CONTINENTALITY AND THE SNOWPACK DENSITY DISTRIBUTION IN THE WESTERN UNITED STATES

by

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ABSTRACT

An index of continentality is used to evaluate the distribution of snowpack density in the Western United States. Continentality describes the climatic differences arising from proximity to major water bodies and from the effects of a continental land mass. The ability of maritime air masses to penetrate inland and impart a moderating effect on surface air temperature is reflected by the continentality index. Close proximity to the Pacific Ocean has the effect of providing abundant moisture for precipitation and minimizing the annual range in temperatures. The continental interior experiences an increased temperature range and a dryer climate. The dependence of snowfall and, ultimately, snowpack density on atmospheric temperature and water vapor supply, suggests a link between continentality and snowpack density. The usefulness of a continentality index to capture climatic conditions relevant to snow density is evaluated.

INTRODUCTION

Mountain snowpack density in the western United States displays a gradient from higher density snow in the Pacific coast mountain ranges to progressively less dense snow in the intermontane transitional region and the interior continental region. The physical processes leading to this distribution, and departures from it, involve the interactions of climatologic, topographic, and geographic factors. The research described here is part of a larger work which investigates snowpack density distribution as a response to a composite of latitude, continentality, temperature, elevation, slope, and aspect. This paper focuses on the use of a continentality index to evaluate snowpack density in the West. Continentality is a broad indicator of climatic regime, characterizing temperature and moisture variations due to geographic differences.

A basic phenomenon which may be apparent, but that is not well-addressed in the literature, is the importance of snowfall density in providing a base condition from which snowpack densification proceeds. It follows that a fresh snowpack of relatively greater density develops from a parenting snowfall of higher density. Likewise, there is an adjustment to snowpack density with the addition of each new snowfall through the season.

Nakaya's (1954) laboratory experiments, which were later confirmed by field measurements of Magono and Lee (1966), demonstrated that air temperature and supply of moisture vapor determine the type of snow crystal formed. Snowfall studies (e.g. Grant and Rhea, 1974; McGurk et al, 1988) have stated that crystal size and type and air space are among important factors for determining snowfall density. Therefore, it is expected that atmospheric temperature and moisture conditions that determine snow crystal form would also affect snowfall density and, ultimately, snowpack density.

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Further, it is hypothesized that a climatic classification capable of quantifying site specific temperature-moisture conditions would provide a means to analyze the distribution of snow density.

Continentality was selected because it provides a numerical index marking the transition from warm/wet to cold/dry climates. The term, continentality, refers to the degree of moderating influence a maritime climate has on continental interiors. Close proximity to the Pacific Ocean has the effect of providing abundant moisture for precipitation and moderating the annual range in temperatures. The continental interior experiences an increased temperature range, dry cold winters, and a summer precipitation maximum. These variations result from the differences in the specific heat capacity and conductivity of land and water.

In the western United States where the prevailing wind flow is westerly, continentality is lowest near the coast and highest inland. In addition to distance from the Pacific Ocean, the inland penetration of moisture is further reduced by the progression of mountain barriers presented by the north to south orientation of the American Cordillera. The moderate maritime climate is held to a narrow region along the west coast; while further inland greater annual temperature ranges occur with colder, dryer winters. It is hypothesized that diminishing moisture availability with distance inland and increased annual temperature range, as expressed by the index of continentality, leads to snowpacks that are relatively less dense than those under the influence of the coastal maritime regime. Thus, an inverse relationship is expected between continentality and snowpack density.

METHODOLOGY

The continentality - snow density relationship in the western United States was evaluated using regression analysis. Snow course data were used to calculate snow densities in mountainous environments. A continentality map of the West was prepared in a geographic information system (GIS), which provided corresponding continentaltiy data for each snow course site. Snow density maps for January 1st, February 1st, March 1st, and April 1st were produced to evaluate seasonal and geographic trends.

Snow Course Data

The snow course data used in this study were made available through the Natural Resources Conservation Service, West Technical Data Center. The criteria for site selection was based on the completeness of the data record. Acceptable sites were those having first of the month depth and water equivalent data for each of 4 months -- January, February, March and April -- covering a 25 year period form 1965 to 1989. A total of 324 snow courses were selected. A 25 year snow density average was calculated for each site.

In the event of missing data, site selections was given the following priority, those sites having:

1) 24 years of January, February, March, and April 1st data,
2) 25 years of February, March, and April 1st data,
3) 24 years of February, March, and April 1st data,
4) 23 years of February, March, and April 1st data.

Continentality Data

Several quantitative expressions of continentality have been derived. The formulae are based on average annual temperature which is corrected for latitudinal differences. (e.g. Gorczynski, 1920; Johansson, 1931; Conrad, 1946; Ivanov, 1959). An index of continentality was calculated according to Gorczynski (1920):

$$C = \frac{1.7 * A}{\sin\phi} - 20.4$$

where: C = the coefficient of continentality
A = the annual temperature range (°C)
Φ = latitude

Average Annual Temperature Range

The annual temperature range for each snow course was determined from estimates of average monthly temperatures from the Legates Willmott World Temperature Database (1990). This database contains an average monthly surface temperature for each 1/2° of latitude and longitude world wide. An annual temperature range was calculated for each of the 1/2° grid points within the study area. Continentality was then determined for each grid point; however, values for each snow course location were still needed.

Idrisi Image Processing

The raster based Idrisi GIS was used to determine values of continentality for each snow course location. A template (base image) georeferenced to the western United States was created in Idrisi. Study area boundaries were set at 50° north and 30° south latitude and at 105° west and 125° west longitude. The image structure was designed so that the 20° of latitude and longitude were represented as 2400 rows and 2400 columns of cells (pixels). Each cell represents 30 seconds (0.008333°) of arc on the ground which is approximately .6 km (.37 mi) along the 50th parallel and .8 km (.5 mi) on the 30th parallel.

The Pointras module was used to import the continentality grid data and attach it to corresponding cells in the raster base image. An interpolation of the 1/2° continentality image was performed using the Interpol module which executes a distance-weighted averaging (l/d^2) technique. The result is a smoothed image where each cell (of 30 seconds of arc) contains a new continentality value. A value for each snow course location was extracted from this image. One drawback to this method is that the interpolation procedure does not account for topographic features that effect changes in temperature and, ultimately, changes in continentality. The values represent broad estimates and not actual values of continentality.

Mountain Range Averages

The data were reduced by aggregating the 324 snow course sites into 72 groups according to mountain range or other topographic features. The groupings and feature names are shown in Figure 1. The polygons represent rough indications of the mountain ranges included in the study. The mean snow density and mean continentality for each group were used in the analysis.

RESULTS AND DISCUSSION

Continentality

Figure 1. Snow course sites grouped by mountain range or terrain feature.

This methodology produced continentality values ranging from -11 to 64 (Figure 2). The lowest values occur along the west coast (from -11 to approximately 15) in places normally below the snowline. The intermontane regions show higher values of continentality than might be expected. This is due to the aridity resulting from topographic rain shadow effects. Dryness leads to a climate with an increased annual temperature range and thus an increased continentality.

The continetality of snow sites ranged from 16 to 49. Areas where the highest values occur (from 50 to 64), such as the intermontane region, are not represented with snow course sites in this study. The reason for this is either that snowcover is marginal in these areas and measurements are not conducted, or the snow course data records did not meet the study criteria. This has a negative effect on the results, since nearly 1/3 of the potential continentality values have not been included. The average values of continentality for each mountain range varied from 18 to 49.

Snow Density

Snow density maps are presented in Figures 3a-d. With the exception of Arizona and New Mexico, missing data do not indicate the absence of snow, but rather that measurements are not routinely made for January 1st. Early season snow, accumulated by January 1st (Figure 3a), shows a density distribution skewed toward the higher values. The lower density snow that is present occurs in the lee of other mountain ranges where available moisture is diminished by the rain shadow effects. Examples found east of the Cascades are Quartz Mt., Yamsay Mt., Calamity Butte, and Stinking Water Pass. Another area of predominately low density snow is found east of the Continental Divide in the lee of the Tetons and the Bitterroot Ranges.

By February 1st (Figure 3b) a snow density gradient begins to develop. Only the far western sites have the highest density snow. Most of the ranges east of the Continental Divide are now in the lowest category. By March 1st (Figure 3c) a longitudinally stratified pattern of snow density is well developed in the West, with few exceptions. Anomalies occur where high density snow is found in areas otherwise dominated by low density snow and vise versa.

High density snow is found in the Teton Range and on the Plateau Pitchstone area of northwestern Wyoming (between the Tetons and Yellowstone Park); an area where surrounding mountain ranges typically have lower density snow. These mountain features present a barrier at the end of an air flow "corridor" formed by the Snake River Plains (Figure 4). Sufficient moisture is able to penetrate inland through this corridor to generate high density snowfall and a higher density snowpack on flanking mountains and at the terminus. A snow density shadow is found in surrounding mountains and on the lee of the Continental Divide. Findings by Mitchell (1975), which showed that the Teton Mountain region experiences frequent intrusions of Pacific air masses during the winter, support this hypothesis.

Higher density snow might be expected in this region because of the greater snow depths associated with increased elevations. While the Teton Mountains exceed elevations of 3000 m the snow courses are situated at 2145 m and 2214 m. The Plateau Pitchstone snow courses are at 2392 m and 2432 m. The occurrence of high density snow at snow courses of lower elevations (Stinkingwater Pass, 1463 m; Boise Mts., 1950 m (avg.); Owynee Mts.,1981 m; and Unnamed Three, 2072 m) along the Snake River corridor indicates that a source of moist air is penetrating inland.

Another anomaly appears in the marginal snow regime found in Arizona. An occurrence of high density snow in the Sierra-Ancha and low density snow on Mingus Mountain is found south of the elevated Mogollon Rim. This indicates a possible variation in moisture sources and/or the

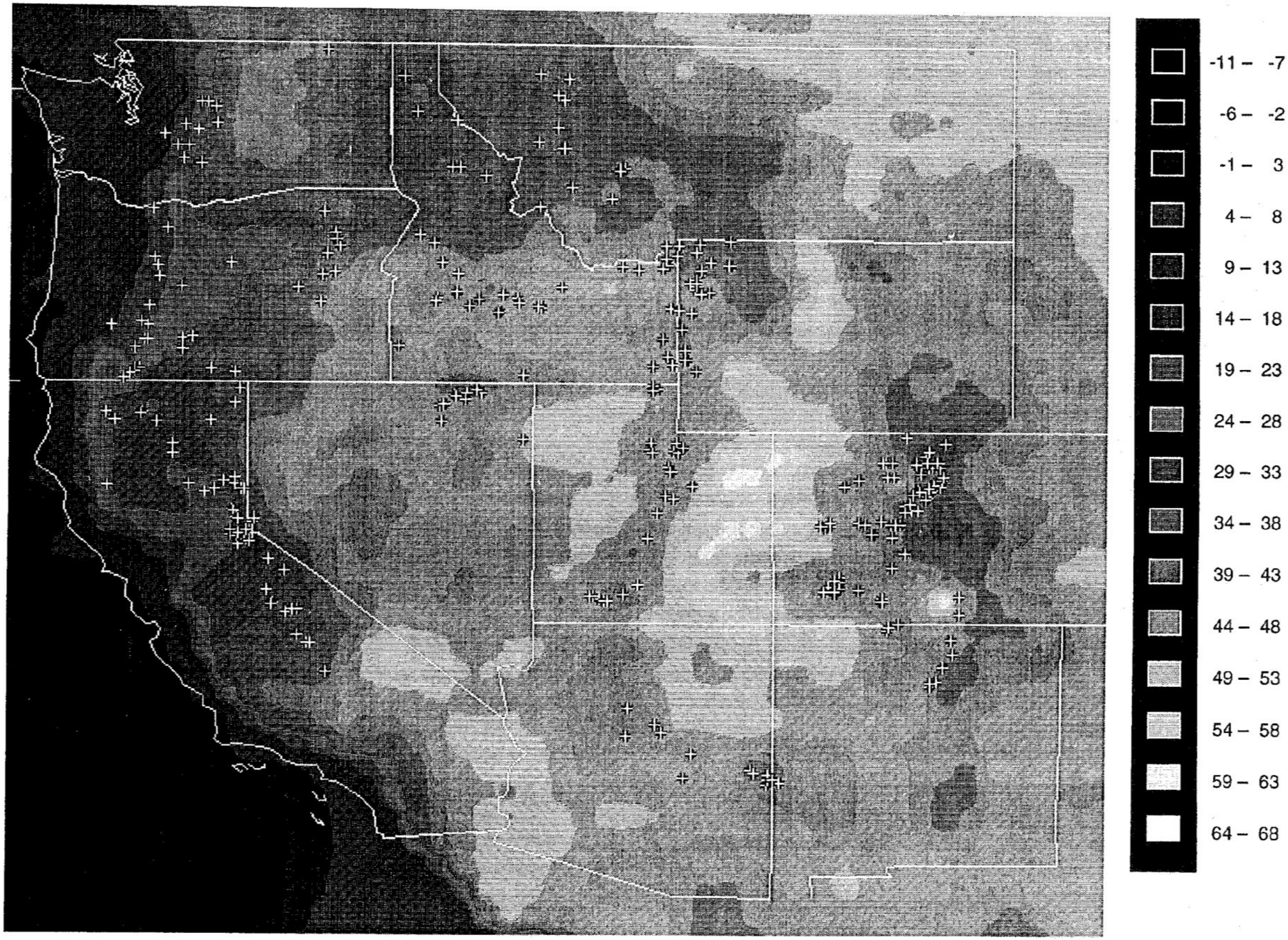
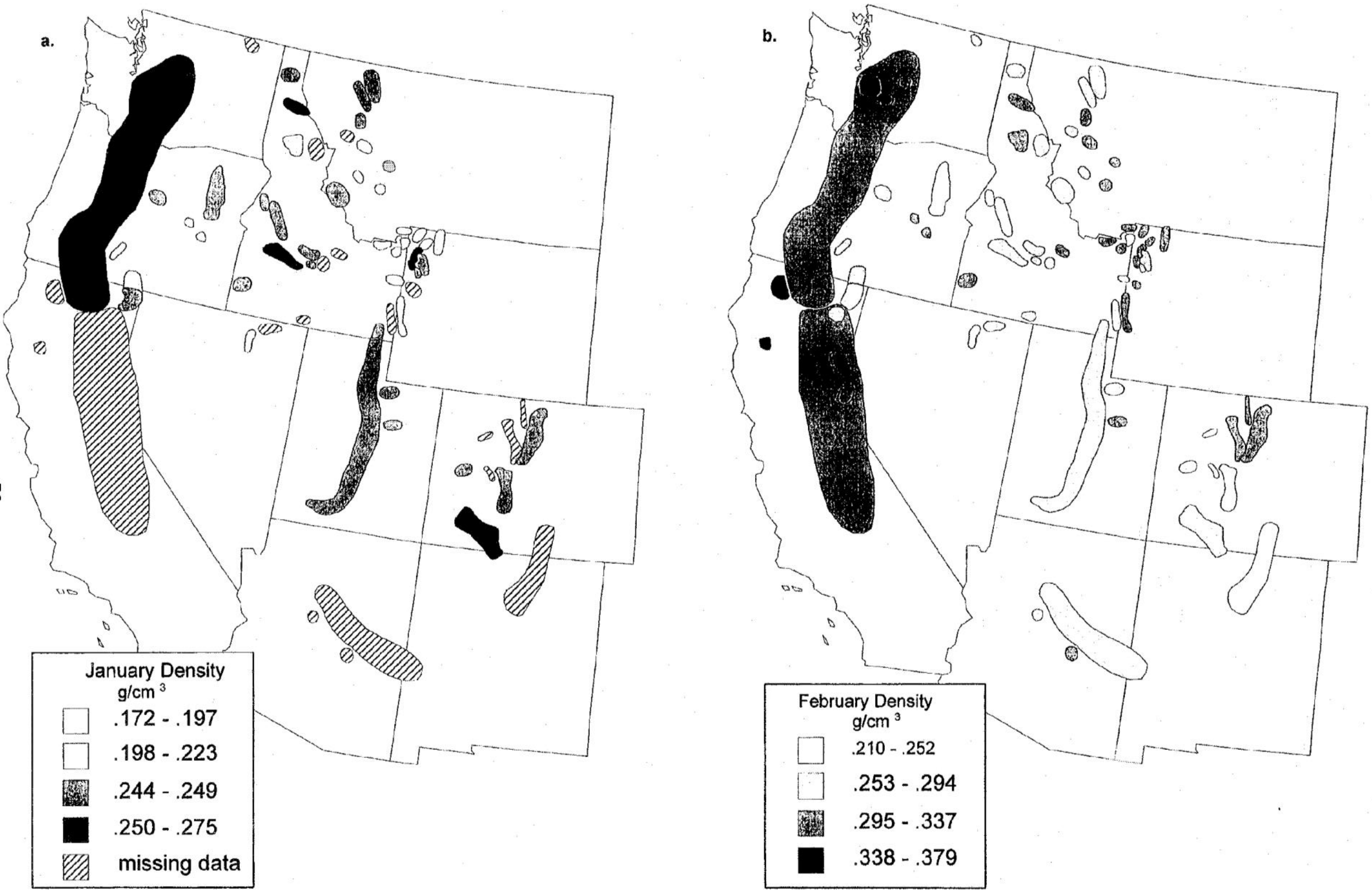
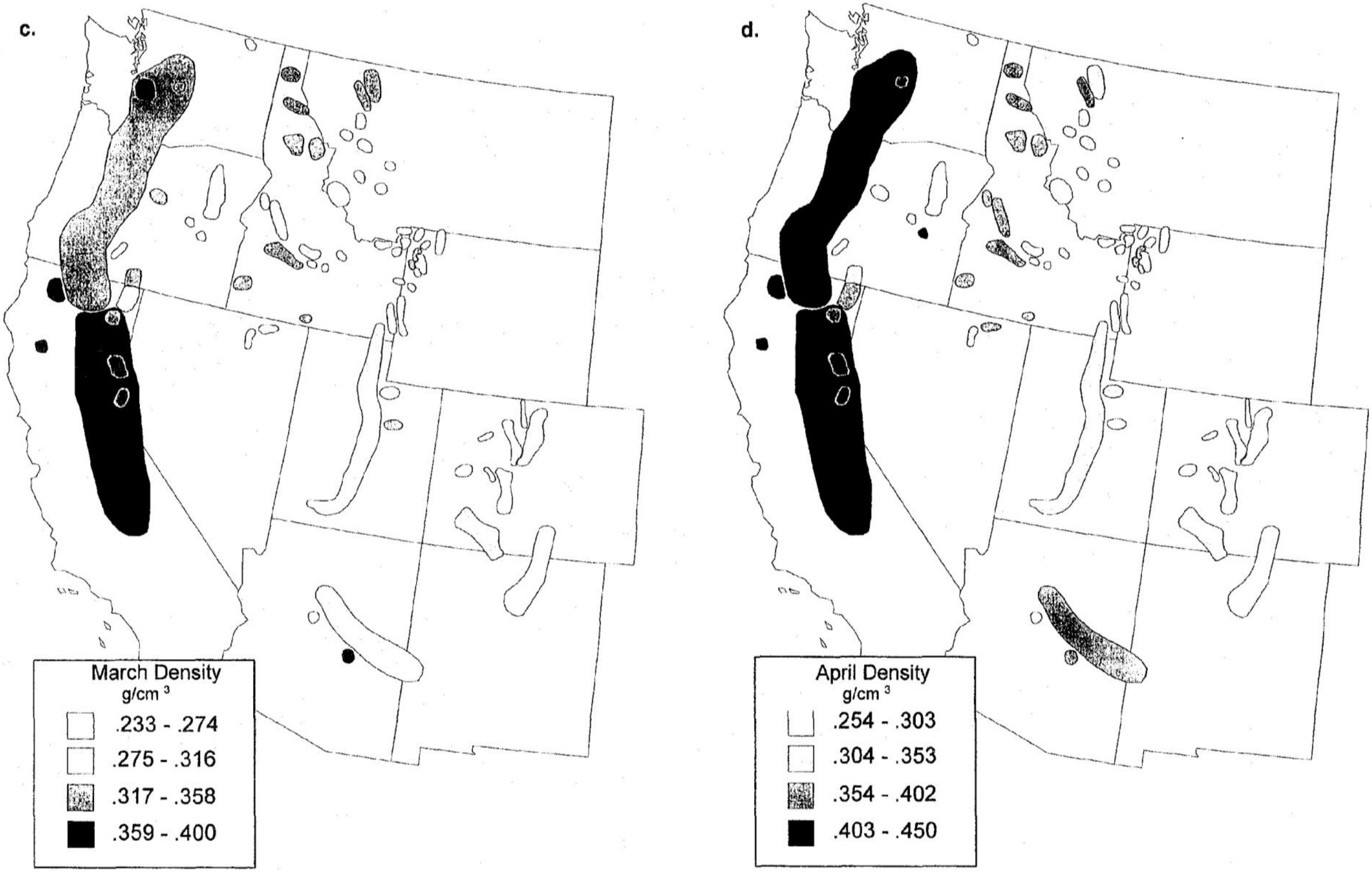


Figure 2. Continentality in the Western United States. Crosses indicate snow course sites.



Figures 3a and b. Seasonal trend in snowpack density.



Figures 3c and d. Seasonal trend in snowpack density.

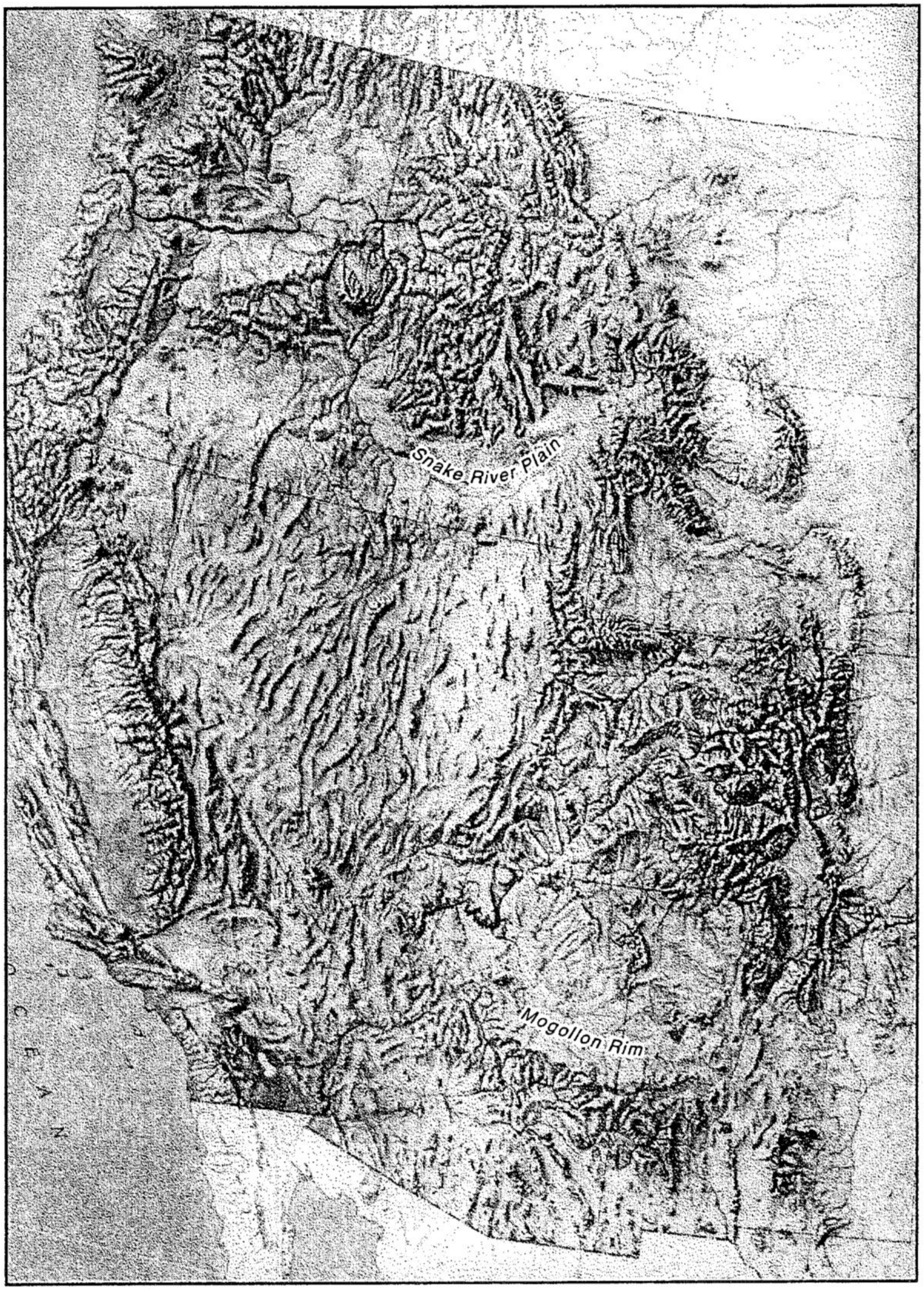


Figure 4. Western United States Terrain Features. (Source: The National Atlas of the United States of America, 1970)

efficiency of orographic processes due to mountain orientation.

The west to east density gradient begins to breakdown by April 1st (Figure 3d). There is an increased occurrence of higher snow densities in the Colorado Rockies. This is in response to the melt-freeze processes that are typically occurring at this point in the season. While far western snowpacks maintain the highest density snow throughout the season, the rate of increasing densification occurs at a faster pace than in continental locations. The late season increase in densification in the interior is due to the prolonged temperatures below the melting point.

Regression Analysis

LInear regression was used to evaluate the strength of the relationship between continentality and snowpack density (Figure 5a-d). An inverse relationship is not apparent until mid-season when snowpack densification is approaching maturity. The correlation improves as the season progresses, then begins to deteriorate by April. The maximum amount of explained variance at 27% occurs March 1st, then drops to 12% by April.

Analysis of the March 1st residuals indicates that low density snowpack were over predicted and high density snowpack were under predicted by the regression model. The greatest errors occurred where continentality values are between the mean and the maximum values in the West. A wide range of snow density occurs in these areas, whereas, only high density snow occurs in areas where the maritime climate regime has greater influence.

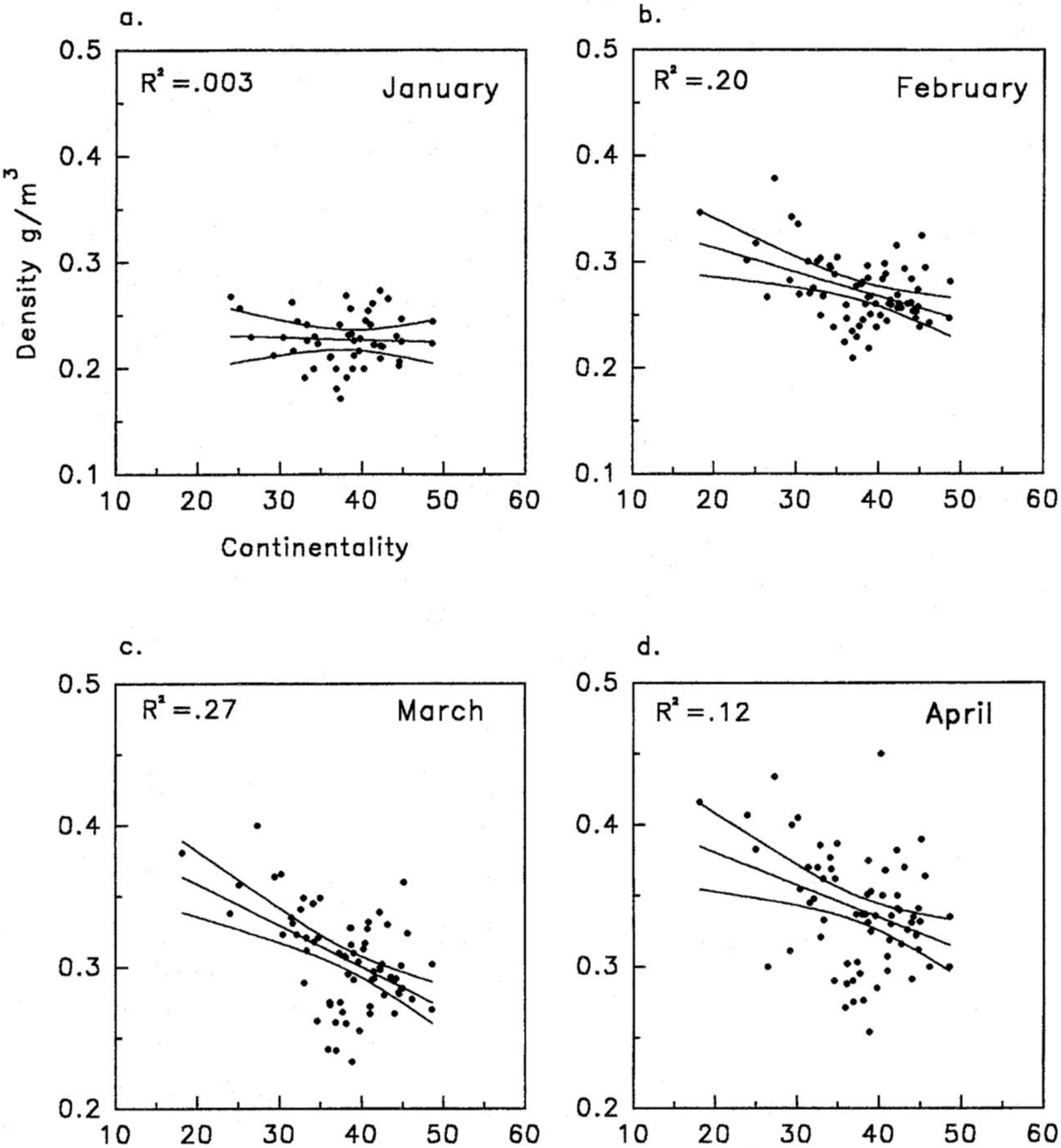
The explained variance increased to 48% when anomalies such as those described above were removed from the regression analysis. This suggests that the phenomena generating these anomalies are not reflected in continentality as it has been calculated here. It is likely that the estimates of annual temperature range are inappropriate because changes in topography were not accounted for during the interpolation.

CONCLUSION

The results of this study provide an overall description of the seasonal trends and spatial distribution of snow density in the western United States as it relates to continentality. The west to east density gradient is not well developed until mid season (March 1st) when sufficient time has passed to reflect the impacts from cumulative snowfalls and continuous metamorphic and densification processes. At this time the correlation to continentality reaches its maximum.

Continentality can provide a rough index for regional mid-season snow density. It is able to show the intrusions of maritime air into interior zones which is helpful in explaining the anomalous conditions in northwestern Wyoming. It is likely that improved estimates of annual temperature range could increase the strength of the relationship.

Continentality alone only partially explains the geographic snow density gradient. A more comprehensive explanation may be forthcoming, when further work, now ongoing takes into account other factors, such as elevation, slope and aspect.



Figures 5a–d. Linear regression of snowpack density and continentality with 95% confidence intervals.

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