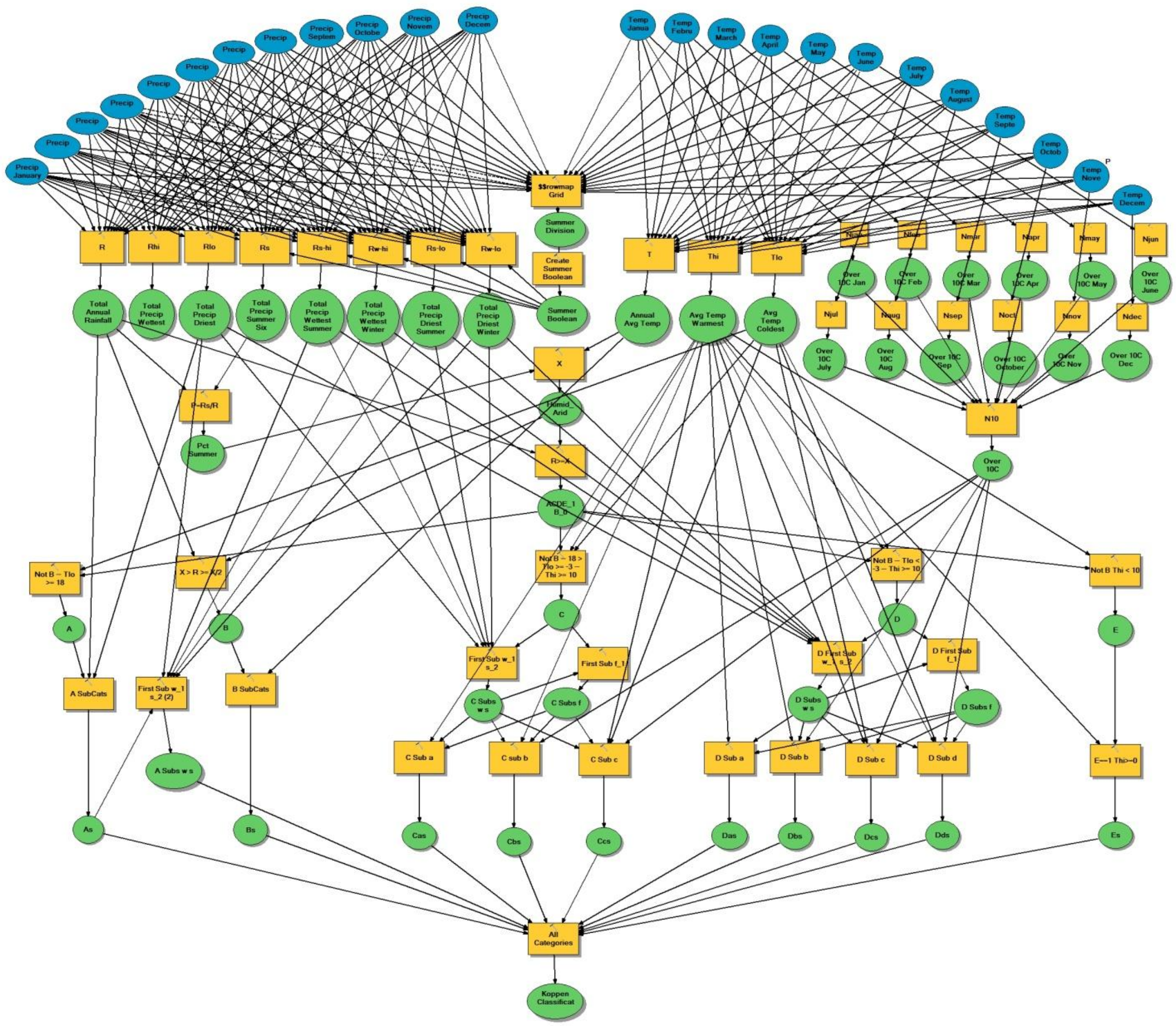
“All Categories” = con(As == 1, 1, As == 2, 2, As == 3, 3, Bs == 1, 4, Bs == 2, 5, Bs == 3, 6, Bs == 4, 7, Cas == 1, 8, Cas == 2, 11, Cas == 3, 14, Cbs == 1, 9, Cbs == 2, 12, Cbs == 3, 15, Ccs == 1, 10, Ccs == 2, 13, Ccs == 3, 16, Das == 1, 17, Das == 2, 21, Das == 3, 25, Dbs == 1, 18, Dbs == 2, 22, Dbs == 3, 26, Dcs == 1, 19, Dcs == 2, 23, Dcs == 3, 27, Dds == 1, 20, Dds == 2, 24, Dds == 3, 28, Es == 1, 29, Es == 2, 30, 0)

Changed to: *"All Categories" = con(As == 1, 1, As == 2, 2, As == 3, 3, Bs == 1, 4, Bs == 2, 5, Bs == 3, 6, Bs == 4, 7, Cas == 1, 8, Cas == 2, 11, Cas == 3, 14, Cbs == 1, 9, Cbs == 2, 12, Cbs == 3, 15, Ccs == 1, 10, Ccs == 2, 13, Ccs == 3, 16, Das == 1, 17, Das == 2, 21, Das == 3, 25, Dbs == 1, 18, Dbs == 2, 22, Dbs == 3, 26, Dcs == 1, 19, Dcs == 2, 23, Dcs == 3, 27, Dds == 1, 20, Dds == 2, 24, Dds == 3, 28, Es == 1, 29, Es == 2, 30, As == 31, 0)*

New: *"Aw & As" = con(As == 1 && Total Precip Driest < 3 && Total Precip Wettest Summer >= 10 * Total Precip Driest Winter, 3, As == 1 && Total Precip Driest < 3 && Total Precip Wettest Winter >= 3 * Total Precip Driest Summer && Total Precip Wettest Summer < 10 * Total Precip Driest Winter, 31, 0)*

ArcModelBuilder Technique

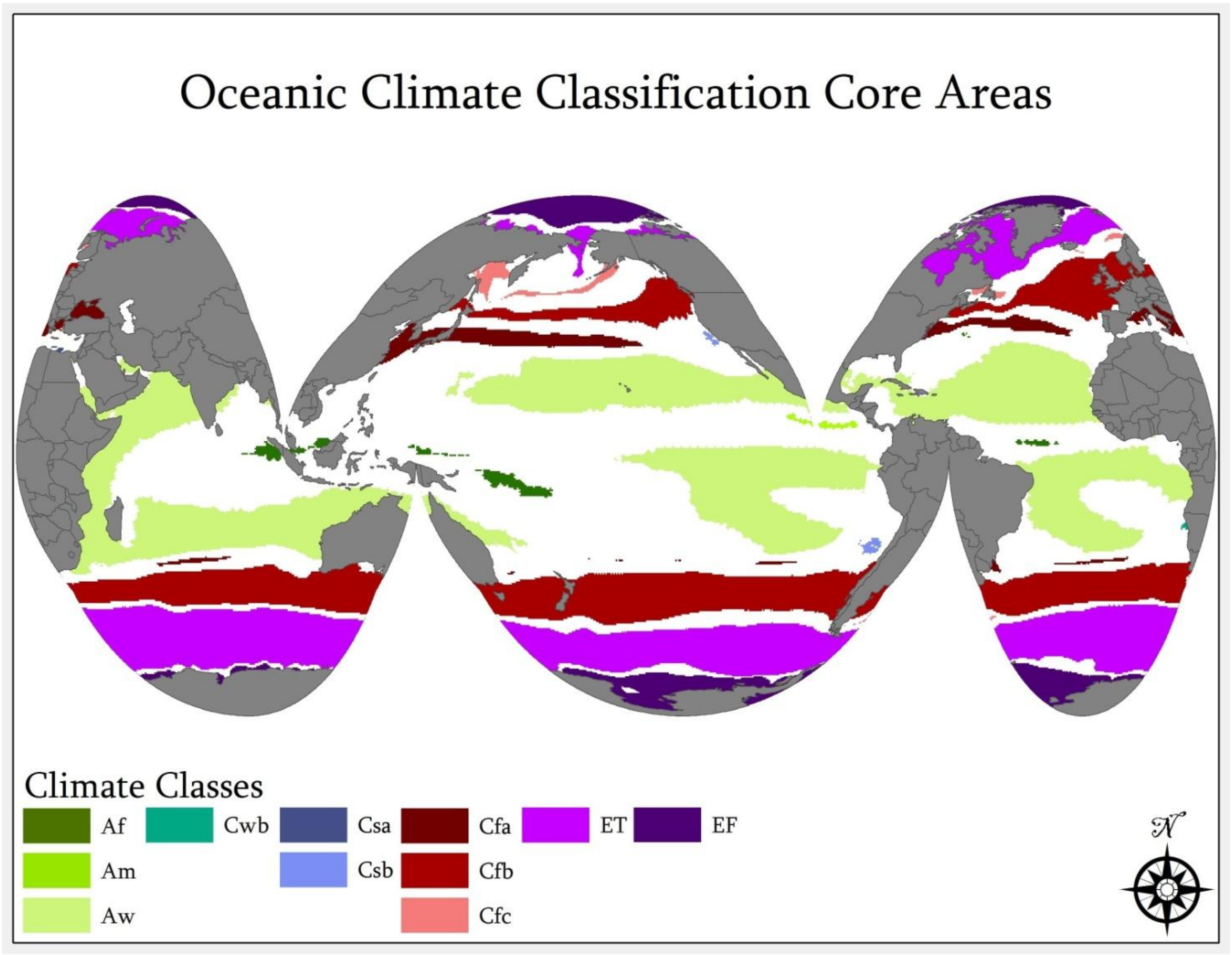
Figure A.1 Köppen climate years model [Source: created by author]



Appendix B - Climate Analyses

Core Area Zones

Figure B.1 Oceanic core area zones from 1980-2008 [Source: created by author]



Individual Climate Frequencies

Figure B.2 Af climate frequency zone [Source: created by author]

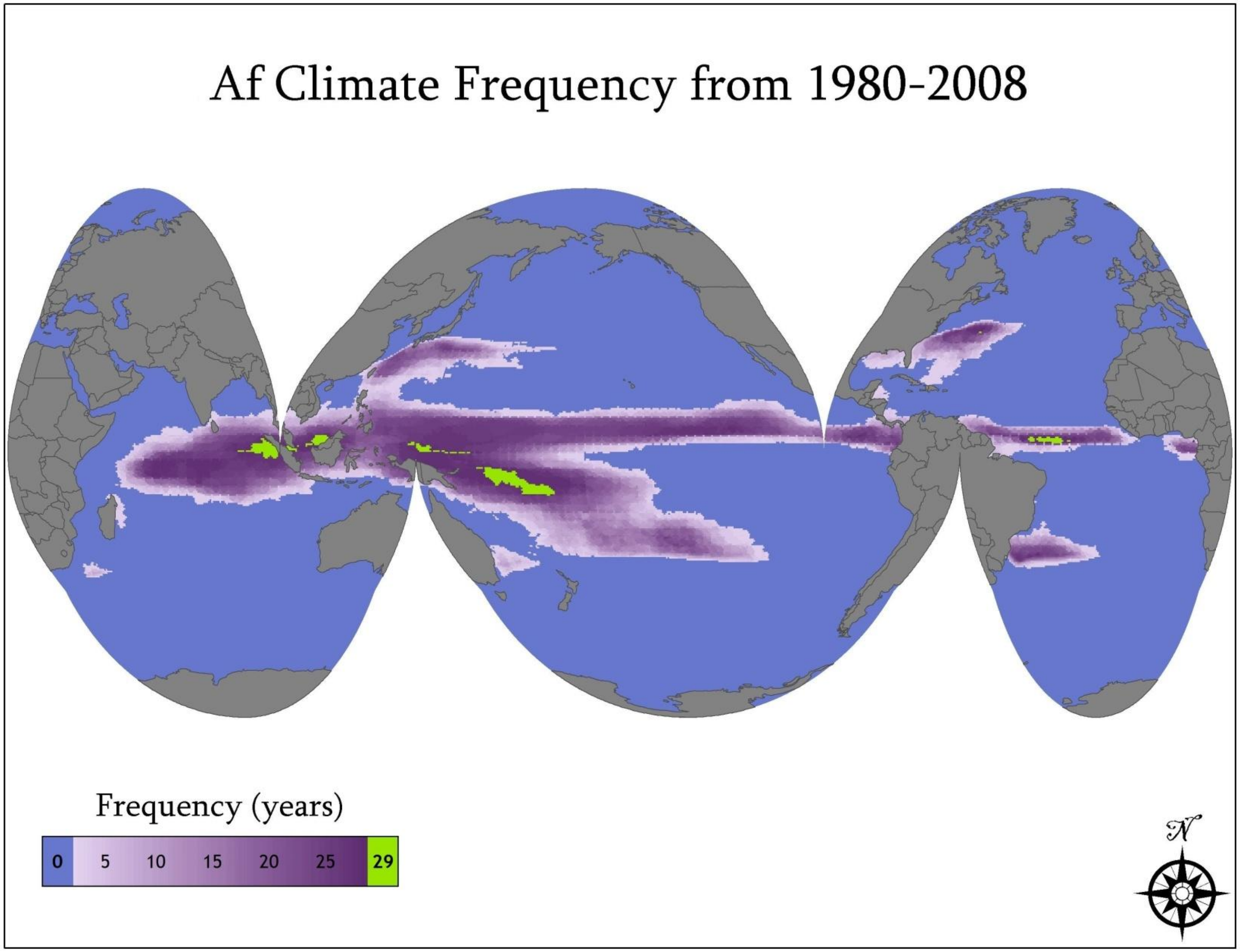


Figure B.3 Am climate frequency zone [Source: created by author]

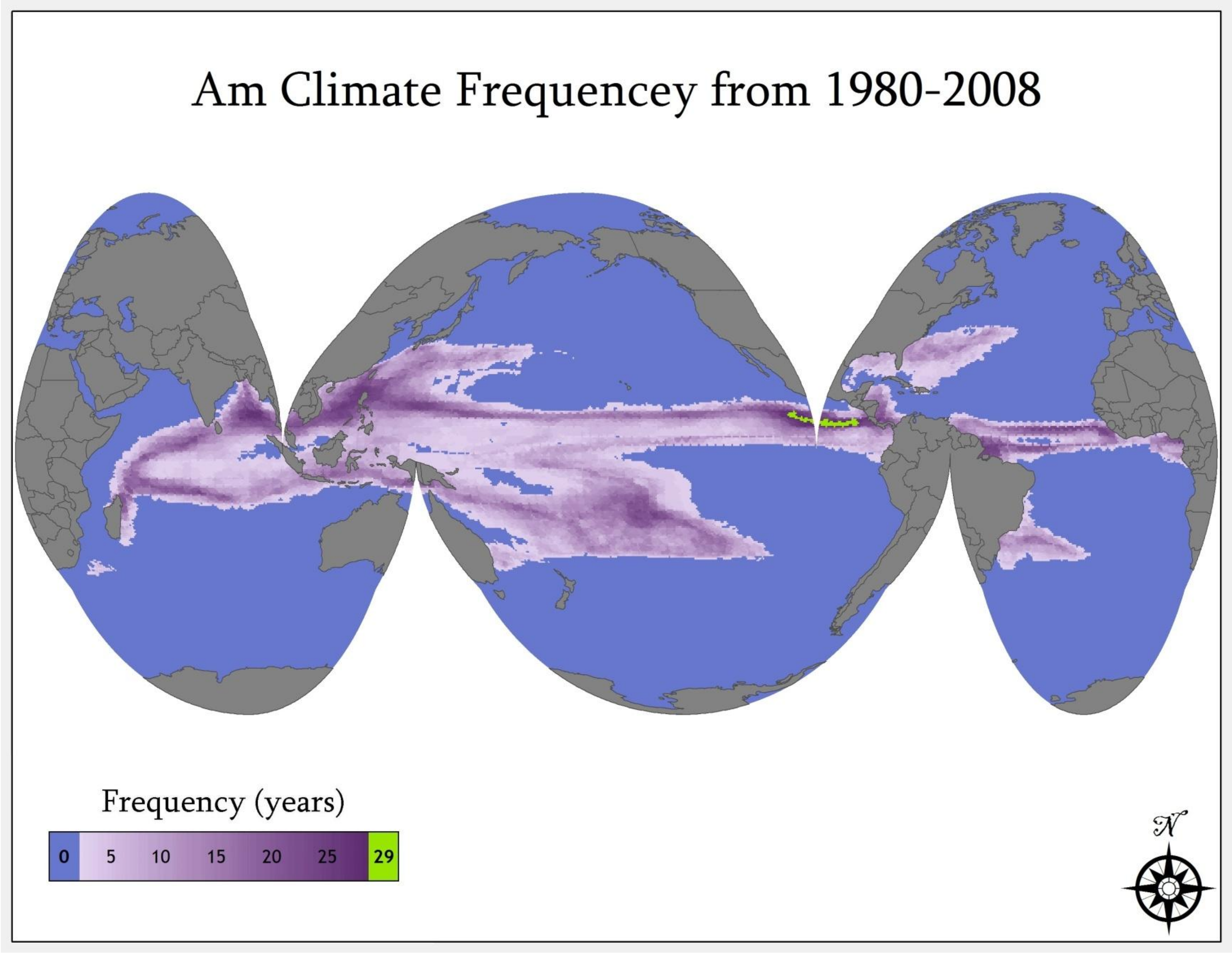


Figure B.4 Aw climate frequency zone [Source: created by author]

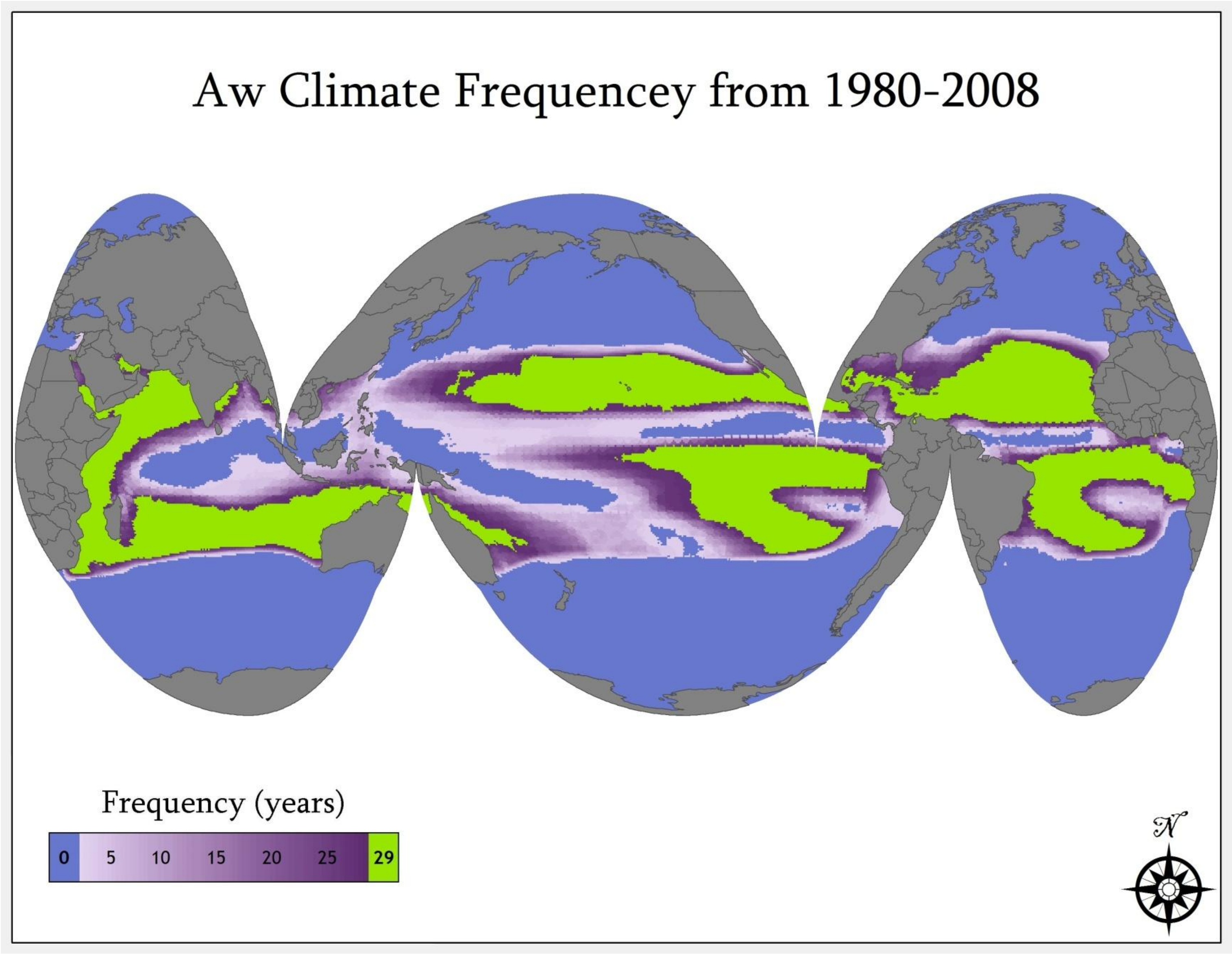


Figure B.5 BSh climate frequency zone [Source: created by author]

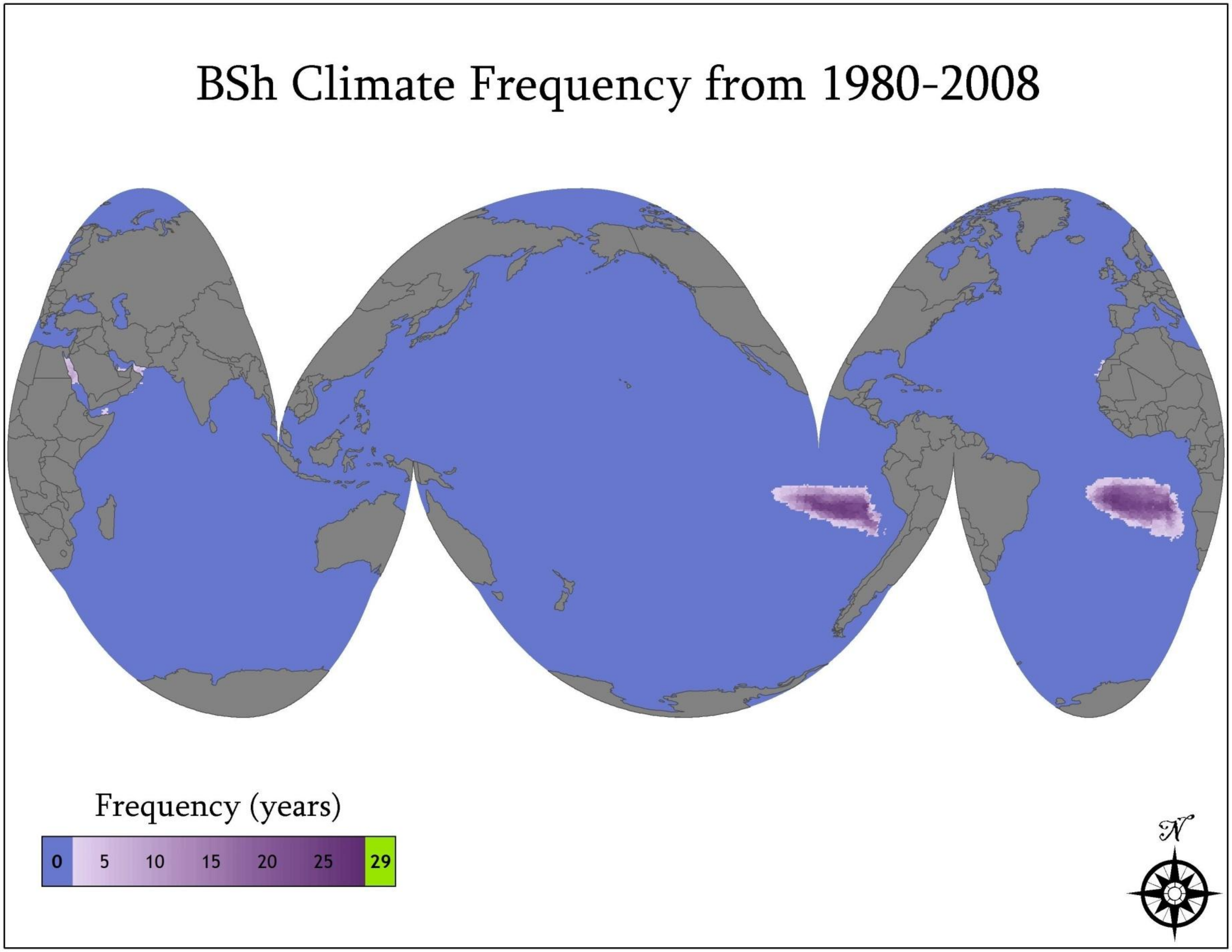


Figure B.6 BSk climate frequency zone [Source: created by author]

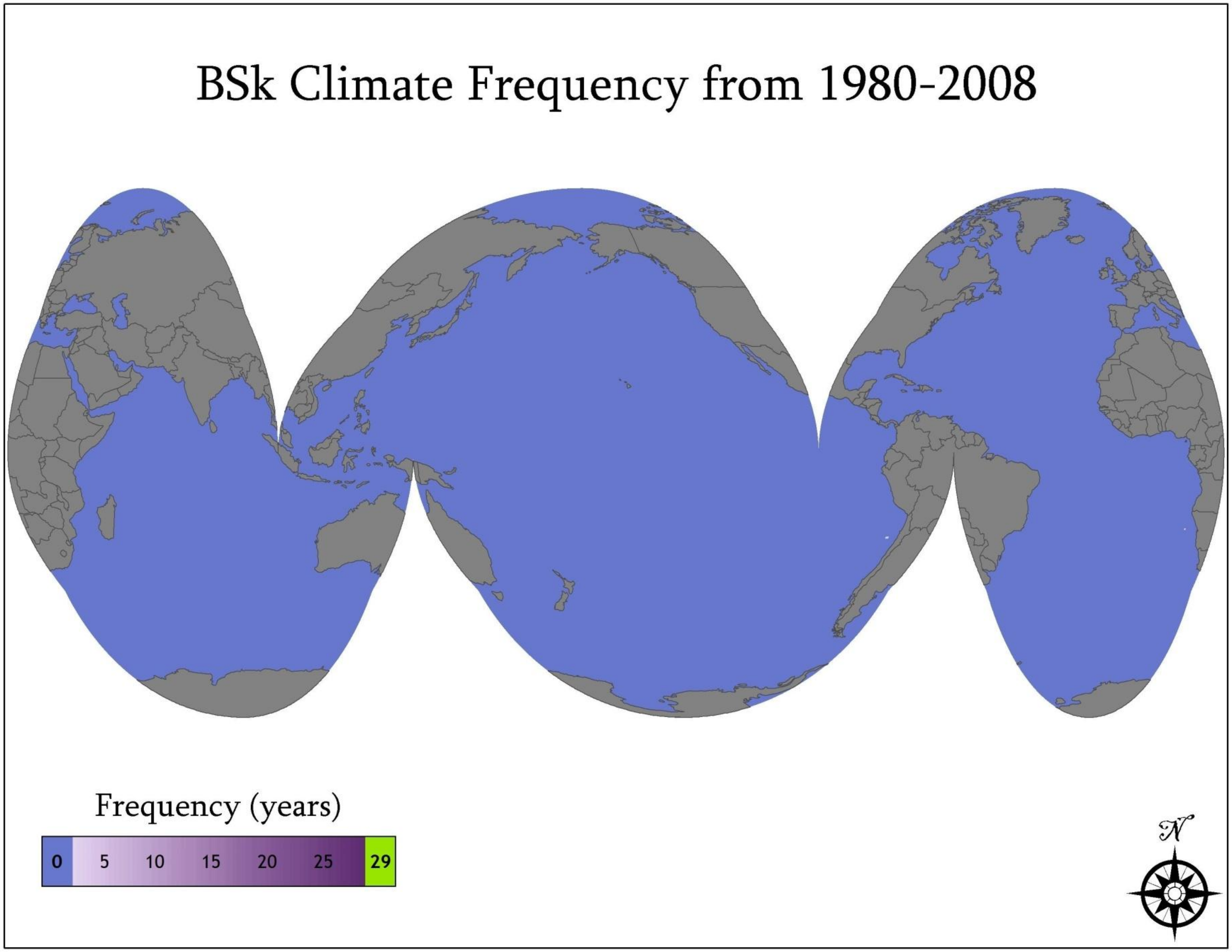


Figure B.7 BWh climate frequency zone [Source: created by author]

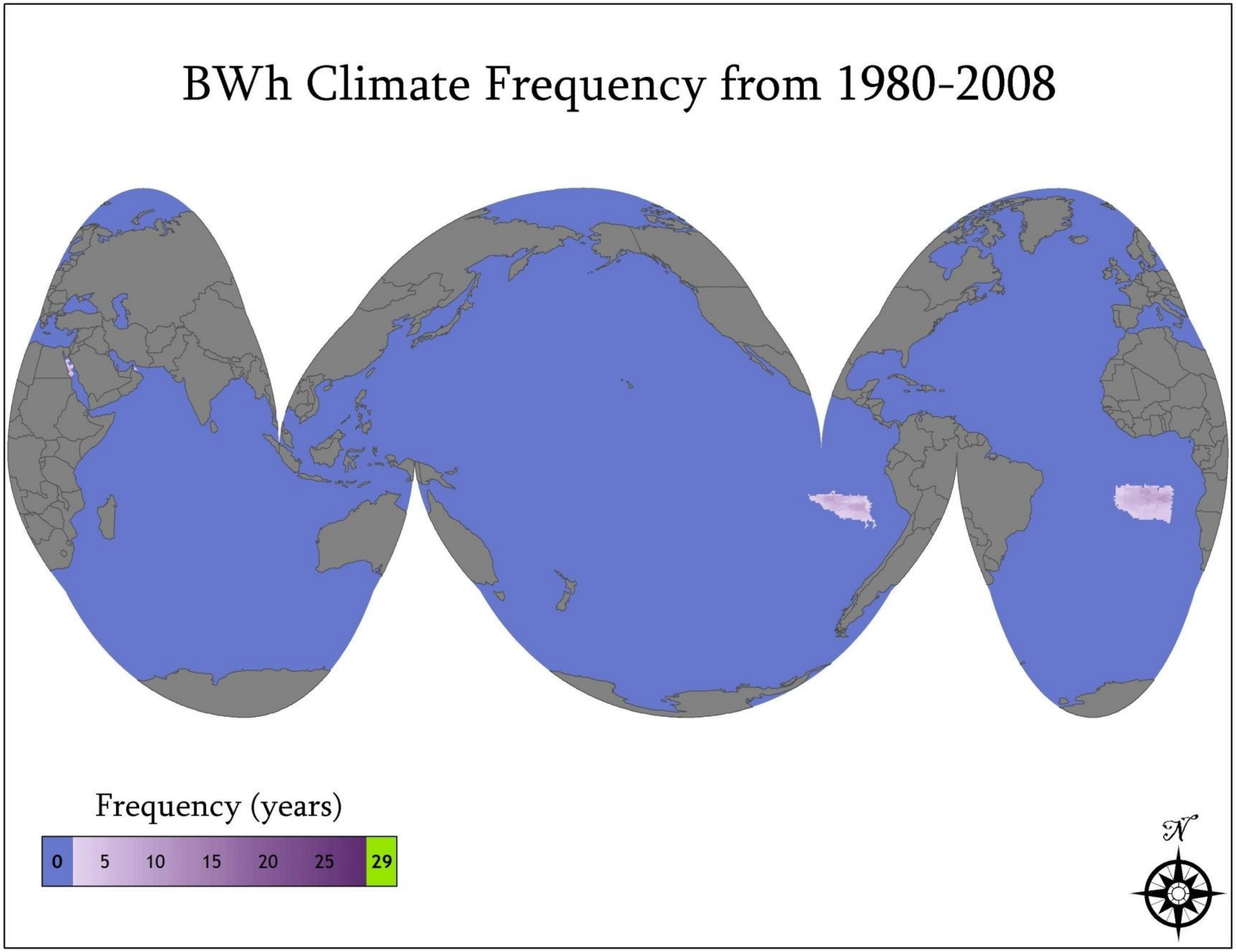


Figure B.8 Cwa climate frequency zone [Source: created by author]

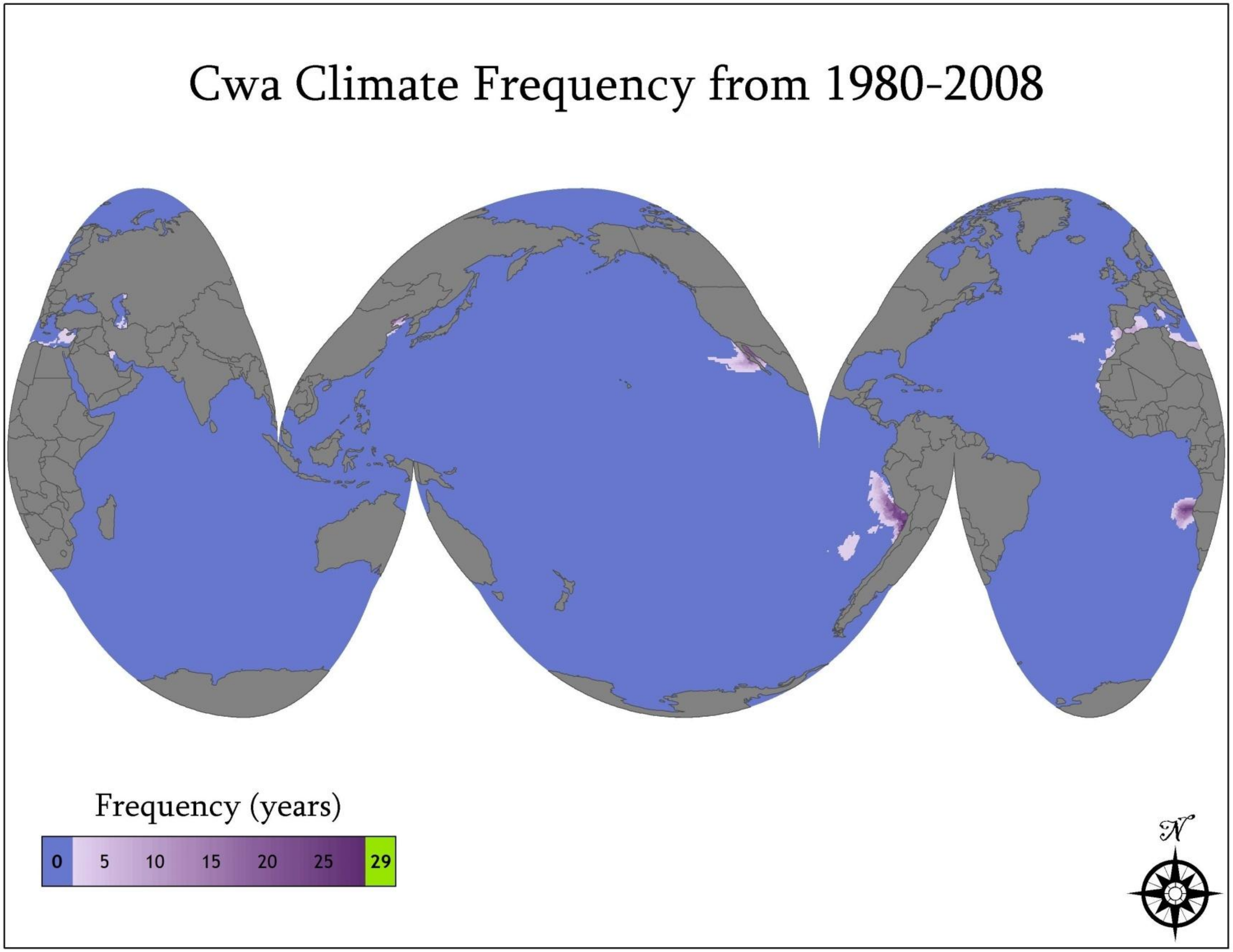


Figure B.9 Cwb climate frequency zone [Source: created by author]

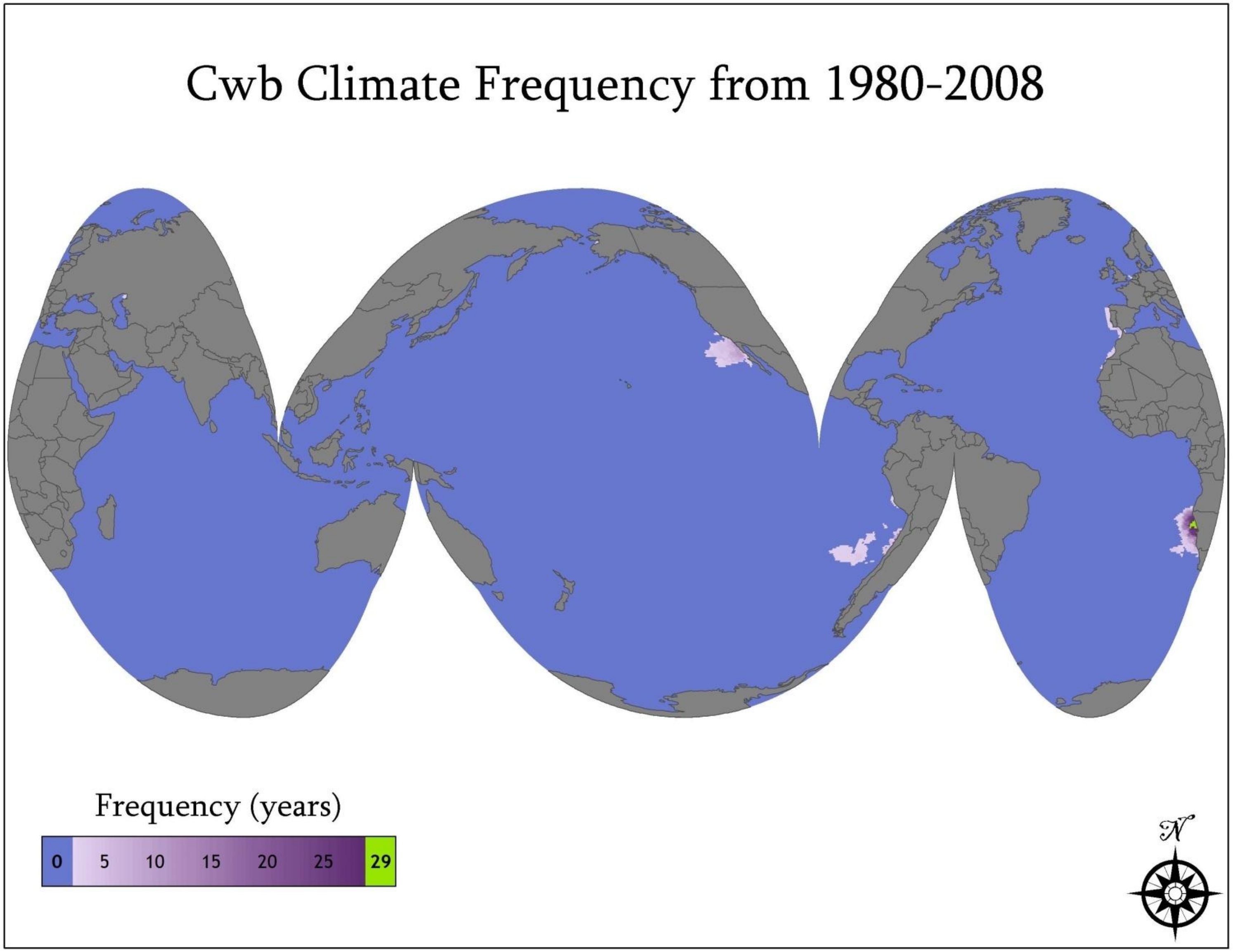


Figure B.10 Cwc climate frequency zone [Source: created by author]

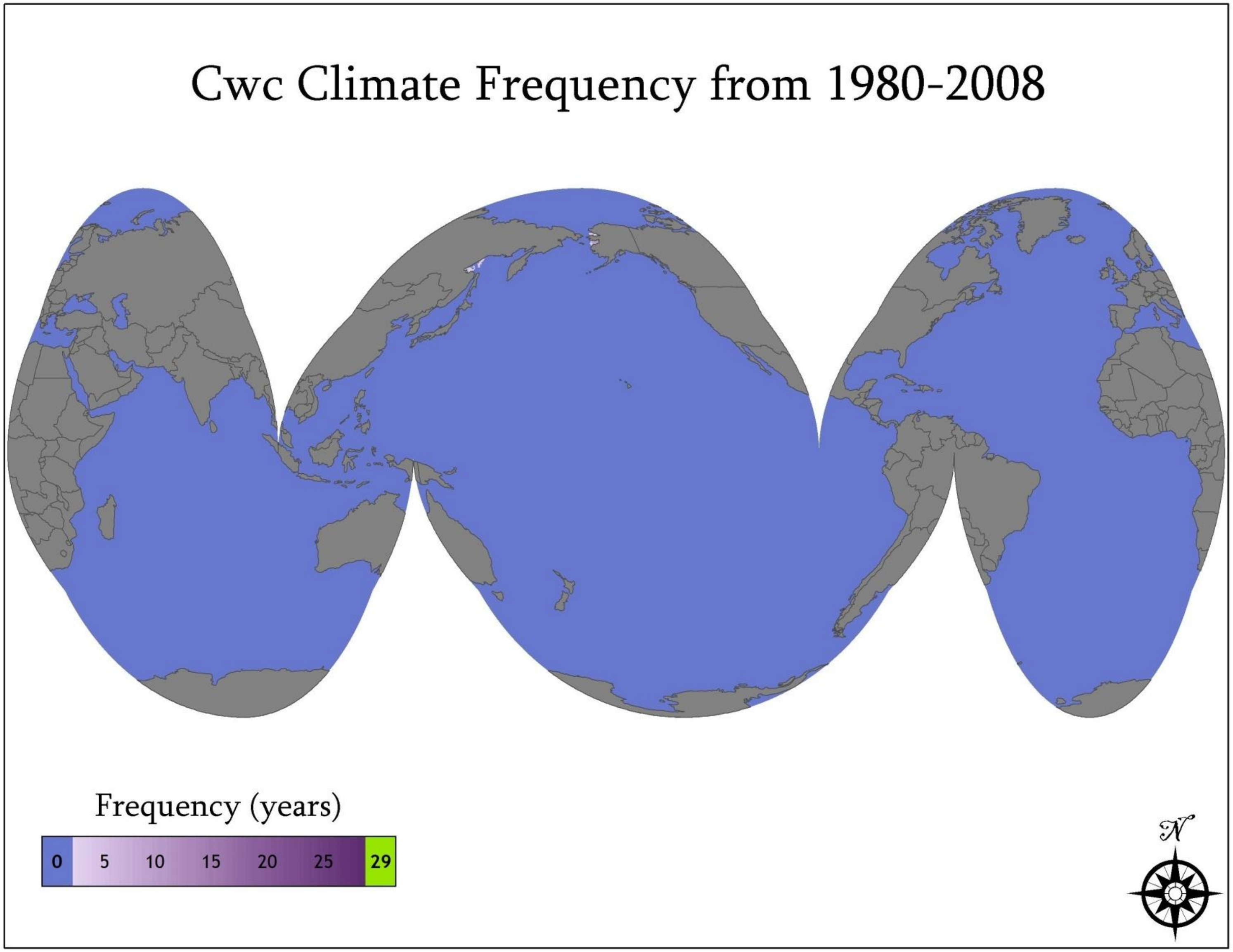


Figure **B.11 Csa climate frequency zone [Source: created by author]**

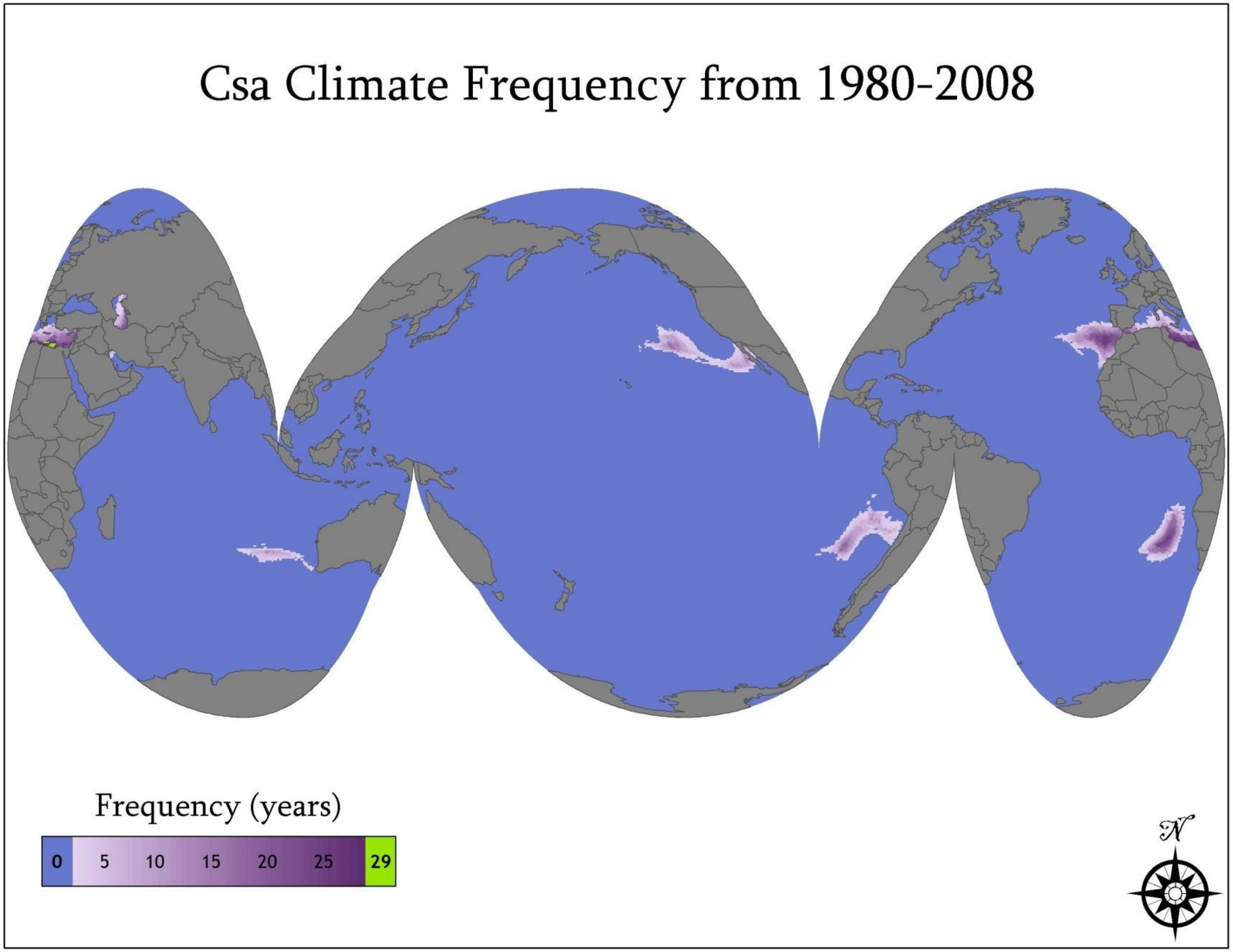


Figure B.12 Csb climate frequency zone [Source: created by author]

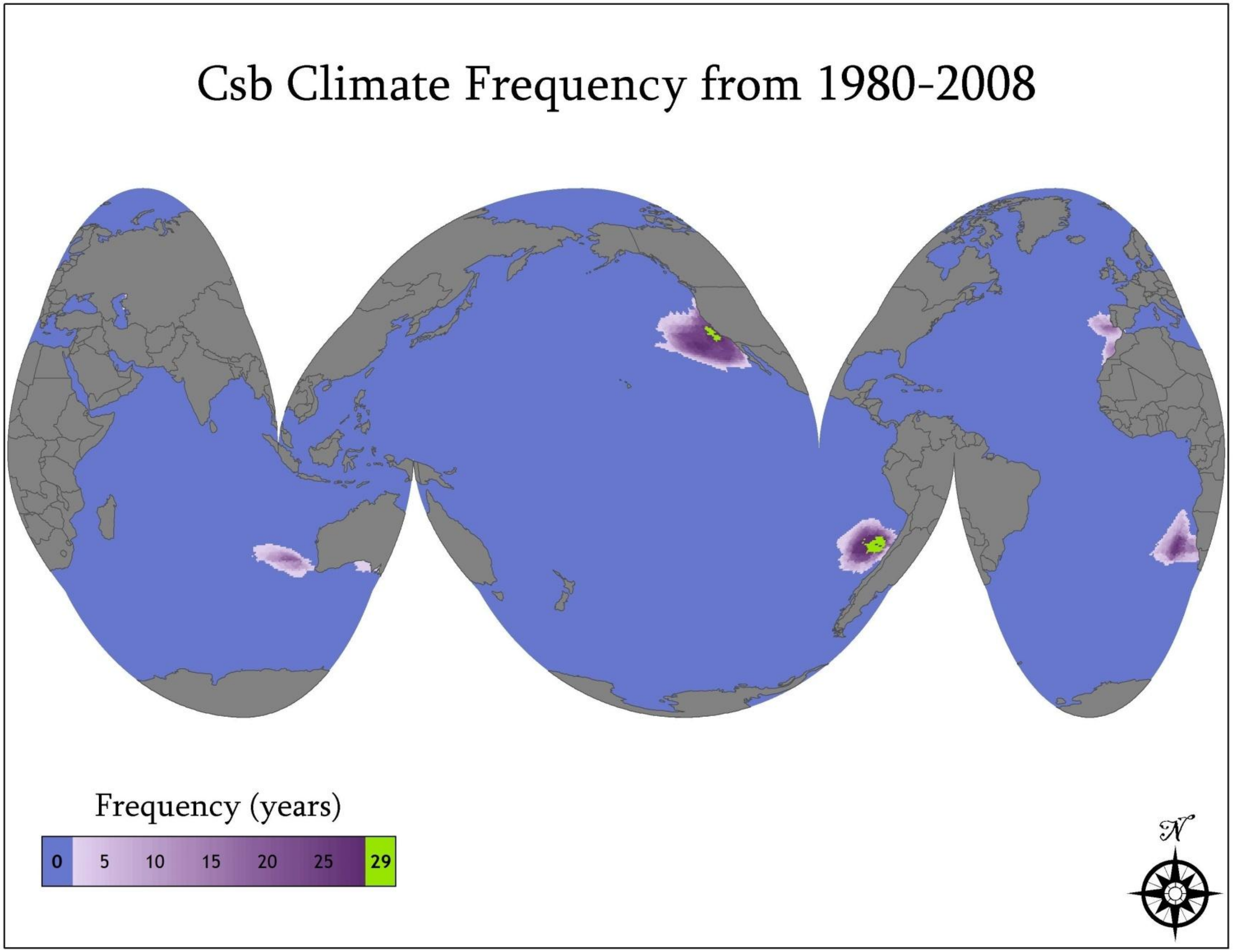


Figure B.13 Cfa climate frequency zone [Source: created by author]

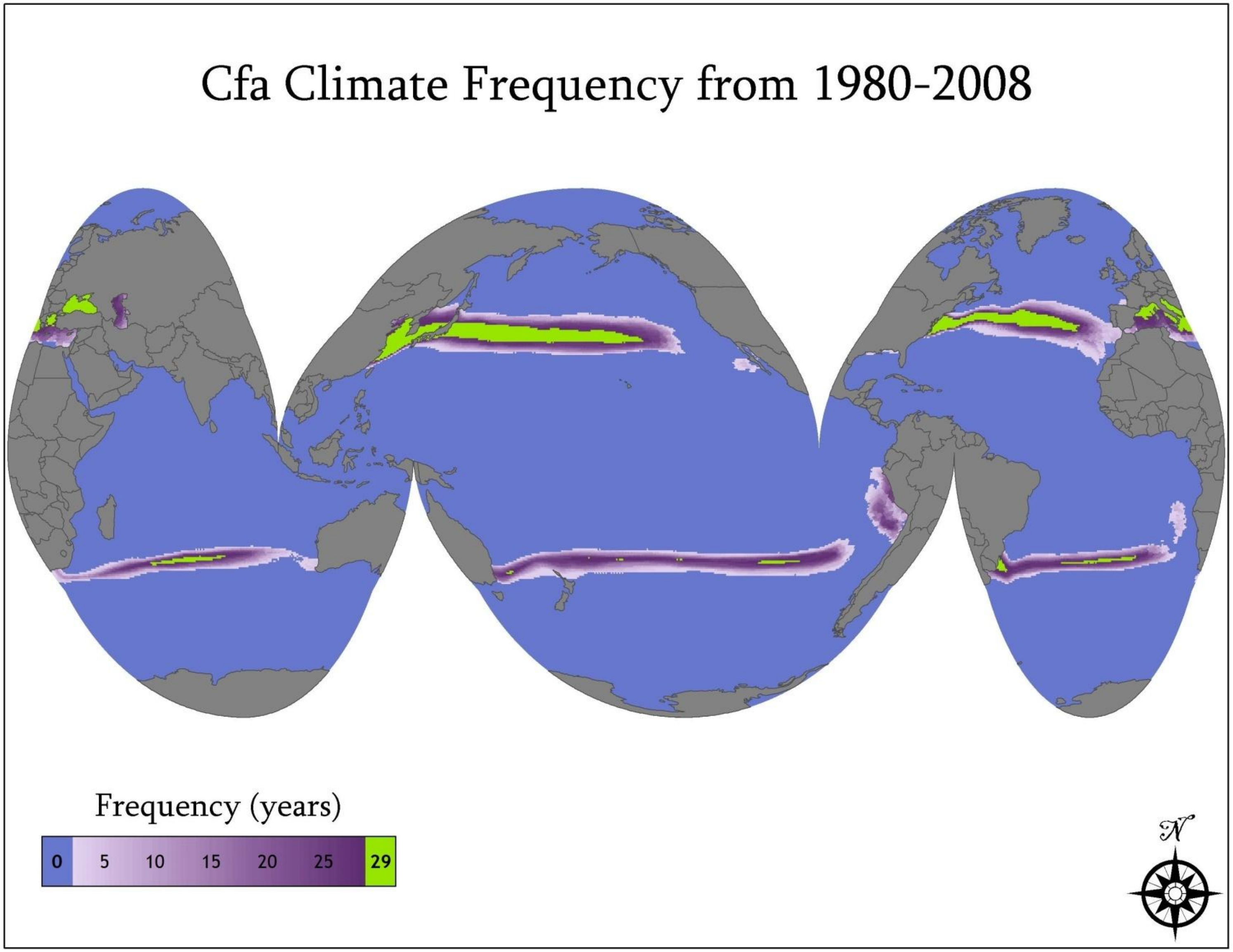


Figure B.14 Cfb climate frequency zone [Source: created by author]

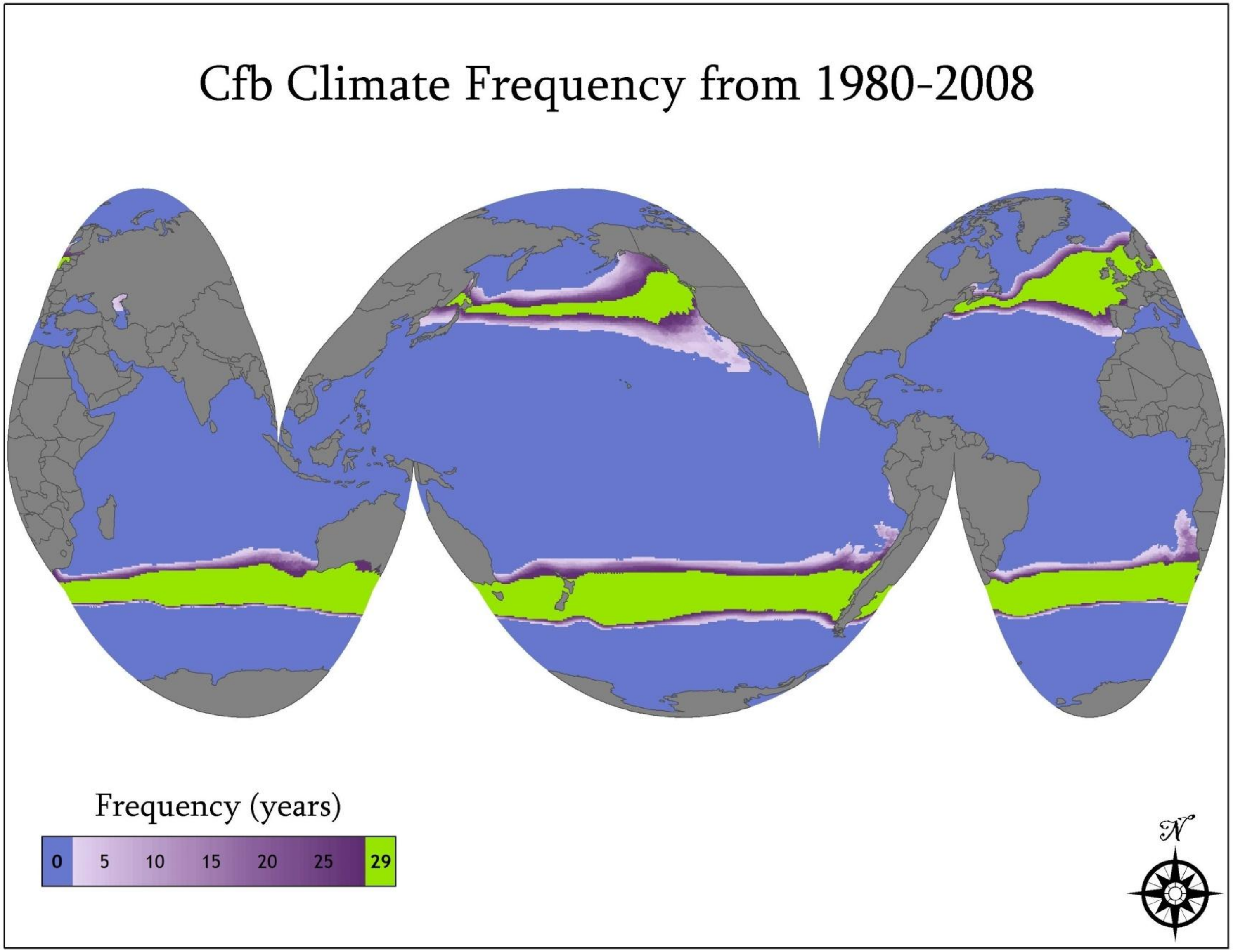


Figure B.15 Cfc climate frequency zone [Source: created by author]

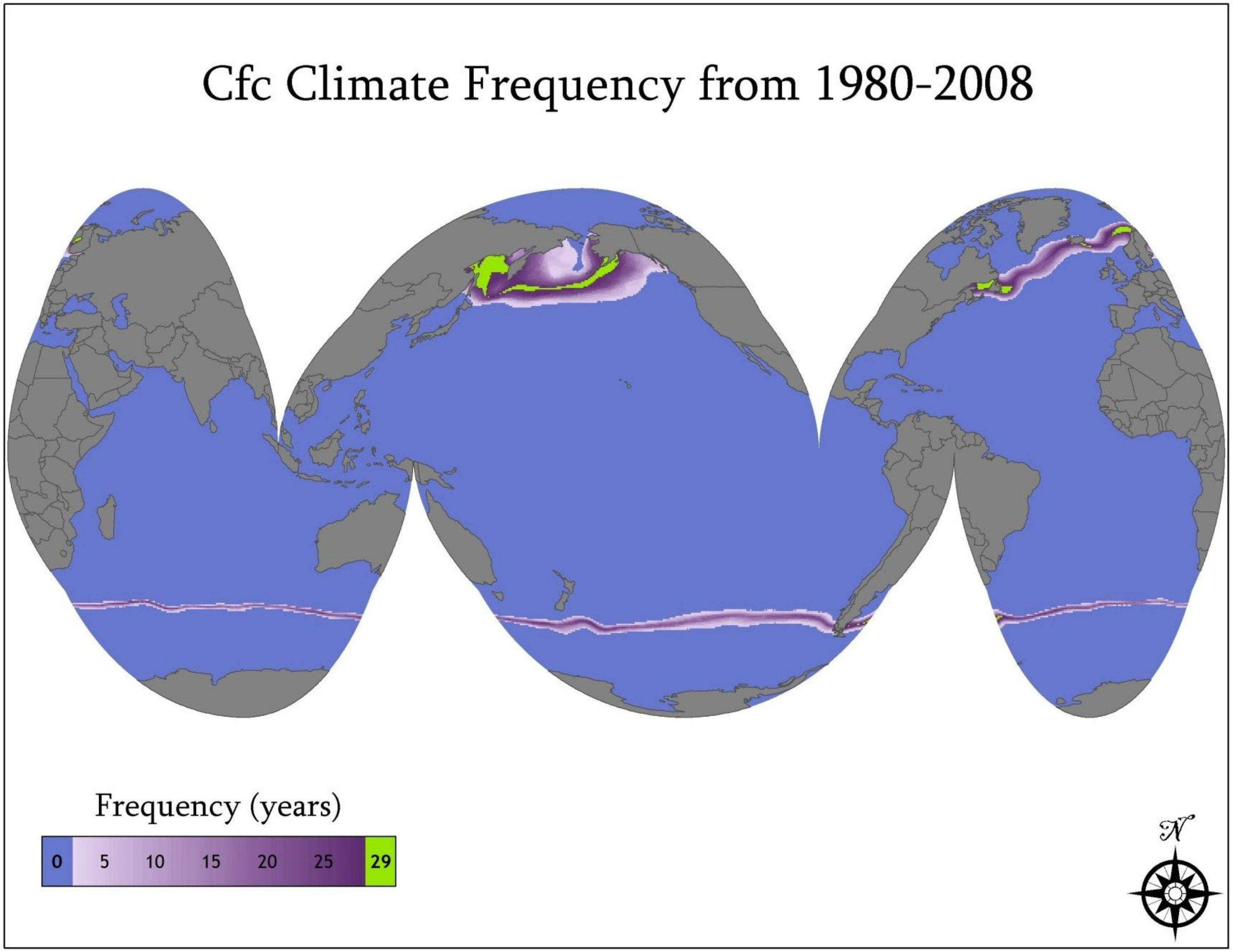


Figure B.16 ET climate frequency zone [Source: created by author]

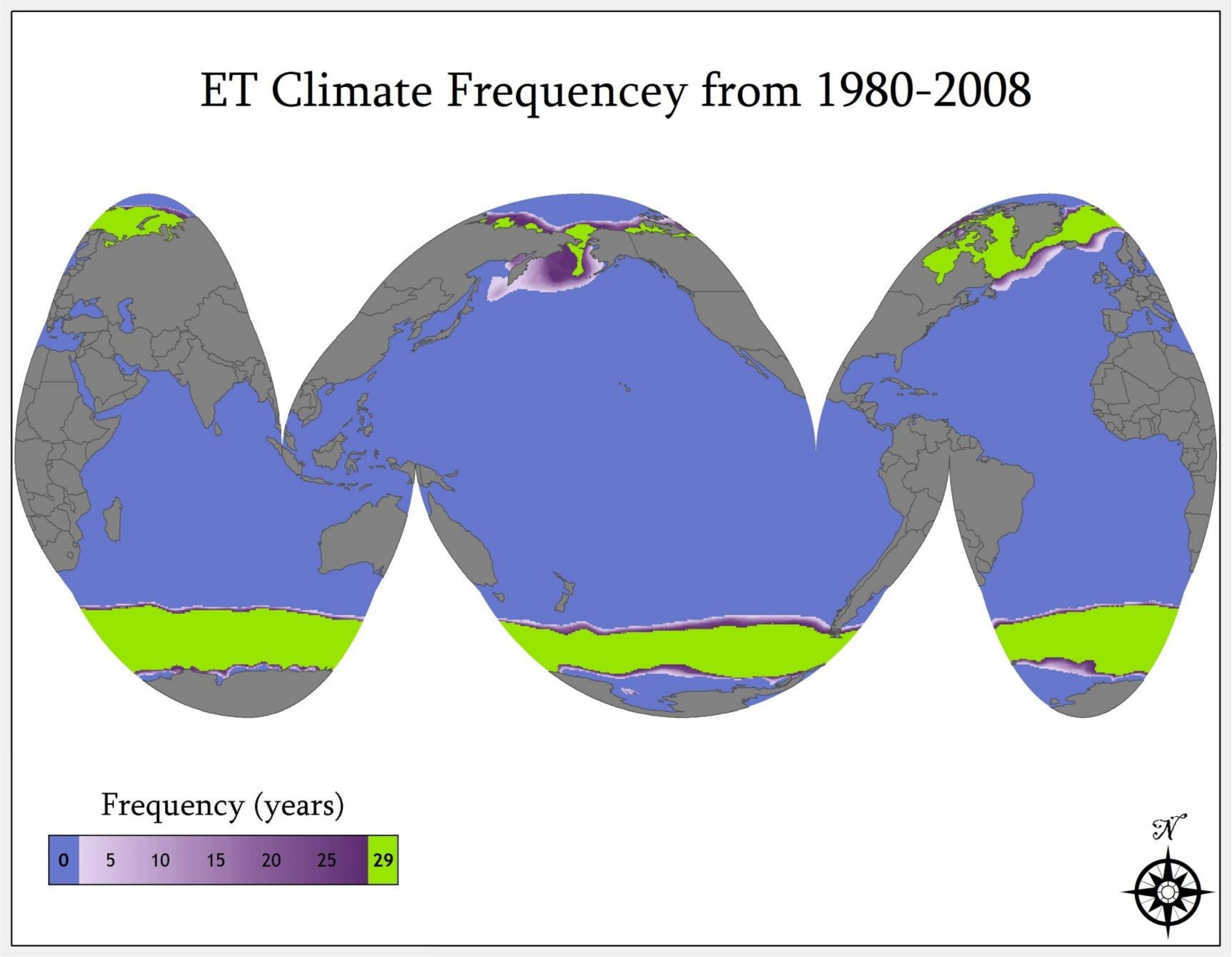
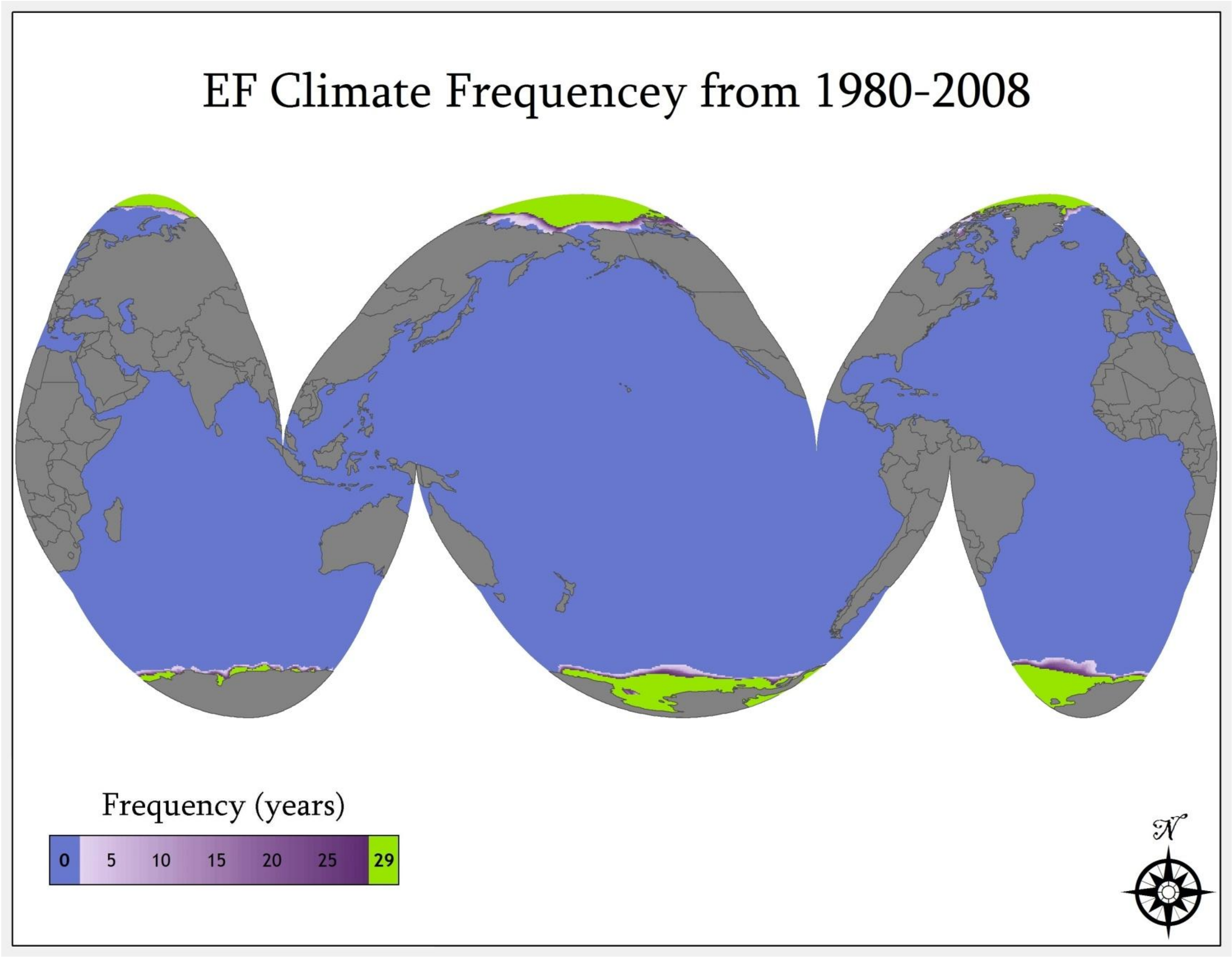


Figure B.17 EF climate frequency zone [Source: created by author]



Appendix C - Climate Year Maps

Figure C.1 Modal oceanic climate classification product [Source: created by author]

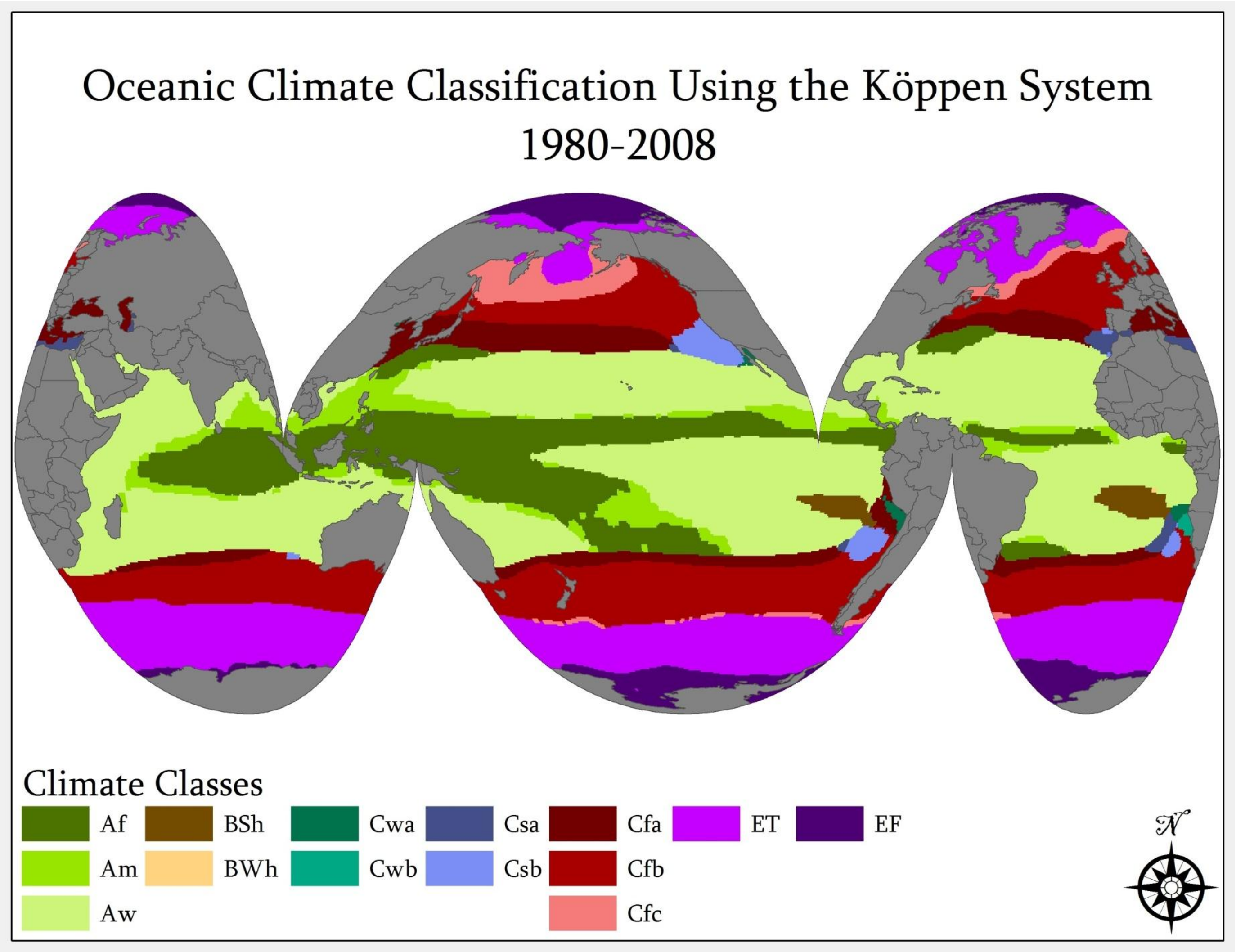


Figure C.2 2008 climate year [Source: created by author]

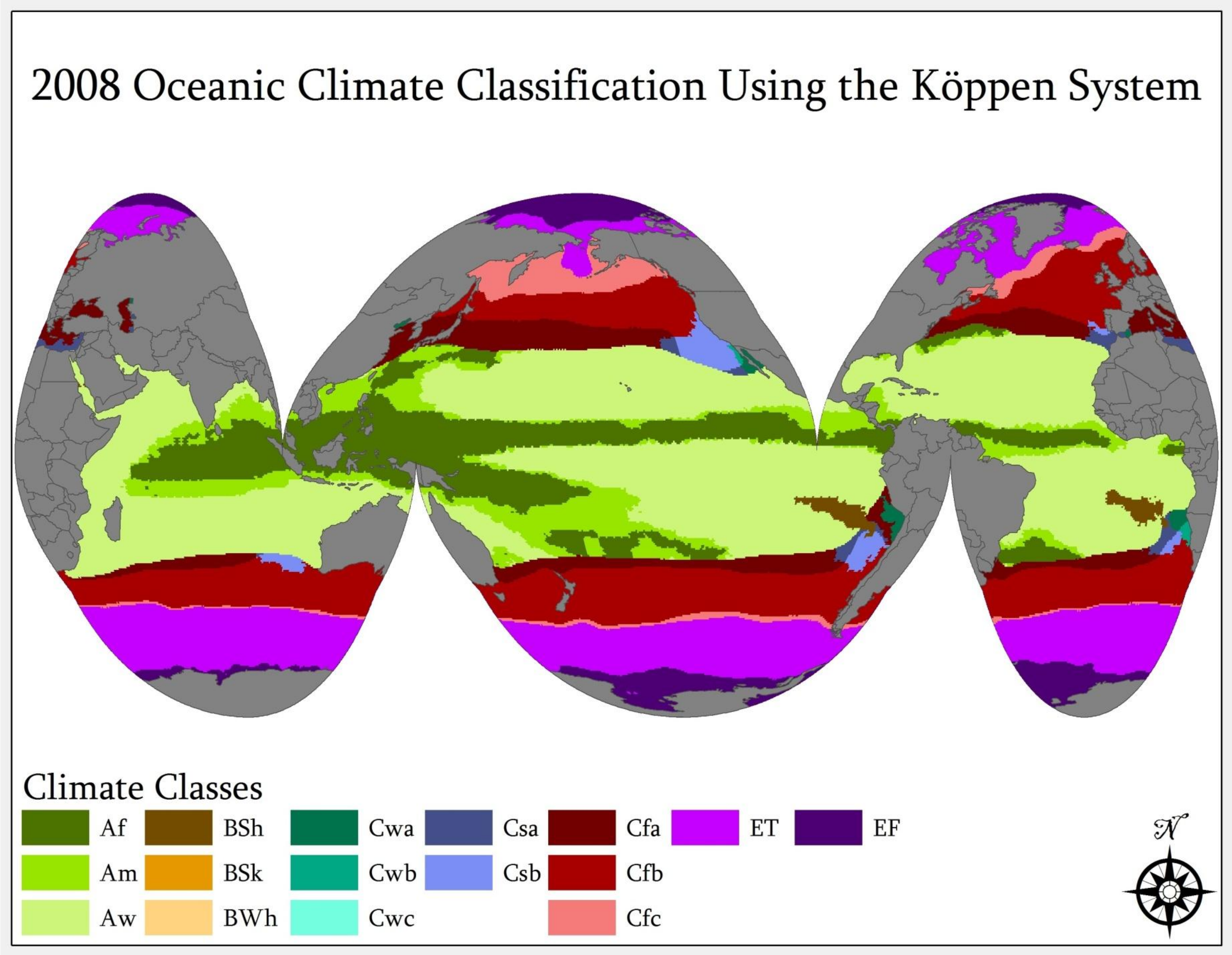


Figure C.3 2007 climate year [Source: created by author]

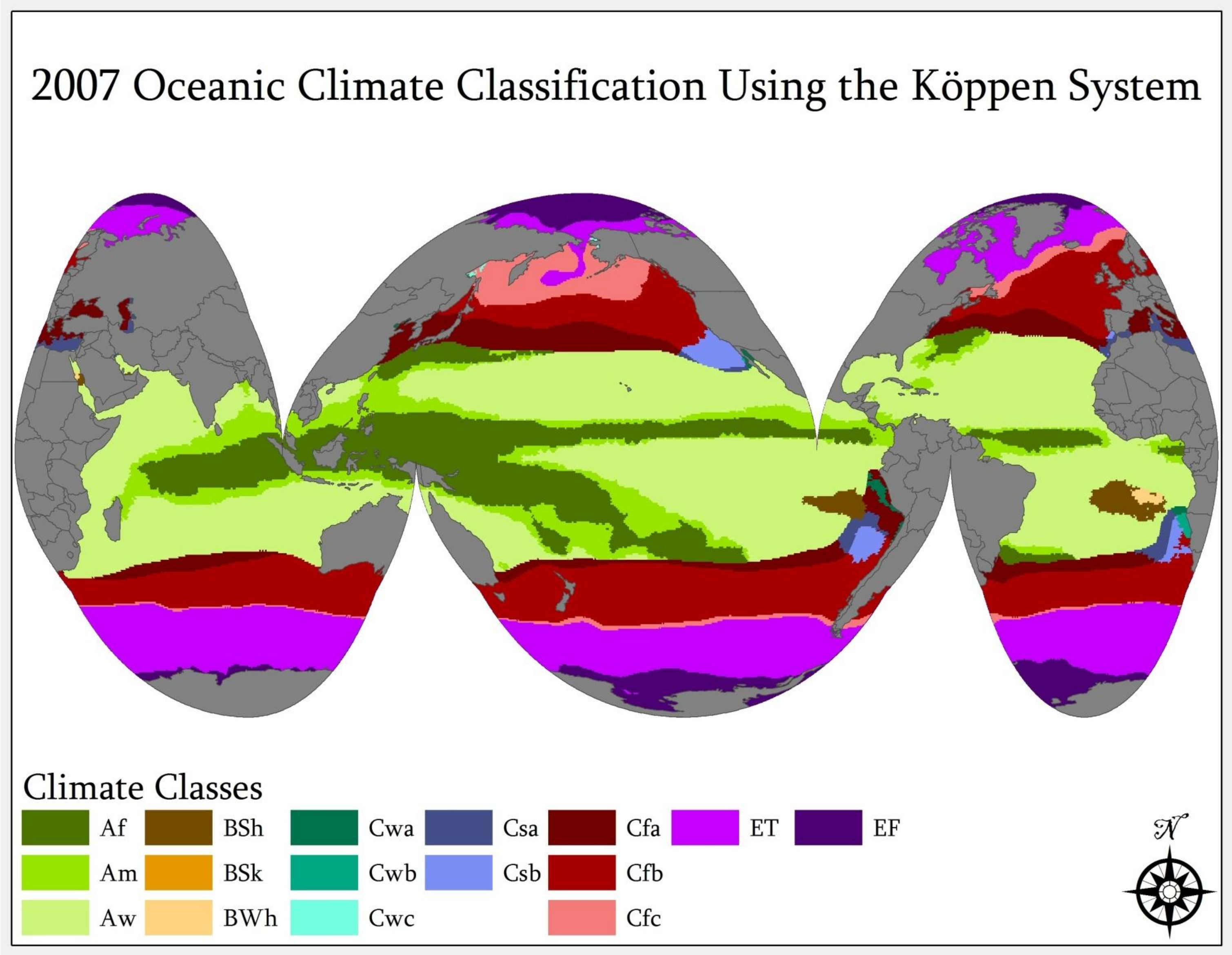


Figure C.4 2006 climate year [Source: created by author]

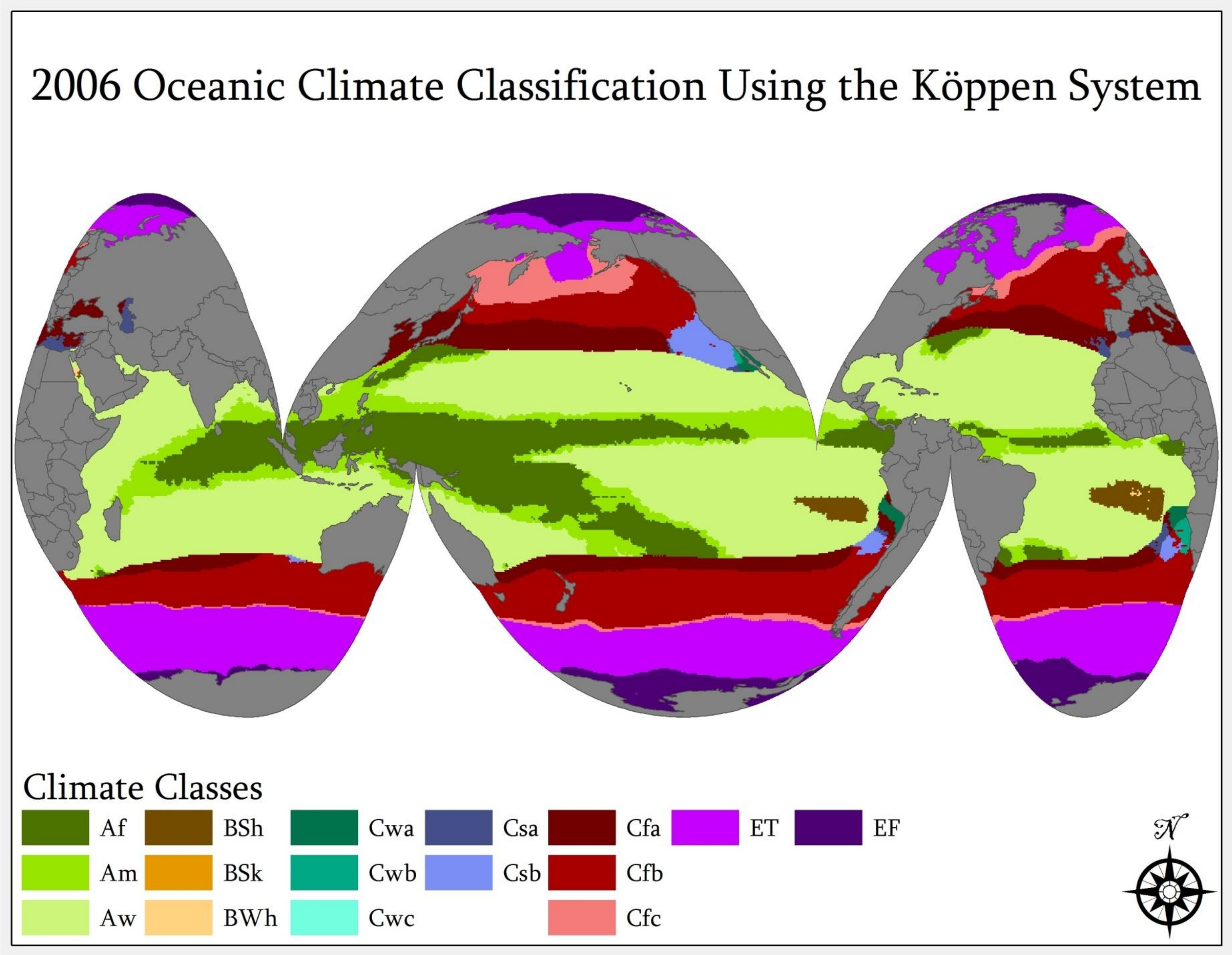


Figure C.5 2005 climate year [Source: created by author]

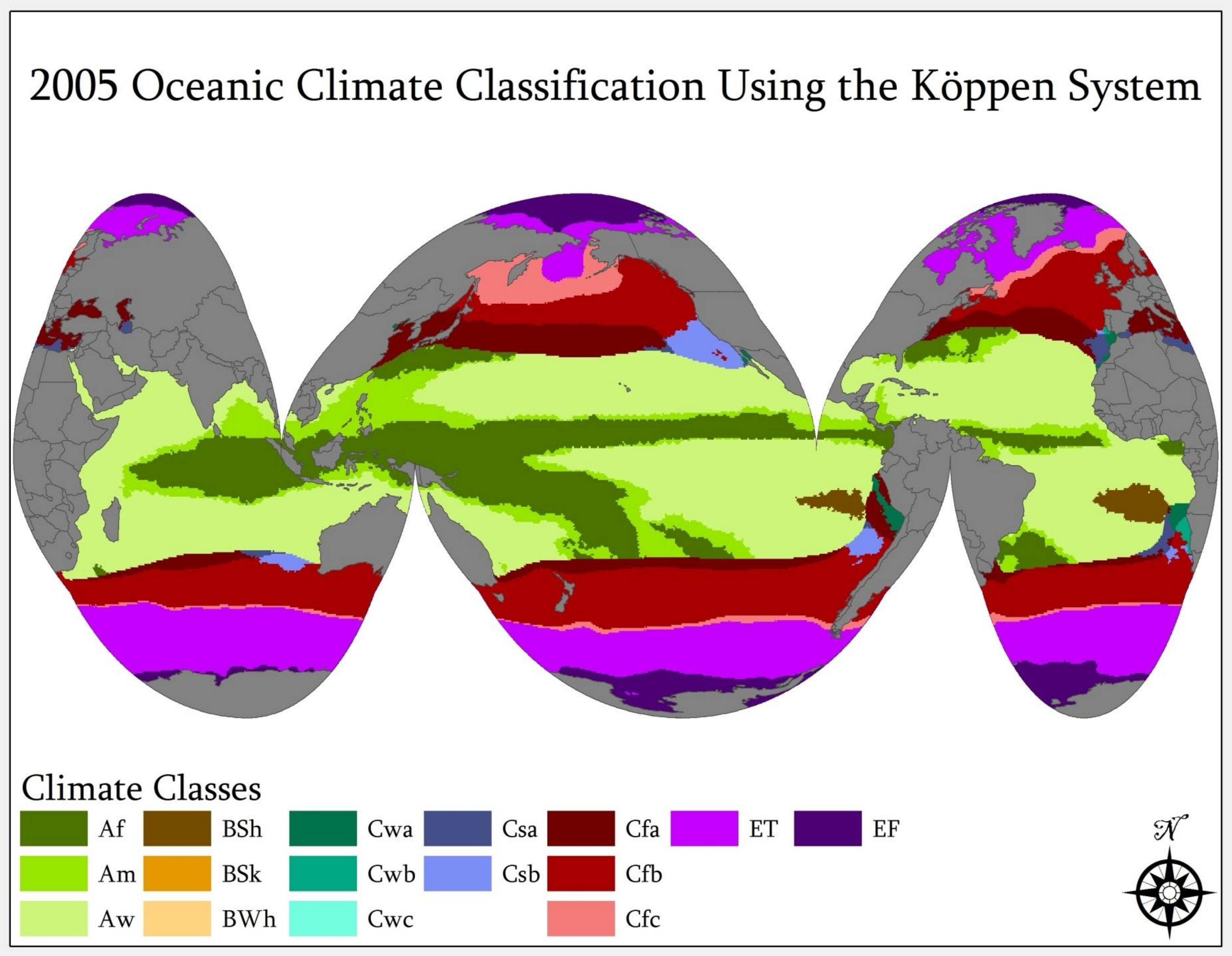


Figure C.6 2004 climate year [Source: created by author]

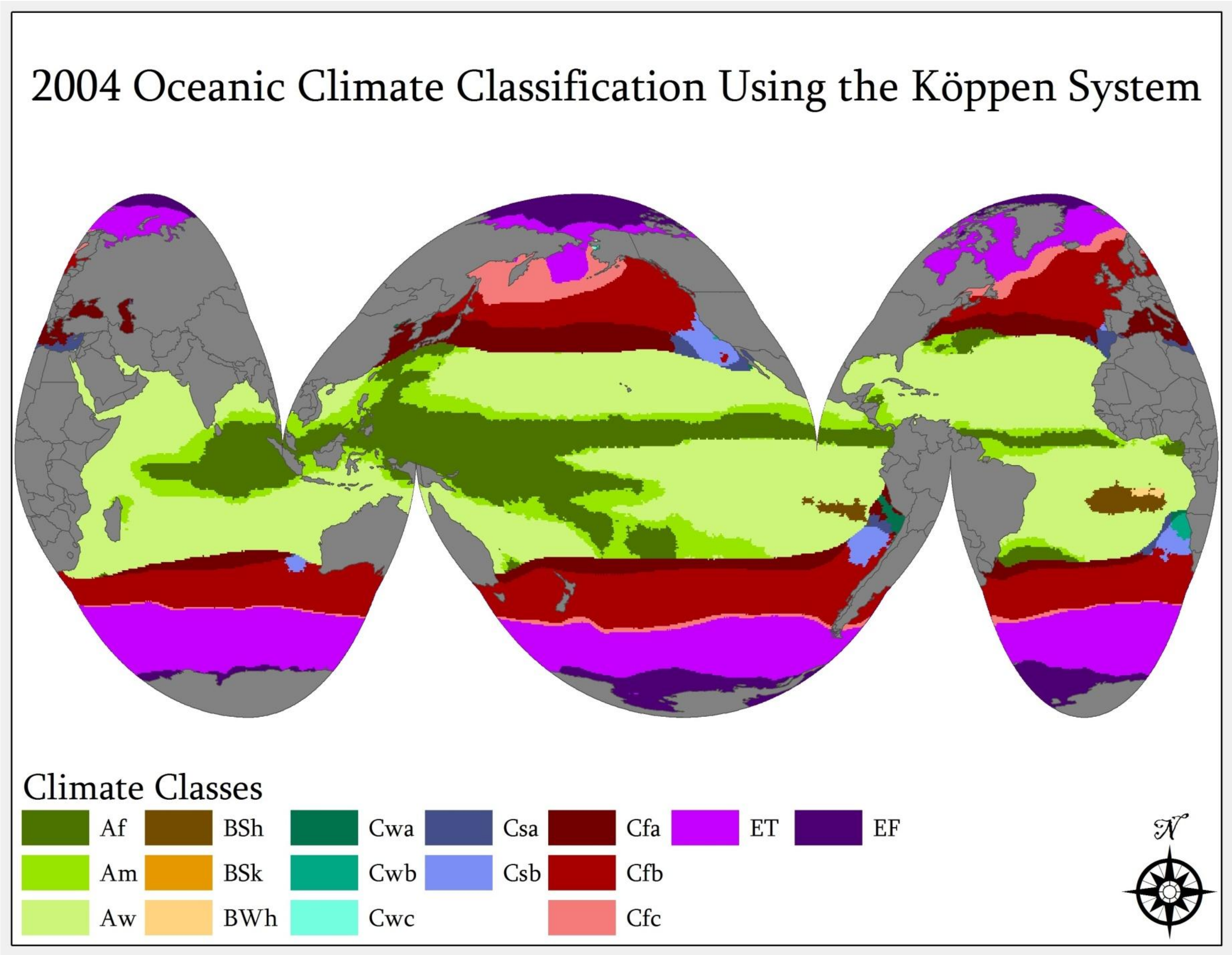


Figure C.7 2003 climate year [Source: created by author]

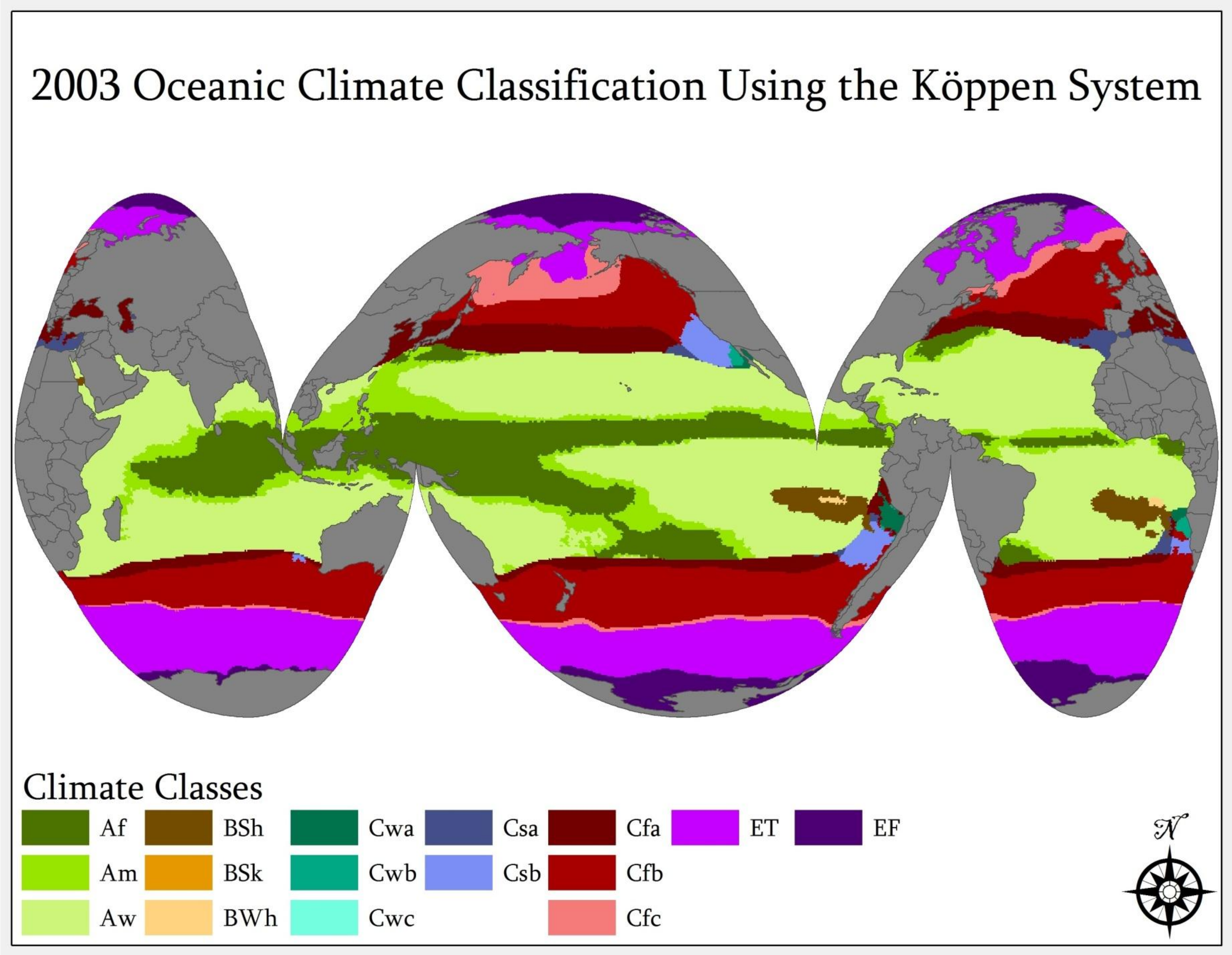


Figure **C.8 2002 climate year [Source: created by author]**

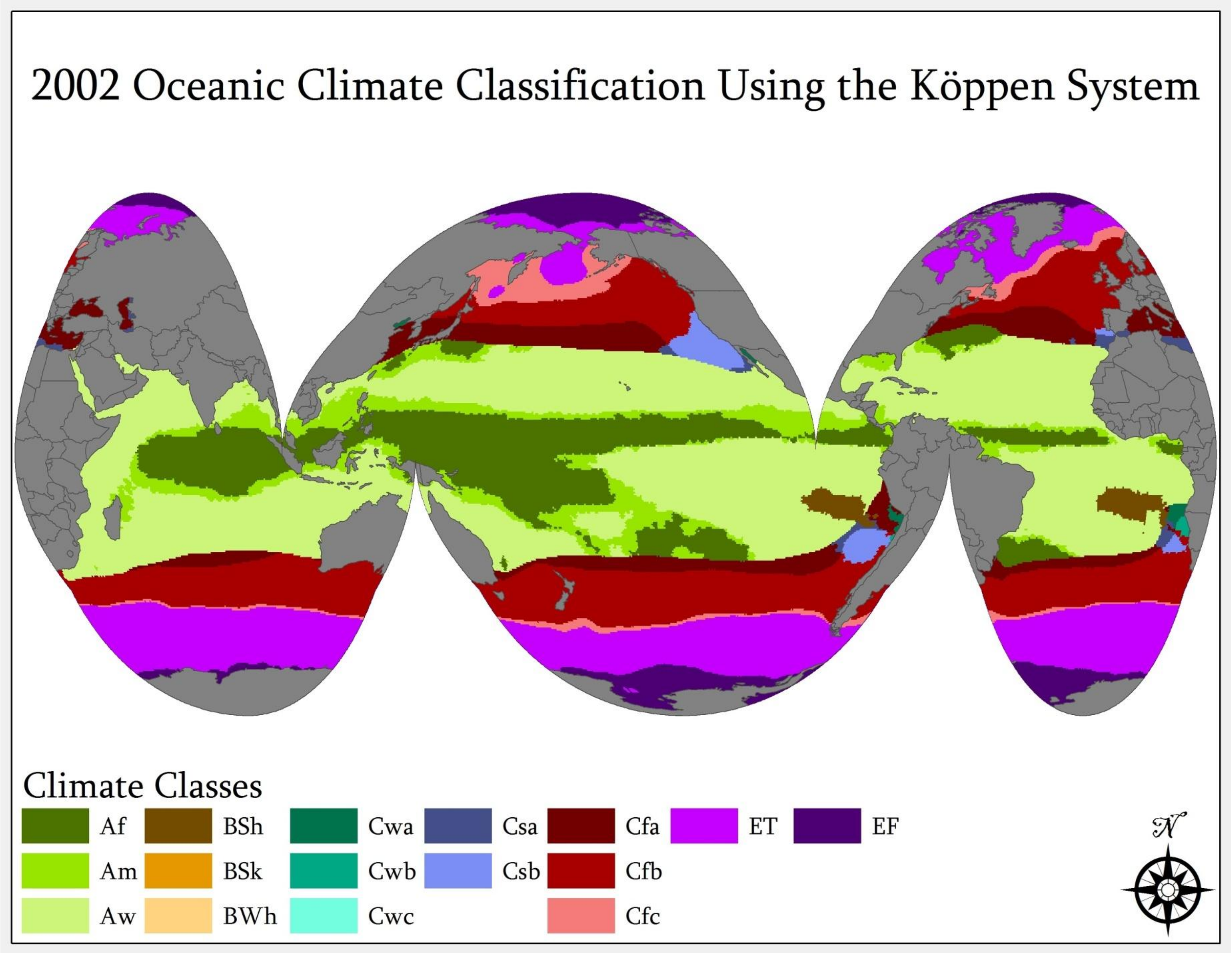


Figure **C.9 2001 climate year [Source: created by author]**

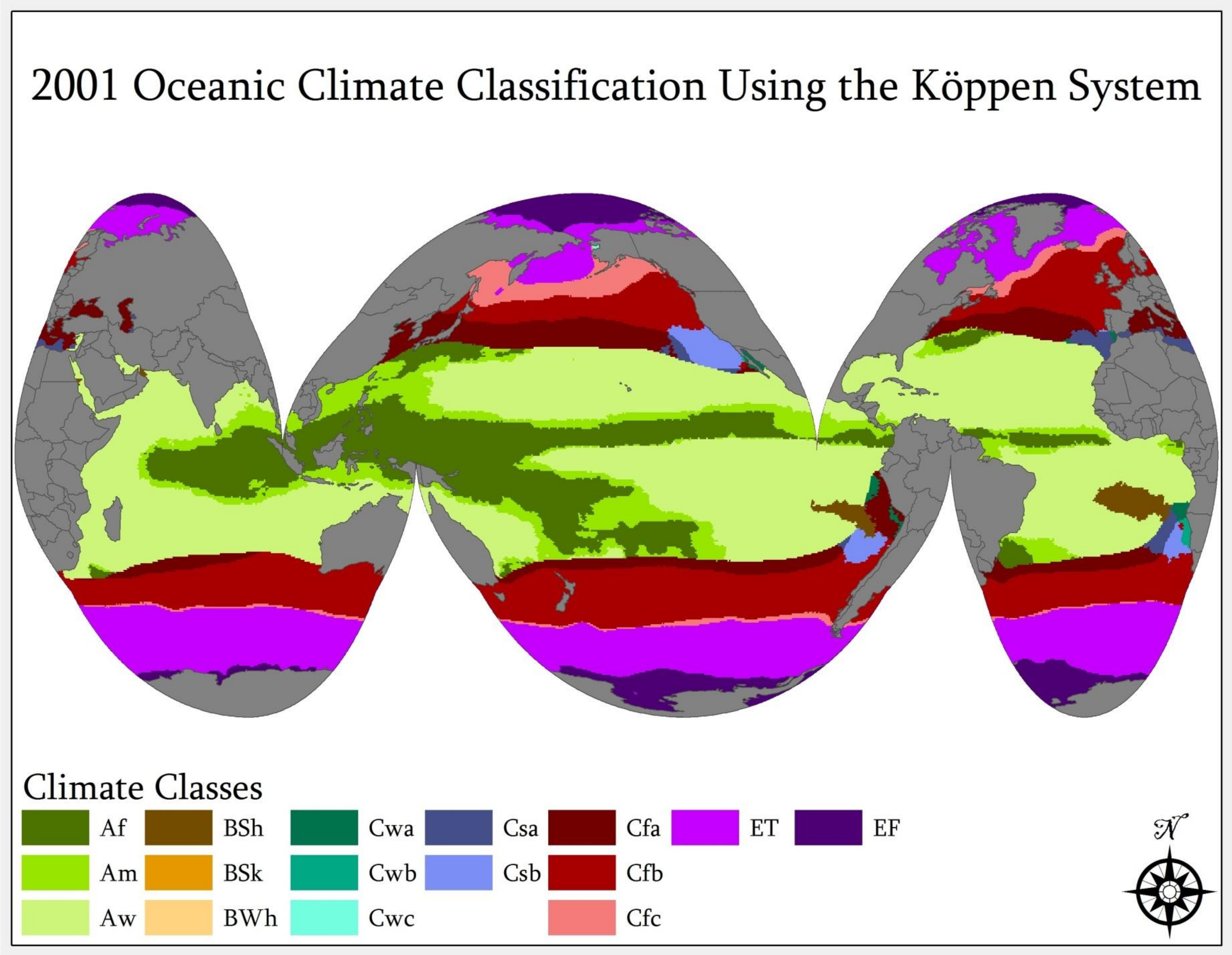


Figure C.10 2000 climate year [Source: created by author]

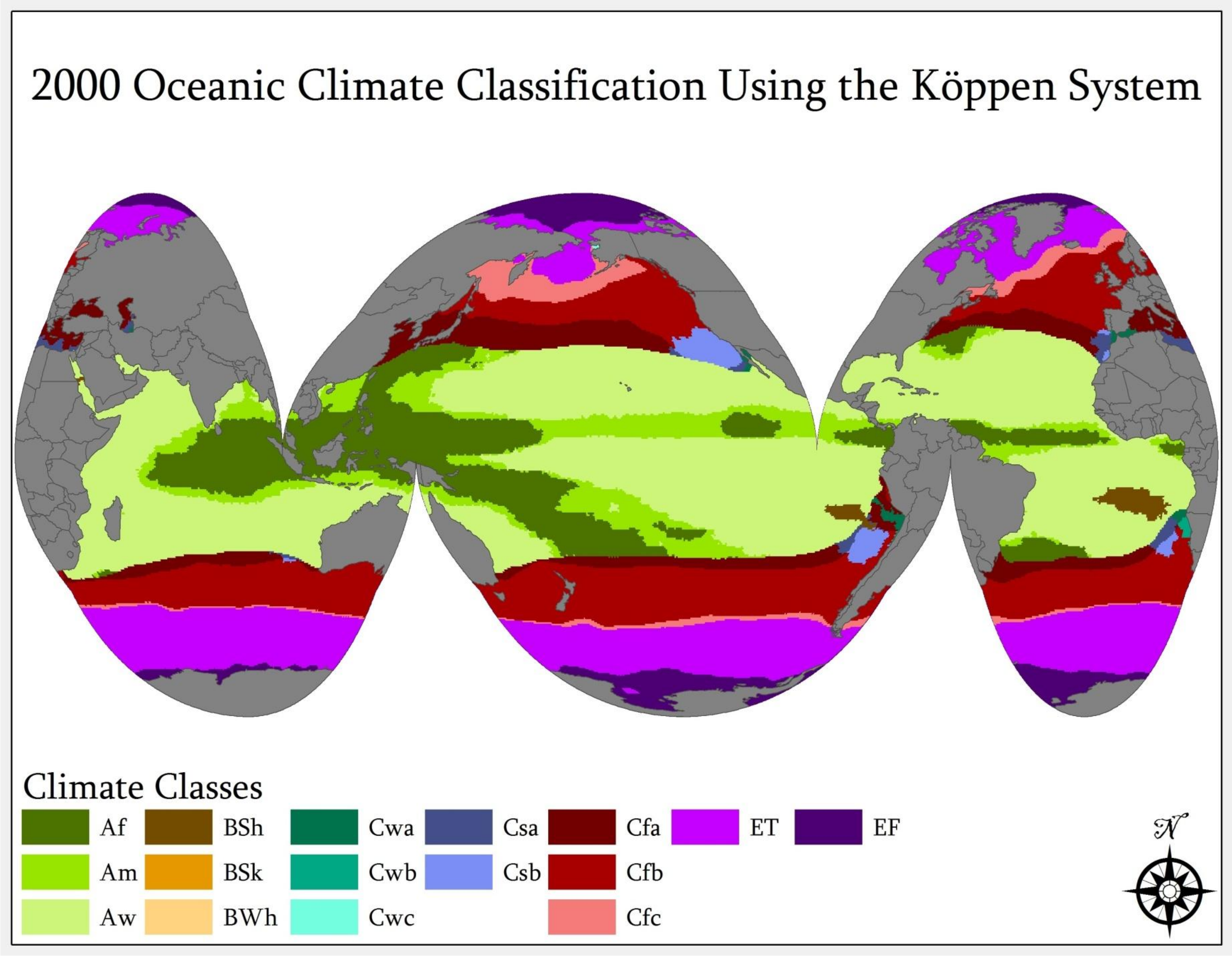


Figure **C.11 1999 climate year [Source: created by author]**

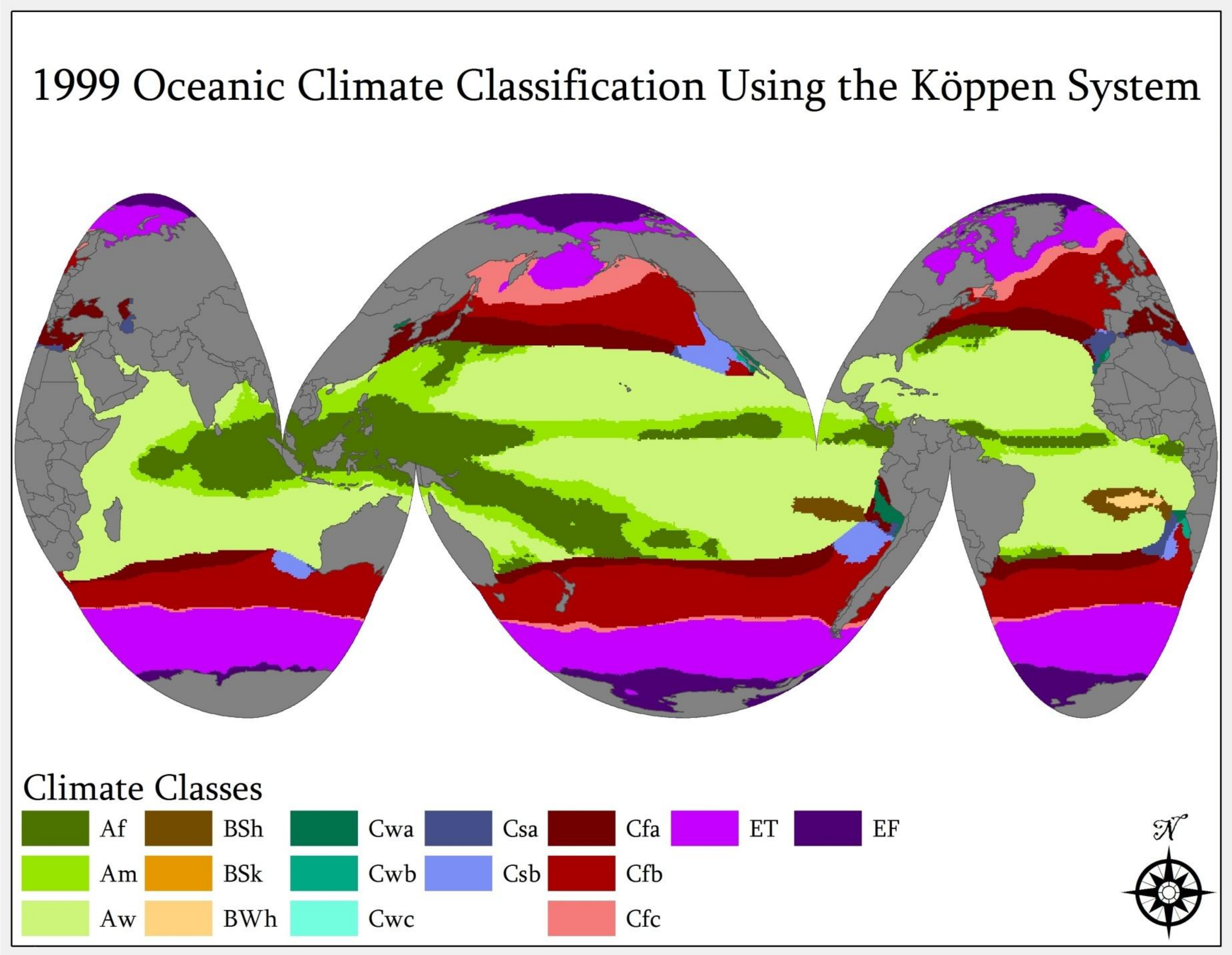


Figure **C.12 1998 climate year [Source: created by author]**

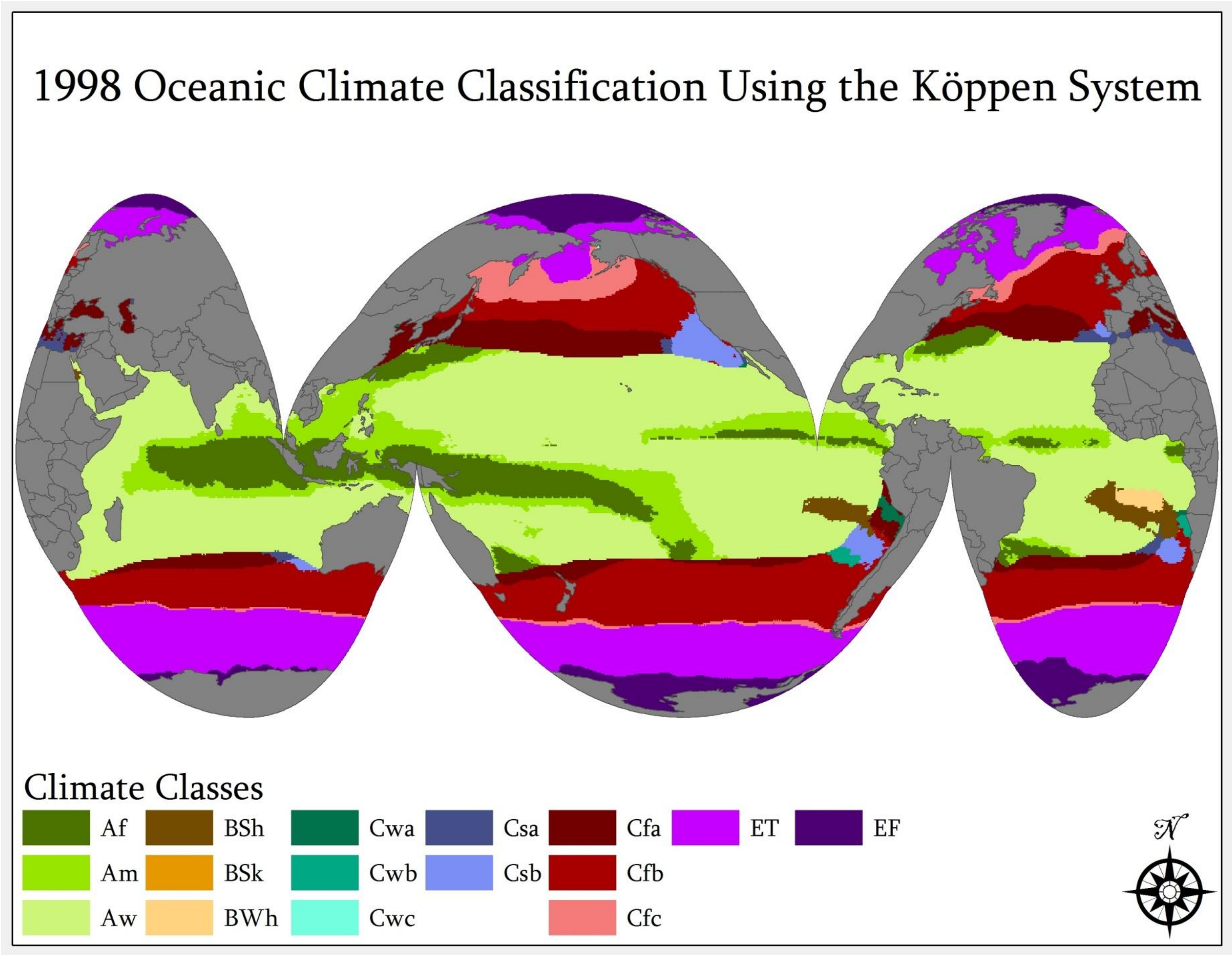


Figure **C.13 1997 climate year [Source: created by author]**

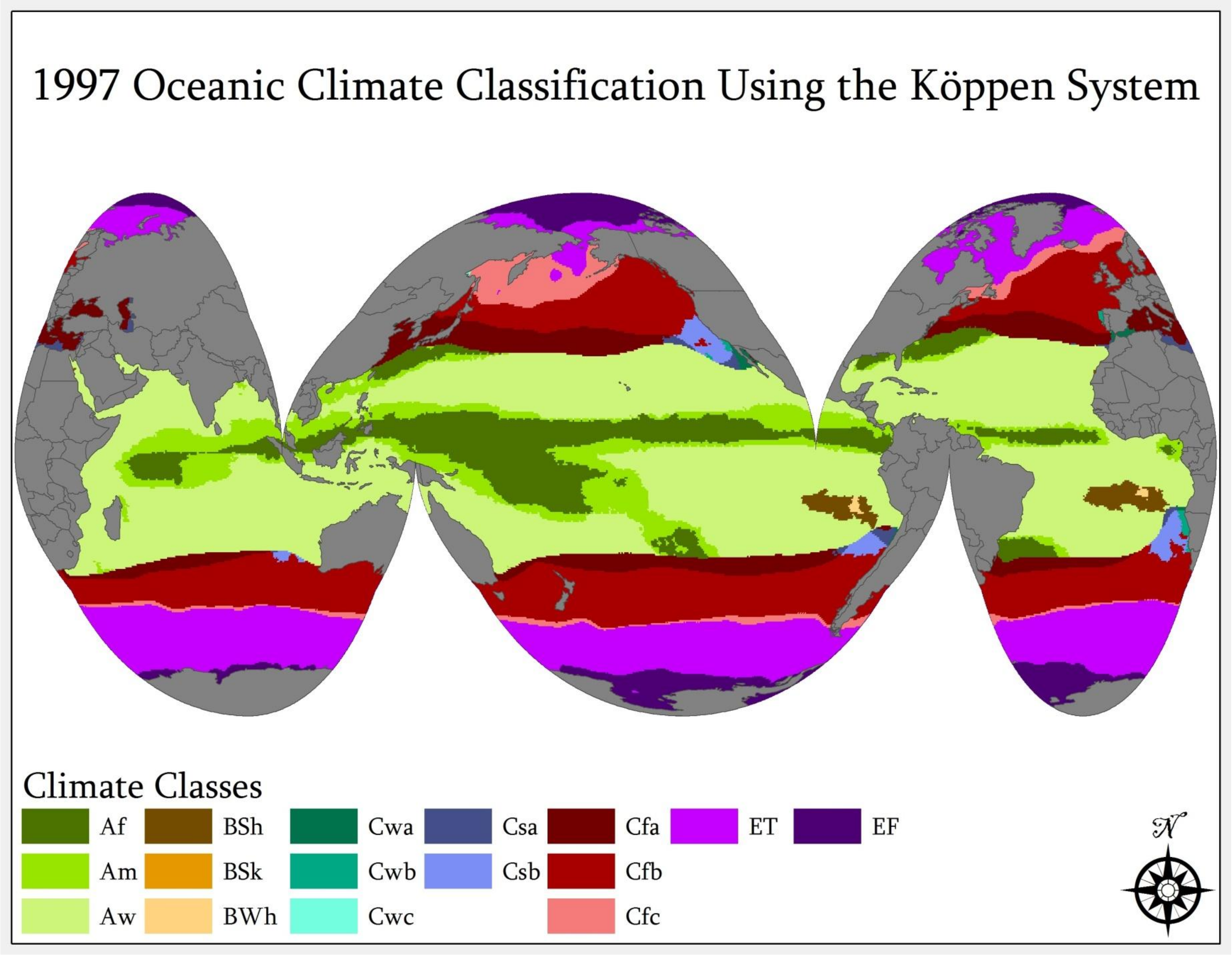


Figure **C.14 1996 climate year [Source: created by author]**

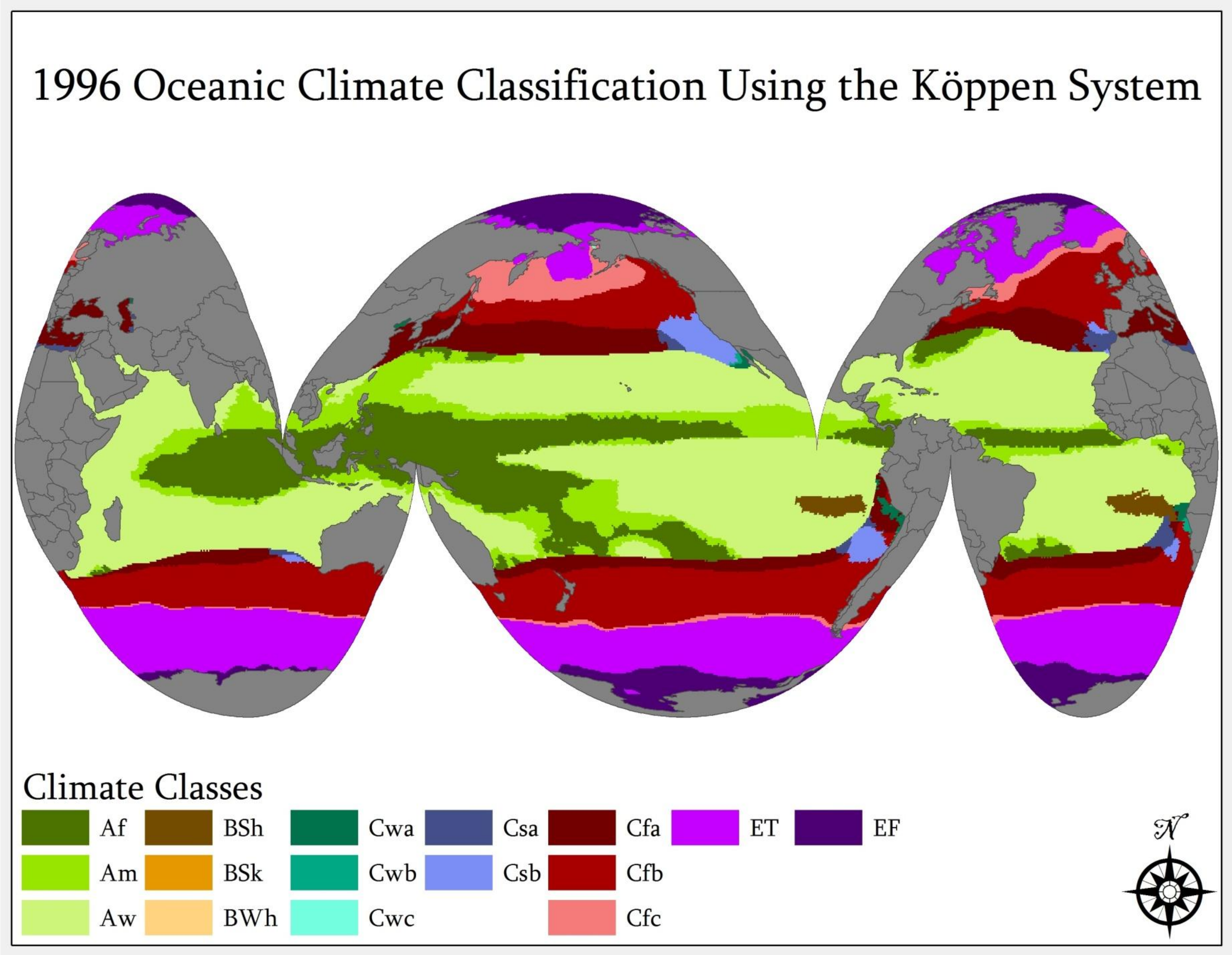


Figure **C.15 1995 climate year [Source: created by author]**

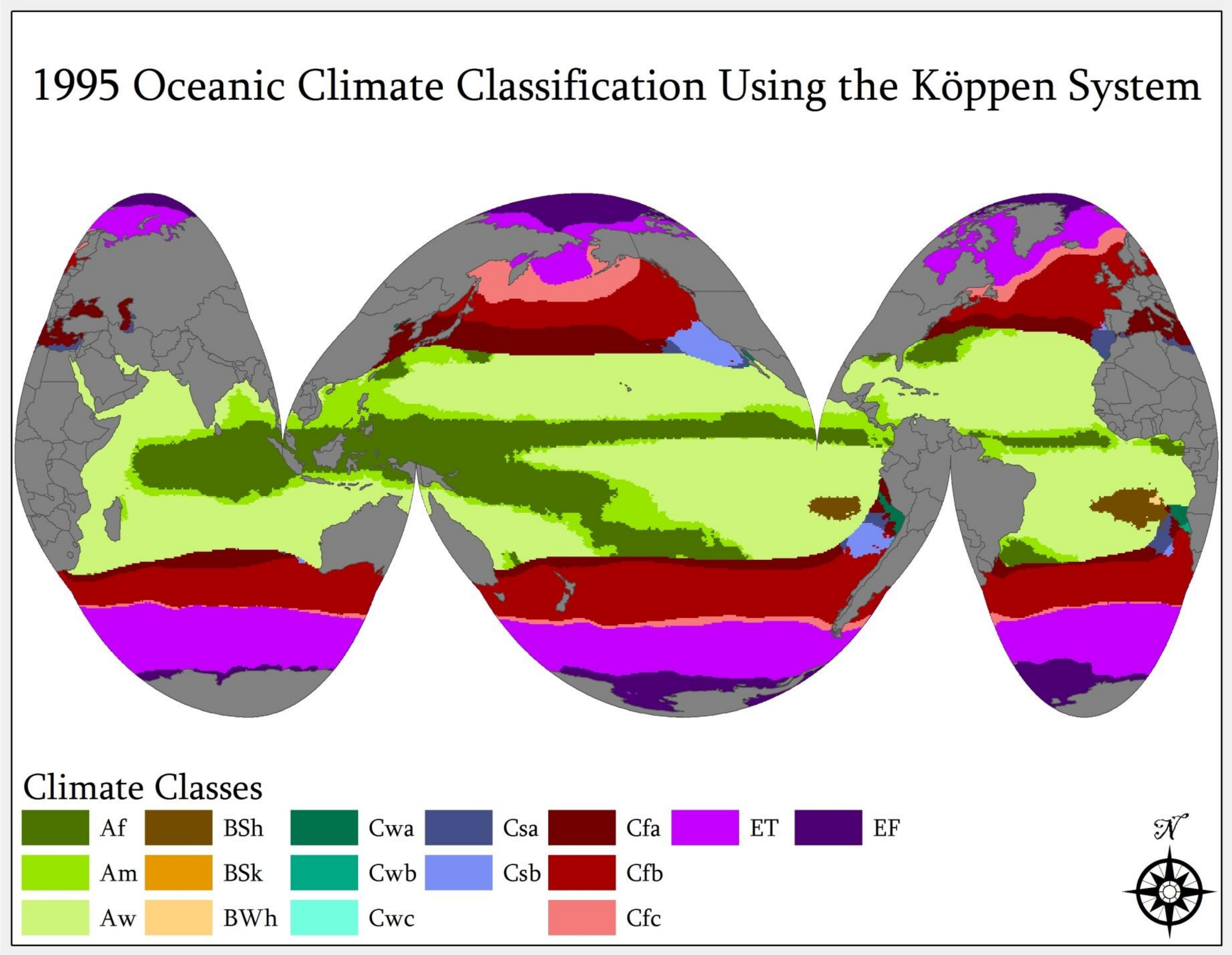


Figure **C.16 1994 climate year [Source: created by author]**

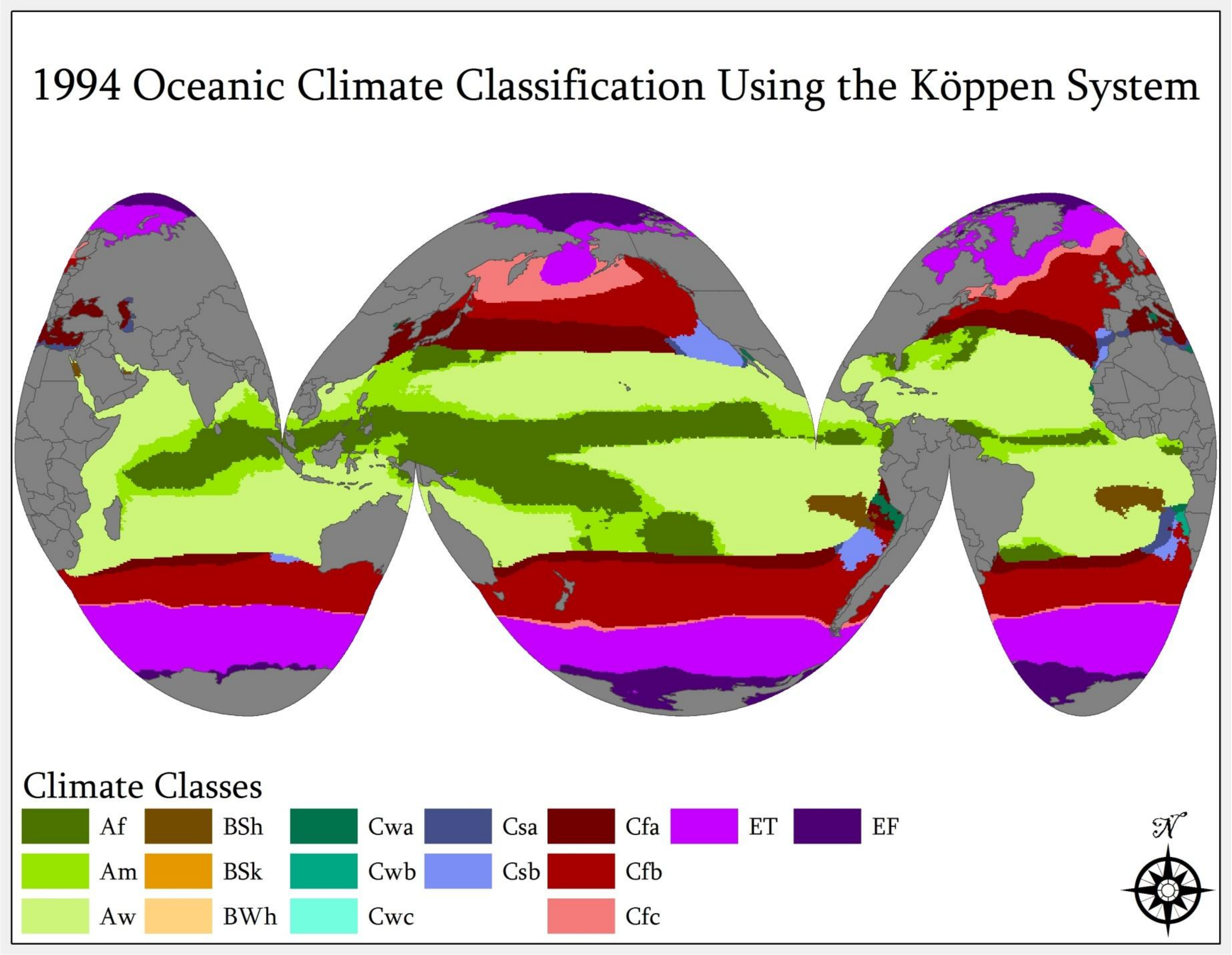


Figure **C.17 1993 climate year [Source: created by author]**

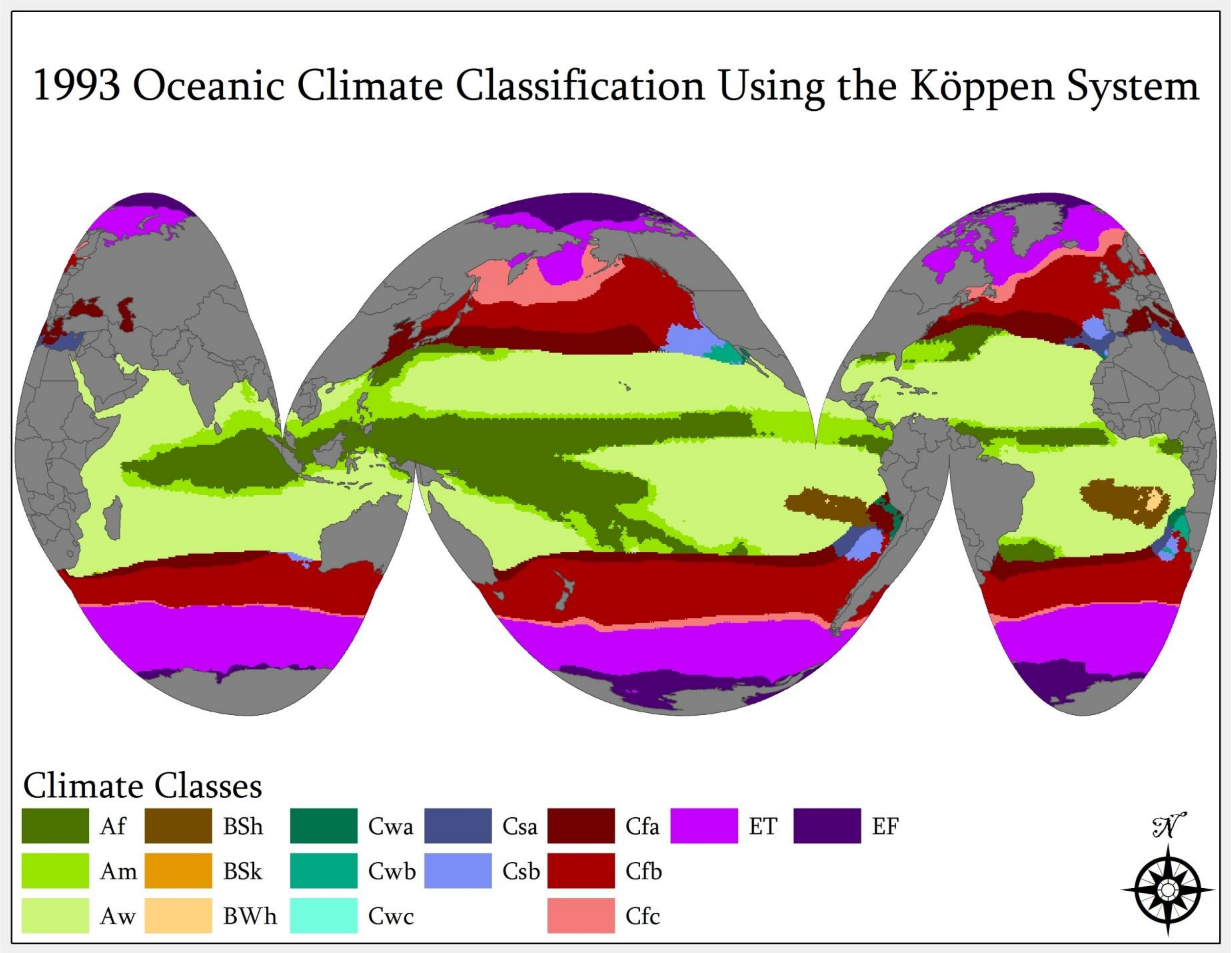


Figure **C.18 1992 climate year [Source: created by author]**

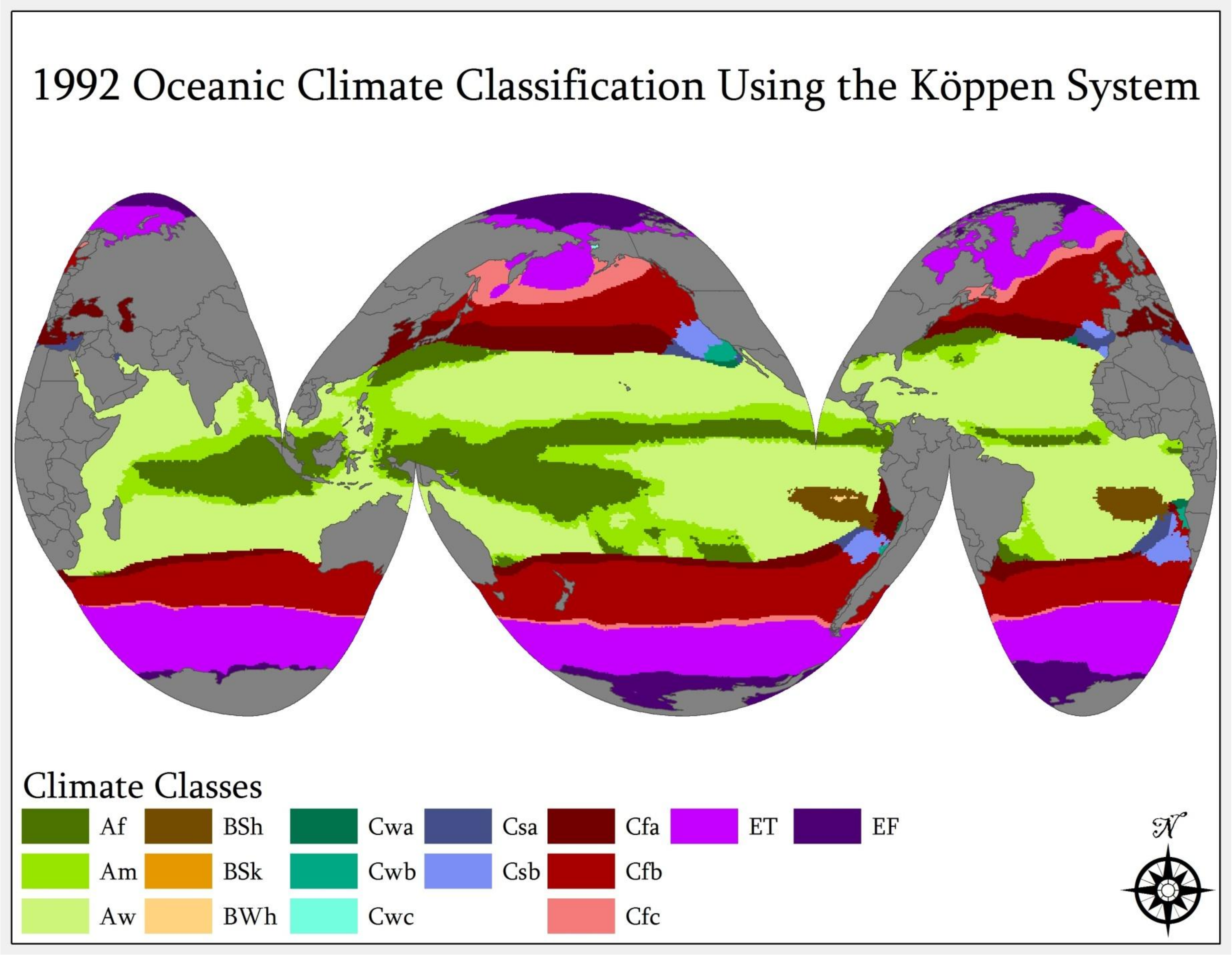


Figure **C.19 1991 climate year [Source: created by author]**

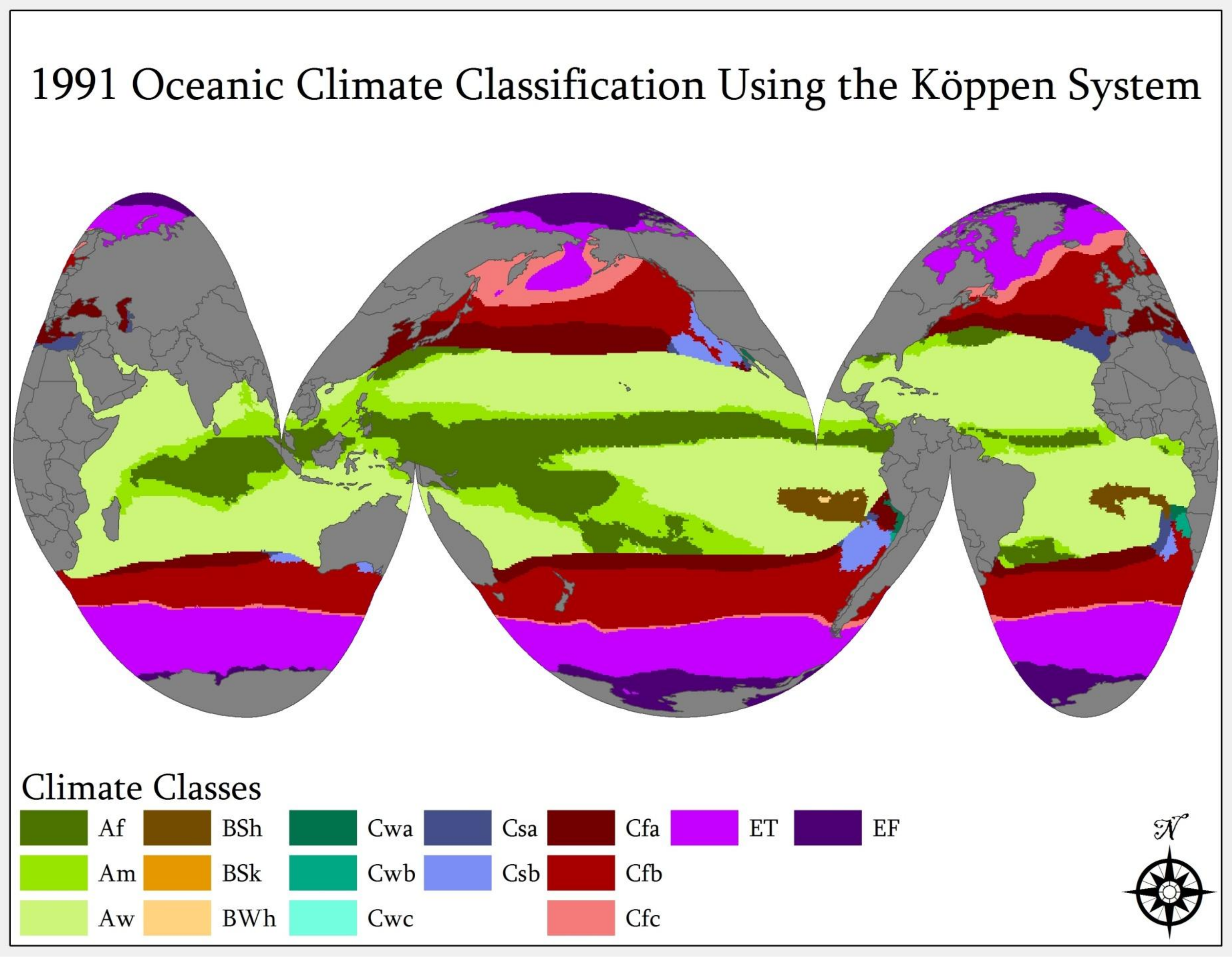


Figure **C.20 1990 climate year [Source: created by author]**

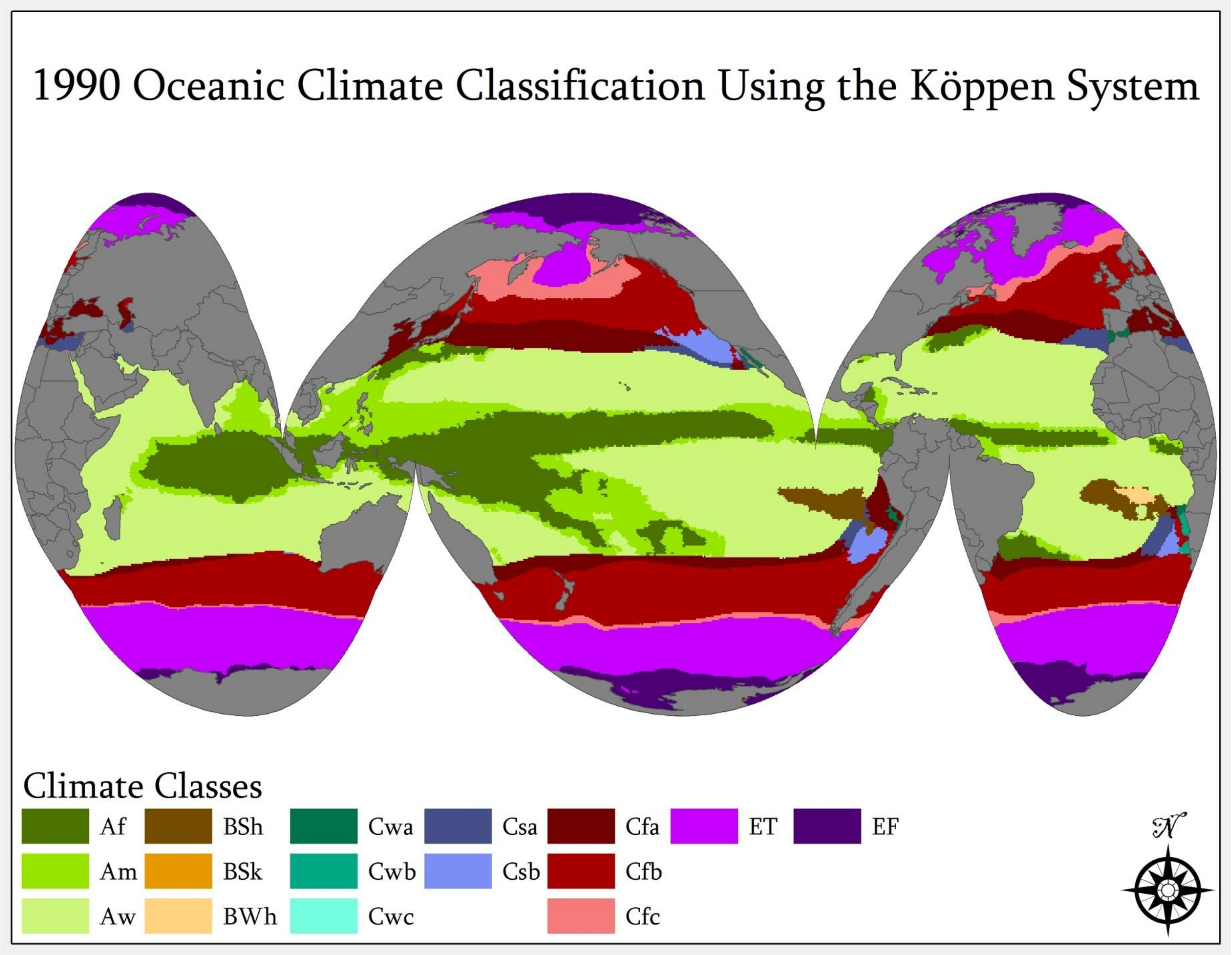


Figure **C.21 1989 climate year [Source: created by author]**

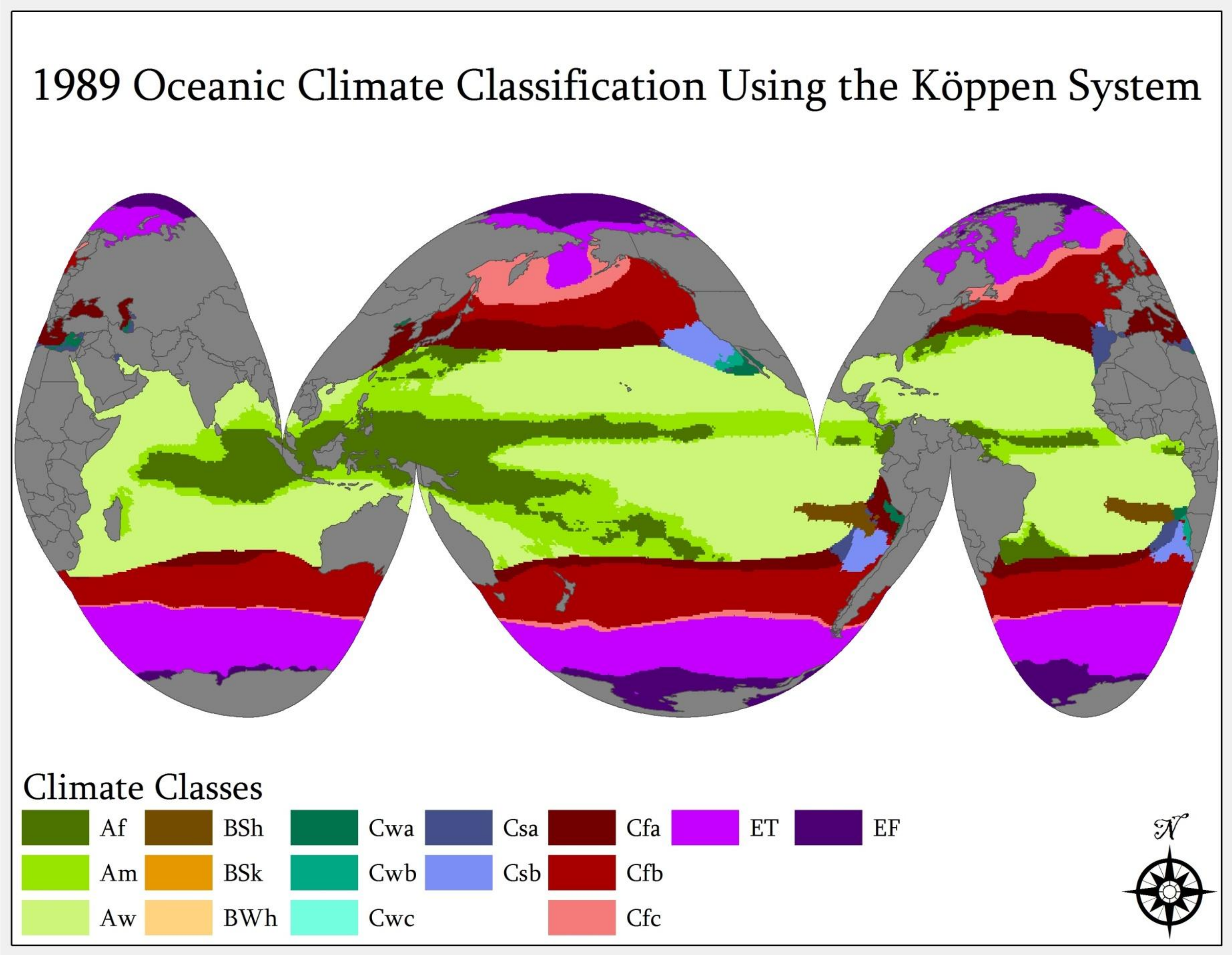


Figure **C.22 1988 climate year [Source: created by author]**

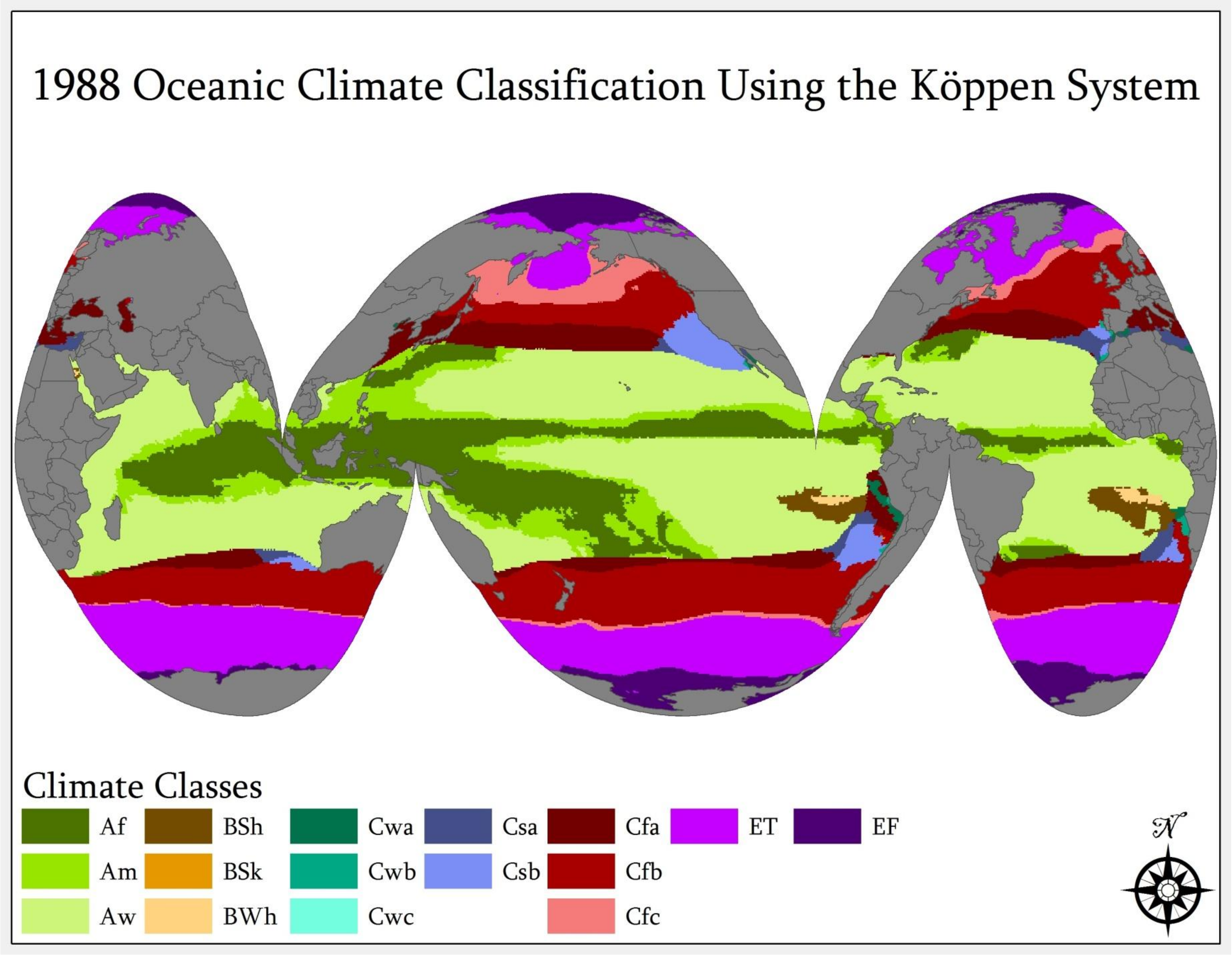


Figure C.23 1987 climate year [Source: created by author]

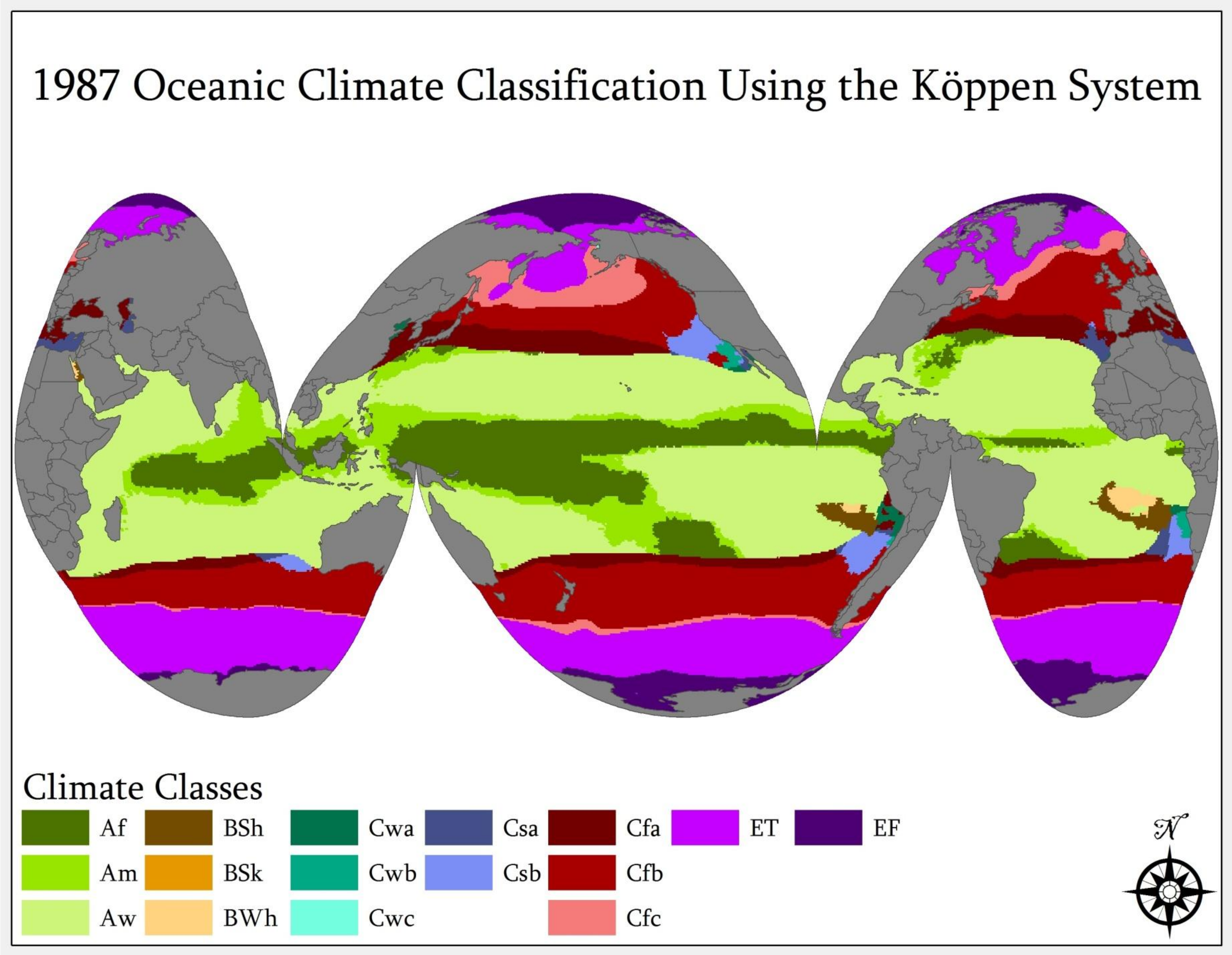


Figure **C.24 1986 climate year [Source: created by author]**

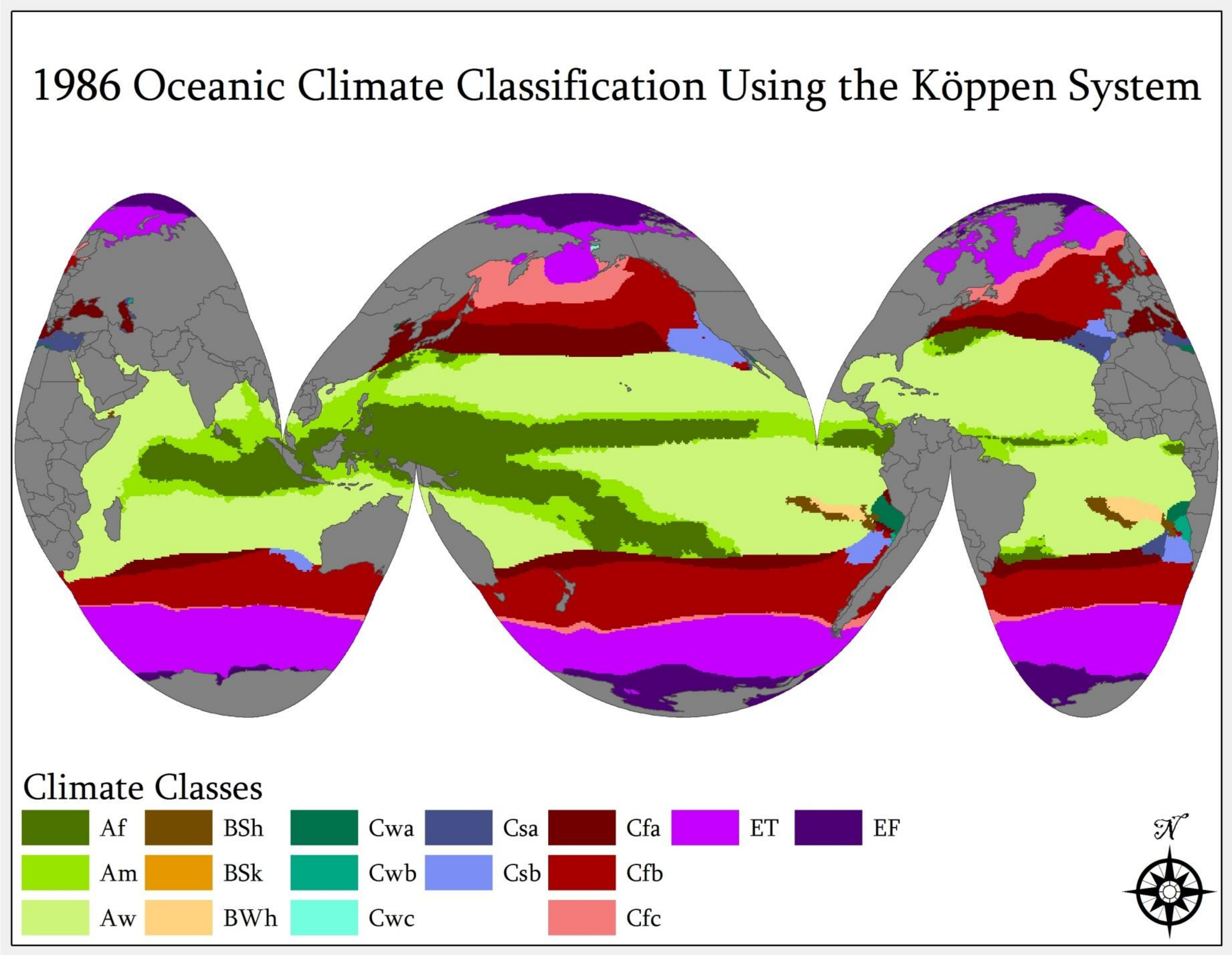


Figure C.25 1985 climate year [Source: created by author]

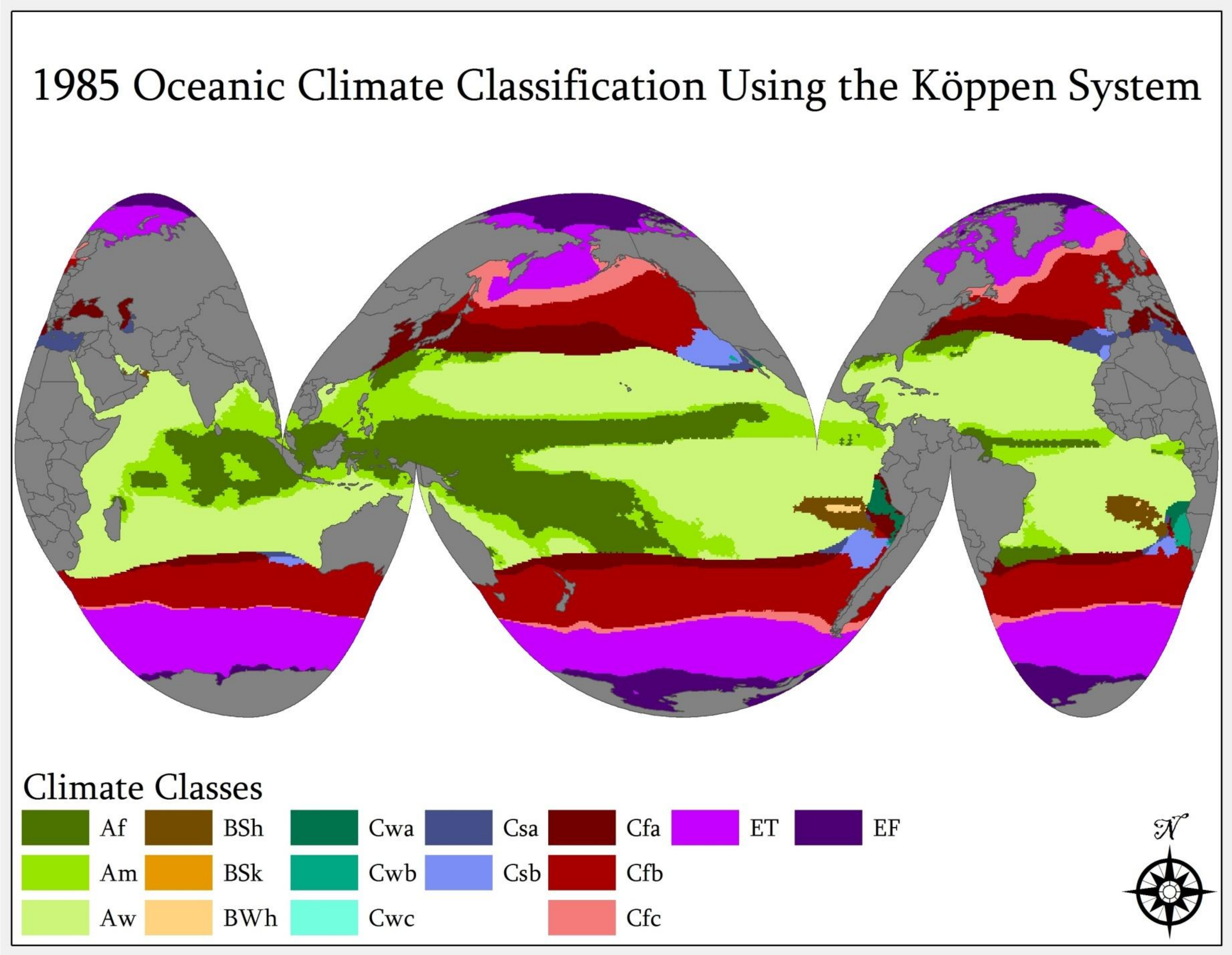


Figure **C.26 1984 climate year [Source: created by author]**

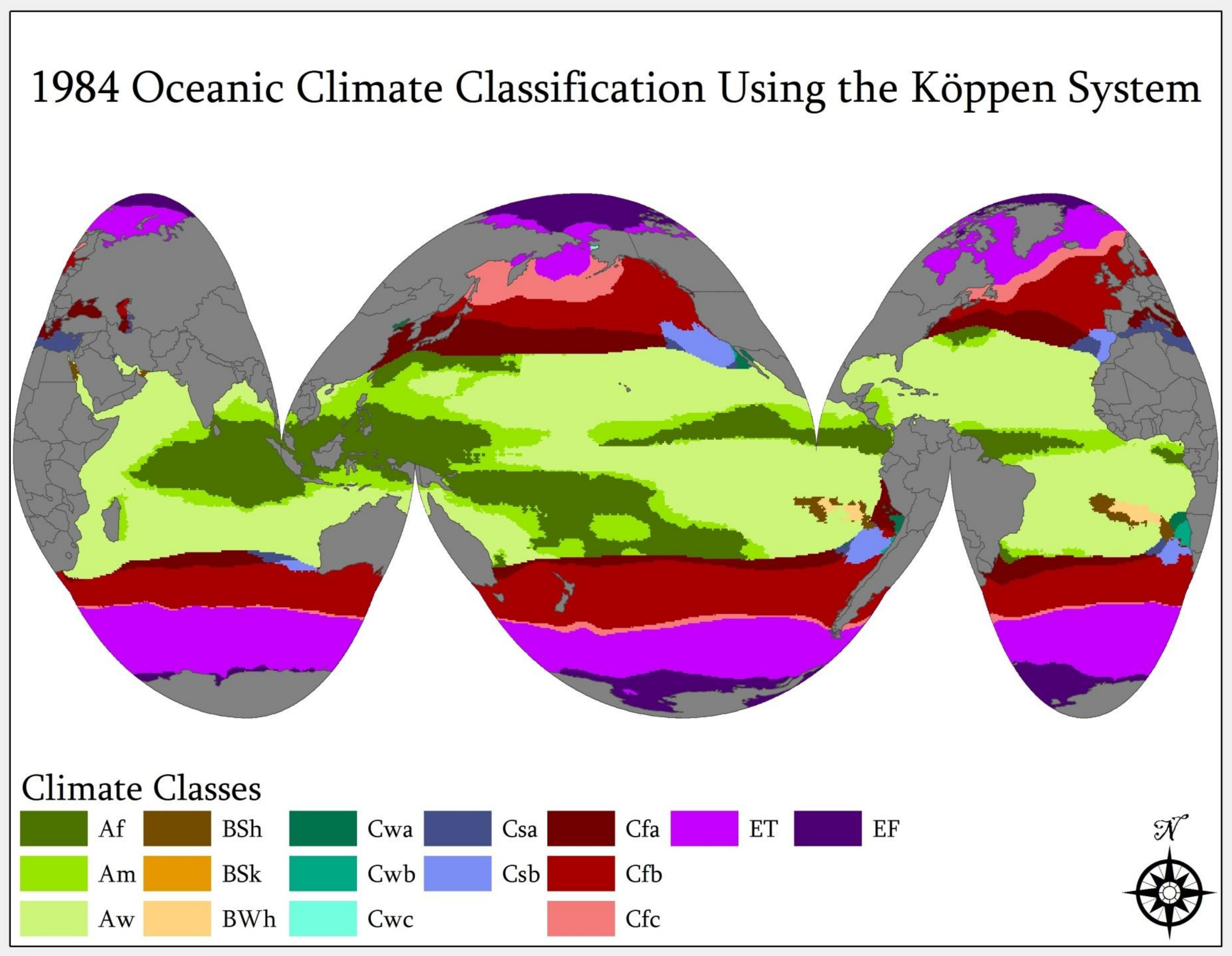


Figure **C.27 1983 climate year [Source: created by author]**

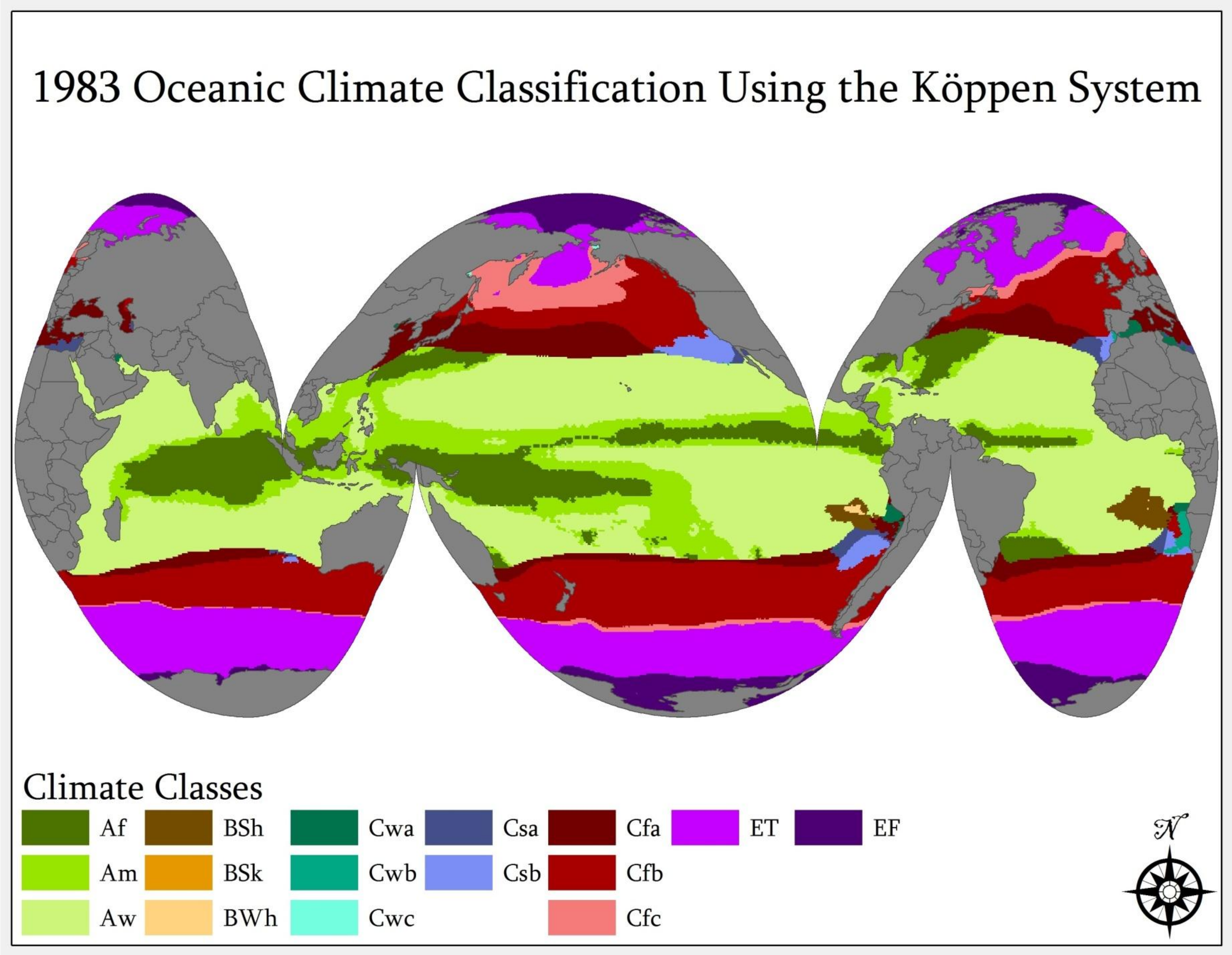


Figure **C.28 1982 climate year [Source: created by author]**

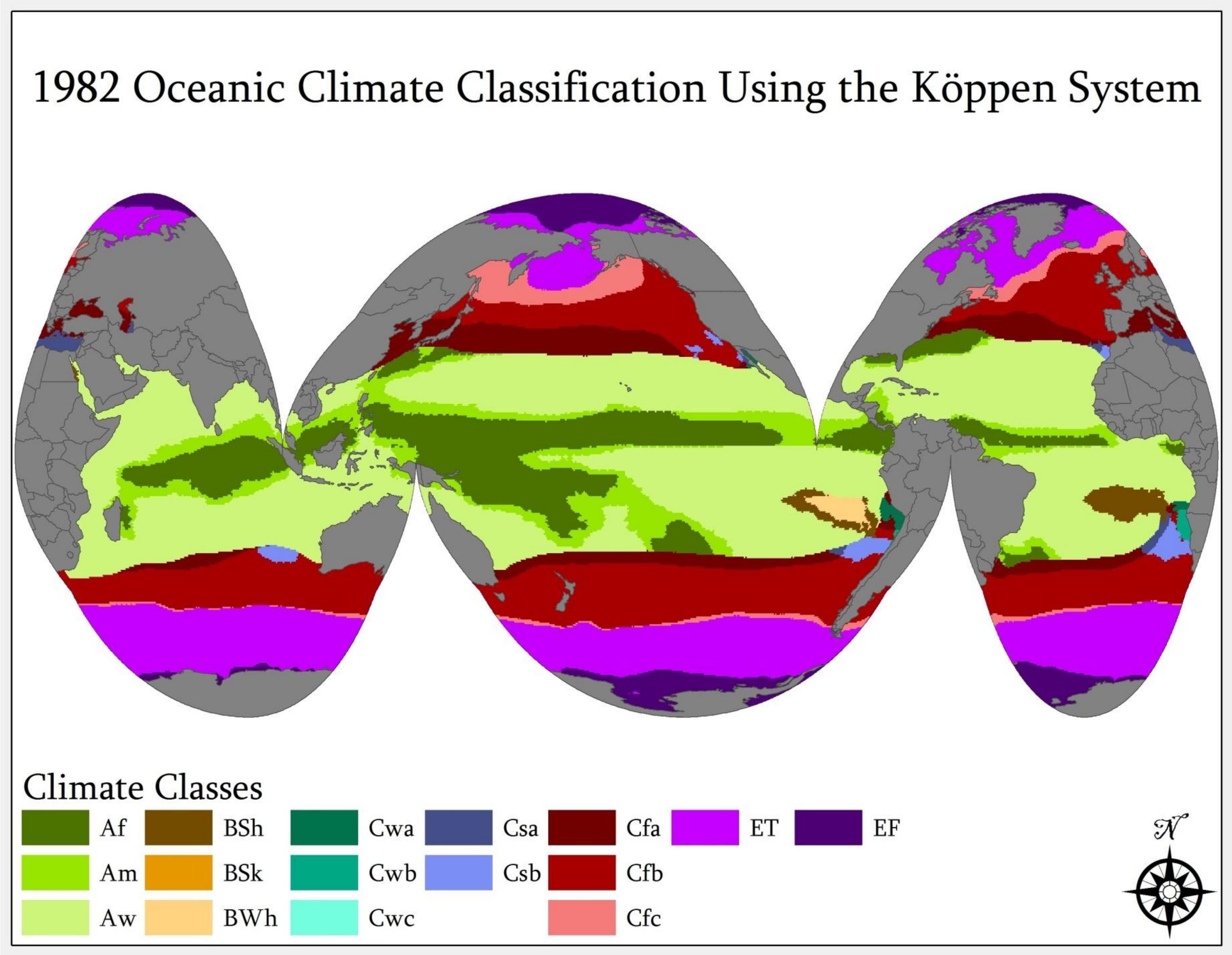


Figure **C.29 1981 climate year [Source: created by author]**

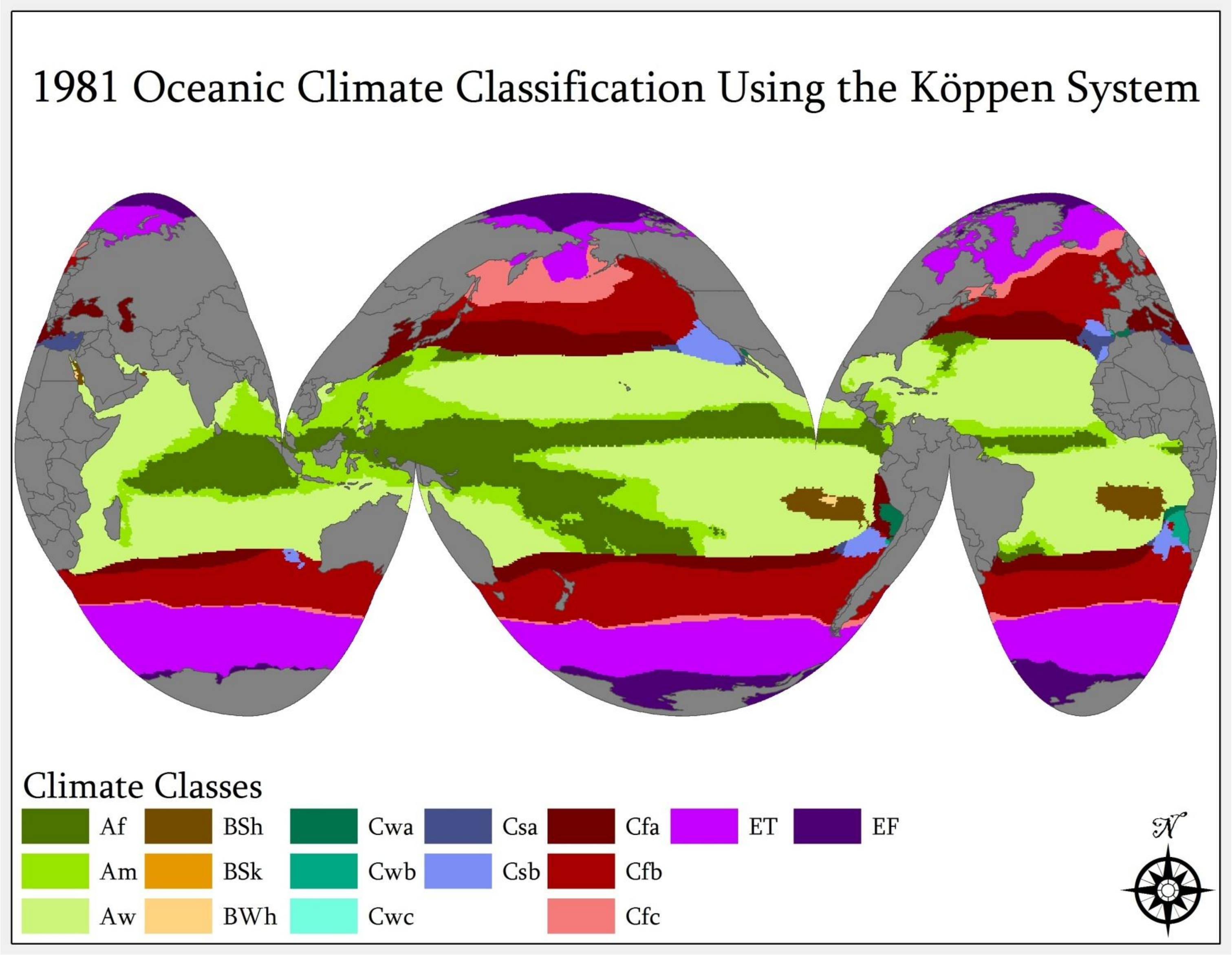
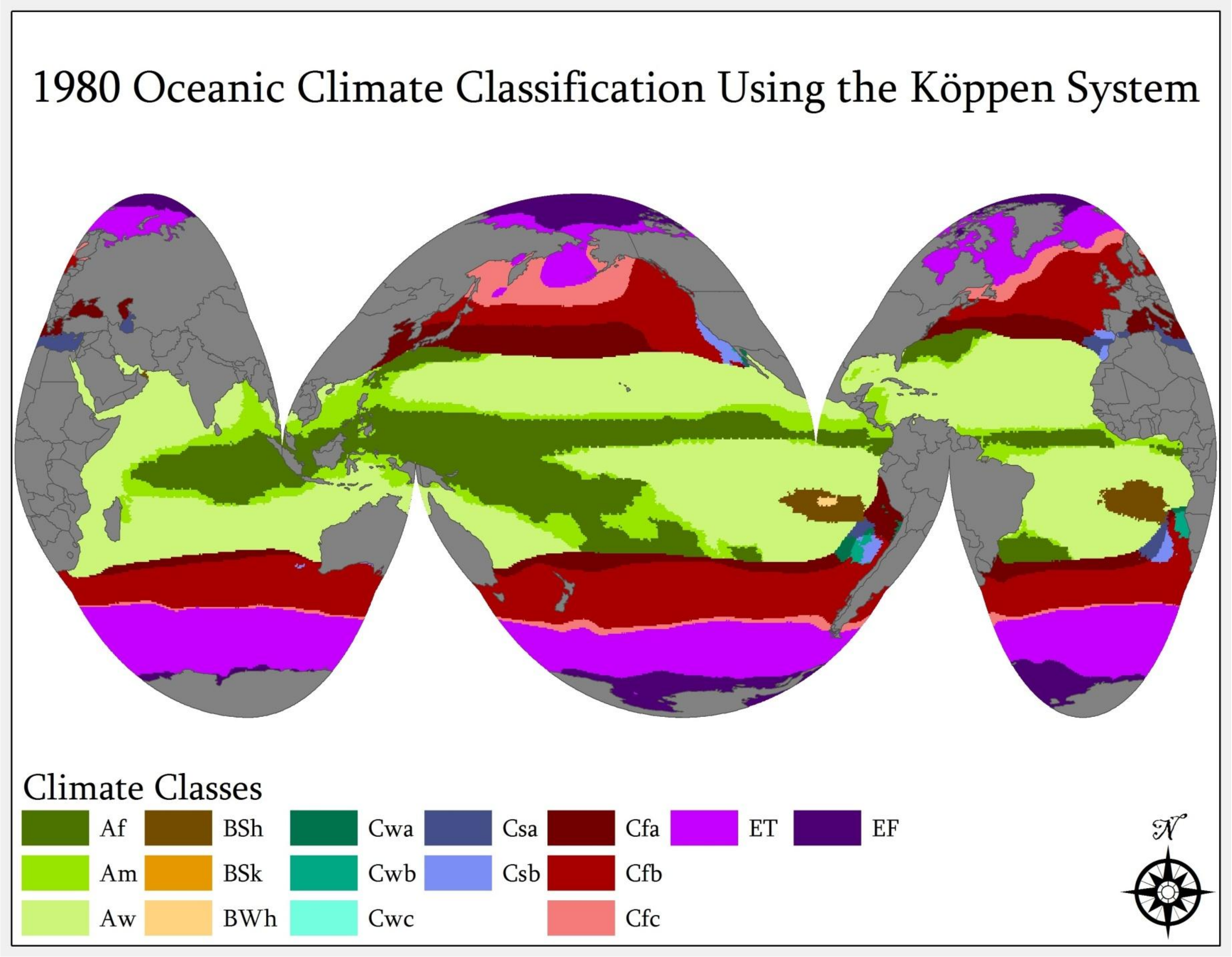


Figure **C.30 1980 climate year [Source: created by author]**



Appendix D - Sea Ice Year Maps

Antarctic Sea Ice

Figure D.1 Antarctic ice shelves [Source: Ted Scambos - NSIDC 2007]

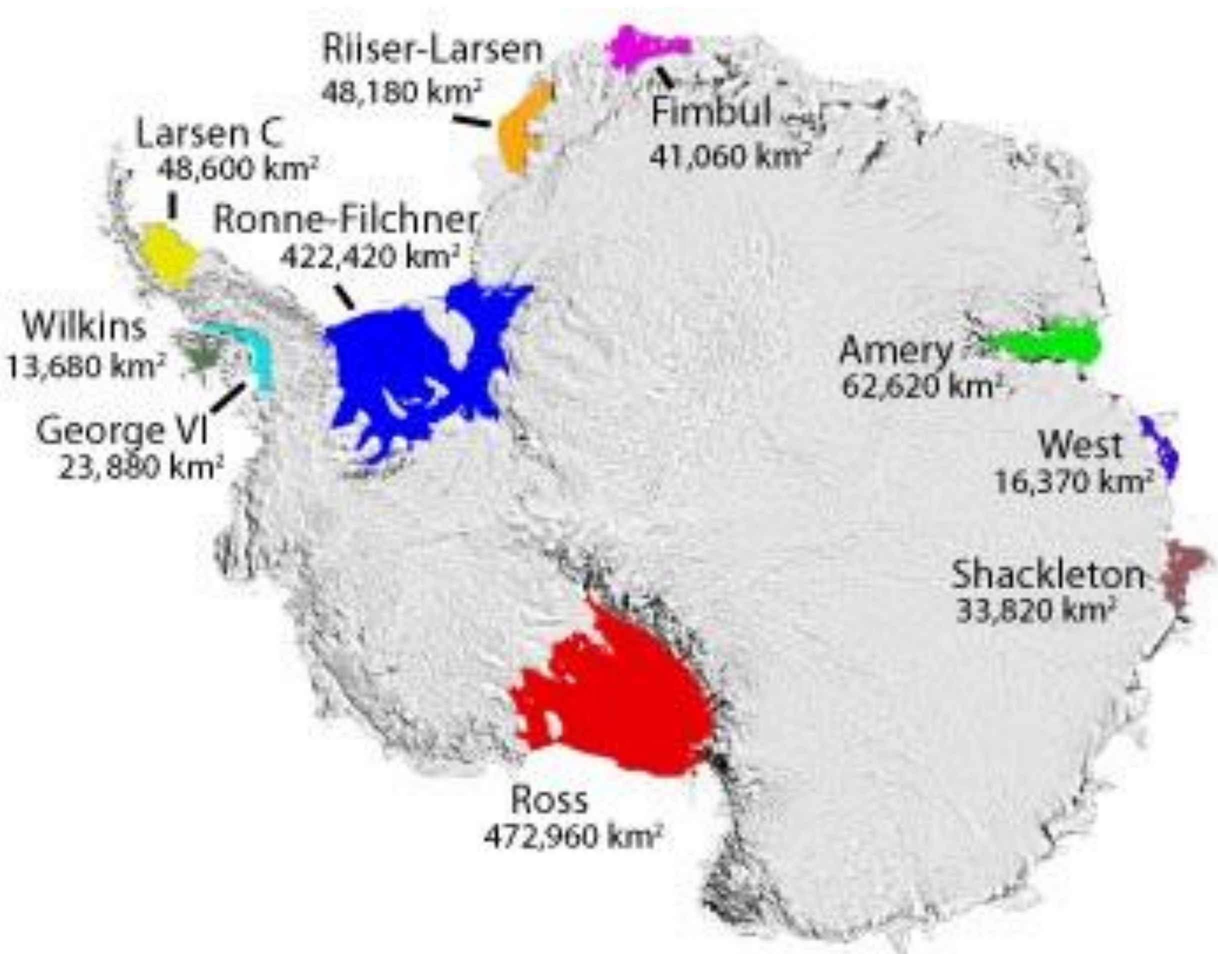


Figure D.2 Antarctic sea ice modal map for 1980-2008 [Source: created by author]

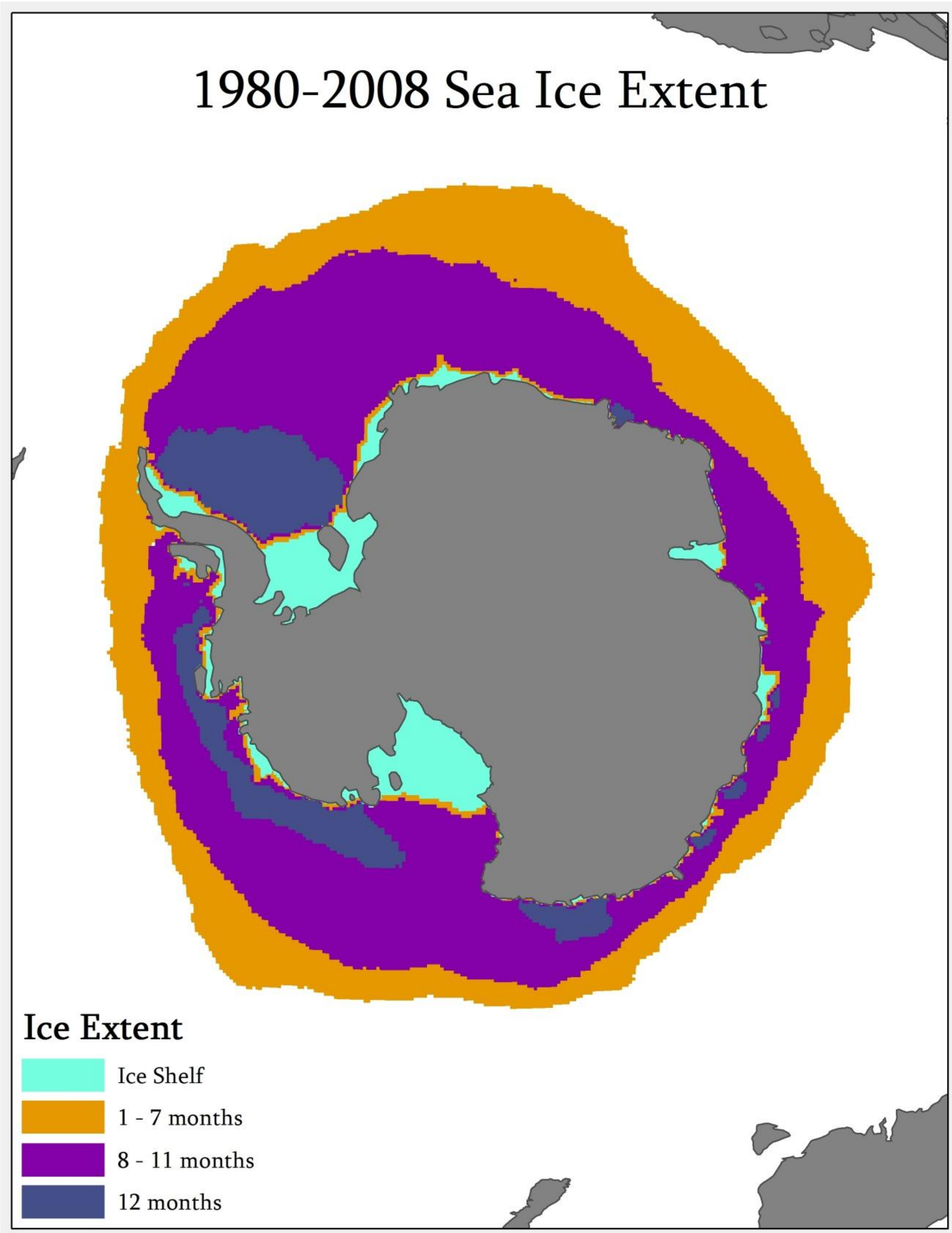


Figure D.3 2008 Antarctic sea ice extent [Source: created by author]

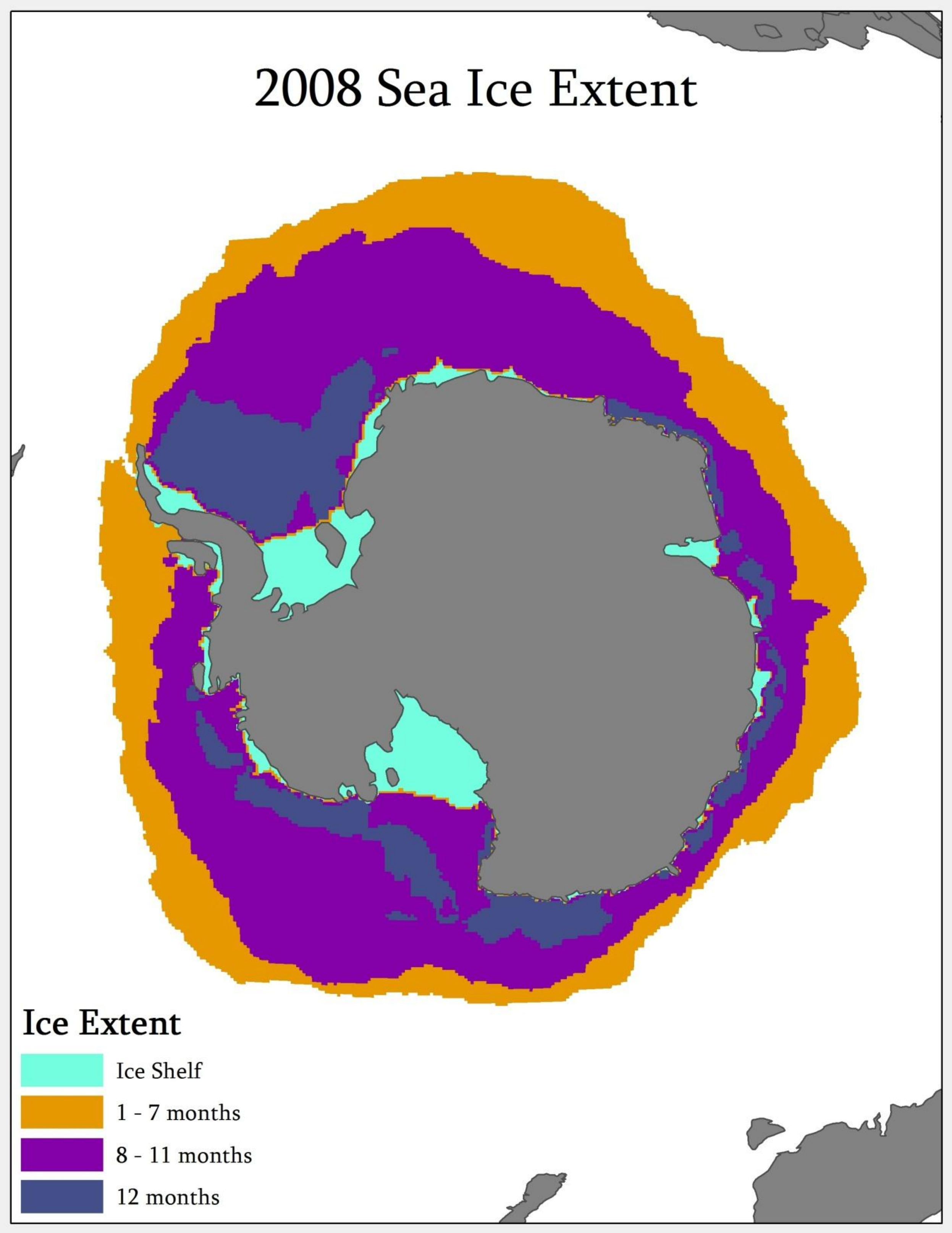


Figure D.4 2007 Antarctic sea ice extent [Source: created by author]

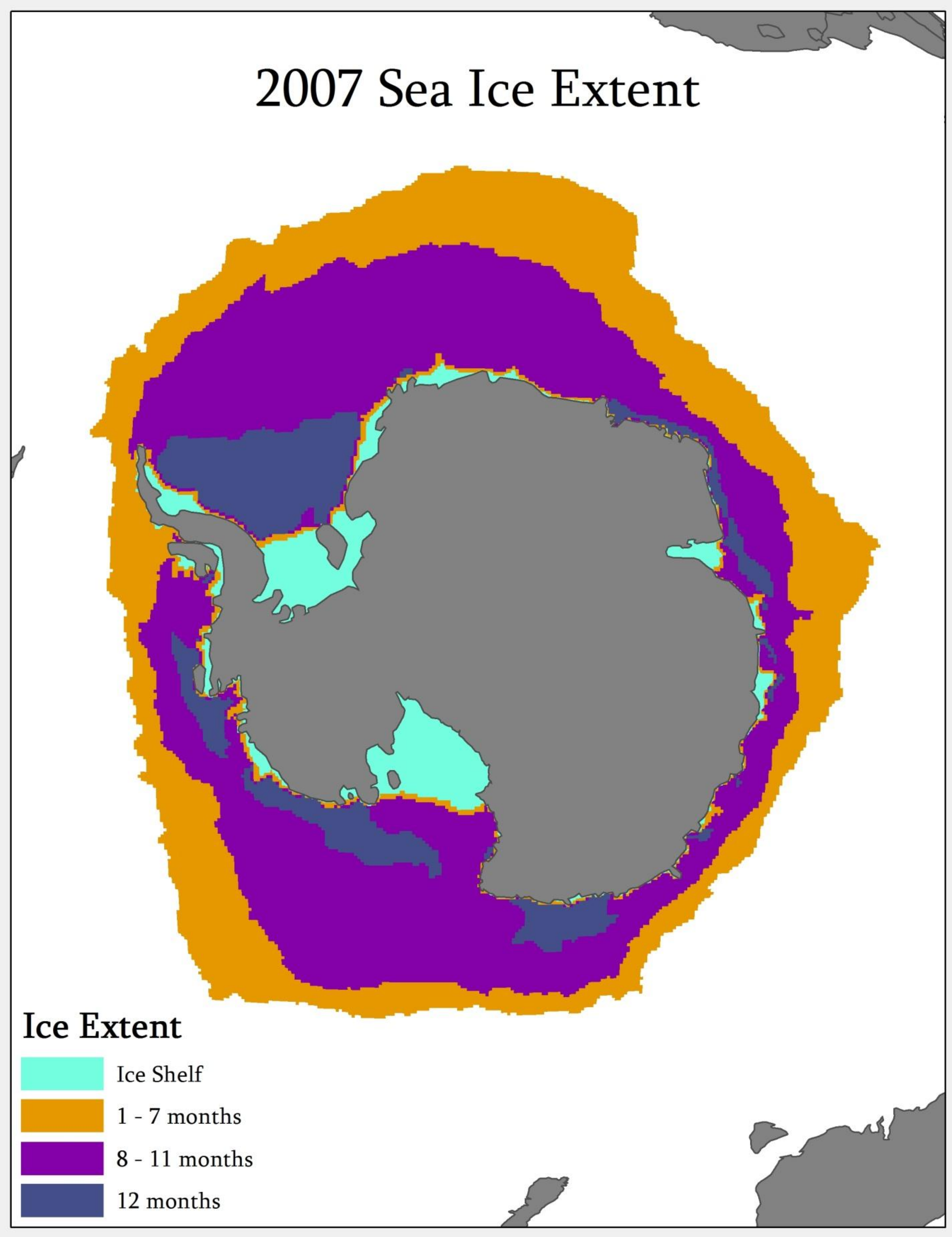


Figure D.5 2006 Antarctic sea ice extent [Source: created by author]

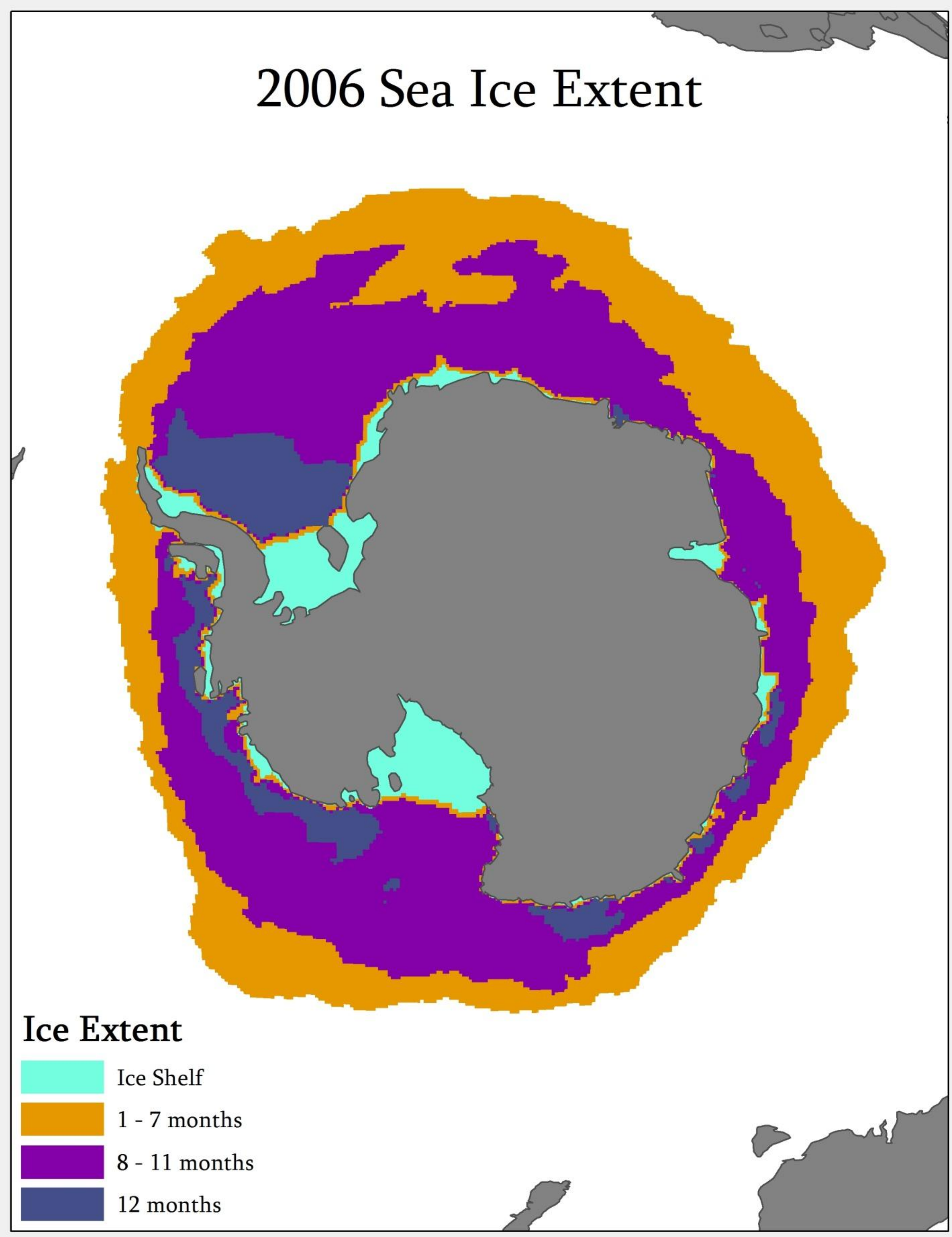


Figure D.6 2005 Antarctic sea ice extent [Source: created by author]

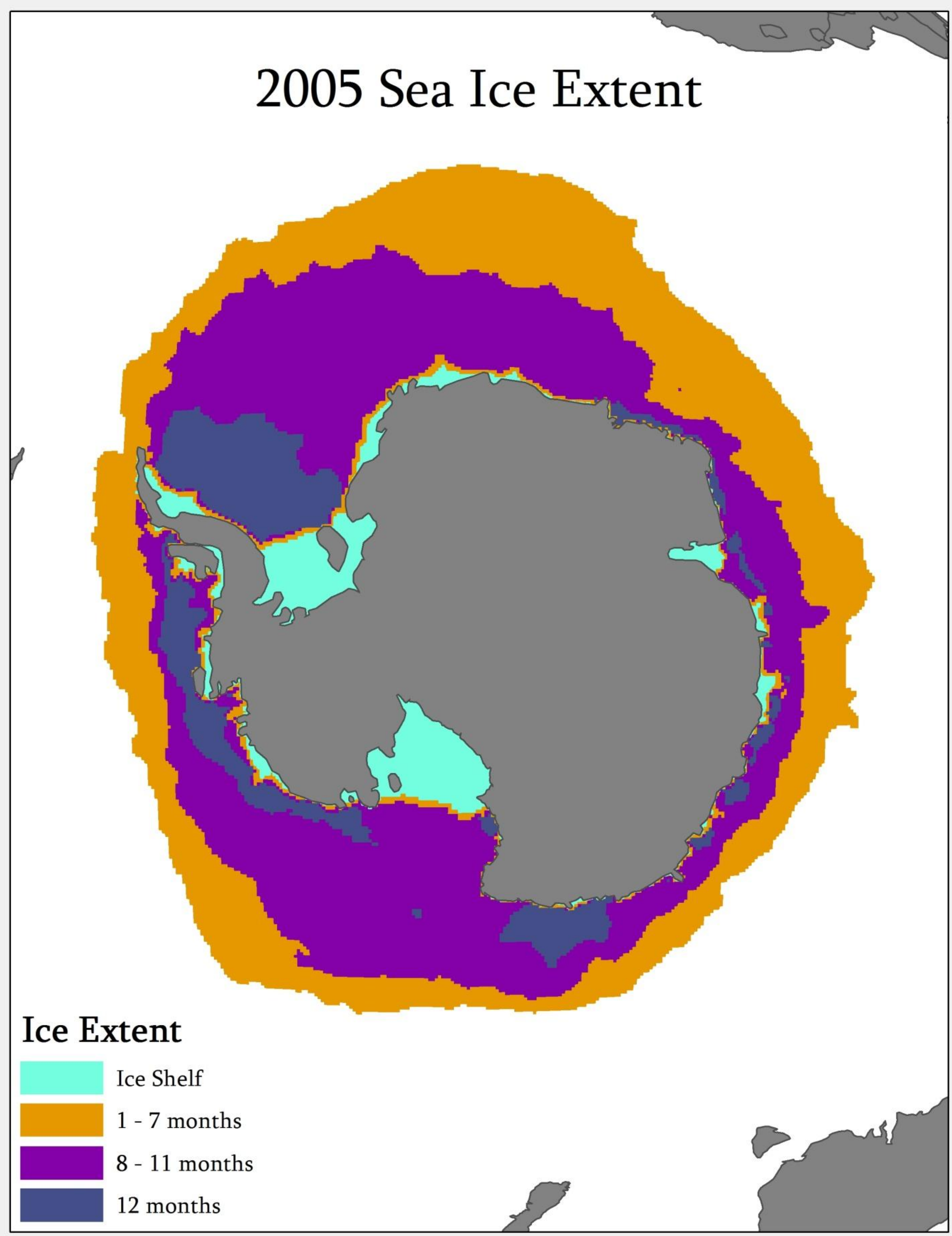


Figure D.7 2004 Antarctic sea ice extent [Source: created by author]

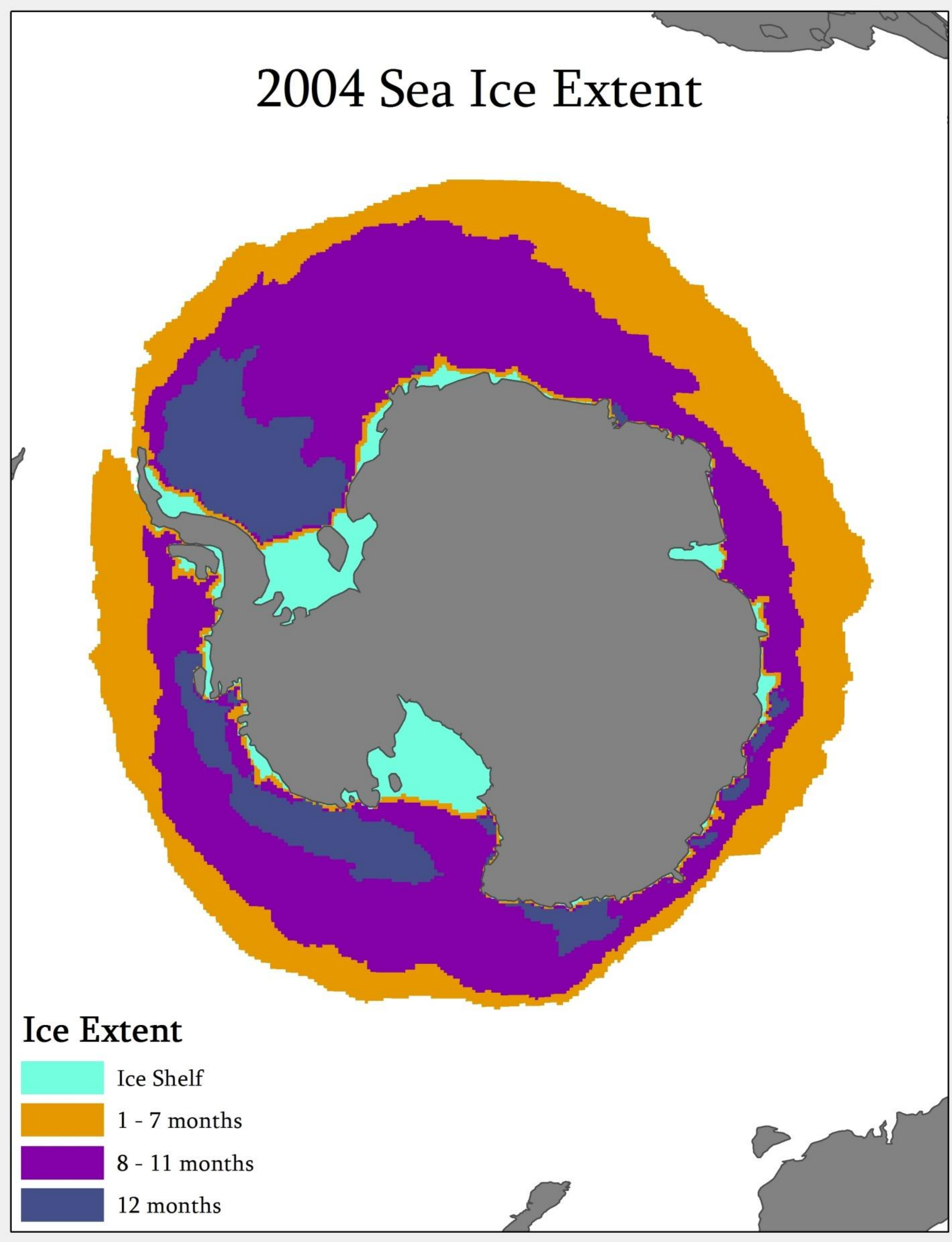


Figure D.8 2003 Antarctic sea ice extent [Source: created by author]

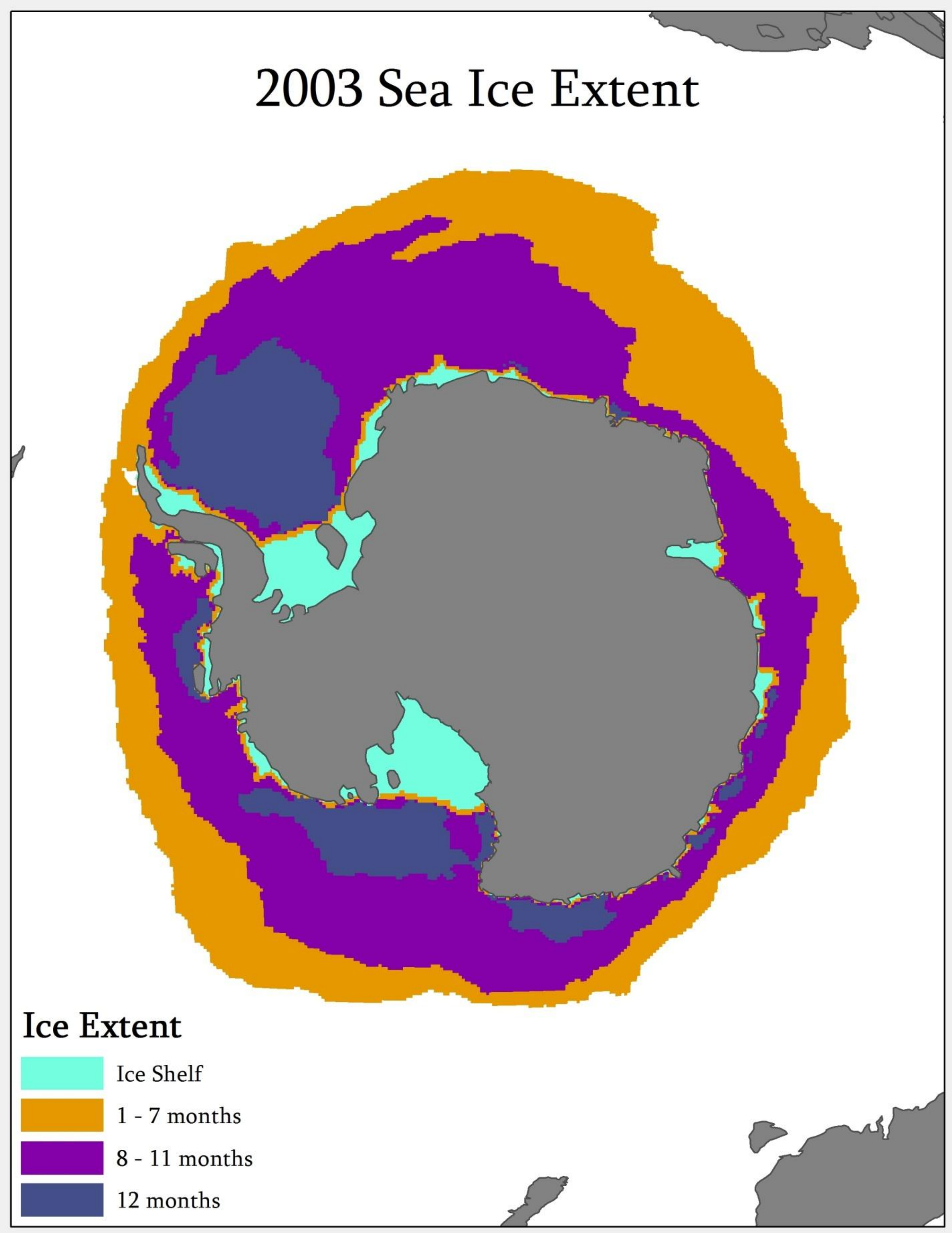


Figure D.9 2002 Antarctic sea ice extent [Source: created by author]

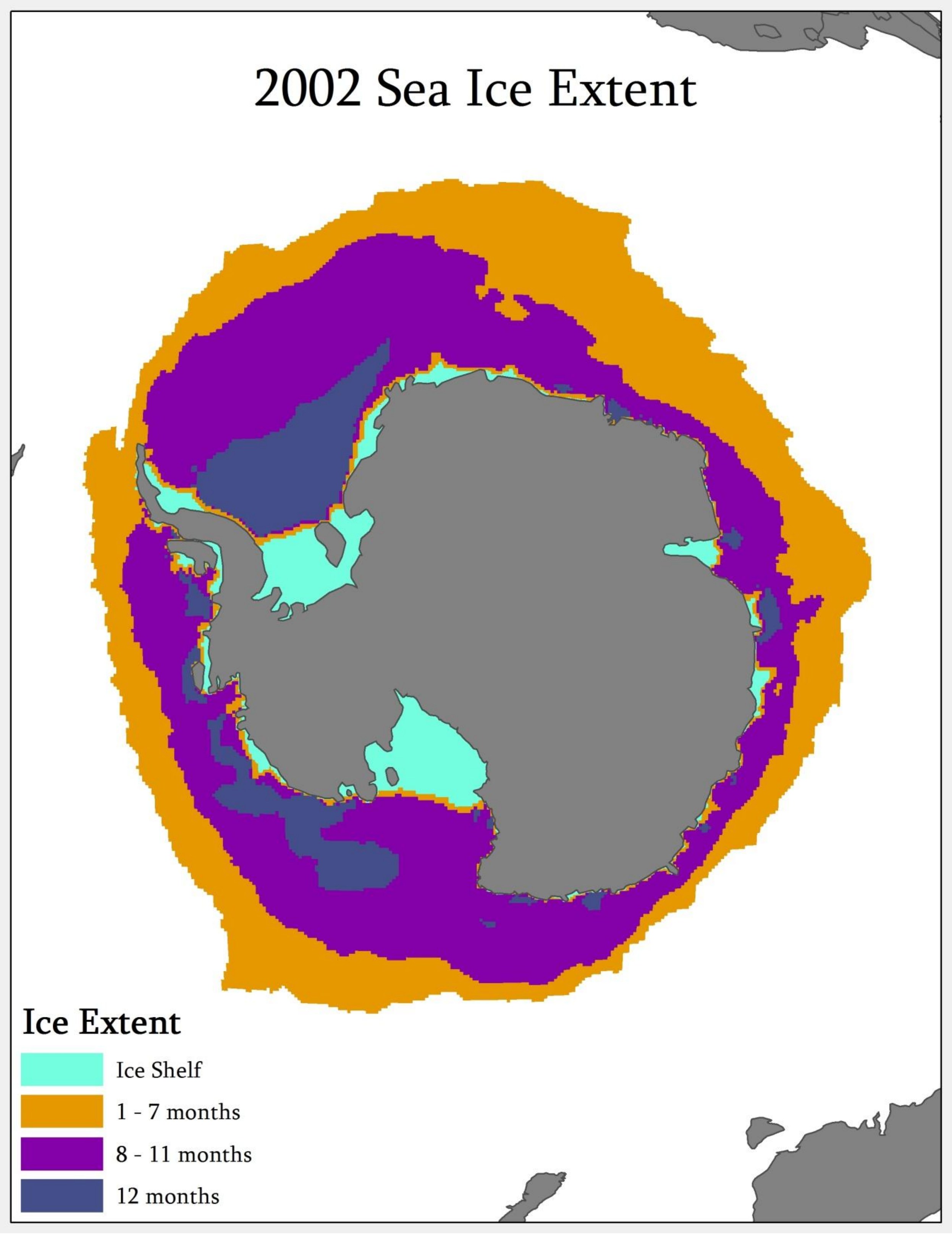


Figure D.10 2001 Antarctic sea ice extent [Source: created by author]

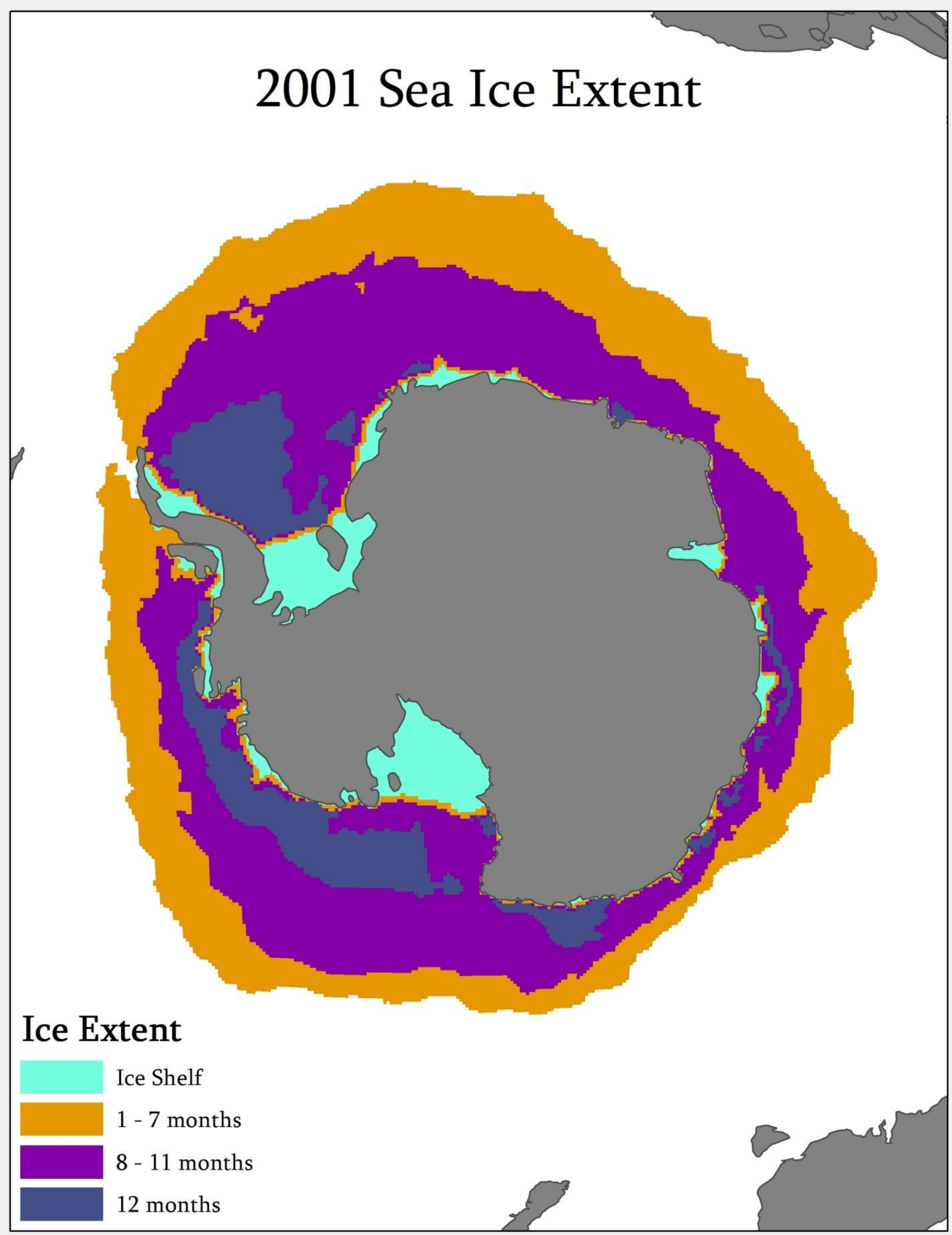


Figure D.11 2000 Antarctic sea ice extent [Source: created by author]

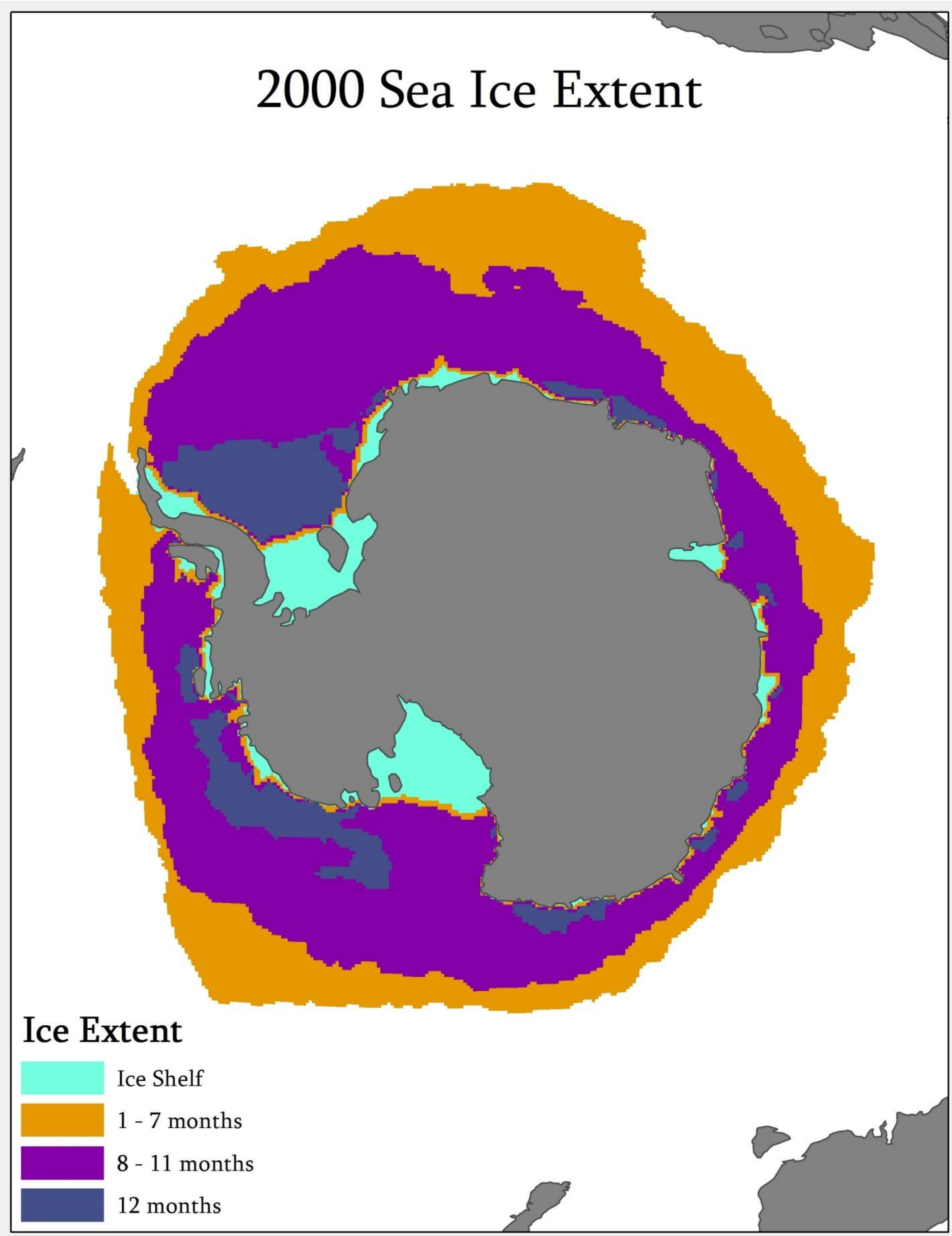


Figure D.12 1999 Antarctic sea ice extent [Source: created by author]

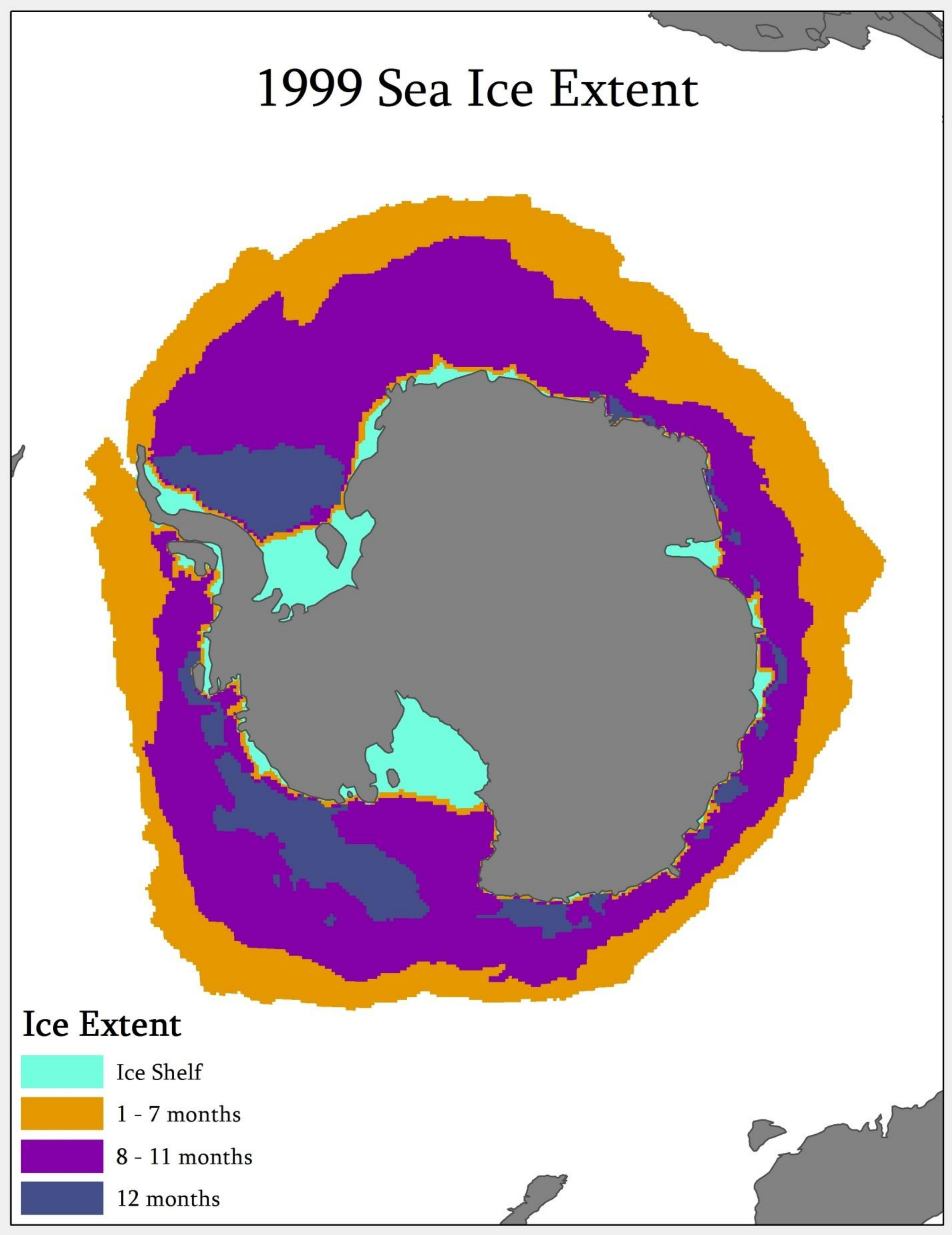


Figure D.13 1998 Antarctic sea ice extent [Source: created by author]

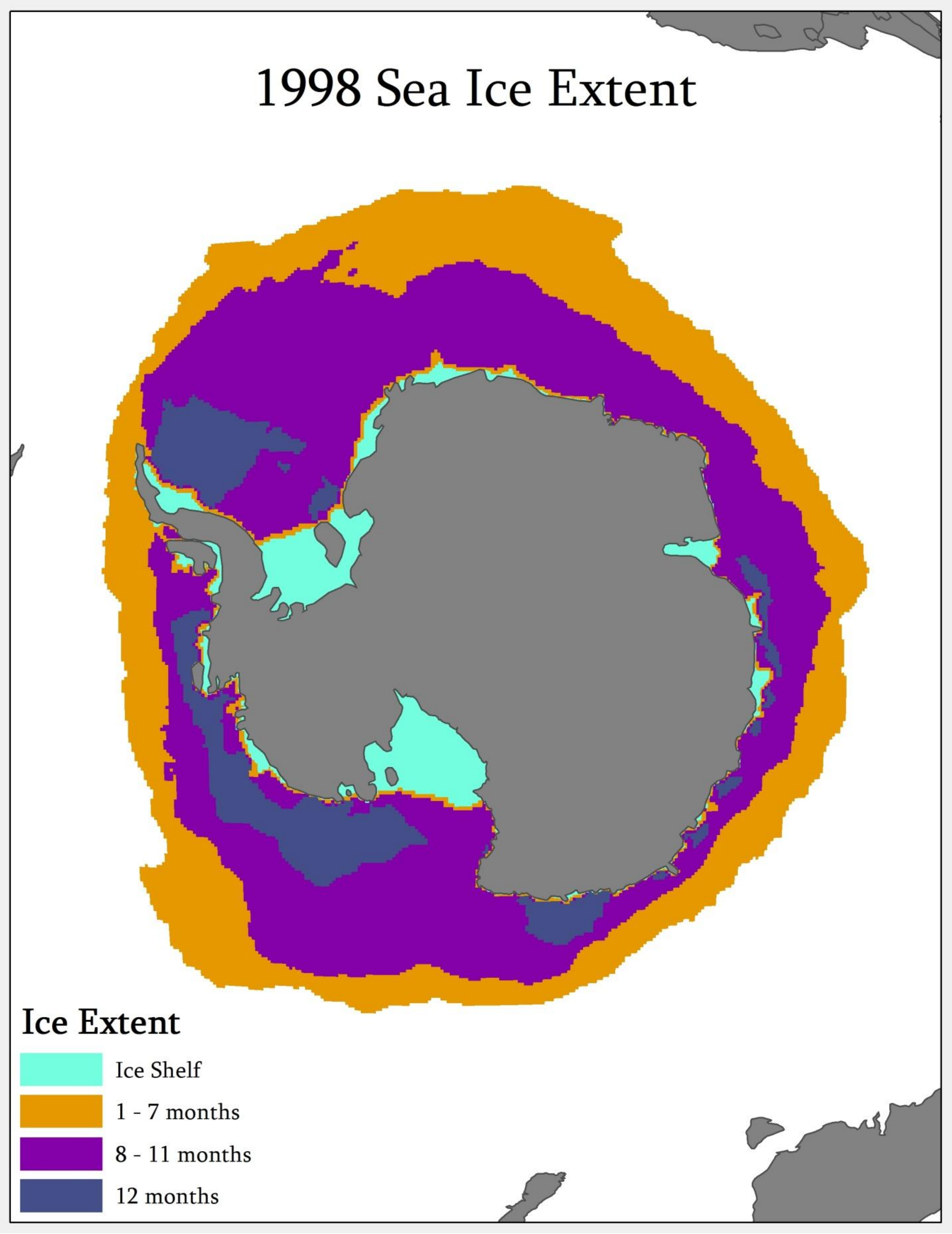


Figure D.14 1997 Antarctic sea ice extent [Source: created by author]

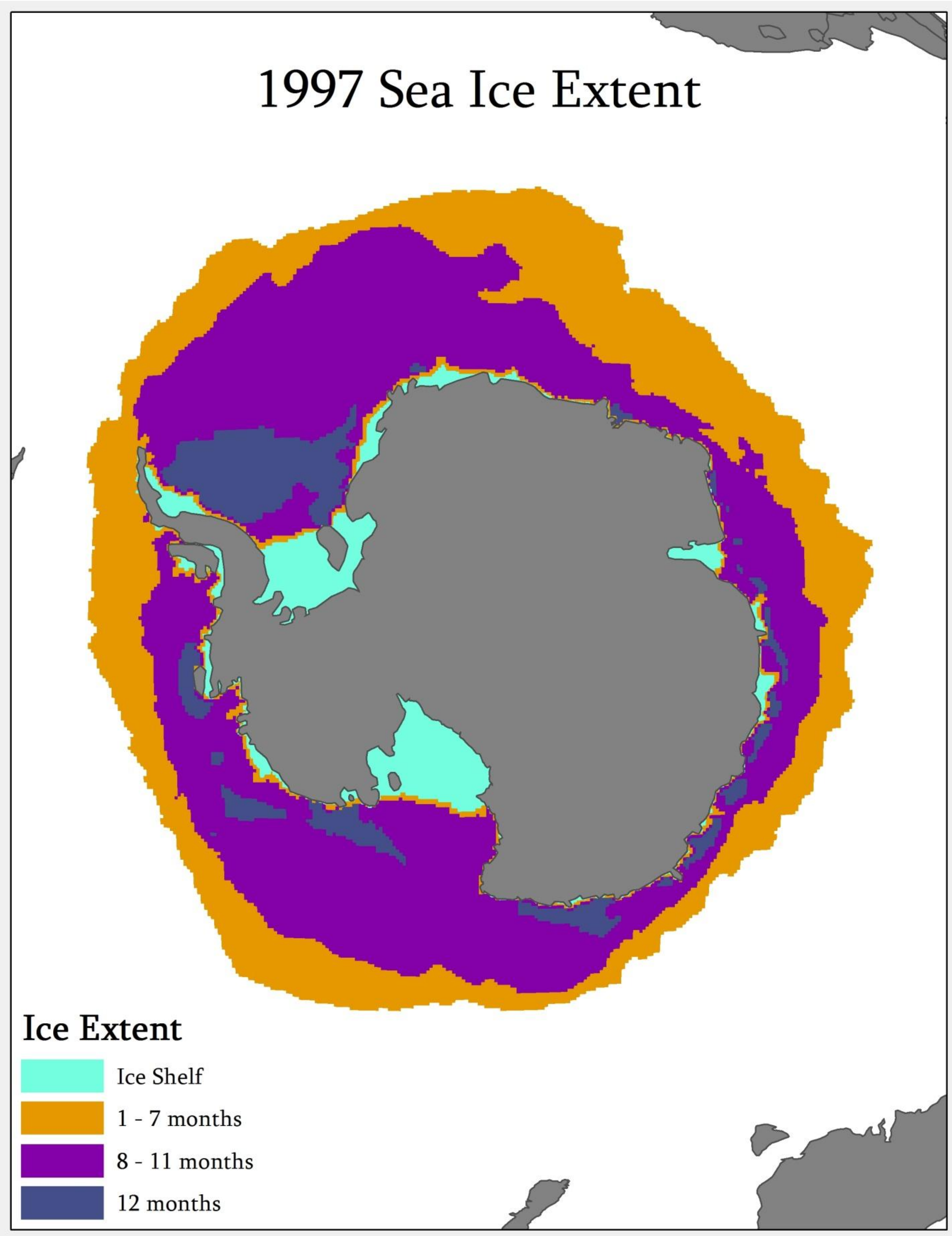


Figure D.15 1996 Antarctic sea ice extent [Source: created by author]

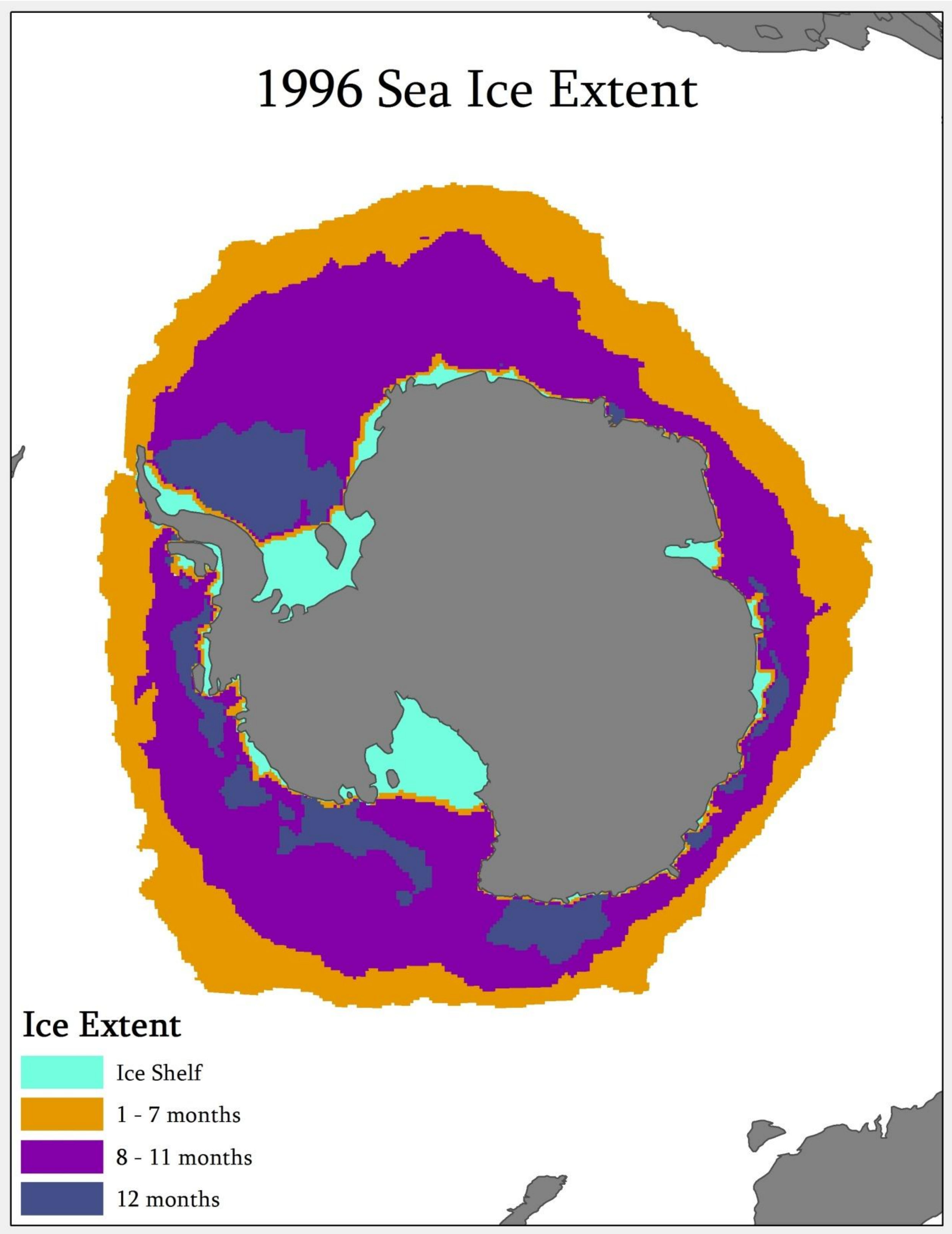


Figure D.16 1995 Antarctic sea ice extent [Source: created by author]

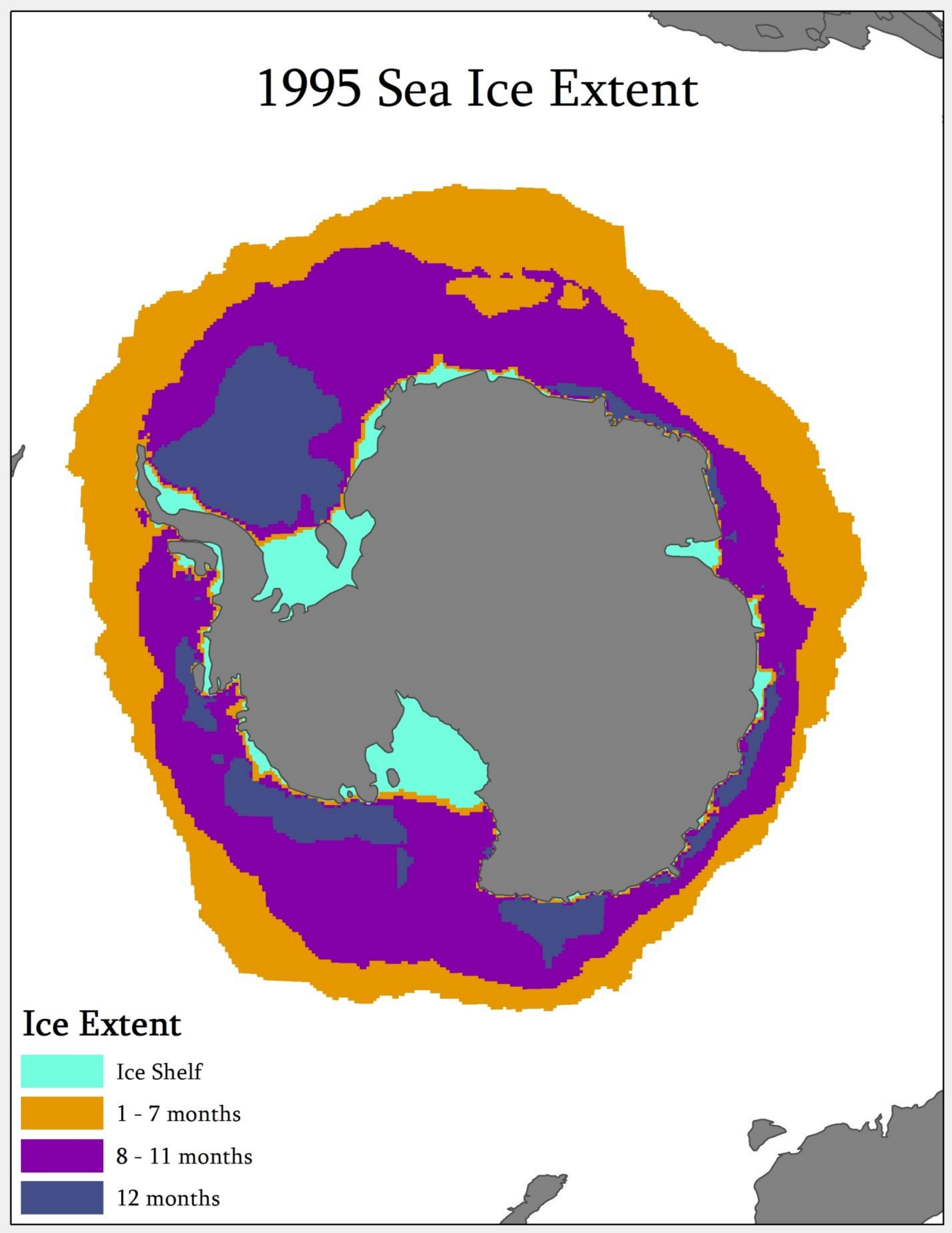


Figure D.17 1994 Antarctic sea ice extent [Source: created by author]

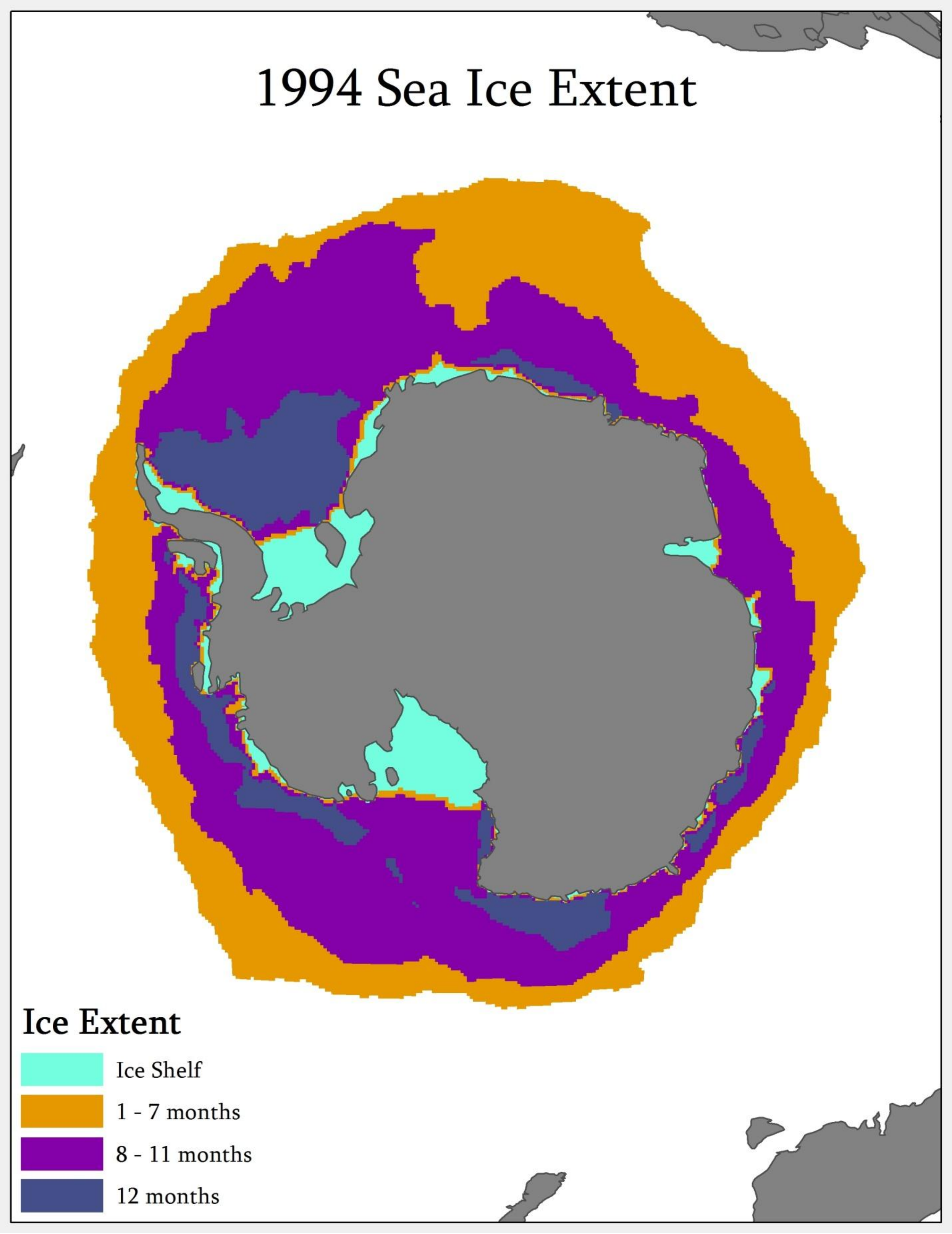


Figure D.18 1993 Antarctic sea ice extent [Source: created by author]

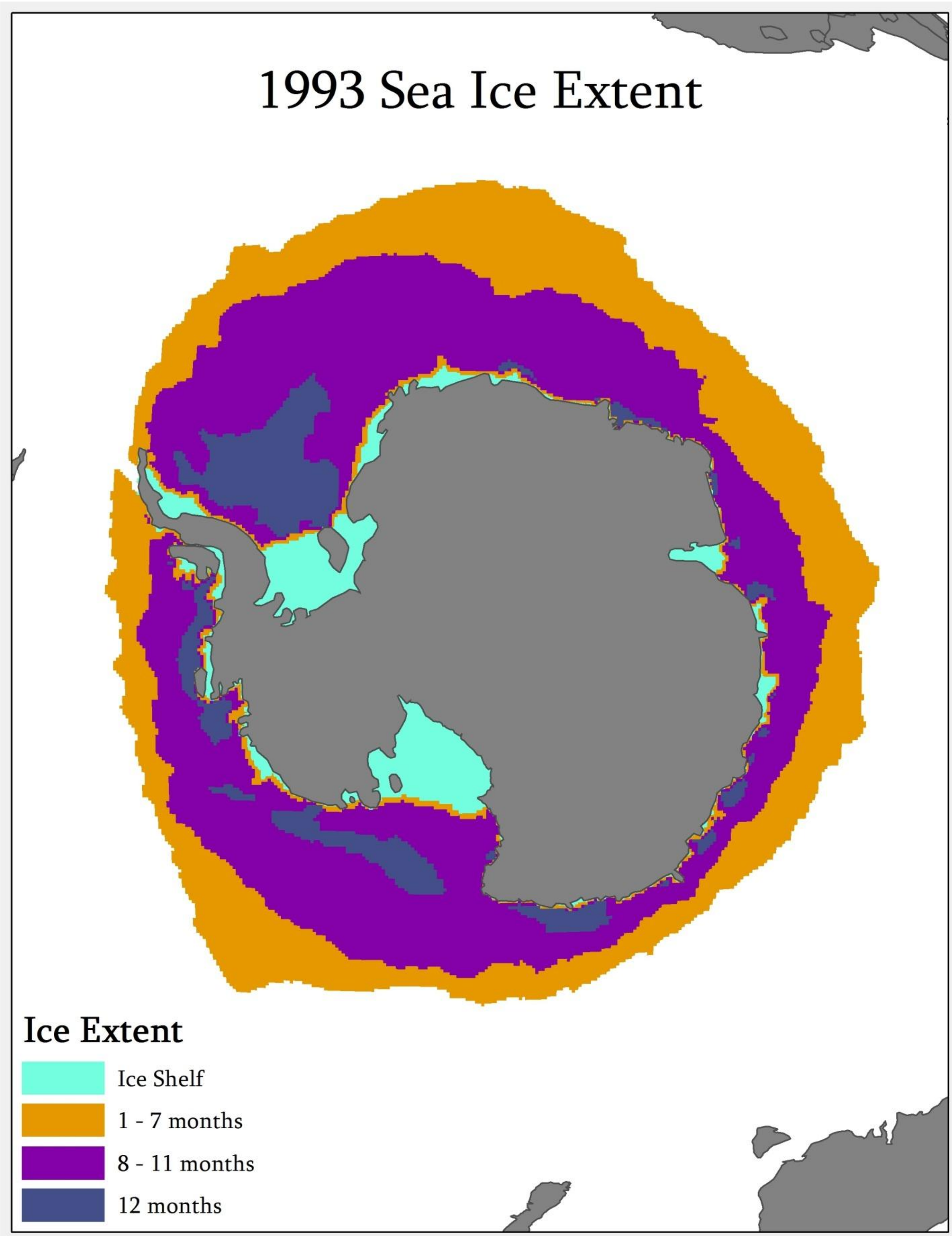


Figure D.19 1992 Antarctic sea ice extent [Source: created by author]

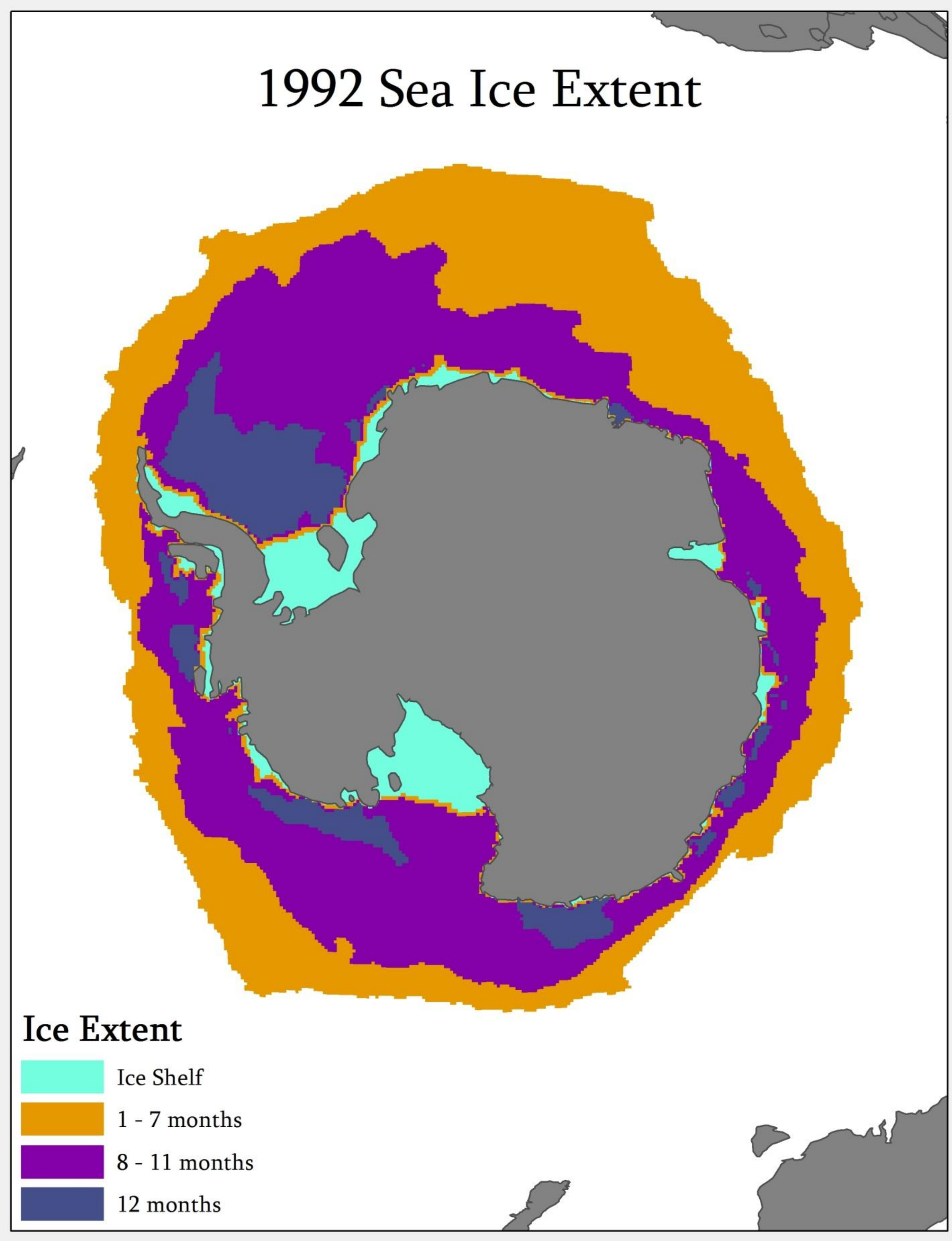


Figure D.20 1991 Antarctic sea ice extent [Source: created by author]

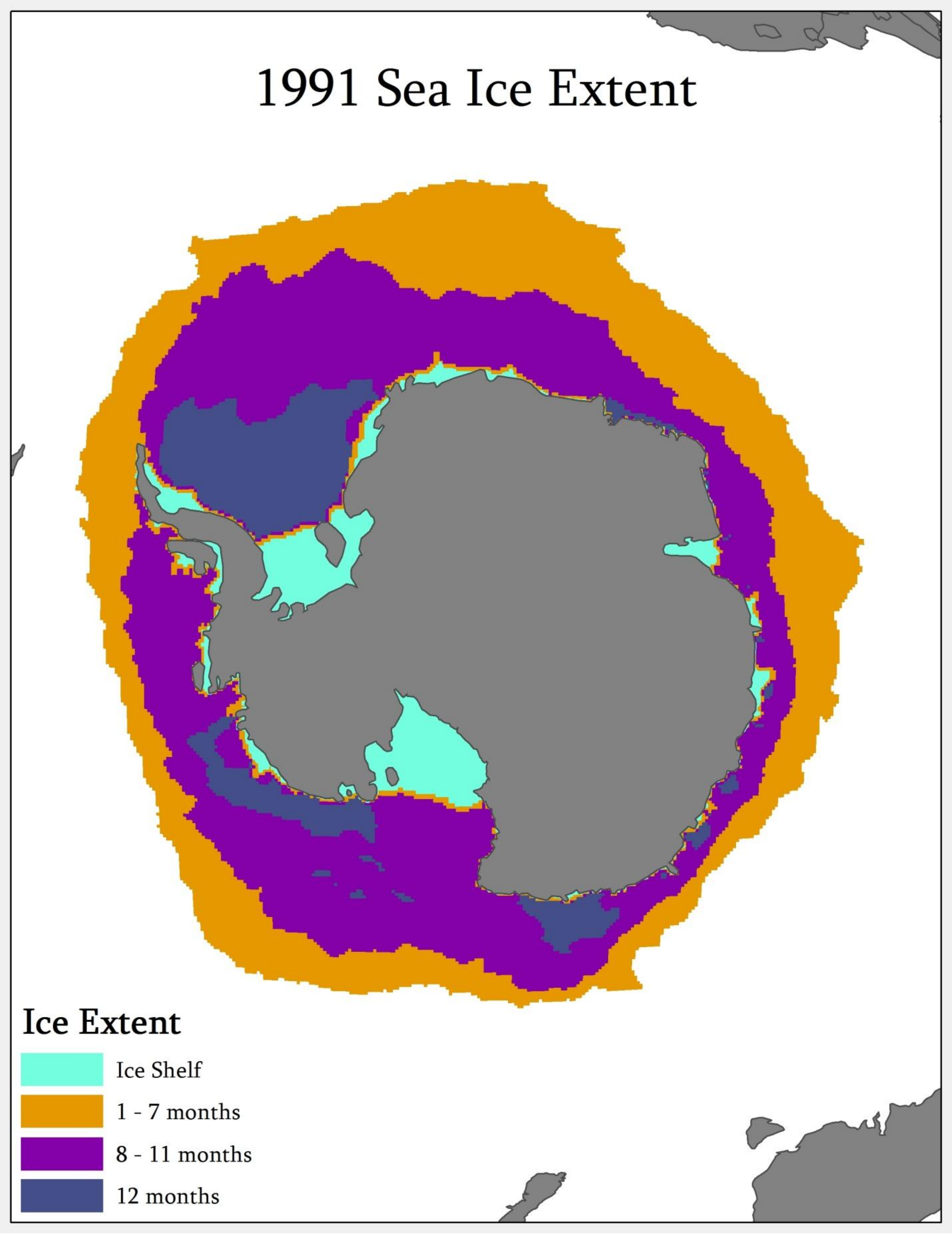


Figure D.21 1990 Antarctic sea ice extent [Source: created by author]

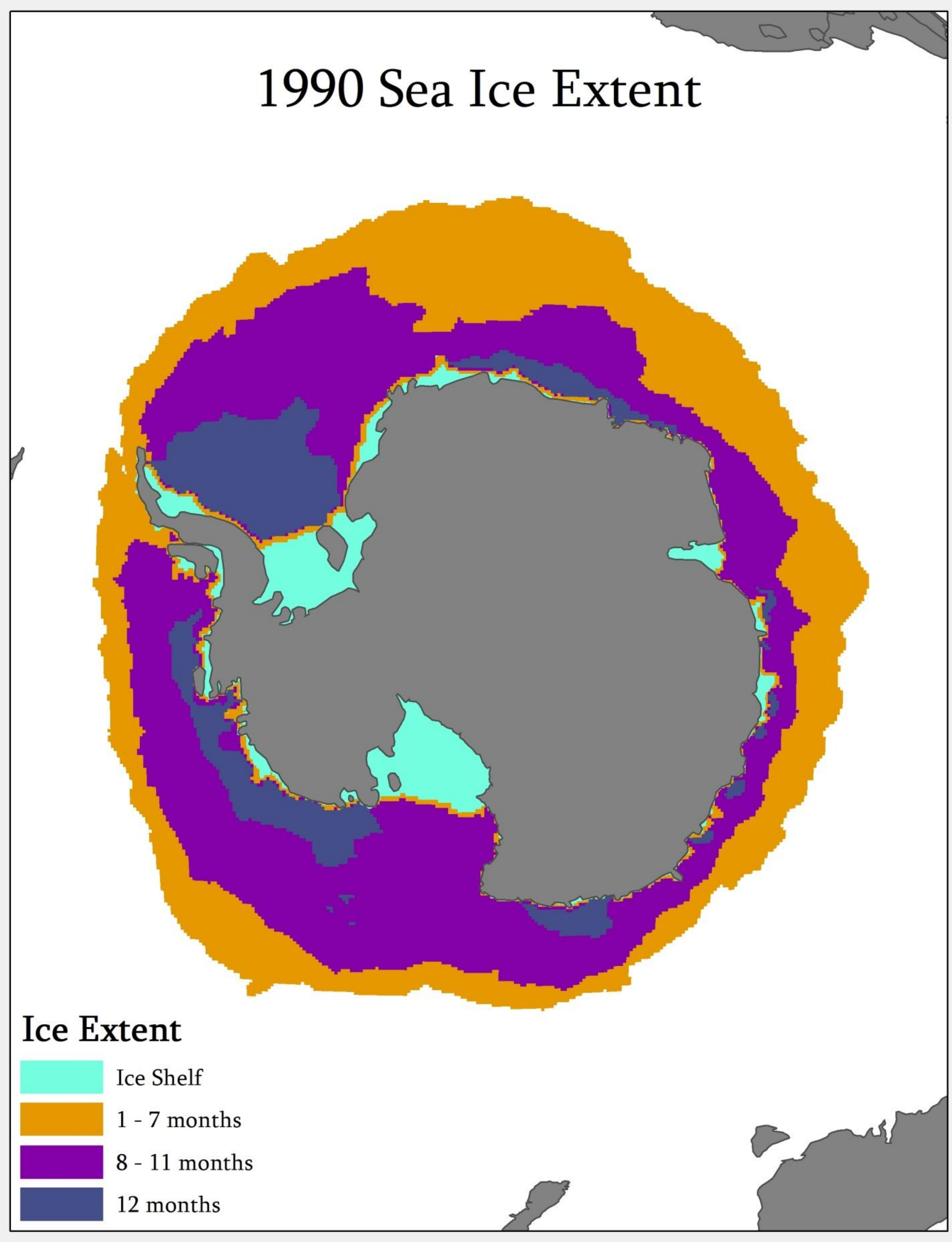


Figure D.22 1989 Antarctic sea ice extent [Source: created by author]

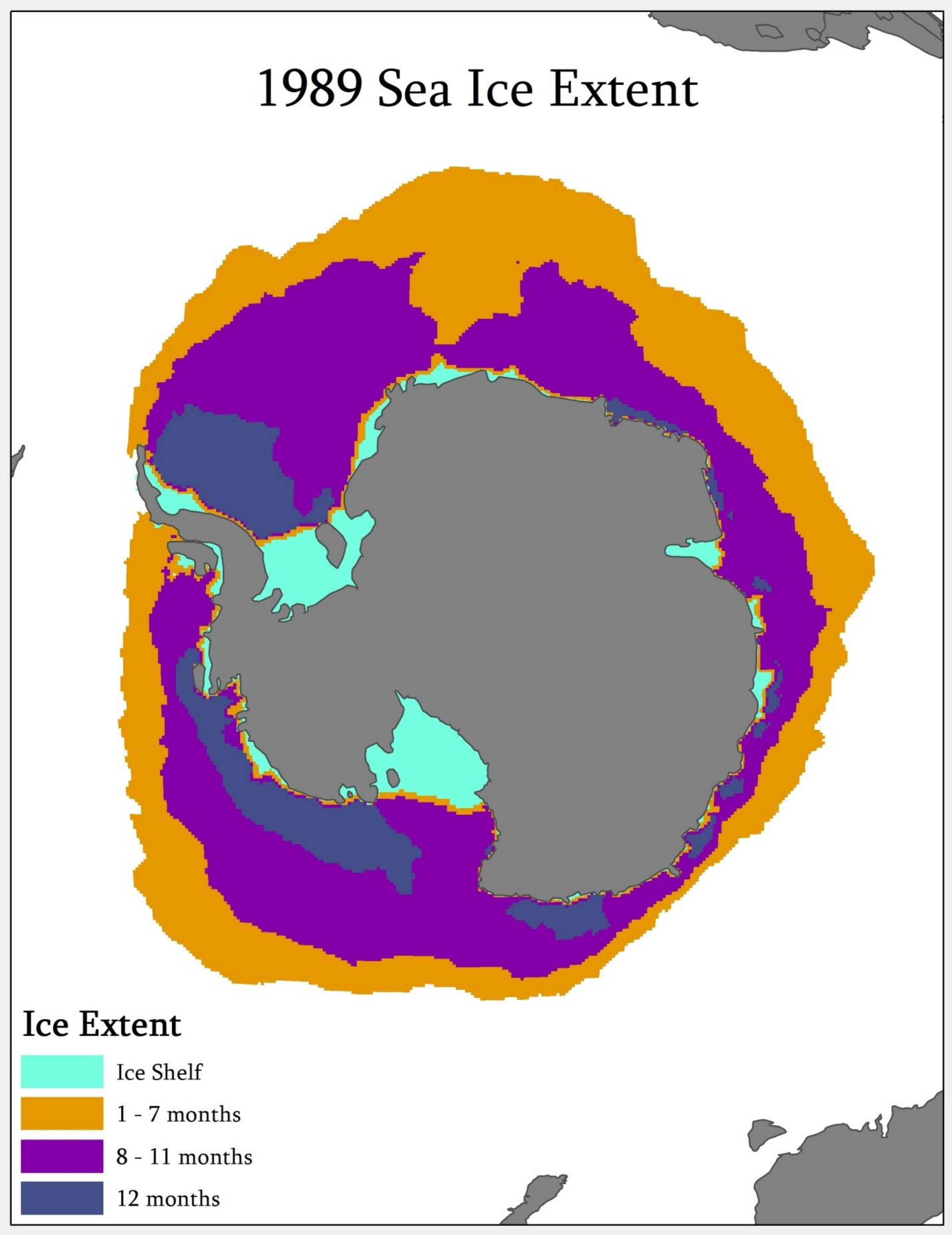


Figure D.23 1988 Antarctic sea ice extent [Source: created by author]

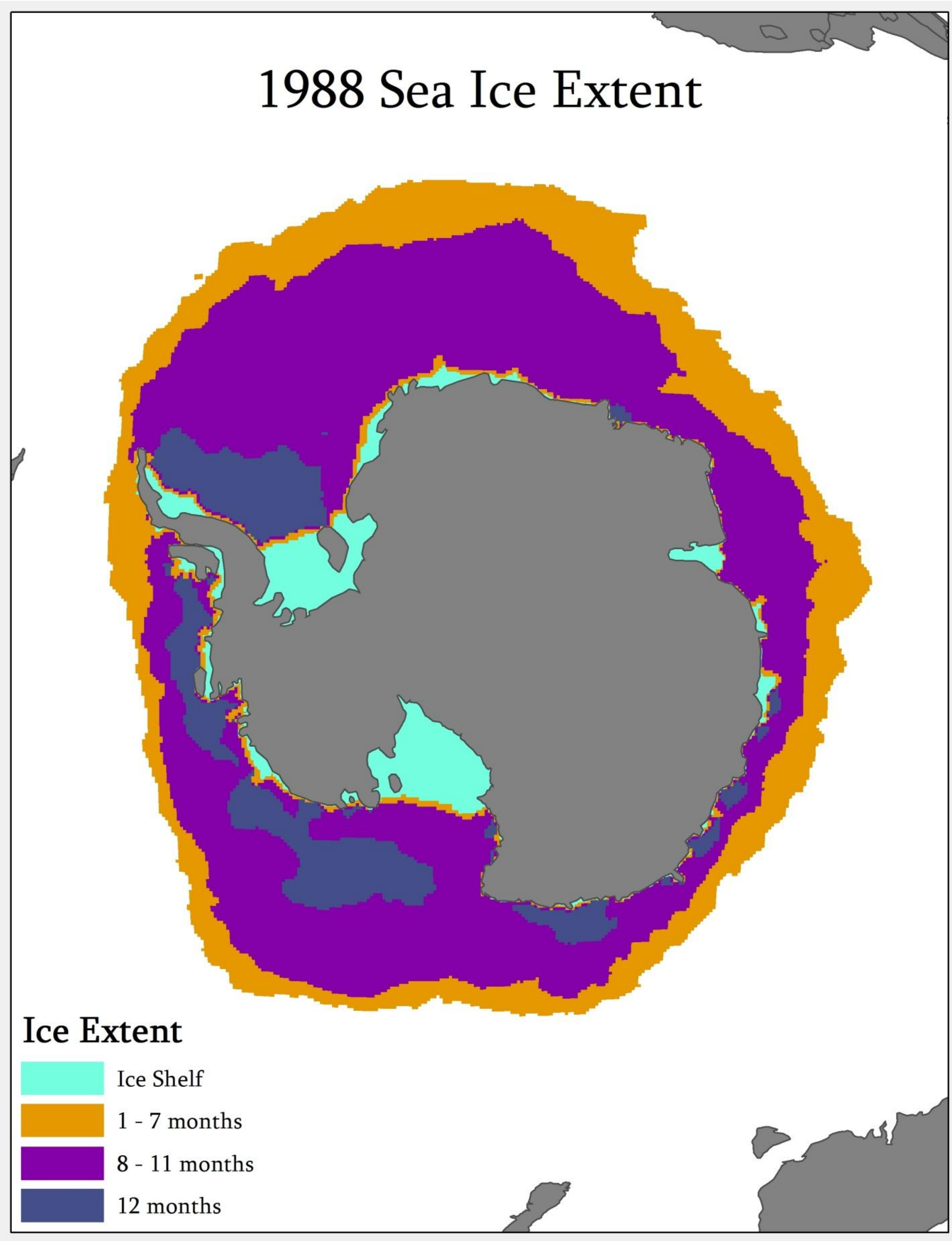


Figure D.24 1987 Antarctic sea ice extent [Source: created by author]

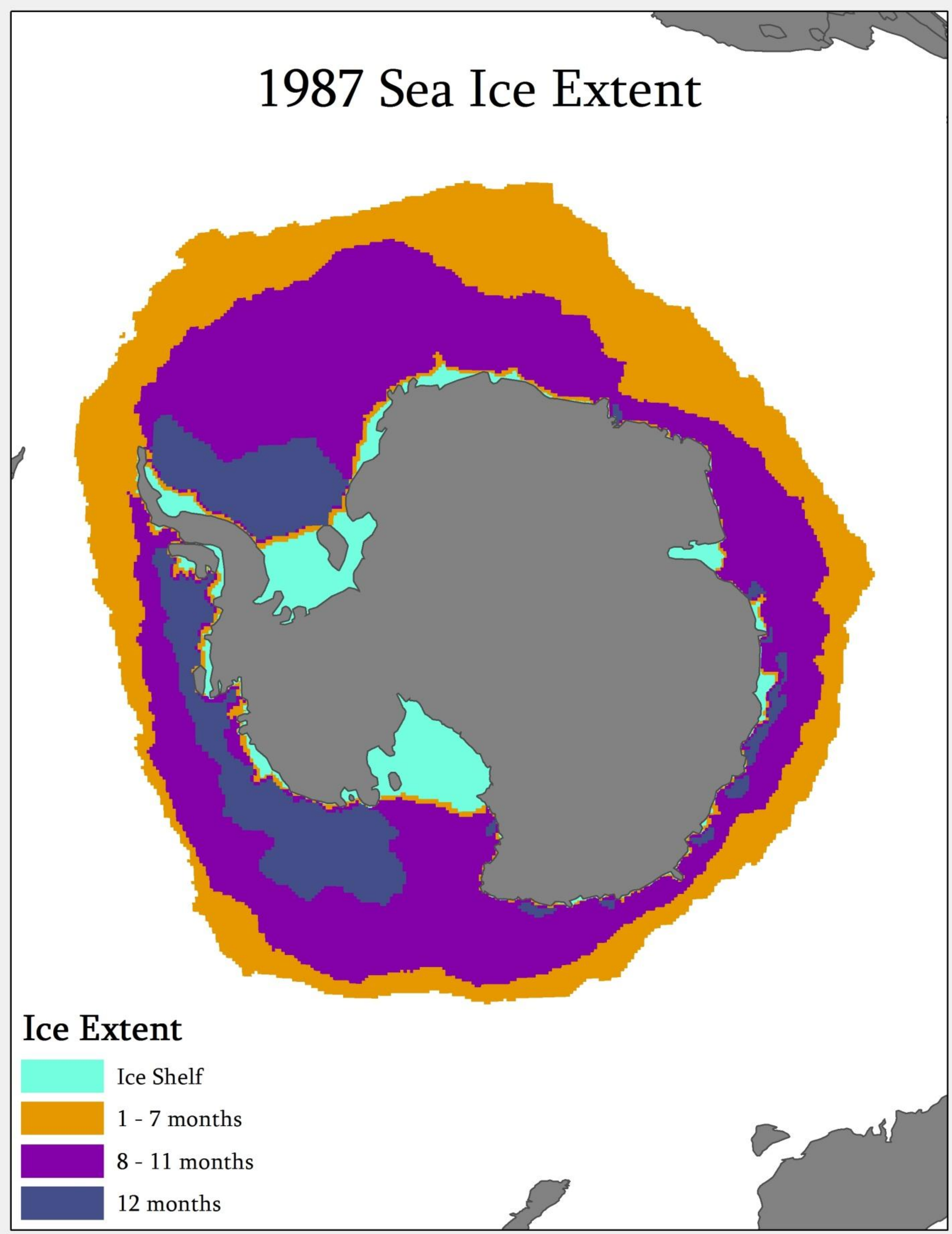


Figure D.25 1986 Antarctic sea ice extent [Source: created by author]

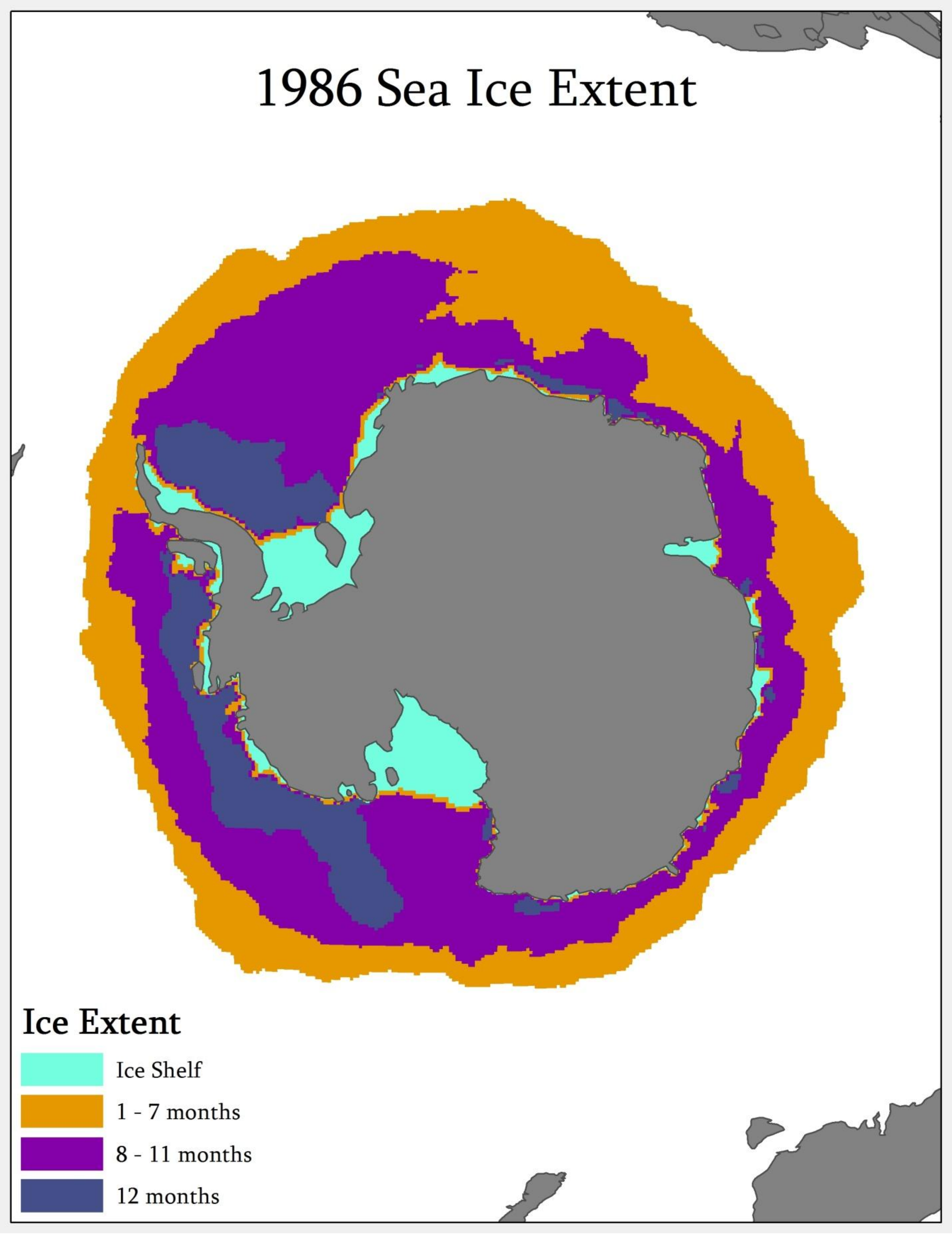


Figure D.26 1985 Antarctic sea ice extent [Source: created by author]

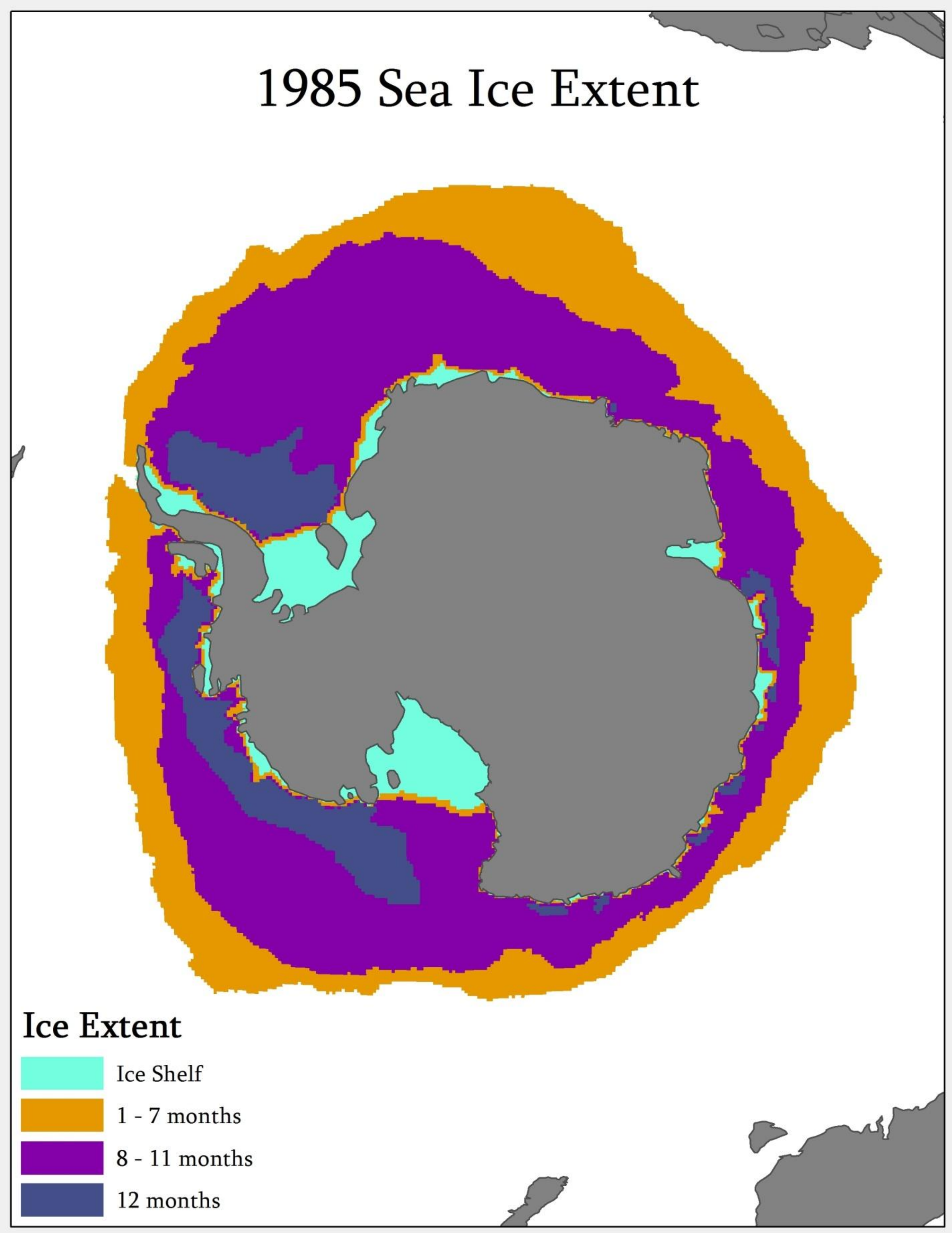


Figure D.27 1984 Antarctic sea ice extent [Source: created by author]

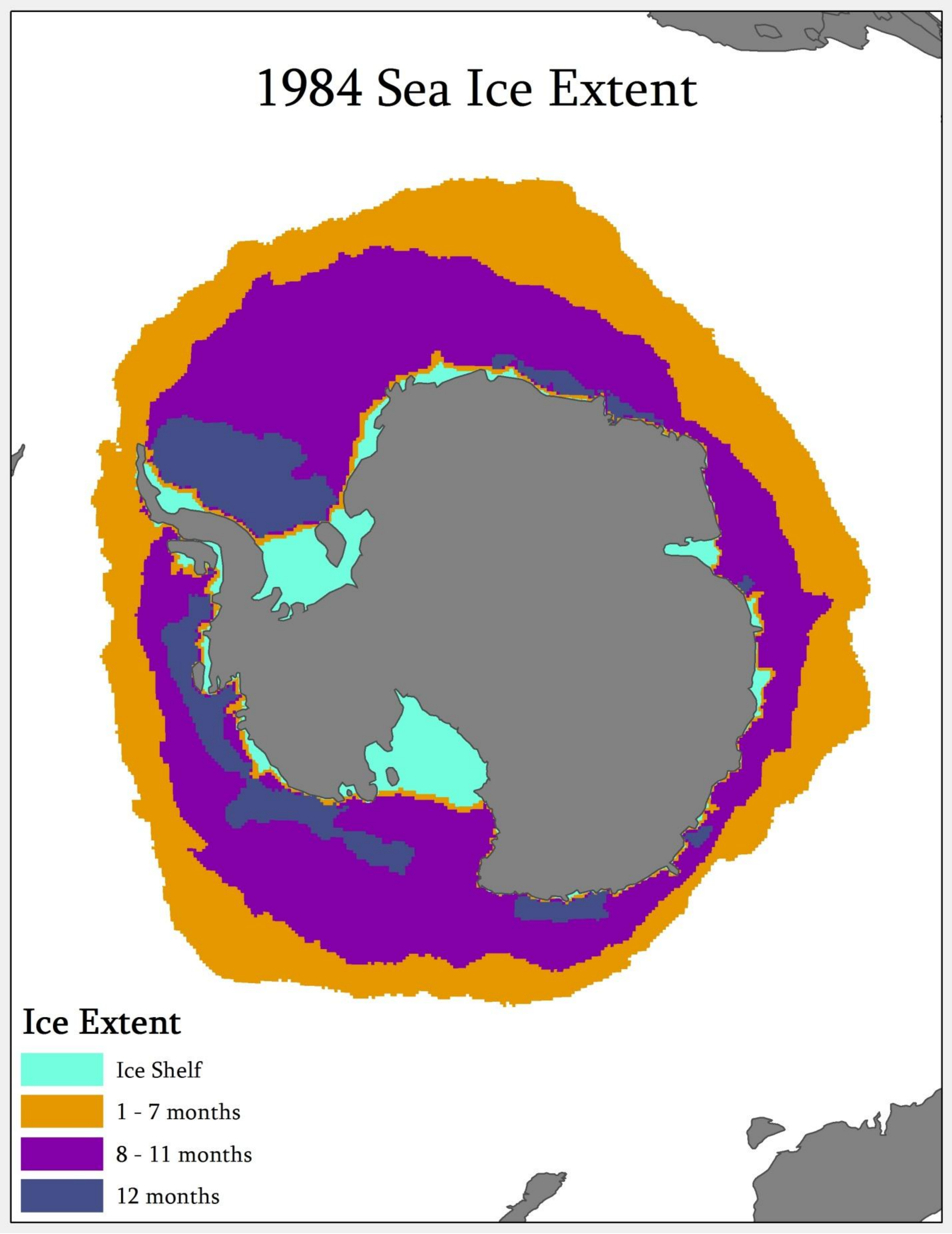


Figure D.28 1983 Antarctic sea ice extent [Source: created by author]

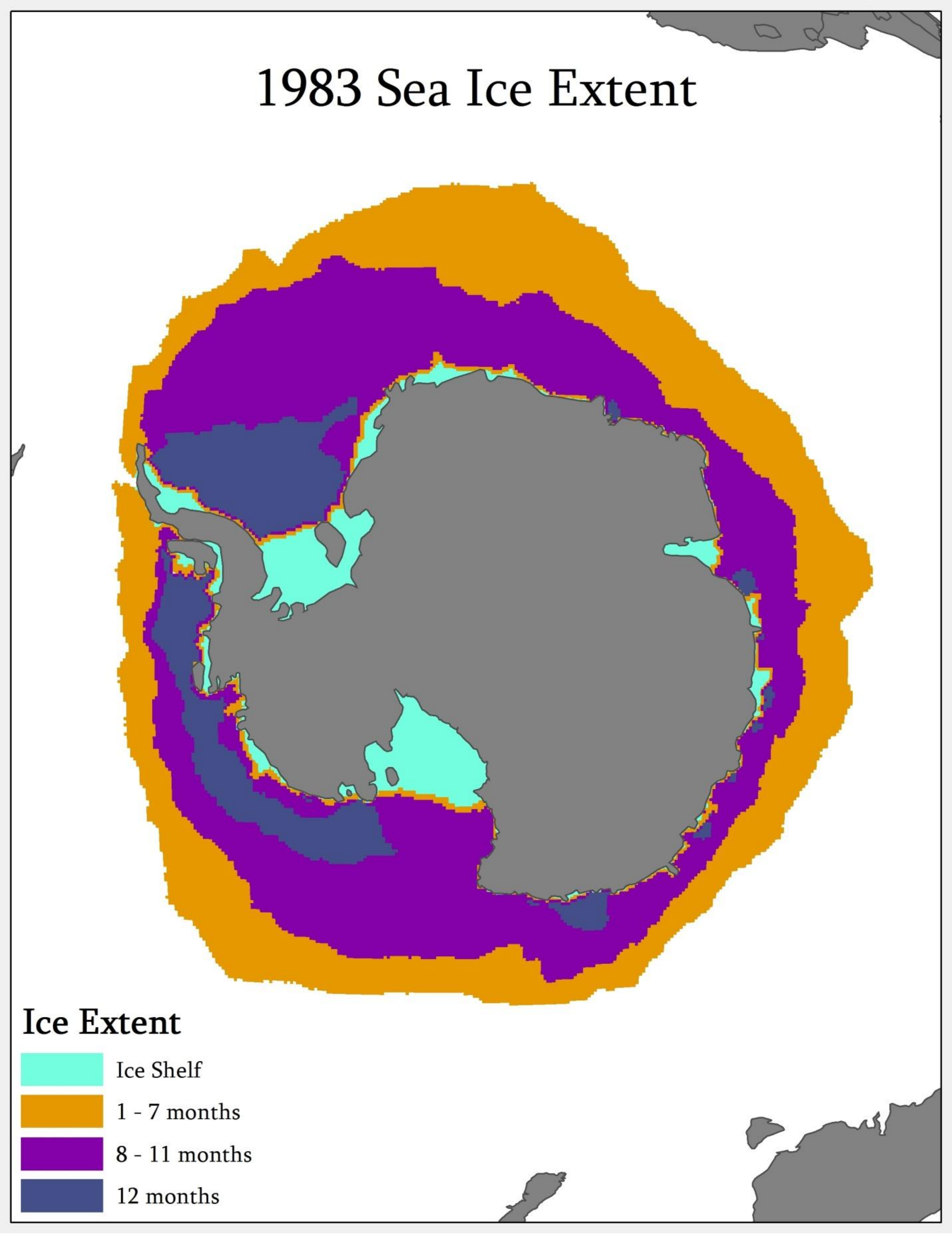


Figure D.29 1982 Antarctic sea ice extent [Source: created by author]

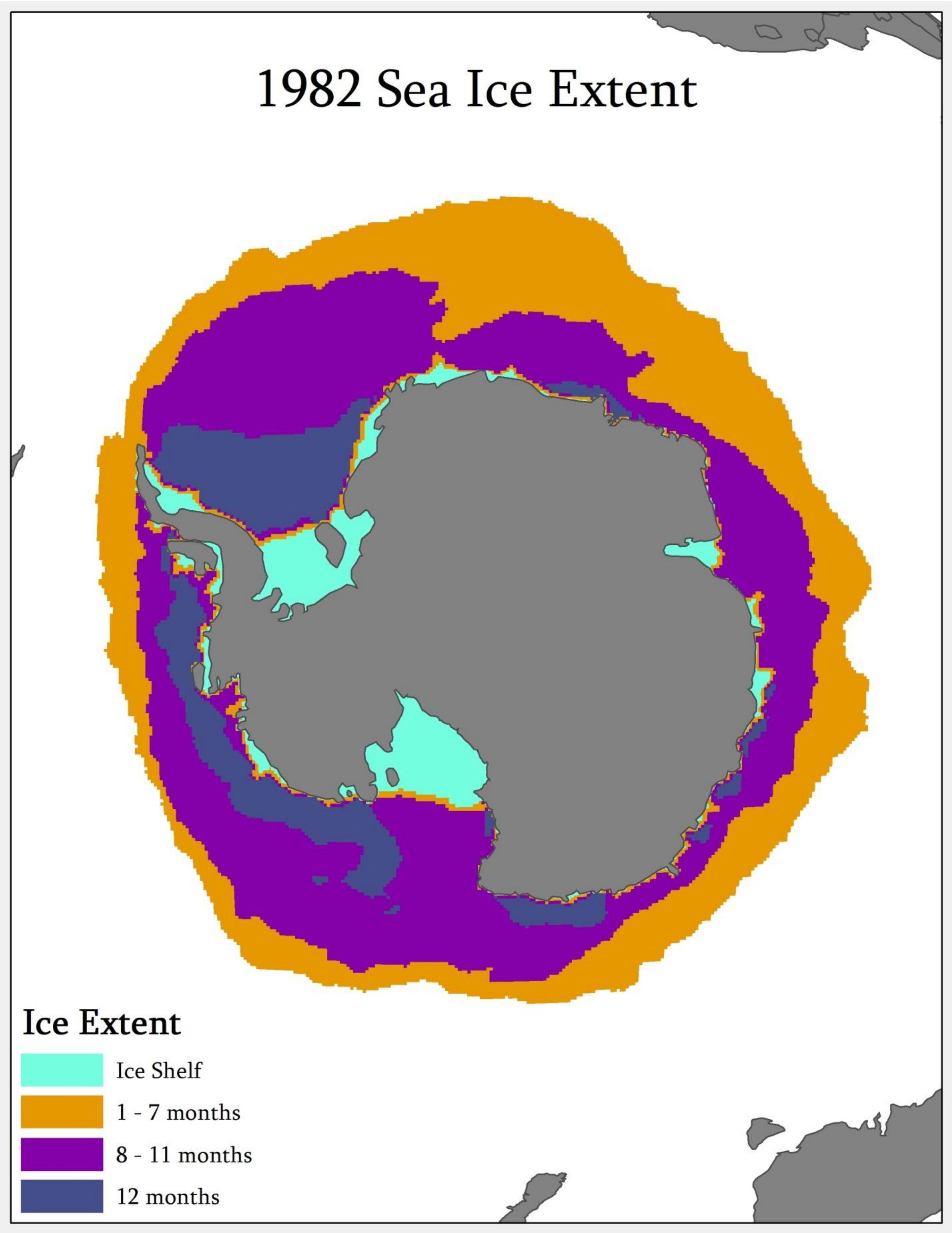


Figure D.30 1981 Antarctic sea ice extent [Source: created by author]

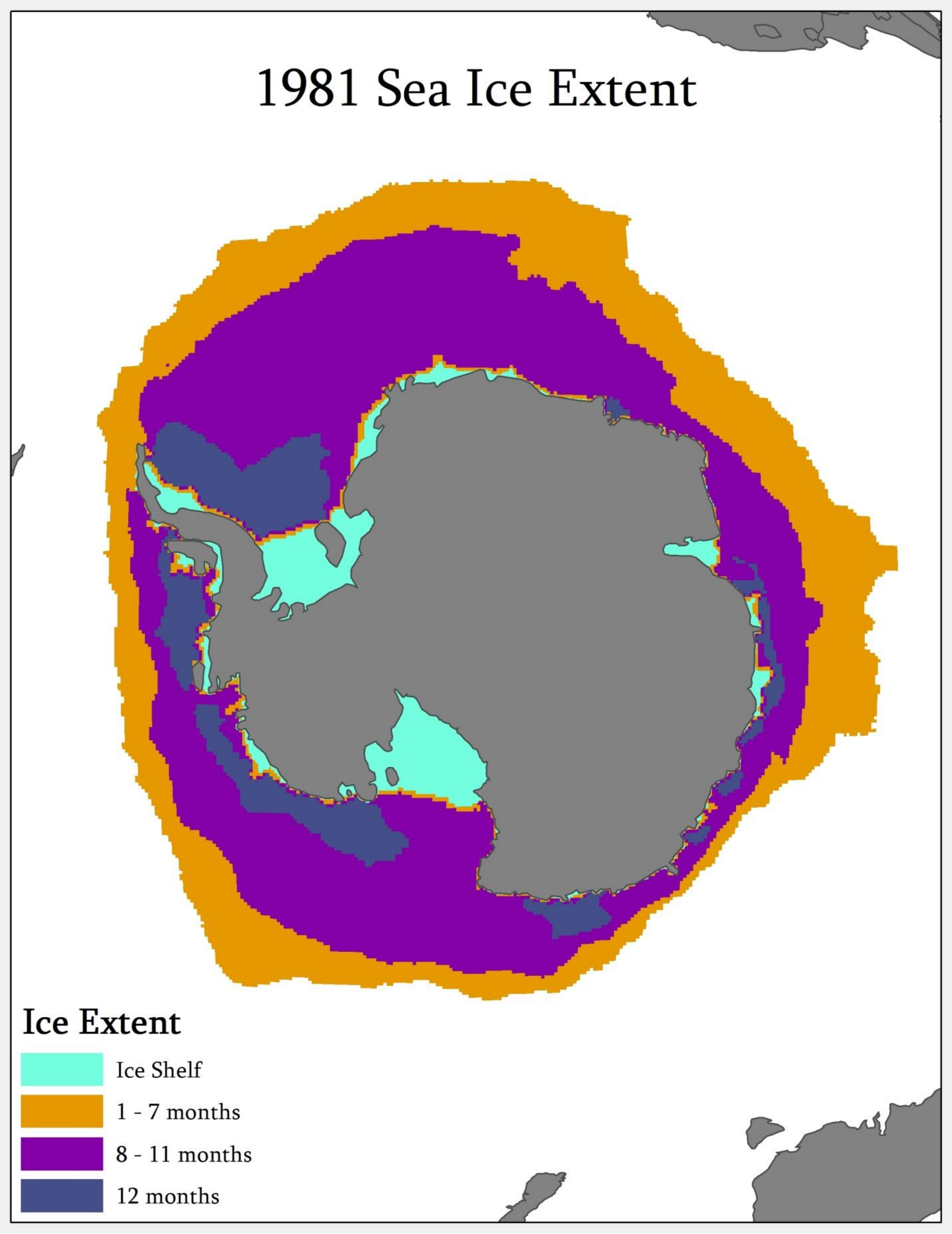
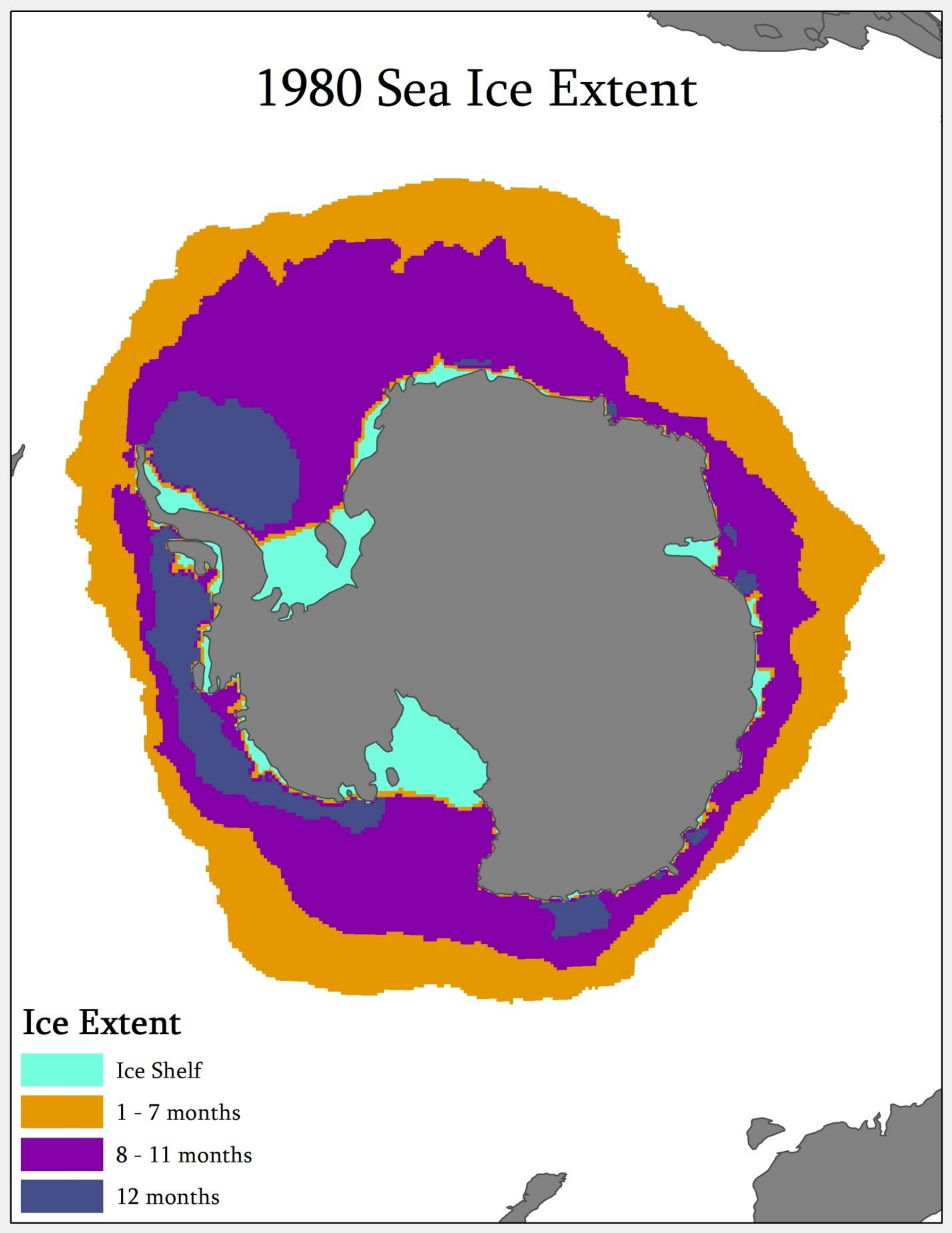


Figure D.31 1980 Antarctic sea ice extent [Source: created by author]



Arctic Sea Ice

Figure **D.32 Arctic sea ice modal map for 1980-2008 [Source: created by author]**

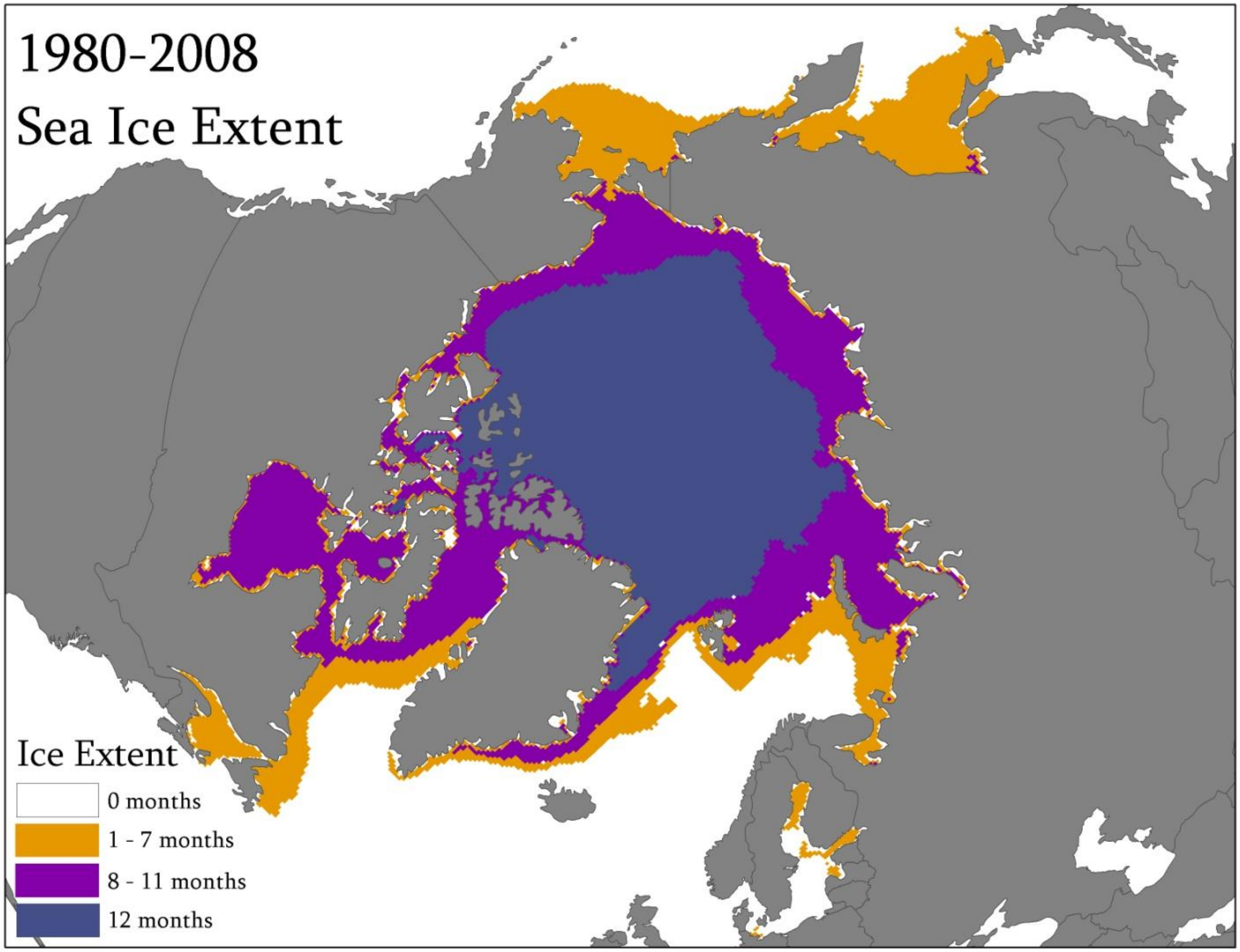


Figure **D.33 2008 Arctic sea ice extent [Source: created by author]**

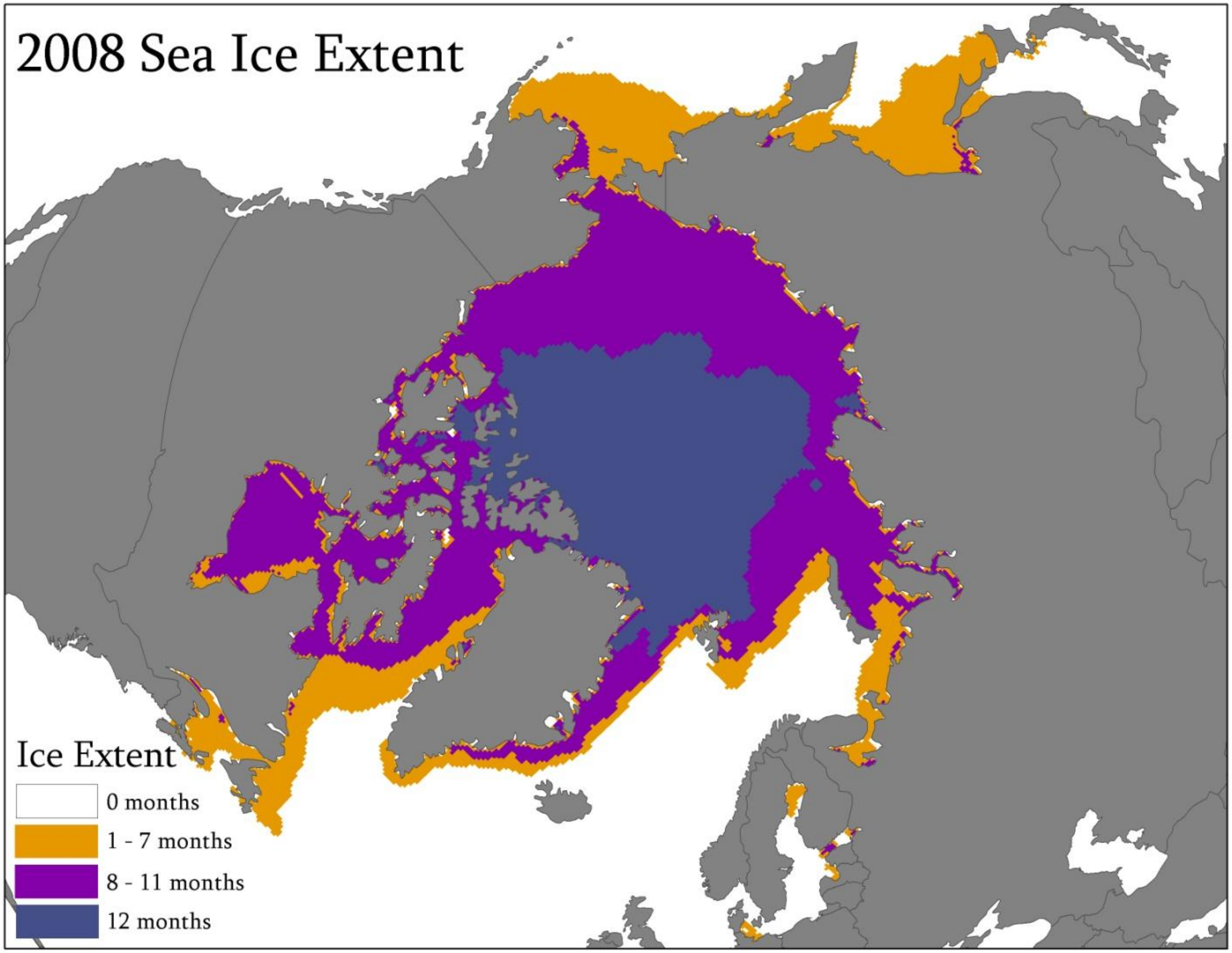


Figure **D.34 2007 Arctic sea ice extent [Source: created by author]**

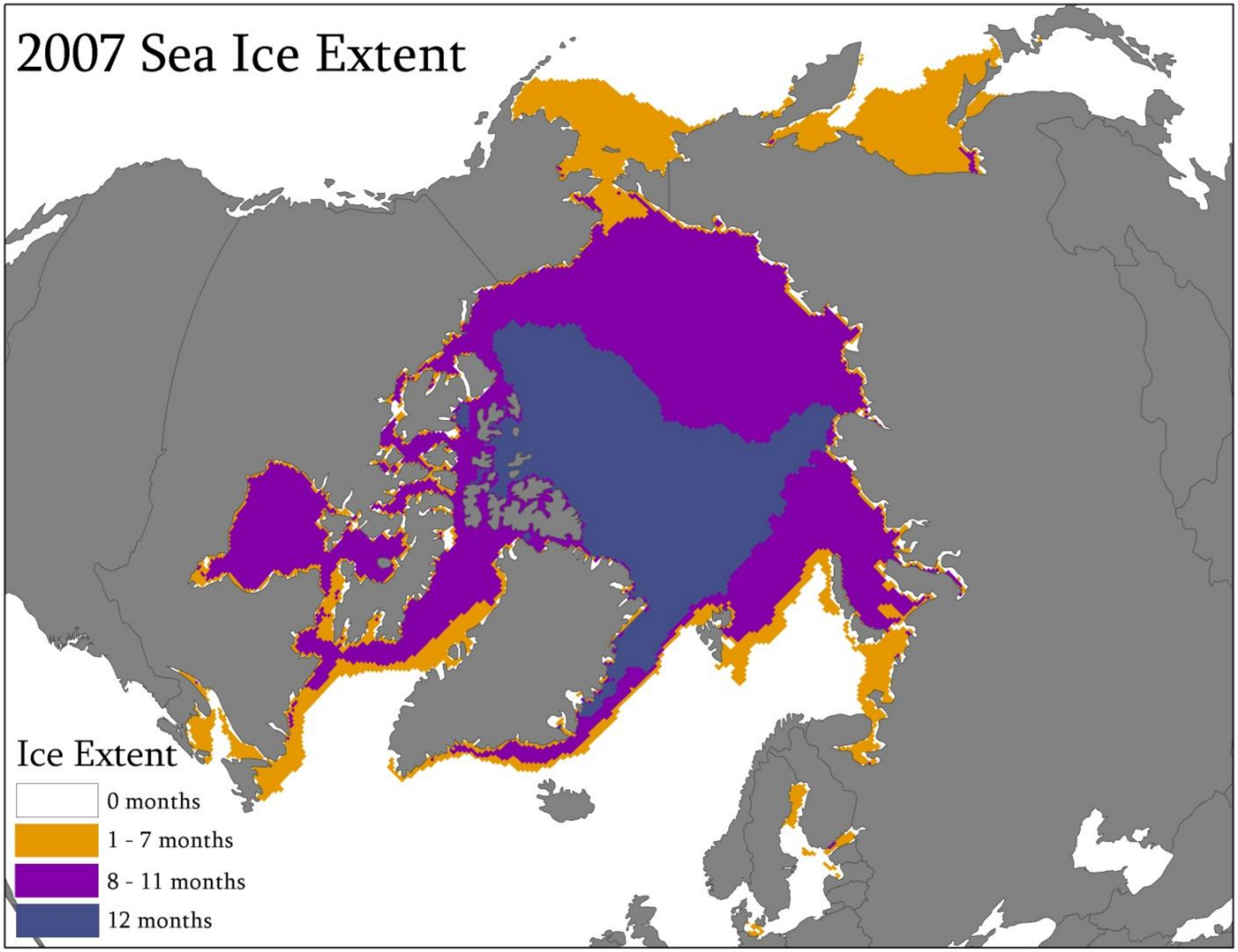


Figure **D.35 2006 Arctic sea ice extent [Source: created by author]**

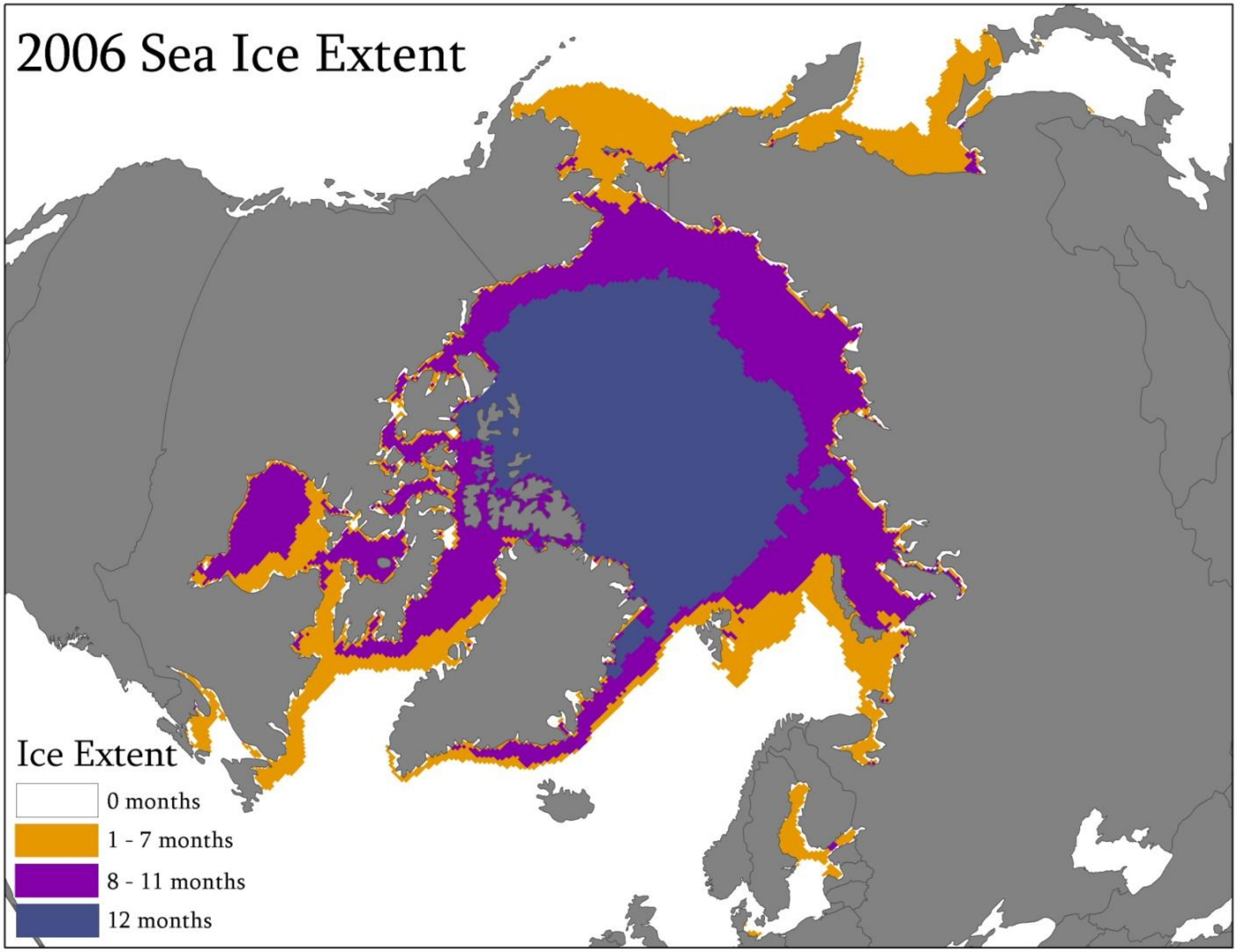


Figure **D.36 2005 Arctic sea ice extent [Source: created by author]**

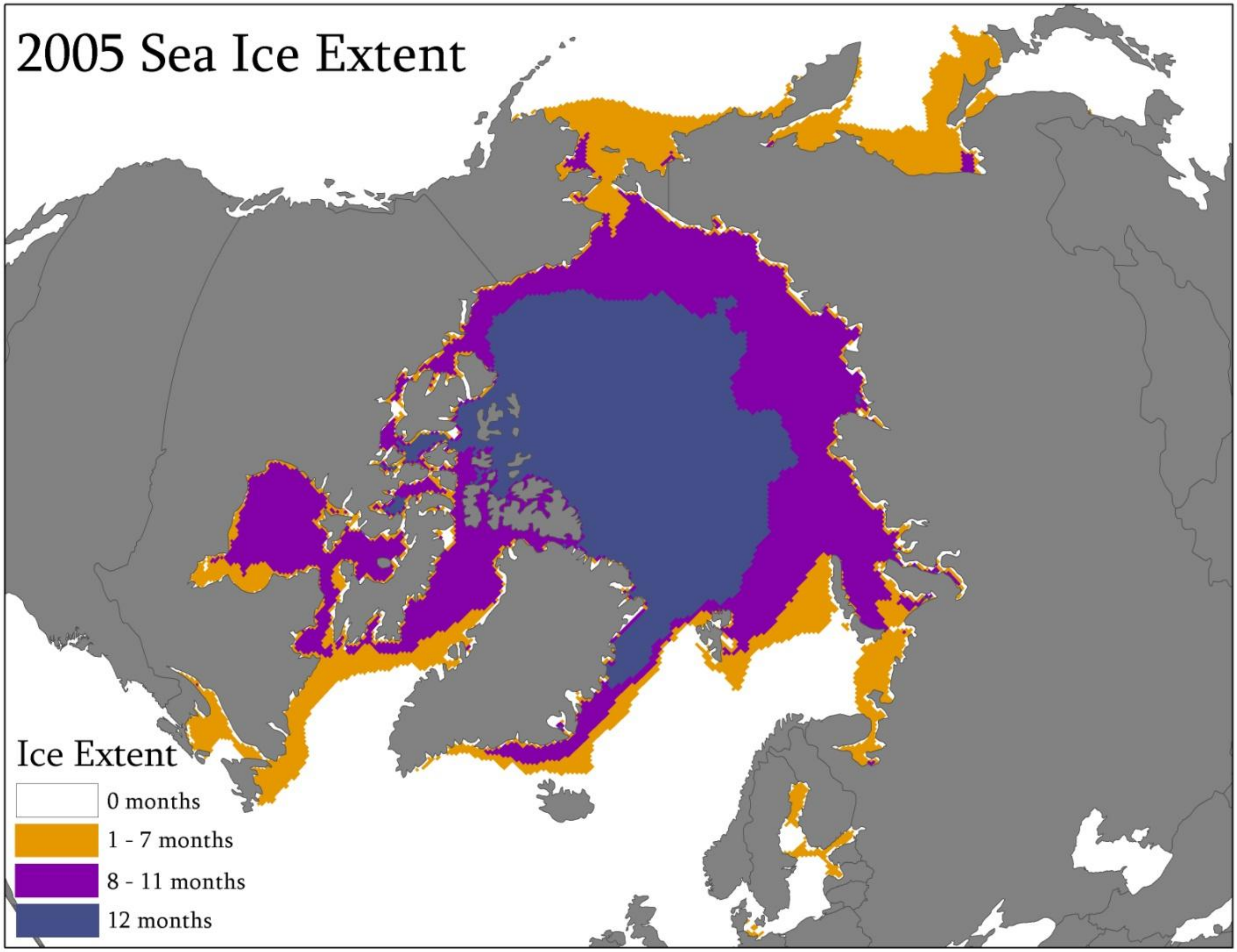


Figure **D.37 2004 Arctic sea ice extent [Source: created by author]**

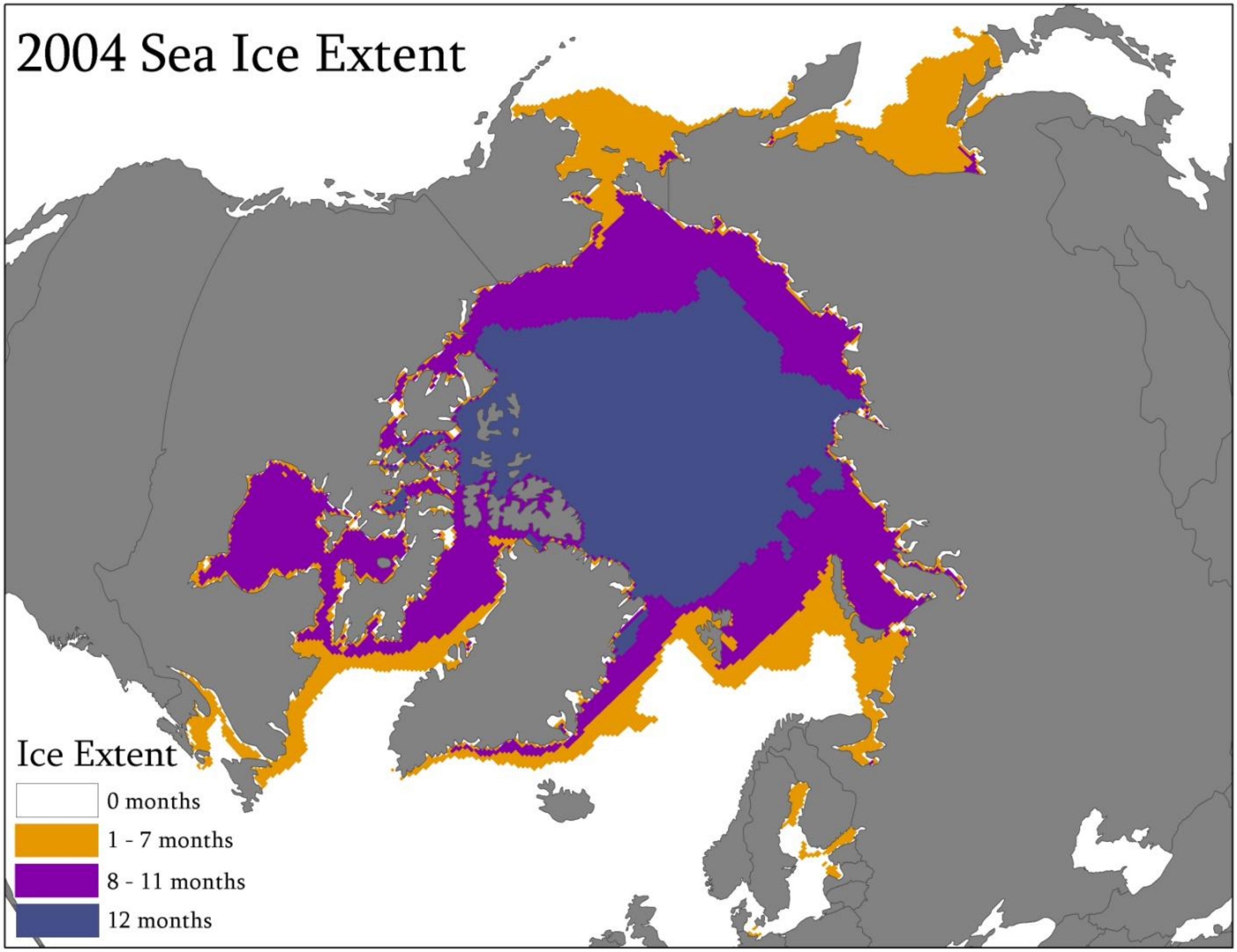


Figure **D.38 2003 Arctic sea ice extent [Source: created by author]**

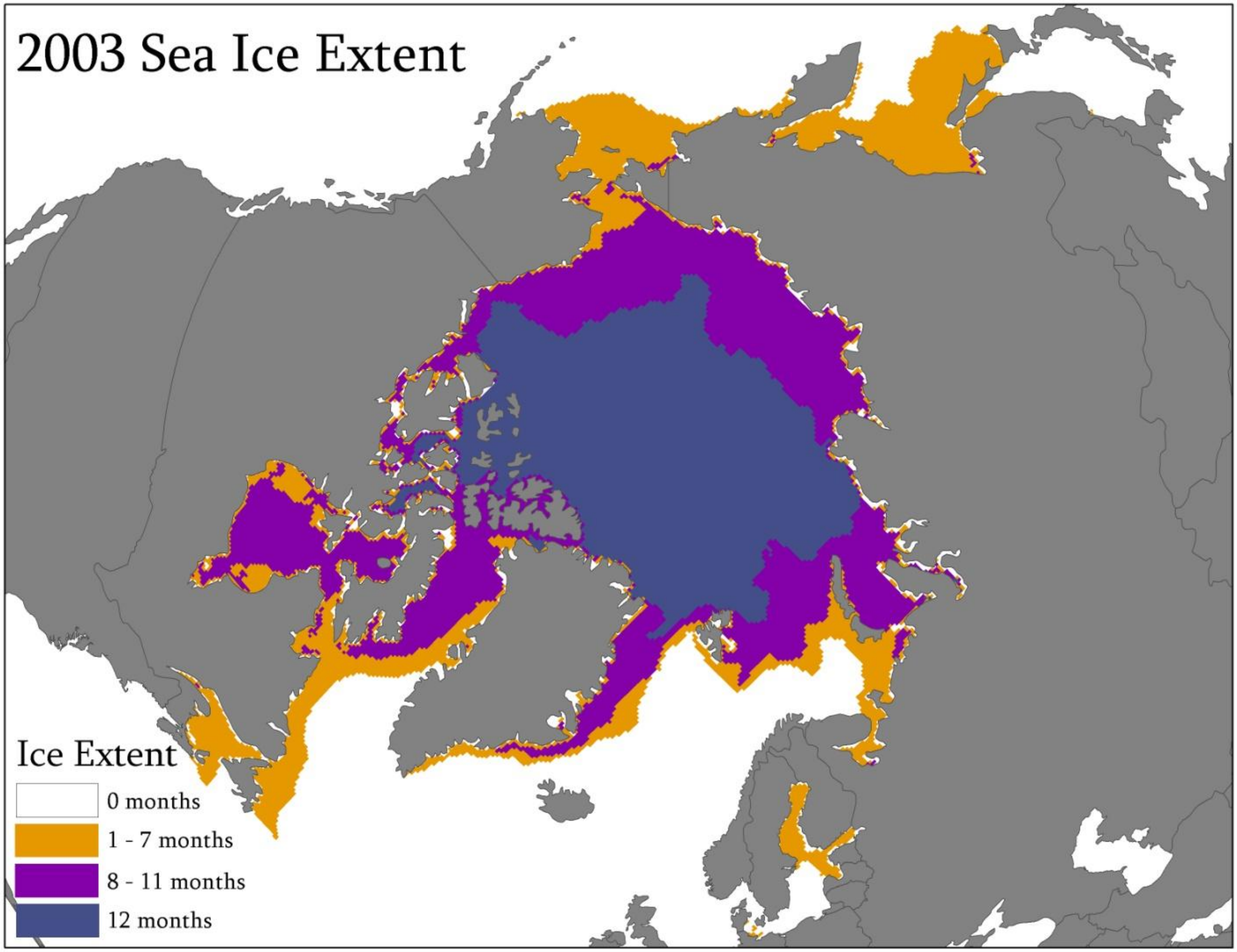


Figure **D.39 2002 Arctic sea ice extent [Source: created by author]**

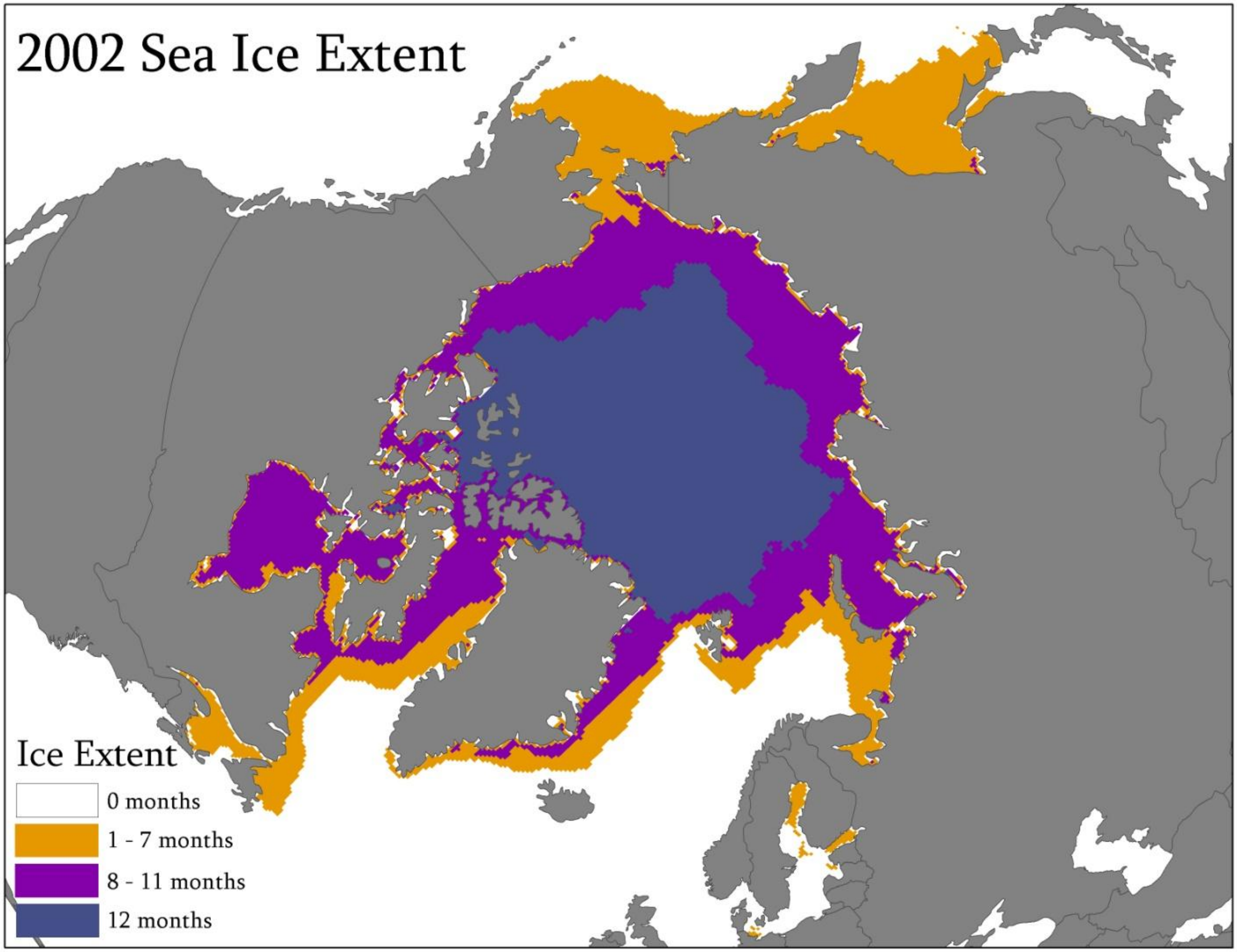


Figure **D.40 2001 Arctic sea ice extent [Source: created by author]**

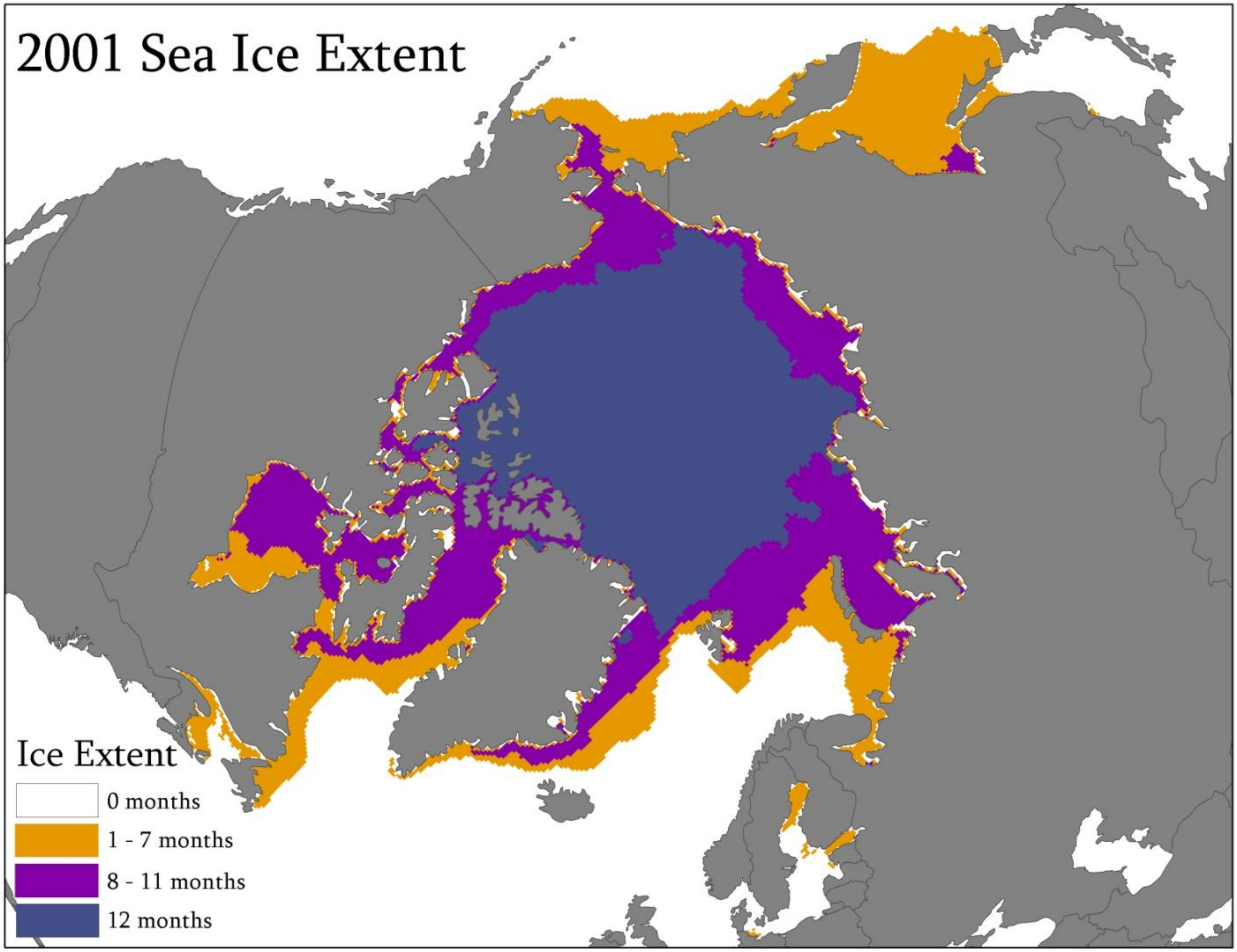


Figure **D.41 2000 Arctic sea ice extent [Source: created by author]**

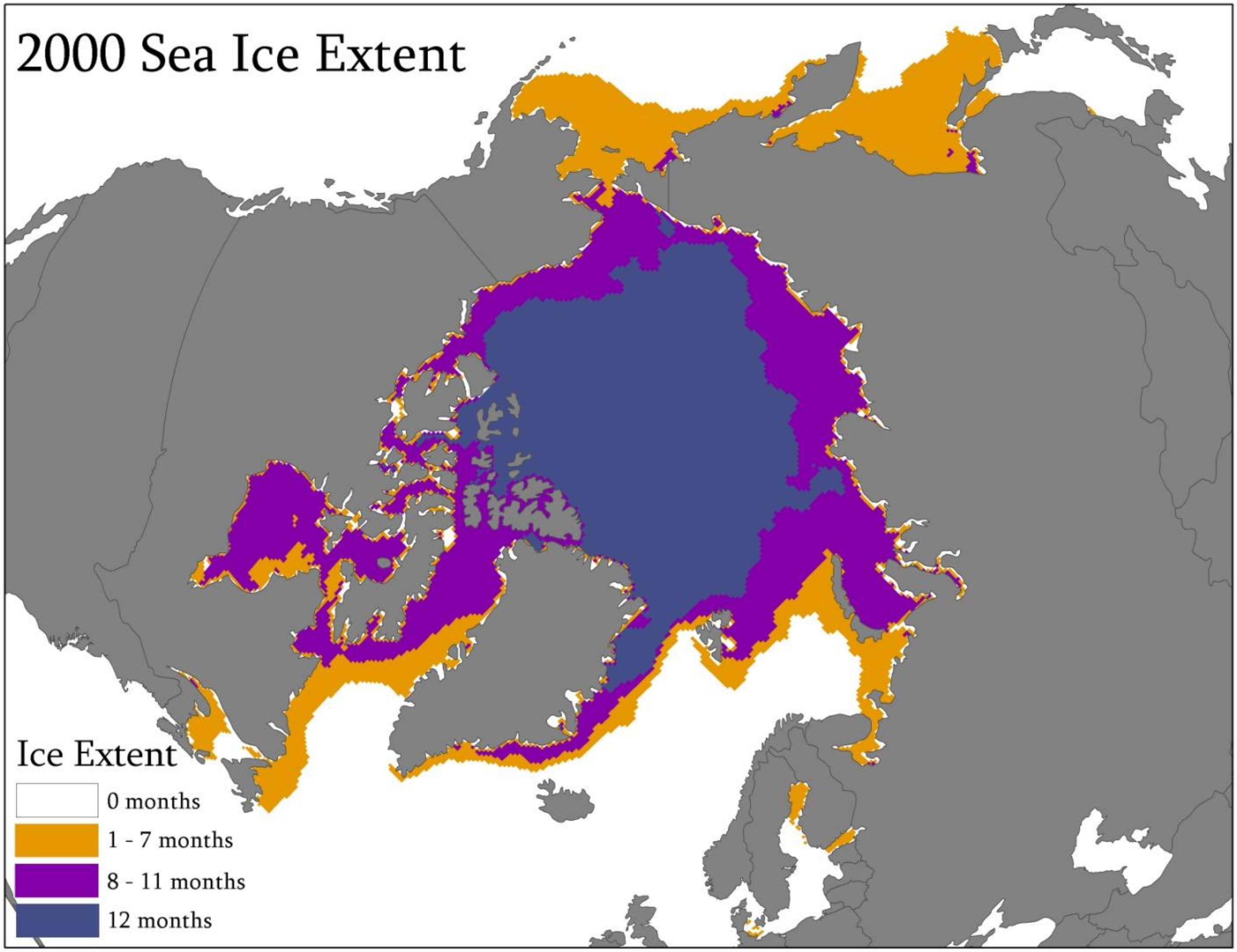


Figure **D.42 1999 Arctic sea ice extent [Source: created by author]**

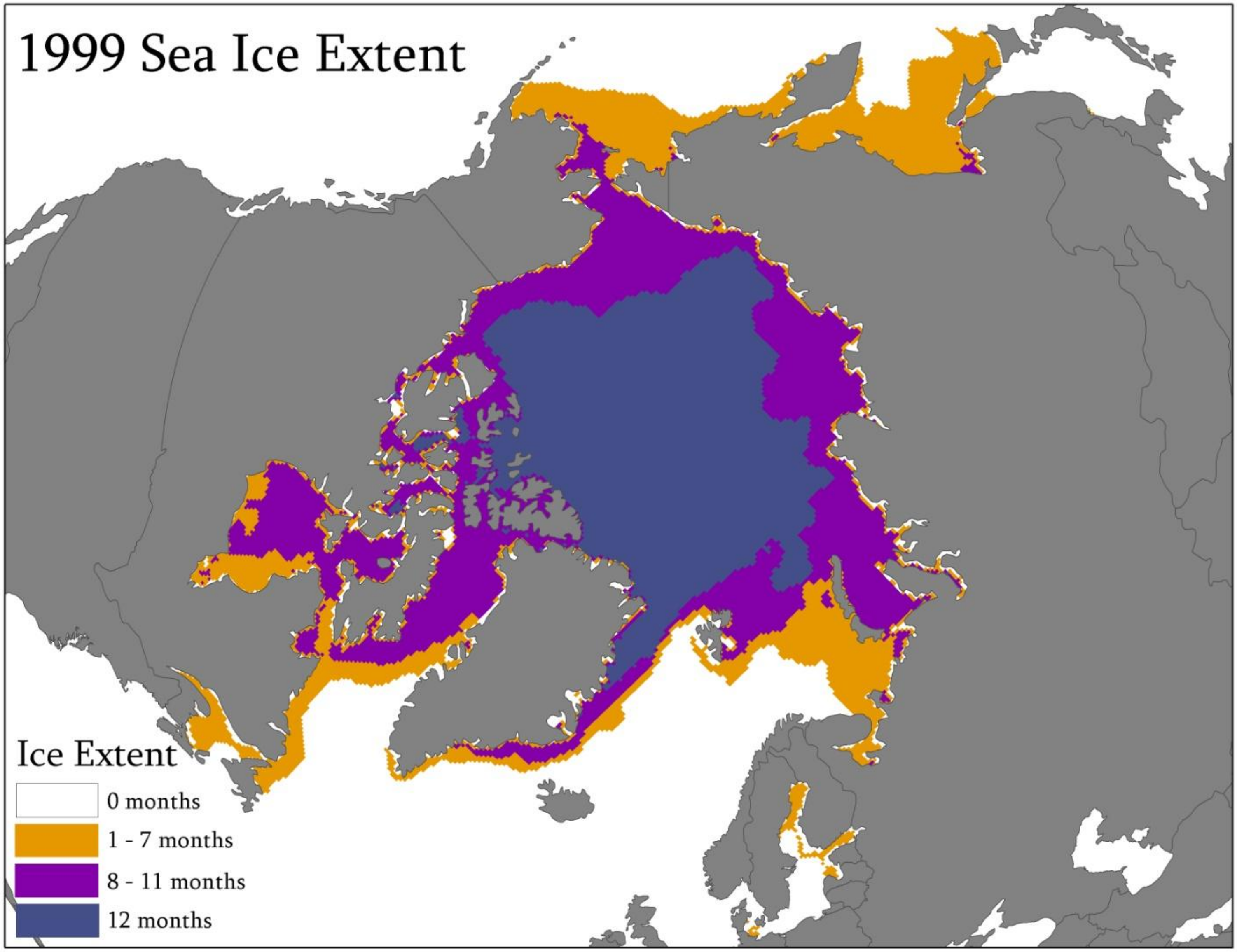


Figure **D.43 1998 Arctic sea ice extent [Source: created by author]**

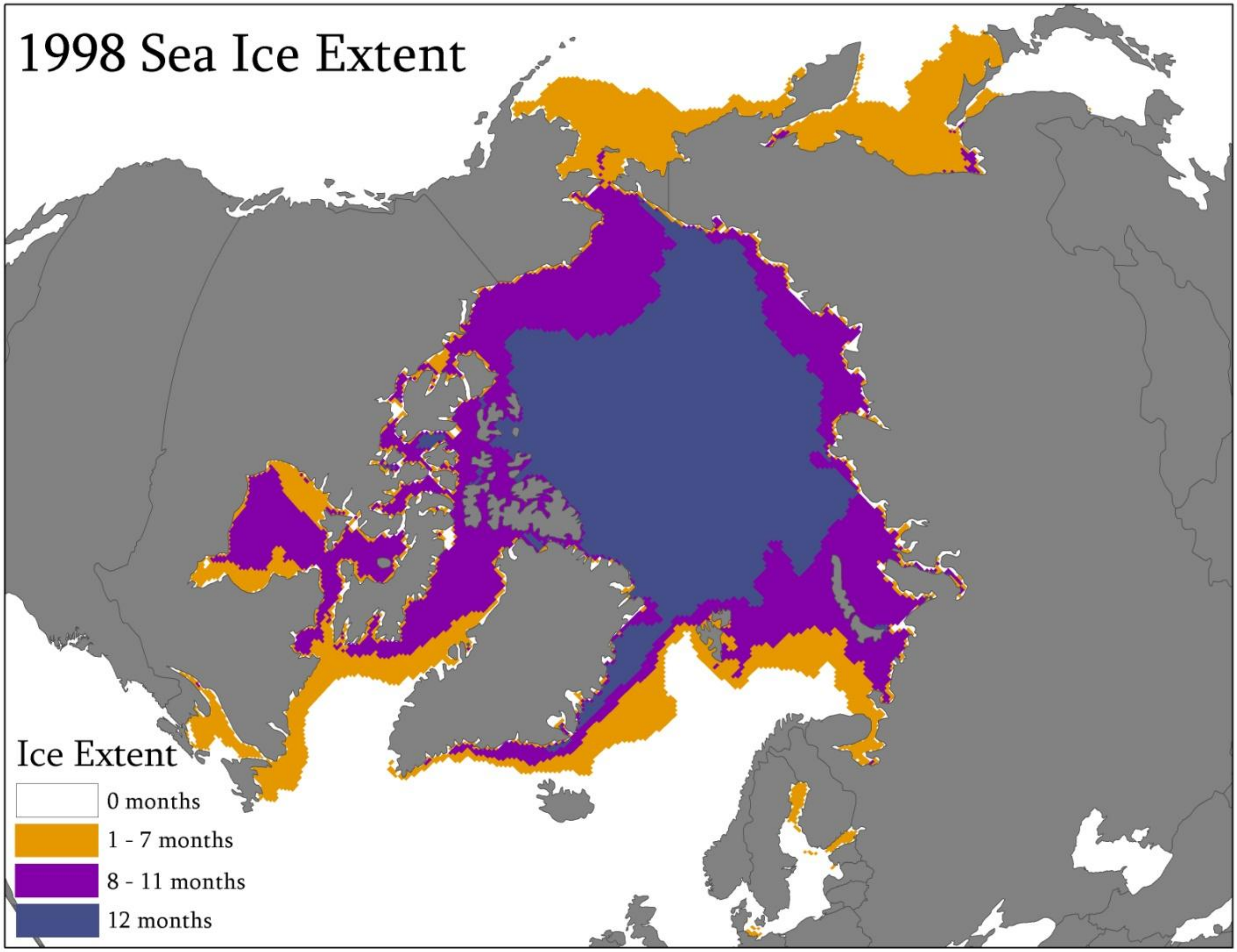


Figure **D.44 1997 Arctic sea ice extent [Source: created by author]**

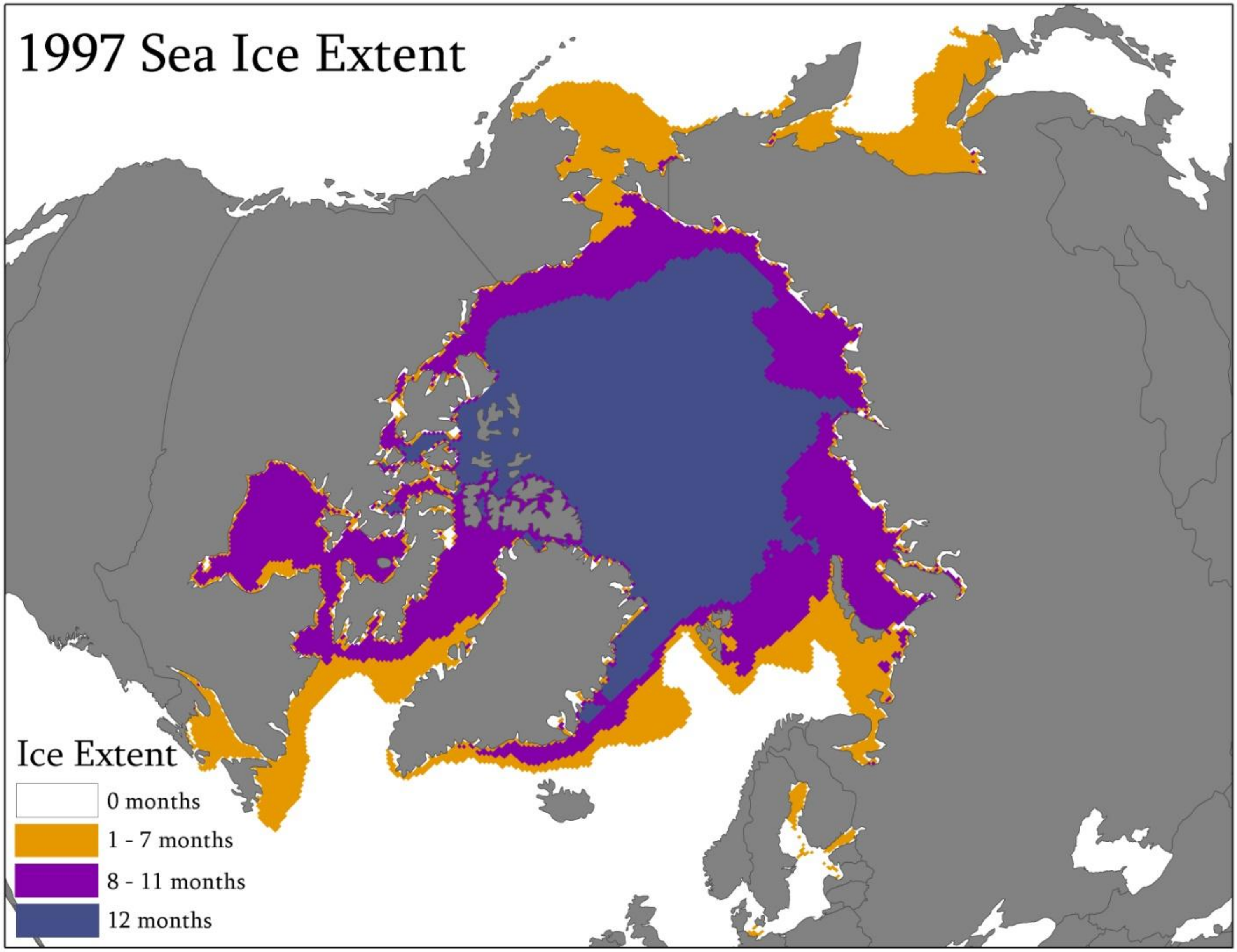


Figure **D.45 1996 Arctic sea ice extent [Source: created by author]**

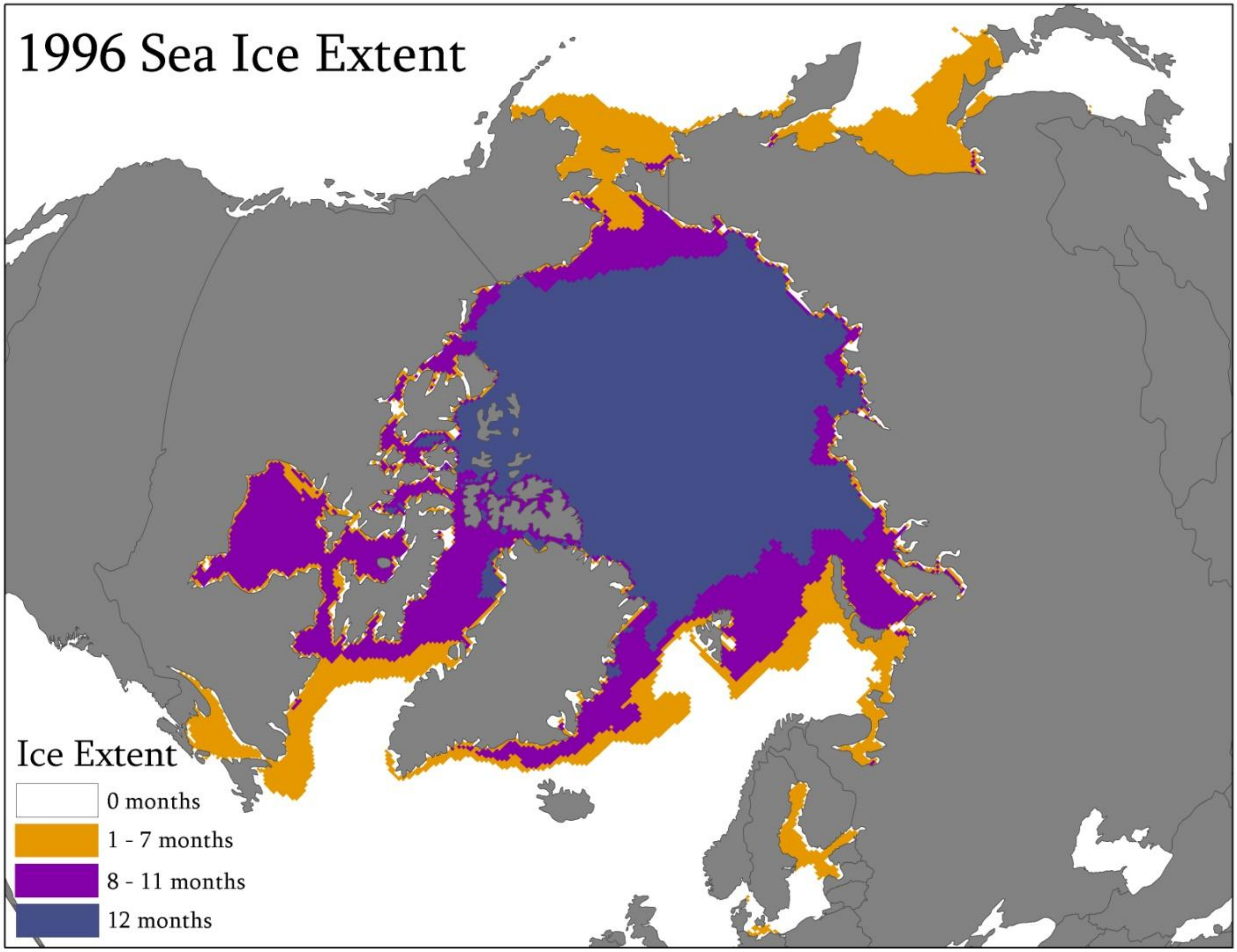


Figure D.46 1995 Arctic sea ice extent [Source: created by author]

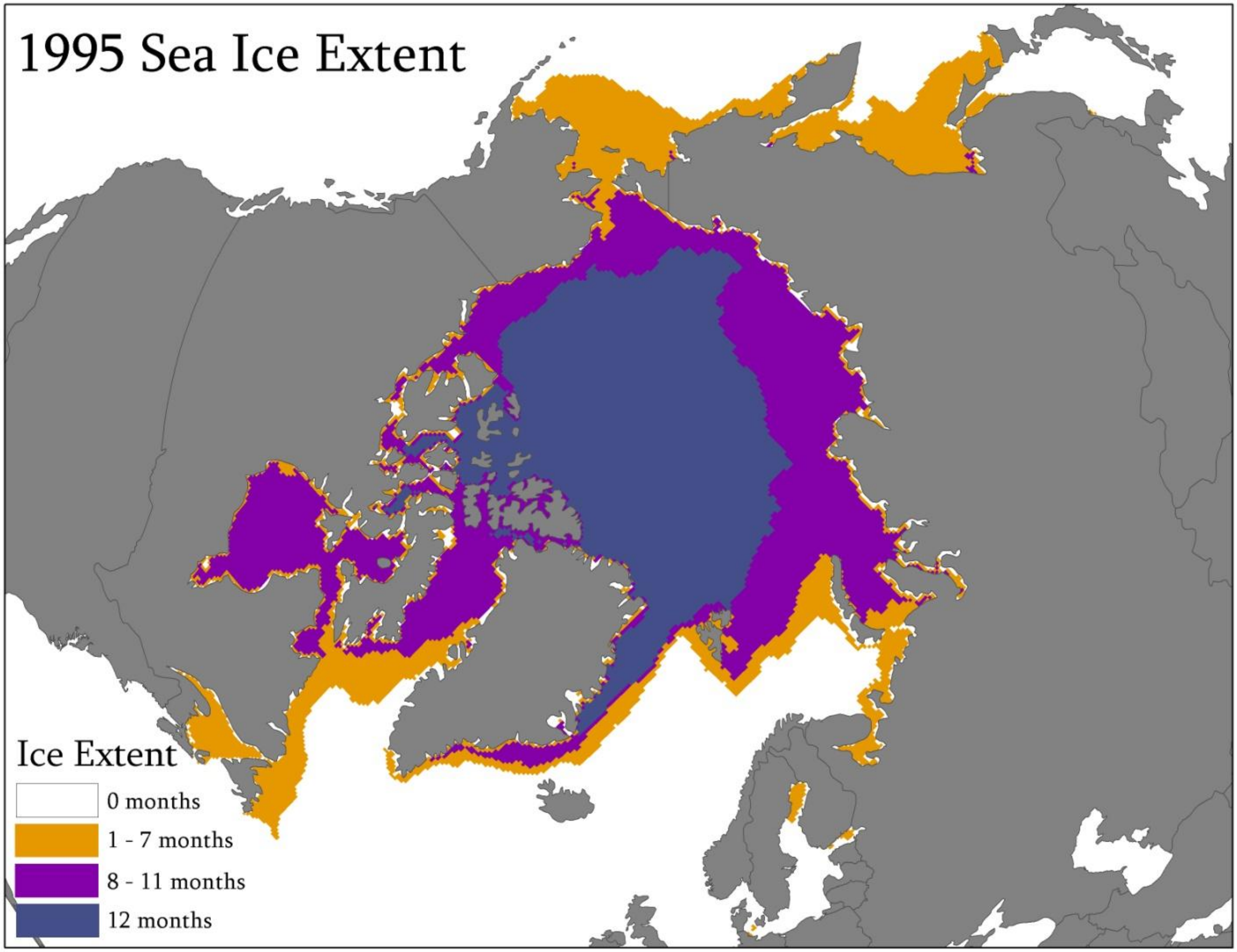


Figure **D.47 1994 Arctic sea ice extent [Source: created by author]**

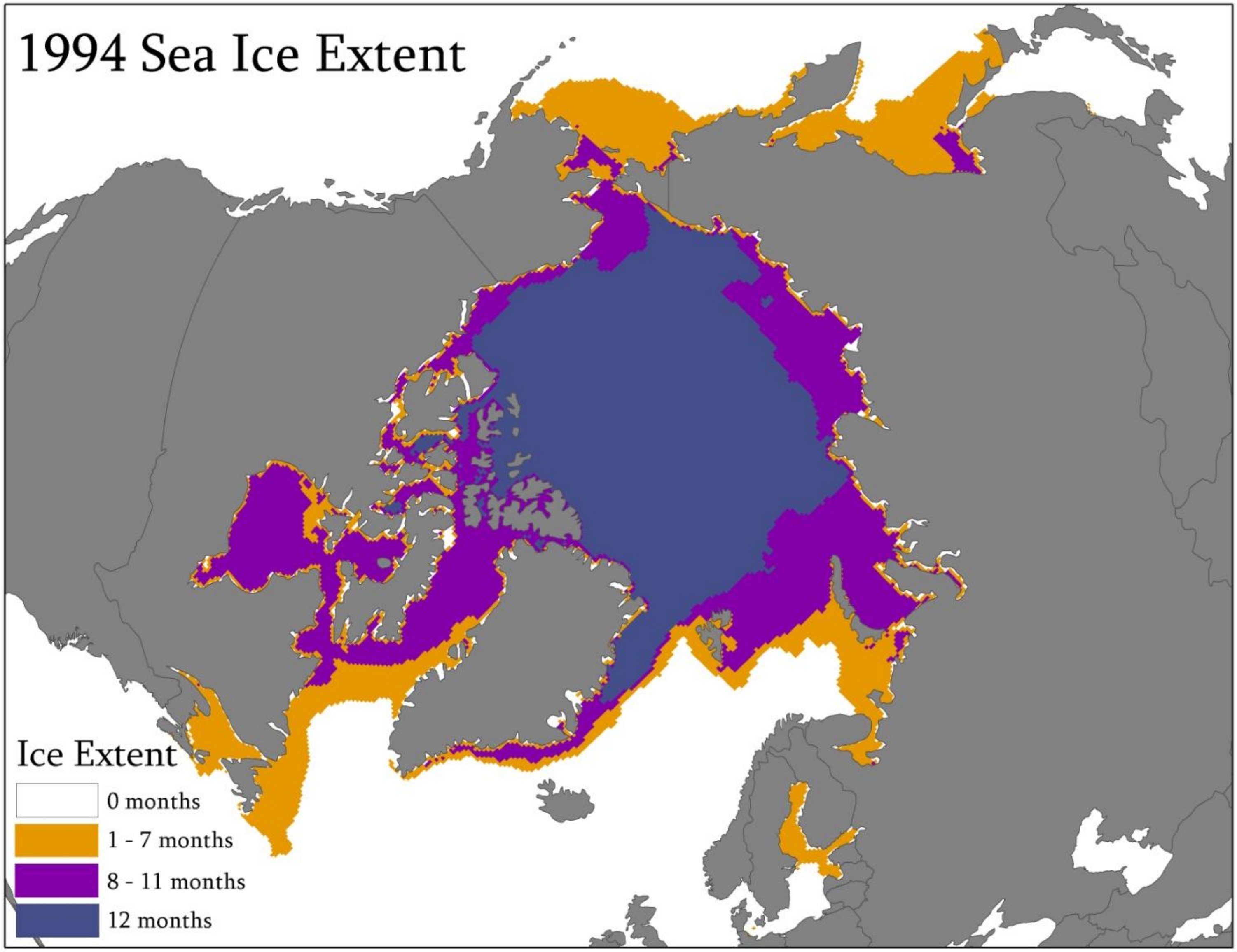


Figure **D.48 1993 Arctic sea ice extent [Source: created by author]**

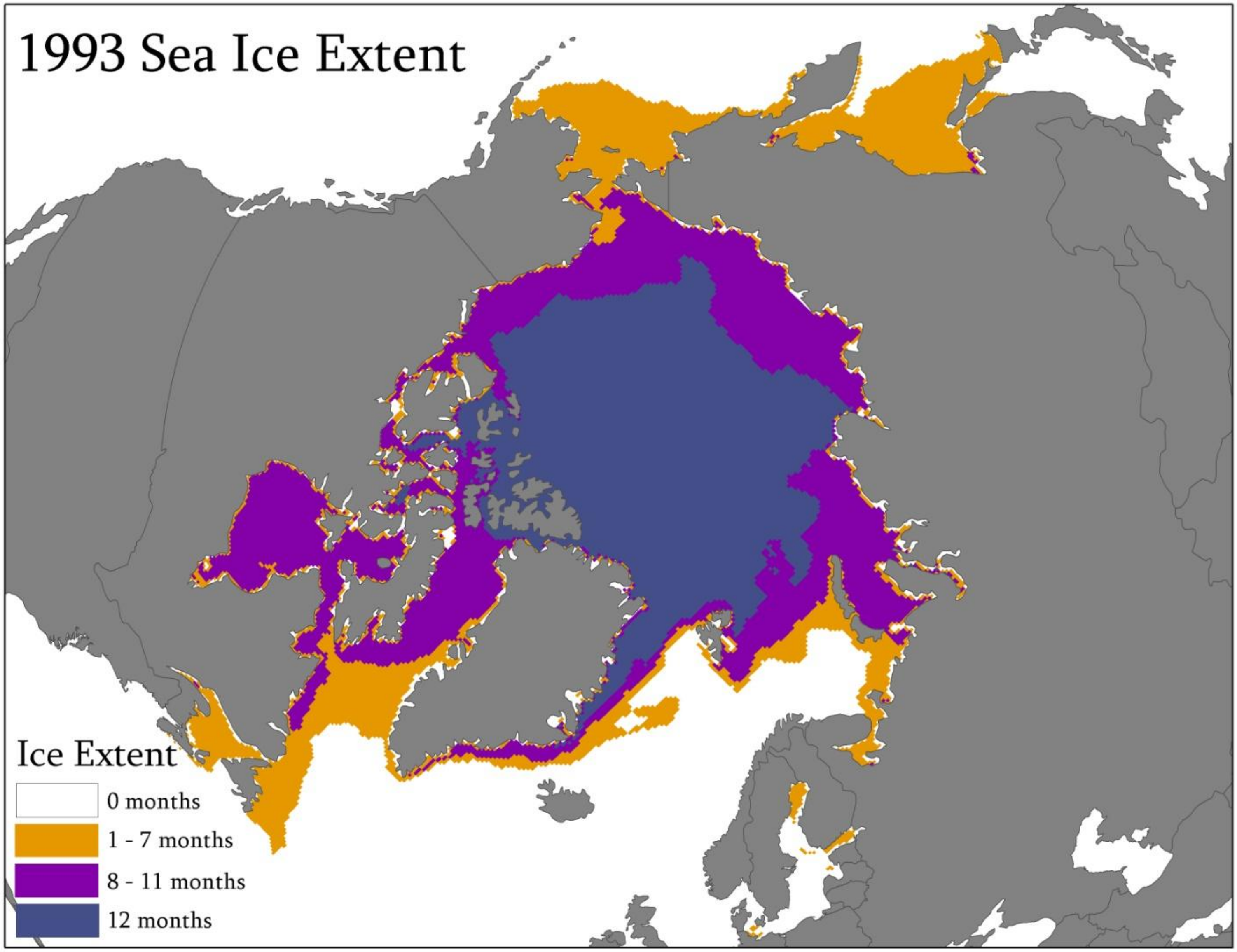


Figure **D.49 1992 Arctic sea ice extent [Source: created by author]**

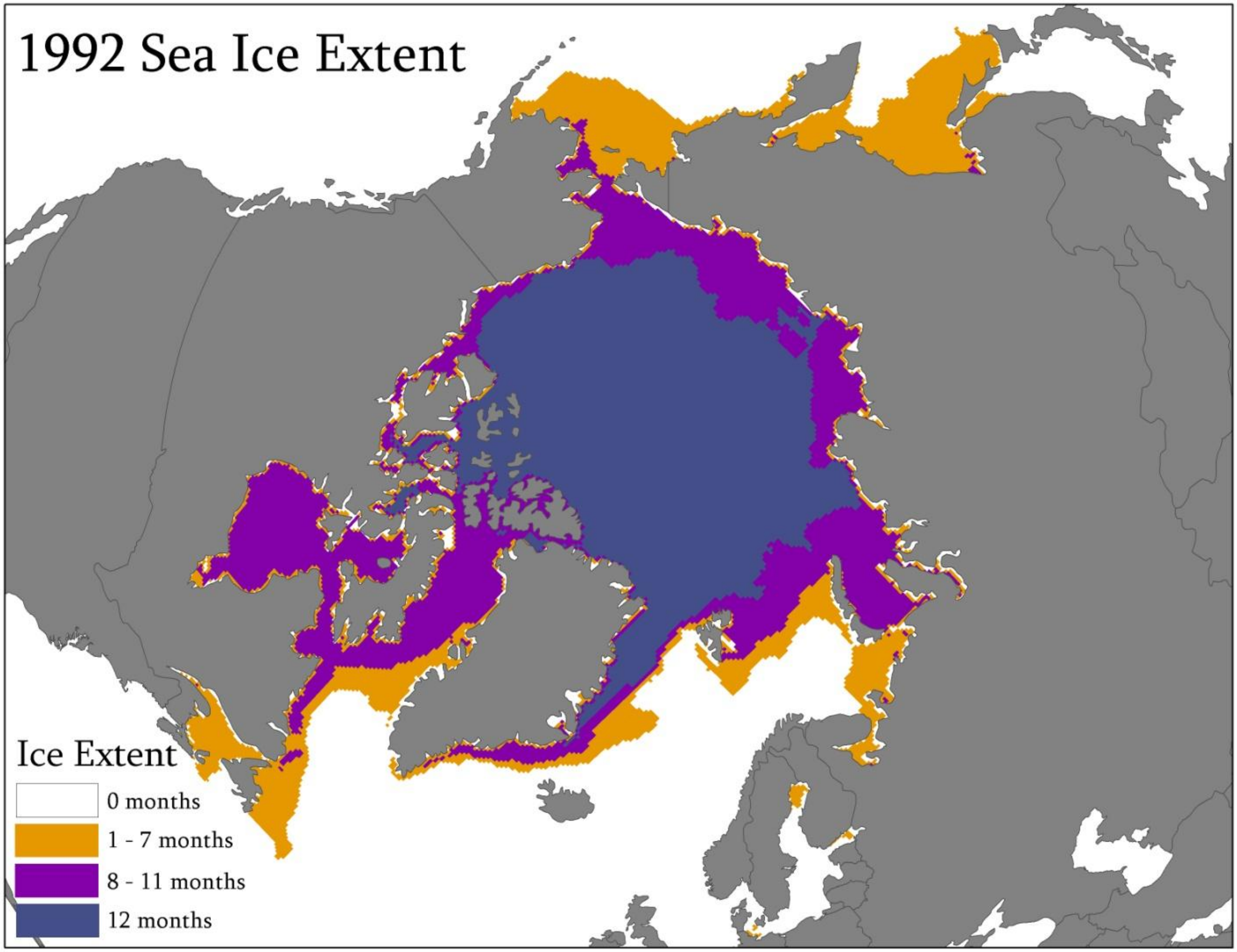


Figure **D.50 1991 Arctic sea ice extent [Source: created by author]**

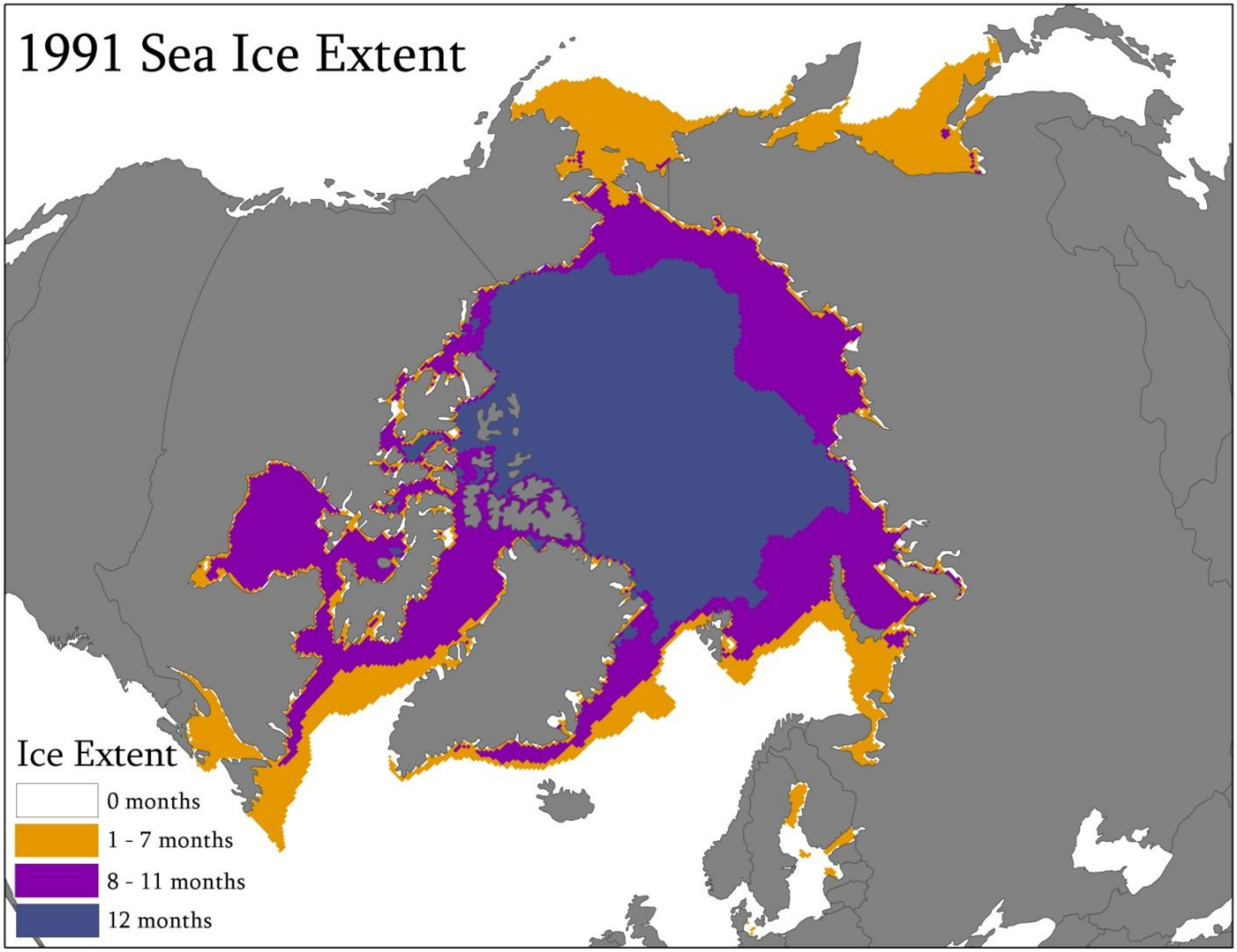


Figure **D.51 1990 Arctic sea ice extent [Source: created by author]**

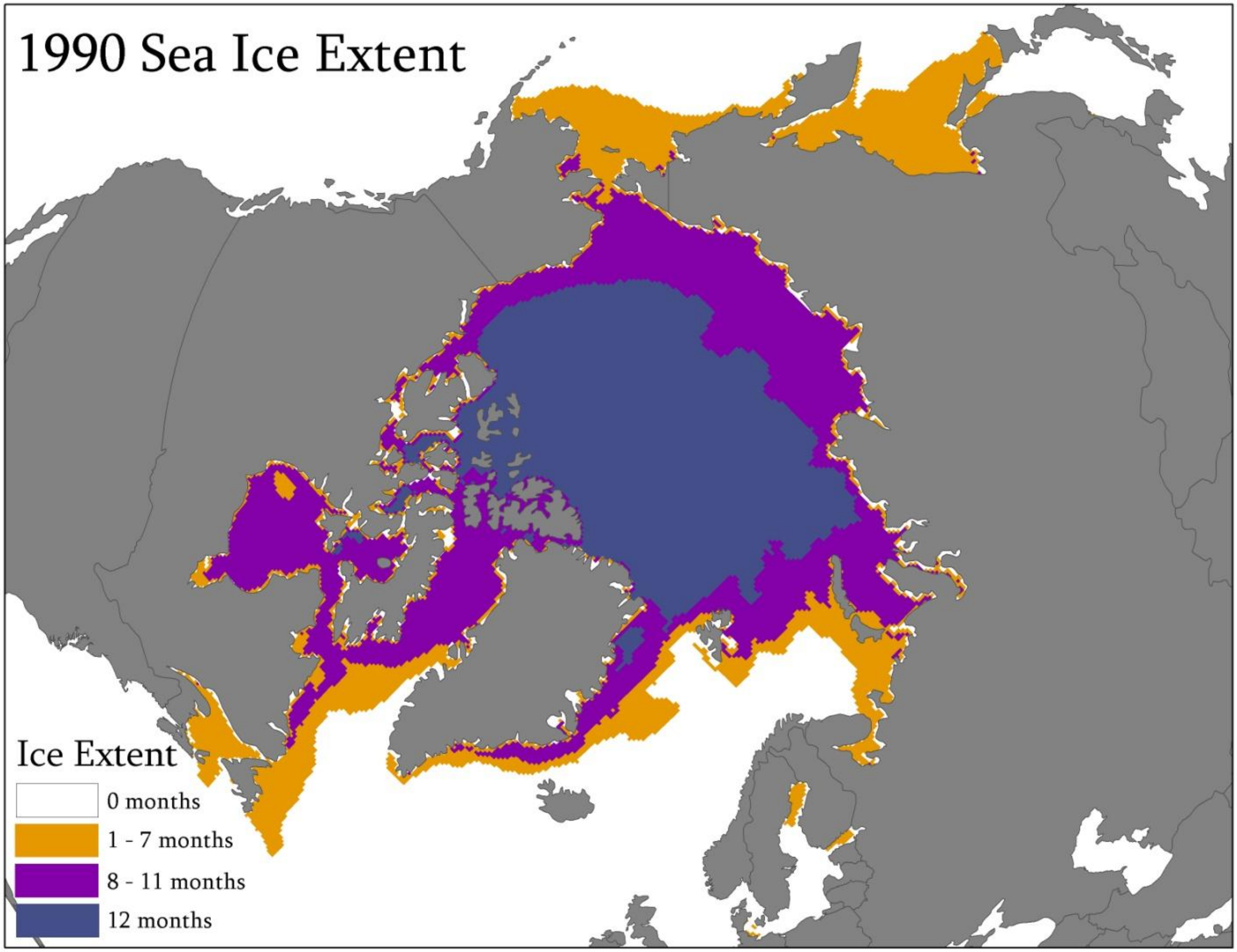


Figure **D.52 1989 Arctic sea ice extent [Source: created by author]**

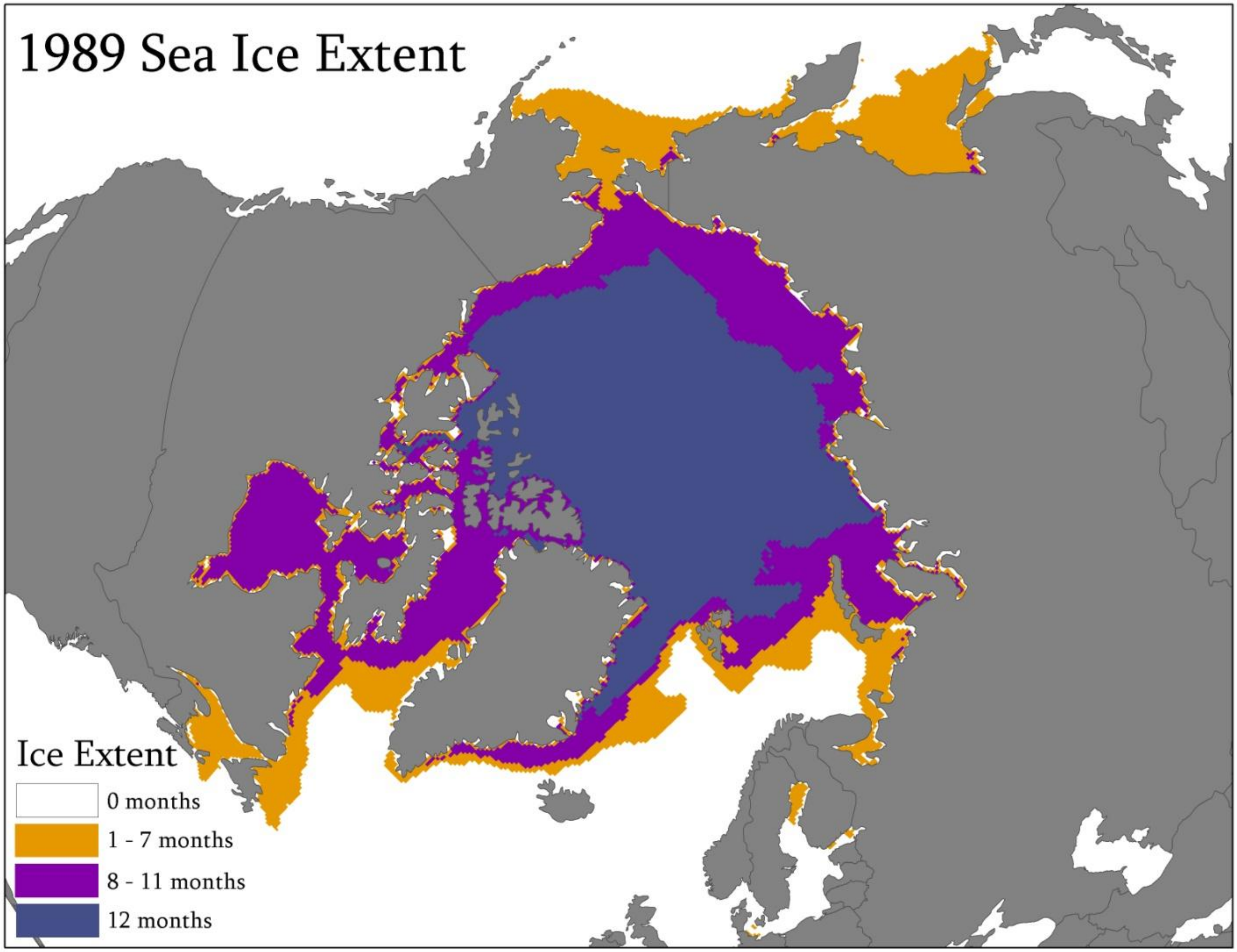


Figure D.53 1988 Arctic sea ice extent [Source: created by author]

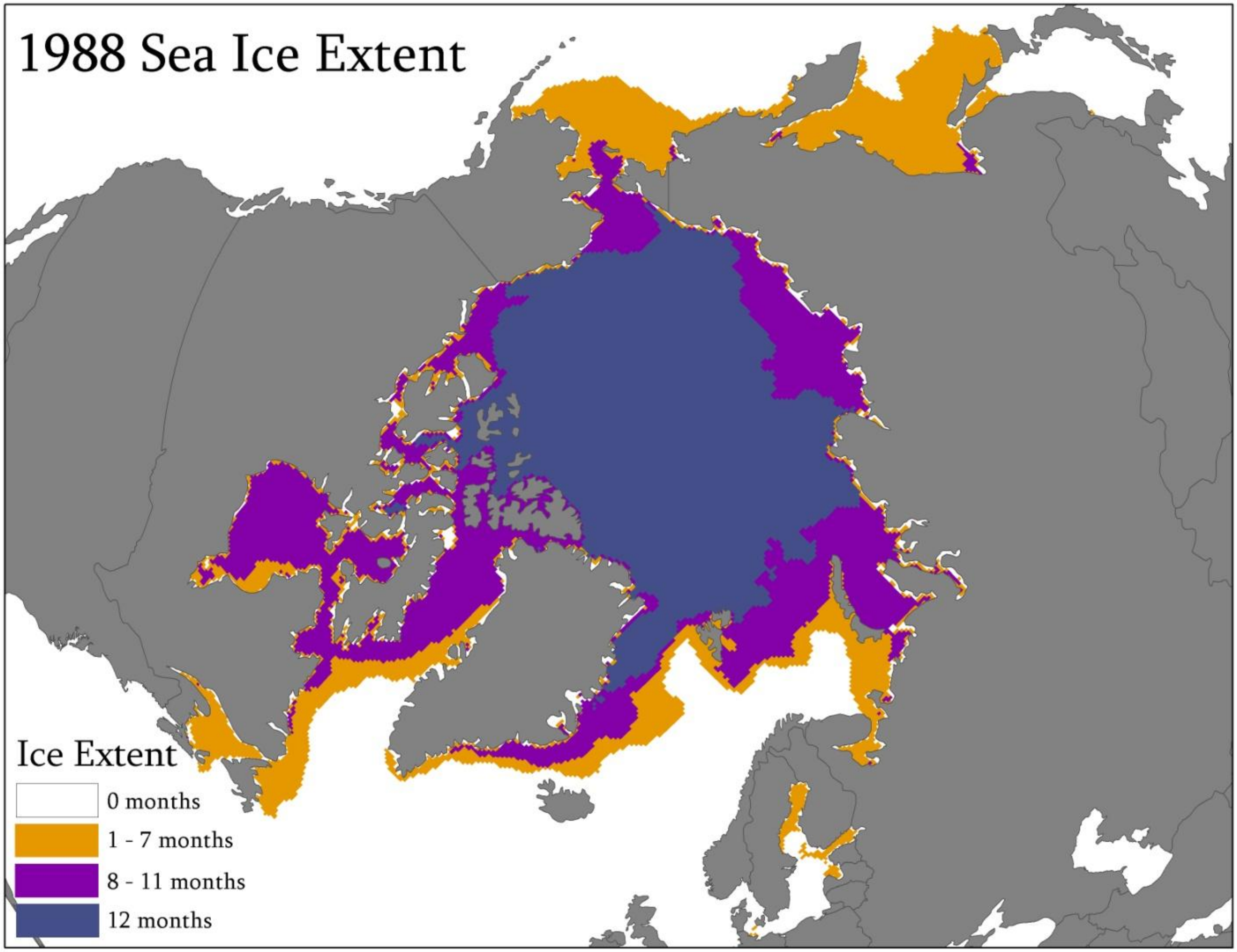


Figure **D.54 1987 Arctic sea ice extent [Source: created by author]**

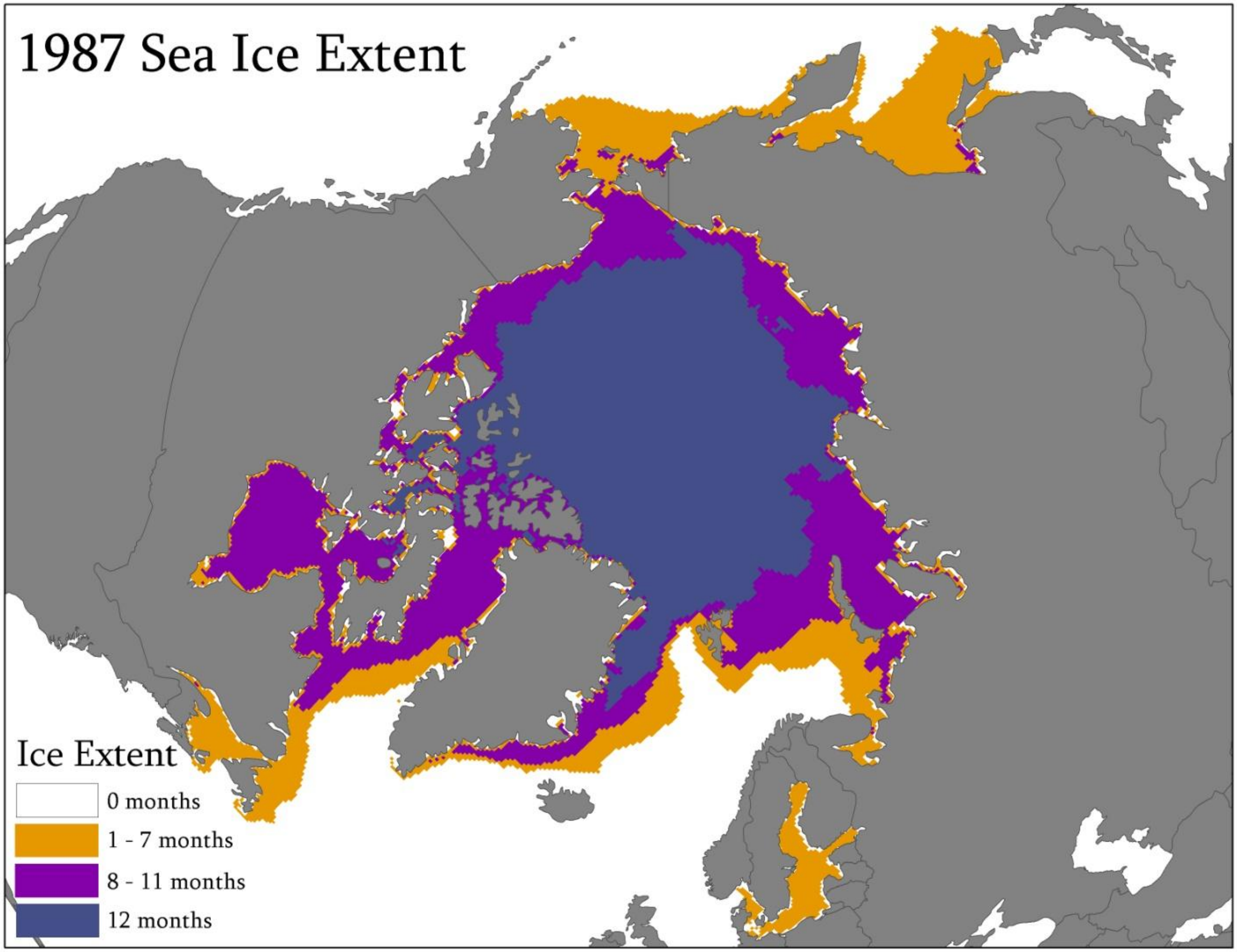


Figure D.55 1986 Arctic sea ice extent [Source: created by author]

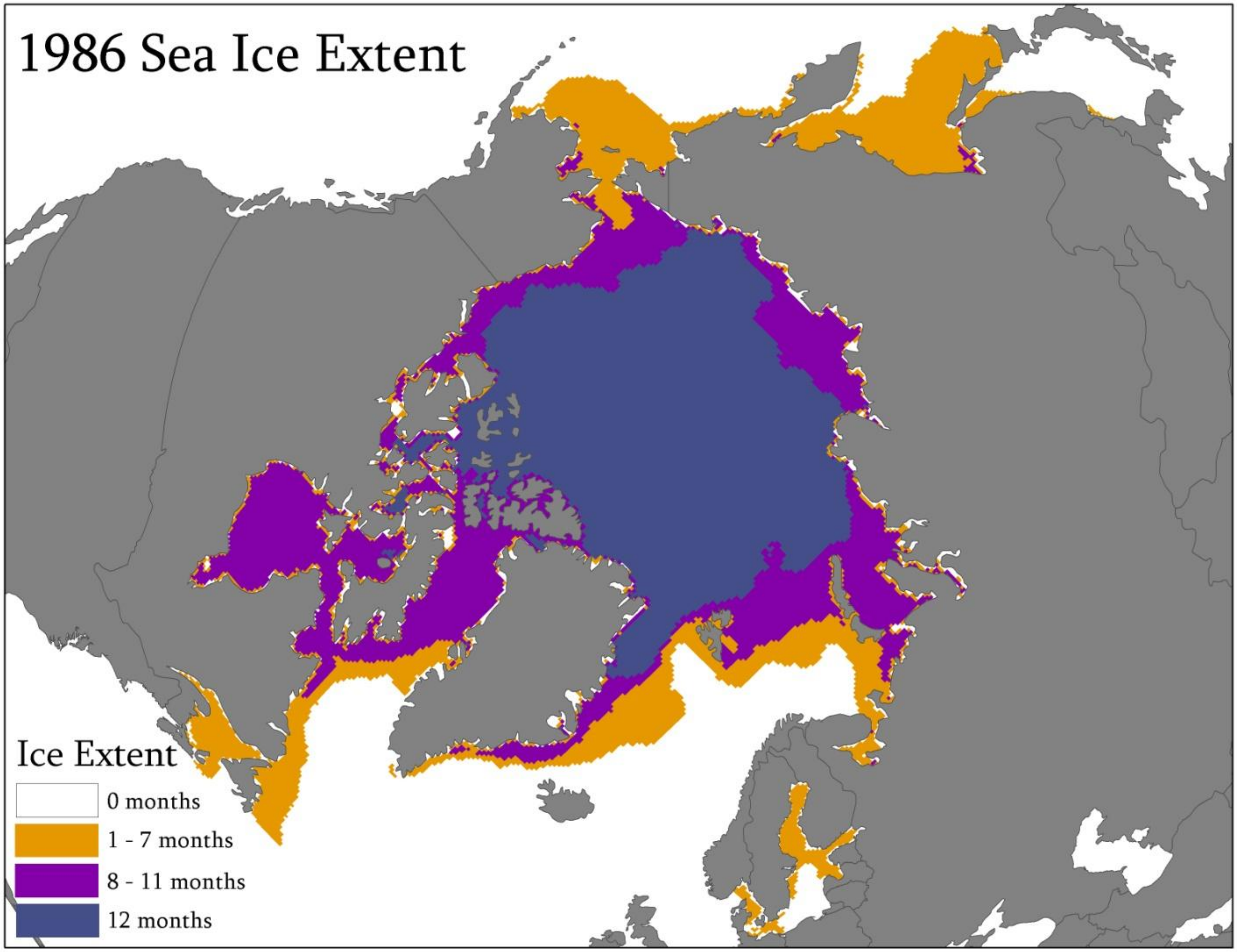


Figure **D.56 1985 Arctic sea ice extent [Source: created by author]**

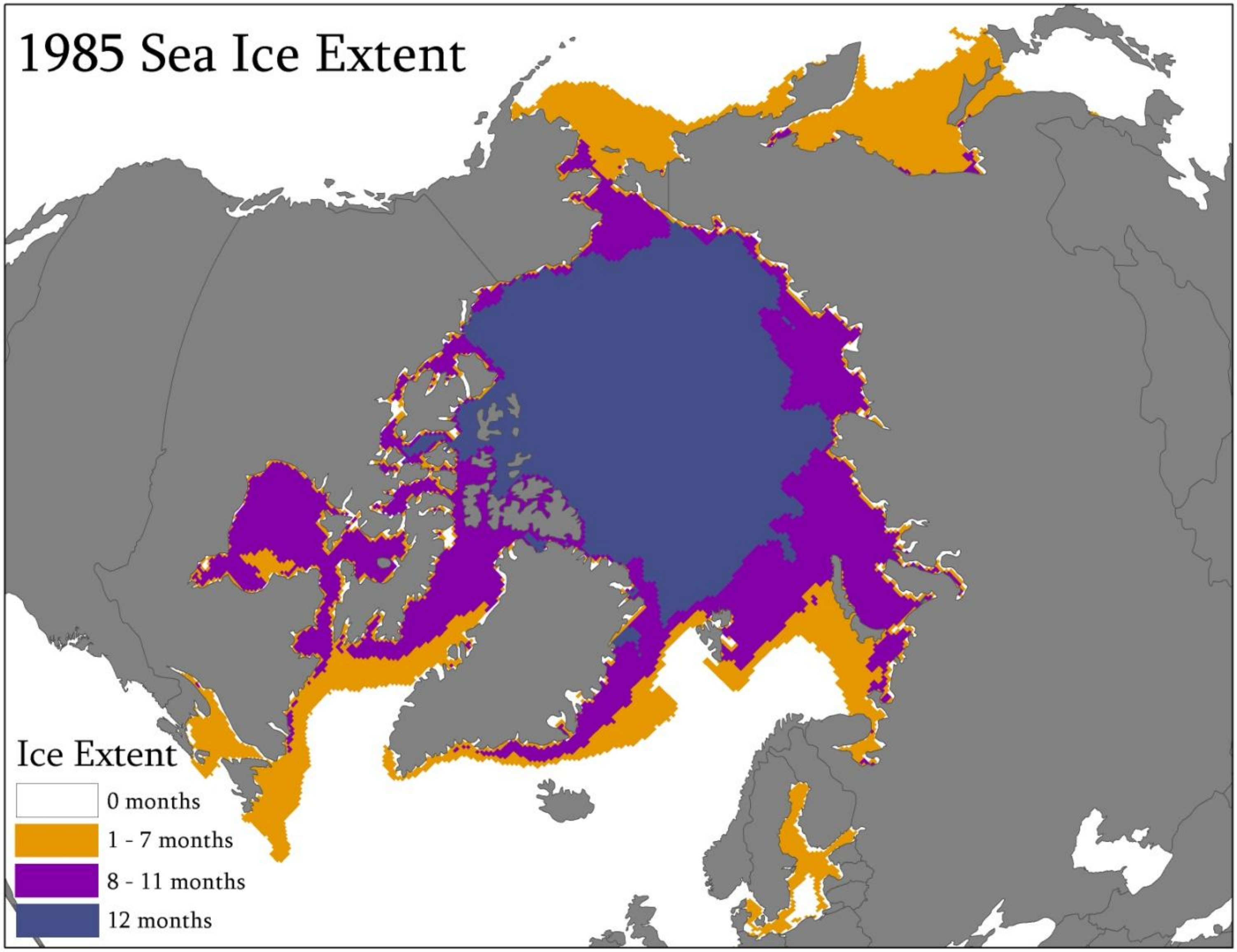


Figure **D.57 1984 Arctic sea ice extent [Source: created by author]**

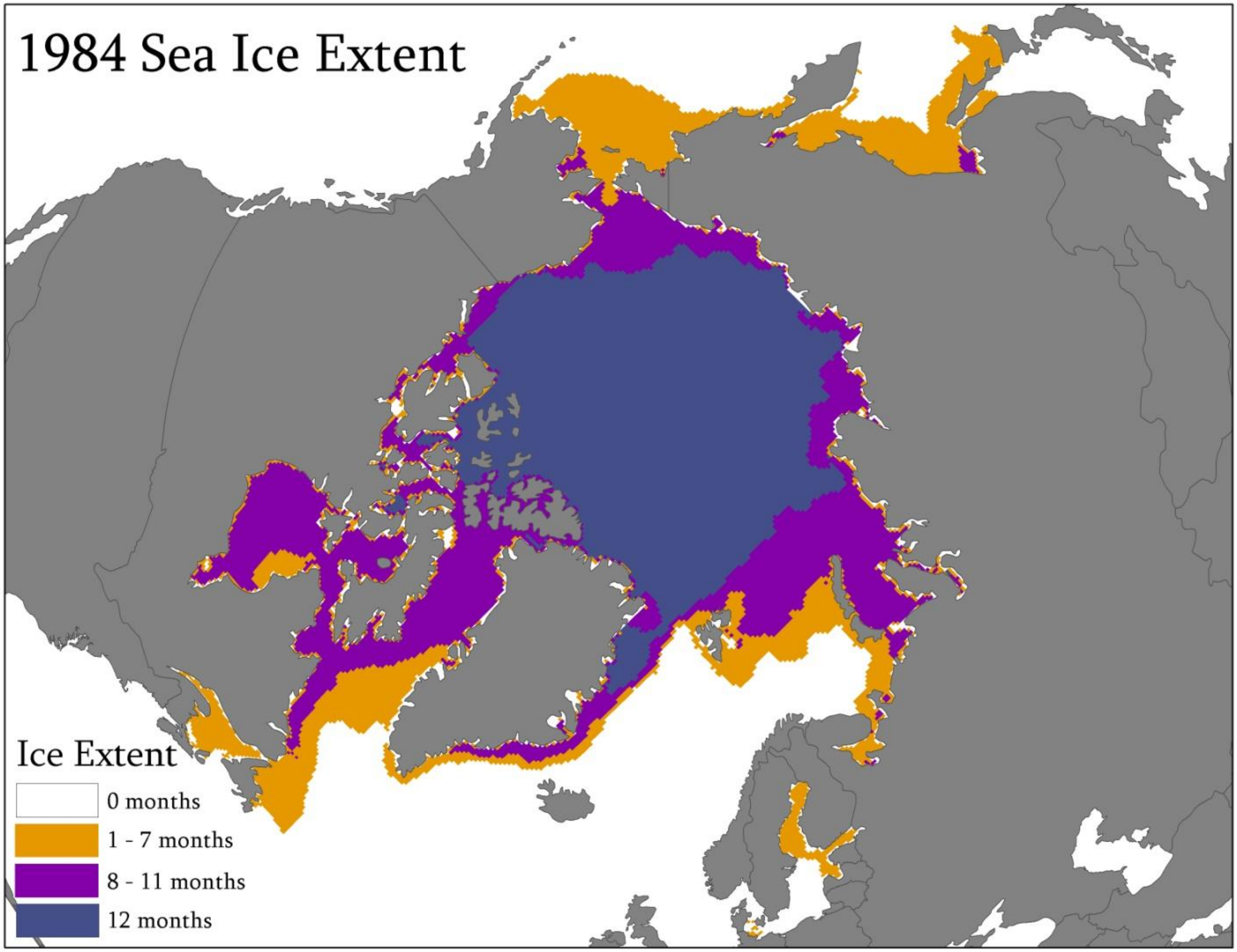


Figure **D.58 1983 Arctic sea ice extent [Source: created by author]**

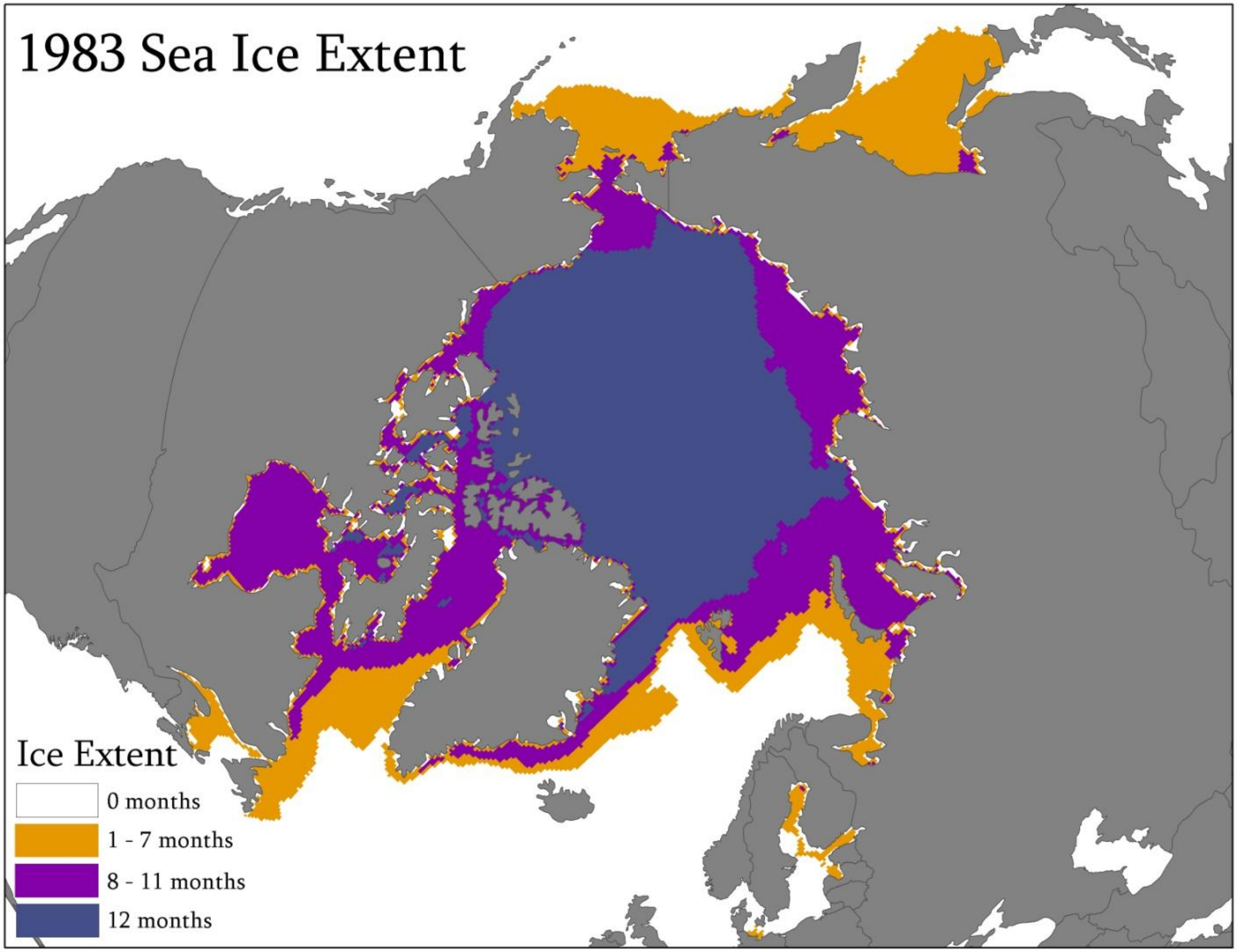


Figure **D.59 1982 Arctic sea ice extent [Source: created by author]**

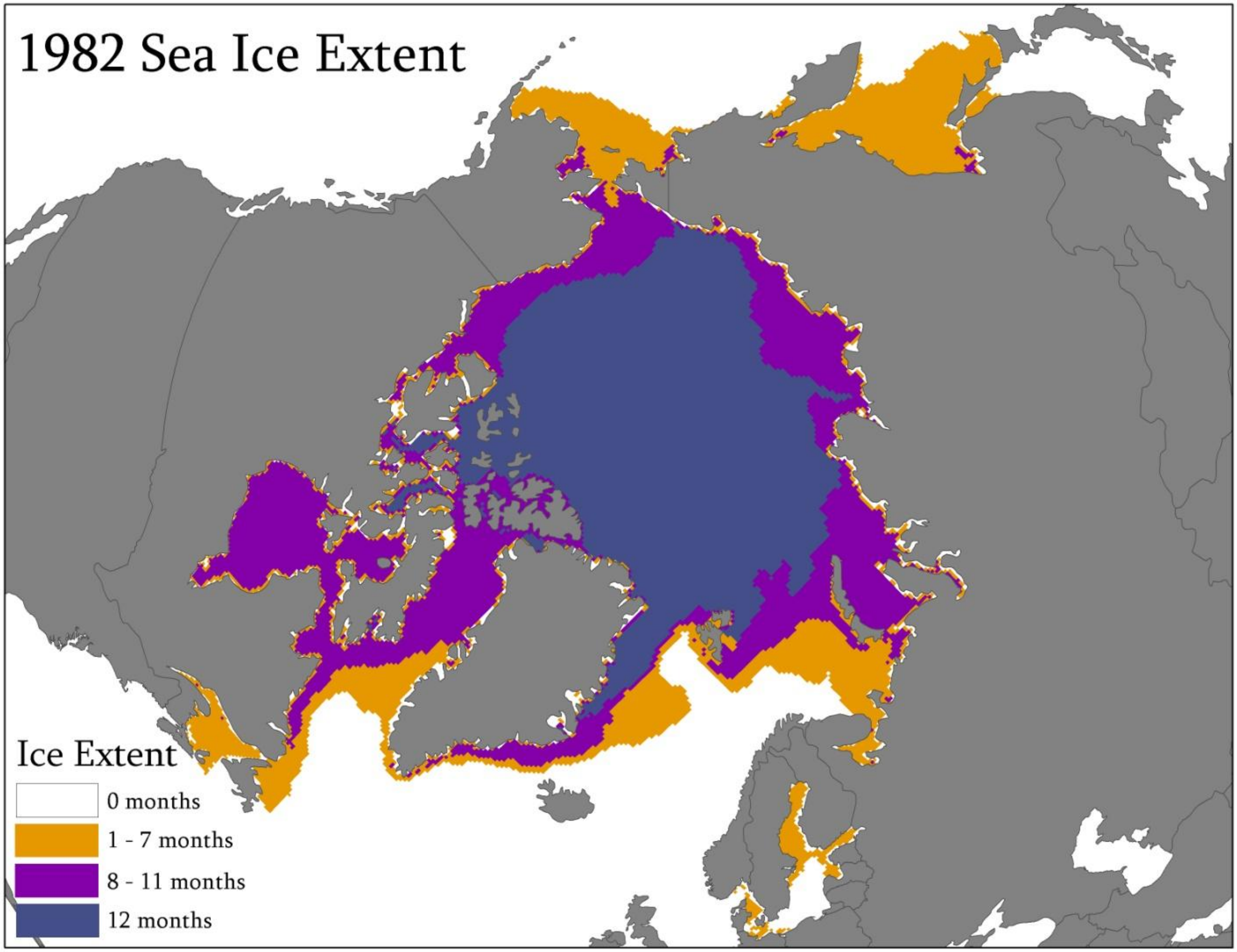


Figure **D.60 1981 Arctic sea ice extent [Source: created by author]**

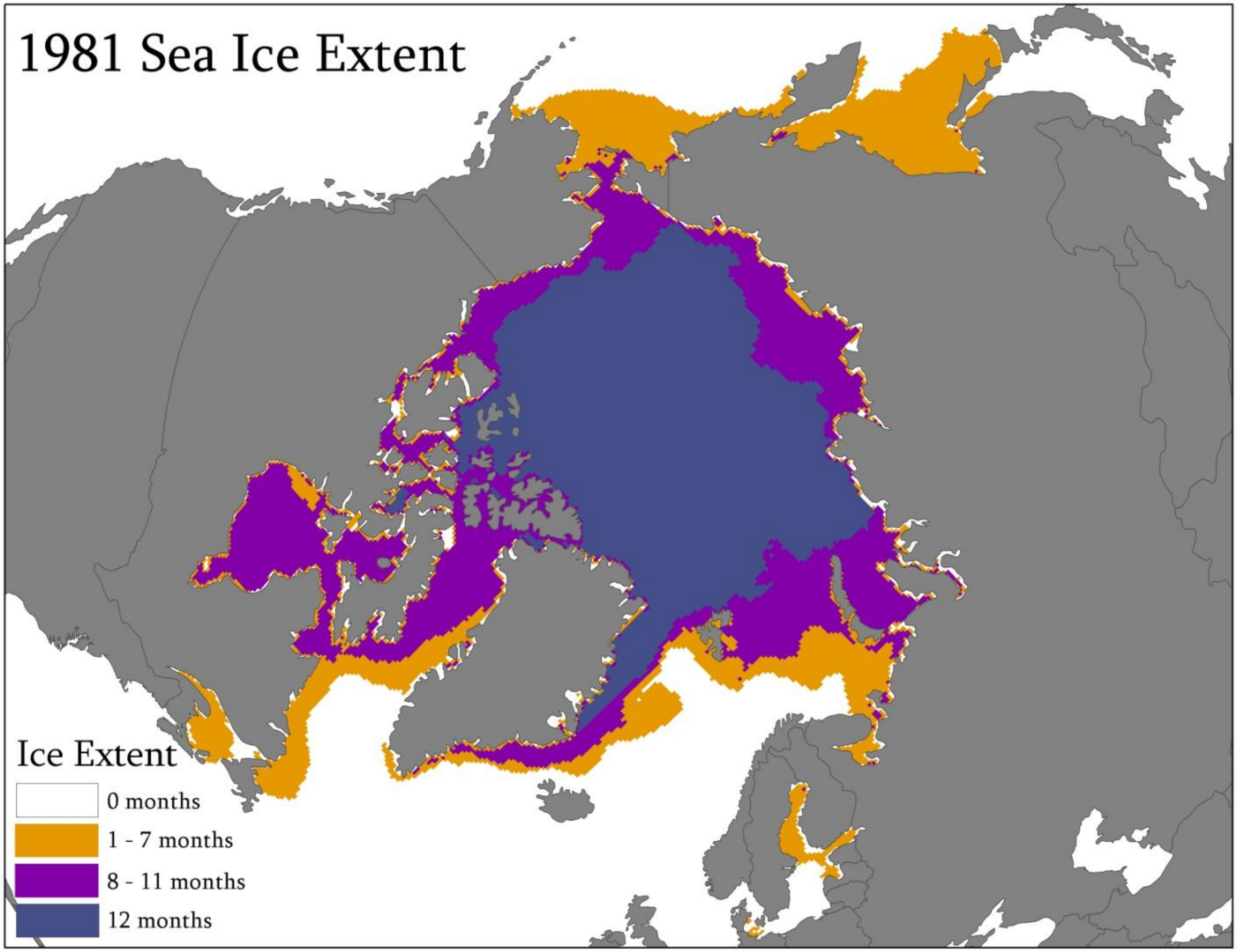


Figure **D.61 1980 Arctic sea ice extent [Source: created by author]**