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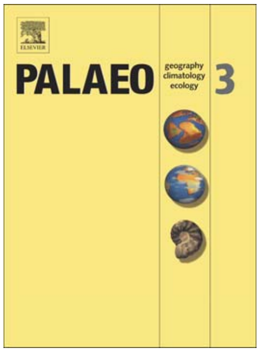

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New Developments in CLAMP: Calibration Using Global Gridded Meteorological Data

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Abstract: Climate Leaf Analysis Multivariate Program (CLAMP) is a versatile technique for obtaining quantitative estimates for multiple terrestrial palaeoclimate variables from woody dicot leaf assemblages. To date it has been most widely applied to the Late Cretaceous and Tertiary of the mid- to high latitudes because of concerns over the relative dearth of calibration sites in modern low-latitude warm climates, and the loss of information associated with the lack of marginal teeth on leaves in paratropical to tropical vegetation. This limits CLAMP's ability to quantify reliably climates at low latitudes in greenhouse worlds of the past.

One of the reasons for the lack of CLAMP calibration samples from warm environments is the paucity of climate stations close to potential calibration vegetation sites at low latitudes. Agriculture and urban development have destroyed most lowland sites and natural vegetation is now largely confined to mountainous areas where climate stations are few and climatic spatial variation is high due to topographic complexity. To attempt to overcome this we have utilised a 0.5° x 0.5° grid of global interpolated climate data based on the data set of New et al. (1999) supplemented by the ERA40 re-analysis data for atmospheric temperature at upper levels. For each location, the 3-D climatology of temperature from the ECMWF re-analysis project was used to calculate the mean lower tropospheric lapse rate for each month of the year. The gridded data were then corrected to the altitude of the plant site using the monthly lapse rates. Corrections for humidity were also made. From this the commonly returned CLAMP climate variables were calculated. A bi-linear interpolation scheme was then used to calculate the climate parameters at the exact lat/long of the site.

When CLAMP analyses using the PHYSG3BR physiognomic data calibrated with the climate station based MET3BR were compared to analyses using the gridded data at the same locations (GRIDMET3BR), the results were indistinguishable in that they fell within the range of statistical uncertainty determined for each analysis. This opens the way to including natural vegetation anywhere in the world irrespective of the proximity of a meteorological station.

Keywords: CLAMP; palaeoclimate proxy; Paleogene; gridded meteorological data

Introduction

CLAMP (Climate Leaf Analysis Multivariate Program) (Wolfe, 1993) belongs to a class of land plant palaeoclimate proxies that are based on the intimate functional relationship that exists between plant architecture (physiognomy) and the environment to which that architecture is exposed. Physiognomic environmental adaptation occurs within the context of the capabilities imparted by the genome honed by long-term natural selection. Non-adapted physiognomies fail to survive, and over time there is a degree of convergence of form largely independent of taxonomy (Spicer, 2000; Spicer, 2007; Spicer, 2008). No single architectural feature of a leaf, or whole plant, determines adaptive success (Lande and Arnold, 1983), and no single feature can be expected to correlate with a single climatic variable. Instead numerous interacting traits influence fitness (Ackerly et al., 2000) and span the architectures of conducting tissues in roots, stems and leaves, overall canopy architecture (Hellicker and Richter, 2008) and foliar physiognomy. Of course in reality environmental conditions are always in a state of flux, as is inter-plant competition. Because of this, congruence between any aspect of physiognomy (e.g. wood anatomy, leaf architecture, canopy structure etc.) and an inherently dynamic environment can never be perfect. Nevertheless uncertainties can be minimized by examining a number of plant characteristics and a variety of environmental variables within populations of diverse taxa.

Because physiognomic adaptations are grounded in the time-stable physical laws governing, for example, fluid flow in vascular systems, diffusion processes through stomata, radiation absorption and emission from leaves, boundary layer processes over plant surfaces and structural mechanics, they display high levels of convergence in space and time. Such physiognomic adaptations contribute significantly to the maintenance of local humid microclimates, and in particular optimal leaf temperatures (Hellicker and

Richter, 2008) and therefore photosynthetic performance, independent of the prevailing external environment. In moderating such local climatic conditions against less optimal regional climates the adaptations reflect larger-scale atmospheric conditions and important feedback processes that determine physiognomic traits.

Unfortunately the plant fossil record preserves only isolated dispersed organs and not whole plants or canopy architectures. Consequently, for palaeoclimatic purposes attention has focused on the leaves of long-lived (woody) dicots that are both relatively abundant in the fossil record and have a demonstrable plasticity in response to the environment to which they are exposed (e.g. (Bailey and Sinnot, 1916; Bailey and Sinnott, 1915; Wilf, 1997). Because fitness is the result of numerous interacting traits, multivariate statistical analysis has proved to be the most effective tool for examining the relationship between foliar physiognomy and climate (Wolfe, 1993).

CLAMP is a procedure for determining palaeoclimate parameters from fossil leaves using as training sets the numerically scored physiognomy of living woody dicots in known climatic regimes. In its most widely used configuration CLAMP is capable of returning the following parameters: mean annual temperature - MAT, warm month mean temperature - WMMT, cold month mean temperature - CMMT, length of the growing season - LGS, mean growing season precipitation - GSP, mean monthly growing season precipitation – MMGSP, precipitation during the three wettest months - 3-WET, precipitation during the three driest months - 3-DRY, specific humidity - SH, relative humidity - RH, and enthalpy. To date the existing training sets are primarily derived from warm to cool temperate climates in North America, and Japan. The PHYSG3AR data set is made up of 173 samples and includes vegetation growing where freezing is prevalent, but the MAT is no lower than –2 °C and the CMMT is warmer than –15.2 °C. A sub-set of PHYSG3AR made up of 144 samples excludes the colder sites where the lowest MAT is 3.9 °C and all the CMMTs are above –10.7 °C. This is the PHYSG3BR data set and offers the most precision for warm climates. Other experimental data sets exist, such as PHYSG3CR, which is the PHYSG3AR set with an additional 20 sites from across the former Soviet Union, including the Siberian interior, where the CMMT is as low as –40 °C (Spicer et al., 2004). In all these data sets the number of vegetation samples from tropical (>23.5 °C) regimes is small (17) and some of these are above 1000 m in altitude and hence in cooler temperature regimes.

The underlying multivariate statistical engine in CLAMP is Canonical Correspondence Analysis (ter Braak, 1986). This is a direct ordination technique that utilizes both the physiognomic data array (the most commonly used being designated PHYSG3BR) and its corresponding meteorological data array (e.g. MET3BR). The positions in multidimensional space of the vegetation samples are defined by the physiognomy of the full range morphologies displayed by leaves from a minimum of 20 woody dicot taxa in each sample. This multidimensional cloud of training set sites is known as “physiognomic space”. Climate vectors are positioned through multidimensional “physiognomic space” using observed meteorological data corresponding to the vegetation sites. Physiognomic space is defined, therefore, by the multidimensional cloud of modern vegetation sites positioned relative to one another using the numerical description of their foliar physiognomy. The vectors are calibrated using the observed climate data and the position of a fossil site along the calibrated vector provides an estimate of the palaeoclimate.

The precision of a climate retrodiction for any given fossil site will 1) be dependant on how close the fossil site plots to a calibrated vector, and 2) the multidimensional proximity of sites in the training sets. At the present time the dearth of calibration sites in subtropical and tropical environments limits the applicability of CLAMP to fossil assemblages deposited at mid to low palaeolatitudes. This limitation is compounded when applied to warmer climates of past so called “greenhouse worlds”, which might have represented warmer climates than seen today.

To overcome this we have embarked upon a programme of adding more modern sites from warm temperate through tropical climate regimes. However in much of the Old World thousands of years of agriculture, coupled with more recent economic growth and urban expansion, have decimated lowland/coastal natural vegetation in areas where meteorological stations have >30 years of continuous records that make up the so-called “climate normals”. The only sites of relatively undisturbed vegetation are now confined to mountain slopes in remote areas where climate stations are lacking.

To attempt to overcome the lack of climatic information in areas where vegetation suitable for CLAMP calibration still exists, we have modified the global gridded climate data set of New et al. (New et al., 1999), to provide a new set of CLAMP meteorological data. Here we test the congruence between the original CLAMP meteorological calibration data and those derived from gridded data and evaluate CLAMP analyses using the gridded calibrations.

Materials and Methods

CLAMP Analysis

The existing CLAMP training sets are made up of foliar physiognomic data derived from a minimum of 20 taxa of woody dicots (trees, shrubs and lianes) collected from natural vegetation growing close (usually within 1 km radius) to a meteorological station at the same altitude. Thirty one character states were scored for each species following Wolfe's (Wolfe, 1993) protocols and as explained on the CLAMP website (www.open.ac.uk/earth-research/spicer/CLAMP/Clampset1.html). Overall physiognomic percentage scores for each site were calculated using the automated spreadsheets available from the CLAMP website. It is worth noting that during this process we detected a few minor errors in Wolfe's original physiognomic scores that we assume were a result of small arithmetic or rounding errors during the manual calculation of the percentage scores. These errors made no appreciable difference (< 0.5 °C) to test palaeotemperature retrodictions, and were always within the statistical uncertainties for all climate parameters. Nevertheless these errors have now been corrected into new site x physiognomic score data arrays that carry the letter "c" at the end of their identifier (e.g.PHYSG3BRC).

CLAMP analyses couple the PHYSG3BRC array with the array of meteorological data observed at the PHYSG3BRC sites. This is the MET3BR data set consisting of in the most part annual averages, the exceptions being three month averages for 3-WET and 3-DRY. A minimum of thirty years of observations were, in the most part, used in compiling these data but the periods over which the observations were made were not standardised (Wolfe, 1993). A gridded meteorological data set, GRIDMET3BR, was calculated for all the PHYSG3BRC sites using the procedure that follows.

Gridded Meteorological Data

The starting point for the gridded data used here is the 0.5° x 0.5° grid of global climate data of New et al. (1999) supplemented by the ERA40 reanalysis data for atmospheric temperature at upper levels. This data set was chosen because it provided humidity data, as well as temperature and precipitation data, necessary to calculate all the CLAMP meteorological parameters. To be consistent and to ensure relative humidity was calculated correctly we chose not to mix published meteorological data sets. The New et al. (1999) data are derived from the World Meteorological Organisation (WMO) 1961-1990 global observed standard normals released in May 1997 through the National Climate Data Center (NCDC), supplemented by other data from national meteorological agencies collated by those authors. This allowed access to more data, particularly spatial, than were available through the NCDC. A maximum of 12,092 ground stations provided the mean temperatures, 10,727 the diurnal temperatures, and 19,295 the precipitation data. Data relevant to humidity and enthalpy were available from fewer stations with vapour pressure and relative humidity being observed at 3887 and 4342 stations respectively. See New et al. (1999) for a more detailed account of data sources, standardizations where more than one definition of a climate variable was used, and uncertainties.

To correct for the effect of altitude, we use a geographically variable lapse rate. This was calculated by using the 3-D climatology of temperature from the ECMWF re-analysis project (Uppala et al., 2005) to yield the mean lower tropospheric lapse rate for each month of the year. These data are on a 96 x 73 grid that was then interpolated onto a 720 x 360 grid (0.5° x 0.5°) using a bilinear interpolation scheme that conserves area averages. This interpolation scheme inevitably smoothes altitudes. The relationship between the observed altitude of the CLAMP calibration sites and those generated by the gridded data set is shown in Figure 1. The gridded data were then corrected to the observed altitude of the exact latitude and longitude of the CLAMP calibration site using the monthly lapse rates and a bilinear interpolation scheme. The specific and relative humidities were also recalculated in light of the lapse rates. If the lapse rate corrected temperature was much colder than the original, then potentially the relative humidity could have been greater than 100%. If this was the case, the specific humidity was adjusted until the relative humidity was equal to 100%. From this the commonly returned CLAMP climate variables were calculated.

The interpolated altitude-corrected climate values derived from the gridded data for the modern 193 CLAMP sites comprising the PHYSG3CRC/MET3CR data sets is referred to here as GRIDMET3CR and is provided on the CLAMP website. PHYSG3CR differs from PHYSG3BR in that it contains twenty additional sites from climates where significant cold is experienced. Comparisons between the observed MET3CR and the gridded GRIDMET3CR are given in Figures 2 & 3.

The most precise version of CLAMP to date, and the one most applicable to warm climates, uses the PHYSG3BRC data set. CLAMP analyses of the PHYSG3BRC physiognomic data using both the original un-gridded MET3BR dataset and the gridded GRIDMET3BR dataset were performed for all 11 climate variables used in standard CLAMP runs. Given that MAT is correlated with both WMMT and CMMT, a second analysis was run with MAT removed. Moreover in view of the poor relationships between some of the gridded and ungridded moisture-related climate variables (Fig. 3) GSP, MMGSP, and RH were eliminated from a second analysis. Precipitation during the three wettest (3-WET) and three driest (3-DRY) months were not excluded so as to retain some indication of seasonality in precipitation. Because SH is directly related to enthalpy it too was removed from the analysis leaving just six climate variables. The axis 1, 2 & 3 scores of this reduced climate data analysis for both gridded and ungridded data are given in Figure 4.

Using the gridded meteorological data inevitably results in a shift in the position of the climate vectors within physiognomic space and consequently a change in the calibration algorithms used to derive palaeoclimate retrodictions. Calculation of palaeoclimate retrodictions is carried out by means of results spreadsheets RES3BRC, RES3ARC and RES3CRC. For the GRIDMET3BR data two new results spreadsheets were constructed: RES3BRGRIDDED for the eleven climate variables and RES3BRGRIDRED for the six climate variables. Both these spreadsheets are available from the CLAMP website (http://www.open.ac.uk/earth-research/spicer/CLAMP/Clampset1.html).

The regression plots for gridded and ungridded axis scores for each climate variable and for the full (11) and reduced (6) suites of variables are given in Figure 4. To test the difference in actual palaeoclimate retrodictions between the gridded and ungridded meteorological data calibrations, physiognomic scores for 50 Paleogene assemblages form North America were analysed (Figure 5). A more comprehensive account of theses sites will be published in due course.

Results and Discussion

Figure 1 shows the relationship between the observed altitude at the CLAMP calibration sample sites and that generated after interpolation of the New et al. (1999) data. Here there is a moderate degree of scatter (R^2 0.8324, SDRes 222 m) which helps explain some of the disparity in Figures 2 & 3 as the effects of topographic smoothing propagate through the data even after correction for the observed heights of the sample sites.

[Figures 2 & 3 near here]

Figures 2 & 3 show the relationship between the original observed MET3CR data set and the gridded data (GRIDMET3CR) for the same sites. For the temperature-related variables (Fig.1) the relationship is good with only a small degree of scatter. CMMT, MAT and enthalpy show the best agreements, while the poorest is shown by WMMT and SH with R^2 values of 0.9384 and 0.9248 respectively. For the moisture-related variables (Fig. 3) large differences are evident between the two data sets, particularly in wetter regimes. This is likely because of the smaller spatial correlation distance of precipitation compared to temperature.

[Figure 4 near here]

Figure 4 shows regression plots for CLAMP axes 1, 2 and 3 calibrated using gridded meteorological data as against the existing calibrations using meteorological data recorded close to the PHYSG3BR vegetation plots. It is clear that there is very little difference in respect of axes 1 & 2 when the usual 11 climate variables are used. The standard deviations of the residuals about the regression (SDRes) are 0.0003 for axis 1 (R^2 0.9999) and 0.0045 for axis 2 (R^2 0.9992). There is slightly more scatter on axis 3, but even here the SDRes is only 0.071 (R^2 0.9902). For the reduced climate data variables the axis 1, 2 and 3 SDRes and R^2 values are 0.0001 and 0.9999, 0.0074 and 0.9989, and 0.1355 and 0.9828 respectively. Although axis 1 is even more congruent with the six climate variables than with the previous 11, and axes 2 and 3 slightly less so, there is no real difference and the reduced climate variables give no loss of precision. The reversal in the direction of slope in axis 1 and 3 plots for the analysis using six climate variables is a consequence of the way the Correspondence Analysis computations are conducted and has no significance in respect of the calibrations or climate retrodictions.

When the observed climate is regressed against the vector scores in axis 1 - 4 space (used for deriving actual retrodictions of the climate variables for fossil sites) the uncertainties as indicated by the SDRes values are similar for both the un-gridded and the gridded data with full and reduced set of climate variables (Table 1).

[Table 1 near here]

[Figure 5 near here]

Figure 5 illustrates the differences in palaeoclimate retrodictions for North American Paleogene floras when using the ungridded and gridded meteorological data and the full (11) meteorological variables. For MAT and CMMT the differences are minor, but the slope and position of the WMMT line suggests that the gridded data tend to overestimate WMMT at temperatures below 23 °C and underestimate WMMT above 23 °C.

Gridded values for both 3-WET and 3-DRY are lower than those for ungridded in wetter regimes. This is consistent with the observations that gridded data generally tend to underestimate precipitation where it is spatially variable. The effect is most pronounced in the dry season when locally intense convective rainfall tends to be more common. This effect is also due to the fact that the ungridded CLAMP meteorological data are biased towards local climates strongly influenced by the proximity of vegetation. This microclimate will tend to be more humid than the regional climate and the lowered evaporational stress experienced by the leaves will encode for an overall wetter regime. The enthalpy graph indicates that the gridded data slightly underestimates enthalpy compared to the ungridded data.

Conclusions

The results presented here show that substituting the existing CLAMP meteorological data (observed at the locations of the vegetation samples used for calibration) by data derived from the New et al. (1999) gridded data, offers a way forward for adding numerous new calibration samples from areas of the globe not served by meteorological stations. However, the spatial averaging inherent in the gridding process results in pronounced lowered precipitation values in the gridded data compared to the ungridded (observed) after CLAMP analysis. The raw data (Figs. 1 - 3) show good correlations in temperature related variables, but with the precipitation/humidity-related variables there is a large degree of scatter, particularly in wetter regimes. Lower (cooler) values are also observed in some gridded temperature related variables, but in general temperature-related variables show strong parity between both data sets.

The marked lower precipitation values in the gridded data can be explained by the high spatial variability in precipitation particularly when, and where, convection-driven precipitation is most prevalent. This spatial variability is most strongly expressed in topographically complex areas relevant to future calibration vegetation sample sites, and in dry (often summer) seasons when localised intense storms produce heavy rainfall in an otherwise dry regime. The 3-DRY gridded values appear to flatten off with respect to the ungridded at high precipitation values. This further suggests the highest rainfall will be associated with the most intense and most localised storms.

The density and spatial distribution of climate stations with continuous precipitation observations greater than 30 years determines the maximum spatial resolution that can be obtained from observational data. Although the New et al. (1999) data included more precipitation observation sites than for temperatures, the spatial granularity required to capture individual storm-scale events could not be achieved particularly when interpolated to a 0.5° x 0.5° grid. This grid scale is the basis for all other widely used global climate data sets and so all suffer from the same limitations. Coupled with the known poor correlation between foliar physiognomy and precipitation in regimes where water is not limiting to growth, it is recommended that high GSP and MMGSP values derived from CLAMP be treated with caution irrespective of which meteorological data set is used for calibration. Low values (i.e. dry regimes) are likely to be more reliable, but only when using the ungridded observations for calibration. Similarly 3-WET and 3-DRY values should be regarded only as indicative of the degree of seasonal variations in rainfall.

Gridded enthalpy values, unlike the temperature variables, are higher than the values observed at the existing CLAMP sites. The cause of this is yet to be determined.

As with all the graphs, including those relating to the Paleogene of North America, the systematic consistency exhibited allows a "correction" factor to be employed to overcome the systematic differences between the gridded and ungridded data. However doing this will force CLAMP to return climate values that are not consistent with the gridded data used for model performance evaluation. Potentially, by using both calibration schemes, CLAMP is capable of returning climate data in relation to ancient vegetation-influenced microclimates as well as climates of a more regional nature. The similarity in the ungridded and gridded data performance also suggests that CLAMP is a robust climate proxy within the constraints of the existing physiognomic biogeographic space.

Acknowledgement

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Figure 1. Regression plot of gridded versus observed altitude at CLAMP PHYSG3CRC calibration sites.

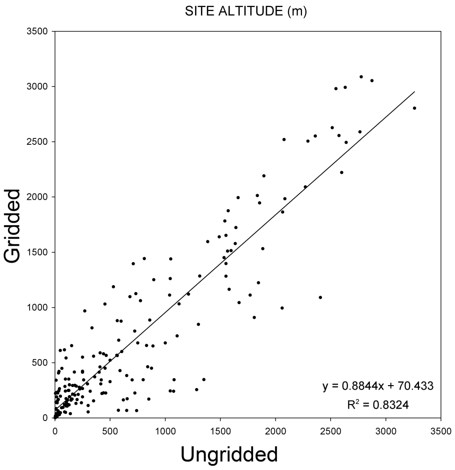


Figure 2. Regression plots of the ungridded MET3CR data set (x axis) versus the GRIDMET3CR data set (y axis) for temperature-related climate variables.

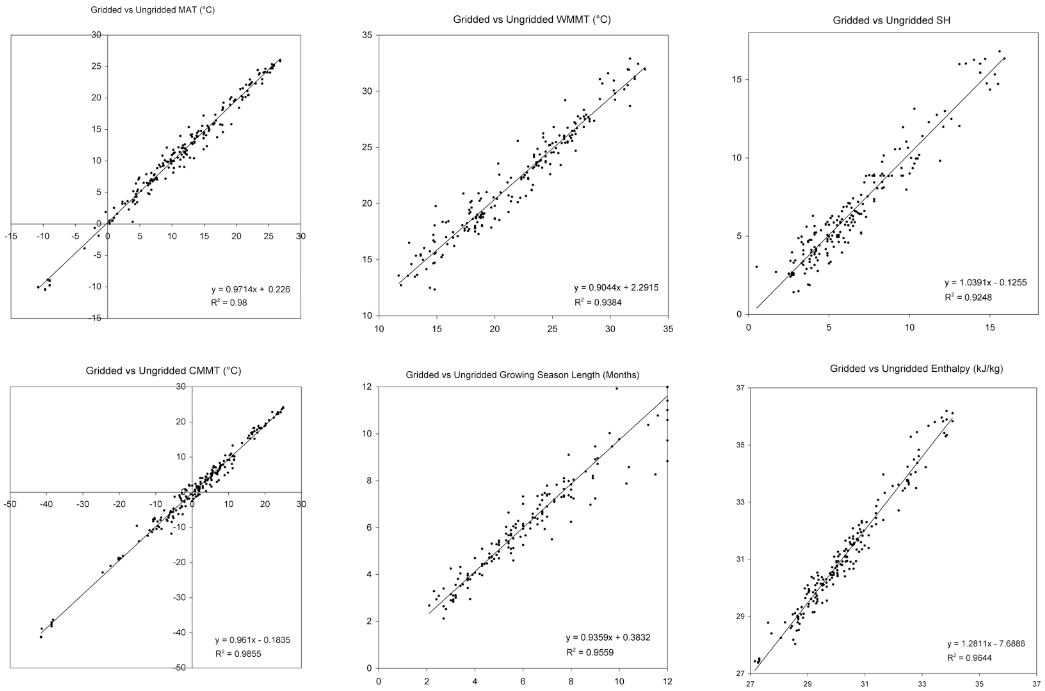


Figure 3. Regression plots of the ungridded MET3CR data set (x axis) versus the GRIDMET3CR data set (y axis) for moisture-related climate variables. Regression lines and goodness of fit are only shown where appropriate.

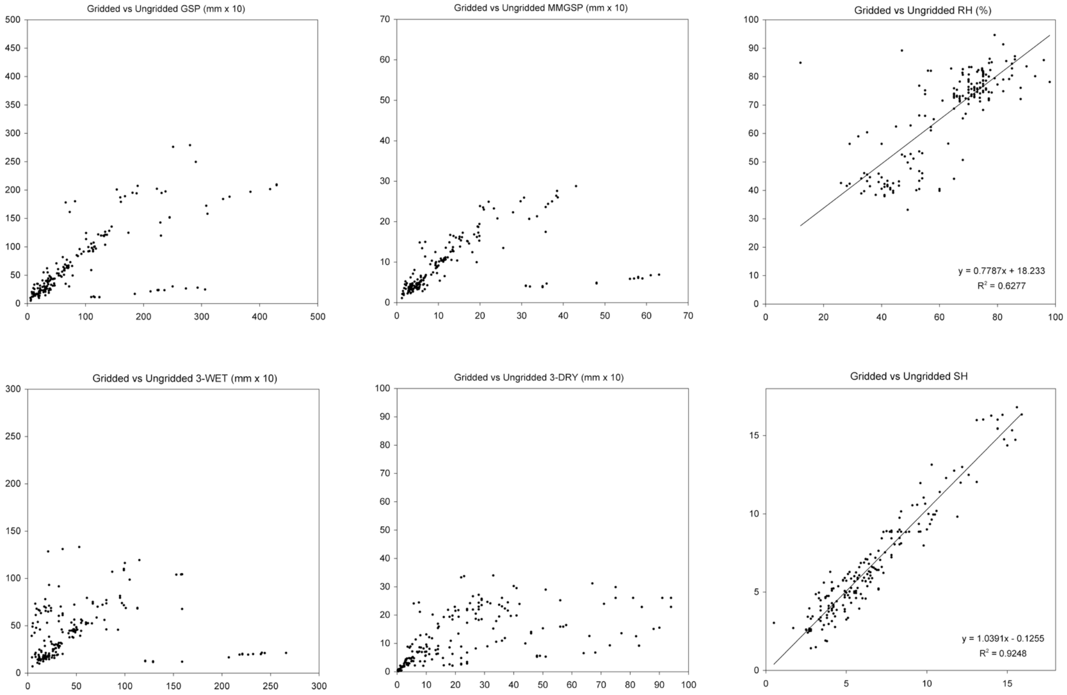


Figure 4. Regression plots of Gridded vs Ungridded meteorological data for PHYSG3BRC CLAMP analyses axes 1, 2 and 3. The upper row shows plots from an analysis with 11 climate variables and the lower row is for an analysis using six climate variables. See text for more details.

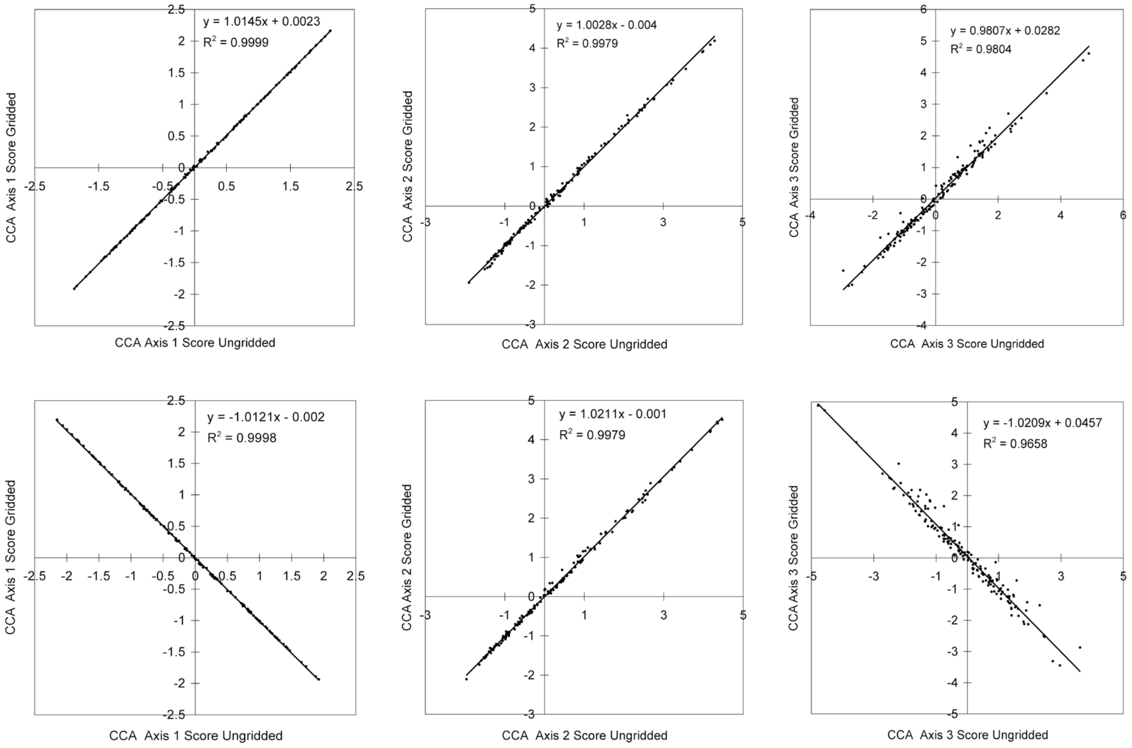
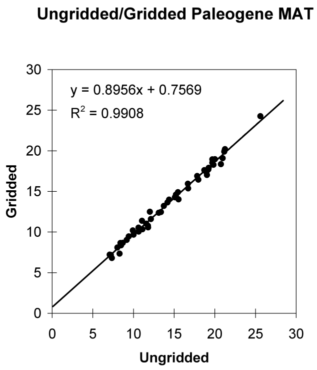
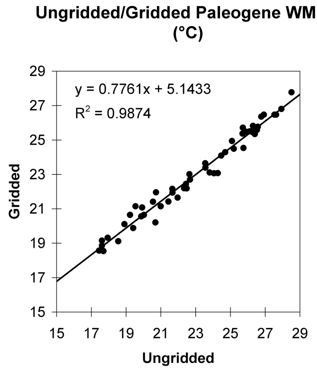
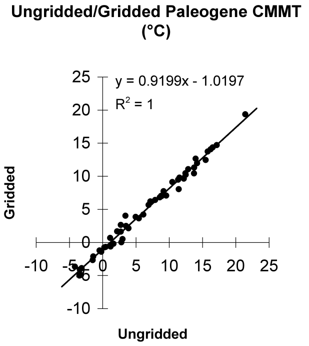
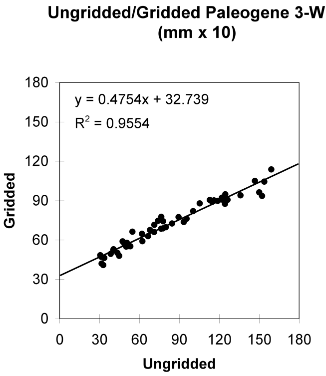


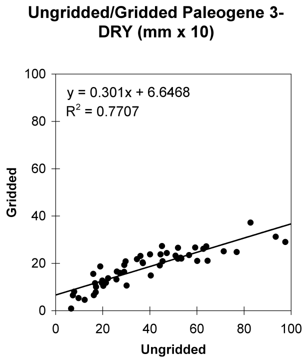
Figure 5. Gridded versus ungridded climate retrodictions for 50 North American Paleogene fossil assemblages. Standard deviations of residuals about the regressions are MAT 0.25 °C, WMMT 0.25 °C, CMMT 0.44 °C, 3-WET 5.4 mm x10, 3-DRY 6.8 mm x10, Enthalpy 0.06 kJ/kg.


Ungridded/Gridded Paleogene MAT (°C)


Ungridded/Gridded Paleogene WMMT (°C)


Ungridded/Gridded Paleogene CMMT (°C)


Ungridded/Gridded Paleogene 3-WET (mm x 10)


Ungridded/Gridded Paleogene 3-DRY (mm x 10)

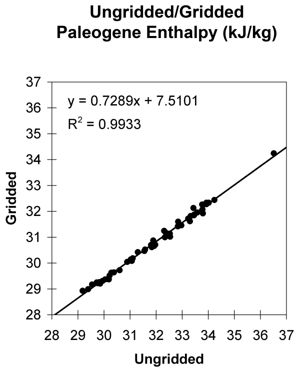

Ungridded/Gridded Paleogene Enthalpy (kJ/kg)

Table 1. Standard deviations of the residuals about the regression lines between the observed climate (ungridded and gridded) and the CLAMP climate vector scores using the PHYSG3BRC data set.

	UNGRIDDED (11 climate variables)	GRIDDED (11 climate variables)	GRIDDED (6 climate variables)
MAT (°C)	1.18	1.13	
WMMT (°C)	1.59	1.41	1.54
CMMT (°C)	1.88	1.86	2.24
LGS (Months)	0.69	0.71	0.72
GSP (mm x 10)	33.61	19.62	
MMGSP (mm x 10)	3.69	2.56	
3-WET (mm x 10)	14.07	13.78	14.03
3-DRY (mm x 10)	9.31	3.20	3.25
RH (%)	7.31	5.28	
SH (gm/kg)	0.91	1.03	
ENTHALPY (kJ/kg)	0.32	0.46	0.43