***Abstract*** – The thawing of permafrost in the northern hemisphere is considered a critical contributor to the characterisation of Earth’s climate. Though monitoring of ground temperature and thaw depth in permafrost cannot be directly observed from satellite sensors, recent models have achieved relatively accurate models through analysing a variety of remotely sensed data in order to indirectly derive permafrost characteristics. In this work, we aim to utilise these model’s results within a deep-learning regression model to propose correlations between the degradation of permafrost and the recent record high temperatures in Europe and particularly Spain. The correlations could support a ‘heater-cooler’ model, in which the shrinking and greening of the northern permafrost region – the ‘cooler’ – is contributing to the leading to a reduced surface albedo that could impact atmospheric circulation. The weakening of the polar jet stream could lead to hot hair from the equator to push northwards - the ‘heater’. If this model were to be a factor in European temperatures it adds additional pressure to the already strained climate goals set out and could alter the results of climate no-return models.

**Introduction**

Permafrost is defined as ground (sediment, soil, or rock) that remains below 0°C for a minimum of two consecutive years [1]. Permafrost is a common cryosphere feature with 24% of exposed land on the northern hemisphere being underlain by permafrost [2]. The occurrence of permafrost is strongly influenced by air temperature, topography, hydrology, snow depth and soil properties, and the decline of permafrost extent over the last 30 years indicates its vulnerability to climate change [14]. The thawing of permafrost is a major threat to local infrastructure and the roughly 5 million people that live in the Artic Circumpolar Permafrost Region (ACPR) [4]. 1 million of these inhabitants live along artic coastlines, which are being particularly affected by coastal erosion that is primarily driven by warming permafrost and sea temperatures [5], resulting in an increase in erosion rates by up to 160% on some coasts compared to the erosion rates in the 1980’s and 90’s [6]. Previous research has utilised machine learning frameworks exploiting C-band synthetic aperture radar and multi-spectral information to forecast that 55% of infrastructure currently on permafrost and within 100km of the arctic coastline will be affected by 2050 [7].

Despite the prevalence and global impact of permafrost thawing, it is only recently that the specifics and implications are being fully explored. The Intergovernmental Panel on Climate Change’s (IPCC) 2014 assessment did not take permafrost emissions into account when calculating future temperature targets, and it was not until an IPCC special report in 2018 that a permafrost thawing model was used. The potential ramifications of permafrost degradation appear profoundly underrepresented and new tools, methodologies and satellite data (e.g. Google Earth Engine, deep learning and the Methane Remote Sensing LiDAR Mission [12]) have created a unique opportunity to further investigate its global effects. The Remote sensing of permafrost is a challenging but advancing endeavour, some below-surface characteristics of permafrost, such as thaw depth, are hard to reliably detect remotely [11]. This is partly due to additional factors, such as soil texture, surface roughness, snow and vegetation which influence signals. However, progress has been made through indirectly deriving permafrost states from other detectable characteristics, for example, identifying permafrost landforms through image classification and permafrost surface deformations by repeat digital elevation models, or radar interferometry [11]. Additionally, permafrost monitoring can become increasingly accurate by combining the information gathered from a multitude of sensors with thermal permafrost models to take advantage of the heterogeneity of permafrost[11].

**Model**

The drastic changes in the permafrost regions have occurred alongside equally intense changes in Europe. Despite the European Environmental Agency (EEA) reporting that there has been a reduce in greenhouse emissions from EU members– 24% less emissions in 2021 than 1990 levels [15], temperatures in Europe have continued to rise faster than the world average [16]. The ten warmest years for Europe have occurred since 2000 [18]. The ‘Paris Agreement’ to limiting the global temperature increase to 1.5°C above pre-industrial levels is becoming ever more unlikely as several European countries have already reached this limit [16,17]. This is displayed in Spain where the average temperature had risen by 1.5°C since 1965 by 2015 and the country has experienced 24 heatwaves between 2010-202, double the amount of the previous decade [31]. It could be hypothesised that these extreme temperatures are due to Spain’s proximity to the subtropical dry zone. The subtropical dry zone is a section of atmospheric circulation where the Ferrel cell and Hadley cell collide at about 30° north/south from the equator. The Hadley cell circulates the solar energy falling on the equatorial belt which heats and rises the air, the moisture contained is released as rain over the tropics and the now dry air continues pole-wards until it collides with the Ferrel cell. This collision sinks the dry air which creates areas of high pressure leading to desert conditions [https://geo.libretexts.org/Courses/Gettysburg\_College/Book%3A\_An\_Introduction\_to\_Geology\_(Johnson\_Affolter\_Inkenbrandt\_and\_Mosher)/13%3A\_Deserts/13.02%3A\_The\_Origin\_of\_Deserts

AND SHOW IN FIGURE].

It has been observed that the Hadley cell has been expanding poleward since 1980, at an approximate rate of 0.1°-0.5° latitude per decade [https://acp.copernicus.org/articles/20/5249/2020/ , <https://journals.ametsoc.org/view/journals/clim/31/11/jcli-d-17-0852.1.xml>]. As the Hadley cell widens, it causes the subtropical dry zone to shift poleward which can lead to a reduction in precipitation and eventual desertification – the degradation of fertile soil into desert - of areas further from the equator than in previous decades [REFERENCE]. The mainland of Spain is circa 36°-43° latitude north of the Sahara Desert and exemplifies the impact of the northwards shift of the subtropical dry zone. This is shown by the Nations Convention to Combat Desertification (UNCCD) stating that 74% of Spain is at risk of desertification and 18% is at a high risk of becoming desert irreversibly. [https://knowledge.unccd.int/sites/default/files/naps/spain-spa2008.pdf]. The south of Spain is most effected, with some research suggesting that all southern Spain could be desert by 2100 [https://www.science.org/doi/full/10.1126/science.aah5015 ]. [GET DIAGRAM TO SHOW?]

[MAYBE GEE DIAGRAM SHOWING CHANGES IN PRECIPITATION SHOWING SPAIN IS GETTING DRIER]

The poleward expansion of the Hadley circulation and thus, the shift in the subtropical dry zone, is caused by the pole-to-equator temperature gradient decreasing [https://www.researchgate.net/publication/264902638\_Poleward\_expansion\_of\_Hadley\_cells]. The difference between northern polar and equatorial temperatures is being shortened by the arctic warming at nearly three times the rate of the rest of the world due to ‘Arctic Amplification’ [13]. Thawing permafrost contributes to his enhanced boreal warming pattern in two ways:

Firstly, permafrost contains a significant amount of greenhouse gasses (GHG) that are released as it thaws. Methane is stored in permafrost as either methyl clathrates or frozen organic matter, as the permafrost degrades, some of this methane is released into the atmosphere [8]. Methane is particularly damaging to the climate and is 28 times as potent as carbon dioxide at conserving heat in the atmosphere [9]. There is nearly twice the amount of carbon stored within permafrost as there is currently in our atmosphere - approximately 1460-1600 billion tonnes of organic carbon [REFERENCE]. On release, the GHG accelerates the greenhouse effect and leads to a positive feedback loop [10].

Secondly, higher active layer thickness and soil temperatures caused by permafrost warming has led to ‘greening’ [19]- taller plants are spreading into areas that were typically tundra and becoming denser across the arctic [19,20] (AS SHOWN IN FIGURE). This ‘greening’ is decreasing the surface albedo of the arctic; denser vegetation is often much darker than the sparse short vegetation that previously inhabited large areas in the growing season and each growing season plants are growing further north [REFERENCE]. Additionally, the high albedo of snow (fresh snow can reflect up to 90% of solar radiation) is heavily reduced when covering the underlying surface of tall/dense vegetation, which causes quicker melting of the snow [21]. The overall reduction in arctic surface albedo leads to an increase of shortwave radiation from the sun being absorbed, further raising temperatures.

These two examples and the aforementioned high rate of large-scale permafrost degradation show the impact of permafrost on the pole-to-equator temperature gradient and thus, the poleward expansion of the Hadley circulation which is causing extreme temperatures in Spain. This forms the basis of the proposed heater-cooler model in which the ‘heater’ is the equator temperature, which is considered to be constant, and the ‘cooler’ is the northern polar temperature which is rising partly because of permafrost thawing. The resulting deficit of difference between pole and equatorial temperature is driving the poleward extension of the Hadley cell and therefore the subtropical dry zone is shifting north and influencing Spain’s climate. To reproduce effects on atmospheric circulation behaviour, *G.M.Lewis* and *W.f.Langford* propose a mathematical model applied to a spherical shell containing rotating Boussinesq fluid as a simulation purely driven by temperature and spherical convection[REFERENCE]. One component is the equation:

Where is the temperature of the inner boundary surface, is a reference temperature, is the total difference in temperature from the pole to the equator and - is approximately proportional to the variation of average annual flux of solar radiation on a planet with axis of rotation tilted approximately 20° in respect to the perpendicular plane of the solar rays at colatitude [REFERENCE BOTH]. The ‘cooler-heater’ model expands on this by introducing the permafrost influences on the polar temperature. The resulting temperature is specified to Spain through its latitude of roughly 40°, so the colatitude . In this model the equator temperature is assumed to be constant. The poles of the model are considered symmetrical and will represent the arctic. The temperature of the northern polar area is affected by many factors which the model considers to be hidden factors, the model incorporates the prior mentioned ways in which thawing permafrost affects arctic temperature so that where is the additional hidden factors affecting polar temperature, is the GHG emissions from thawing permafrost containing trapped gasses, is the GHG emissions from decomposition of organic carbon revealed by thawing permafrost and is the surface albedo. represents the temperature affect of albedo and represents the warming greenhouse effect of GHG. Thus, the ‘heater-cooler’ model depicting a relationship between permafrost thawing and temperatures in Spain can be:

This ‘heater-cooler’ model hypothesises that the global circulation of air which redistributes thermal energy and prevents the equator becoming increasingly hotter and the poles increasingly colder; is unbalanced by the rising temperatures in the arctic, of which one factor is the regression of permafrost. This could then be a factor in the extreme temperatures in Europe of which Spain is an example. A deep-learning regression model could be effective in identifying a correlation between the melting permafrost and high temperatures

https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2004RG000157#:~:text=Snow%20can%20be%20interrupted%20and,et%20al.%2C%202001%5D.

Text

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**Data**

The European Space Agency Permafrost Climate Change Initiative (ESA CCI) added permafrost as an ‘Essential Climate Variable’ (ECV) in 2018, since then the Permafrost CCI has developed and publicised permafrost maps primarily derived from satellite measurements as ECV products. The latest ESA CCI data products are selected for a deep-learning regression model because of the variety of data types, length of data and accuracy. The data that will be used for the model is: Ground Surface Temperature, Ground Temperature at 1m,2m,5m and 10m depth, Active Layer Thickness and Permafrost Extent. All the ESA CCI datasets are annual averages covering the northern hemisphere (north of 30°) from 1997-2019 with a spatial resolution of 926.63m. The thermal model is constrained by MODIS and downscaled ERA5 data [27]. It has been argued that only continuous and discontinuous permafrost can be identified by climate models due to coarse resolution [32], so only continuous permafrost data will be used from the Permafrost Extent database. Discontinuous permafrost cannot be used because it does not reliably depict trends as [SHOWN IN FIGURE} permafrost becomes sparser; the continuous permafrost becomes discontinuous, while discontinuous permafrost becomes sporadic, so the extent of discontinuous permafrost might remain the same despite changes. Additional monthly land surface temperature data for 2000-2010 is collected from the ESA Data User Element (DUE) Permafrost product set with a 25km spatial resolution. The ERA5 dataset is used to gather 2m air temperature monthly average information for Spain and any other countries at 0.25°x0.25° resolution [33].

Why just used continuous

Time & spatial

Why just using continuous not sparse

**Methodology**

The ESA CCI datasets were processed to retrieve annual average ground temperatures at the surface and 1m, 2m, 5m and 10m depth, average active layer thickness. The ESA CCI permafrost extent for the northern hemisphere was processed to obtain the percentage of observed sections that classify as continuous permafrost. According to the International Permafrost Association zonation: 90-100% permafrost underlain in an area distinguishes continuous permafrost . Outliers were defined as values more than three scaled median absolute deviations; this was particularly relevant for the active layer thickness dataset which has large deviations of several metres in extreme cases due to incorrect ground stratigraphies [27]. The 2m air temperature ERA5 monthly aggregates were collated in Google Earth Engine where country specific data was acquired by masking data not within the specified geometry. The geometry was defined by layering the FAO Global Administrative Unit Layers (GAUL) Country Boundaries dataset over the ERA5 dataset and filtering by GAUL country codes. To investigate correlation between permafrost state and European temperatures a deep-learning regression model is attempted with individual country max 2m air temperature as the target variable. Initial attempts at applying a deep learning model were constrained by the shortness of data with the ESA CCI only covering annual summaries from 1997-2019. Monthly land surface temperatures from the ESA data User Element (DUE) Permafrost full product set from 2000-2010 were considered in a pre-model process to understand the weighting of the ESA dataset parameters in relation to a smaller temporal resolution. This allowed an increase in the volume of data and allow the use of monthly 2m air temperature averages rather than annual. The data is first split into a training, validation and test sets which will be used for a holdout validation strategy [MAKE A DIAGRAM]. The architecture consists of an input layer composed of 27 dense input neurons. This is followed by two hidden layers with 50 neurons each which are Rectified Linear Unit (ReLU) activated. ReLU was chosen because of its effective gradient propagation with relatively sparse data and to avoid the ‘vanishing gradients problem’ [28]. The final layer is the output layer containing one neuron with a linear activation function. Weights are optimized over 10 epochs through a mini-batch gradient descent algorithm with a mini-batch size of 1 to account for the relatively small data size and to create a high model update frequency. The model aims to minimize error values that are calculated through a Mean Squared Error loss function (MSE). MSE was chosen because of its applicability to regression problems.

is a data point, is its predicted value and is the total number of data points.

Graph of holdout validation strategy

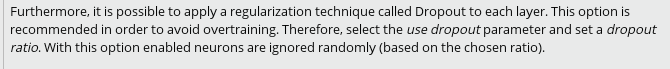
Graph of data stuff

Could still talk about smoothing (factor 50) in methodology

Talk about and show results of predictions non-extened

One-hot encoding

How cause & change is hard to prove so comparing results between other countries is important



**In Methodology can talk about getting the data like this:  
A picture containing text

Description automatically generated**

**Data handling and Visualisation little chapter at the end**

**Results & Discussion**

Due to the monthly temporal resolution of the DUE LST data in the pre-model study, a reasonably high correlation was expected on account of the natural oscillation of temperature over the months. This expectation proved correct with the overall correlation of permafrost factors: (monthly DUE Land Surface Temperature and Annual average active layer thickness, ground surface temperature, ground temperature at 1,2,5,and 10m depth, percentage of continuous permafrost) and the monthly max 2m air temperature in Spain being calculated as 0.847 +/- 0.066 with a relative error lenient of 9.26% +/-1.23%. Out of the variable factors, the DUE average LST was weighted the most (0.277), followed by the average ground temperature at the surface, d 5m depth and the active layer thickness. This is likely because the DUE LST data is monthly and therefore correlates more reliably with the monthly 2m air temperature in Spain. The active layer thickness was expected to be heavily weighted as it has long been a key indicator of permafrost state [8,9,11,13] and it’s allocated weight benefits the model’s accuracy. The temperature at 5m depth was unexpectedly heavily weighted, this could be because it fluctuates less than temperatures at a 1m and 2m depth but still represents trends more accurately than the temperature at 10m depth [SHOWN IN FIGURE]. While this model suggests a strong correlation between the temperatures in Spain and permafrost variables, the result on its own does not determine that the correlation isn’t a result of global warming affecting both areas, rather than one affecting the other. To understand the result in context, the 2m air temperatures of Ireland and Iceland were put through the regression model. The resultant overall correlation between the permafrost variables and the 2m air temperature in Ireland was 0.83 +/- 0.051, and even lower for Iceland: 0.828 +/- 0.049. The high latitude of both countries would suggest that they should be more consonant with the variables of permafrost, Iceland is at a higher latitude than some cases of continuous permafrost[2]. Additionally, Iceland and Ireland are exposed to arctic maritime air mass – air which is influenced by the underlying surface of the arctic which is predominately permafrost. Despite these influences, the 2m air temperature in Spain has a higher correlation with permafrost than that of Iceland and Ireland. This advocates that there is a link between the decrease in permafrost and the rising extreme temperatures in Europe, particularly prevalent in the south, as Spain exemplifies.

These results were considered in the regression model which considered the calculated weights of parameters to propose an equation to predict the max July temperatures in Spain with the degradation of permafrost from the ESA CCI dataset:

In which Average Active Layer Thickness (m), = Average Ground Temperature at 5m Depth (C°), = Percentage of observed Continuous Permafrost pixels (observed from north of 30° with a spatial resolution of 926.63m), = Average Ground Surface Temperature (C°) & = July 2m Air Temperature in Spain.  
The model performed

I propose that a factor behind the strong correlation between extreme temperatures in Spain and the reducing extent of permafrost can be defined within a ‘heater-cooler’ model in which the ‘cooler’ is the northern hemisphere permafrost that is in a rapid decline. The thawing of permafrost and subsequent ‘greening’ is causing a lower surface albedo which is reducing the amount of short-wave radiation being reflected. This could impact atmospheric circulation similarly to how changes in snow cover and sea ice do [22,23,24,25,26]. Consequently, the ‘heater’ – radiation absorbed from the Sun at the equator and circulated through the Hadley cell causing tropical rainforests and deserts – is not being balanced by the heat-release at the pole. One such way atmospheric circulation could be impacted is the lessening of the temperature difference between the Polar cell and Ferrel cell which weakens the Polar Jet stream and allows warmer air to push northwards [30]. Spain epitomises the drastic affects of extreme temperatures and desertification [31].  
Permafrost data is still too sparse and there are too many factors in air temperatures and global climates to be conclusive, but the information presented and developed in the deep-learning regression modes shows the need for further research and proposes a hypothesis of a potential global issue. Future projects such as phase 2 of the ESA CCI Permafrost data products might allow for further exploration of the topic by providing primarily satellite derived data of a greater accuracy and density.

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