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The spatial variation in degree days derived from locational attributes for the 1961 to 1990 period

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The relationship between degree days and locational attributes for a selection of sites in Ireland were examined in order to objectively extrapolate values for unmeasured locations. While a number of previous researchers have employed similar methodologies in order to map the geographical variation for selected degree-day thresholds, the authors seek to expand on this existing research through the inclusion of a denser network of stations and for a longer time period (1961 to 1990). Degree days were calculated on a daily basis for three selected threshold temperatures, 0 ºC, 5 ºC, 10 ºC, in order to provide a more accurate assessment of the accumulated monthly energy available at each station. The geographical distribution of degree days was then mapped employing a stepwise linear regression which related locational parameters for each station to the calculated monthly accumulations. While none of the selected thresholds are specific to any plant or insect species they are indicative of the likely spatial variation in degree days due to location and elevation. It is intended that the derived spatial distributions will be useful in providing a basis for assessing likely changes in the thermal regime arising as a consequence of climate change over the course of the present century with the associated potential impact on spatial location of arable cropping in Ireland.

*Keywords***:** degree days; Ireland; mapping; regression; spatial variation

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Introduction

Degree days provide a simple estimate of the accumulated heat energy available over the growing season or life cycle of an organism and represent an important factor for all biological development. The rate of growth and phenological development of individual plant and insect species has been found to increase almost linearly from a base to a limiting temperature threshold (Cesaraccio *et al.*, 2001). Thus, the concept of the degree day is based on three assumptions; a base temperature exists such that a plant species will not grow if temperatures are below this value, plant growth is proportional to an accumulation of energy above a threshold temperature and species maturation occurs only after a specific number of degree days is attained (Burke, 1968).

A number of authors have highlighted an issue with the concept of degree days, such as a changing relationship between temperature and growth during various stages of the life cycle (Wang, 1960). While temperature is a primary factor affecting phenological development, other factors, such as moisture availability, also play a crucial role. Despite the fact that the use of degree days ignores additional environmental factors which are known to affect plant growth, their use has found widespread application due to their practical utility in phenological and other studies (Wang, 1960; Idso *et al.*, 1978). A number of authors have examined the spatial variation in degree-day totals, either implicitly (Burke, 1968) or explicitly (McEntee, 1978; Hargy, 1997) for a selected number of locations in Ireland. The described methods are further developed by examining data from a greater number of stations over an extended time period. It is intended that the derived geographical variation in accumulated degree days presented in this paper would provide a useful input tool for assessing crop suitability at a particular location and for assessing the likely impacts of climate change on the thermal regime at specific locations, both measured and unmeasured.

Materials and Methods

Data sources

Daily data for both maximum (T_{max}) and minimum (T_{min}) temperature were obtained for a total of 50 stations in Ireland; 40 of which were obtained from the Irish synoptic and climatological network, maintained by Met Éireann, supplemented with an additional 10 stations from Northern Ireland, obtained from the British Atmospheric Data Centre (BADC), for the period 1961 to 1990 (Figure 1). These stations were selected as they had 80% or greater data capture for the period under investigation. While the obtained data from the Met Éireann network were not subjected to any formal homogeneity testing, experienced meteorological officers man the synoptic stations and all data are provided with quality control flags indicating whether a value has been directly read or estimated. All values not directly measured or recorded were removed from the present analysis. The selected stations range in elevation from 6 to 213 m and consist of a mixture of both inland and coastal locations. While the upper elevation may limit extrapolation at higher levels most arable land occurs well below this threshold. Prior to assessing the spatial variation in degree days due to location, the selected stations were subjected to a nearest neighbour analysis to ensure they comprised a random spatial distribution. The nearest neighbour index was calculated as follows:

$$R = \frac{d_{obs}}{d_{ran}}$$

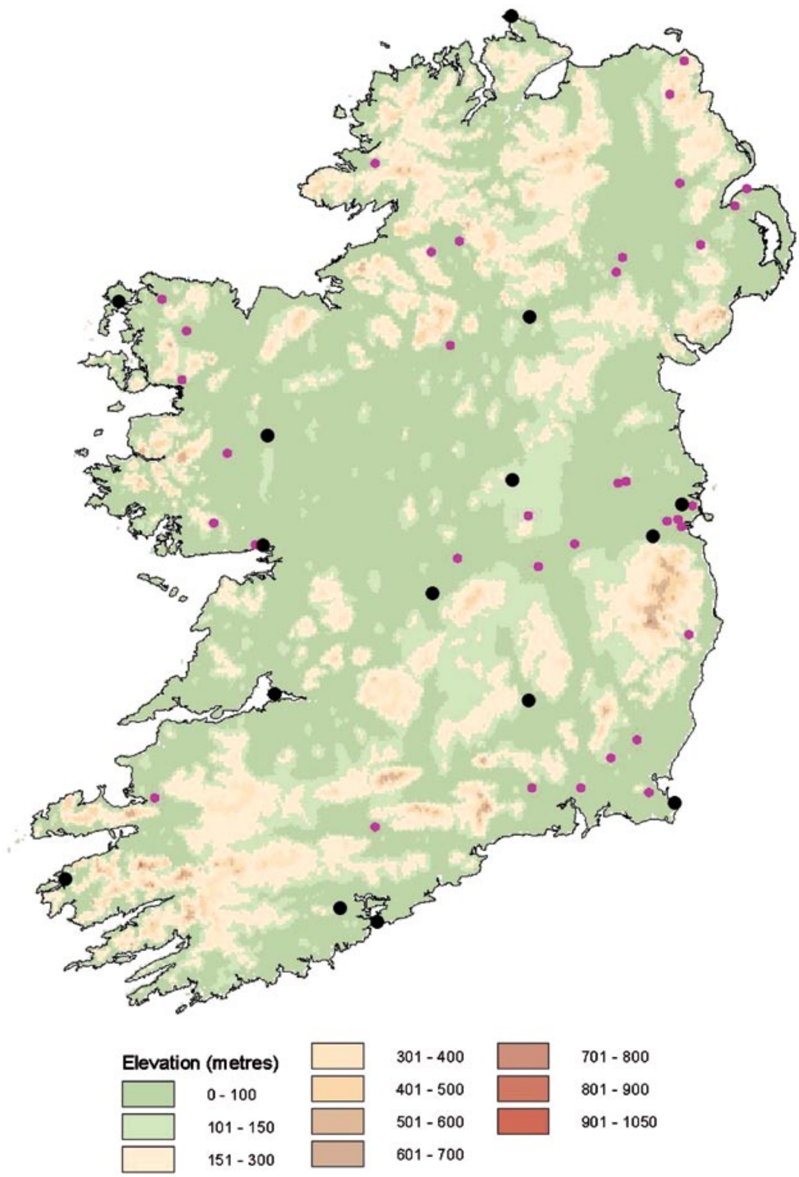

Figure 1. Elevation and location of synoptic (●) and climatological stations (•) employed in the analysis.

where d_{obs} = observed mean nearest neighbour distance and d_{ran} = expected nearest neighbour distance for a random distribution of stations.

The index varies between 0.0, indicating a clustered distribution, and 2.15, indicating a dispersed distribution of stations. A value of 1.0 indicates a random pattern. Applying this formula to the stations employed in this analysis yielded a value of R = 0.96, indicating a random distribution.

Methodology

For this study, the calculation of degree days was based on the standard single triangle method above a threshold or base temperature (T_b), as follows:

where $T_{min} > T_b$ degree (°C) days = $\frac{T_{max} + T_{min}}{2} - T_b$,

where $T_{max} < T_b$ there are no degree days above the base temperature, therefore degree days below the base temperature = $T_b - \frac{T_{max} + T_{min}}{2}$,

where $T_{max} > T_b$, $T_{min} < T_b$ and mean temperature (T_{mean}) $> T_b$ degree days above the base temperature are calculated as $\left(\frac{T_{max} - T_b}{2}\right) - \left(\frac{T_b - T_{min}}{4}\right)$ and degree days below the base temperature are calculated as $\left(\frac{T_b - T_{min}}{4}\right)$,

where $T_{max} > T_b$, $T_{min} < T_b$ and $T_{mean} < T_b$, degree days above the base temperature are calculated as $\left(\frac{T_{max} - T_b}{4}\right)$ and degree days below the base temperature are calculated as $\left(\frac{T_b - T_{min}}{2}\right) - \left(\frac{T_{max} - T_b}{4}\right)$ (Meteorological Office, 1928).

Based on these equations, degree days were calculated for three threshold temperatures (0 °C, 5 °C, 10 °C), for all stations for the 1961 to 1990 period. The 1961 to 1990 period was selected as it represents the standard 'normal' period employed by the World Meteorological Organisation (WMO), and is the period against which past and future changes in climate are generally assessed. Having calculated daily degree days for each site and threshold temperature, monthly accumulations were then derived and subsequently averaged for each month of the year for the 30-year period from 1961 to 1990 to produce a typical meteorological year. These 30-year averaged monthly accumulations were derived taking cognisance of missing values in order that the calculated values were representative across all stations and for each month.

To derive a relationship between degree days and locational variables, the 30-year averaged monthly accumulated degree days, represented by the typical meteorological year, for each site and threshold were entered into separate stepwise multiple linear regressions with locational attributes as candidate predictors. The candidate predictor variables included distance (km) from the origin, represented by eastings (x) and northings (y), the log of each station's distance from the nearest coast, derived from the Irish National Grid, and elevation (m). The use of such locational variables has been found to produce good results for deriving the spatial variation in climate variables in Ireland (McEntee, 1978; Hargy, 1997; Goodale *et al.*, 1998; Sweeney and Fealy, 2003). The multiple regression takes the form of the following equation:

$$D = c + \beta_1 x + \beta_2 y + \beta_3 \text{lndist} + \beta_4 e$$

where

D = degree days for specific threshold
c = constant
$\beta_{1.4}$ = regression coefficients
x = eastings from the origin (km)
y = northings from the origin (km)
lndist = natural logarithm of station distance (km) from nearest coast
e = elevation (m)

A number of previous authors have employed some index of continentality when mapping the spatial distribution of climatic variables in Great Britain (Lennon and Turner, 1995) and Ireland (Hargy, 1997). Continentality measures such as distance from the coast (Matzarakis and Balafoutis, 2004) or the logarithm of distance from the coast (Hargy, 1997) represent the 'coastal effect' induced by sea breezes along coastal margins. This coastal effect, which results from a heating differential between land and surrounding water surfaces, results in cooler temperatures being recorded along coastal margins during the summer months while, warmer temperatures are generally recorded, relative to inland locations, during the winter months. In this study the logarithm of a station's distance from the nearest coast was employed to represent this effect as it replicates the coast-interior-coast contrast evident in temperatures in Ireland, used as the primary input variable for calculating degree days. The use of this variable has previously been found to be a very significant variable for mapping degree days in Ireland (Hargy, 1997).

Results

The relationship between accumulated degree-day totals, calculated for a typical meteorological year, and the locational parameters employed in this analysis are shown in Tables 1 to 3. Results for degree days with a base threshold of 0 °C (Table 1) suggest that between 59 and 86% of the variation can be explained, employing the locational parameters alone. Both the elevation and northings variables were found to be the most consistent predictors of degree days for the selected threshold for all months.

For degree days with a base threshold of 5 °C, adjusted R^2 values range from 64 to 90% (Table 2). Again, both elevation and northings appear to be the most consistent variables, while the eastings variable is also seen to be important for most months. Elevation and northings again appear as the most consistent variables for predicting degree days with a base threshold of 10 °C, contributing to equations for all months (Table 3). The importance of the eastings contribution only becomes apparent during the summer and early autumn months. The distance from the coast also appears as an important predictor for the spring, summer and autumn seasons. In contrast to the calculated coefficients for the lower degree-day

Table 1. Calculated regression coefficients for selected variables relating accumulated degree-day totals, with a base threshold of 0 °C, to locational variables[1] for a selection of sites in Ireland

Month	Regression coefficients					Adj. R^2	s.e.
	Intercept	Elevation (m)	X (km)	Y (km)	Log distance		
Jan	202.9	–0.181	–0.043	–0.094	–10.85	0.867	9.7
Feb	177.2	–0.201		–0.104	–8.71	0.862	8.9
Mar	231.6	–0.272		–0.097	–8.45	0.836	10.7
Apr	272.1	–0.257		–0.082	–6.76	0.720	13.0
May	350.0	–0.299		–0.066		0.599	12.9
Jun	413.0	–0.270	0.064	–0.075		0.600	11.8
Jul	482.8	–0.272	0.090	–0.117		0.672	12.4
Aug	479.6	–0.266	0.060	–0.104		0.684	11.2
Sep	424.4	–0.246		–0.079	–4.14	0.806	8.7
Oct	365.0	–0.182		–0.079	–8.67	0.868	7.9
Nov	252.8	–0.154		–0.099	–13.96	0.845	11.5
Dec	228.9	–0.141	–0.064	–0.077	–12.53	0.846	10.8

[1] Elevation, eastings (X), northings (Y) and the natural logarithm of distance from the coast.

Table 2. Calculated regression coefficients for selected variables relating accumulated degree-day totals, with a base threshold of 5 °C, to locational variables[1] for a selection of sites in Ireland

Month	Regression coefficients					Adj. R^2	s.e.
	Intercept	Elevation (m)	X (km)	Y (km)	Log distance		
Jan	75.6	–0.100	–0.026	–0.063	–2.615	0.903	3.6
Feb	64.3	–0.098	–0.028	–0.051	–1.452	0.892	3.2
Mar	94.1	–0.175	–0.024	–0.062		0.868	4.5
Apr	134.1	–0.187	–0.037	–0.057		0.821	5.7
May	197.9	–0.245		–0.059		0.690	8.9
Jun	264.2	–0.260	0.060	–0.077		0.646	10.5
Jul	329.2	–0.268	0.086	–0.119		0.692	11.8
Aug	325.1	–0.267	0.058	–0.104		0.737	9.9
Sep	269.7	–0.255	0.029	–0.086	–3.308	0.842	7.5
Oct	210.8	–0.205		–0.081	–4.878	0.893	5.9
Nov	116.1	–0.147		–0.085	–4.462	0.900	5.0
Dec	94.8	–0.112	–0.035	–0.067	–3.666	0.897	4.4

[1] Elevation, eastings (X), northings (Y) and the natural logarithm of distance from the coast.

thresholds, the distance from the coast appears to be more important during the spring and early summer months for accumulated degree days associated with the higher threshold of 10 °C. The removal of this variable in the stepwise regression procedure for the winter months is also likely to explain the lower adjusted R^2 values, of 48 to 55%. Higher values (65 to 88%) are associated with the summer and autumn months.

Having developed regression models relating accumulated degree days to locational variables, for each selected base threshold and month, the calculated regression coefficients were then employed in conjunction with a GIS (Geographic Information System) to produce mapped climate surfaces of accumulated degree days for all locations. Essentially, a number of raster grids, each representing a mapped surface of each of the locational

Table 3. Calculated regression coefficients for selected variables relating accumulated degree-day totals, with a base threshold of 10 °C, to locational variables[1] for a selection of sites in Ireland

Month	Regression coefficients					Adj. R^2	s.e.
	Intercept	Elevation (m)	X (km)	Y (km)	Distance		
Jan	4.5	–0.016		–0.005		0.481	1.0
Feb	4.0	–0.013		–0.005		0.471	0.9
Mar	9.6	–0.033		–0.009	0.453	0.428	2.0
Apr	24.6	–0.074		–0.015	1.728	0.552	3.2
May	58.8	–0.126		–0.024	2.526	0.501	5.8
Jun	114.7	–0.213	0.053	–0.069	3.017	0.647	8.4
Jul	171.7	–0.270	0.080	–0.118	2.886	0.720	10.6
Aug	173.6	–0.232	0.056	–0.106		0.797	7.9
Sep	121.4	–0.217	0.031	–0.081		0.850	5.6
Oct	70.9	–0.124		–0.053	–0.995	0.882	3.3
Nov	20.0	–0.039		–0.025	–0.495	0.835	1.6
Dec	8.5	–0.027		–0.010		0.639	1.3

[1] Elevation, eastings (X), northings (Y) and the natural logarithm of distance from the coast.

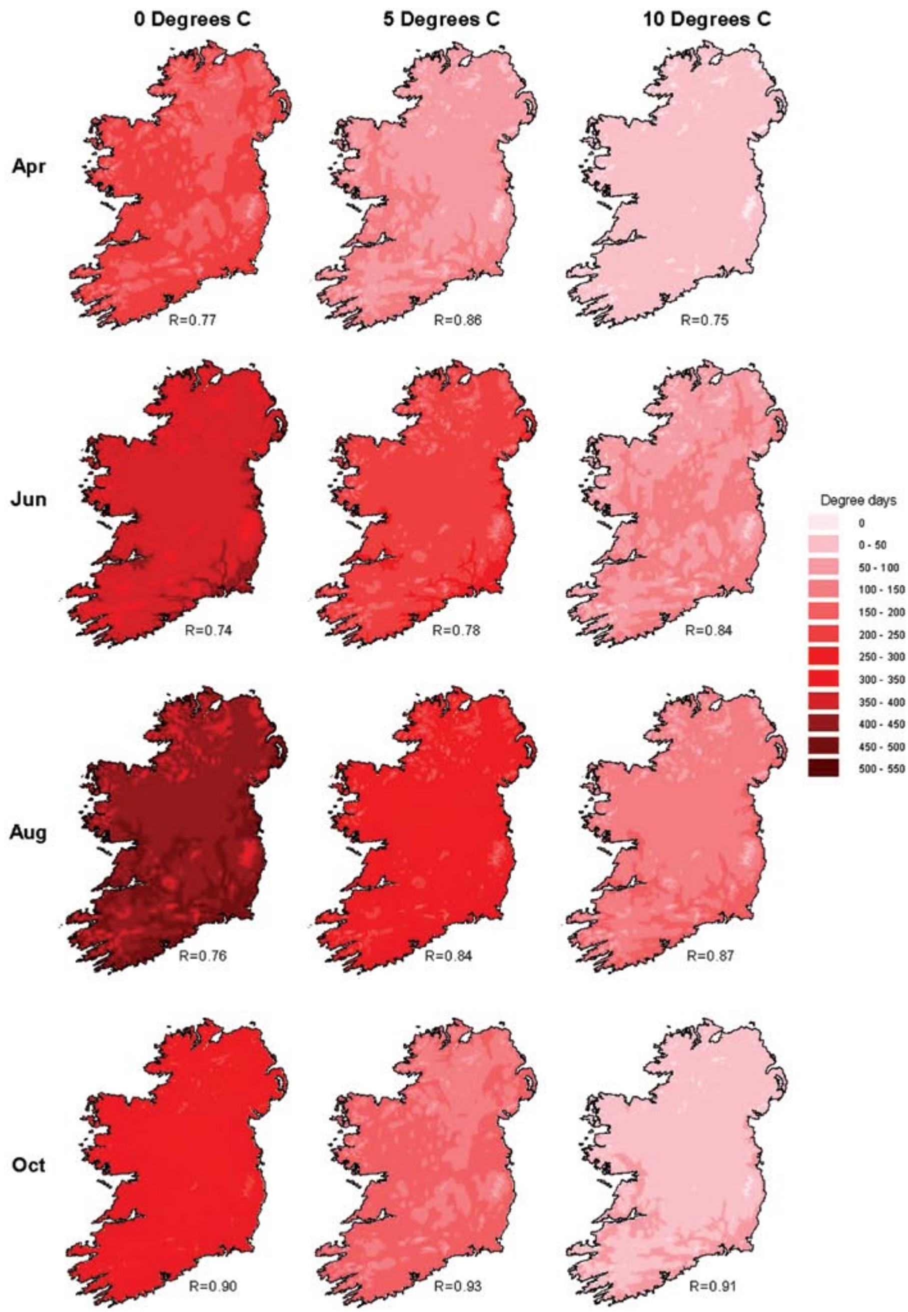

Figure 2. Spatial variation in accumulated degree days, for selected thresholds and months. Values represent the average monthly accumulated degree days for the 1961 to 1990 period or (typical meteorological year). R values represent the correlation between observed station values and values predicted by the spatial models employed to predict monthly accumulated degree days.

variables, were employed as inputs to produce a continuous surface of the spatial variation of accumulated degree days for each of the base temperature thresholds for unmeasured locations. The inputs used were a digital terrain model for elevation and grids of eastings, northings and the logarithm of distance from the coast. The results for a selection of months are shown in Figure 2.

The digital elevation model (DEM) employed in this analysis was derived from the 30 Arc Second Global Elevation (GTOPO30) dataset from the U.S. Geological Service. The resolution of the GTOPO30 DEM is approximately 1 km in the north-south direction at the latitude of Ireland. The dataset was reprojected to the Irish National Grid and resampled to a resolution of 1 km^2. While this resolution is considered adequate for mapping climate surfaces, it is likely to result in an under representation of elevation on peaks and ridges, such as those found on the McGillicuddy Reeks, while plateau-like mountain tops, such as those in Wicklow, are likely to be more accurately represented. As a consequence, results for high-elevation/high-relief locations will be less representative than for low-elevation/low-relief locations. As productive agriculture is generally limited by both elevation and terrain, the impact of employing this DEM is not considered to be critical to the results presented.

In order to validate the mapping technique, values representing modelled station locations, were extracted from the continuous mapped surfaces and compared with actual calculated accumulated degree-day values from each station. Both modelled and actual values were compared employing the Pearson's correlation and all correlations were found to be significant at the 0.01 level (Table 4).

A comparison of the calculated mean degree-day totals at both Valentia, a coastal station, and Kilkenny, an inland station, and modelled degree days for both of these locations based on the mapping procedure, for each month and for selected base thresholds are shown in Figures 3 and 4. Modelled values match the calculated station values quite closely for both stations and for all months. Mean degree-day accumulations for Valentia, for the months from March to October inclusive, for a base threshold of 0 °C (2,933) compare to the modelled degree day accumulations (2902), indicating the usefulness of the mapping technique and the potential for calculating degree days at unmeasured locations.

The importance of location relative to the coast during the late autumn, winter and early spring months is important, particularly for the 0 °C threshold. At Valentia, there were 201 accumulated degree days for January over the 1961 to 1990 period, while for Kilkenny there were only 81 degree days (40%). While the difference in the number of accumulated degree-days decreases between these sites up until the month of July, when the number of degree days at Kilkenny exceeds those of Valentia,

Table 4. Correlation[1] between accumulated degree-day totals, for selected thresholds, calculated from observed data and degree-day totals derived for station locations by the spatial models

Month	Degree-day temperature threshold		
	0 °C	5 °C	10 °C
Jan	0.89	0.91	0.63
Feb	0.88	0.90	0.63
Mar	0.86	0.86	0.70
Apr	0.77	0.86	0.75
May	0.75	0.79	0.75
Jun	0.74	0.77	0.84
Jul	0.80	0.81	0.87
Aug	0.81	0.84	0.87
Sep	0.89	0.90	0.92
Oct	0.90	0.92	0.91
Nov	0.88	0.92	0.87
Dec	0.89	0.92	0.76

[1] All correlations were significant at $P < 0.01$.

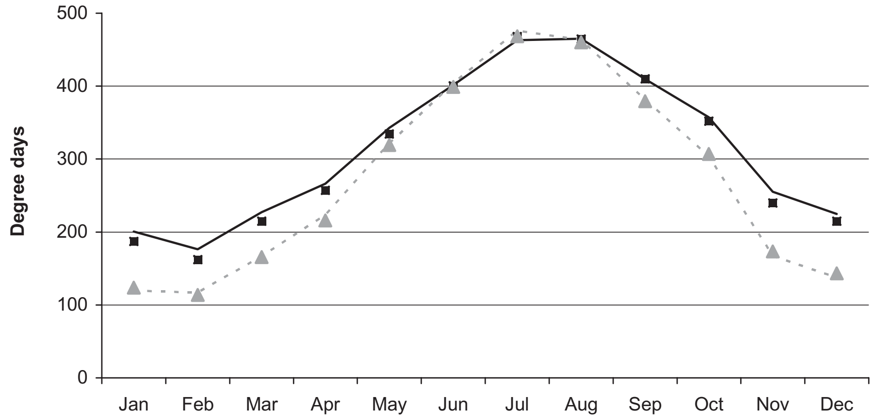

Figure 3. Comparison of observed (Obs) and modelled (Model) degree days, for a base threshold of 0 °C, for Valentia (Val.), a coastal station, and Kilkenny (Kilk.), an inland station. (—— Obs Val. - - - - Obs Kilk. ■ Model Val. ▲ Model Kilk.)

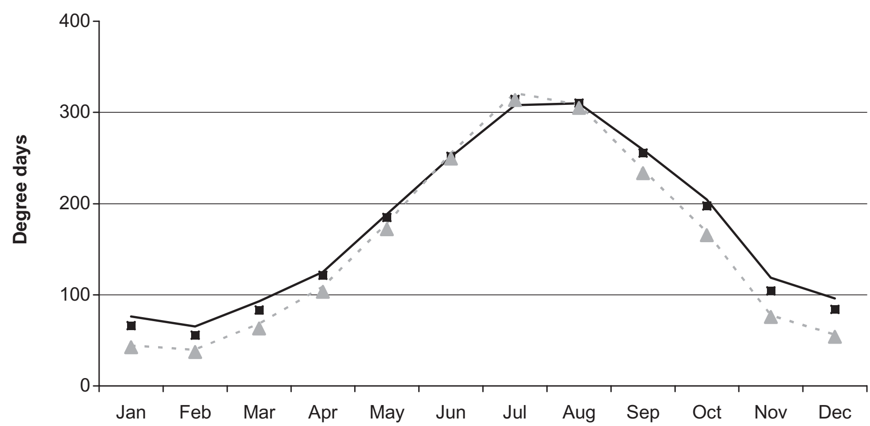

Figure 4. Comparison of observed (Obs) and modelled (Model) degree days, for a base threshold of 5 °C, for Valentia (Val.), a coastal station, and Kilkenny (Kilk.), an inland station. (—— Obs Val. - - - - Obs Kilk. ■ Model Val. ▲ Model Kilk.)

degree days at Valentia exceed those of Kilkenny in subsequent months.

On an annual basis, the thermal advantage of coastal locations is even more marked (Keane and Sheridan, 2004); for example, there were on average 3,790 (modelled 3,706) annual accumulated degree days at Valentia, for 0 °C threshold, while at Kilkenny, there were 3,281 (modelled 3,269) mean annual accumulated degree days over the 1961 to 1990 period. Even at Malin Head, in the extreme north of the country, mean annual accumulated degree days of 3,414 (modelled 3,390) exceed those of Kilkenny when compared on an annual basis.

To illustrate this 'coastal effect' on degree days, annual accumulated degree days for the 0 °C threshold were calculated from the monthly mapped surfaces. The annual accumulated degree days were then converted to standard deviations and these values were mapped in 1 s.d. intervals, above and below the mean (Figure 5). Based on this analysis, a narrow margin along low-lying coasts in counties Wicklow,

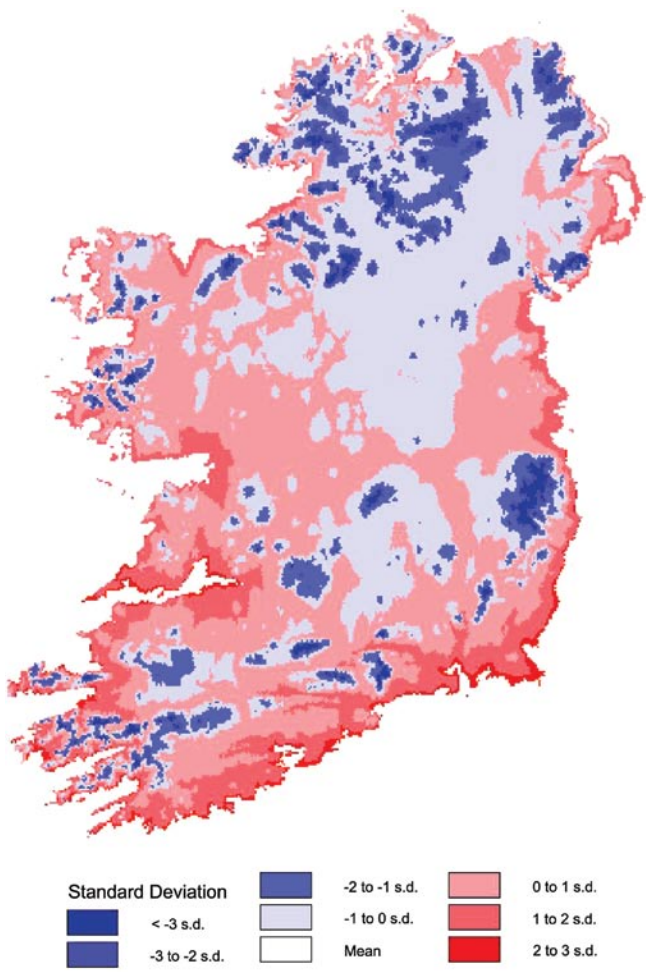

Figure 5. Annual accumulated degree days, for the 0 °C threshold, converted to standard deviations from the mean. A marked narrow margin with values of between 2 to 3 standard deviations from above the mean is evident around the Irish coastline, from Wexford to Clare.

Wexford, Waterford, Cork, Kerry and Clare is evident with values of between 2 to 3 s.d. above the mean. This coastal margin is between 1 to 3 km in width; findings which are similar to McEntee (1978).

Discussion

The variance explained by the locational parameters suggests that location is an important factor in determining accumulated degree days at a site. The variance accounted for by these locational variables suggests that accumulated degree days could be adequately modelled for unmeasured locations. The methodology and results presented have the potential to be exploited for any purpose that requires knowledge of degree days totals, previously only available for site specific locations, such as weather stations. The ease of implementation of the described methodology also means that specific temperature thresholds, relevant for a particular application, can be readily mapped employing just locational and elevational parameters. It is intended that the mapping technique and resultant datasets could be incorporated into a decision-support tool providing important agri-environmental information for relevant stakeholders. Additional work should also be undertaken with regards to assessing the impact of future climate change and what effect this may have on accumulated degree days and on subsequent changes in the spatial pattern of agricultural production in Ireland.

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