Refinement of Eocene lapse rates, fossil-leaf altimetry, and North American Cordilleran surface elevation estimates

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Key words

- North American Cordillera
- Eocene climate
- Global climate model
- Fossil leaf paleoaltimetry
- Temperature and moist enthalpy lapse rate

Abstract

Estimates of continental paleoelevation using proxy methods are essential for understanding the geodynamic, climatic, and geomorphic evolution of ancient orogens. Fossil-leaf paleoaltimetry, one proxy approach, uses fossil-leaf traits to quantify differences in temperature or moist enthalpy between coeval coastal and inland sites along latitudes. These environmental differences are converted to elevation differences using their rates of change with elevation (lapse rate). Here, we evaluate the uncertainty associated with this method using the Eocene North American Cordillera as a case study. To do so, we develop a series of paleoclimate simulations for the Early (~55 – 49 Ma) and Middle Eocene (49 – 40 Ma) period using a range of elevation scenarios for the western North American Cordillera.

Simulated Eocene lapse rates over western North America are ~5 °C/km and 9.8 kJ/km, close to moist adiabatic rates but significantly different from modern rates. Further, using linear lapse rates underestimates high-altitude (> 3 km) temperature variability and loss of moist enthalpy induced by non-linear circulation changes in response to increasing surface elevation. Ignoring these changes leads to kilometer-scale biases in elevation estimates. In addition to these biases, we demonstrate that previous elevation estimates of the western Cordillera are affected by local climate variability at coastal fossil-leaf sites of up to ~8 °C in temperature and ~20 kJ in moist enthalpy, a factor which further contributes to elevation overestimates of ~1 km for Early Eocene floras located in the Laramide foreland basins and underestimates of ~1 km for late Middle Eocene floras in the southern Cordillera.

We suggest a new approach for estimating past elevations by comparing proxy reconstructions directly with simulated distributions of temperature and moist enthalpy under a

range of elevation scenarios. Using this method, we estimate mean elevations for the North American Cordillera of ~2 km using proxy temperatures and ~3 km using proxy moist enthalpy. This discrepancy is likely related to an inconsistency between the proxy data for temperature and moist enthalpy. The combination of temperature and moist enthalpy estimates implies a warm and dry environment, which is inconsistent with geological evidence for humid conditions. Our study emphasizes that lapse rates in warm climate were likely much different than today's, and highlights the advantages of using climate models to understand past climate states and regional circulation patterns to derive more accurate paleoelevation estimates using proxy temperature and moist enthalpy.

1. Introduction

The development of surface elevation informs our understanding of past geodynamic processes, regional climate patterns, and the distribution and evolution through allopatric speciation of ancient flora and fauna. Paleoelevation techniques have been widely used to constrain the surface uplift history of the North American Cordillera (e.g., Chase et al., 1998; Wolfe, 1998). Geological evidence suggests that this region was higher in the past, but how high and when the peak elevations were reached remains controversial (e.g., Sonder and Jones, 1999). Erosional dissection across the Rockies has long been viewed as evidence that Cordilleran uplift occurred during the Late Cenozoic (~10 Ma) (Graf, 1987). However, geophysical, tectonic, structural, and sedimentological evidence indicate that the crustal conditions necessary to support a high plateau existed across western North America during the late Cretaceous (~71 – 55 Ma) (DeCelles, 2004) and early Cenozoic (55 Ma to 28 Ma) (Chamberlain et al., 2012). Paleoelevation estimates based on stable isotopic compositions of soil and lacustrine carbonates,

volcanic deposits, and organic materials support the presence of an early, high plateau and indicate that the western North American Cordilleran may have been as high as 3 - 4 km during the Eocene (Mix et al., 2011; Chamberlain et al., 2012; Feng et al., 2013).

Studies using fossil-leaf paleoaltimetry indicate somewhat different elevations depending on whether temperature or moist enthalpy was used as an altimeter. Estimates using temperature suggest a high plateau with peak elevations ≥ 3 km across the Laramide foreland province but relatively low elevations in the hinterland region during the Early to Middle Eocene (~55 to ~40 Ma) (Chase et al., 1998). Estimates using moist enthalpy, in contrast, yield elevations of ~3 km in the northern reaches of the Cordillera, but relatively low elevations (2 km) to the south (Wolfe, 1998). The discrepancies in the paleoelevations and geometry of the Cordillera estimated through fossil leaf, and stable isotope paleoaltimetry confound our understanding of the tectonic history of the region. For example, peak elevations in the hinterland, inferred from stable isotope records, and a significant north-south topographic gradient, inferred from both stable isotope records and moist enthalpy reconstructions, are consistent with the idea that high topography propagated from north to south with piecemeal removal of mantle lithosphere (Chamberlain et al., 2012). Alternatively, the occurrence of peak elevations in the Laramide foreland province, as indicated by temperature estimates, provides support for the idea that underthrusting of the oceanic plate beneath North American continental lithosphere and eastward propagation of basal décollement might have driven the uplift (DeCelles, 2004).

Methods for reconstructing past surface elevations rely on proxies of environmental properties, such as fossil leaves, that can be related to surface elevation. Characteristics of fossil leaves including leaf size, and margin, have been related to near-surface temperature and moist

enthalpy, both of which vary as a function of surface elevation. Fossil-leaf altimetry uses the inferred temperature (see a review by Meyer, 2007) or moist enthalpy (e.g. Forest et al., 1999; Forest et al., 2007) difference between two different fossil locations, in combination with modern or theoretical lapse rates, to calculate surface relief between the sites.

In previous studies that apply fossil-leaf altimetry, temperature lapse rates have typically been estimated by dividing surface temperature differences between two coeval sites at similar latitudes by their elevation offset, resulting in values of $\sim 2 - 5$ °C/km across the western U.S. (Wolfe et al., 1992). The moist enthalpy lapse rate has been taken to be 9.8 kJ/km based on the theoretical considerations of the conservation of energy within an air parcel (see Section 2.1 and Forest et al., 1999). To estimate absolute surface elevations, coastal fossil sites have often been used to provide a sea-level reference (e.g., Meyer et al., 2007).

Uncertainties in fossil-leaf altimetry have been attributed to the interpretation and scoring of leaf characteristics. Leaf-climate relationships are calibrated from modern studies, and have uncertainties of $\sim 2 - 5$ °C (Forest, 2007; Miller et al., 2006; Peppe et al., 2011; Spicer et al., 2005; Teodoridis et al., 2010; Wilf et al., 1997), and $\sim 5.5 - 13.4$ kJ (Forest et al., 1999; Peppe et al., 2010), equivalent to surface elevation uncertainties of $\sim 0.5 - 1.4$ km assuming modern global (5 °C/km) or theoretical (9.8 kJ/km) lapse rates. Leaf-climate relationships are weakened by the complicated responses of leaf physiognomy to the growing environment. For example, toothed margins of fossil leaves are usually related to temperature, but other factors such as local water, plant type (deciduous vs evergreen and woody vs non-woody), leaf thickness, and wood type (ring-porous vs diffuse-porous) (Peppe et al., 2011; Royer et al., 2012) are also closely linked to this trait. To further complicate matters, leaf shape, size, and margin are shown to be controlled

by phylogeny and may not maintain the same climate-leaf characteristics relationship in the past as present (Little et al., 2010). This problem can partially be resolved by incorporating phylogenetic variations into calibration of climate-leaf characteristics relationships (Peppe et al., 2011), a measure that is yet to be further explored. The scoring of leaf traits is another source of uncertainty. Estimates of leaf size, from which humidity and moist enthalpy are derived, can vary depending on the method of measurement (Peppe et al., 2010) and the classification system used (Wilf, 1998). Uncertainties in measured leaf size can lead to biases in the hypsometric estimates of present-day North American elevations of up to 2 km (Peppe et al., 2010).

The temperature and moist enthalpy lapse rates used to translate proxy differences between sites to elevation estimates are another potential source of bias that have not been investigated. In the absence of a good alternative, most previous studies have used modern lapse rates (e.g. Chase et al., 1998; Ghosh et al., 2006; Wolfe et al., 1998). However, there is no reason to think that lapse rates have remained constant through time especially on regional scales. Different climate and topographic conditions can profoundly influence both temperature and moist enthalpy lapse rates. For example, in climate simulations with elevated CO₂, the middle troposphere undergoes preferential moistening and warming, which weakens vertical stratification and giving rise to shallower lapse rates (Poulsen and Jeffery, 2011; Soden, 2005). Conversely, cold climates likely exhibit stronger tropospheric stratification and greater lapse rates. In addition, climate models simulate substantial changes in temperature and humidity due to Andean and Tibetan Plateau surface uplift. The uplift of southern Tibet leads to a regional increase of ~5 – 10 kJ in moist enthalpy (Boos and Kuang, 2010). Similarly, diabatic heating in response to Andean uplift enhances moisture convergence over the range (e.g., Feng et al., 2014;

Insel, et al., 2009; Poulsen et al., 2010) and doubles the moisture content of local air masses at high altitudes (Insel et al., 2009), leading to a potential reduction in temperature and moist enthalpy lapse rates.

Similar complexities likely contribute to discrepancies between elevation estimates for the Eocene North American Cordillera derived from fossil leaf temperatures and estimates derived from moist enthalpy. In order to resolve these discrepancies, we re-evaluate and refine hypsometric estimates using a global climate model. First, we explore differences between Eocene and modern lapse rates across the western U.S. using estimates from high-resolution modern observations and Eocene climate simulations. Then, we calibrate possible biases in elevation estimates introduced by changes in local atmospheric circulation due to the uplift. Finally, we utilize our Eocene climate simulations to estimate elevations of the western North American Cordillera through a comparison of model simulations and proxy data. Differences in our estimates from published results are subsequently analyzed and discussed.

2. Methods and data

2.1 Calculation of moist static energy and moist enthalpy

The use of moist enthalpy to deduce past surface elevations was pioneered by Forest et al. (1995) with the assumption that under adiabatic conditions, and ignoring small changes in kinetic energy ($\ll 1\%$), the moist static energy of an air parcel is conserved. Hereafter, moist enthalpy, and moist static energy are referred to as ME, and MSE. MSE is defined as the sum of ME and geopotential (gH):

$$MSE = C_p T + L_v q + gH \quad (1),$$

and ME is defined as:

$$ME = C_p' T + L_v q \quad (2).$$

C_p' is the specific heat capacity at constant pressure of moist air; T (K) is the surface temperature (K); L_v ($J\ kg^{-1}$) is the latent heat of evaporation for temperatures between 238 and 308 K (List, 1984); q is the specific humidity (kg/kg); g ($9.8\ kg\ m\ s^{-2}$) is the gravitational acceleration and H (m) is altitude. In (1), the specific heat capacity for moist air is calculated as:

$$C_p' = C_p(1-q) + C_w q \quad (3)$$

where C_w and C_p are the specific heat capacities of liquid water ($4186\ J\ kg^{-1}\ K^{-1}$) and dry air ($1004\ J\ kg^{-1}\ K^{-1}$). If MSE of an air parcel is conserved ($\Delta MSE = 0$), changes in ME within the parcel are compensated by changes of geopotential ($\Delta ME = -\Delta gH$). This relationship gives the lapse rate of ME ($-\Delta ME/\Delta H$):

$$-\Delta ME/\Delta H = g \quad (4)$$

which is equivalent to $9.8\ kJ/km$.

The conservation of MSE implies that thermo-dynamic changes to an air parcel during lifting are purely adiabatic, an assumption that is not met under many circumstances. At any given location, the MSE is determined by the net energy transport and radiation flux. These fluxes sum to zero if averaged over a sufficiently large region and through the atmospheric column. However, the conservation is not always met locally within the lower troposphere where the paleoelevation is of research interest.

2.2 Moist adiabatic lapse rate

The moist adiabatic lapse rate is another atmospheric characteristic that can be potentially exploited by fossil-leaf paleoaltimetry. Present-day zonal mean tropospheric temperature lapse rates are nearly moist adiabatic within tropical (Xu and Emanuel, 1989) and extratropical regions

during wet seasons (Schneider and O’Gorman, 2008). We compare simulated Eocene temperature-elevation distributions with those predicted by moist adiabatic lapse rates in order to understand whether these theoretical lapse rates are applicable to paleoaltimetry of the Eocene North American Cordillera. The derivation of moist adiabatic temperature lapse rates requires stricter assumptions than derivation of ME lapse rates, including that cooling and condensation is both adiabatic and unidirectional and that all condensation is immediately removed from the parcel. The moist adiabatic lapse rate (Γ_s) can be calculated using the equation (Holton, 2004):

$$\Gamma_s = \frac{g}{c_p} \frac{[1 + L_v q_s / RT]}{[1 + \varepsilon L_v^2 q_s / (c_p R T^2)]} \quad 5)$$

where ε here is the ratio of molecular weight of water to that of dry air and q_s is the saturation specific humidity; $R=287 \text{ J kg}^{-1} \text{ K}^{-1}$ is the gas constant. Typical values of Γ_s are between 4 and 5 °C/km in warm and humid environments. Calculation of Γ_s requires knowledge of T and q_s at the condensation level, which is determined to be ~1 km above the sea level based on Eocene ensemble simulations. At this elevation, climatological mean relative humidity is over 90 % across the Cordilleran region.

2.3 GCM experimental design

We developed a series of Eocene simulations, using ECHAM5, for two purposes: (i) to evaluate lapse rates under past climate conditions, and (ii) to compare simulated temperature and ME with fossil leaf estimates as a means to identify likely elevation conditions for the Eocene fossil-leaf reconstructions. ECHAM5 is a global three-dimensional atmospheric general circulation model (Roeckner et al, 2003). The atmospheric model is configured with 19 vertical levels and a spectral triangular truncation of 106 horizontal waves (~1° horizontal grid spacing). All simulations include early Eocene boundary conditions and fixed sea-surface temperatures

(SSTs). Eocene paleogeography and topography are based on reconstructions from Scotese et al (1998) and Bice et al. (2000), and the vegetation distribution is from Sewall et al. (2000). Sedimentary and stratigraphic evidence suggests that the foreland region of the Cordillera was occupied by numerous closed basins that at times contained large lakes (Dickinson et al., 1988). These basins are represented in our simulations with low elevations of 0.5 km and a lake fraction of 50% (Fig. 1). Atmospheric CO₂ is specified as 1120 ppm, consistent with proxy reconstructions (Beerling and Royer, 2011). Atmospheric N₂O and CH₄ are set to present-day values of 306 ppb and 1.65 ppm. Monthly SSTs were calculated using the procedure described in Feng et al. (2013), which consists of 1) using ECHAM5 with a slab ocean model and present-day observational ocean heat flux to estimate the zonal distribution of SST, and 2) then adjusting the resulting meridional SST distribution to replicate the reconstructed meridional gradient of Eocene SSTs (See Fig. 1. in Feng et al., 2013).

Our simulations differ only by the prescribed heights of the North American Cordillera. The Cordilleran hinterland is represented as an ellipsoidal plateau with the peak elevation raised incrementally from 1 to 4 km at 0.5 km intervals (Fig. 1). The spatial extent of the hinterland is prescribed based on the distribution of stable isotopic compositions of oxygen ($\delta^{18}\text{O}$) and hydrogen (δD) in authigenic minerals and organic materials (Chamberlain et al., 2012; Mix et al., 2011). Sharp spatial gradients in $\delta^{18}\text{O}$ and δD are typically interpreted to result from isotopic rainout during orographic precipitation, and as a result signify topographic gradients. Strong Eocene isotopic gradients are found along slopes of the northern Sierra Nevada ($\sim 25\text{‰}$ in δD) (Mulch et al., 2006) and between the Yellowstone region and central Wyoming ($\sim 8\text{‰}$ in $\delta^{18}\text{O}$) (Fan et al., 2009; 2014; Sjostrom et al., 2006). Based on these gradients, the western boundary of

the Eocene Cordilleran hinterland in the model is placed along the Sierra Nevada Mountains and eastern boundary along the central Rockies and roughly follows the Cordilleran thrust belt to the south. All experiments were run for 20 model years and reach equilibrium within the first 5 years. Model results are reported as averages of the last 15 years. No apparent trends (<0.03 °C/decade) in global mean land surface temperature are detected over this period. An additional simulation with present-day boundary conditions was also conducted in order to evaluate model skill in simulating temperature and ME across the modern western U.S.

Fig. 1. Prescribed western North American elevations (km). The North American Cordillera is systematically raised from a maximum elevation of 1 to 4 km in 0.5 km intervals (a-g). Foreland basins east of the Cordilleran hinterland are 0.5 km high and have a 50% lake fraction.

ECHAM5 was chosen for this study because it exhibits reasonable skill in simulating many aspects of modern and Eocene North American climate including the distribution of modern precipitation over western North America (Cook et al., 2008; Salathé, 2006) and the strength and location of the Aleutian low and the storm track over the Pacific Northwest

(Salathé, 2006). In addition, ECHAM5 simulates Eocene temperature and precipitation patterns in agreement with the majority of flora-based mean annual temperature and precipitation reconstructions across lowland western North America (Fig. S1, and Feng et al., 2013) and with previous modeling results using a high-resolution (50 km) regional climate model (Sewall and Sloan, 2006). The model underestimates precipitation amounts derived from early Eocene paleofloras (Wilf et al., 1998) across low elevation regions (Fig. S1, and Feng et al., 2013), a bias also noted in other modeling studies (Sewall and Sloan, 2006).

2.4 Calculations of modern and Eocene lapse rates

We calculate and compare lapse rates of surface temperature and ME from Eocene simulations and modern observations. Lapse rates are determined as the slopes of the least square regression between either surface temperature or ME and elevation at locations of observations and simulations. The uncertainty is reported as the 95% confidence interval of the slope. All results are calculated using mean annual climatologies.

Simulated lapse rates are derived from mean-annual 2-m temperature and ME at each model grid point. Modern lapse rates of temperature are calculated from station observations of at least two years in duration, of which there are a total of 2002 across the western continental U.S. (34 °N to 49 °N, west of 104 °W) (<http://www.ncdc.noaa.gov/cdo-web/>). Previous estimates of temperature lapse rates were calculated by dividing differences between individual inland and coastal stations along latitudes by their elevation differences (Wolfe, 1992). The application of high-resolution observational data allows refinement of these lapse rates over a continuous space. Due to the small number of stations (38) with complete observational records of all the parameters (surface temperature, dew point and pressure) required to calculate ME, ME lapse

rates are calculated using the Modern Era Retrospective-analysis for Research and Applications (MERRA) data (Rienecker et al., 2011). Co-located surface elevation values are estimated by bin-averaging 10' USGS elevation data (derived from the 30'' GTOPO30 dataset, US Geological Survey) into the MERRA grid (0.5° grid spacing). We calculate ME using 33-yr mean annual climatological averages (1979-2011). We have also estimated lapse rates using the North American Regional Reanalysis data (Mesinger et al., 2006). The results are similar for both reanalysis data. For simplicity, only the MERRA results are reported here.

Modern lapse rates of temperature and ME are reported for three regions including: the western coastal region (Fig. 2, red filled circles), the central Basin and Range and Columbia Basin region (Fig. 2, cyan filled circles), and the eastern Rocky Mountain and Colorado Plateau area (Fig. 2, green filled circles).

Fig. 2. Locations of climate stations in the NCDC database (small filled circles) and Eocene fossil sites (large filled circles). Modern observations are grouped into three sets according to different topographic conditions (red filled circles: coastal; cyan filled circles: Columbia Basin and Basin and Range; green filled circles: Rocky Mountains and Colorado Plateau). Gridded MERRA data are grouped into the same groups using the same latitude and longitude boundaries. Eocene sites (black filled circles) are compiled from Chase et al. (1998) and Wolfe et al. (1998).

2.5 Lapse rate-independent paleoaltimetry

We estimate Eocene North American Cordilleran elevations by directly comparing proxy reconstructions of mean-annual temperature and ME with values from each of our Eocene simulations. Our hypsometric estimates are the heights in the model at which simulated mean-annual temperature and ME match those derived from fossil leaves. This approach has the distinct advantage of taking into account non-linear variations in temperature and ME associated with uplift-induced circulation changes, which is overlooked when adopting the traditional fossil-leaf altimetry method based on using linear lapse rates. Hypsometric estimates are derived for three zonal transects centered at 42, 44, and 47 °N. Simulated temperature and ME are averaged over 5° latitudinal swaths for each transect. Proxy temperature and ME are binned into these transects by proximity.

3. Results

3.1 Modern and Eocene lapse rates of temperature and ME

Modern lapse rates of temperature and ME display distinct spatial variability across the western continental U.S. (Fig. 3 and Table 1). Temperature lapse rates are close to moist adiabatic rates (~4 - 5 °C/km) in the humid northern and central regions but approach the dry adiabatic rate (9.8 °C/km) in the semi-arid southwestern U.S. Lapse rates in this region are much higher than the ~3 °C/km lapse rate reported by Wolfe (1992). This difference arises from the fact that lapse rates in Wolfe (1992) were estimated incorrectly using California coastal temperatures (~13 - 16 °C from 33 to 38 °N), which are ~10 °C colder than low elevation continental interior temperatures (Figs. 3b and c).

Fig. 3. Observed modern temperature (T, left) and ME (ME, right) versus elevation (H). a-c) Mean-annual 2-m air temperature and elevation across zonal swaths at a) $47 \pm 2^\circ\text{N}$, b) $42 \pm 2^\circ\text{N}$, and c) $36 \pm 3^\circ\text{N}$. d-f) Mean-annual ME and elevation across the same zonal swaths. Locations are indicated by color-coding and correspond to the regions indicated in Fig. 2 for both temperature and ME. Regressions are only calculated for inland points (green and cyan).

ME lapse rates (Fig. 3 and Table 1) over the western U.S. are lower than the theoretical lapse rate (9.8 kJ/km, Section 2.1), indicating that MSE is not strictly conserved and increases at

high altitudes. The budget of MSE is determined by the net radiative flux and transport of MSE. Spatial variations in net surface radiative flux across the western U.S. are quite small ($< 5 \text{ W/m}^2$, based on MERRA data), indicating that the additional MSE comes from energy transport. The climatologic mean meridional circulation shows net northward transport of tropical air masses with high MSE towards high altitudes of the Cordillera (Fig 4a). This additional input of MSE increases the high-altitude ME, and lowers the ME lapse rate.

Table 1. Modern and Eocene lapse rates of terrestrial temperature and ME calculated from observations and simulations across transects of the western North America from the north to the south.

	Modern		
	Observed lapse rates		
	North (47 ± 2 °N)	Central (42 ± 2 °N)	South (36 ± 3 °N)
Temperature (°C/km)	4.0 ± 0.4	4.1 ± 0.3	6.8 ± 0.2
ME (kJ/km)	7.1 ± 0.5	7.8 ± 0.3	8.4 ± 0.3
	Simulated lapse rates		
Temperature (°C/km)	3.9 ± 1.2	3.7 ± 1.5	7.2 ± 1.6
ME (kJ/km)	7.3 ± 1.1	8.1 ± 0.8	8.4 ± 0.8
	Eocene		
	Simulated lapse rates		
	North (47 ± 2 °N)	Central (42 ± 2 °N)	South (36 ± 3 °N)
Temperature (°C/km)	4.8 ± 0.2	4.9 ± 0.2	5.1 ± 0.3
ME (kJ/km)	10 ± 0.3	10.7 ± 0.3	11.6 ± 0.3

ECHAM5 simulates reasonable elevation distributions of present-day temperature (Figs. S2a-c) and ME (Figs. S2d-f) across the western U.S. (compare Fig. S2 to Fig. 3). Simulated present-day lapse rates are close to observed rates (Table 1). The model underestimates

temperature lapse rates across the Coastal Range and Sierra Nevada Mountains, resulting from unresolved sharp topographic gradients across these ranges. This bias may be smaller in our Eocene simulations, since the Western Cordillera is thought to have been broader during the Eocene (DeCelles, 2004), and therefore, is better resolved in the model.

Simulated Eocene lapse rates differ significantly from modern rates (Table 1). Eocene ensemble lapse rates of temperature and ME are nearly invariant for the northern, central, and southern transects of the western North America and are close to the adiabatic lapse rates (Fig. 5a-b, thick dash lines for temperature (section 3.3.2) and 9.8 kJ km^{-1} for ME (section 3.3.1)). The differences between modern and Eocene lapse rates reflect changes in the mean climate and topography. Under warm Eocene conditions, the southern transect has greater low-level humidity, a source of latent heat, leading to lower temperature lapse rates than under the modern semi-arid conditions in the same region. Enhanced Eocene ME lapse rates are associated with a reduction in the influence of meridional energy transport due to 1) a shallowing of the meridional gradient of MSE in the Eocene resulting from a shallower meridional SST gradient, which reduces the effect of energy transport; and 2) blocking of meridional airflow due to the higher elevations of the Cordillera, which reduces the transport by airflow (Fig. 4b). This reduction leads to better conservation of MSE, and in turn, an ME lapse rate that is close to the adiabatic rate (9.8 kJ/km).

Fig. 4. Simulated mean annual MSE (shaded) and circulation (vectors) averaged between 100 and 110 °W across the (a) modern and (b) Eocene North American Cordillera. White regions represent topography.

3.2 Uplift-induced circulation change at high altitudes

Simulated Eocene temperature and ME for a specific location can vary considerable from the means for the elevation, as indicated by the width of boxplots of temperature and ME (Fig. 5). The interquartile range of temperature and ME is generally small across low-elevation ranges (≤ 2 km) with long tails skewed toward warm temperature and high ME, which reflect the influence of coastal air mass mixing. The interquartile ranges of temperature and ME generally widen at elevations above 2.5 km, with the full data range reaching ~ 8 °C and 8 kJ in the 4-km case (Fig. 5). The broadening of the distributions of temperature and ME with elevation indicates high variability around the mean, reducing the confidence that a linear lapse rate can capture the elevation-dependence of these parameters. Deviations of alpine temperature and moist enthalpy at higher elevation result from two distinctive aspects of uplift-induced circulation changes: 1) the warming and influx of MSE due to development of the paleo-North American Monsoon at

the leeward side of the Cordillera; and 2) the cooling and loss of MSE due to intensification of mountain gravity waves.

Monsoonal circulation is largely absent in the low-elevation cases (< 3 km), but becomes prominent on the leeside of the Cordillera in the high-elevation cases, as indicated by greatly enhanced July to September precipitation (Fig. 6a-c). The development of leeside monsoonal circulation in response to the uplift has been observed by previous studies (Feng et al., 2013; Sewall and Sloan, 2006). This monsoonal circulation brings warm tropical air from the Gulf of Mexico to the high altitudes of the eastern Cordillera, leading to significant warming of alpine temperatures in the eastern flank.

Fig. 5. Simulated mean-annual Eocene temperature (top) and ME (bottom) versus elevation for all prescribed-topography experiment. Thick dashed lines in (a-b) depict temperature changes following the moist adiabatic lapse rates calculated according to Section 2.2. To identify spatial variability of lapse rates, the North American Cordillera region is separated into northern (47 ± 2 °N, top) and southern (42 ± 2 °N, bottom) regions. Data are gathered from the western coast to 100 °W. Boxplots display the spread of data (interquartile range, IQR) at each elevation. Whiskers indicate the full range of the data. The spread of alpine temperature and ME increase at high elevation (> 2.5 km).

Mountain gravity waves are present in all cases, as indicated by the oscillation of 500-hPa vertical velocities between positive and negative values across and downstream of the plateau (Figs. 6d-f). The alpine vertical velocities show upward motion on the windward side of the plateau, strong subsidence above the plateau, and damped oscillations in the downwind direction (Figs. 6d-f). Mountain gravity waves greatly intensify in high-elevation (> 3 km) cases, as signified by an increase in the absolute magnitudes of 500-hPa vertical velocities. Mountain gravity waves are known to affect vapor $\delta^{18}\text{O}$ lapse rate by downward mixing of air parcels above high topography (Galewsky, 2009; Poulsen and Jeffery, 2011; Feng et al., 2013). Likewise, enhanced subsidence above the plateau (Figs. 6d-f) promotes downward mixing of upper-level air parcels low in ME, causing high-altitude depletion of ME in our experiments. Inland from the Cordillera (east of 100 °W), ME continues to decrease as a result of rainout following the airflow from the Pacific. This drying effect is largely independent of elevation

changes and is partially compensated by the monsoonal input of high ME air masses along the eastern flank of the Cordillera (Fig. S3).

Fig. 6. Circulation responses to increasing Cordilleran elevation in the model. (a-c) West-east distribution of July-September precipitation (mm/month) across the plateau. Note the intensification of monsoonal precipitation on the leeside (eastern side) of the plateau as elevations increase. (d-f) West-east distribution of annual mean vertical velocity at 500 hPa. The pressure velocity is multiplied by -1 so that negative values indicate subsidence and positive values indicate upward motion. Error bars on each point represent the full range of values across 5° latitude centered at 42 °N, 44 °N and 47 °N.

3.3 Simulation-based hypsometric estimates

To avoid biases related to changing climate states and uplift-induced circulation changes, we estimate elevation based on the direct comparison between our paleoclimate simulations and proxy reconstructions of temperature and ME (Section 2.4). Using this method, simulated temperatures match proxy values when prescribed maximum elevations are between 1.5 to 2 km

for the northern Cordilleran hinterland and between 2 to 2.5 km for the central and southern Cordilleran hinterland (Figs. 7a - c). In contrast, the match between simulated and proxy ME occurs for a Cordillera with maximum elevations of 3 to 3.5 km across all transects (Figs. 7d - f). Importantly, the estimates of maximum elevation derived from temperature and ME comparisons differ by ~ 1 km. Even for lowland sites, elevation estimates from proxy ME are generally higher than those based on temperature.

4 Discussion

4.1 Sources of temperature- and ME-derived elevation inconsistencies

In this section, we discuss the possible sources for the ~ 1 km inconsistency between our temperature-derived and ME-derived estimates of Eocene Cordillera elevations. This inconsistency is likely related to uncertainties arising from the proxies, rather than from the model, as we describe below.

Model biases could account for the inconsistency in two ways. One possibility is that simulated temperatures are too low at high-elevation fossil sites, leading to an underestimate of Cordilleran elevations. We note that the model does not exhibit a systematic temperature bias; simulated temperatures match low-elevation proxy temperatures reasonably well (Fig. S1). A high-elevation cold bias, however, would also mean that ME is too low (eq. 2, increasing temperature causes increasing ME), leading to an underestimate of ME-derived elevations as well, which can hardly eliminate the elevation inconsistency. A second possibility is that simulated humidity (q) at high-elevation fossil sites is too high. This bias would result in an overestimate of latent heat (Lq) and ME, leading to an overestimate of Cordilleran elevations (Higher elevations are need to reach the relatively low proxy alpine ME). However, we find no

support for this possibility; in fact, the model may have a dry bias, as it underestimates Eocene precipitation rates across the Cordillera (Fig. S1).

The elevation inconsistencies could also originate from the proxy estimates of temperature and ME. To evaluate this, we test whether the proxies are consistent with independent geological observations by estimating specific humidity (q) at the fossil alpine sites from proxy estimates of ME (between 295 to 300 kJ) and temperature (10 to 12 °C, Fig. 7). Using equation (2), alpine specific humidity is calculated to be between 4.3 and 5.5 g/kg, values that are comparable to MERRA observations for the present-day, semi-arid, western U.S. (3.7 – 5.3 g/kg, 33 - 49 °N, 112 – 103 °W). These estimates are inconsistent with the high annual rainfall abundances estimated from Eocene fossil leaves using data from the climate leaf analysis multivariate program (CLAMP) (Gregory and Chase, 1992; Wing and Greenwood, 1993) and leaf area analysis (Wilf et al., 1998). Furthermore, the semi-arid conditions inferred from proxy ME and temperature are at odds with fossil evidence for the presence of abundant conifer forests in central Idaho (Erwin and Schorn, 2005), northeastern Nevada (Axelrod and Bailey, 1969), southern British Columbia, and northeastern Washington (Greenwood et al., 2005), all of which indicate a humid environment in the early Eocene.

Our analysis of specific humidity suggests that proxy estimates of ME are too low or estimates of temperature are too high. Peppe et al. (2010) report a potential explanation for the underestimate of ME: traditional categorical measurement methods underestimate leaf areas, which are used to reconstruct temperature and ME. This bias affects ME more than temperature. Using the present-day CLAMP climate-leaf traits dataset, ME and temperature are underestimated by up to ~13 kJ and ~2.5 °C (equivalent to ~2.5 kJ ME) (Fig. 3 in Peppe et al.,

2010). If this bias is applicable to Eocene fossil leaves, the substantial underestimate of ME would account for the anomalous dry conditions and the higher elevations that we have estimated using ME. Correcting for both proxy temperature and ME biases would reduce our temperature-derived and ME-derived elevation estimates for peak plateau heights by up to ~0.5 and ~1.3 km, respectively, thereby, reducing the offset between temperature-derived and ME-derived elevation estimates from ~1 km to ~0.2 km.

4.2 Elevation underestimates due to model resolution

Though we reject model bias as a source of inconsistency between our elevation estimates, our modeling is certainly not free of shortcomings that add uncertainty to our estimates. As in most paleoclimate modeling studies, our results must be considered in light of our imperfect knowledge and representation of boundary conditions (e.g. atmospheric CO₂, vegetation, sea-surface temperatures, paleogeography, etc.) for the Eocene, and the further possibility that we are missing important climate forcings (e.g. Poulsen et al., 2015). In addition to these general caveats, a source of uncertainty in our absolute elevation estimates of the Eocene North American Cordillera specific to this study arises from our comparison of relatively coarse resolution climate model results with sparse fossil floras. Significant amount of fossil floras are found within intermountain basins that would have been located at lower elevations with warmer and moister microclimates than their alpine surroundings. Our simulations do not capture this fine-scale topography and the associated climate variability. Therefore, the assumption (by us and previous workers) that fossil floras have recorded mean alpine environments may lead to an underestimate of the broad-scale elevation. Future high-resolution reconstructions of surface

reliefs, and the development of spatially continuous fossil floral sites will refine these elevation reconstructions.

Fig. 7. Zonal distribution of proxy and simulated Eocene temperature (left, a-c) and ME (right, d-f) at inland sites. Simulated-values represent 5° zonal averages across the Cordillera for each elevation scenario centered at 47 °N (top), 44 °N (middle) and 42 °N (bottom). Proxy records are mapped to each transect based on proximity and are colored and shaped by age. The error bars on the proxy temperature records depict the ranges of estimates compiled from Chase et al.

(1998), Greenwood and Wing, (1995), Gregory and Chase, (1994), Povey et al., (1994), and Wing and Greenwood, (1993).

4.3 Comparison of paleoelevation estimates for the North American Cordillera

Our elevation estimates based on Eocene climate simulations differ from previous reconstructions using lapse rates of temperature and ME in two ways. First, our estimates using proxy temperatures are systematically lower than previous estimates by up to 2 km at Cordilleran foreland sites (Figs. 8a-c). Second, based on the elevation estimates from both temperature and ME altimetry, we find high elevations of 2-3 km along the Cordilleran hinterland (Figs. 8b-c, e-f) and lower elevations of 1-2 km in the foreland basins of southwestern North Dakota (Figs. 7, 8a and d), western Wyoming (Figs. 7, 8b and e) and Colorado (Figs. 7, 8c and f) (locations of fossil sites are indicated in Fig. 2). This topographic gradient is absent in previous studies.

Fig. 8. Comparison between published paleoelevation estimates (filled squares) and our estimates based on Eocene climate simulations (hollow squares) using temperature (left column, a - c) and ME (right column, d - f) altimetry. Proxy estimates of temperature and ME are colored by age (Early to late Middle Eocene: dark blue to light blue). Thick dash lines indicate the longitudinal range of the Laramide foreland province. Rectangular boxes indicate the location of the Eocene Cordilleran plateau in previous studies (red) and by our estimates (blue).

There are several reasons for these differences. First, previous hypsometric estimates assumed a temperature lapse rate of 3 °C/km (Wolfe, 1998) that is lower than the lapse rates (~5 °C/km, Table 2) simulated in our Eocene runs. The higher lapse rates in our simulation lower hypsometric estimates by up to ~1.3 km. Second, our estimates are derived from direct comparisons between simulations and proxy values at inland sites, while previous estimates were based on temperature and ME differences between coastal and inland sites. This latter approach assumes that temporal climate variability along the coast is representative of inland sea-level conditions at equivalent latitudes. However, Eocene reconstructions do not support this assumption. In Fig. 9, inland temperature and ME from similar longitudes (therefore, similar distance from the western coast), show muted variations from the Early to late Middle Eocene. In contrast, variability in coastal temperature and ME between these times is up to 8 °C and 23 kJ. The magnitudes of coastal proxy temperature and ME, and hypsometric estimates, show strong correspondence when comparing hypsometric estimates of previous studies and ours (Figure 8, filled and hollow squares), i.e., warmer coastal temperature and ME during the Early Eocene and middle Middle Eocene correspond to higher hypsometric estimates in previous studies (Fig. 8, dark blue and grey blue), while colder temperature and smaller ME correspond to lower hypsometric estimates in previous studies (Fig. 8, sky blue).

The reasons for the proxy coastal variability and the strong contrast in climate variability between coastal and inland proxy sites are unclear. The lack of inland climate variability could be the result of compensating elevation changes. However, for this explanation to hold, the inland sites must have all experienced the same elevation adjustments, i.e., uplift from the Early to early Middle Eocene (counteracting the coastal cooling), subsidence from the early to middle

Middle Eocene (counteracting the coastal warming, and increasing ME), and uplift again in the late Middle Eocene (counteracting the cooling, and decreasing ME). This multiphase elevation adjustment of the Eocene Cordillera lacks support from known geological evidence.

Fig. 9. Temporal evolution of fossil leaf temperature (red) and ME (blue) at coastal (stars) and inland sites (filled circles). The sizes of the filled circles indicate the longitudes of the sites and increase eastward from the Pacific coast. The inland sites with the same marker size are from the same longitude, and have similar continentality (similar distance from the western coast). It can be seen that inland sites of similar longitudes have roughly invariable temperature and ME during the Early to Middle Eocene. Data are from Chase et al., (1998) and Wolfe et al (1998).

4.4 Implications for paleoaltimetry using fossil leaf physiognomy

A common practice in paleoaltimetry, including fossil-leaf paleoaltimetry, is to use modern lapse rates as approximations for paleo-lapse rates. Previous work has shown that this is a poor assumption for stable isotope lapse rates (e.g., Ehlers and Poulsen, 2009; Feng et al.,

2013; Fiorella et al., 2015; Insel et al., 2012; Poulsen et al., 2010; Poulsen and Jeffery, 2011). Our experiments extend this conclusion to temperature and ME, and demonstrate that lapse rates of temperature and ME vary as a function of climate state and elevation. In warm and moist climate states, such as the Early to Middle Eocene, annual mean lapse rates approach moist adiabatic rates, which in the present-day climate is mainly a tropical troposphere feature. In cold and dry climate states, such as the present-day and the last glacial period, lapse rates likely differ from the adiabatic rates in extratropical regions depending on the atmospheric moisture content and vertical and meridional mixing rates.

Previous paleoflora-based paleoaltimetry studies have generally overlooked the possibility that uplift-induced temperature and ME responses may be nonlinear. Our results find clear uplift-induced nonlinearity in both ME- and temperature distributions across the Eocene North American Cordillera; this finding and the potential for kilometer-scale elevation biases are similar to those found previously in stable oxygen isotope based paleoaltimetry (Insel et al., 2012; Poulsen et al., 2010). Nonlinearity in the distributions of temperature and ME along slopes of the North American Cordillera is particularly pronounced at elevations above 3 km. In the case of the Eocene North American Cordillera, these nonlinear variations may lead to kilometer-scale elevation biases in temperature and ME altimetry using linear lapse rates (determined by the range of temperature and ME distribution in the 4-km case in Fig. 5). Further, elevation biases display clear correspondence with uplift driven circulation changes across the Eocene Cordillera (Fig. 6). The warming effect due to monsoonal flow leads to the greatest elevation underestimates using a linear temperature lapse rate in the leeside eastern flank of the Cordillera (Figs. S3a-c). Downward mixing of low ME air masses induced by mountain gravity waves leads

to the greatest elevation overestimates using a linear ME lapse rate across the central Cordilleran plateau (Figs. S3d-f). Away from regions with temperature and ME that are sensitive to circulation changes, linear lapse rates may still be applicable to paleoaltimetry estimates of the Eocene Cordillera. However, without a clear understanding of the past atmospheric circulation patterns around the Cordillera and their response to surface uplift, identifying regions for which linear lapse rates could be applied would be impossible.

The biases summarized here may influence previous studies that applied linear lapse rates of temperature or ME to determine past elevations in North America and at other orogens. Lapse rate response to both global climate and circulation changes associated with surface uplift, including mountain gravity waves and monsoonal circulation, are observed across major orogenic regions, such as the Tibetan Plateau (Boos and Kang, 2010; Poulsen and Jeffery, 2011), central Andes (e.g. Insel et al., 2012; Poulsen et al., 2010), and Sierra Nevada (e.g. Galewsky, 2009). Consequently, reevaluation of previous lapse rate-based paleoaltimetry estimates (e.g. Ghosh et al., 2006; Spicer et al., 2003; Wolfe et al., 1997) may be needed to account for errors induced by these biases.

5. Conclusions

On the basis of a comparison of fossil leaf and simulated early Eocene temperature and ME, we estimate ~2 – 3 km paleoelevations for the Eocene western North American Cordillera, and low elevations of the adjacent Laramide foreland basins (< 2 km), respectively. The topographic gradient between the Cordillera and Laramide foreland basins is absent in previous fossil-leaf altimetry estimates, but occurs in our estimates and independent estimates using stable

isotope paleoaltimetry (Mix et al., 2011; Feng et al., 2013). These differences are likely due to two factors: First, simulated Eocene temperature lapse rates (~ 5 °C/km) are significantly higher than previously assumed, accounting for elevation differences of ~ 1 km. Second, large temporal variations in coastal proxy temperature and ME during the Early to Middle Eocene, which are absent at inland sites, were included in previous elevation reconstructions, accounting for a further ~ 1 km elevation bias.

Our elevation estimates, using temperature and ME, disagree by ~ 1 km. The higher range of estimates, using ME, are close to stable isotope based estimates (Mix et al., 2011; Feng et al., 2013), but the lower range, using temperature, is systematically lower by 1 - 2 km. This disagreement likely arises from the proxy reconstructions of temperature and ME, which seem to be incompatible. Specific humidity derived from these reconstructions implies semi-arid conditions, similar to modern, across the Cordillera during the Early to Middle Eocene, which are inconsistent with humid conditions indicated by fossil evidence of abundant alpine forests and proxy estimates of high precipitation rates.

Our results illustrate the danger of estimating paleoelevation using modern lapse rates or assuming constant lapse rates. We find that temperature and ME lapse rates vary significantly between climate states and are sensitive to uplift-induced changes in circulation and atmospheric moisture content. Ignoring these changes could result in kilometer-scale elevation biases over the Eocene North American Cordillera and may lead to even larger biases over other orogenic regions (such as Tibet) that are thought to have experienced more substantial changes in elevation and climate in the past.

Acknowledgements

This study was supported by NSF EAR grants 1019420 and 0907817 to C. Poulsen. We would like to acknowledge high-performance computing support from Yellowstone (ark:/85065/d7wd3xhc) provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation. We are grateful for two reviewers' constructive comments and suggestions for improving this paper. R. Feng would also like to acknowledge helpful discussions with colleagues of Climate Change Research Lab at the University of Michigan (<http://www.umclimate.com>). The simulation data are available to readers upon request.

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