***Abstract*** – The thawing of permafrost in the northern hemisphere is considered a critical contributor to the characterisation of Earth’s climate. While permafrost degradation is increasing at an accelerating rate, the climate of southern European countries, in particular Spain, have been breaking temperature records and facing longer heat wave durations and spreading desertification. This paper argues that these concurrent climate crises are not separate results of global climate change, but rather interlinked events in which permafrost has a level of causality. This is explored in a heater-cooler model that explores and attempts to represent the impact of thawing permafrost on the pole-to-equator temperature gradient, and on Spain’s climate. The model is further explored through a deep learning ‘Long Short-Term Memory’ network to assess the suggested correlation between permafrost state in the arctic and extreme temperatures in Spain. If this model were to be a factor in European temperatures it adds additional pressure to the already strained climate goals 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 occurring at a high rate and has major implications both globally and locally [5,6,7].

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].

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].

**Model**

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 [43][SHOWN 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 [36 , 37]. 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. [47]. The south of Spain is most effected, with some research suggesting that all southern Spain could be desert by 2100 [48]. [Shown in figure]

[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 [42]. 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 [6]. On release, the GHG accelerates the greenhouse effect and contributes to a positive feedback loop of thawing permafrost [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 [6]. 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 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 of the Hadley cell 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 builds 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 hypothesis portrays the impact of thawing permafrost on the temperatures in Spain through a purely latitudinal viewpoint, other anthropogenic and natural factors are incorporated as impacts on the ‘cooler’ variable as hidden factors . The two explored factors that link permafrost with polar temperatures have a form of inverse relationship [AS SHOWN IN DIAGRAM] which is represented by . The model provides a simplified expression of temperature in Spain in which the temperature is dispersed latitudinally by a differential curve [AS SHOWN IN DIAGRAM].

To test the model, a FSTM deep learning approach can be made to analyse the relationship between permafrost and Spain temperatures that the ‘heater-cooler’ model suggests. The extent of permafrost greening can be inferred from increases in surface temperatures and active layer thickness, GHG release from permafrost can be approximated from the general degeneration of permafrost – this assumes a generalised release of carbon from permafrost when in reality, biome and other factors influence the volume of GHG release [6].

**Data Preparation**

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 FSTM 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 (C°), Active Layer Thickness (m) 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. Google Earth Engine (GEE) is used to collect 2m air temperature monthly information for Spain and any other countries at 0.25°x0.25° resolution from the ERA5 dataset [33].

The annual permafrost surface temperature is extrapolated to monthly averages by following the distribution of the ESA DUE monthly land surface temperature. The extent of continuous permafrost is identified from the dataset through the sum of elements with a permafrost-underlain of 90-100%, as classified by the International Permafrost Association zonation [ALL ABOUT FROZEN GROUND REFERENCE]. The data is standardised as a percentage of observed continuous permafrost to clearly display trends. The extent of continuous permafrost and the active layer thickness annual averages are extrapolated to monthly averages according to the frost index cosine approximation proposed by F.E.Nelson and Samuel I. Outcalt [41].

**Deep Learning FSTM Regression Network**

To analyse the proposed ‘heater-cooler’ model, data from which the GHG released, and albedo decrease of permafrost can be correlated, is processed through a deep learning LSTM recurrent neural network. Given the suggested causality between permafrost state and temperatures in Spain, the algorithm aims to predict monthly max 2m air temperatures in Spain from the inputted: continuous permafrost extent (%), average active layer thickness (m), and average ground surface temperature (C◦). LSTM is a variant of a Recurrent Neural Network (RNN), a neural network which supports processing of sequential data by looping within hidden layers to preserve the state of nodes while stepping through the sequential input data. The interpolated data contains monthly averages from 1997-2019, RNN was selected because it allows for previous inputs to be considered in the machine learning process which makes it particularly applicable to time-series data problems. RNN’s frequently suffer from the vanishing gradient problem, where the derivative of the loss function with respect to the weights repeatedly becomes smaller as the network updates the weights of older layers, and the exploding gradient problem in which error gradients accumulate into large gradients that destabilise the network. LSTM removes these problems by regulating the cell what’s remembered within a cell – the ‘cell state’ - with gates composed of sigmoid () layers; a ‘forget gate layer’ is used to identify which previous information should be kept, a ‘input gate layer’ then decides on the values to be updated and a layer creates the new candidate values, the cell state is then updated by the scaled candidate values, the output of the module is then based on the filtered cell state [40].

The FSTM deep learning regression network used to predict Spain’s’ monthly max 2m air temperatures given three permafrost factors consists of four hidden layers: An input layer, a LSTM layer consisting of 200 hidden units, a dense layer, a dropout layer with a probability of 0.5 to nullify an input – this alters the network architecture between iterations to prevent the network overfitting, another dense layer and finally the output regression layer. The loss function applied is defined as the half mean squared error of the predicted responses for each time step:

Where = number of responses, = Sequence length, = target output, = network prediction. The network utilises Adaptive Moment Estimation (ADAM) optimised gradient descent with an initial learning rate of 0.01, the optimisation combines the advantages of the ‘momentum’ and ‘Root Mean Square Propagation’ gradient descent algorithms to create an extremely well performing optimisation [39]. The gradient threshold is set to one to further prevent the exploding gradient problem and the data is standardised to have zero mean and unit variance before training to prevent divergence.

**RESULTS & GRAPHS OF MODEL PREDICTIONS AND RMSE**

Discussion

The results show a strong correlation between the extent of continuous permafrost, ground surface temperature of permafrost, active layer thickness and monthly 2m max air temperatures. The low RMSE of the testing data applied to the LSTM deep learning regression algorithm (RMSE: 0.374) advances the hypothesis that permafrost degradation is a factor in the high temperatures in Spain. An obvious impugn to the reliability of the results is that both permafrost and Spanish temperatures are influenced by the global warming climate. To suggest at least a partial causality between permafrost and Spanish climate; the FSTM deep learning regression algorithm is applied to monthly ERA5 max 2m air temperature data of Sweden and Finland. If the deep learning algorithm is only correlating permafrost features with European air temperatures because of overall global warming, then it connotes that the algorithm would be more accurate when applied to countries with similar climates too permafrost zones. Both countries are at a higher northern latitude than Spain [EDITOR NOTE: Need to insert bit about countries related climate to permafrost zone, share the same arctic maritime air mass as permafrost etc..]. Despite the climatical similarities, the algorithm’s predictions were less accurate when predicting future temperatures of Finland’s’ max monthly 2m air temperature (RMSE: 3.254) and Sweden’s max monthly 2m air temperature (RMSE: 3.475), this suggests that the correlation between permafrost state and Spain’s climate is not purely a mutual result of global warming- but that there is a causation between the two. This contributes to validating the ‘cooler-heater’ model’s hypothesis of diminishing permafrost impacting the balance of equatorial and polar temperature gradients which in turn, alters atmospheric circulation in the form of Hadley Cell expansion, that leads to the subtropical zone shifting poleward and therefore, warming the climate of Spain.

It is indubitable that both permafrost, and Spain’s climate are affected by the global rise in temperatures, as well as a multitude of other factors. The ‘heater-cooler’ model could be expanded perpetually with additional attributes, one recommendation would be to incorporate the climate impacts of the polar jet stream, which is shifting northwards but also weakening as a result of the pole-to-equator temperature gradient [45,46]. This allows warmer air to push northwards and remain in place for abnormally long periods of time [38], which could be used to expand the model to link permafrost state to the duration of heatwaves in Spain. In its current form, the ‘heater-cooler’ model hypothesises the connection between permafrost and high temperatures in Spain and is emboldened by hypothetical bifurcation theory [46], current atmospheric circulation trends [36,37] and FSTM deep learning regression. The model makes assumptions in the interpolation of data and in its standardisation of albedo and GHG impacts, which vary depending on an immense number of factors. While this might alter the in-world practicality of the model, the overall theme of the ‘heater-cooler’ model – suggesting that permafrost state is affecting the Spanish climate – is unaffected. The implications of the ‘cooler-heater’ model affect ‘point-of-no-return’ climate estimations [35]. Permafrost degradation continues to accelerate and could already be past the point of a positive feedback loop [34], the model infers that as a result the temperatures in Spain will continue to rise, fuelling the desertification of the country. The model expresses permafrost as a factor of the climate crisis in Spain, advocating the intrinsic interconnectivity of the global climate.

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