International Journal of Scientific Research and Engineering Development-– Volume 2 Issue 5, Sep – Oct 2019

Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

The Correlation Between Alaska's Increasing Annual Atmospheric Temperature and Decreasing Permafrost Depth

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Declarations of Interest: None

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Abstract:

Over the past 70 years, the state of Alaska has exhibited an increase in average annual temperature and a decrease in overall permafrost depth. Permafrost degradation can result in the release of carbon dioxide and methane into the atmosphere and threatens the structural integrity of the tundra. Previous studies have focused on the permafrost's active layer thickness as well as changes in permafrost depth of specific sites throughout Alaska. However, there is a significant lack of research that focuses on permafrost depth spanning the entire surface area of the region. The purpose of this research is to determine if a direct correlation exists between increasing average annual temperature and decreasing permafrost depth throughout Alaska. Data in this research was compiled from two year groups, 1950 – 1975 and 2000 – 2019, utilizing data allocated from previously compiled datasets and historical archives such as the National Snow and Ice Data Center, National Oceanic and Atmospheric Administration, and the CALM Network. Data analyzed via Inverse Distance Weighted and Simple Kriging methods of interpolation produced a series of maps showing a dramatic decrease in permafrost depth between the two year groups, with permafrost receding from 50% coverage to less than 25% coverage. These maps also show an increase in average annual temperature that is inversely proportional to latitude. Overall, the data indicates that there is no direct correlation between average annual temperatures and permafrost depth for permafrost layers penetrating less than 300 meters, while very deep permafrost – penetrating over 300 meters – must maintain an average annual temperature below 21.11°F.

Keywords **—Alaska, permafrost, permafrost degradation,permafrost depth, AAT**

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I. INTRODUCTION

Permafrost covers over one-quarter of the Earth's ground surface area, including 9 million square miles of the Northern Hemisphere and all of Antarctica's exposed land. In North America, permafrost occupies roughly 30% of the land, and extends through 85% of Alaska [15]. Carbon stores within global permafrost – approximately 1,830 Pg – are estimated to be 2.2 times greater than what is found in Earth's current atmosphere [5]. Structurally, permafrost prevents the erosion of the arctic and sub-arctic tundra, preventing thermokarst lakes and wetlands from deteriorating. However, the melting of permafrost can lead to the formation of sludge as soil mixes with water [6]. This results in landslides and liquefaction flows that permanently alter the landscape. Permafrost thawing also results in the release of previously trapped carbon dioxide and methane. The release of these greenhouse gases increases atmospheric temperatures, thus increasing the melt rate [5]. The melting permafrost also has the potential to reawaken trapped bacteria and viruses previously thought to be extinct or eradicated. In 2014, a 30,000 year old sample of permafrost yielded a viable specimen of Pithovirus, a giant double-stranded DNA virus known to infect amoebas [11].

Previous studies on permafrost degradation mainly focus on global permafrost active layer thickness (ALT). ALT describes the uppermost layer of permafrost that thaws and refreezes on an annual basis. While these studies universally indicate that the ALT is increasing in depth, they do not provide information on the depth of the entire permafrost layer as a region. Some studies, such as those spearheaded by the USGS and Alaska Science Center [10], document a significant decrease in overall permafrost depth on a semi-regional basis. The most recent study on the Kenai Peninsula shows degradation of up to 60%, with some locations as shallow as 1.08 feet. Jones, Baughman, Romanovsky, and Parsekian's research provides a working model for documenting changes in permafrost across the span of multiple decades. This research details the degradation of permafrost on the Kenai Peninsula from 1960 to 2016. Modern data was collected via field studies, while past data uses historical data located at the Alaska Department of Fish and Game Moose Research Center, and uses GIS software to create radiograms of permafrost distribution, displaying spatial and temporal patterns of permafrost loss. Furthermore, the report discusses the impact of permafrost degradation on the local environments, noting that degradation in one area can positively impact the degradation of another area. However, the Kenai Peninsula only covers one small semi-region of Alaska. While the methodologies and results may be applied to the rest of the state, it is too specific to represent Alaska's entirety.

Recent studies from the Geophysical Institute of the University of Alaska, conducted by Osterkamp, focus on the increase in Alaska's permafrost temperature, and utilize borehole readings to monitor long-term temperature readings. Osterkamp's report [13] provides a fundamental introduction to long-term permafrost temperature monitoring from the years 1977 to 2003. This research not only reports drastic temperature increases, but also provides easily transferable methodologies for annual data collection and interpretation for other groups intending to mimic these studies. Additionally, Osterkamp's research shows a variance in permafrost warming rates, with warming occurring faster in arctic areas, particularly the northwestern coastal region, and slower in central and inland areas. The borehole locations utilized by Osterkamp range from West Dock Prudhoe Bay in north-eastern Alaska to Eagle River in south-eastern Alaska, roughly following the 150° parallel in a relatively straight line. However, this research does not extend throughout central and western regions of Alaska, and remains constrained to the boreholes following the aforementioned singular parallel.

Studies conducted on overall Northern Hemisphere permafrost include regions such asthe Qinghai-Tibetan Plateau in western China [5]. Researchers Guo and Wang have linked the region's permafrost degradation with an increase in average annual temperature (AAT), and show a strong correlation between China's human activity and an increase in ALT depth. It is likely that these same correlations are present between Alaska's permafrost and North America's AAT. Guo and Wang's research also simulates historical changes in Alaska's permafrost from the years 1901 to 2010. Their report uses permafrost data gathered from the Circumpolar Active Layer Monitoring Network, which is routinely used to validate arctic climate modelling. Furthermore, the research also reports annual average air temperatures as well as active layer thickness. The results of such research show clear increases in air temperature as well as decreases in overall permafrost distribution. Results were verified using modern observed distribution maps. However, the area of focus for this research includes the entire Northern Hemisphere, and the authors showed a particular interest in the Qinghai-Tibetan Plateau region.Overall, there is a significant lack of research that focuses on both the overall state of Alaska as well as total permafrostdepth.

Therefore, this study proposes that there is a direct correlation between Alaska's increase in AAT and decrease in permafrost depth. The results of this study show a series of maps that outline Alaska's AAT and permafrost depth from the time periods 1950-1975 and 2000-2019. These maps show the extent of change in temperature and degradation, and indicate a visible correlation between these changes. The results are validated based on observations of ALT degradation and AAT of present-day conditions. Figure 1 shows the extent of the study area, which includes the westernmost islands of the maritime climate zone.

II. DATA AND METHODOLOGIES

A. Data

The data used in this research consists of four original datasets divided into two groups. The first group contains a dataset that documents Alaska's AAT from the years 1950 – 1975 and a dataset that documents Alaska's AAT from the years 2000 – 2019. AAT readings were collected from a combination of weather stations and borehole readings of each site's surface temperature. The National Oceanic and Atmospheric Administration provides an archive of historical weather and climate data [12]. The majority of AAT readings were collected from this database. Additional data was also collected from the Circumpolar Active Layer Monitoring (CALM) Network's previously compiled datasets [4]. The 1950 – 1975 AAT dataset contains 389 data points. The 2000 – 2019 AAT dataset contains 6614 data points.

The second group contains datasets that document Alaska's permafrost depth, corresponding with the aforementioned years. All readings in these datasets were collected from borehole measurements. These borehole measurements were collected from The Permafrost Laboratory [3], The National Snow and Ice Data Center [2][9], The Global Terrestrial Network – Permafrost [7][8], The International Arctic Research Center Data Archive, and The CALM Network [4]. The 1950 – 1975 dataset contains 71 data points. The 2000-2019 permafrost depth dataset contains 1067 data points.

All datasets were created using Excel and include the geographical location of each borehole or weather monitoring station in decimal degrees, the name of each site, and the year which the data was collected. Previous original datasets related to permafrost-affected soil thermal conditions were used as a reference when compiling the datasets used for this research. Wang, Jafaroy, and Shaefer's dataset [14] demonstrates proper methodology for creating a new dataset from previously collected data, which includes information from 72 monitoring sites, and consists of 41,667 data points. This prototype for data management is compatible with all GIS software, as well as model-dataintercomparison tools. Due to extreme weather and location conditions, Wang, Jafaroy, and Shaefer's dataset is only 77% complete. However, data was quality controlled through harmonization evaluation. While the dataset provides adequate

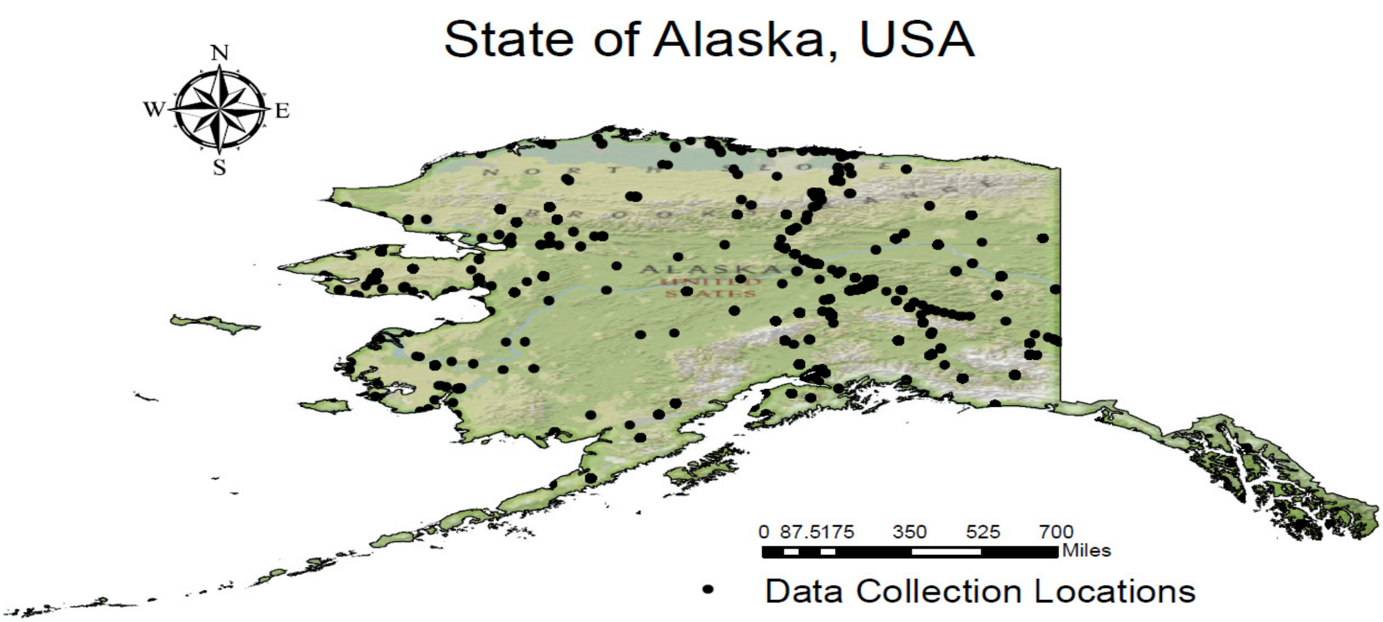

Fig.1 Extent of study area

information for northern and eastern Alaska, there is little to no data available for western Alaska.

B. Methodologies

The results of these newly compiled datasets are shown through a series of maps. These maps provide a clear visualization of past and modern conditions, and provide a platform to visually convey the extent of correlation. This research utilizes the geographic information system software ArcGIS to create the map series. ArcGIS is available worldwide and is the most commonly used GIS software in both commercial and private settings.

The first step in creating these maps includes the definition of Alaska's state boundaries. All boundaries are defined by the World Geodetic System 1984, and all subsequently imported data conforms to this Geographic Coordinate System. After defining the state boundaries, the datasets are imported and XY data points are created from the longitude and latitude event tables. Since the data points are discontinuous and frequently separated by great distances, interpolation is used to create a model of the missing spatial data. The result is a complete surface model representing the entire region defined by the state boundary.

While analysing the data through interpolation, any data with multiple values for a single location is transformed to a mean value. For example, each weather station in the 2000-2019 AAT dataset contains the average monthly temperatures from January to December. Instead of using 12 different data points to represent a single year, the temperature values are averaged to represent the mean value for a single year. This process helps ensure that equal weight is given to all data point locations. This process also eliminates any outlying variables that do not represent permanent change. This is particularly important when analysing borehole data. Batir, Hornbach, and Blackwell's decade-long research outlines how these variables can affect an individual borehole. Their report [1] integrates previous studies, such as Osterkamp's research, into borehole monitoring methodologies from the years 1996 to 2006. While their study focuses on a singular borehole, the report details variances in readings due to prevailing winds, mining operations, and latent heat from unnatural sources. Furthermore, the study discusses possible influences on sub-surface temperature changes that may contribute to permafrost degradation. Monitoring a singular site for an extended period of time allows for the identification of temporary outside influences, such as mining operations and weather patterns, which may permanently impact borehole temperature readings from creating outlying data information.

The two permafrost datasets in this study use Inverse Distance Weighting as the preferred method of interpolation. IDW assumes that near-points are more alike than far-points. That is, data points that are far away have less influence than data points that are near. IDW is also appropriate for densely presented data points. Considering that any point of permafrost data is expected to be similar to its adjacent points, and the datasets being analysed may contain over 1,000 data points, IDW creates the most accurate spatial model for permafrost depth.

The two temperature datasets use Simple Kriging as the preferred method of interpolation. Kriging is the most common method of interpolation, and is suitable for data that remains relatively stationary and linear. Although weather patterns are generally not stationary, average annual temperature is considered stationary and linear, as it assumes that temperature steadily decreases as latitude increases. Simple kriging differs from ordinary kriging in that it assumes a known mean. Therefore, when comparing the AAT for two separate time periods of the same location, simple kriging creates the most appropriate spatial model.

III. RESULTS

The results of this analysis show a clear degradation of permafrost depth between the years 1950-1975 (Fig. 2) and 2000 – 2019 (Fig. 3). During the years 1950-1975, the deepest permafrost present in northern Alaska penetrated 300 to 884 meters deep, and covered almost half of Alaska's total surface area. The shallowest reported permafrost depths in southern Alaska penetrated 10 meters deep. During the years 2000 – 2019, the deepest permafrost present in northern Alaska penetrated no more than 300 meters deep and extended throughout only a small portion of the state. Permafrost penetrating no more than 30 meters deep makes up the majority of all permafrost throughout Alaska, including roughly 75% of northern Alaska. Overall, these results show a dramatic decrease in total permafrost depth with some northern regions losing over 600 meters of permafrost depth. Fig. 4 shows the comparison of permafrost depths of the time periods between 1950-1975 and 2000-2019. Here, results show the overall degradation of Alaska's permafrost, with only the northwest region retaining significant depths.

The results of this analysis also show a significant increase in AAT between the years 1950-1975 (Fig. 5) and 2000-2019 (Fig. 6). During the years 1950-1975, the lowest AAT present in northern Alaska was 10.03°F, while the highest AAT present in southern Alaska was 45.34°F. The lowest temperatures, ranging from 10.03°F to 21.11°F, extended throughout slightly less than half of Alaska's total surface area. During the years 2000-2019, the lowest AAT present in northern Alaska was 21.11°F, while the highest AAT present in southern Alaska was 45.82°F. The lowest temperatures, ranging from 21.11°F to 25°F, extend through approximately one-quarter of Alaska's total surface area. Overall, these results show that the northern regions of Alaska are susceptible to an increase in AAT than the southern regions. While the arctic regions of Alaska have experienced an overall increase in AAT of 11.08°F, the maritime regions have experienced an increase of only 0.48°F. Figure 7 shows the comparison of temperatures of these two time periods. Here, results show that the 1950-1975 temperature region of 10.03°F to 21.11°F, represented by the darkest blue contour, experienced AAT temperatures as high as 33°F in the 2000 – 2019 time period.

Fig. 8 shows the comparison of Alaska's permafrost depth and AAT from the years 1950 – 1975. Results show that the deepest permafrost depths (300-884m) exist only when accompanied by an AAT of 21.11°F or colder. However, the comparison does not indicate that mid-range permafrost depths (100-300m) require any specific AAT range, as permafrost penetrating 200-300 meters deep is present in central Alaska as well as the warmer southern maritime regions. Fig. 9 shows the comparison of Alaska's permafrost depth and AAT from the years 2000 – 2019. Results show that the deepest permafrost depths (100-300m) require an AAT between 21.11°F and 25°F. The minimum AAT does not fall below 21.11°F, and there is no visual permafrost that penetrates past 300 meters. Low-to-mid-range permafrost depths (1-50m) penetrate throughout Alaska's entirety regardless of temperature variations.

Taking Fig. 8 and Fig. 9 into consideration, results indicate that the presence of permafrost with a depth of 1 meter to 300 meters does not require any minimum average annual temperature. However, results show a clear correlation between very low temperatures and very deep permafrost depths. During the 1950-1975 period, minimum AAT presented as low as 10.03°F in the same areas where maximum permafrost depth penetrated up to 884 meters. However, during the 2000-2019 period, minimum AAT has risen to at least 21.11°F in those areas, while permafrost has decreased to 300 meters or lower in depth and decreased half the extent in surface area.

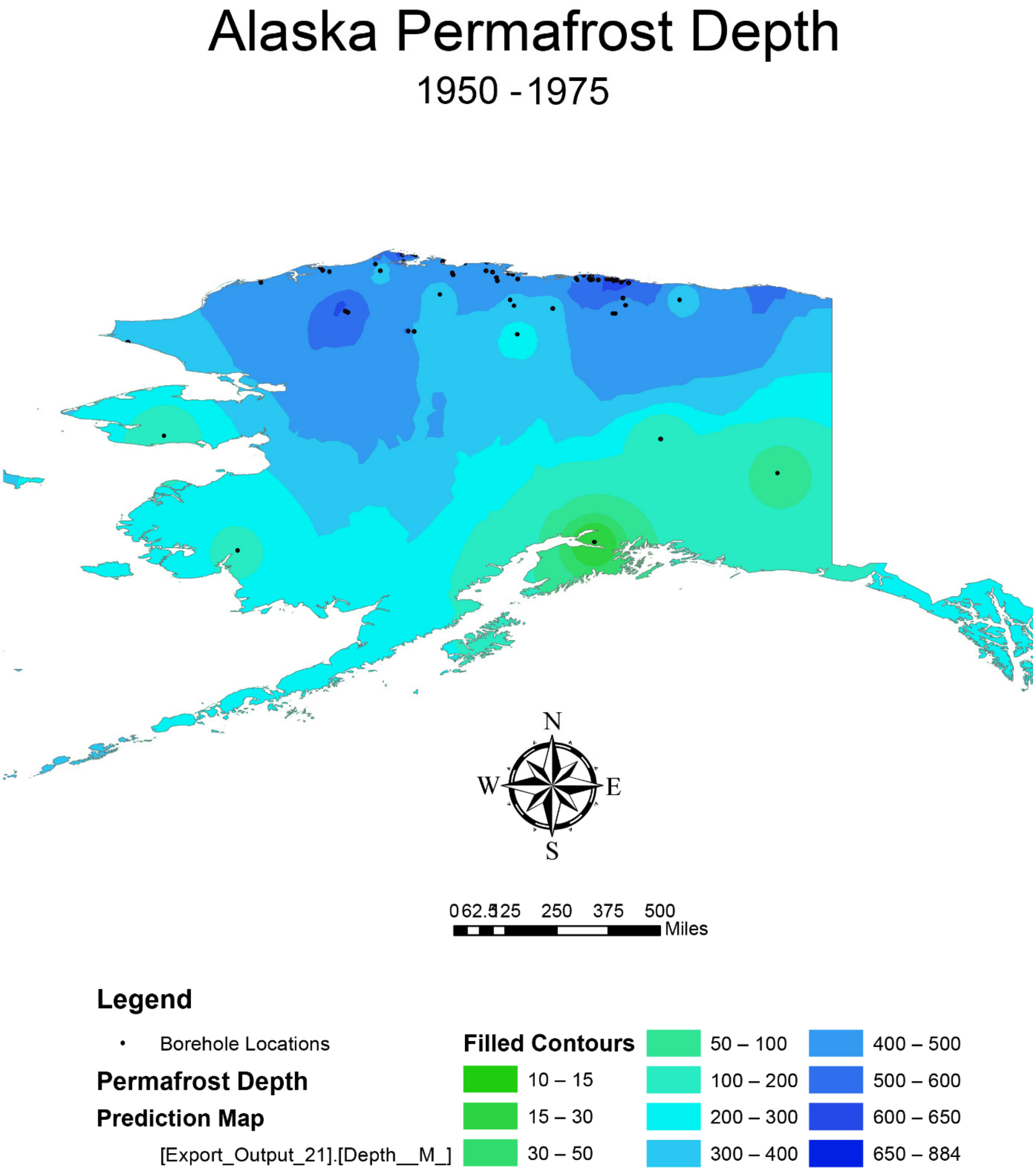

Fig. 2Alaska permafrost depth 1950 – 1975

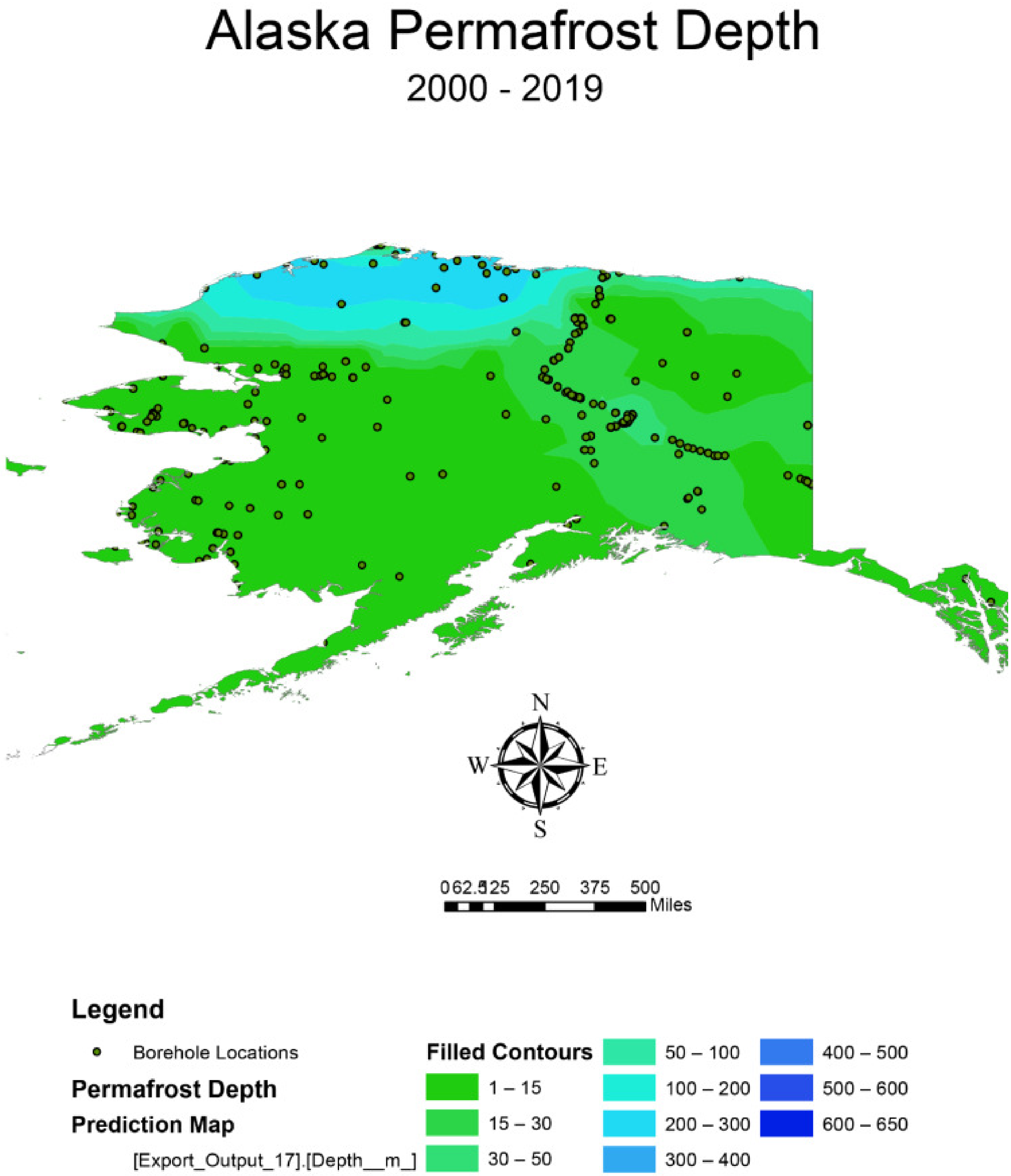

Fig. 3 Alaska permafrost depth 2000 – 2019

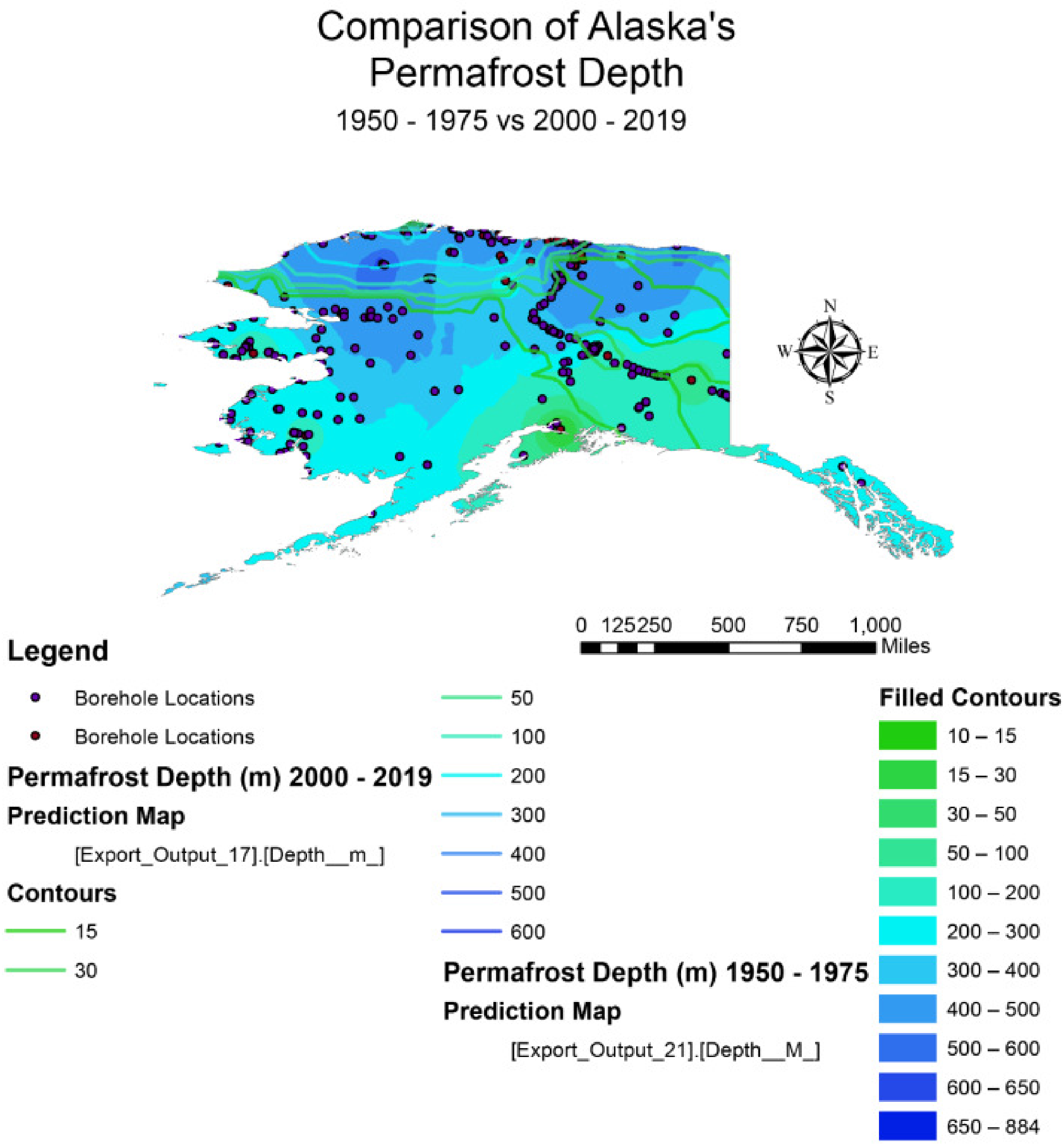

Fig. 4Comparison of Alaska's permafrost depth 1950 – 1975 versus 2000 – 2019

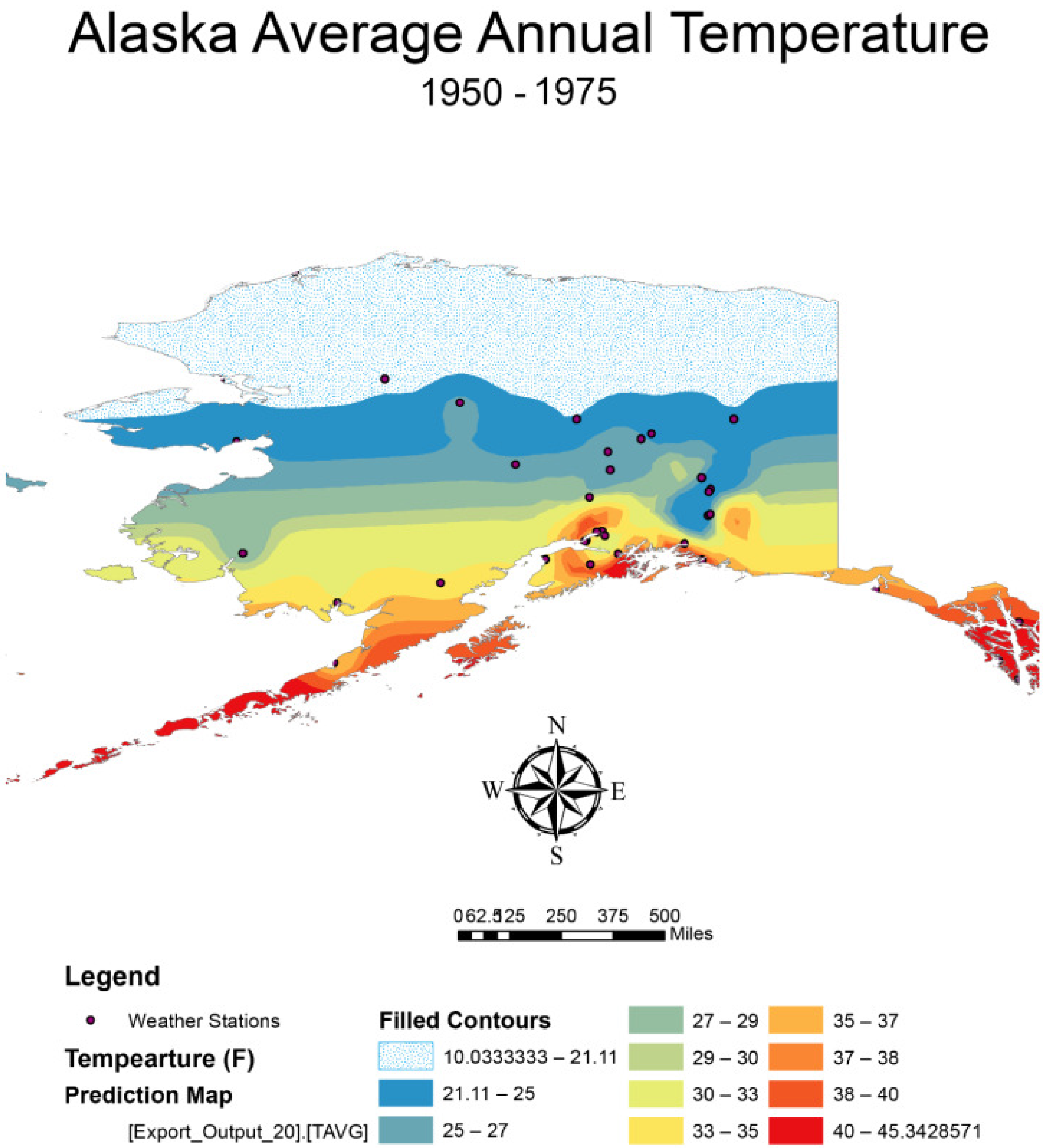

Fig. 5 AlaskaAAT 1950 – 1975

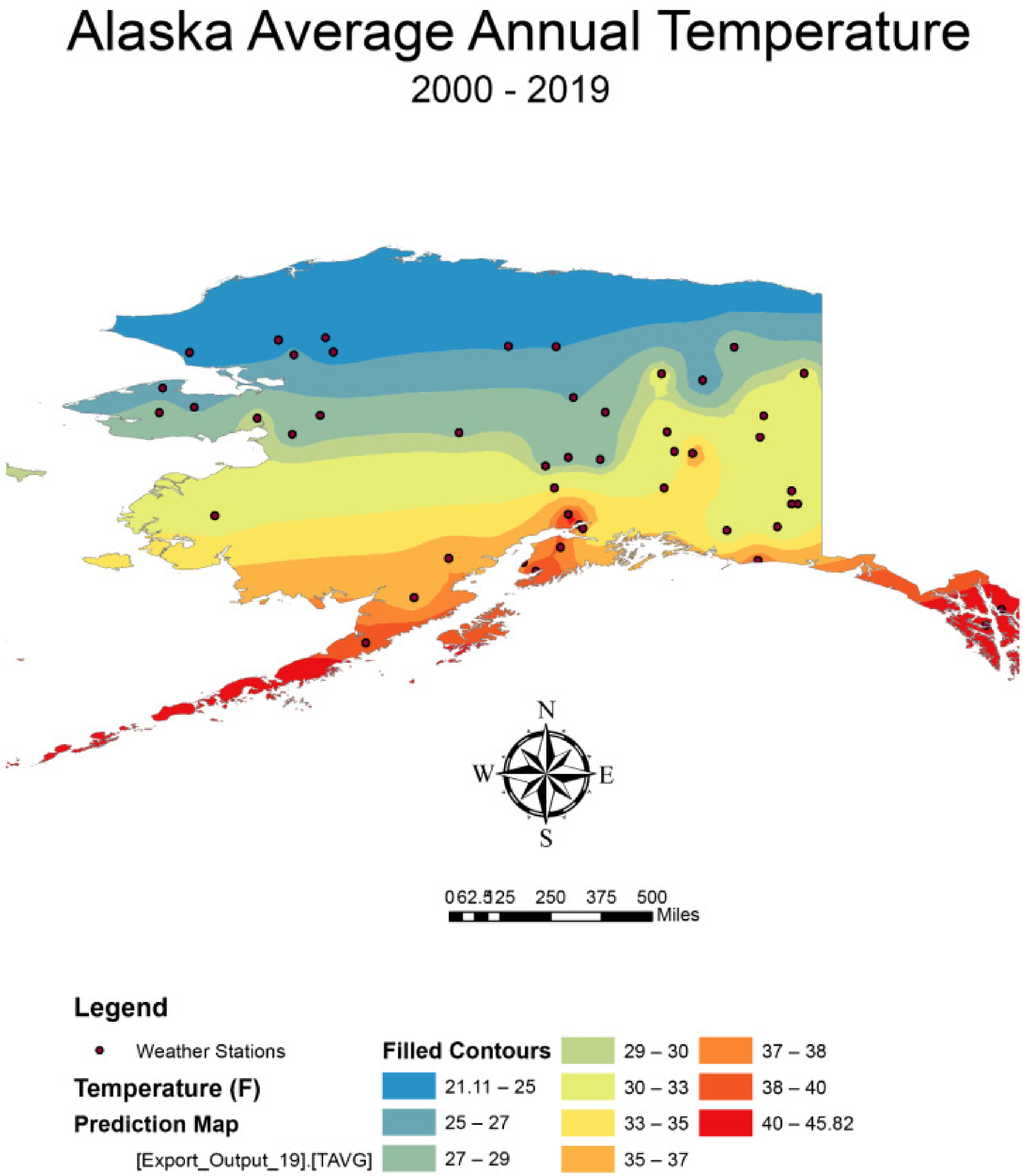

Fig. 6 AlaskaAAT 2000 – 2019

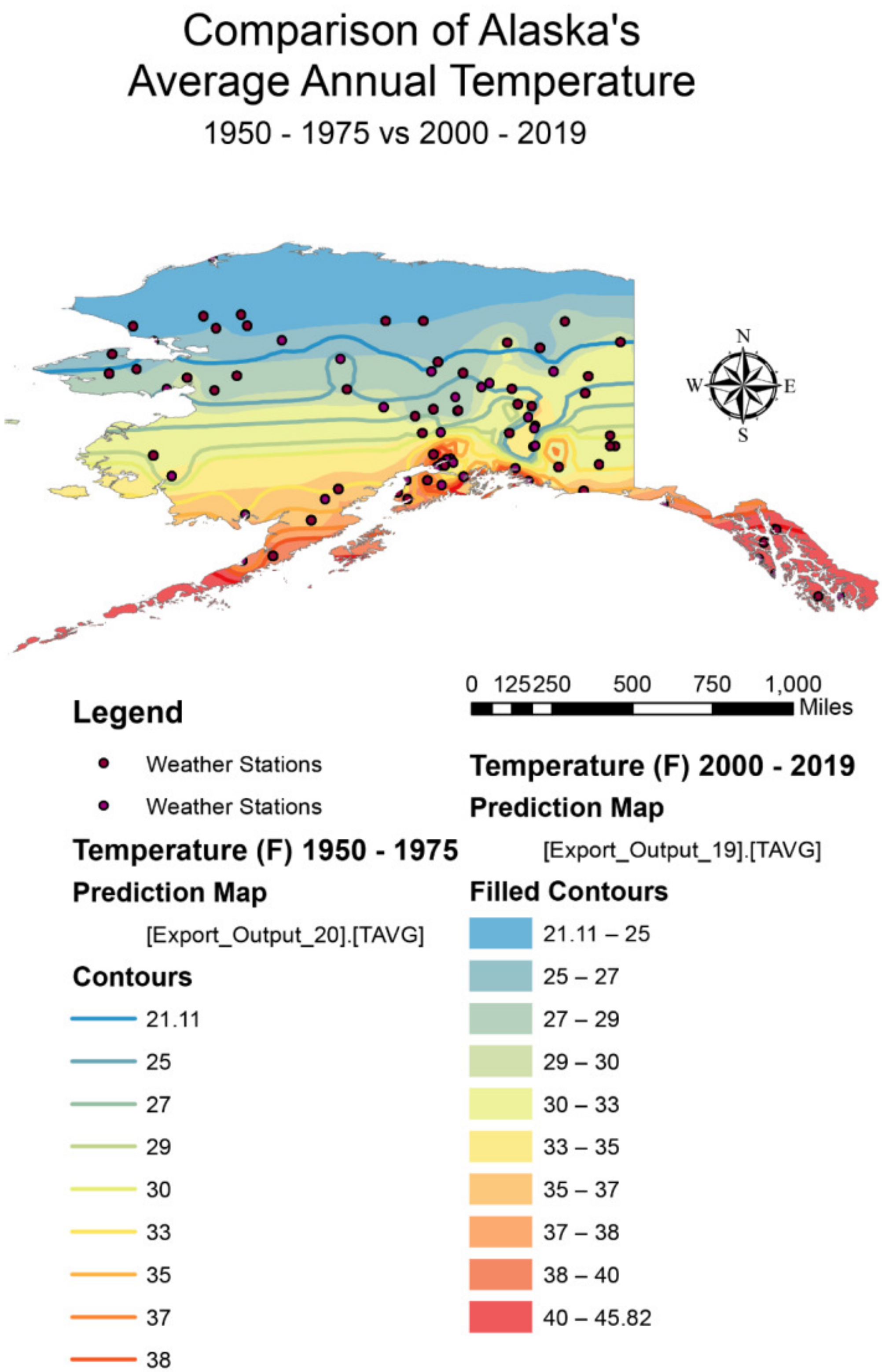

Fig. 7 Comparison of Alaska's AAT 1950 – 1975 versus 2000 – 2019

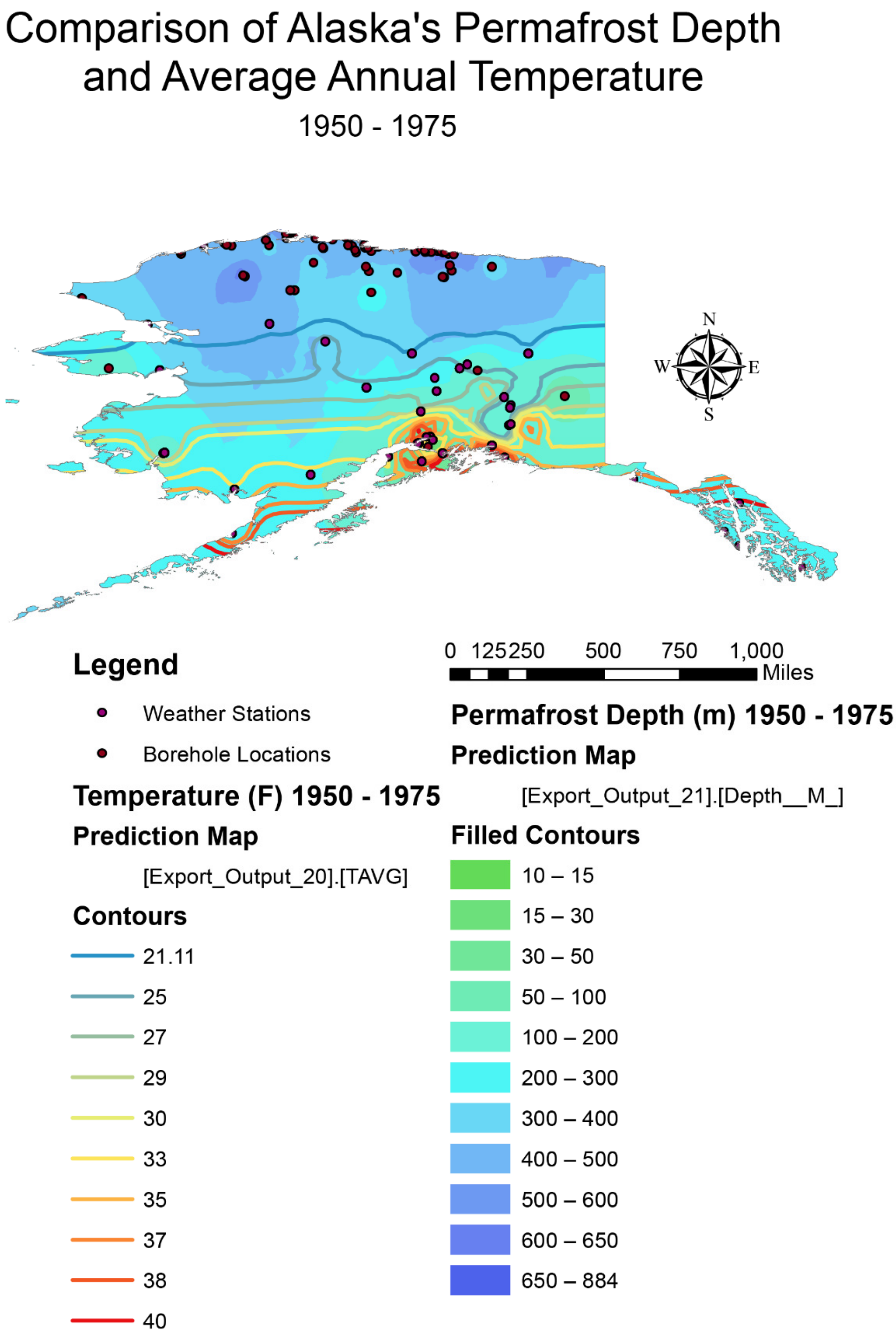

Fig. 8 Comparison of Alaska’s permafrost depth and AAT 1950 - 1975

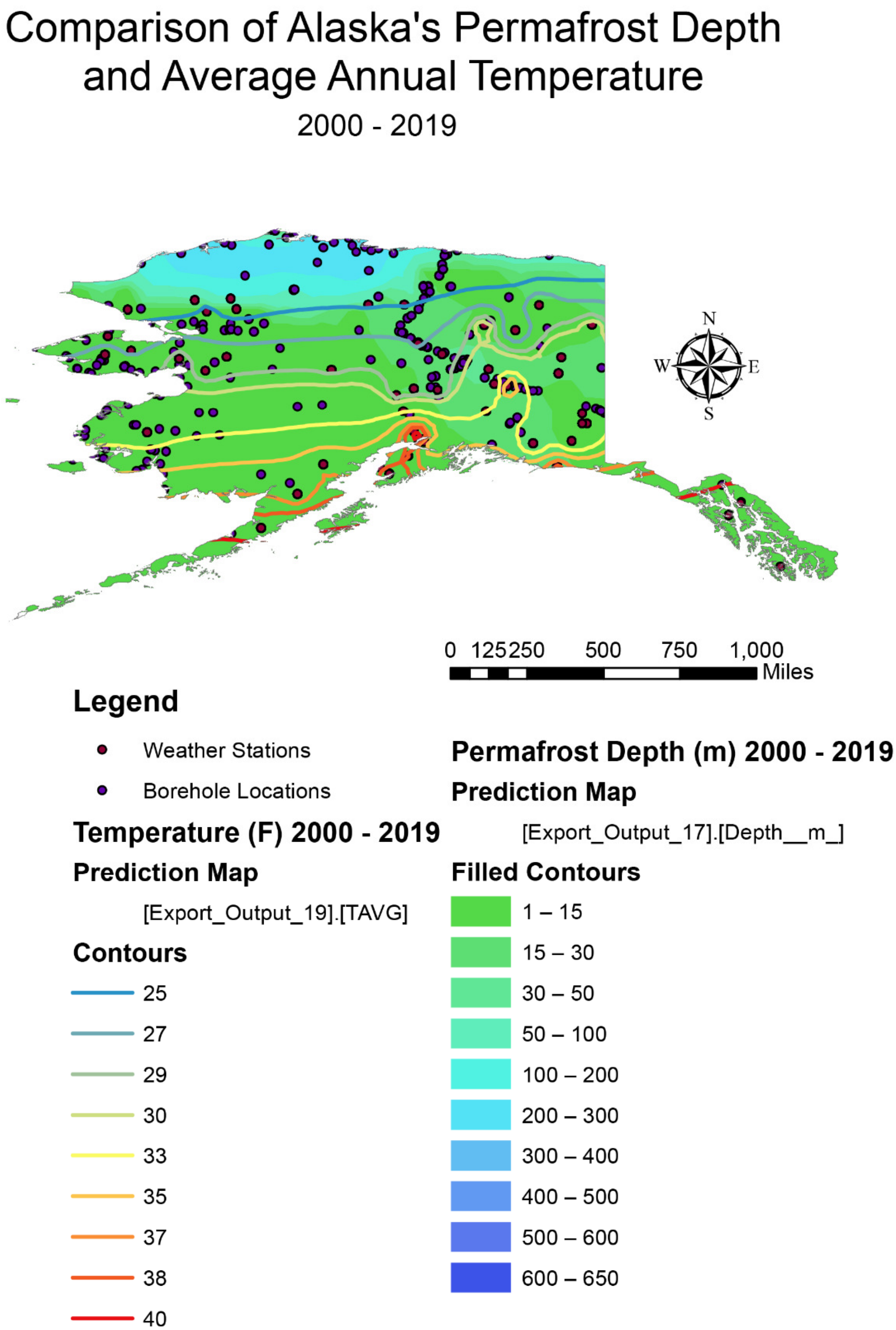

Fig. 9Comparison of Alaska's permafrost depth and AAT 2000 – 2019

IV. DISCUSSION

The hypothesis that there is a direct correlation between Alaska's increase in AAT and decrease in permafrost depth is partially accurate. It was expected to find clearly defined regions of permafrost that decreased in depth as average annual temperature increased. Although there does not appear to be a direct correlation between AAT and permafrost depth of 300 meters or less, results indicate that very deep permafrost penetration of 300 meters or more requires a minimum AAT of 21.11°F. Therefore, the study concludes that there is a direct correlation between Alaska's increase in minimum AAT and decrease in permafrost of depths greater than 300 meters. The study is still valuable, as it yields information on the disappearance of very deep permafrost classifications. Furthermore, the study confirms that permafrost depths have decreased while AAT has increased over the past 70 years. This indicates that there is some correlation between permafrost and temperature activity in general, although the two may not always be directly linked.

Analysis of the overall 1950-1975 permafrost depth was limited due to the overabundance of northern borehole sites, coupled with the sporadic or non-existent central and southern borehole sites. It is possible that the lack of data points throughout central and southern Alaska negatively impacted the spatial analysis of permafrost depth. It is important to note that the immediate areas around these central and southern data points show shallower penetrations than areas adjacent to these data points. However, these permafrost depths still do not breech the 300m threshold for very deep permafrost.

If additional research is conducted, collecting missing data should be a top priority. While borehole information on recorded permafrost depths from the years 1950 – 1975 is available from the Alaska Fish and Wildlife Department, these records are not made available on any public database. These records must be accessed in person at each area's individual Fish and Wildlife Department, thus requiring travel to and around the state of Alaska. A centralized database that contains each location's historical data would eliminate the difficulty in accessing information.

V. CONCLUSIONS

This research investigated the possible correlation between Alaska's increasing AAT and decreasing permafrost depth using data collected from previously compiled datasets and historical archives that document permafrost depth and surface temperature using both borehole and weather station readings. Data was analysed using the Inverse Distance Weighted and Simple Kriging methods of interpolation, producing a series of maps that spatially analyse both permafrost and temperature events between the time periods of 1950 – 1975 and 2000 – 2019. Visual comparison showed a direct correlation between very deep permafrost penetration of 300 meters or greater and a minimum AAT of at 21.11°F or lower. However, permafrost penetration of 300 meters or less was present throughout the region regardless of temperature variations. Overall, this research shows that while Alaska continues to experience an increase in AAT and decrease in permafrost depth, a direct correlation can only be made between very low temperatures and very deep permafrost.

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