**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 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 [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 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 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 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 factors explored 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]

* Key causes of greening are active layer thickness and surface temperature increasing
* Key causes of GHG release is overall shrinking of permafrost can be shown by reduction in continuous permafrost, give reference for how these link
* These key factors + hidden factors define the ‘cooler’ variable, and can be processed through a FSTM Deep learning model to see the correlation with temperatures in Spain and test the model
* Data
* Data interpolation