The Role of Elevation on Temperature Trends in the Western United States: A Comparison of Three Statistical Methods

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Just the Facts….

- Mountains regions occupy 25% of global land surface area
- Approximately 26% of the world's population lives in mountainous regions or their foothills
- 40% of world's population relies on water sources originating from mountains
- Mountains often contain high biodiversity and a large proportion of the plant/animal species are endemic
- It's been said the only common aspect among the world's mountainous regions is their complexity (climate, topography, ecology, etc.)

So, given the fact that mountain topography, ecology, etc. is so complex, is it possible to find common climatological trends or characteristics among mountain ranges?

What makes mountain meteorology so complex?

Answer: Scale!!

Four Main Variables:

1) Latitude
2) Continentality (air masses, seasonality)
3) Altitude (lapse rates)
4) Topography

"Topoclimatology" – (50m to 20km)

Terrain complexity largely controls meteorological complexity (biological, too)**!**

Talk Outline

- Introduction – Mountain Meteorology
- Motivation: Are mountainous areas more sensitive to potential climate change?
- Methods: Linear regression, K-means clustering, and Seasonal Trend Analysis
- Results: Do trends vary by elevation and/or mountain range in the western U.S.?
- Conclusions: Are there possible implications for western United States mountainous regions?

Receding glaciers probably represent the largest, most obvious changes over the past century.

Grinnell Glacier – Glacier National Park (Montana)

Mount Hood – Oregon (summer)

Source: http://www.worldviewofglobalwarming.org/pages/glaciers.html

Despite these changes….

- Mountainous regions have been poorly studied, in general (climate, ecology, etc.)

But Why?

- sparse population = neglected study region
- Physical access difficult
- Representation error for single stations
- Standardization problems

Ok, so what do we know?

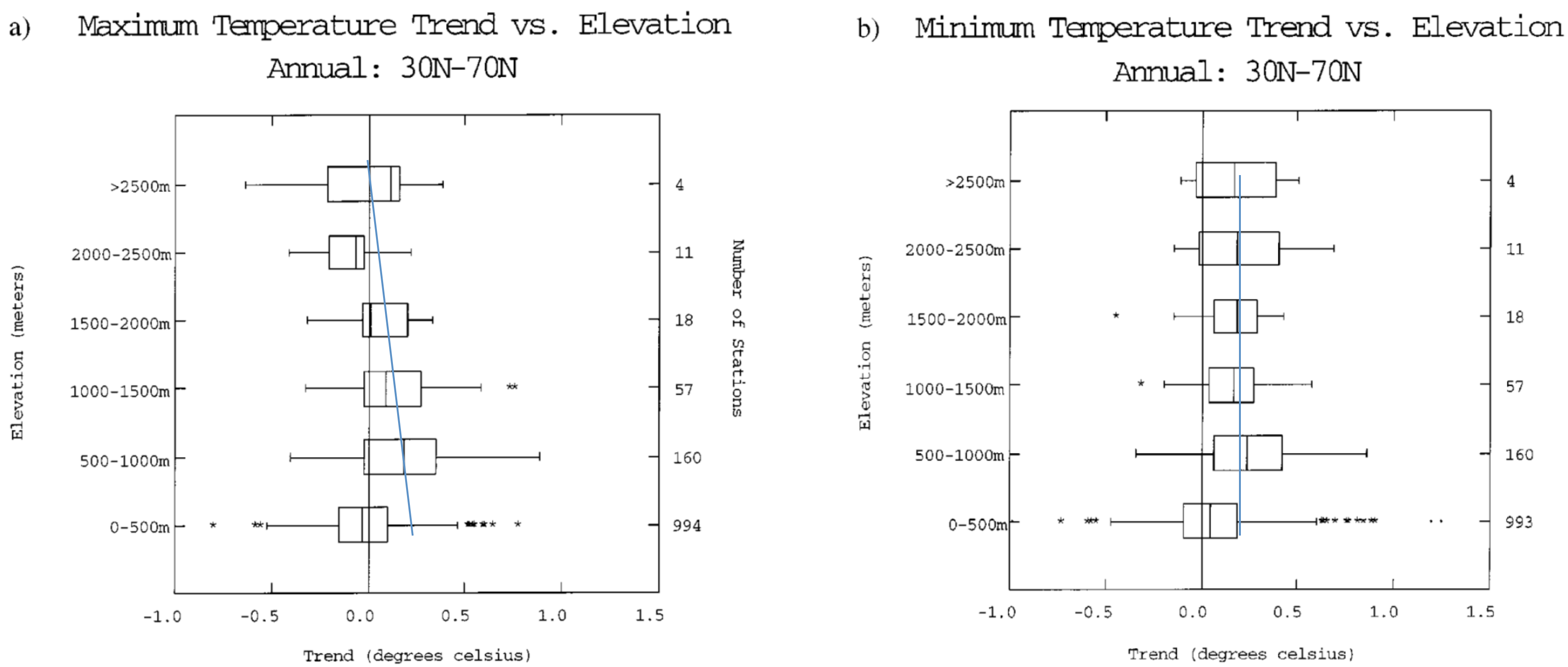
General trends **(°C/decade)** are difficult to identify and are highly dependent on number and locations of GHCN stations. Based on this data, lower elevations tend to be warming faster than higher elevations (except Africa) and European trends are the smallest in magnitude. North American trends are moderate.

Mean temperature trends by continent: 1948 - 2002

Continent	Number of Sites	Surface Trend Deg C/decade	High Elevation	Middle Elevation	Low Elevation
N. America	552	0.123+/-0.014	0.088+/-0.022	0.122+/-0.020	0.161+/-0.030
S. America	33	0.127+/-0.051	0.057+/-0.095	0.149+/-0.072	0.174+/-0.087
Europe	162	0.041+/-0.040	0.061+/-0.079	-0.008+/-0.072	0.070+/-0.051
Africa	41	0.140+/-0.040	0.168+/-0.074	0.110+/-0.068	0.140+/-0.072
Asia	280	0.151+/-0.027	0.108+/-0.045	0.173+/-0.050	0.172+/-0.043
Australia	14	0.134+/-0.066	0.130+/-0.109	0.193+/-0.138	0.091+/-0.109
Antarctica	2	-0.063+/-0.176	NA	NA	NA
		.119	**.102**	**.122**	**.135**

Source: (Pepin and Lundquist, 2008).

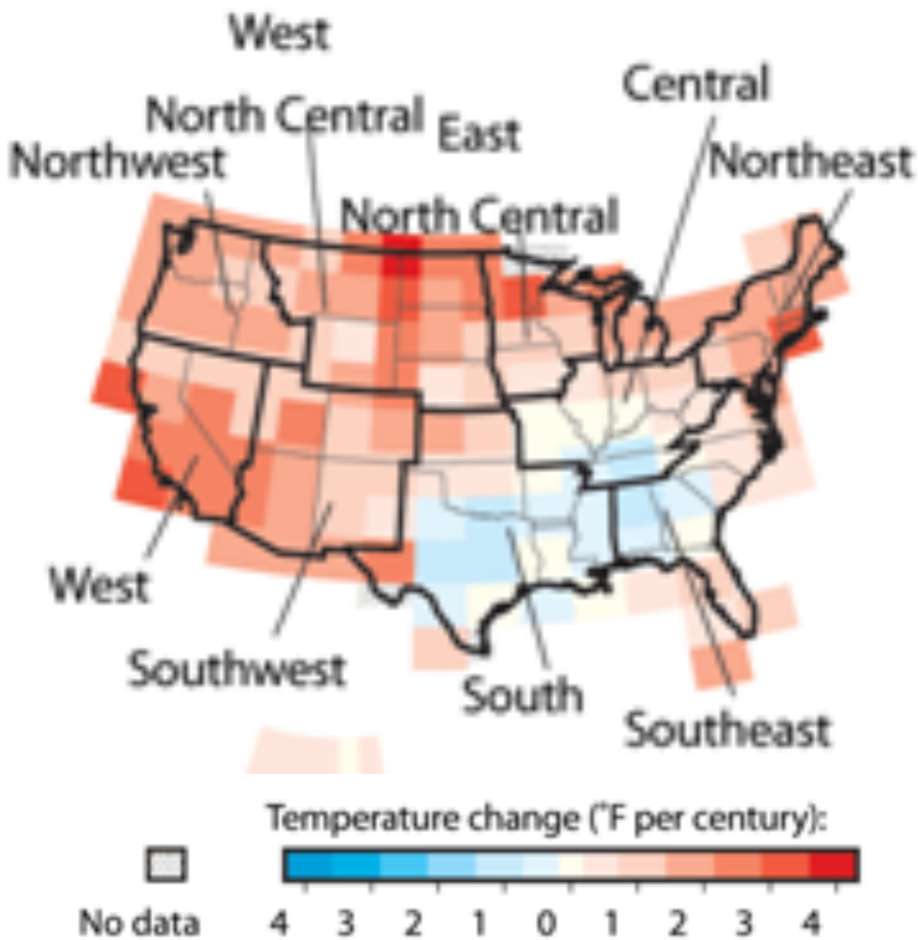
Previous Research: Mid-Latitude Elevational Trends for Minimum and Maximum Temperatures



Maximum temperature trends **(°C/decade)** generally decrease with elevation. So do those for minimum temperature trends, but they decrease much more slowly.

Source: (Diaz and Bradley, 1997)

General U.S. Mean Temperature Trends since 1901 (Source: NOAA)



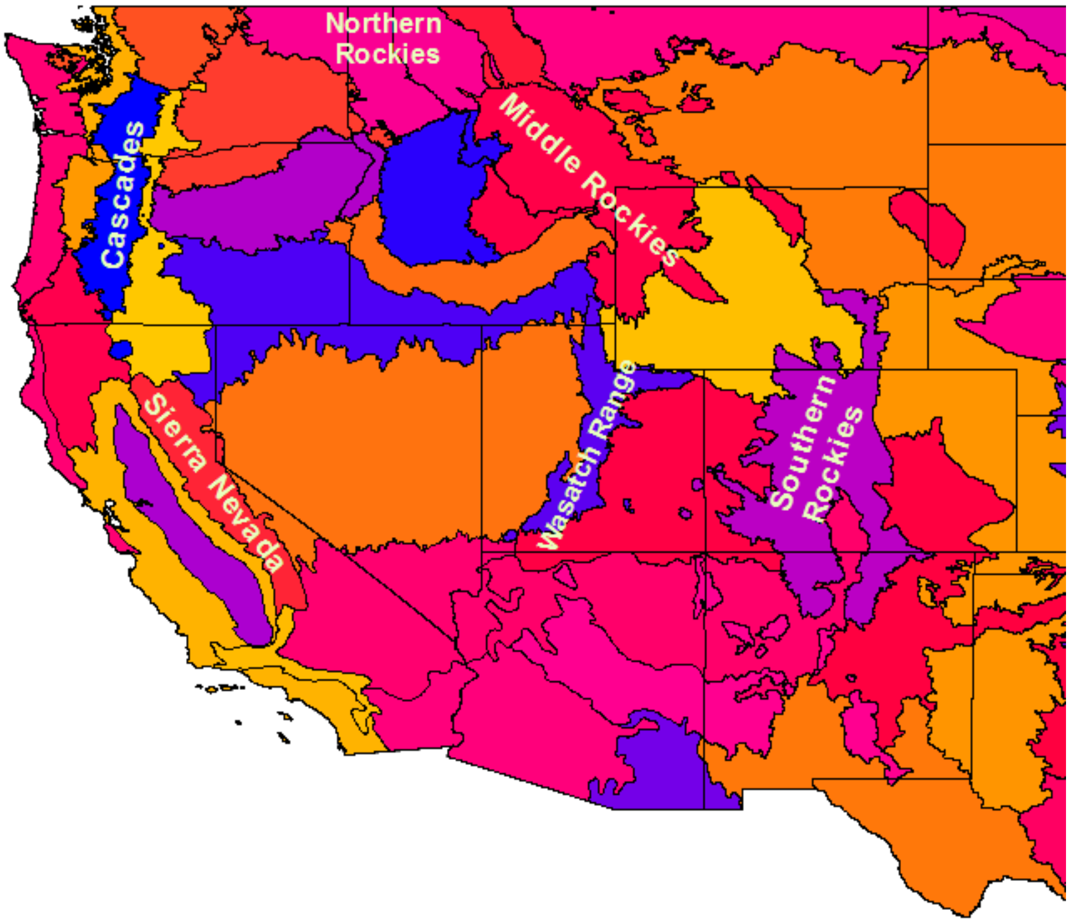
Study Objectives

- Use a high resolution, geospatially adjusted data set to study elevational temperature trends in western U.S. (1941 – 1970 and 1971 – 2000)

Study Questions

1) Has the western U.S. experienced trends in mean surface temperature and do they differ by elevation?
2) Do different mountain chains experience different trend patterns?

Study Regions



Region	Mean Elevation (m)	Area (Km^2)
Cascades	881.7	76194.7
Sierra Nevada	1417.3	133754.2
Northern Rockies	1128.2	116043.6
Middle Rockies	1997.2	253857.0
Southern Rockies	2279.9	313946.3
Wasatch Range	2063.7	125150.4

Bailey's Level III Ecoregions are used as the basis for defining the geographic areas of each mountain chain (based on precipitation and temperature patterns).

Since high resolution is important, where and how do we get accurate, high resolution data?

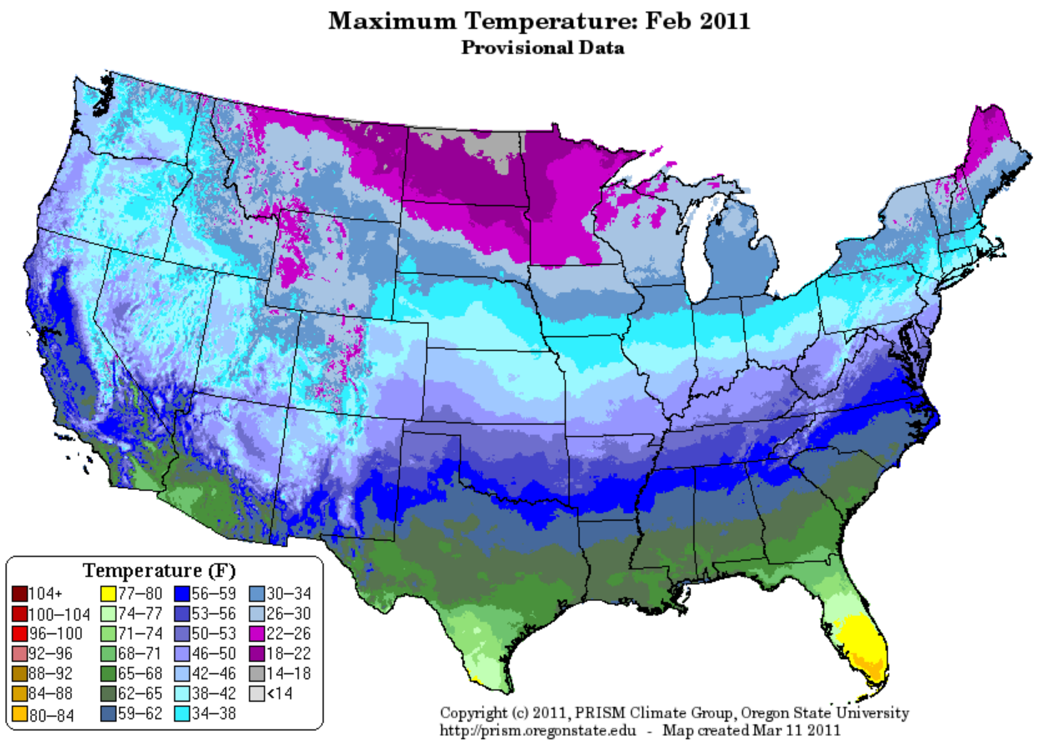
Several choices (based on literature review):

1) Global Climate Models
2) Regional Models (NARR/NARCCAP)
3) Statistically downscaled regionally model data
4) Satellite
5) Observations alone – fine for local studies, but can't generalize observations without some sort of adjustments (or a lot of adjustments)
6) **Knowledge Based Downscaling – not just a basic interpolation technique (such as kriging or inverse weighting), but a knowledge based algorithm**

PRISM

(Parameter-elevation Regression on Independent Slopes Model)

- Daly, Christopher et al. (2008) – Oregon State University
- Monthly (1895 – 2011)
- 4km or 800m resolution



How does PRISM work?

PRISM uses a knowledge based system (KBS) which "injects knowledge into a climate mapping system"

Major Components

1) Elevation
2) Terrain Induced Climate Transitions (rain shadow, topographic facets)
3) Two Layer Atmosphere & Topographic Index
4) Coastal Effects

Moving window Regression

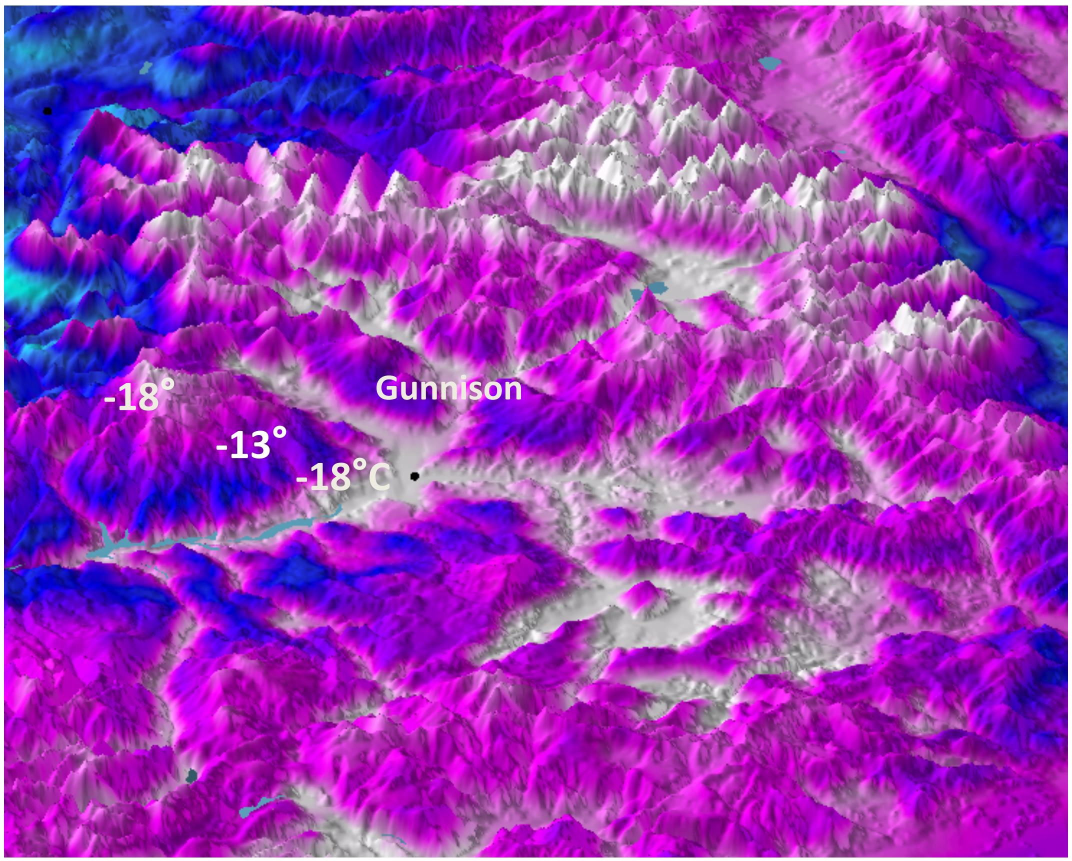
Combined weight of a station is:

$$\mathbf{W = \mathit{f}\,\{W_d\ W_z\ W_c\ W_f\ W_p\ W_l\ W_t\ W_e\}}$$

- Distance
- Elevation
- Clustering
- Topographic Facet (orientation)
- Coastal Proximity
- Vertical Layer (inversion)
- Topographic Index (cold air pooling)
- Effective Terrain Height (orographic profile)

One example of PRISM's algorithm detecting/reproducing inversion layer - ('banana belt') of CO Rockies

Inversions (1971-00 January Minimum Temperature
Central Colorado)



Dominant PRISM KBS Components

Elevation

Topographic Index

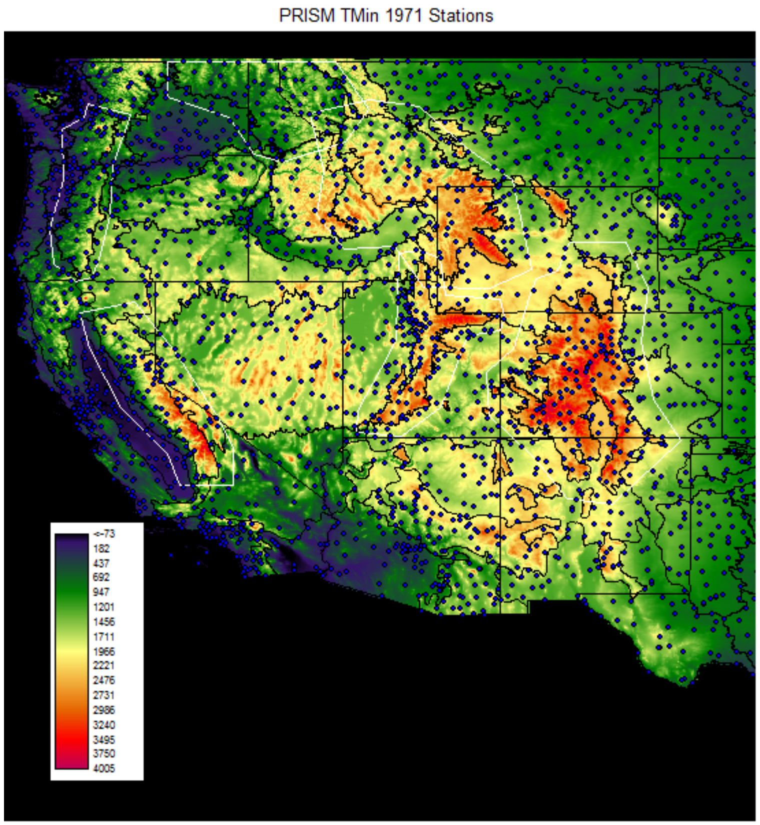
Inversion Layer

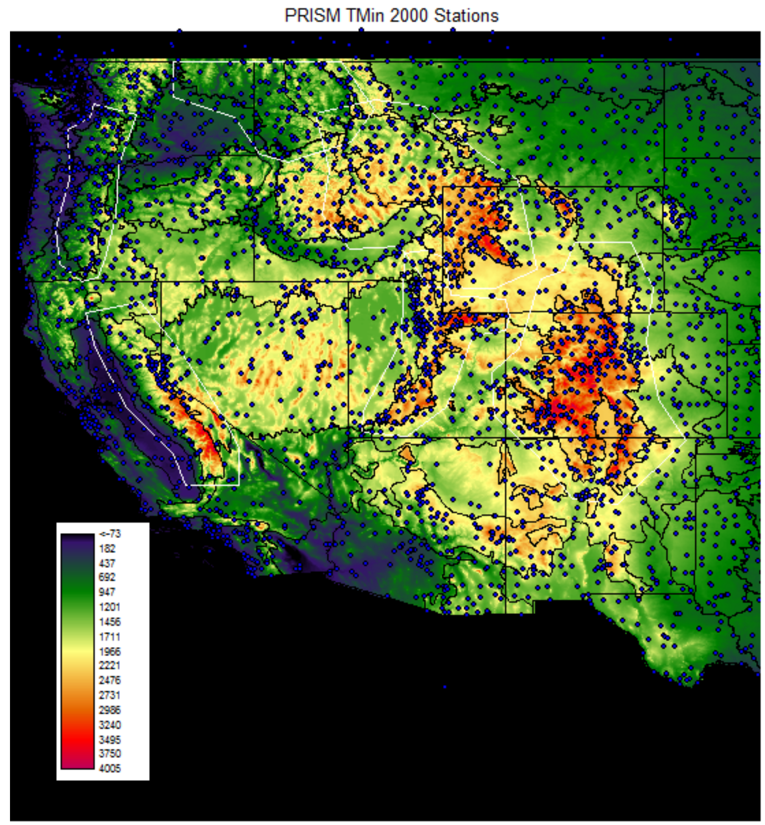
Source: PRISM Overview (5-8-08)

Statistical Methods

1) Linear Regression – on mean temperature trends for each ecoregion (°C/yr) and elevational trend analysis (°C/yr/km)
2) K-means cluster analysis – as a complement to linear regression, used to determine elevational trends for entire western U.S. (°C/yr/km)
3) Seasonal Trend Analysis – on mean monthly temperatures for each ecoregion; this is a general harmonic regression analysis to pick out general seasonal temperature/timing trends

Digital Elevation Model and Elevational Temperature Trend Regions



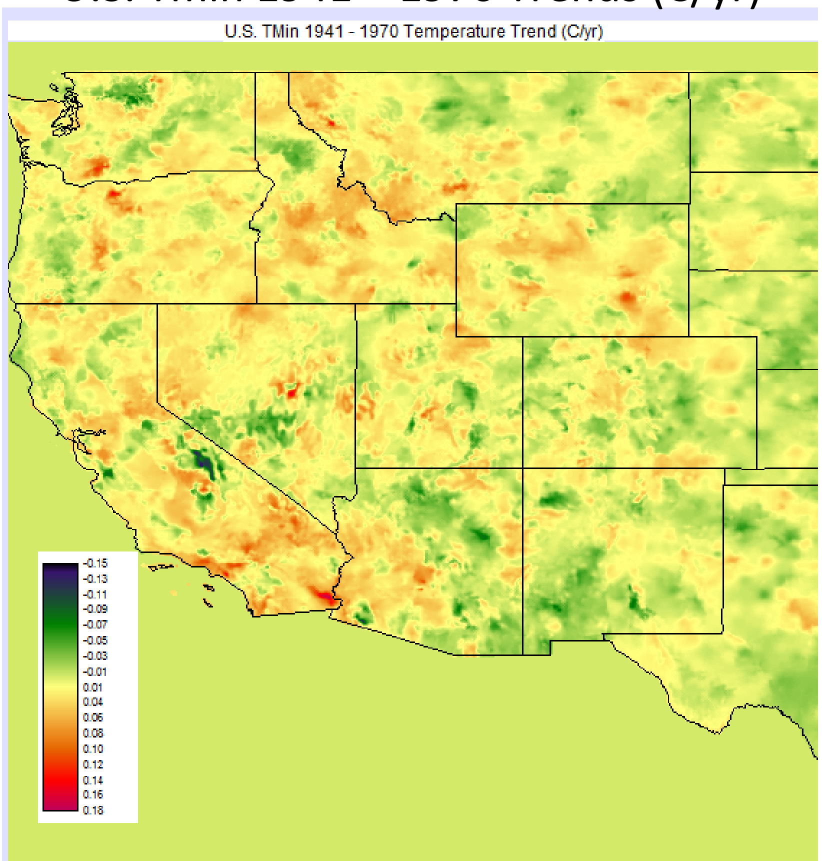


White areas indicate buffered ecoregions for elevational trend analysis.

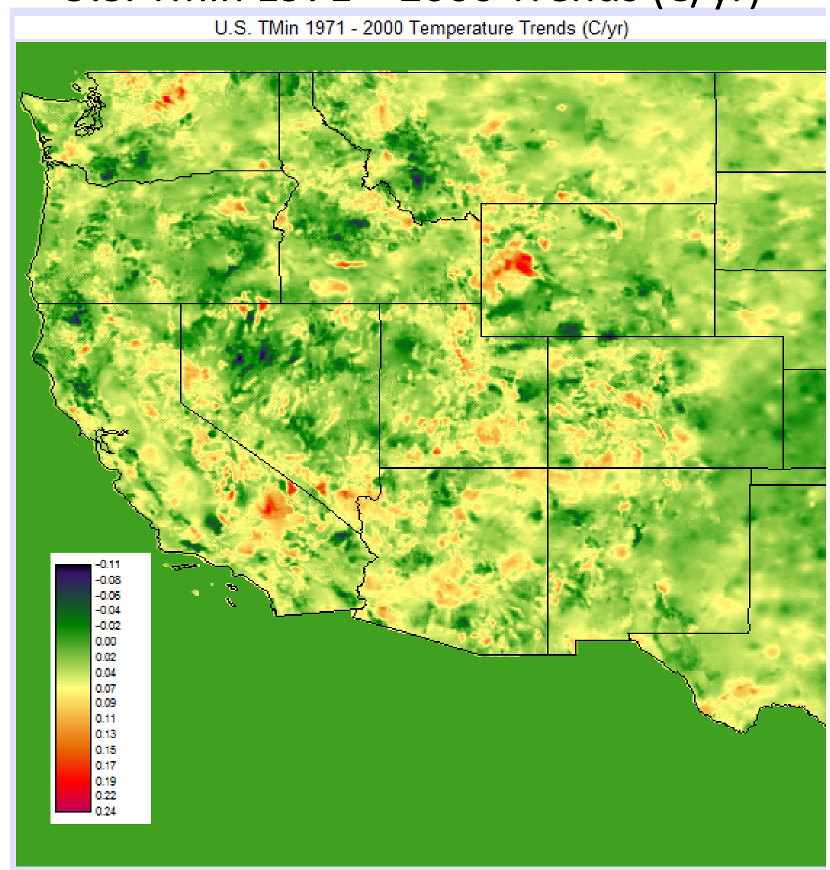
These are buffered to include more stations and a greater elevation range.

Results

U.S. Tmin 1941 – 1970 Trends (C/yr)

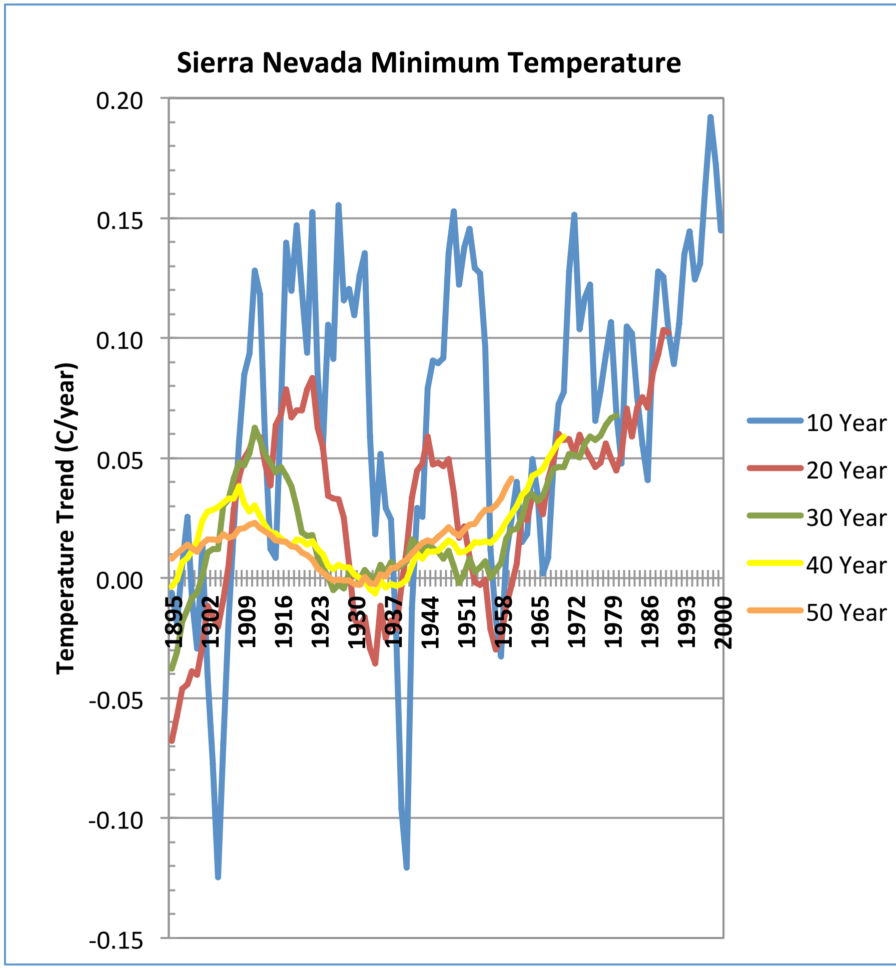


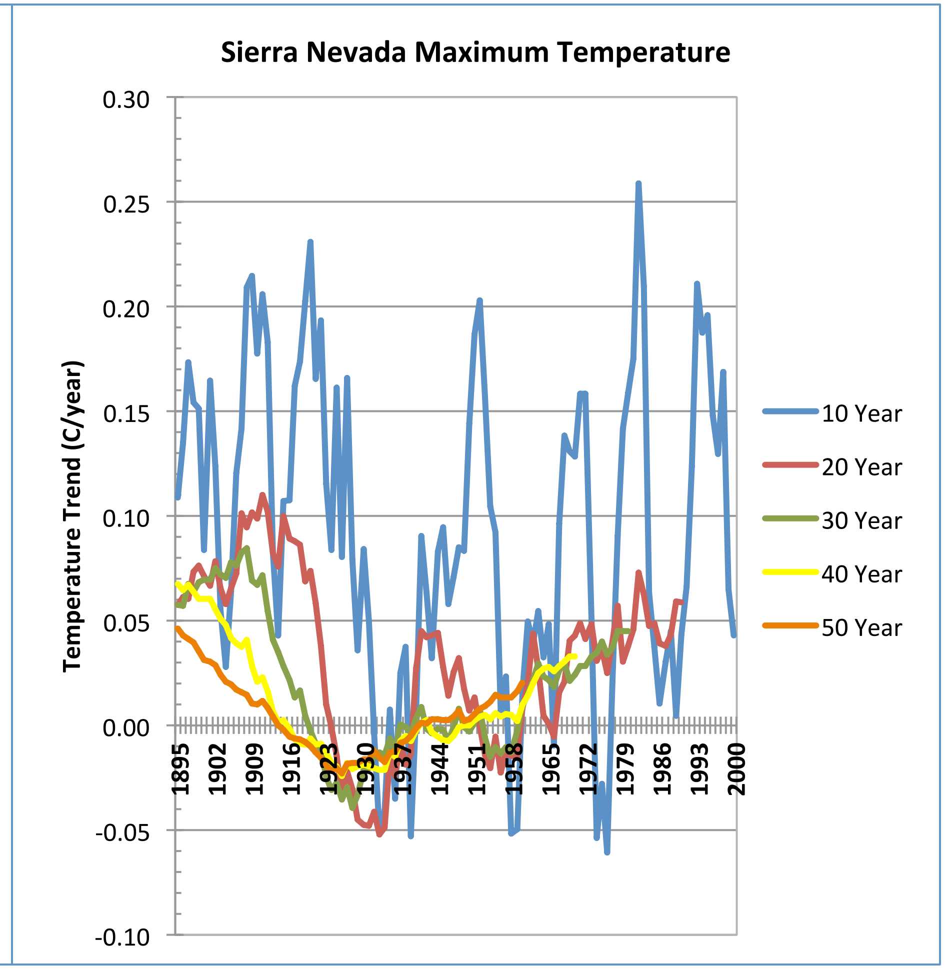
U.S. Tmin 1971 – 2000 Trends (C/yr)



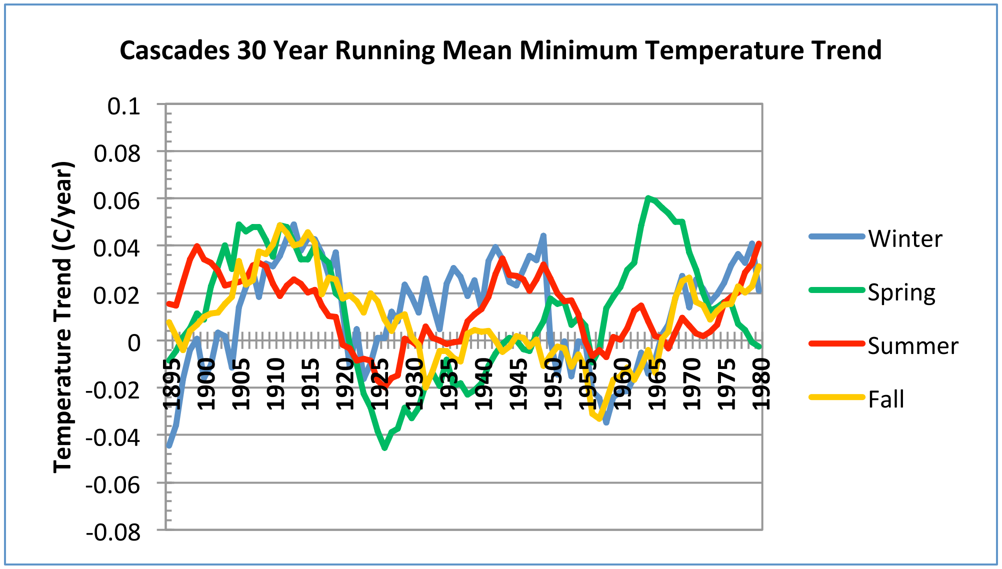
- Generally, trend maps don't clearly outline mountain ranges
- This is probably good, since it's an indication that PRISM isn't biased toward using elevation as a forcing for temperatures or temperature trends

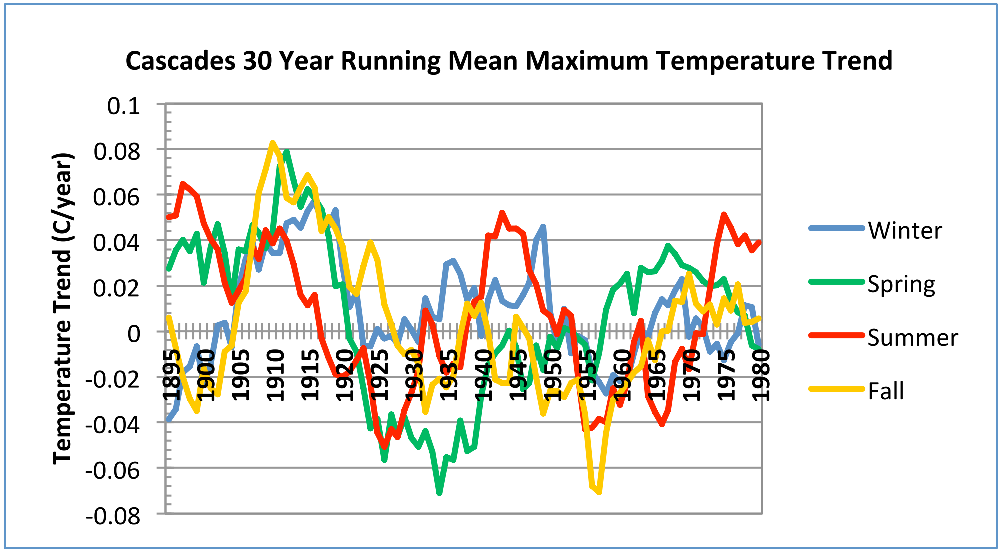
Why 30 Year Running Means?





Mean Temperature Trends - Cascades





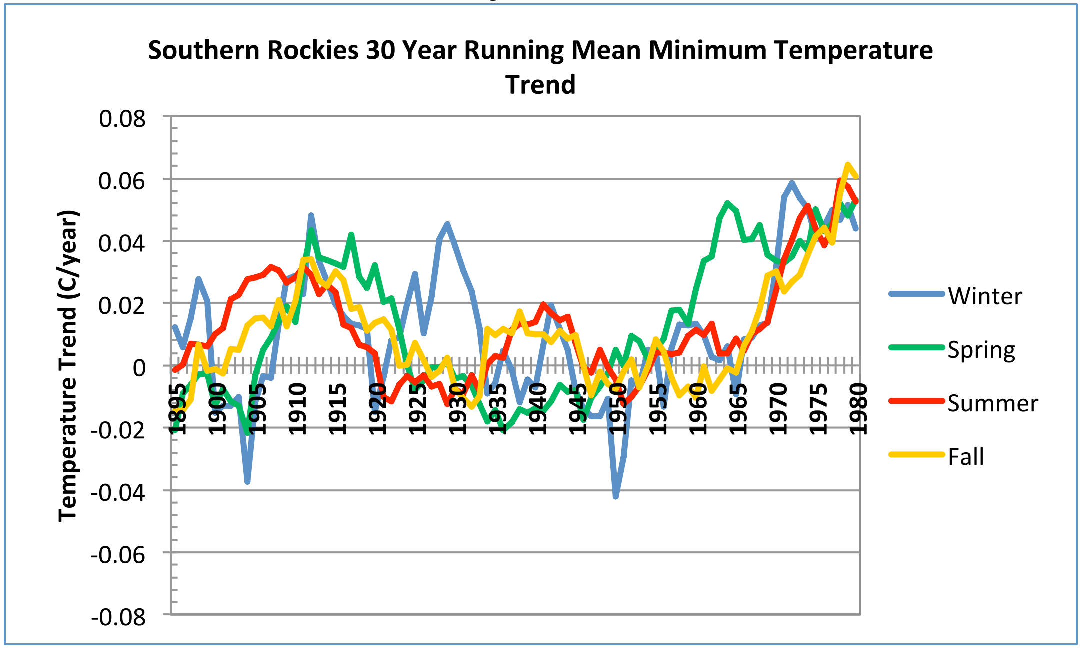
- Cascades experience relatively little variation in mean temperature trends

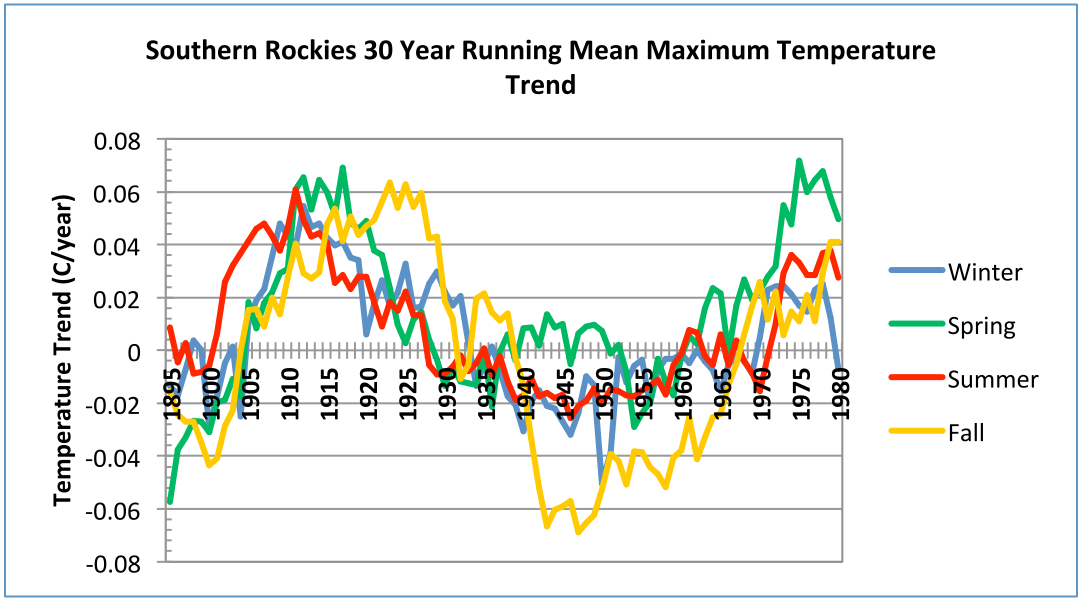
-Maximum trends are more variable than minimum trends

- Spring trends tend to peak before by 1965 and then decrease

- Summer maximum trends are rising the fastest, perhaps due to the lack summer precipitation

Mean Temperature Trends – Southern Rockies



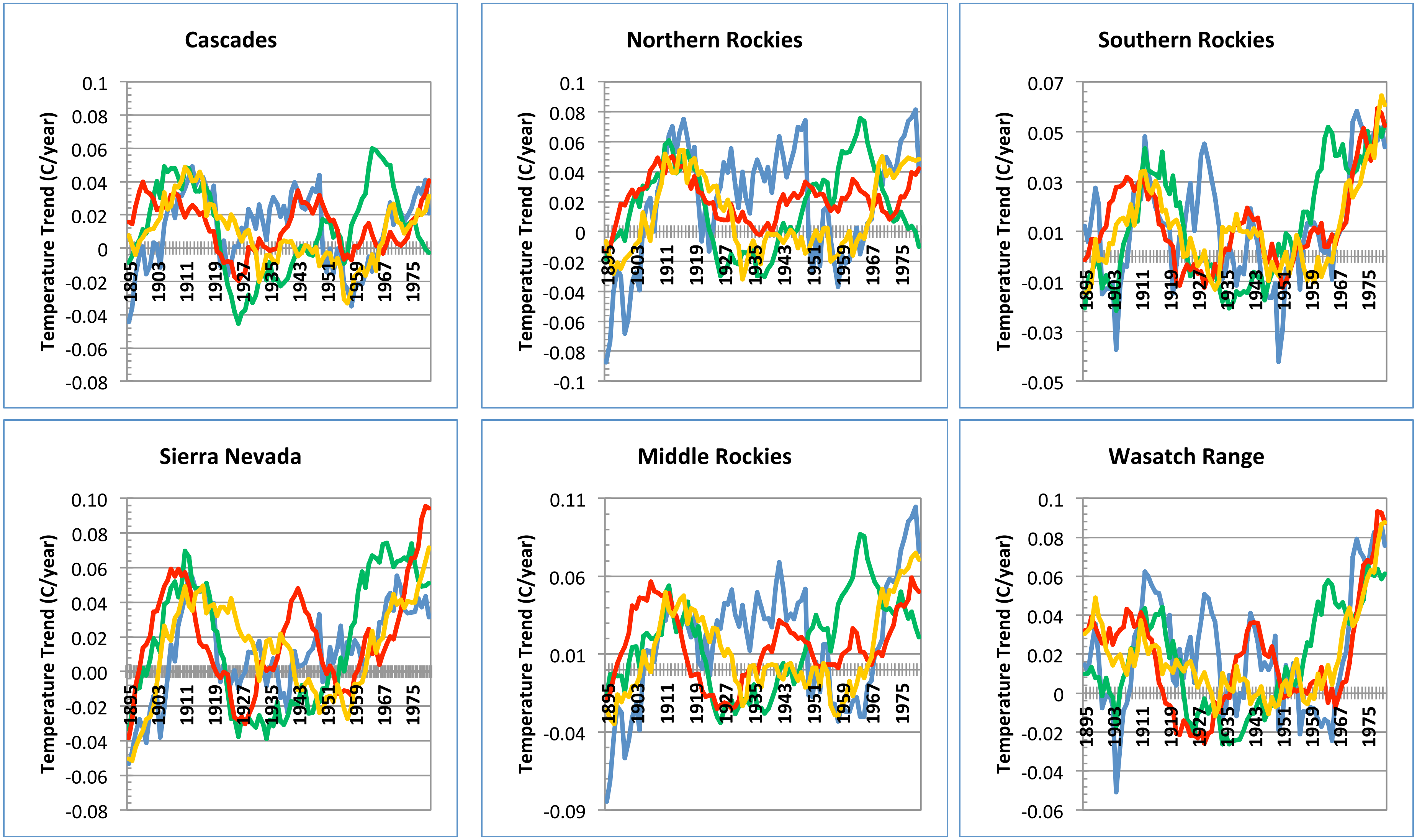


-Similar to the Cascades, minimum trends for the SR are less variable overall. But, they experience a larger, recent trend.

-Maximum trends experience a large cyclical pattern, with a peak in the 1910's and another recent peak.

-Spring trends are earlier for minimum trends, but for maximum trends they are only larger.

Minimum Mean Trends



Blue = Winter **Green = Spring** **Red = Summer** **Orange = Fall**

Maximum Mean Trends

Blue = Winter **Green = Spring** **Red = Summer** **Orange = Fall**

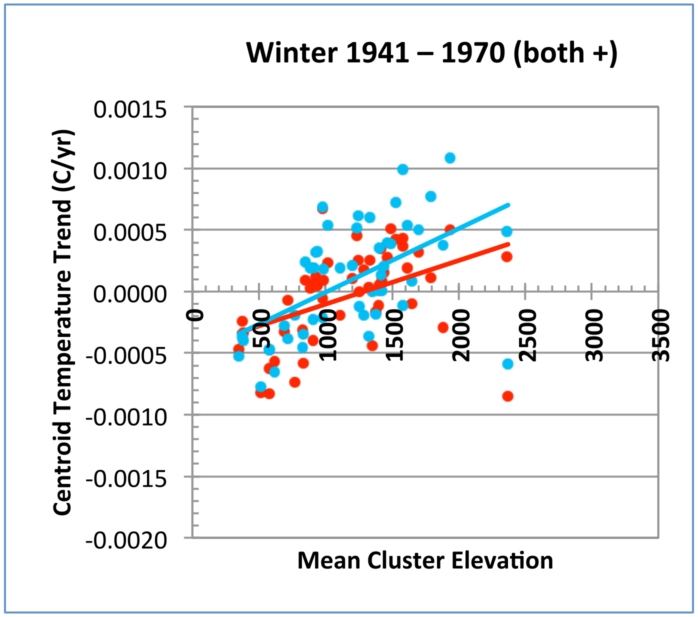
Elevational Temperature Trends - Clustering

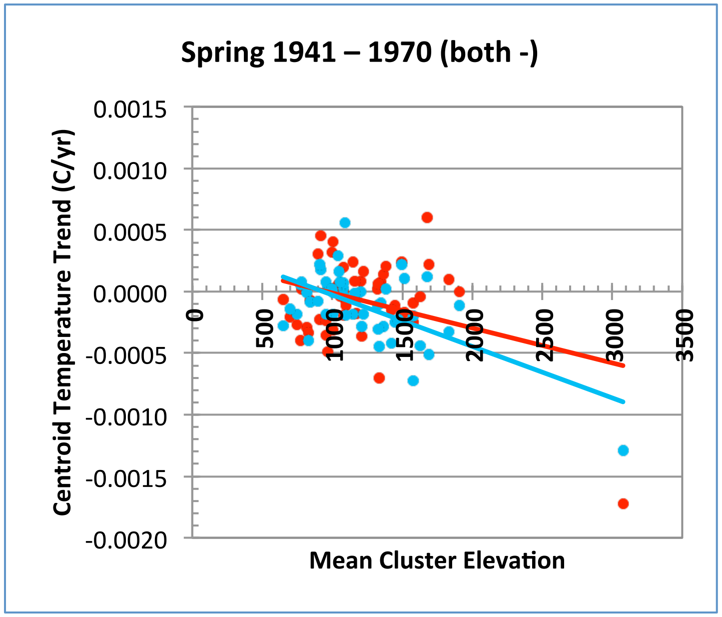
What is K-Means Clustering?

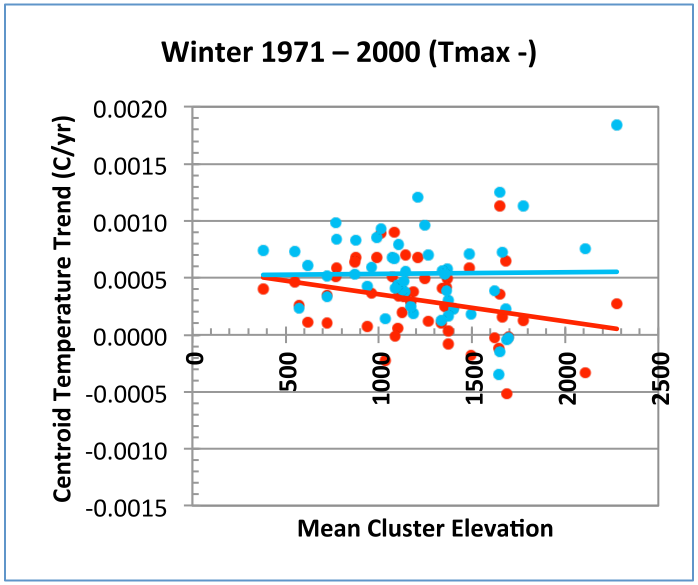
-An iterative data mining technique that divides a set of observations into a specific number of groups (clusters) where the intra-cluster variance is minimized and the inter-cluster variance is maximized

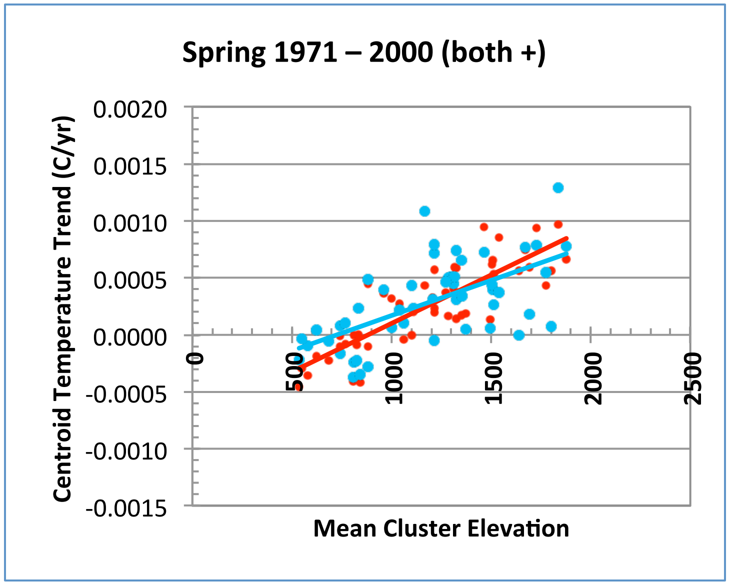
- Performed for both minimum and maximum temperature trends for two periods, 1941 – 1970 and 1971 – 2000 for the entire western U.S. (west of 105°W)

Four Variable Results – each season separately

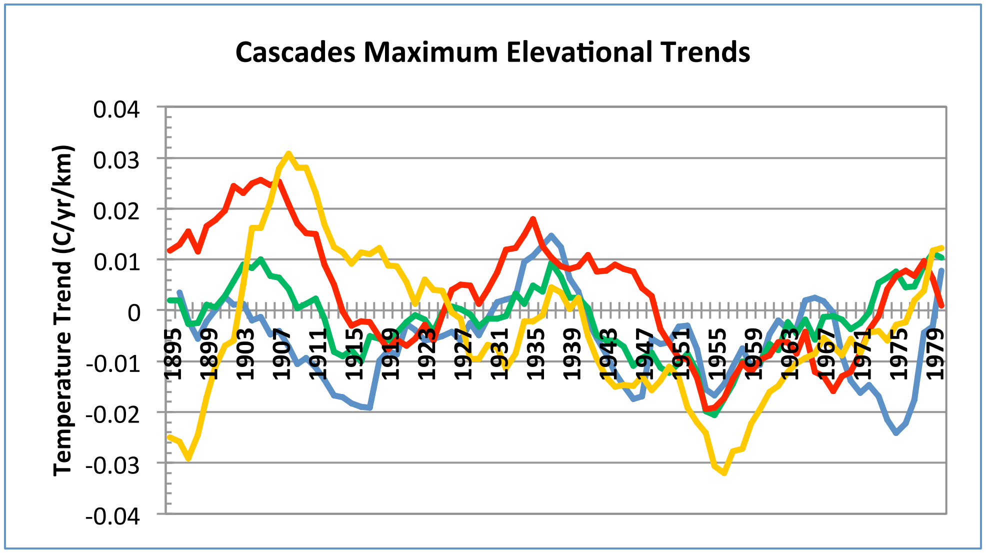


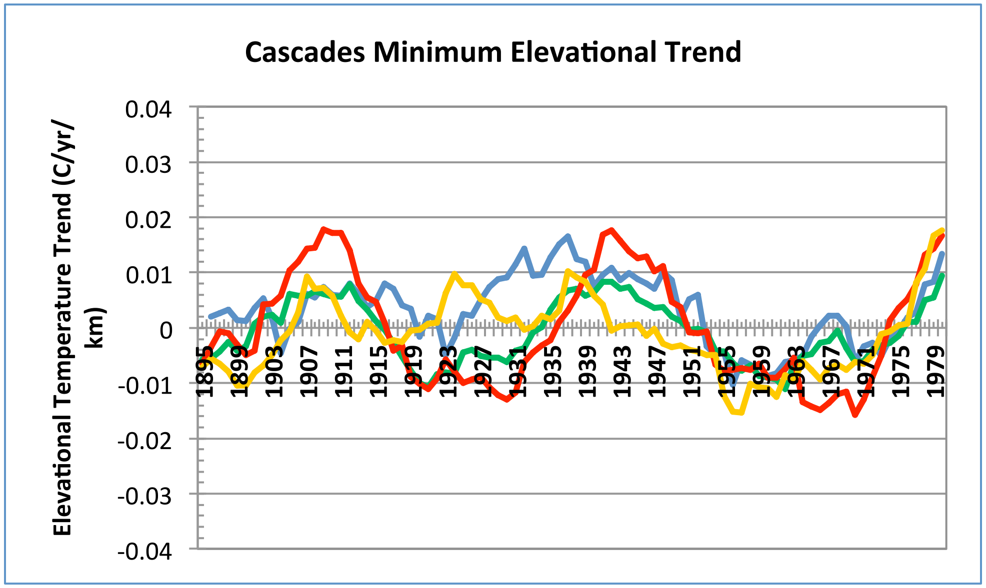






Elevational Temperature Trends – Linear Regression

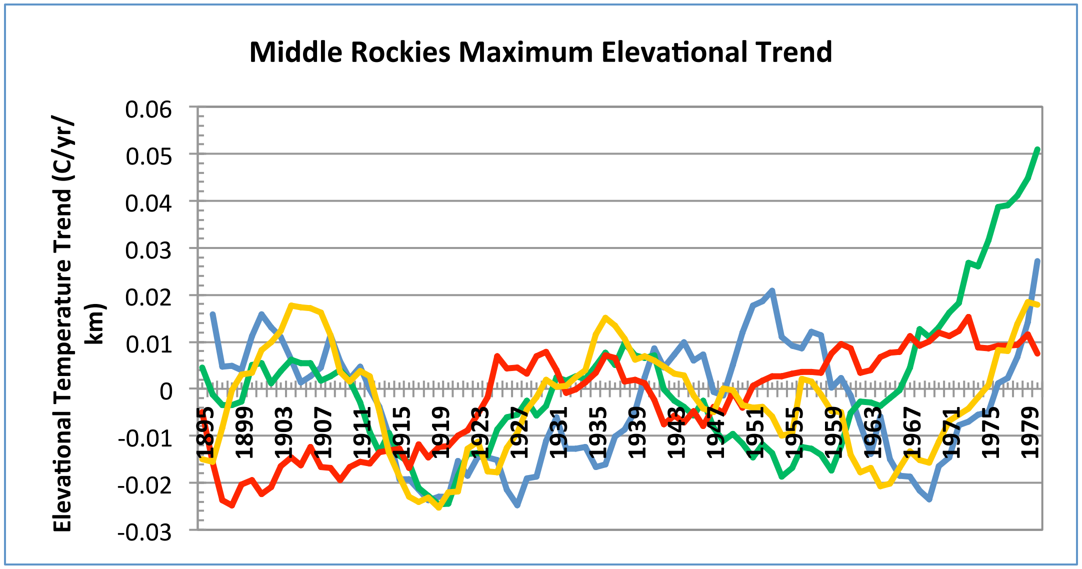


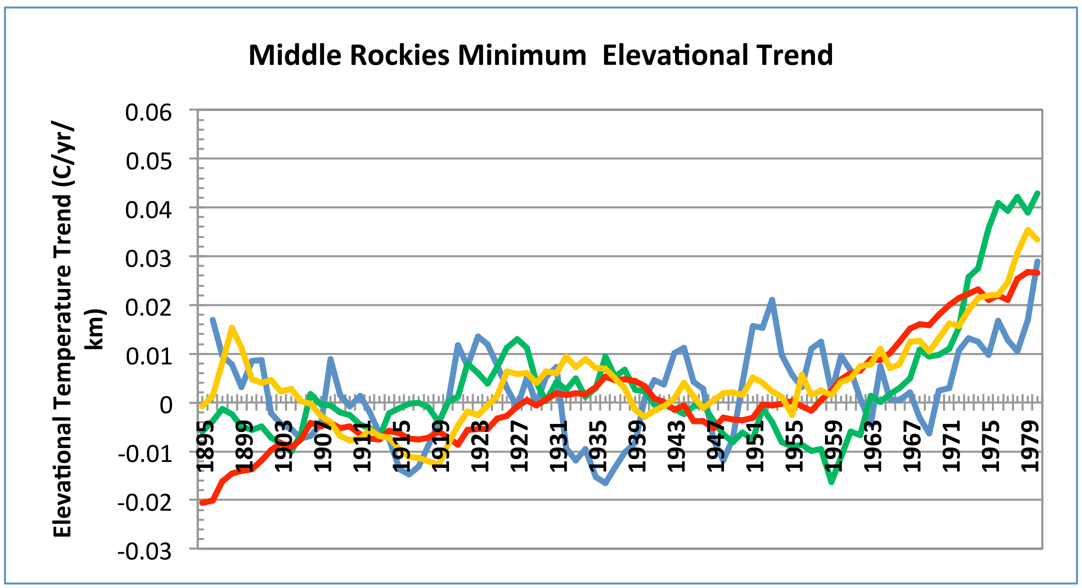


Maximum trends show a general decrease in magnitude with time.

Minimum trends show a cyclical pattern, and have recently converged.

Elevational Temperature Trends – Linear Regression

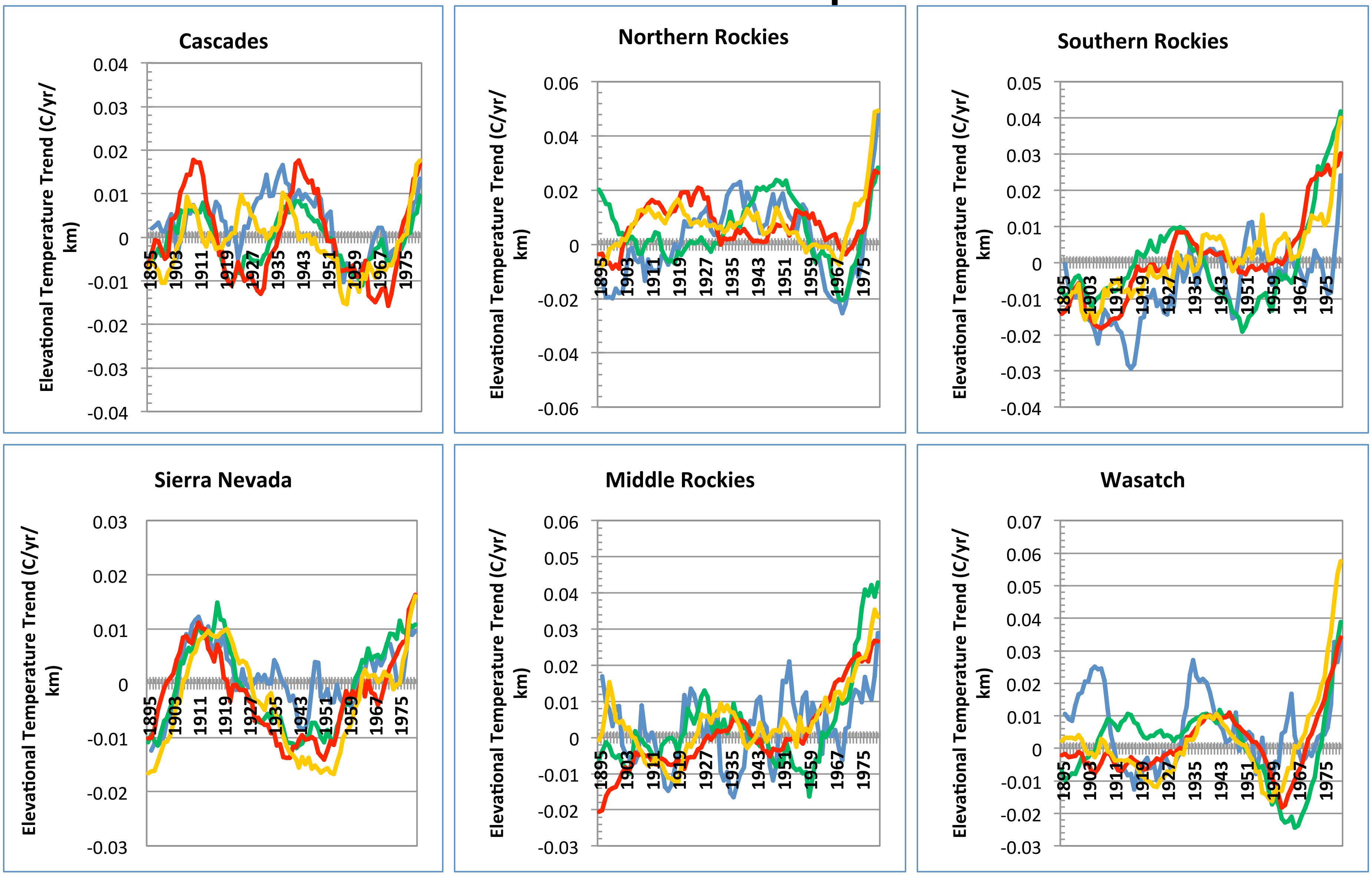




Both minimum and maximum trends show large increases after 1960.

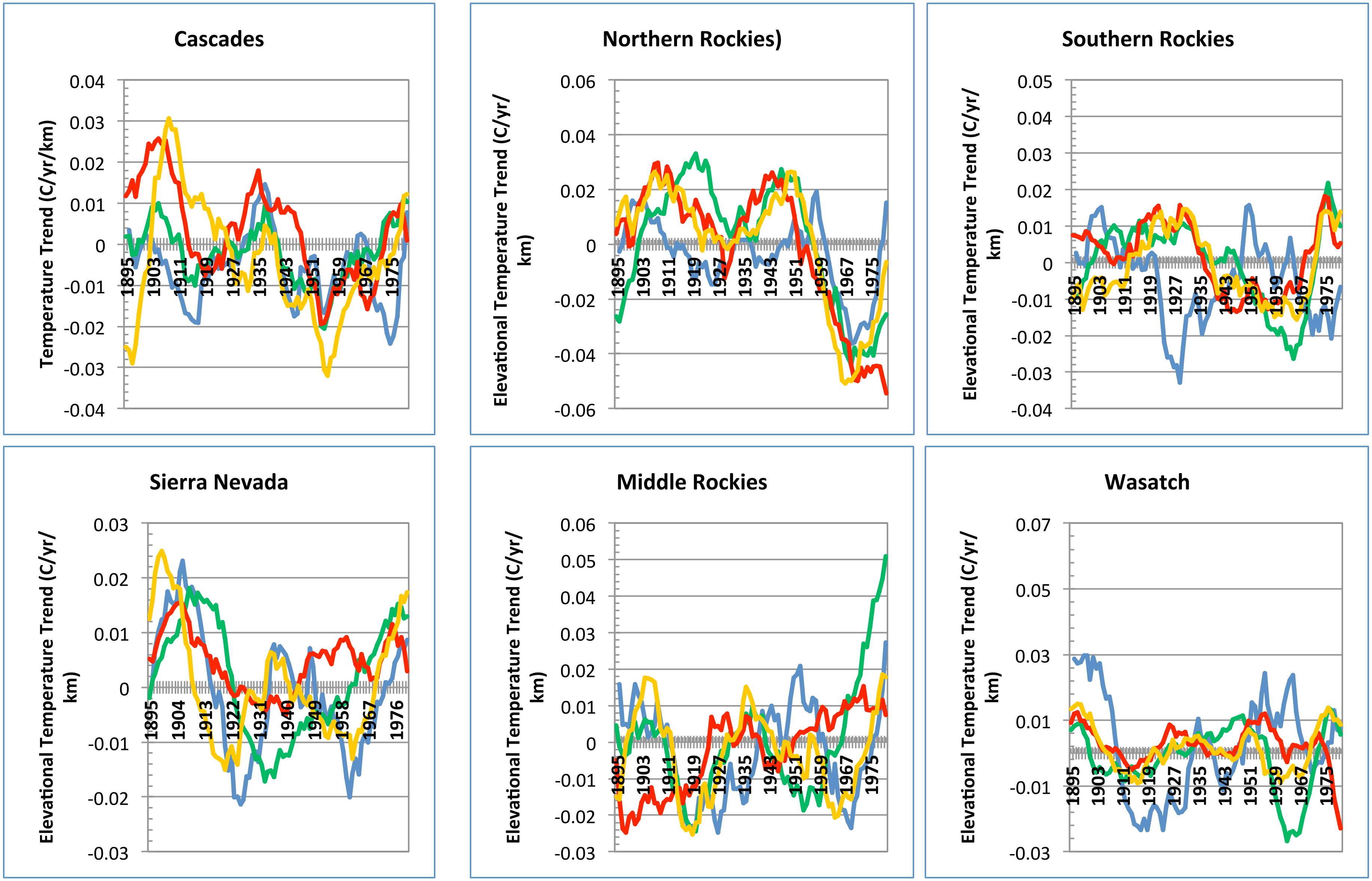
Maximum spring elevational temperature trends show the greatest difference with elevation

Minimum Elevational Temperature Trends



Blue = Winter **Green = Spring** **Red = Summer** **Orange = Fall**

Maximum Elevational Temperature Trends



Blue = Winter Green = Spring Red = Summer Orange = Fall

Results – Seasonal Trend Analysis

Developed by Ronald Eastman of Clark Labs , Clark University, MA (Eastman, et al. 2009)

What is Seasonal Trend Analysis (STA)?

Uses harmonic regression to determine general seasonal curves (timing and temperature magnitude)

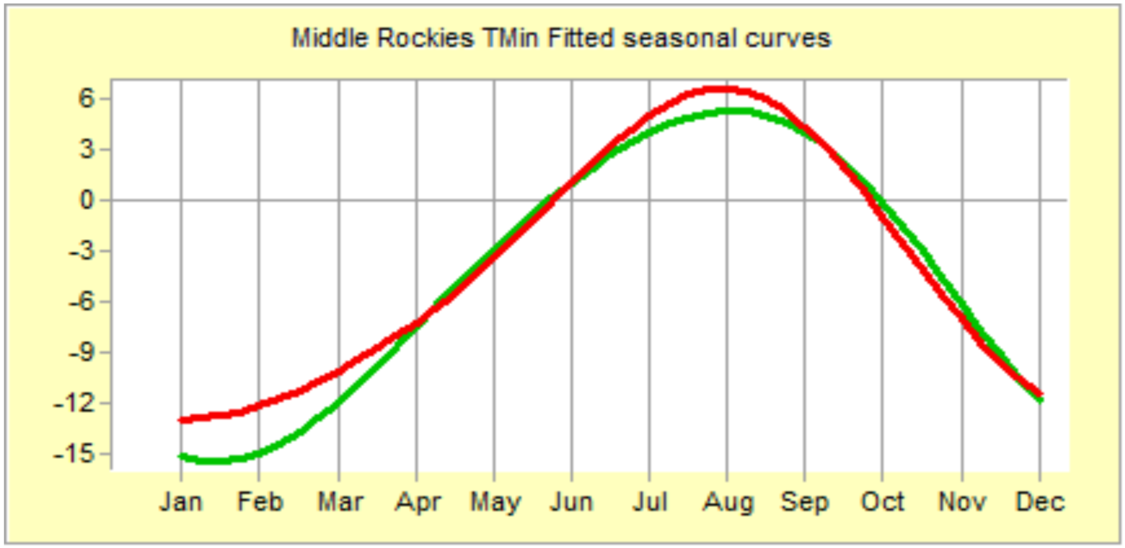
Designed to ignore sub-annual variations and to be robust to short term variability up to 29% the length of the time series

Seasonal Trend Analysis – cont'd

- 1942 – 1971 and 1971 – 2000
- Based on actual temperatures, _**not**_ trends

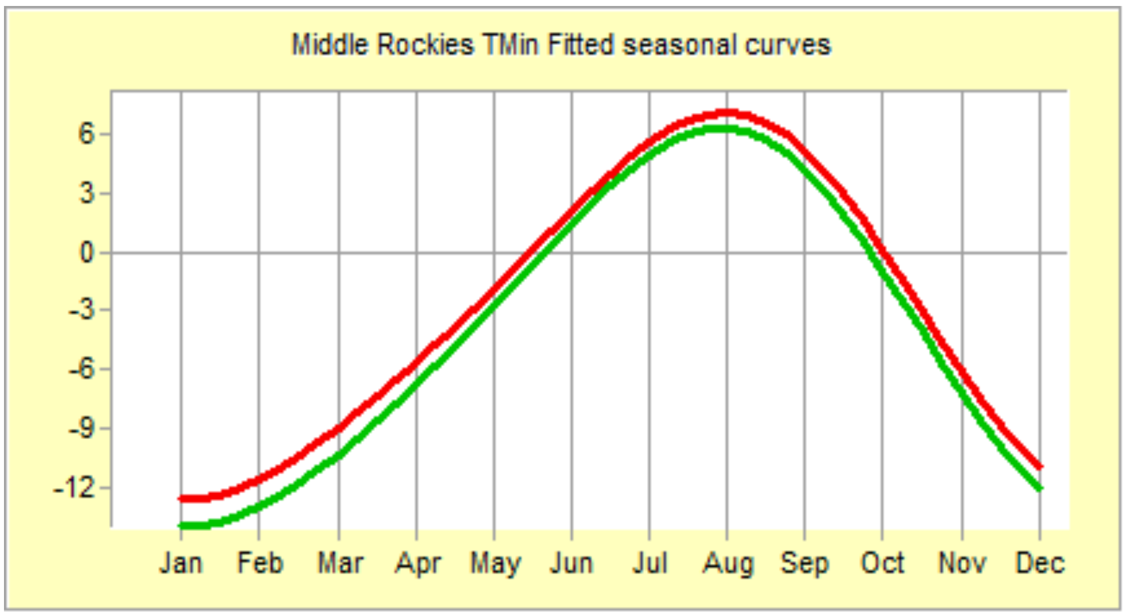
- Provides a good snapshot of the shorter term seasonal trends or variations

“Average” Tmin STA Profiles



Minimum Temperature

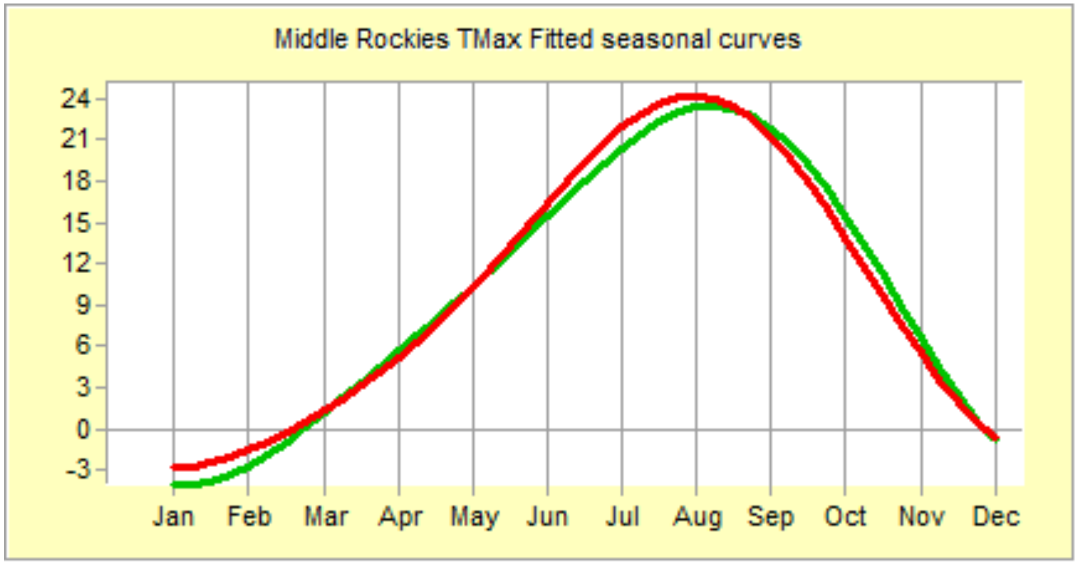
1942 – 1971



Minimum Temperature

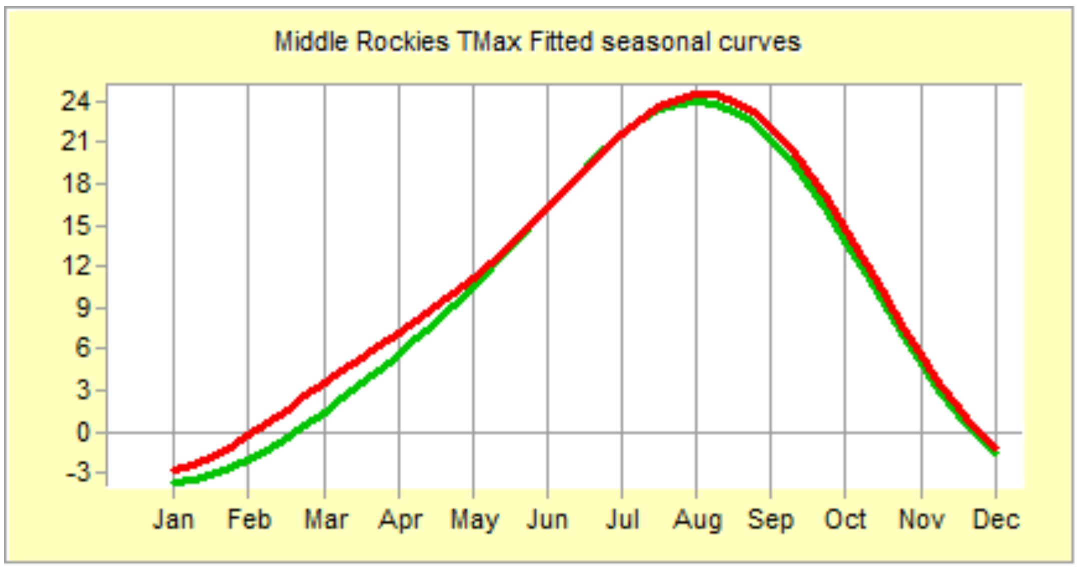
1971 – 2000

“Average” Tmax STA Profiles



Maximum Temperature

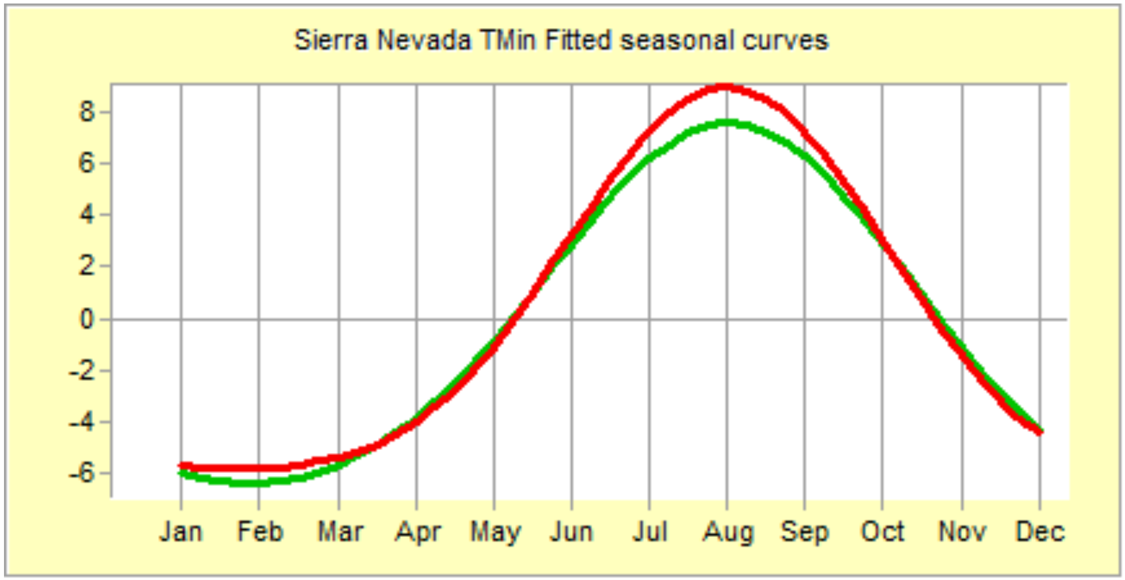
1942 – 1971



Maximum Temperature

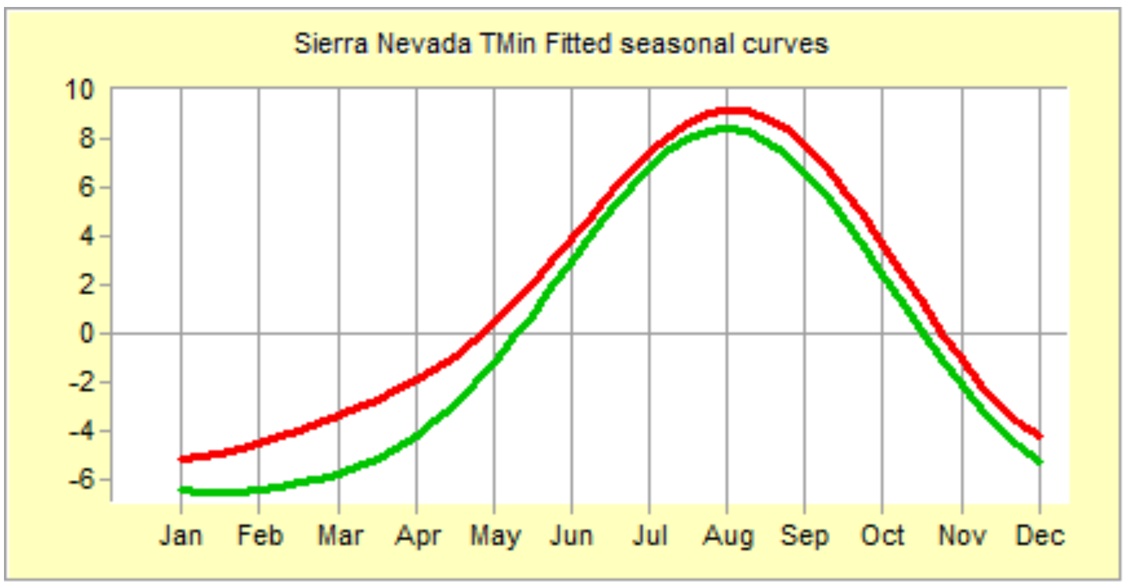
1971 – 2000

Sierra Nevada - STA



Minimum Temperature

1942 – 1971



Minimum Temperature

1971 – 2000

Discussion – Literature Comparison

- Cluster analysis shows strong positive spring temperature trend relationship with elevation – Is this in contrast to Pepin and Lundquist (2008)?
- Conklin and Osborne-Gowey (2010 MTN CLIM conference) used 800m data to study Sierra Nevada temperature trends. Do our analyses agree?

Summary – temperature trends

- Recent mean temperature trends are positive for fall, summer, winter
- Mean spring trends peaked about 1960 in most regions and then began a decline
- Mean maximum temperature trends tend to be more variable than minimum trends
- Elevational trends follow similar patterns as mean trends, but spring trends are the strongest (no timing difference, however)

Why might spring trends be the strongest or peak earlier than the other seasons?

Reduced winter snowpack

Snow can melt earlier

Spring temperatures can rise faster

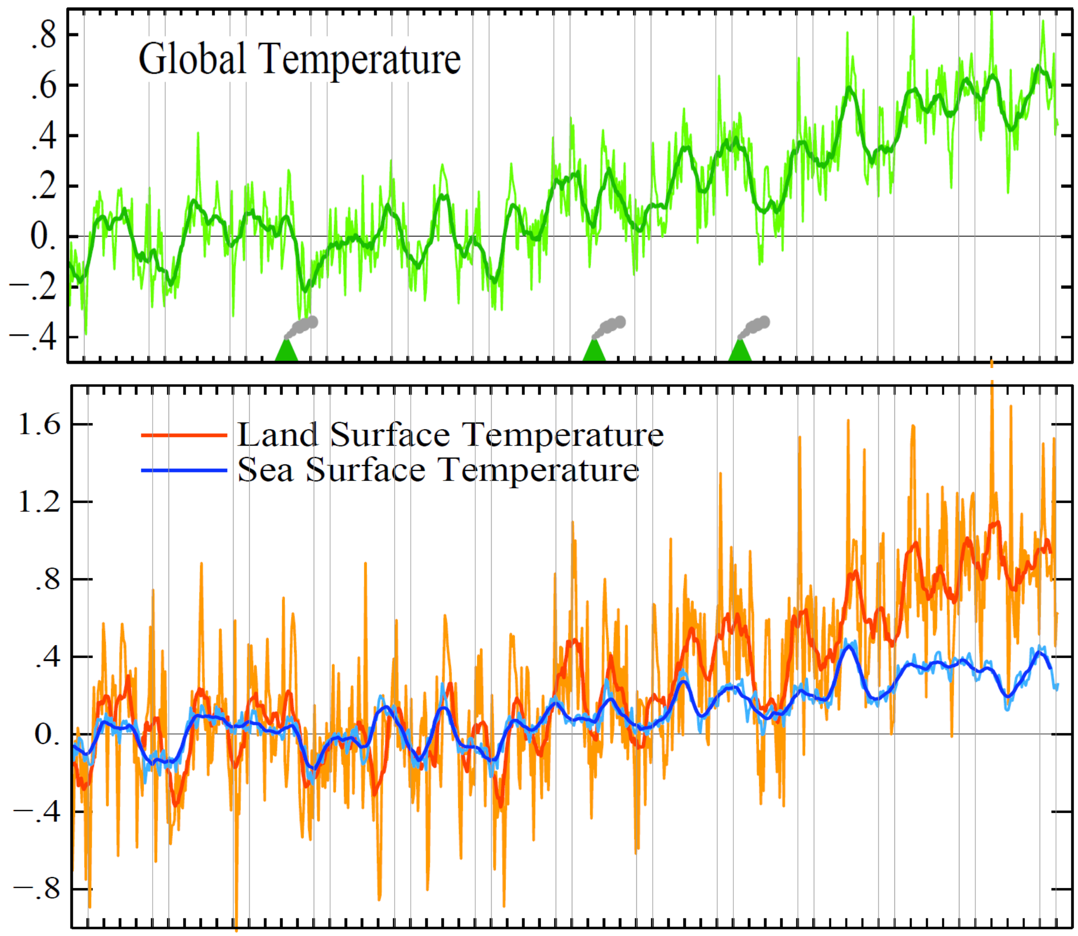
One more question…

- Recall
  - Cascades & Sierra Nevada highly variable elevational trends throughout time period
  - But, Rockies and Wasatch generally experience relatively flat elevational trends through 1960, and then experience rapid increases

Why?

Cascades and Sierra Nevada – highly maritime influenced, so the more continental a range is, the less effect ENSO/other ocean variability has.

Land vs Sea Surface Temperature Anomalies (°C) Since 1950



Source: http://www.columbia.edu/~mhs119/Temperature/T_moreFigs/

Future Work

- Use 800m data for analysis
- Cluster individual ecoregions
- Do STA by elevation
- Do a snow cover/temp trend analysis
- Future data sets look very promising - several projects have or are installing very high density observation networks (“massive air and stream temperature sensor networks”) across the western U.S.

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Daly, Christopher et al. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology,* DOI: 10.1002.

Diaz, Henry F. and Bradley, Raymond S. (1997). Temperature variations during the last century at high elevation sites. *Climatic Change*, Vol. 36, 253 – 279.

Pepin, Nick and Lundquist, Jessica. Temperature trends in North American mountains: a global context. Poster. Presented at CIRMOUNT, Silverton, CO, June 9 – 12, 2008.

One issue: Surface temperature trends vs. free air temperature trends

- **Surface temperatures** – affected by surface complexities
- **Free air temperatures** – temps of atmosphere not directly in contact with/affected by surface

- Complex issue and extremely poorly understood, as it deals with trends in lapse rates.
- Measured to be significantly different in some cases (the opposite, in fact). Interaction with the surface may be changing the surface trend (as indicated by the greatest warming located near the 0°C isotherm – snow/ice feedback).
- Mountain summits and locations where air can move freely experience a much more consistent, linear trend. Pepin and Lundquist (2008) state that this doesn't necessarily mean mountains are more sensitive to potential climate change, but that they are taking a better record of the free air temperature.

Vuille and Bradley (2000), Pepin and Losloben (2002), and Gaffen et al. (2000).

"Geospatial Climatology"

- A relatively new field which studies the effect of physiographic features on climate

Some (Relatively) Specific Factors

1) **Solar Radiation** – varying exposures, facet directions, slope angles, sunlight totals, etc.
2) **Synoptic pattern** – cloud cover, overall wind speed/direction, precipitation, humidity, etc.
3) **Land Cover** – urban, forest, grassland, desert, lake/stream, glacier, etc. and <u>*changes*</u> in land cover through space – (creates certain wind patterns when combined with other two factors that further influence temperature patterns)

Why should we care about such high resolution patterns?

- Ecological/biological gradients mirror the high climatological gradients (and resulting hydrological gradients)

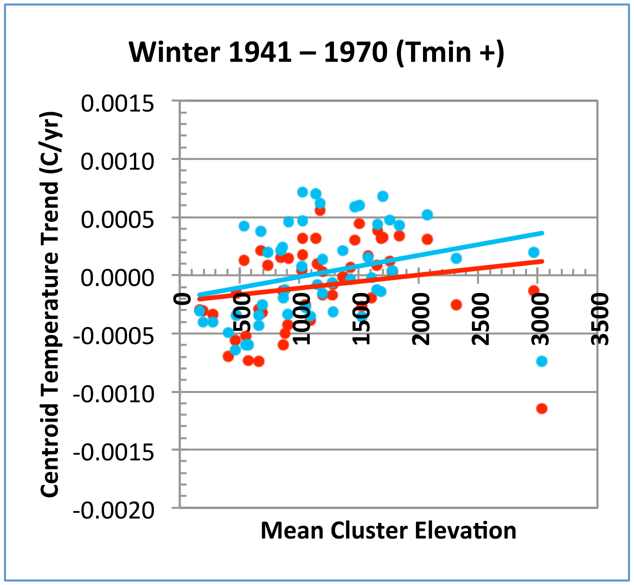
One (of countless) really cool example: The larvae of the black, basking caterpillar grow faster on a sun facing, warm slope, and emerge as a butterfly up to 5 weeks faster! (Weiss, et al. 1988)

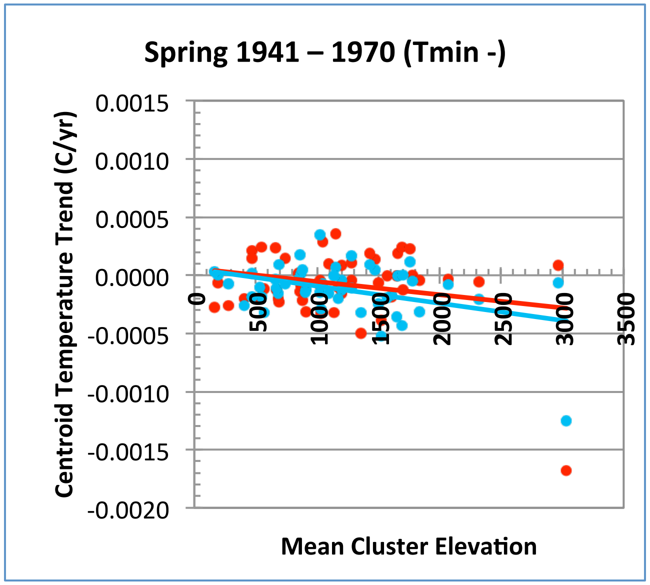
Since high resolution is important, where and how do we get accurate, high resolution data?

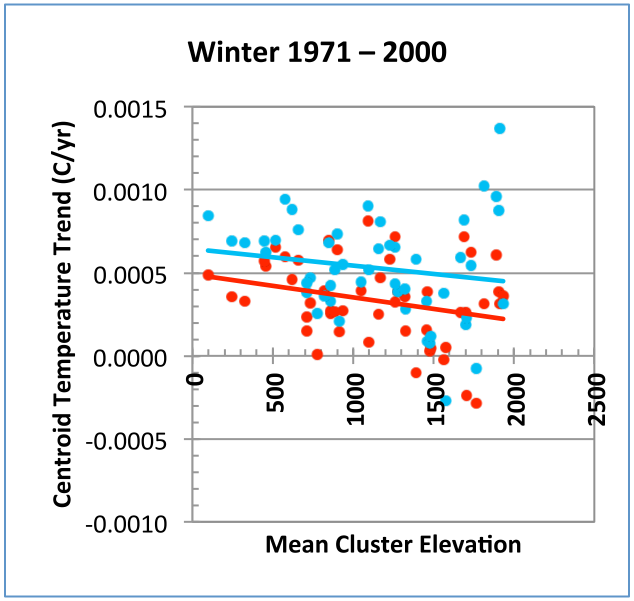
Several choices (based on literature review):

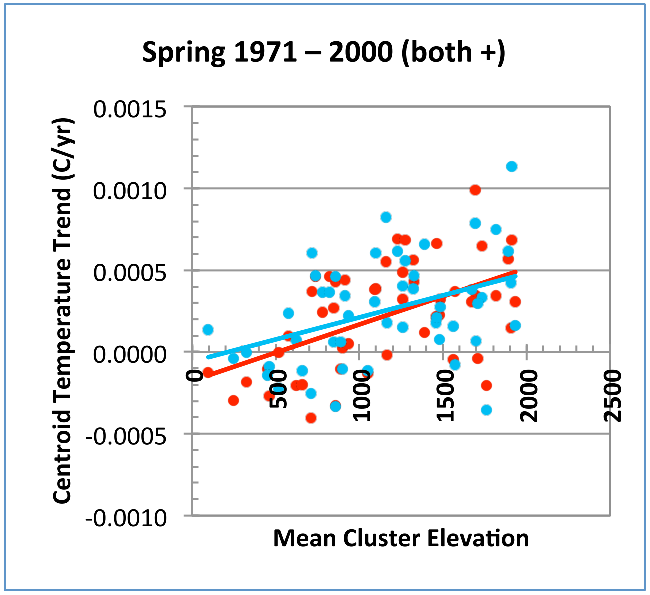
1) Global Climate Models – very low resolution, Pepin and Lundquist (2008) indicate they produce too strong a warming feedback at the 0°C isotherm
2) Regional Models (NARR/NARCCAP)- a lot better, but a 32 or 50 km resolution is still much too low
3) Statistically downscaled regionally model data – may be good, but covers relatively short time periods and small areas (10 – 12 km resolution ok, but not great)
4) Satellite – may be good, but requires processing/interpretation of an enormous amount of data, covers a relatively short time period, and some of this data has never been looked at or processed
5) Observations alone – fine for local studies, but can't generalize observations without some sort of adjustments (or a lot of adjustments)
6) **Downscaling – not just a basic interpolation technique (such as kriging or inverse weighting), but a knowledge based algorithm**

Sixteen Variable Results – yearly seasonal averages









Despite these changes….

- Mountainous regions have been poorly studied, in general (climate, ecology, etc.)

But Why?

- Remoteness means generally sparse population, so neglected since deemed 'less important'
- Remoteness also means physical access for installation and maintenance of monitoring equipment is difficult
- High complexity of terrain means one station represents only a small portion of region/mountain chain
- Making standard weather observations (or others) is difficult across such a large portion of world, due to everything from different cultural, political, and even scientific standards/goals