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Quantitative Relations of
Continental Physiography and Climate
Submitted to The Journal of Geology
Master of Science in Geology
Department of Geological Sciences
The University of Michigan

Author

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Title:

Quantitative Relations of Continental Physiography and Climate

Submitted for Publication in:

Journal of Geology

In lieu of thesis in partial fulfillment
Of the requirements for the degree of
Master of Science in Geology
Department of Geological Sciences
The University of Michigan

Accepted by:

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Dependence of Continental Physiography on Climate

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Abstract

The spatial distribution of elevations and slopes on continents is a primary expression of complex interactions between tectonic and climatic systems. As a geomorphic record, spatial variations of continental physiography with latitude afford some insight into the relative importance of tectonic and climatic processes on Earth-surface elevations. Because rates of tectonism and climatically mediated erosion vary in both space and in time, it is probable that heights of land and steepness of the associated slopes change across climatic regimes and during the tectonic evolution of a landmass. Because modern digital elevation models (DEMs) afford ample data on continent surface elevations across the complete range of equator-to-pole climate zones, we have undertaken an evaluation of the dependence of continental physiography on climate using the latitudinal gradient as a proxy for first-order change in temperature and precipitation.

One approach to an assessment of the dependence of topography on latitudinally dependent variation in climate is to generate elevation versus area relations, hypsometric curves, for individual latitudinal bands and to compare these with global hypsometry. The shapes of both total and latitudinal continental hypsometries can be largely explained by elevation distributed as an exponential function of the root of area of land. Maximum elevations within each 1-degree band of latitude exhibit cosinusoidal variation with latitude and are interpreted as primarily reflecting decrease of surface area of continents with latitude. Model and measured hypsometries with normalized maximum elevations and total areas exhibit no significant latitudinal variation. This suggests that spatial variation in Earth-surface topography, as manifest by area-elevation relations, is largely insensitive to latitudinal position and associated climate.

Another approach to assess differences in global topography with mean temperature and precipitation is to directly examine variation in Earth-surface slopes as a function of elevation and latitude. The distributions of slopes of continental surfaces were derived from the DEM elevation data. Mean slope primarily covaries with elevation, but also increases with absolute latitude. Cryogenically mediated processes of continental denudation are apparent as steeper slopes at higher latitudes, and are the basis of these systematic changes. The coincidence of increases in subaerial slopes and stasis in relative distributions of elevations suggests that poleward regions are also more dissected than their equatorial counterparts.

Elevations of Continental Surfaces

Introduction

The past two decades have experienced a great profusion of interest in understanding the nature of couplings between global tectonic and climatic systems. These efforts have resulted in much evidence for a series of direct and indirect mechanisms that give rise to rather profound changes in patterns of atmospheric circulation (Rea, 1998), precipitation (Kleinert, 2001), climate (Raymo, 1992), rate of crustal uplift and denudation (Montgomery, 2001; Small, 1995), chemical weathering (Jacobson, 2003), and sedimentation (Peizhen, 2001). In order to assess the relative importance of interactions between tectonic and climatic systems on continental physiography at global scales, we have undertaken examination of changes in several aspects of continental topography as they vary through equator to pole changes in climate gradients. Because it has been argued that evidence for geologically-recent climate change might also be interpreted as evidence for coeval change in rates of tectonic uplift (e.g. Molnar and England, 1991), and because the principal metrics of climate such as mean annual temperature and mean annual precipitation also vary significantly with distance from the equator (e.g. Legates and Willmott, 1990a,b; IAEA/WMO, 1998; Figure 1), here we examine global-scale changes in continental landform as a function of latitude in order to establish the presence and potential importance of any association between climatically mediated processed of denudation and the nature of resultant topography.

A global, rather than a more localized approach, is appropriate for several reasons. First, and perhaps most pragmatically, current datasets offer a wealth of measurements collected at regional scales on areas and elevations of continental surfaces by which to test various hypotheses about change as a function of global location. Additionally, examination of relations between climate and tectonic processes at a global scale includes all existing current, and geologically recent local variability in surface geomorphology and, as such, produces the most robust connection between Earth surface tectonic and climatic systems as a whole. Here, we have adopted an approach whose foundation is the statistical analysis and characterization of continental topography in order to quantitatively discuss covariance of climate, tectonics, and physiography. To these ends, we examine two primary expressions of continental physiography: elevation as described by GTOPO30 (1996), a global 30 arc second Digital Elevation Model (DEM), and slopes calculated therefrom.

Continental hypsometry

Description of the areal extent and distribution of the Earth surface elevations in both continental and oceanic realms has been a fundamental goal of physical sciences for at least the last two centuries. Many early measurements of ocean depths were made by Sir John Murray (1888) who reported thousands of soundings from explorations of the H.M.S. Challenger. In addition to determinations of ocean bathymetry, Murray (1888) produced some of the earliest published tables of continental elevations, and presented a general description of continental physiography as being similar to that of a cone. Some 33 years later, Kossinna (1921) pointed out that accurate description of average land elevation required the compilation of data from contours of an equal area map; he also produced the first hypsometric curve, a plot that relates the area at or above a specific elevation to that elevation (see Fig. 1). Because Kossinna (1921) chose to plot elevation on the ordinate and cumulative area on the abscissa, the curve gives the perspective of a topographic profile, but it also inverts the sense of dependency of the measured data. Nonetheless, and in spite of the fact that global hypsometry has since been refined on the basis of vast amounts of newer data, modern and historical hypsometric curves are nearly identical. Because hypsometries are snapshots of the topographic evolution of the Earth's surface, they have been used to investigate such diverse phenomena as Phanerozoic sea level change (Algeo and Wilkinson, 1991), Cenozoic mantle dynamics (Lithgow-Bertelloni and Gurnis, 1997), fluvial erosion (Strahler, 1954), and ocean basin tectonics (Menard and Smith, 1968; Harrison, 1998). Although continental hypsometry has been analyzed extensively in the context of tectonic theory (Harrison, 1983), a modern first-order mathematical description for continental topography has yet to be presented.

The most current data on Earth surface elevations are distributed by the Eros Data Center of USGS (*http://edcdaac.usgs.gov/gtopo30/gtopo30.html*). Information pertaining to the data sources and accuracy can be found accompanying the online data. The dataset has a grid, or raster, structure, and it represents average elevations contained within individual areas whose sides that are 30 arc seconds in length. Implicitly, the grid structure is comprised of data at equiangular distances with a total of approximately 270 Million elevations for all subaerial crust. In order to compute the distribution of continental elevations, the area of Earth's surface represented by each grid cell was calculated based upon its bounding latitudes. (Snyder, 1987) Total areas were then tabulated for 1-meter increments, the maximum precision given in GTOPO30 (1996).

The hypsometric curve that represents the area/elevation relation for all continental surfaces is very to similar to that derived for a solid of rotation with elevations that decrease exponentially along a radial profile. The model will hereafter be referred to as a cone (although not a true cone with constant slope). The conic model has a basal area equal to the total continental area (147×10^6 km^2) and a maximum elevation of 8,752m, the maximum elevation in GTOPO30 (1996). The exponential profile of the conic model describes the relation of elevation to the radius, or distance from the axis of rotation.

$$(1) \qquad f(r) = \text{Elevation} = E_0\, e^{-kr}$$

By substituting the expression of radius as a function of area, $r = \sqrt{(a/\pi)}$, an explicit area/elevation relation, or model hypsometry, can be written as equation 2, a square-root exponential distribution.

$$(2) \qquad f(a) = \text{Elevation} = E_0\, e^{-k\sqrt{(a/\pi)}}$$

The decay constant of the exponential profile, or conic slope, is 0.068%/km, and was calculated by regression. Although the conic slope could be analytically determined knowing only the maximum elevation and total area of the cone, there is error associated with actual maximum elevation reported in the data, and therefore fitting the model to the data will produce a much more robust representation (Fig. 1).

Because of differences in material properties between glacial sheet ice and continental lithosphere, ice-covered regions have hypsometries that are distinct from those of ice-free landmasses (Harrison, et al., 1983). A continental hypsometry exclusive of Antarctica and Greenland was then calculated in order to determine any possible effects on the fit to the model. The ice-free continental model has a basal area of 1.32×10^6 km^2 and a conic slope of 0.079%/km. Although, removing the ice-capped portions of continental area from the dataset slightly increases the numeric correlation of the model to the data, it is negligible. Overall, ice-free and total continental hypsometries are very similar, and each are well replicated by conic models whose radial profiles ere exponential in form.

Although the fit to the total continental dataset with Equation 2 returns a Pearson correlation coefficient, r-squared value, of 0.959, there are systematic deviations between the model and elevation data at lower elevations (Figure 3). Above about 170m, there is good agreement between GTOPO30 (1996) elevations and those expected for the cone with an exponential profile wherein conic elevation decreases exponentially with each linear increase in radial distance. Conversely, below an elevation of ~170m, elevation data are best replicated by a model that takes the form of Equation 3, one in which elevation decreases linearly with the natural logarithm of the radial distance or square root of area as is shown.

$$(3) \qquad f(a) = \text{Elevation} = E_o - \beta \ln(a^{0.5})$$

Although the concatenation of these two numeric models removes the misfit at the low elevations, the r-squared value remains 0.959. This is because the elevations vary over four orders of magnitude, and the concatenated model changes fewer than 2% of all values by less than 50% on average.

Because elevations of continents near passive tectonic margins are almost entirely less than 200 meters, it seems clear that the change in aspect of the hypsometric profile from exponential (i.e. Eq. 2) to logarithmic (i.e. Eq. 3) might be manifest as a line of inflection relatively high on the coastal plains. It could be that the 170m contour divides coastal plain into two regions with somewhat disparate histories wherein the lower region has been affected by Pleistocene relative sea level variations as a result of fluctuating polar and continental ice volumes (Farrand, 1962; Mitrovica, 1994). Because an elevation of ~170 meters is close to that which separates largely Cenozoic passive margin successions from older pre-rift sequences, it is also reasonable that this transition might be interpreted as a necessary consequence of active tectonics. Specifically, well-developed coastal plains do not rim active tectonic margins, and the inflection of the continental profile might therefore simply be due to the marked difference in hypsometries of active and passive margins (e.g. Algeo and Wilkinson, 1991). Most likely, the higher elevations represent dominantly erosional surfaces in equilibrium with the ambient hydrologic regime as described by Langbein and Leopold (1962), and lower surfaces are largely depositional in character.

Regardless of the origins of the apparently different metrics that describe continental hypsometry above and below ~170m, there is excellent agreement between GTOPO30 (1996) elevation data and a hypothetical conical continental landmass with exponential profiles. This mathematical model provides a framework for comparing regional hypsometries in a quantitative fashion and investigating departures from global norms.

Continental hypsometry as a function of latitude

Because modern hypsometry is a reflection of the constructional and erosional history of a considered area, it must be dependent on initial hypsometry, on the time dependent rate of landscape change(vertical change), and on the total amount of time over which the various processes of change have been working. If elevations of a landscape respond to local erosion rates, they also ought to covary with modes and magnitudes of denudation. In order to test this hypothesis, continental hypsometries were derived by degree latitude and compared to the total continental hypsometry as modeled in the previous section. To that end, it is apposite to ignore both initial states of landscapes and the total timeframe of their respective morphogenesis. We justify this omission in part because such data are unavailable at a global scale, but mostly because we are unaware of any compelling theoretical or pragmatic arguments for systematic latitudinal variation in type or intensity of tectonic process. We then make the assumption that tectonic activity throughout geologic time is not correlated with latitude, and that initial hypsometries are similarly uncorrelated. We further make the uniformitarian assumption that distributions of intensity and style of denudation process at any latitude are largely invariant over the span of geologic time represented by continental landforms. It is therefore argued that continental histories reflect the sum of secular variation in conditions over landmasses moving and evolving through various climatic belts, and that has likely had a large effect in minimizing differences between continents. It is recognized that spatial and/or temporal heterogeneities might indeed be a significant factor in influencing the hypsometry of latitudinal bands. Perhaps obviously then, if latitudinally systematic changes in rates of net denudation and uplift processes over a longitudinally homogeneous world are less than the variability over our real heterogeneous Earth, then the dependence of continental scale physiography upon geomorphic processes that vary within a latitudinal gradient will never be observable. Finally, and to the degree that tectonic activity is uncorrelated with latitude, we suggest that any observed change in continental hypsometry with latitude reflects an expression of equator to pole climatic gradients attributable to temperature and precipitation dependence on latitude.

In order to determine the actuality and magnitude of change in continental hypsometry as a function of latitude, area/elevation relations were tabulated for 139 1-degree bands of latitude extending from 55° S to 83° N latitude from GTOPO30 (1996). Because each of these bands represents dissimilar areas and ranges of elevations, and because changes in the form of the hypsometric curves independent of those variables (whether or not they vary independently of ambient climate), each data set was first normalized to common horizontal (area) and vertical (elevation) scales. The method of normalization was adapted from that employed by Strahler (1954) to compare fluvial systems with different absolute drainage areas and total relief. Although each axis, or variable, is scaled independently, the nature of the relation between the two remains unaltered through scaling. To accomplish normalization, each measurement of area and elevation for any given latitude was transformed by its ratio with the total area and maximum elevation within that band.

After normalizing hypsometric curves of each of the 139 latitudinal sections, we calculated models for the conic profiles *excluding* the lower portions that represent about 17% of ice-free continental land area and about 5% of the model conic profile length. Although these proportions are not wholly insignificant, our current understanding does not offer particular insight into the nature of physiographies of continental lowlands and, as such, it is difficult to justify the inclusion of these likely depositional, passive margins when attempting to evaluate the role of climatic variation in erosion on continental topographies. Moreover, if a climatic signal is manifest as latitudinal change in area/elevation relations, there will surely be an associated record across the portions of land surfaces above ~170m.

When normalized areas and elevations are ordered relative to absolute latitude, qualitative inspection of the resultant surface suggests that latitudinal hypsometries do not display any obvious trend with respect to their position along the equator to pole continuum (Fig. 4). Moreover, the principal descriptor of each normalized latitudinal hypsometry is the decay constant of the exponential distribution (e.g. Figure 2). These were also calculated for all 139 bands of latitudinal data by regressing the square root of conic area with the natural logarithm of its related elevation. This metric does not vary as a function of latitude, nor is it significantly correlated with mean annual temperature or mean annual precipitation.

In order to further evaluate the possible dependency of continental hypsometry on latitude, differences between normalized GTOPO30 (1996) data and those predicted from the best-fit exponential conical model were also calculated. Those residuals also fail to reveal any apparent change with respect to latitude (Fig. 5). Because neither hypsometries for normalized best-fit exponential cones, their decay constants, nor residuals between best-fit models and GTOPO30 (1996) elevations covary with latitude, we conclude that global scale size distributions of modern continental elevations have no dependency on geologically recent climatic conditions.

Slopes of Continental Surfaces

Introduction

Hypsometric analysis provides an excellent method for quantitatively describing the area-weighted distribution of continental surface elevations, both globally and for any specific latitudinal band. However, this approach does not preserve any information associated with the real spatial variation of elevations on Earth's surface. That is, a hypsometric curve can be thought of as a perfectly ordered spatial permutation of elevations of continental surfaces: a form where the highest elevation leads to sequentially decreasing heights in all directions, as the conic model. Although this representation of continental landforms generally fails to capture those aspects of geomorphic entities that relate to their natural spatial arrangement, slopes of landform surfaces intrinsically record the local contiguity of topography, and they therefore offer some information about landscapes that hypsometric distributions of elevations cannot.

Slopes of fluvial channels have been intensively investigated for more than a century (e.g. Gilbert, 1876; Powell, 1877; Davis, 1909). Hack (1957) demonstrated that stream slope and upstream drainage area relate to equilibrium hydrologic energy of the landscape, by Langbein and Leopold (1962) and Connelly (1972) who proposed that a stream profile of minimum work has an exponential profile. More recently, slopes have been used to quantitatively evaluate a rock uplift rate (Whipple and Tucker, 1999; Kirby and Whipple 2001) in tectonically active regions. Because these and many other studies provide general understanding of processes that act on landform slopes, it hypothesized that slopes of continental surfaces demonstrably interrelate with climatic conditions. We therefore attempt to characterize the nature of slopes of continental surfaces as they vary across Earth.

Slope data

In order to quantitatively evaluate magnitudes and distributions of land surface slopes, data were generated from original elevation values of GTOPO30 (1996). Before assignment of slope values to each grid cell, two transformations were necessary to accommodate the equiangular spacing of the cells. First, linear distances between adjacent cell centers were calculated. Second, areas of cells as a function of latitude were also tabulated in order to avoid biases that arise from increased linear sampling density along equator to pole transects. In adopting this method, slopes were then calculated as the discrete change in elevation divided by calculated linear distance over a nine-neighbor cellblock, adapted from Burrough (1986). Slope distributions were then weighted by the amount of area that they represent. It is noted that DEM data could potentially have been transformed into a set of equal-area projections, with one for each major landmass, and slope distributions might have then been calculated directly without area weighting. However, this method is not as desirable because elevations of cells would necessarily have been resampled when grid data were reprojected. Although such resampling only changes the original distribution of elevations in a large dataset like GTOPO30 (1996) a small amount, it nonetheless would have introduced an avoidable source of error, and we therefore chose the former method for deriving continental slopes. Furthermore, computing slopes from calculated intercellular distances and distributions from calculated cellular areas, avoids the problems in picking appropriate projections as discussed by Finlayson et al. (2002).

The results of these transformations include slopes that range from 0 to 200 m/km, with a mean of 2.9 m/km. This maximum value (200 m/km) represents a 20% grade, or a slope of about 11 degrees. This is a value that is lower than those typical in alpine territories, and clearly reflects the fact that slopes generated from GTOPO30 (1996) largely fail to capture the grades of steeper mountainous terrains whose roughness exists on spatial scales smaller than 1 square kilometer, the approximate equatorial size of a 30 arc-second cell. Although this admittedly biased representation of mountainous features does not invalidate analysis of continental slopes (it leads to a more compressed rather than a truncated distribution of slope values), the numeric specifics are valid only at length scales of approximately 1 km.

In order to identify the existence and magnitude of any climatic influence on continental physiography as represented by slopes of subaerial surfaces, it is necessary to describe spatial heterogeneity of slope values at a global scale. This is possible because physiography is the current sum of historical tectonic and climatic processes imparted upon landscapes and because tectonic activity has no known dependence upon latitudinal position. It is therefore hypothesized that latitudinal variations of slope distributions on continents can be ascribed to change dependent on climate. These are the same arguments presented for interpreting a climatic affect for latitudinal changes of hypsometry.

In order to ascertain the dependency of landform grades on latitude, slopes were extracted from GTOPO30 (1996) by grid cell, and were associated with the mean elevation and latitude of the cell from which slopes were calculated. Data were derived for each 1 degree of latitude and each 1 meter of elevation, resulting in the generation of ~350,000 points between 0 and 83 degrees of absolute latitude and between 1 and 8,752 meters of elevation. Because many cells share common elevation and latitude combinations, data with duplicate location values (i.e. absolute latitude, elevation) were weight-averaged by area to produce a unique value for each individual latitude and elevation combination. While these values persist (with increasing sparseness) to over 8 km, they provide nearly complete coverage up to 80 degrees of latitude and 3 kilometers of elevation, and allow for the visualization of variation of landform slope as a function both elevation and absolute latitude (Figure 7).

Slopes as a function of latitude

Average slope data were analyzed with respect to absolute (rather than actual) latitudinal position for several reasons. Most importantly, in a world of where climatic symmetry mimics latitudinal symmetry, average slope would be similar for latitudes equidistant from the equator. Then by combining measurements from northern and southern hemisphere data, more robust estimates of average slope would thereby be produced. Although the spatial coincidence of climatic and latitudinal symmetry might not exactly be the case currently, it is close to the extent that the climatic equator manifest as the Intertropical Convergence Zone that separates barometric highs and lows of northern and southern hemispheric origin. With weather patterns constantly cross the Equator so the line representing the ICZ oscillates at random north and south of the Equator (e.g. Krom, et al., 2002). In addition, if average slope does change with distance from the equator, then the symmetry imposed on slope as a function of latitude will likely create a maximum or minimum at, or close to, the equator.

When slope is plotted as a function of elevation and absolute latitude, it can be seen that the distribution of average landform slopes over the Earth's surface is, not surprisingly, primarily correlated with elevation (Figure 6). Plots of landform slope versus elevation exhibit positive covariance; slopes are more strongly correlated with elevation and show smaller standard deviations at lower elevations (Figure 7). This covariance is also a requisite consequence of the nature of stream profiles as hollow curves (e.g. Broscoe, 1959; Morris, 1999), a relation also strongly reflected in the shape of the Earth's continental hypsometry.

Two other noteworthy features are also evident on plots of surface slope versus elevation. First, maximum continental elevation attained within each band of latitude generally decreases poleward. While this trend might merely reflect a spurious coincidence of tectonism across equatorial bands, it is also the pattern that would be expected if regions of tectonic activity were distributed randomly over Earth's surface. If regions of uplift were in fact independent, poleward decrease of maximum elevation should occur only because area bounded by latitudinal bands also decreases poleward. Comparison of maximum continental elevations with those anticipated from Earth latitudinal areas alone suggests the presence of some modest correlation, with elevations at equatorial latitudes being somewhat lower than anticipated and those within temperate latitudes being somewhat higher (Figure 6). Some of the difference between this cosine trend and actual maximum elevations probably reflects the fact that major orogens span several tens of degrees of latitude.

Second, and certainly of greatest importance to this study, examination of variation in Earth surface slopes with elevation and latitude shows that relations between slope and elevation, and slope and latitude, are spatially heterogeneous. Although steeper slopes occur at higher elevations, it is also apparent that, at any specified elevation, slopes increase with increasing latitude. This dependency of slope on both elevation and latitude is well illustrated by the superposition of a first-order trend surface on slope data plotted in elevation-latitude space (Figure 6). This surface is defined as:

$$\text{slope} = \beta_0 + \beta_1 * \text{elevation} + \beta_2 * \text{latitude} \qquad (4)$$

Equation 4 has three parameters that are determined by minimizing the misfit between land surface slopes and those defined by the trend surface. These parameters are: β_0 = -111, β_1 = 0.318 /m, and β_2 = 9.73/degree; they demonstrate that continental slopes are positively related to both elevation and absolute latitude. As an excellent first-order approximation, this trend surface accounts for over 40% of spatial variance in the slope data.

Slope data on Figure 6 average 1 m/km but this value is somewhat misleading. Slope values themselves are composed of slopes averaged over every meter of elevation and every degree of latitude. As a result, two points of data on Figure 6 could represent significantly different amounts of Earth-surface area. A more accurate average slope can be derived by weighting the original GTOPO30 (1996) data by the amount of area included in each cell. The value of mean subaerial continental slope obtained by such area weighting is 2.9 m/km or about 10 arc minutes; this is the grade necessary to elevate Medicine Bow Peak (in the Snowy Range of Wyoming) to 3.6 kilometers (12,000 ft) over the 1,250 kilometers of horizontal distance between the Mississippi River and the Wyoming Front Range. The relative importance of change in elevation and change in absolute latitude in controlling Earth-surface slopes can be found algebraically by solving for the ratios of Δelevation and Δlatitude for the trend surface. This yields:

$$(5) \qquad \beta_1 / \beta_2 = \Delta\text{latitude} / \Delta\text{elevation}$$

In detail this ratio will vary from region to region over the elevation-latitude surface (Figure 6), but on average a 30-meter change in elevation has the same average effect on slope as does a 1-degree change of latitude. That effect is less at low elevations, and greater at high elevations. Conversely, a 1-meter change of elevation has the same mean effect on slopes as does 2-arc minute change of latitude.

Discussion and Conclusions

From within the dynamically linked climatic and tectonic systems, it is reasonable to theorize that, at global scales of consideration, a climatic dependence of land surfaces could be distinguished from that of a tectonic dependence. Furthermore, a current wealth of data on continental elevations can be used to test various hypotheses regarding the interactions of global scale physiography, climate, and tectonics. Specifically, the overall dependence of continental landscapes upon climate might be extracted from global elevation datasets by analyzing the covariance of physiographic metrics and latitude. This is possible because Earth's latitudinal climatic gradient is not spatially coincident with a systematic tectonic gradient.

Hypsometric curves are area-weighted distributions of elevations of landforms, and the hypsometry of all continental surfaces is closely approximated by a square-root exponential distribution. Much in the manner of Murray (1888) who envisaged continents as cones, the square root exponential can be thought of as a conic form with elevations that decrease exponentially along a radial profile. This hypsometry largely reflects the fact that Earth's landmasses possess surfaces that derive from the inherently exponential nature of stream and river profiles. Although elevation distributions exhibit systematic departures from exponential profiles over the lowest several hundred meters of subaerial surfaces, hypsometric models as exponential cones robustly capture major relations between total area, maximum elevation, and radial decay constant among continental landmasses, and are a natural geometric analog of hypsometric curves.

Hypsometries of landmass agglomerates within one-degree latitudinal bands are also closely approximated by square-root exponential distributions. From this it can be shown that area/elevation relations are largely described by the maximum elevation and total area within each latitudinal band. Agreement between latitudinal hypsometries and those for exponential cones further implies that each latitudinal band contains a relatively unbiased sample of global topography and provides for the generally satisfied prediction that maximum elevation within any individual band will vary cosinusoidally with absolute latitude. Latitudinal hypsometries and differences between latitudinal hypsometry and their best-fit exponential cones do not appear to exhibit significant systematic variation across the Earth's latitudinally stratified climate zones.

From this we conclude that change in climate alone may be insufficient to significantly alter maximum elevations at regional scales. This conclusion is somewhat at odds with those of Bonnet and Crave (2003) who suggest that change in regional climate regimes such as a decrease in precipitation will potentially lead to an increase in the mean and maximum elevations of a previously steady-state interfluve landscape. Brozovic (1997) and Montgomery (1994) also argue that mean and maximum elevations correlate with glaciation of mountainous regions, but we must conclude that at length scales of 1 kilometer, there is no connection between mean or maximum elevation and relative importance of glacial process to a landscape- in agreement with theoretical considerations of Whipple, et al. (1999). Although glacial processes impose significant changes on local hypsometry, mountainous regions comprise a relatively small fraction of continental surfaces and, as such, their modification will have a relatively small effect on latitudinal hypsometry.

Although distributions of continental elevation are insensitive to Earth's latitudinal climatic gradient, distributions of land surface slopes are not. Globally, landform slopes derived from GTOPO30 (1996) exhibit a positive correlation with parent elevations. This relation is irrespective of latitude and is strongest at lower elevations where slope variance is a minimum. In addition, at comparable elevations, subaerial slopes increase with increasing latitude, and although the effects of elevation and latitude on slopes are almost certainly not independent, a first-order trend surface accommodates over 40% of total variance of the Figure 7 surface. On the basis of these data, we conclude that latitudinal changes in temperature and or precipitation serve to impart differences between the physiographies of equatorial and polar regions.

Although the actuality of this latitudinal difference in geomorphology seems apparent, its origins are less clear. As a first approximation, landform slope must in part reflect differences in elevation across landmass surfaces and their relative areas. Because GTOPO30 data reveal no systematic change in either maximum elevations or relative areas among latitudinal bands that are not anticipated for those due to spherical geometry, steeper slopes at higher absolute latitudes seemingly reflect some influence of cryogenic-related processes of landform evolution. Some insight into the nature of these processes is gained from comparison of latitudinal hypsometries and surface slopes. Although it might be expected that steeper slopes at higher latitudes would also be expressed as some sort of systematic variation in hypsometry, both measured hypsometry (Figure 5) and differences between model and measured hypsometry (Figure 6) show no important variation with latitude. However, in addition to net relief, continental hypsometry also reflects the degree to which surfaces have been dissected. Because landforms of poleward latitudes are characterized as having steeper slopes than their equatorial analogs but equivalent hypsometries, we conclude that colder, dryer regions of the world are also generally more dissected at length scales of approximately 1 kilometer.

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Figure Captions

Figure 1. Latitudinal distributions of (A) mean annual temperature (MAT) and (B) mean annual precipitation (MAP) from 894 station records (diamonds) in the International Atomic Energy Agency - World Meteorological Organization Global Network for Isotopes in Precipitation (GNIP) database (IAEA/WMO, 1998). Heavy lines are least-square regressions for second-order polynomials with fit parameters labeled. N is number of station records. Pearson correlation coefficients are from linear regressions between polynomial fits and datasets respectively.

Figure 2. Total continental hypsometry. Gray is line hypsometric curve from all non-zero data in GTOPO30 and black line is hypsometric curve of exponential conic model fit to continental data using equation 2. K is the exponential decay constant of the conic radial profile. The Pearson correlation coefficient is from a linear regression between real and model elevations.

Figure 3. Total continental hypsometry between. Gray is line hypsometric curve from all non-zero data in GTOPO30. Thick black line is best-fit model shown in figure 2 and is determined with model of exponential decrease in height with linear increase in conic profile radius. This is dashed below ~170 m where systematic misfit of model to data occurs. Thin black line is combined model of equation 2 above 170 m and equation 3 below.

Figure 4. Global hypsometry by latitude (abscissa) as normalized area (ordinate) below normalized maximum elevation for 139 one-degree latitudinal bands from 55°S to 83°N latitude. Note a general absence of variation readily ascribed to poleward distance.

Figure 5. Residuals of data and best-fit models (Fig. 4) of continental hypsometry plotted relative to latitude. Note a general lack of variation easily attributed to latitudinal position.

Figure 6. Average slopes of continental surfaces as a function of elevation (ordinate) and absolute latitude (abscissa). Open areas are elevation-latitude coordinates not presently represented by continental surfaces on Earth. Diagonal lines are contours of a

first-order trend surface through slope values. Slope is expressed as rise/run in m/km. Data were derived for each degree of latitude and meter of elevation, resulting in ~350,000 points poleward to 83° latitude and 8,753 meters. Data points appear stretched along latitude axis because there are 6500 divisions for elevation axis and only 83 for latitude axis. The average slope over all continental surfaces is about 1 m/km. Heavy black and white line is the best-fit cosine of maximum elevation at each latitude ($r^2 = 0.49$). Tibetan Plateau is visible as grouping of low slope values around 5 km and 35 degrees.

Figure 7. Plot of mean and standard deviation of subaerial continental slope as a function of elevation (lower) and cumulative land area (upper). Note that slope and elevation exhibit positive covariance. Solid line is a linear regression between slope and elevation to 2.3 km, which includes 95% of continental land area. Over this interval, mean continental landform slope increases at rate of 4.41 mm/km for every meter increase in elevation ($r^2 = 0.96$).

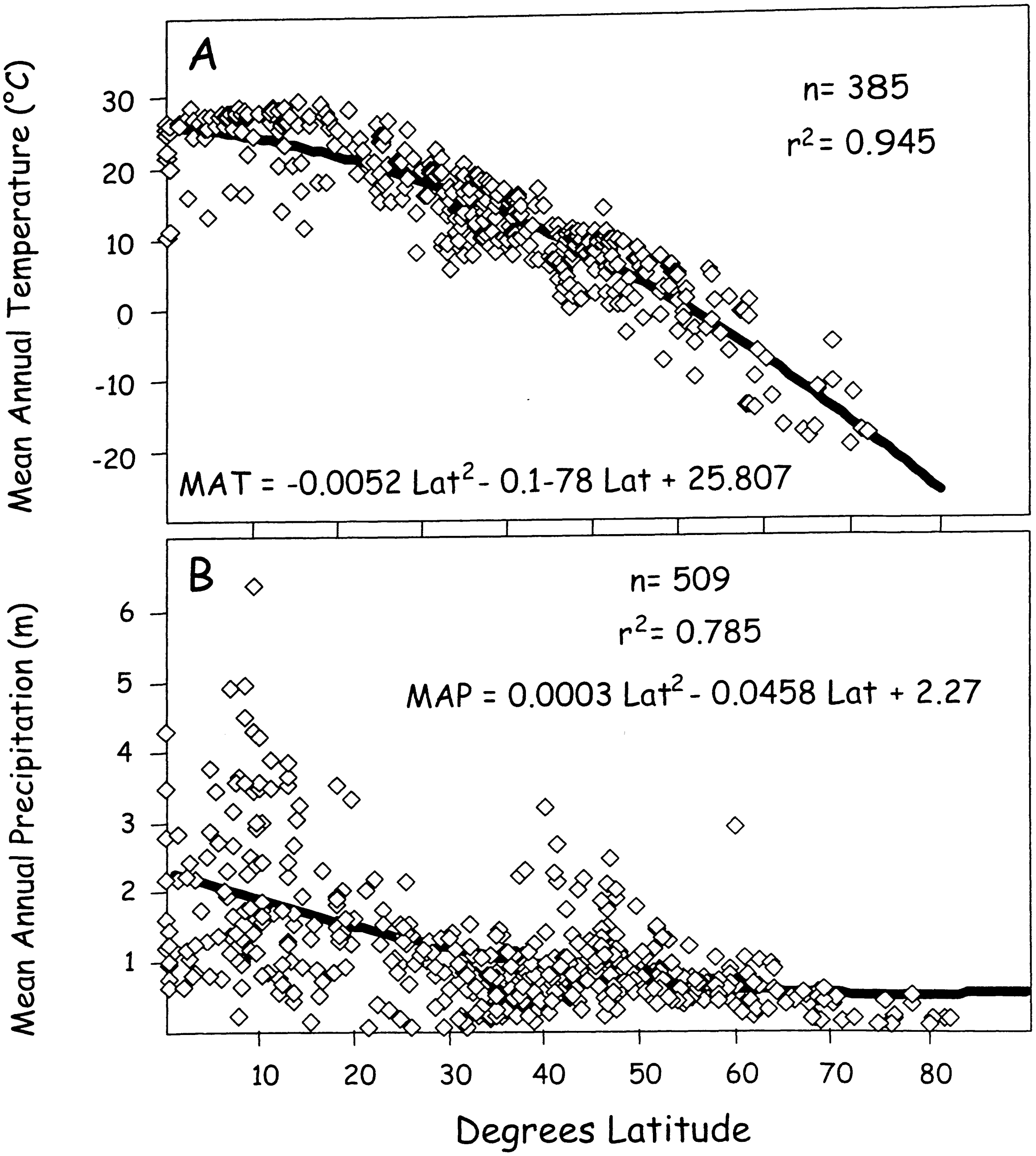
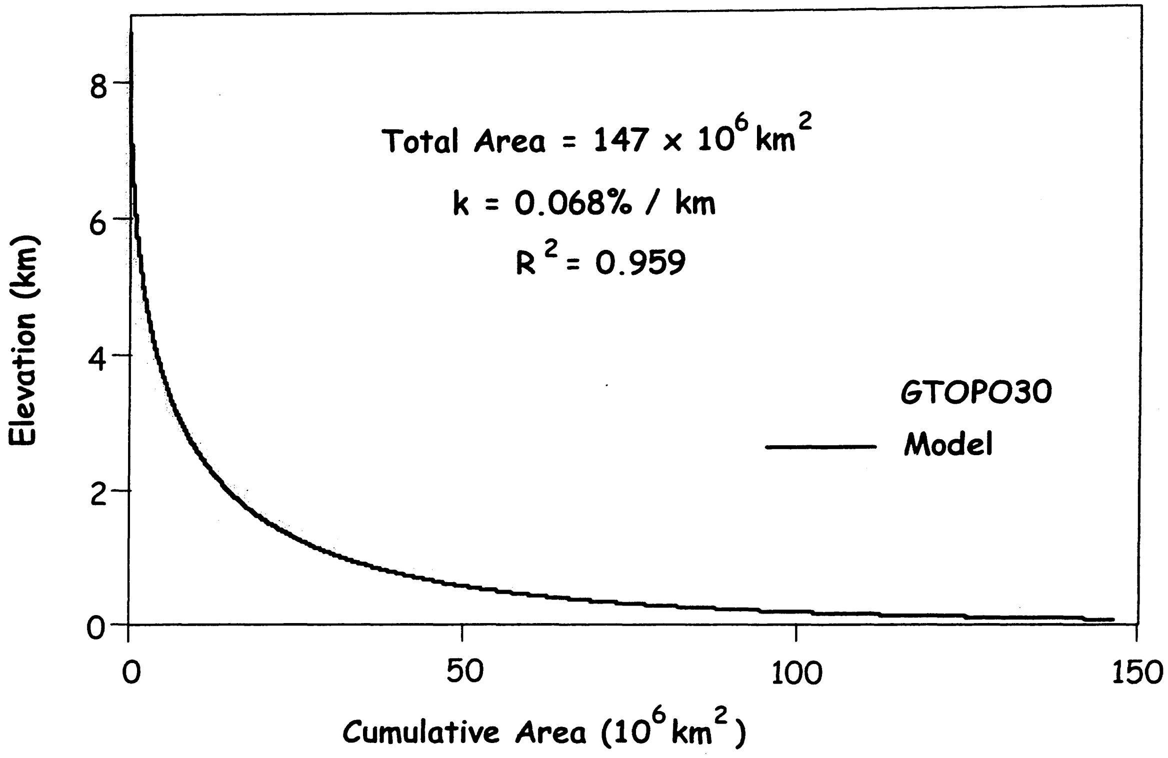

A
n= 385
r^2= 0.945
MAT = -0.0052 Lat^2- 0.1-78 Lat + 25.807
Mean Annual Temperature (°C)
30
20
10
0
-10
-20
B
n= 509
r^2= 0.785
MAP = 0.0003 Lat^2- 0.0458 Lat + 2.27
Mean Annual Precipitation (m)
6
5
4
3
2
1
10
20
30
40
50
60
70
80
Degrees Latitude

Figure 1



Total Area = 147 x 10^6 km^2
k = 0.068% / km
R^2 = 0.959
GTOPO30
Model
Elevation (km)
0
2
4
6
8
0
50
100
150
Cumulative Area (10^6 km^2)

Figure 2

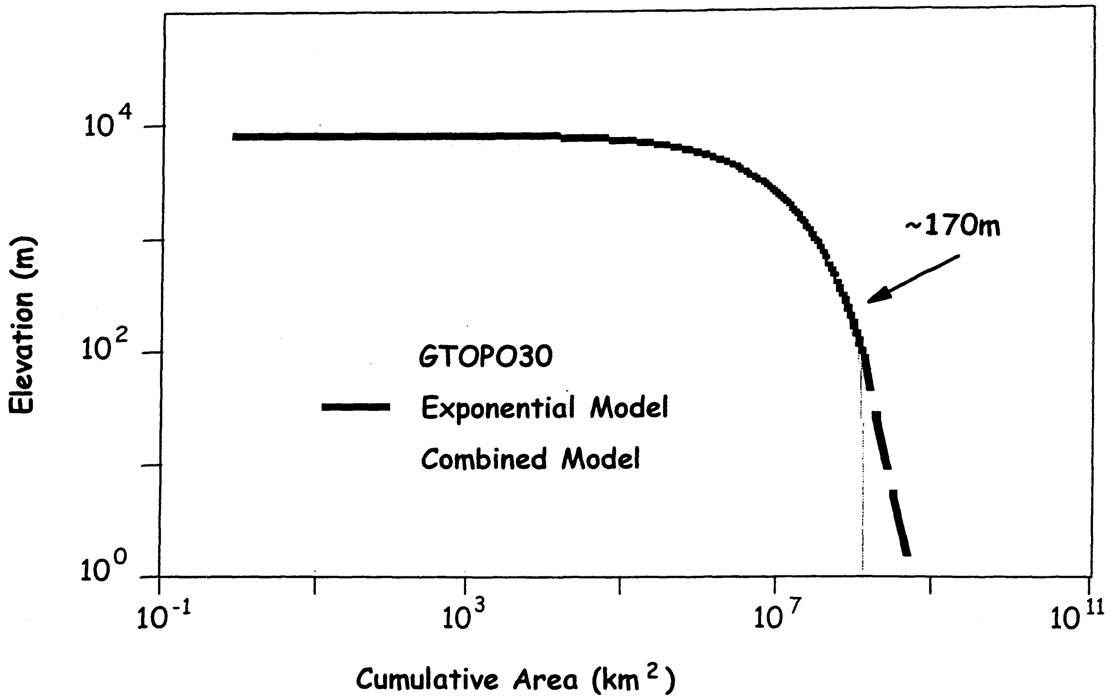

10^4
10^2
10^0
Elevation (m)
10^-1
10^3
10^7
10^11
Cumulative Area (km^2)
~170m
GTOPO30
Exponential Model
Combined Model

Figure 3

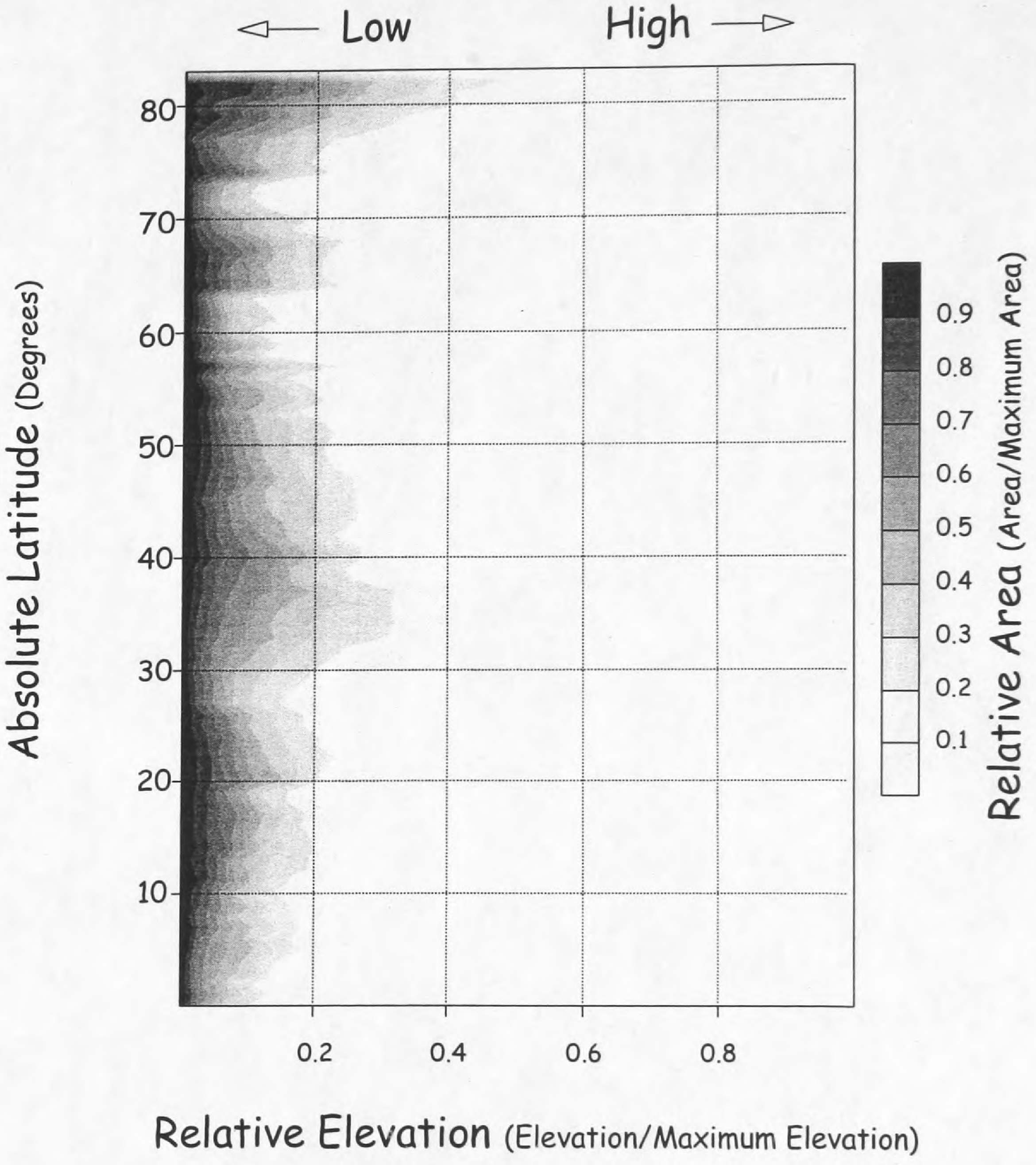

Low
High
Absolute Latitude (Degrees)
80
70
60
50
40
30
20
10
0.2
0.4
0.6
0.8
Relative Elevation (Elevation/Maximum Elevation)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Relative Area (Area/Maximum Area)

Figure 4

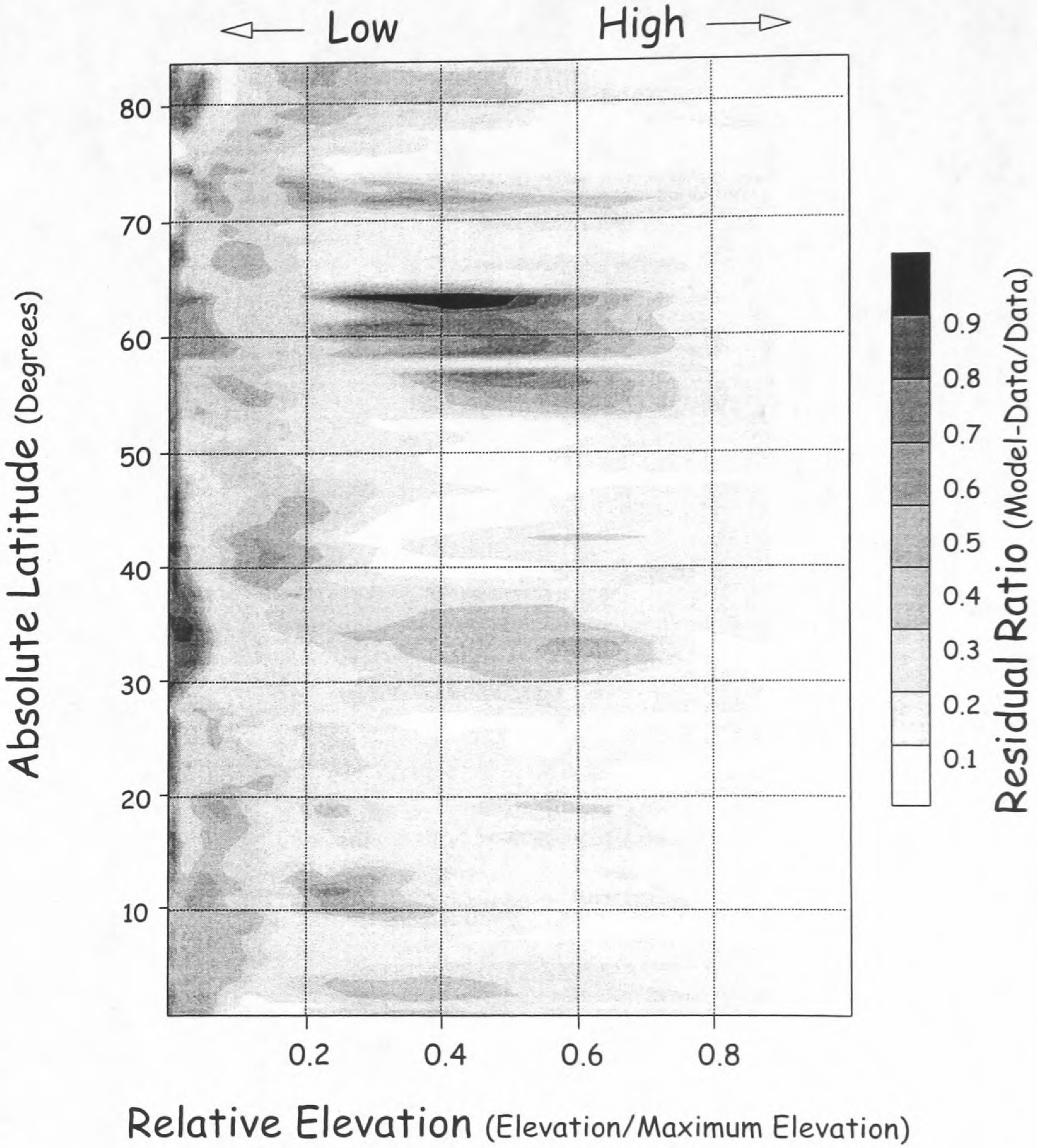

Low
High
Absolute Latitude (Degrees)
80
70
60
50
40
30
20
10
0.2
0.4
0.6
0.8
Relative Elevation (Elevation/Maximum Elevation)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
Residual Ratio (Model-Data/Data)

Figure 5

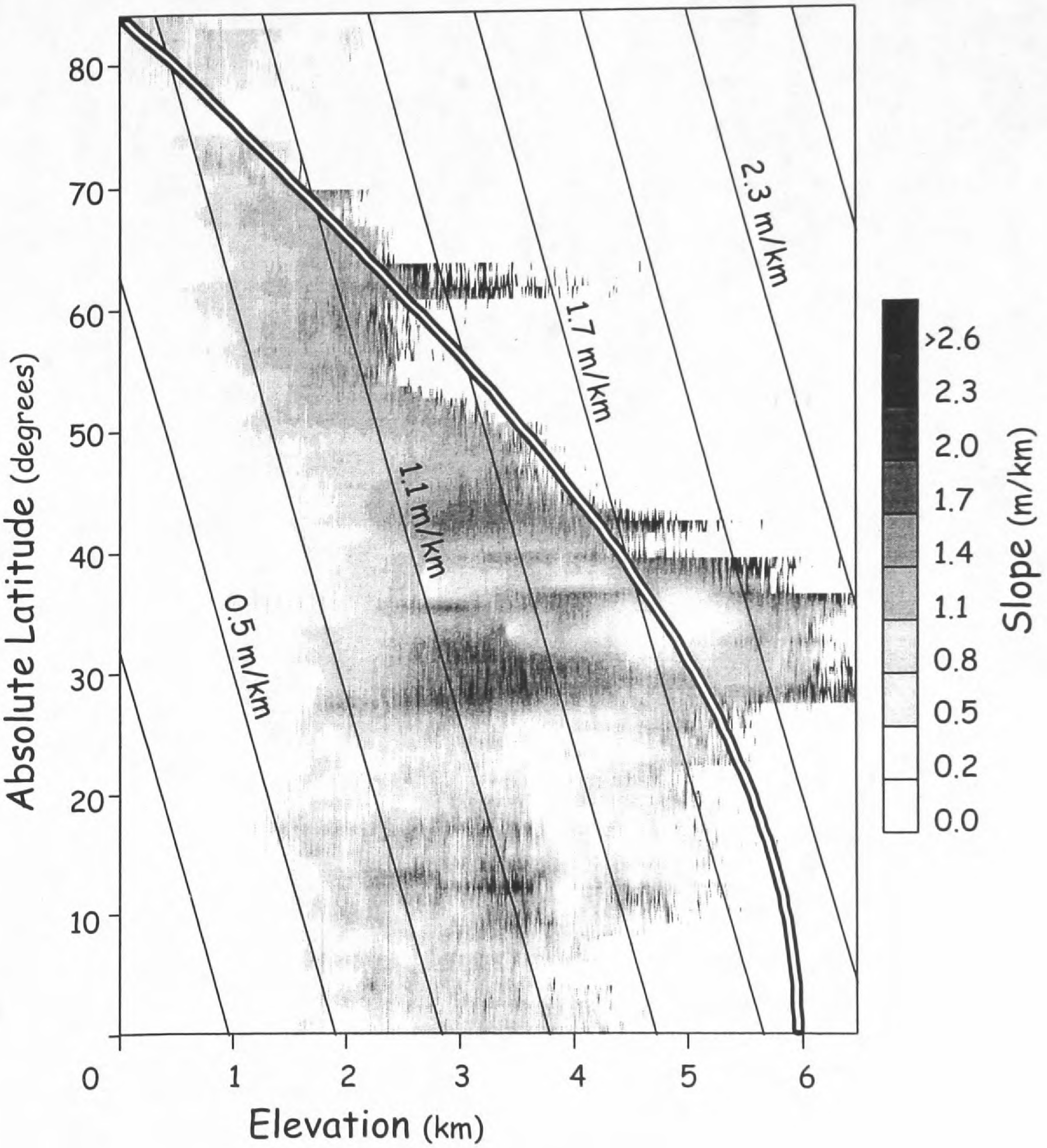

Absolute Latitude (degrees)
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
Elevation (km)
0.5 m/km
1.1 m/km
1.7 m/km
2.3 m/km
>2.6
2.3
2.0
1.7
1.4
1.1
0.8
0.5
0.2
0.0
Slope (m/km)

Figure 6

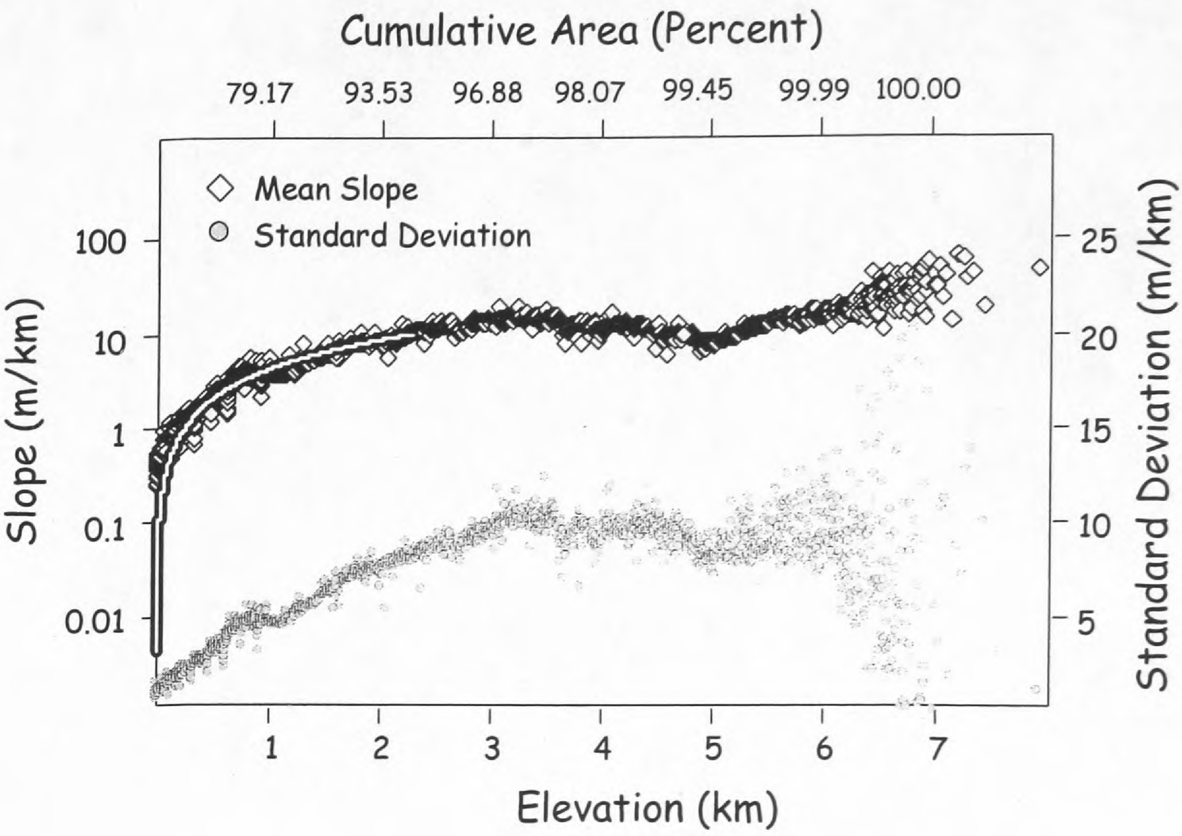

Cumulative Area (Percent)
79.17
93.53
96.88
98.07
99.45
99.99
100.00
◇ Mean Slope
○ Standard Deviation
Slope (m/km)
100
10
1
0.1
0.01
Standard Deviation (m/km)
25
20
15
10
5
1
2
3
4
5
6
7
Elevation (km)

Figure 7