



Recent Accelerated Warming in Western United States Mountains

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John T. Abatzoglou

Western Regional Climate Center

Desert Research Institute

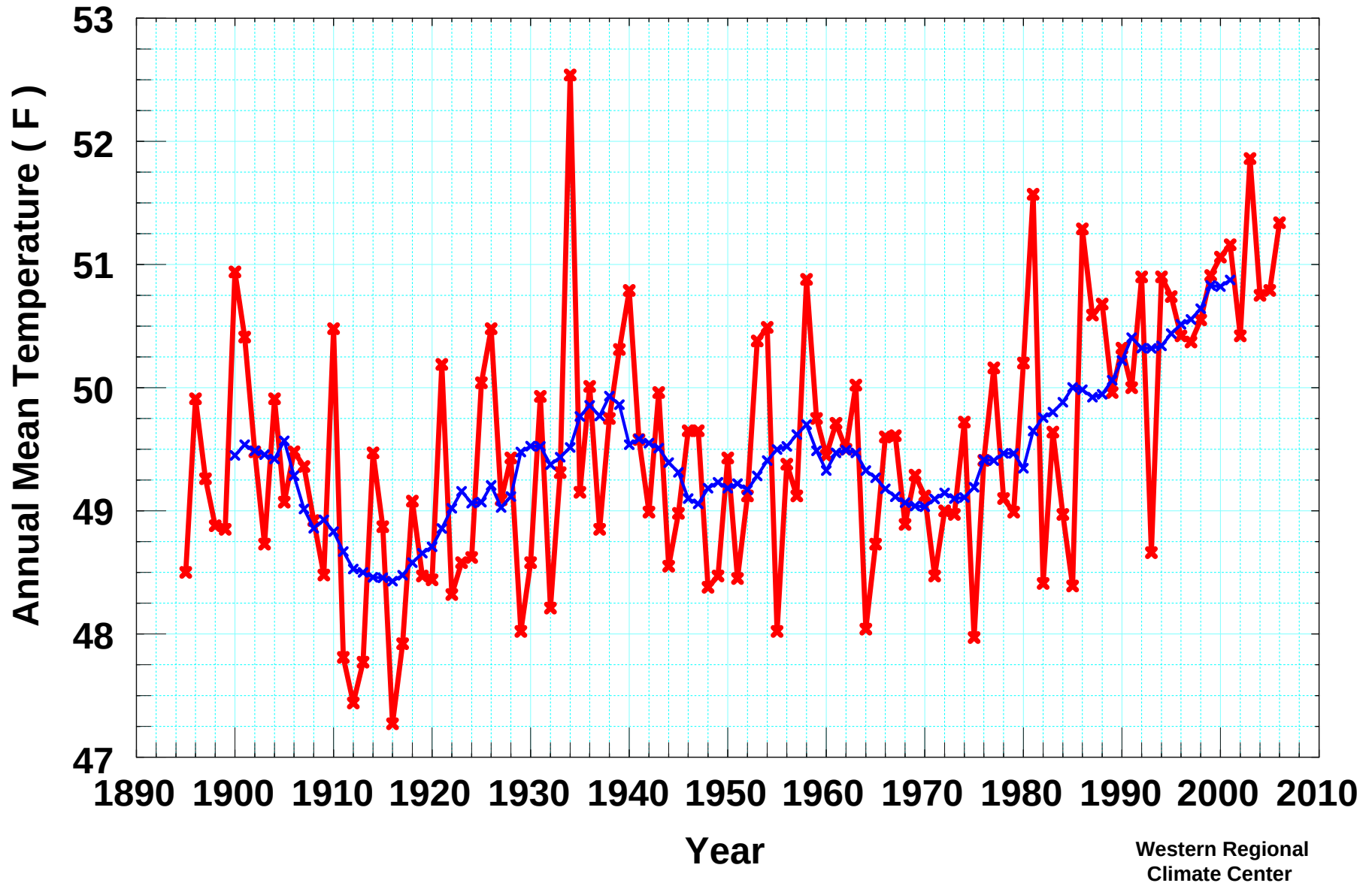
Reno Nevada

AGU San Francisco

December 12, 2007



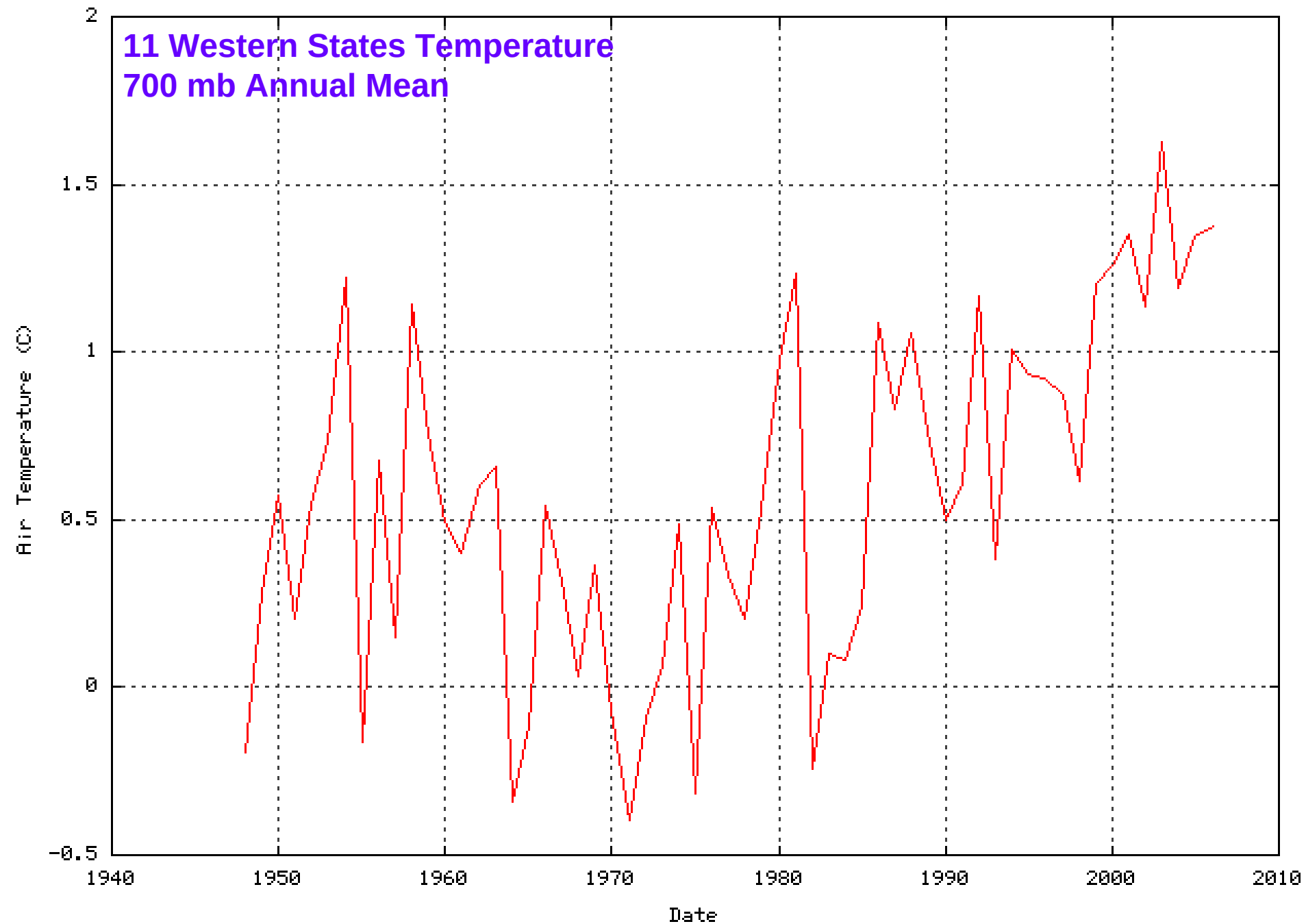
Western United States (11 states) Annual Jan-Dec Temperature
Provisional data from NCDC / CPC. Blue: 11-year running mean.
Units: Deg F. Data source NOAA cooperative network, thru Dec 2006.



**Fixed
Pressure**

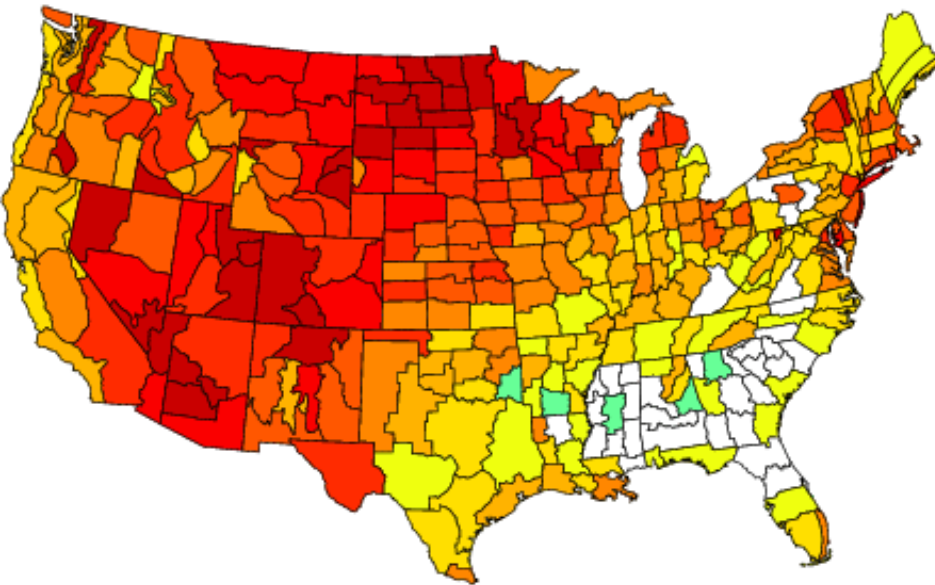
Air Temperature (NCEP Reanalysis) Jan to Dec:50N to 32N and -124W to -104W averaged

**11 Western States Temperature
700 mb Annual Mean**

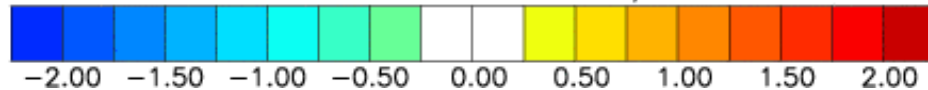


Annual Mean Temperatures, 2000-2006. Departures from 1895-2000 Mean.

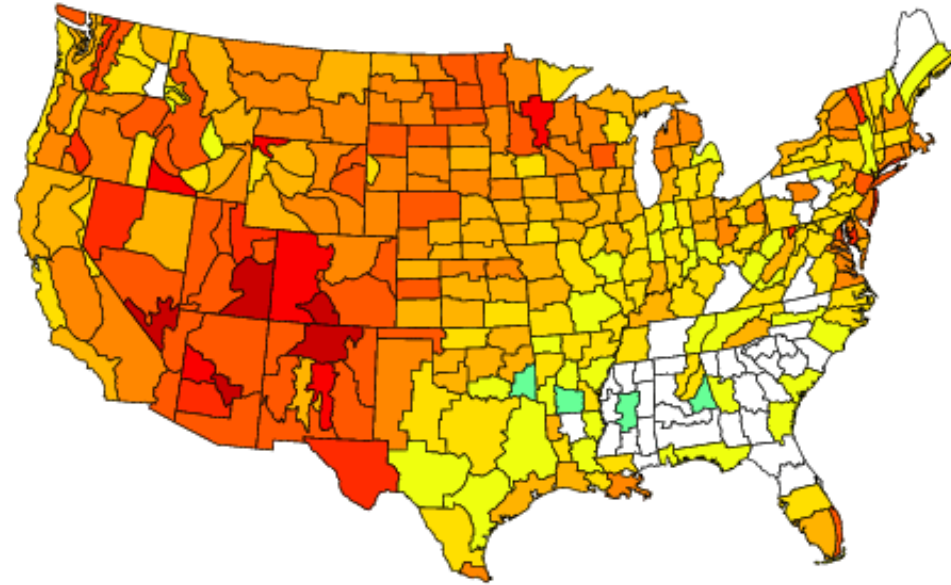
Composite Temperature Anomalies (F)
Jan to Dec 2000 to 2006
Versus 1895–2000 Longterm Average



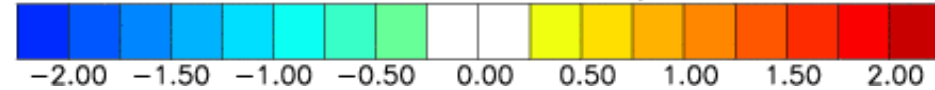
NOAA/ESRL PSD and CIRES-CDC



Composite Standardized Temperature Anomalies
Jan to Dec 2000 to 2006
Versus 1895–2000 Longterm Average



NOAA/ESRL PSD and CIRES-CDC

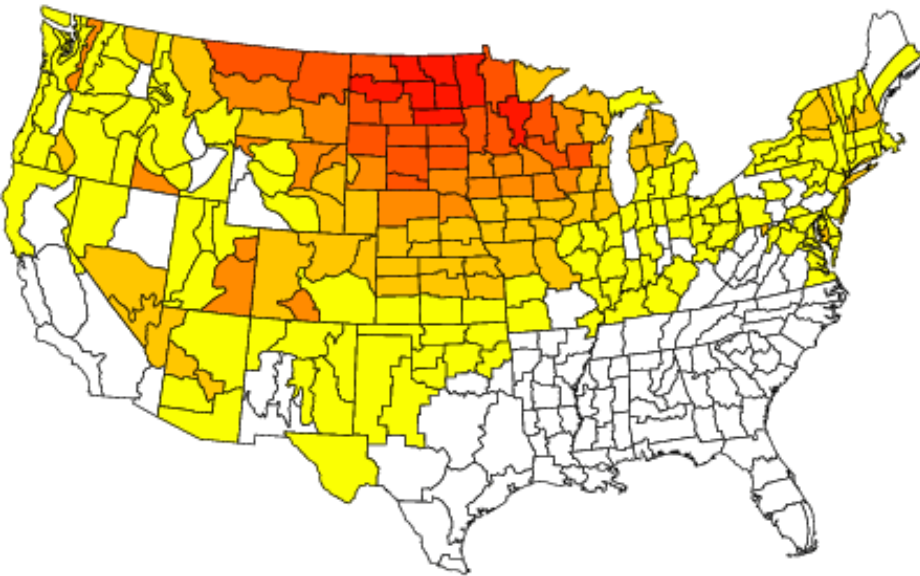


Non-standardized. Units: Degrees F. Normalized (standard deviations).

The West dominates recent U.S. warming.

Winter (Dec-Jan-Feb) Mean Temperatures, 1999/2000-2006/2007. Departures from 1895-2000 Mean.

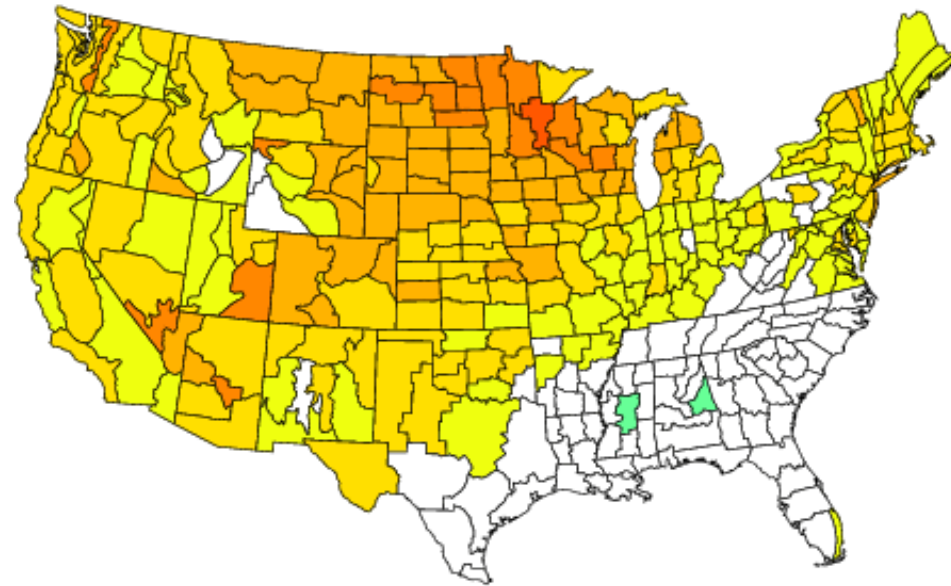
Composite Temperature Anomalies (F)
Dec to Feb 1999–** to 2006–07
Versus 1895–2000 Longterm Average



NOAA/ESRL PSD and CIRES-CDC

-6.0 -4.0 -2.0 0.0 2.0 4.0 6.0

Composite Standardized Temperature Anomalies
Dec to Feb 1999–** to 2006–07
Versus 1895–2000 Longterm Average



NOAA/ESRL PSD and CIRES-CDC

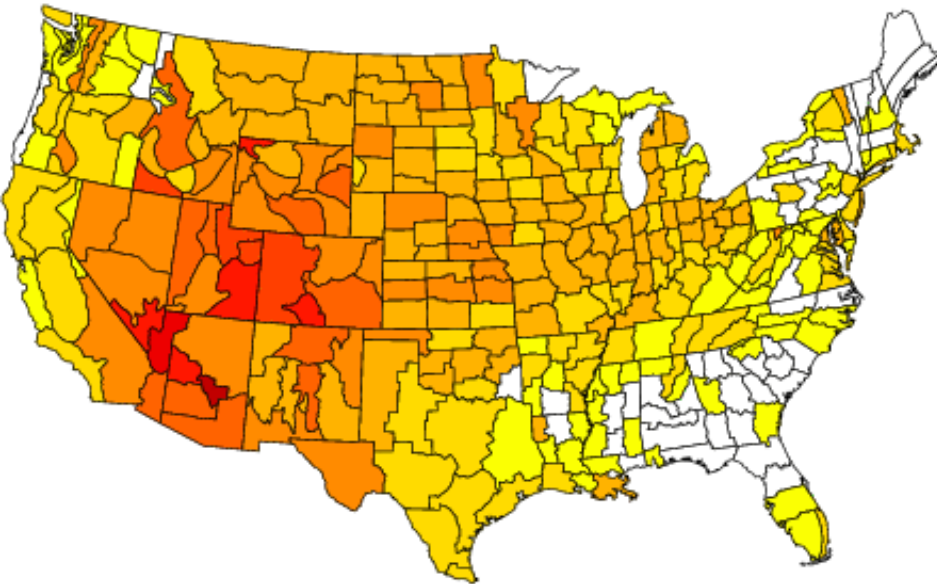
-2.00 -1.50 -1.00 -0.50 0.00 0.50 1.00 1.50 2.00

Non-standardized. Units: Degrees F. Normalized (standard deviations).

The West and North dominate recent U.S. warming.

Spring (Mar-Apr-May) Mean Temperatures, 2000-2007. Departures from 1895-2000 Mean.

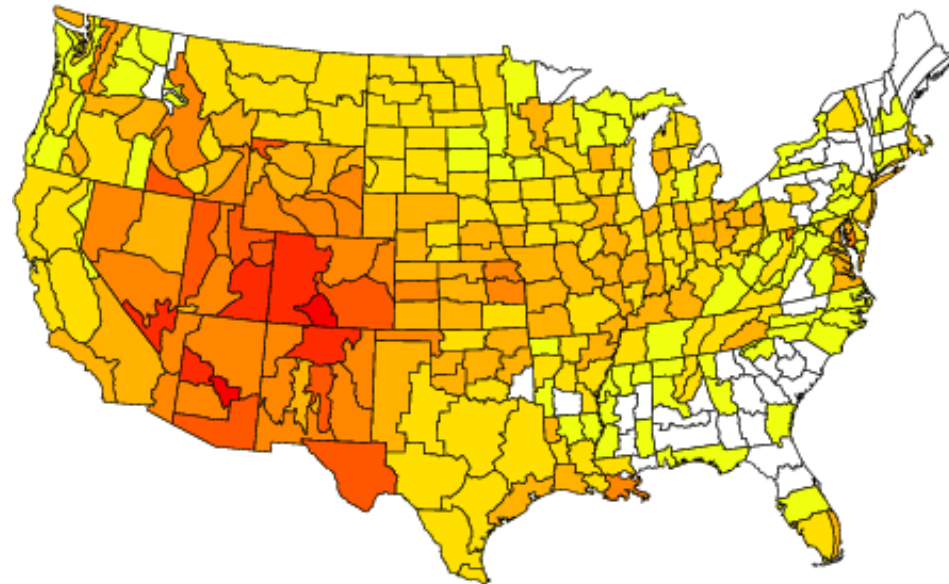
Composite Temperature Anomalies (F)
Mar to May 2000 to 2007
Versus 1895–2000 Longterm Average



NOAA/ESRL PSD and CIRES-CDC

-5.0 -4.0 -3.0 -2.0 -1.0 0.0 1.0 2.0 3.0 4.0 5.0

Composite Standardized Temperature Anomalies
Mar to May 2000 to 2007
Versus 1895–2000 Longterm Average



NOAA/ESRL PSD and CIRES-CDC

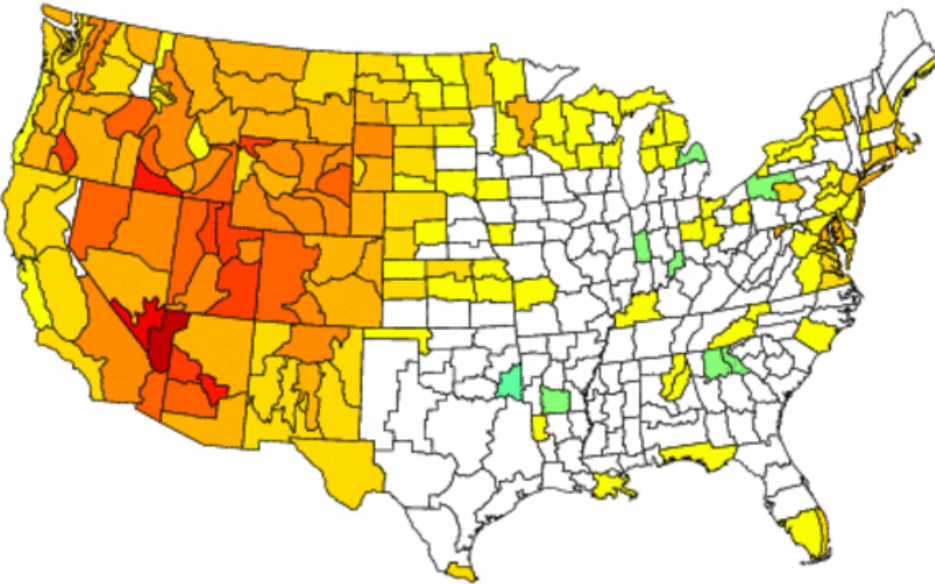
-2.00 -1.50 -1.00 -0.50 0.00 0.50 1.00 1.50 2.00

Non-standardized. Units: Degrees F. Normalized (standard deviations).

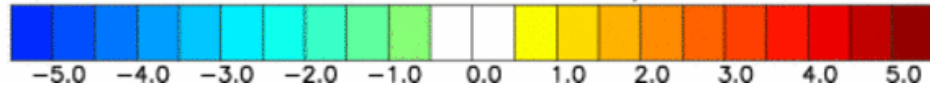
The West dominates recent U.S. warming.

Summer (Jun-Jul-Aug) Mean Temperatures, 2000-2007. Departures from 1895-2000 Mean.

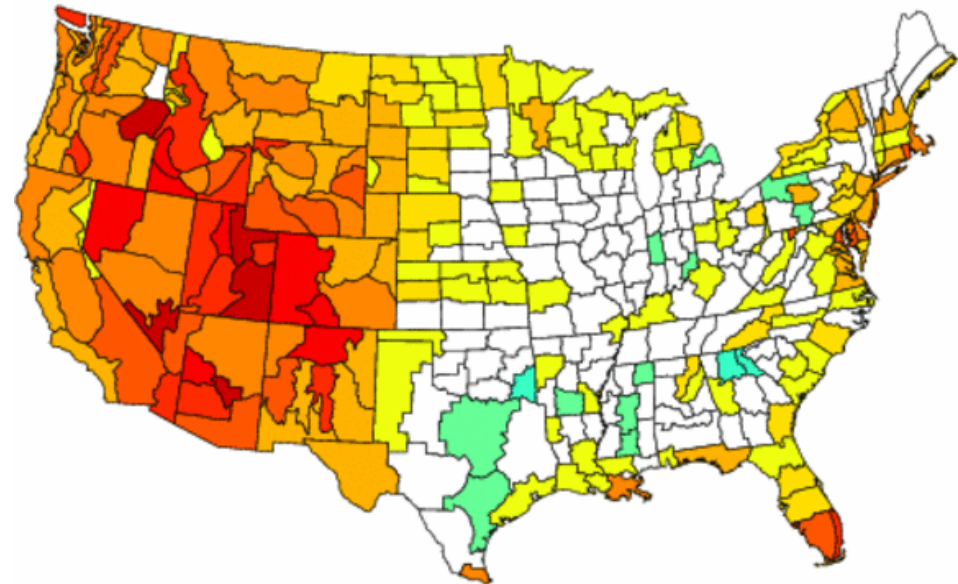
Composite Temperature Anomalies (F)
Jun to Aug 2000 to 2007
Versus 1895–2000 Longterm Average



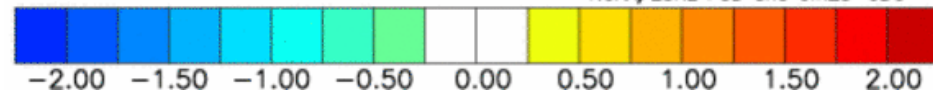
NOAA/ESRL PSD and CIRES-CDC



Composite Standardized Temperature Anomalies
Jun to Aug 2000 to 2007
Versus 1895–2000 Longterm Average



NOAA/ESRL PSD and CIRES-CDC

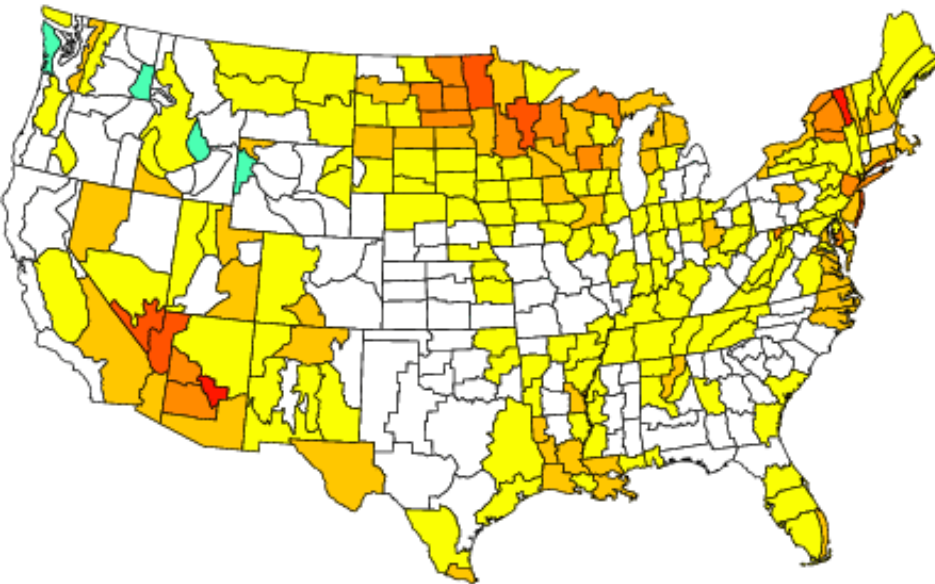


Non-standardized. Units: Degrees F. Normalized (standard deviations).

The West dominates recent U.S. warming.

Autumn (Sep-Oct-Nov) Mean Temperatures, 2000-2006. Departures from 1895-2000 Mean.

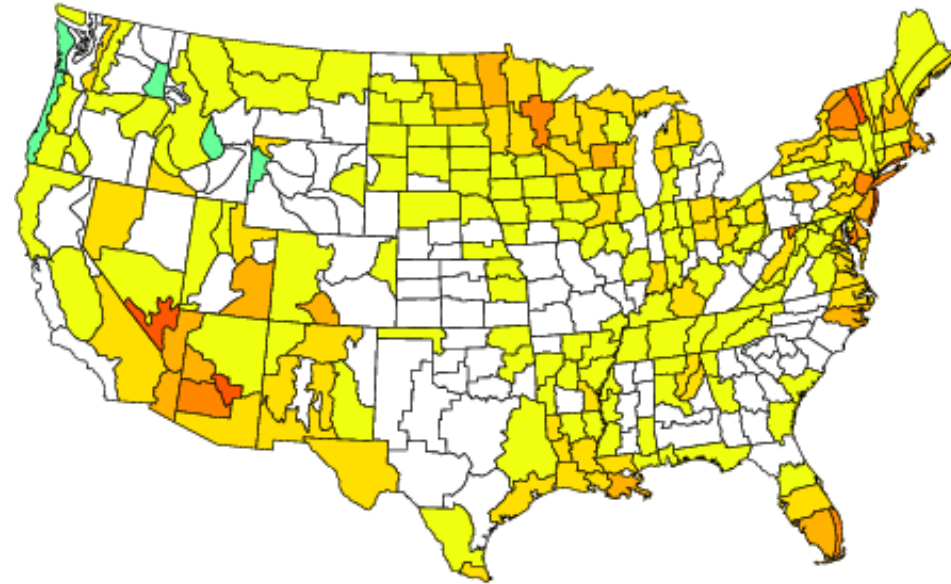
Composite Temperature Anomalies (F)
Sep to Nov 2000 to 2006
Versus 1895–2000 Longterm Average



NOAA/ESRL PSD and CIRES-CDC

-3.0 -2.0 -1.0 0.0 1.0 2.0 3.0

Composite Standardized Temperature Anomalies
Sep to Nov 2000 to 2006
Versus 1895–2000 Longterm Average



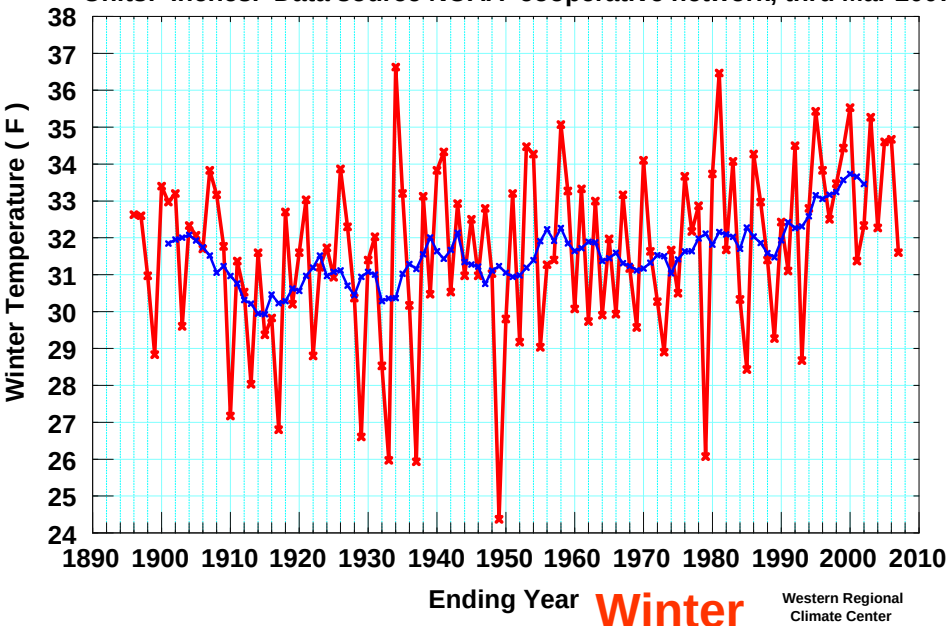
NOAA/ESRL PSD and CIRES-CDC

-2.00 -1.50 -1.00 -0.50 0.00 0.50 1.00 1.50 2.00

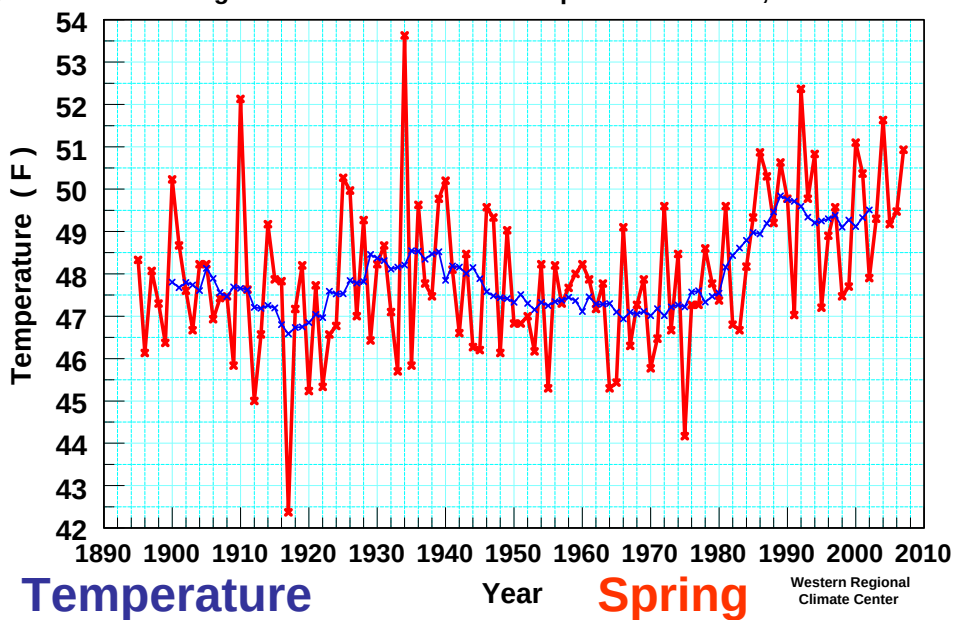
Non-standardized. Units: Degrees F. Normalized (standard deviations).

The West dominates recent U.S. warming.

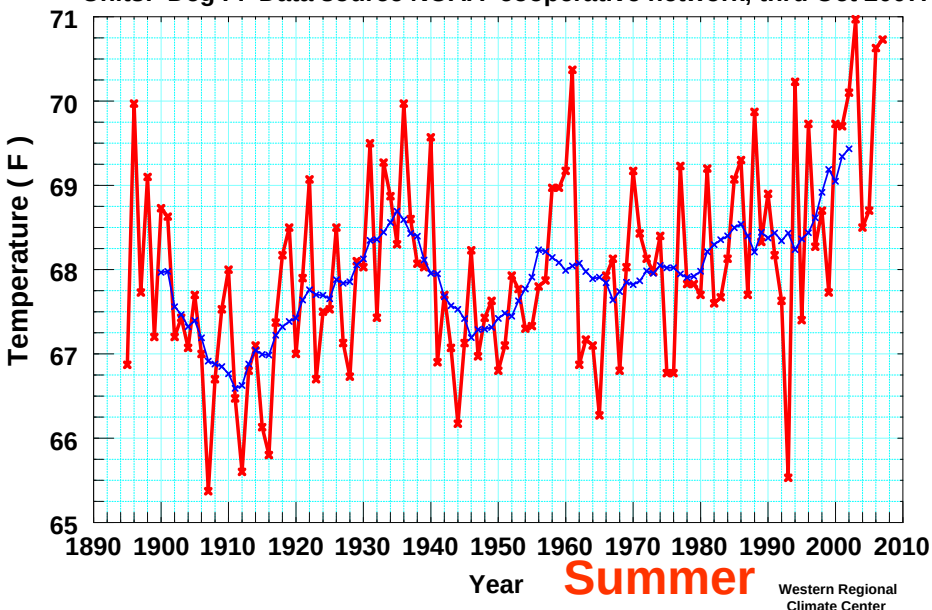
Western United States (11 states) Dec-Jan-Feb Temperature
Provisional data from NCDC / CPC. Blue: 11-year running mean.
Units: Inches. Data source NOAA cooperative network, thru Mar 2007.



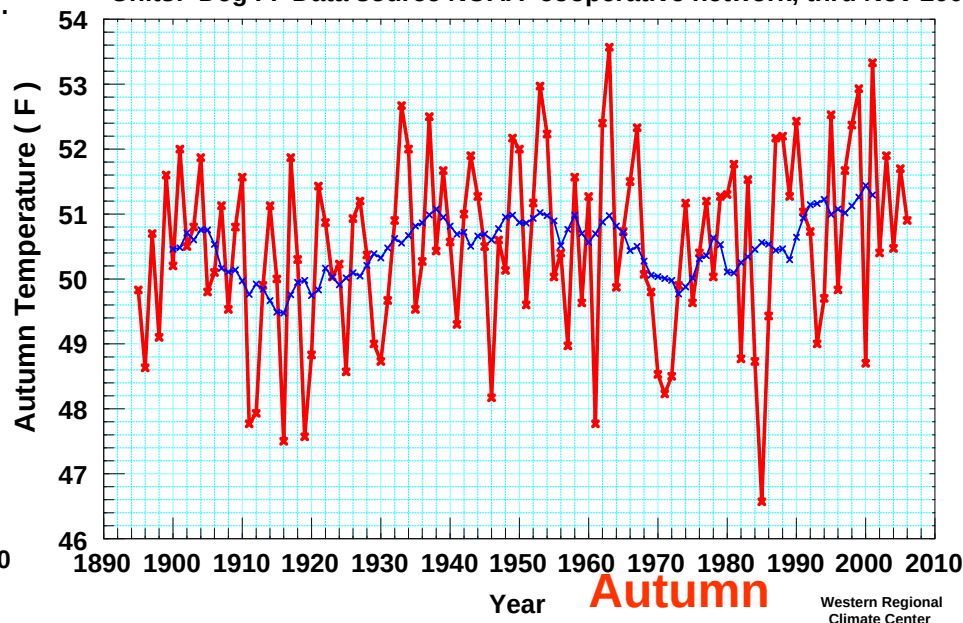
Western United States (11 states) Mar-Apr-May Temperature
Provisional data from NCDC / CPC. Blue: 11-year running mean.
Units: Deg F. Data source NOAA cooperative network, thru Oct 2007.



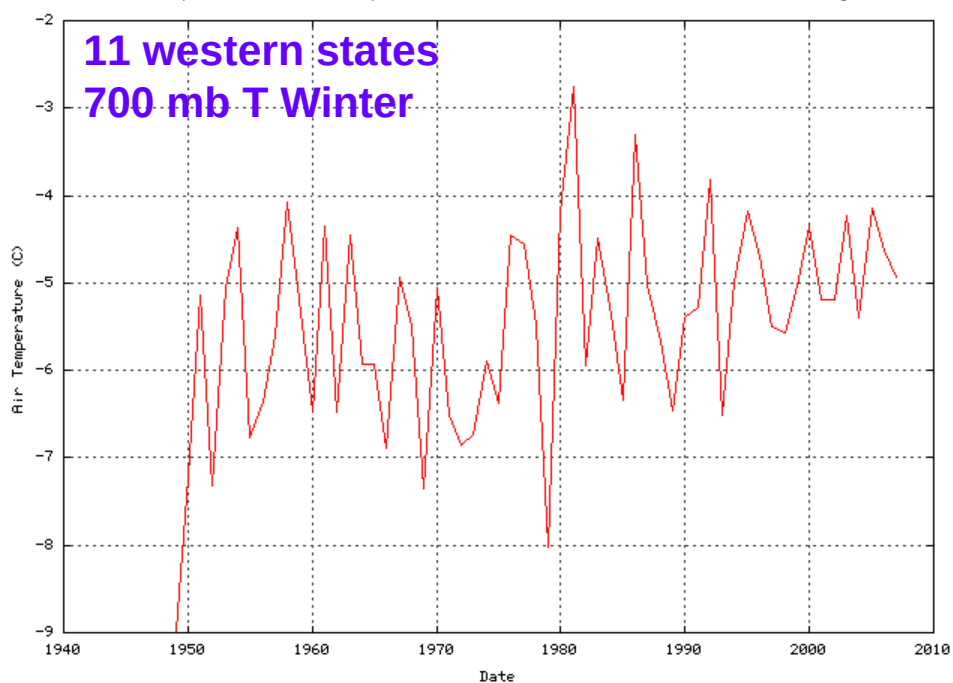
Western United States (11 states) June-July-August Temperature
Provisional data from NCDC / CPC. Blue: 11-year running mean.
Units: Deg F. Data source NOAA cooperative network, thru Oct 2007.



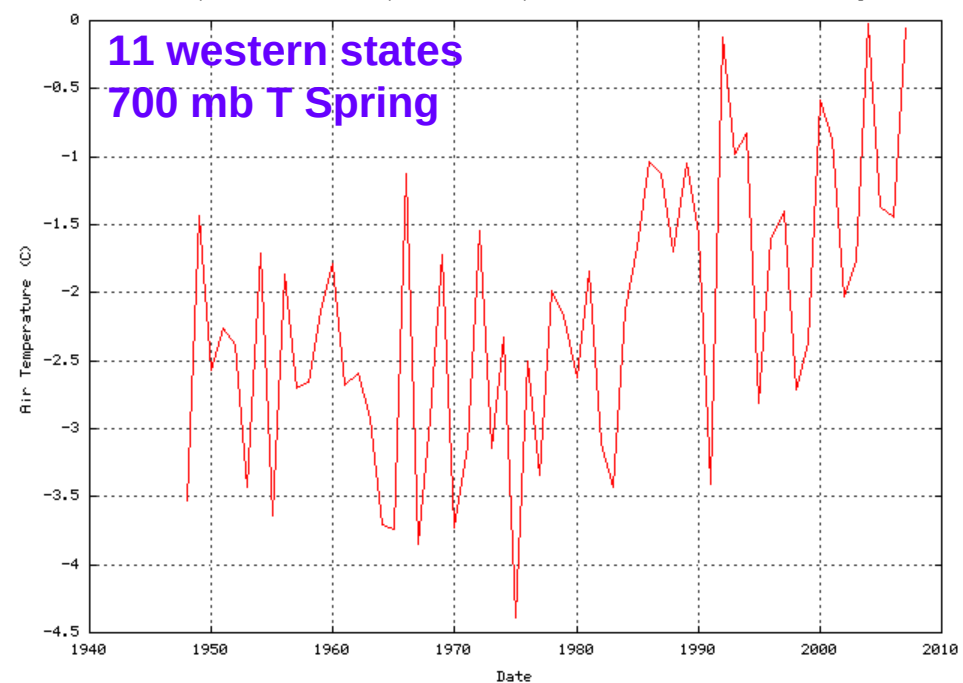
Western United States (11 states) Sept-Oct-Nov Temperature
Provisional data from NCDC / CPC. Blue: 11-year running mean.
Units: Deg F. Data source NOAA cooperative network, thru Nov 2006.



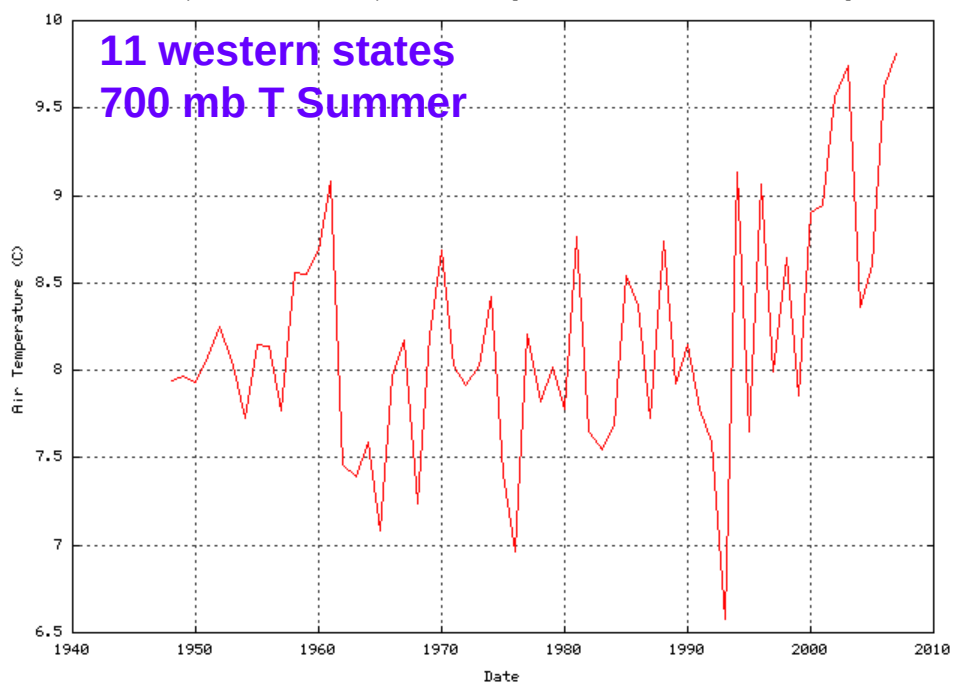
Air Temperature (NCEP Reanalysis) Dec to Feb:50N to 32N and -124W to -104W averaged



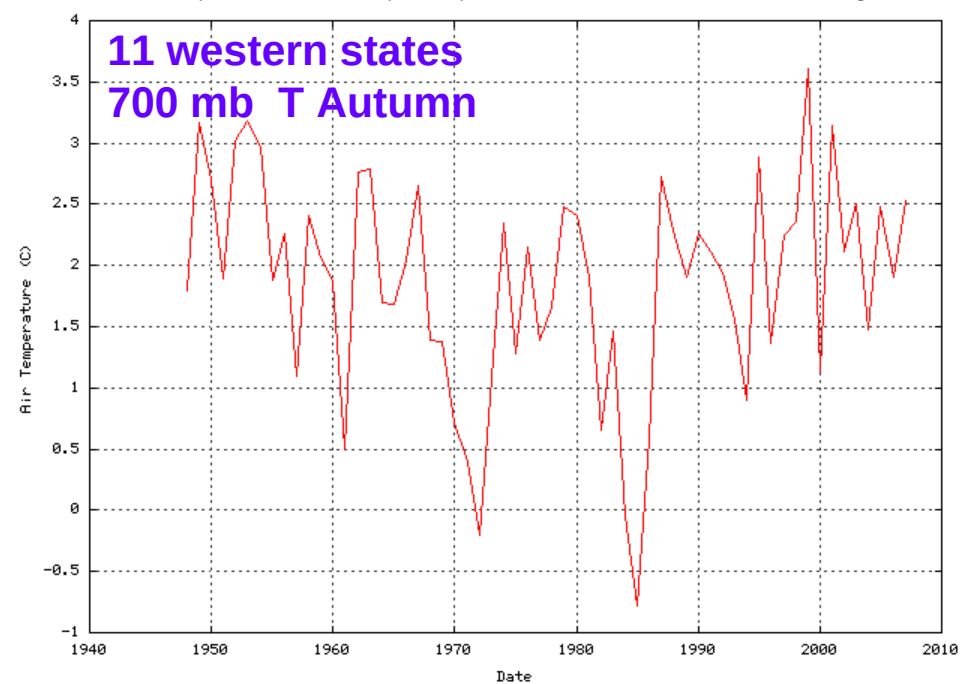
Air Temperature (NCEP Reanalysis) Mar to May:50N to 32N and -124W to -104W averaged



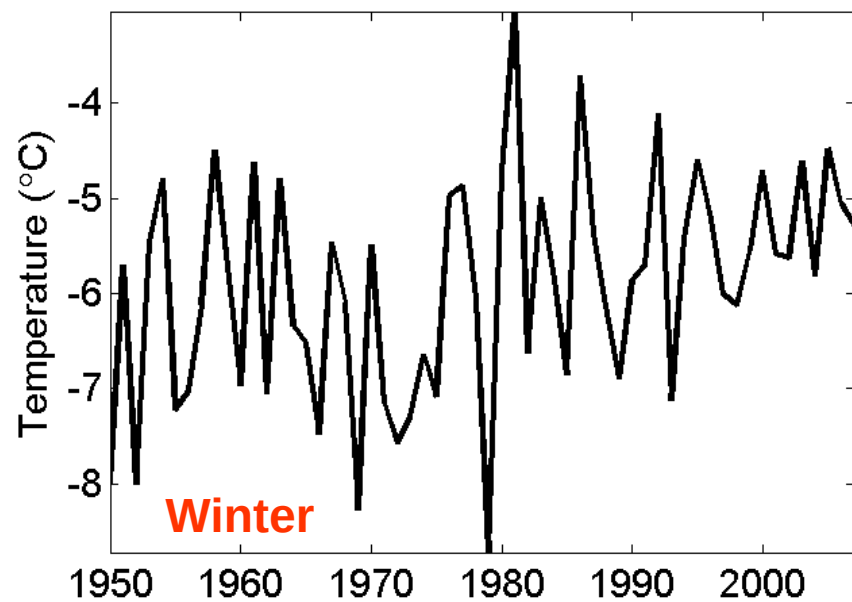
Air Temperature (NCEP Reanalysis) Jun to Aug:50N to 32N and -124W to -104W averaged



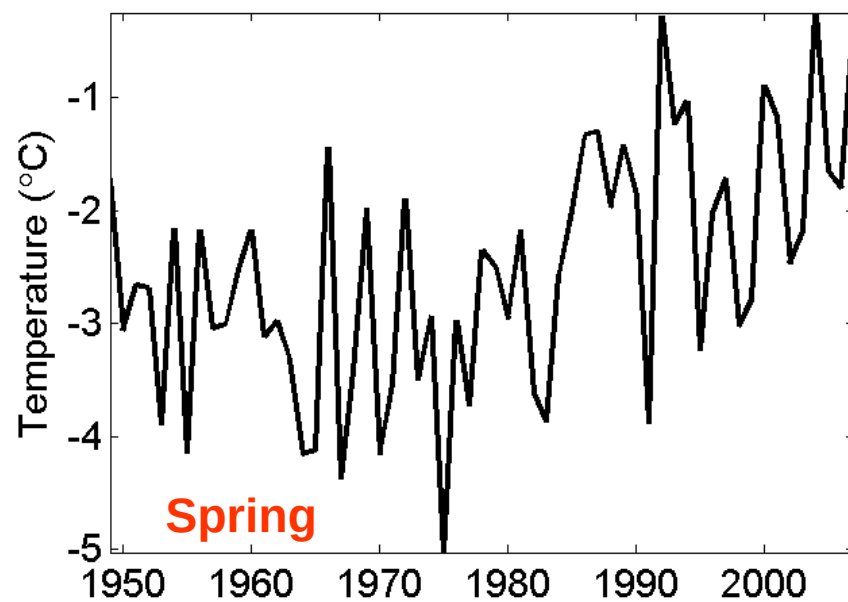
Air Temperature (NCEP Reanalysis) Sep to Nov:50N to 32N and -124W to -104W averaged



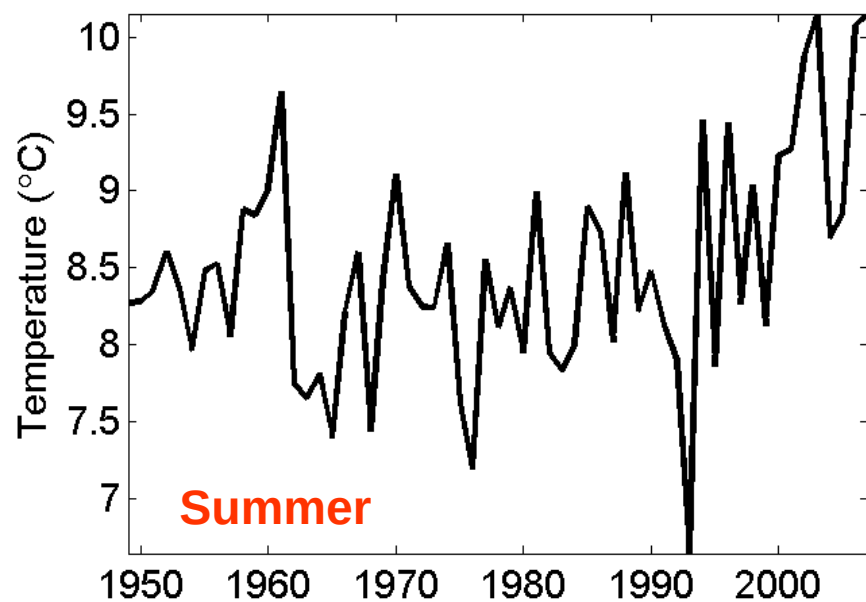
Western US 10,000 ft, DJF



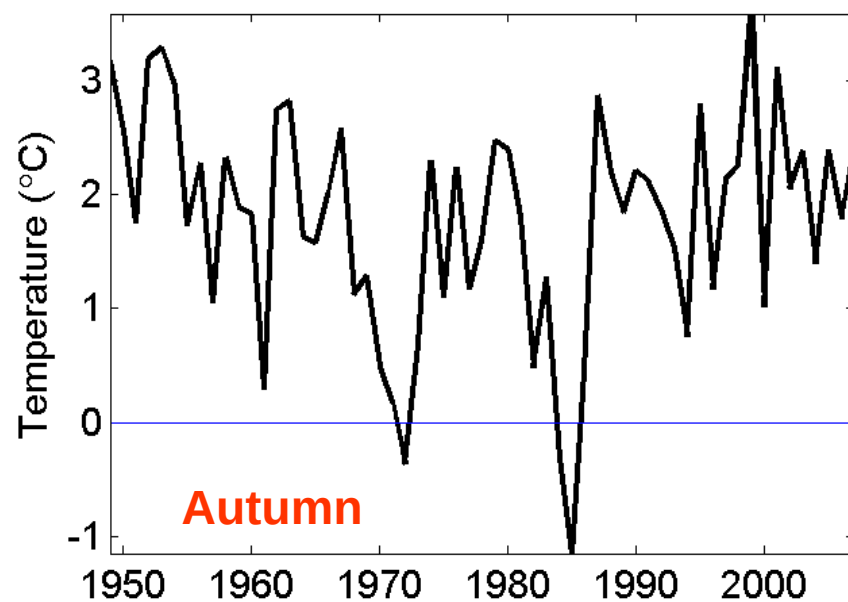
Western US 10,000 ft, MAM

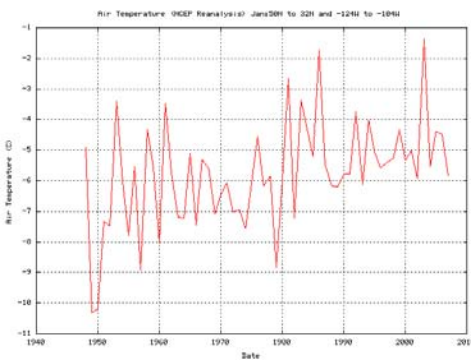


Western US 10,000 ft, JJA

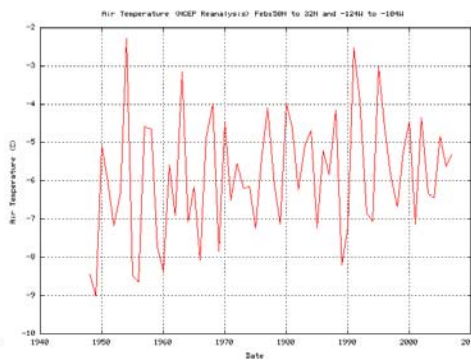


Western US 10,000 ft, SON

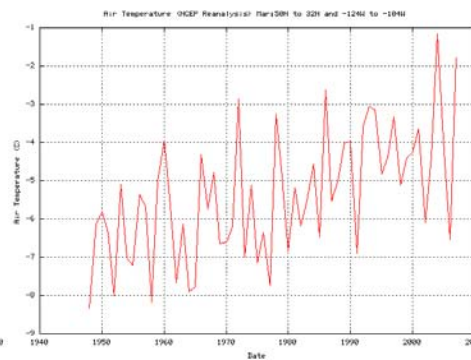




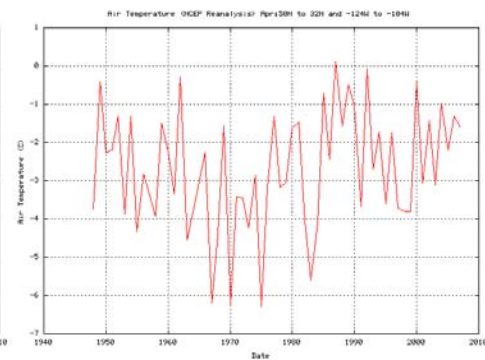
Jan



Feb

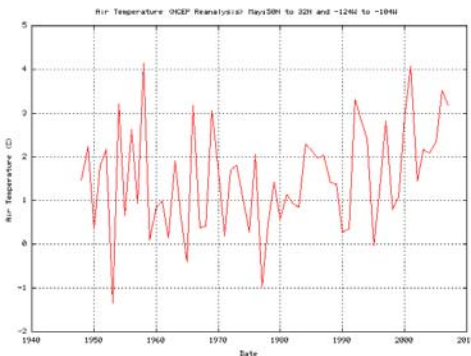


Mar

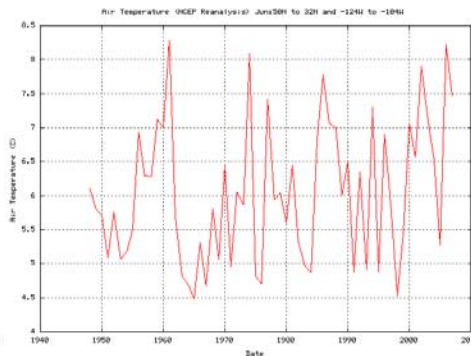


Apr

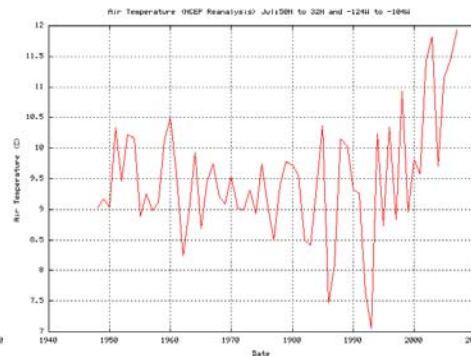
Western States 700 mb Temperature (C)



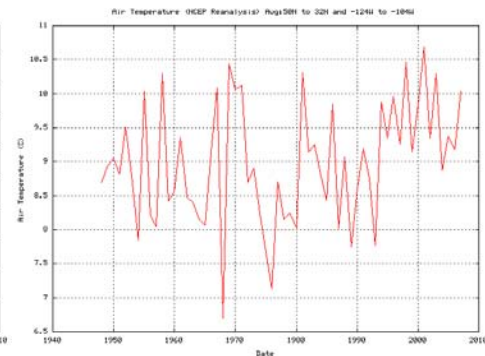
May



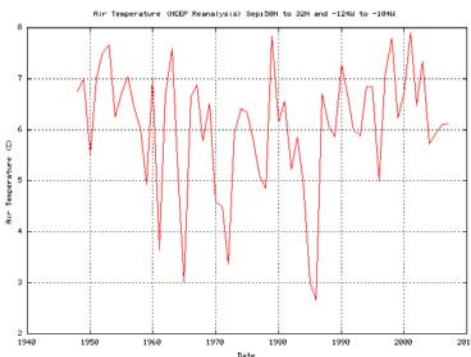
Jun



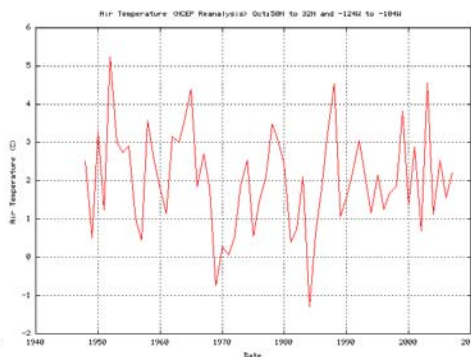
Jul



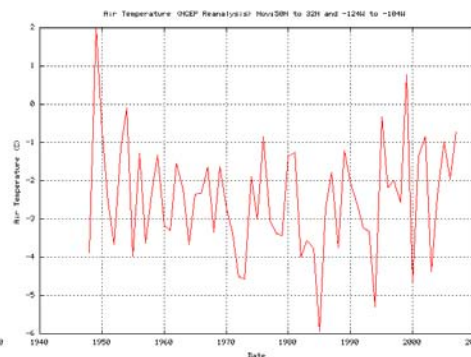
Aug



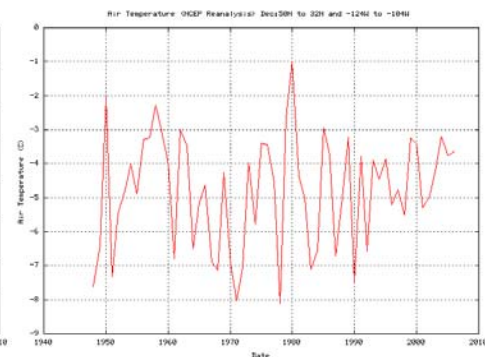
Sep



Oct

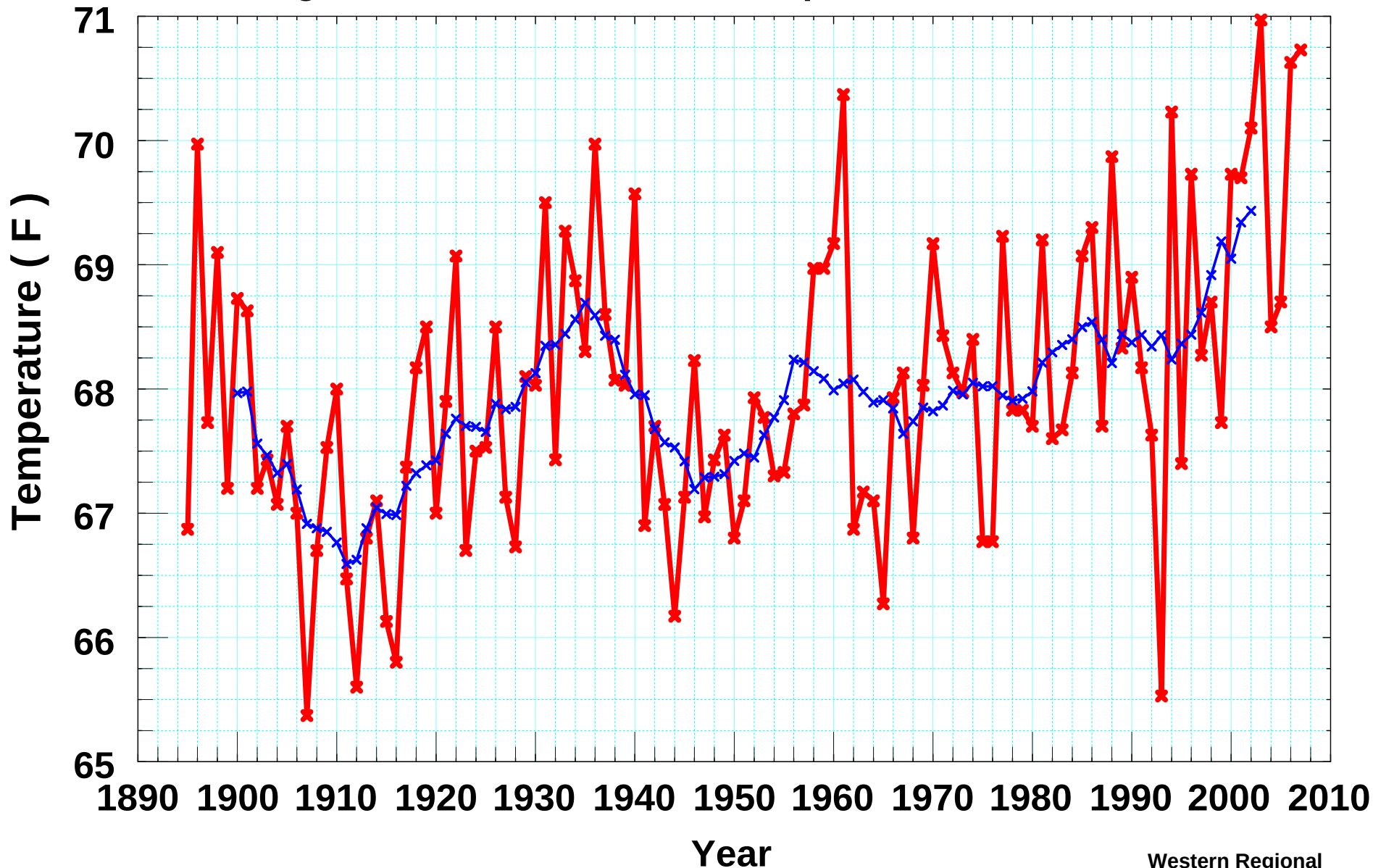


Nov



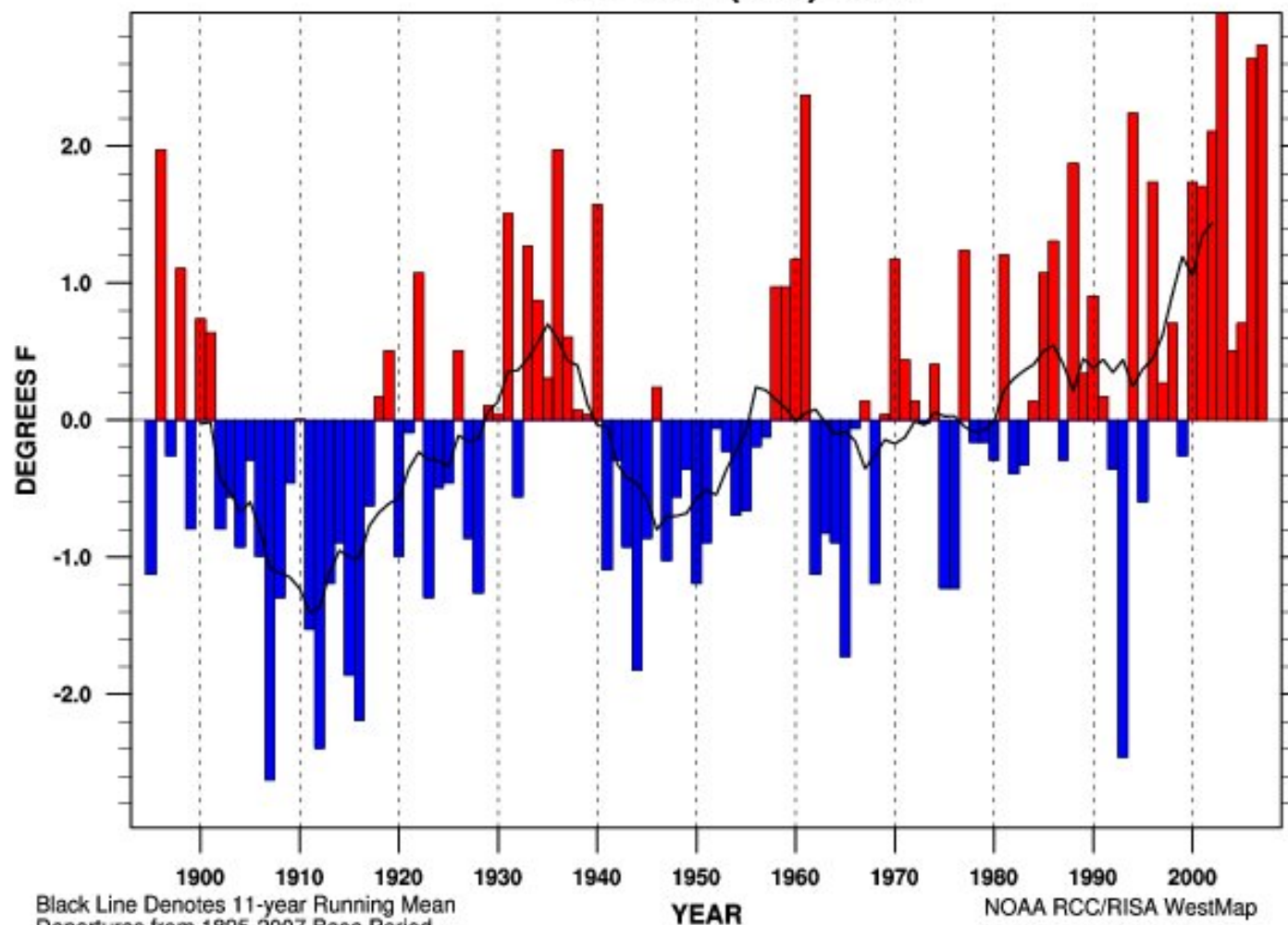
Dec

Western United States (11 states) June-July-August Temperature
Provisional data from NCDC / CPC. Blue: 11-year running mean.
Units: Deg F. Data source NOAA cooperative network, thru Oct 2007.



Western United States Mean Temperature Departure Summer (JJA) Mean

Data from
PRISM



Linear Trend 1895-2007 $+ 1.39 \pm 0.61^{\circ}\text{F}/100\text{yr}$

Warmest Year 71.0°F ($+2.9^{\circ}\text{F}$) in 2003

Coldest Year 65.4°F (-2.6°F) in 1907

2007 70.7°F ($+2.7^{\circ}\text{F}$)

Base Period Statistics
1895-2007

MEAN 68.0°F

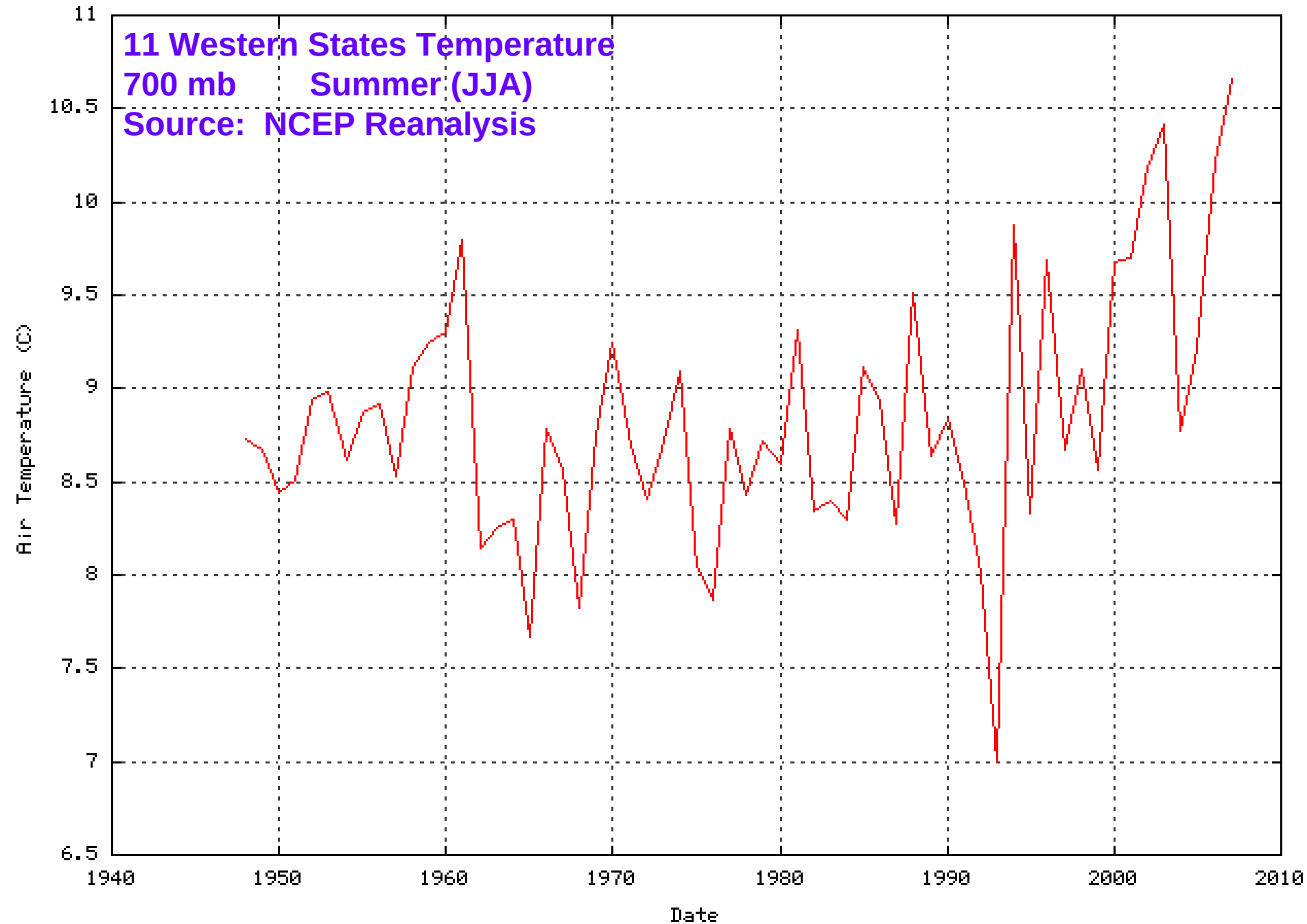
STDEV 1.16°F

RANK 112 of 113

**Fixed
Pressure**

Air Temperature (NCEP Reanalysis) Jun to Aug:50N to 32N and -120W to -104W averaged

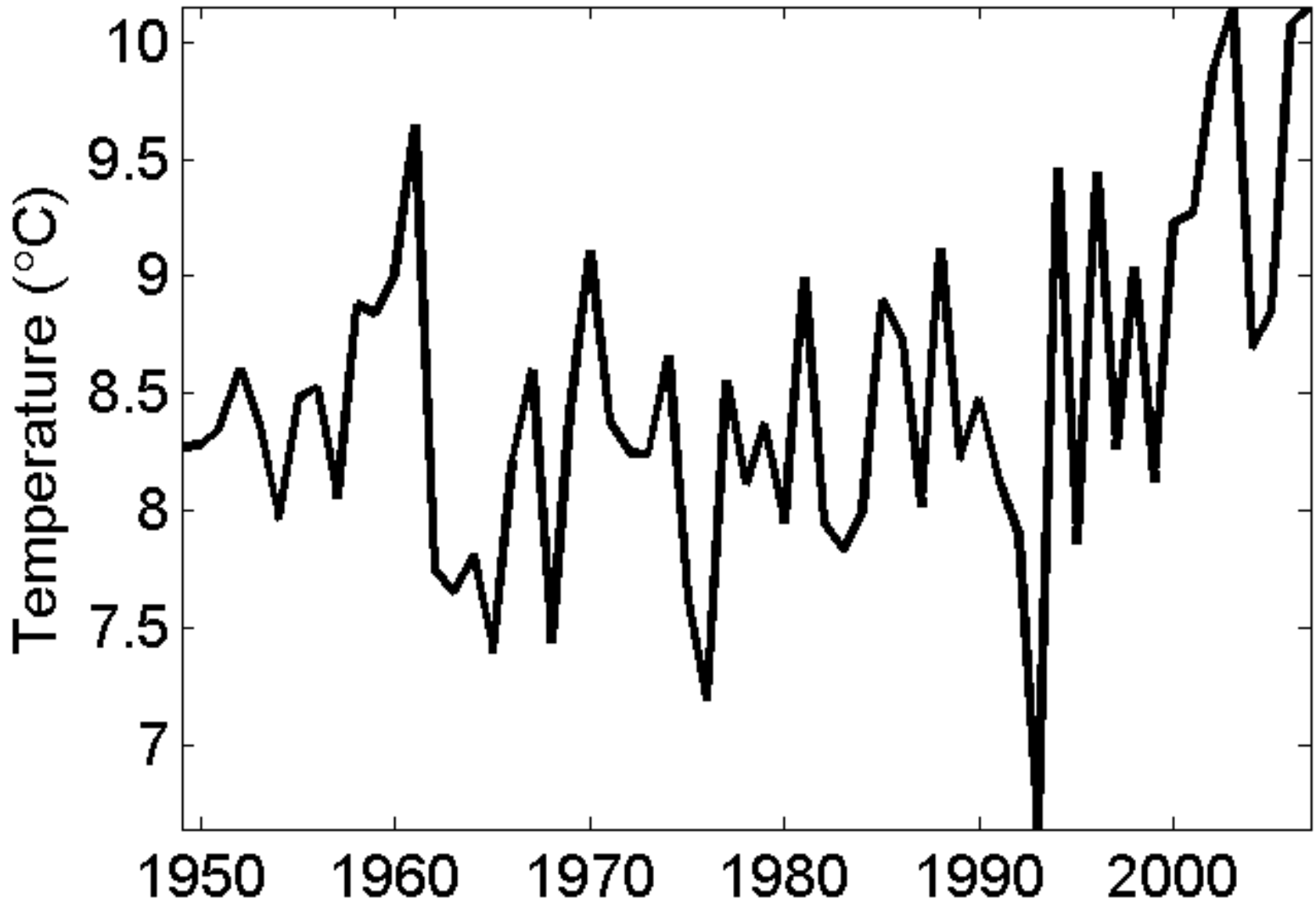
**11 Western States Temperature
700 mb Summer (JJA)
Source: NCEP Reanalysis**



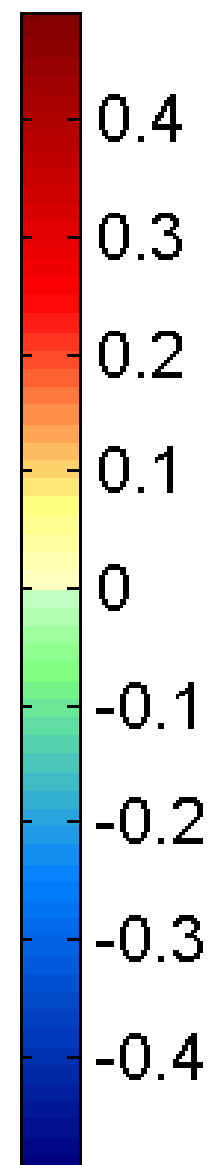
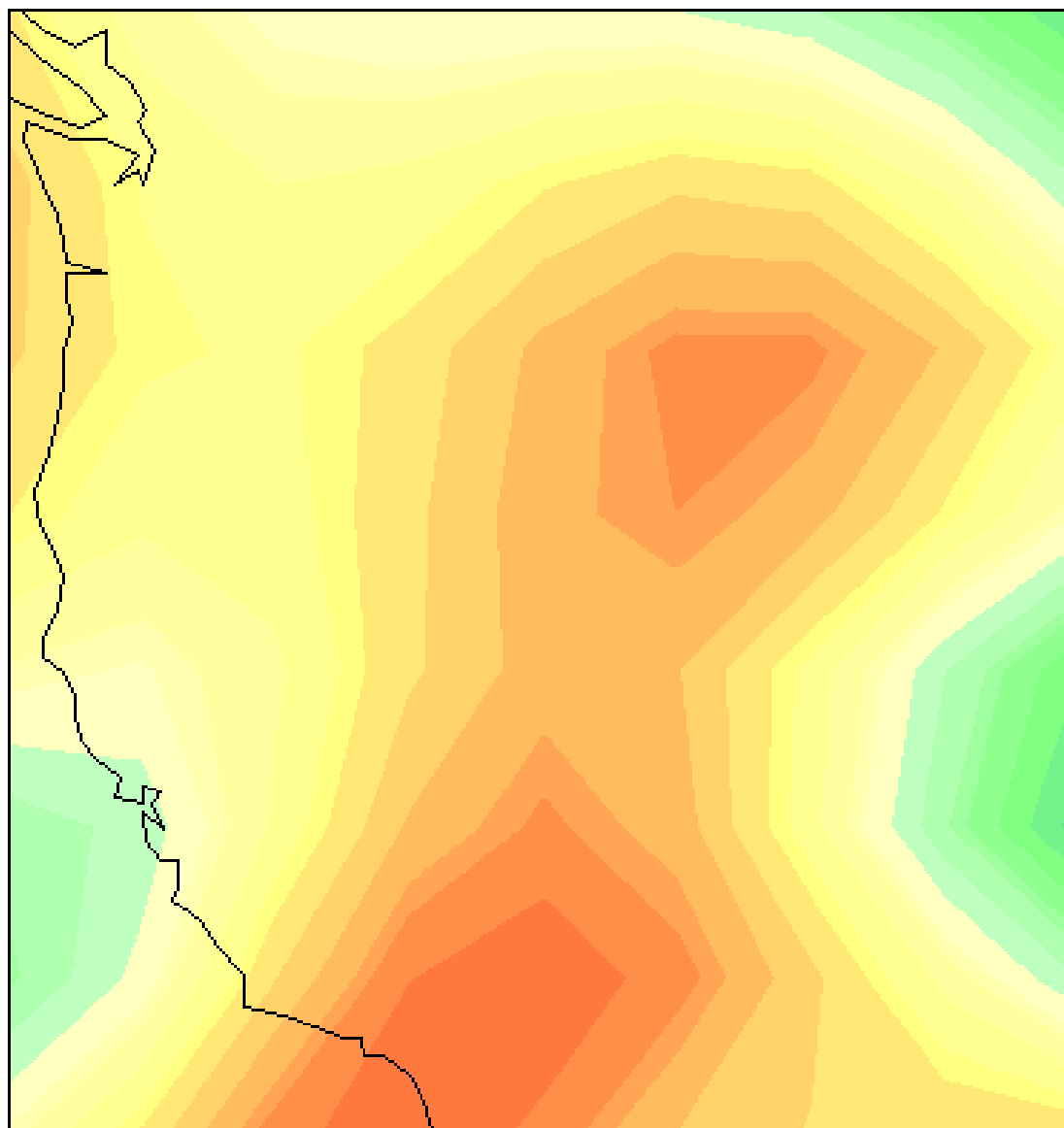
Fixed Elevation

Data from
NCEP
Reanalysis

Western US 10,000 ft, JJA



JJA 2000ft



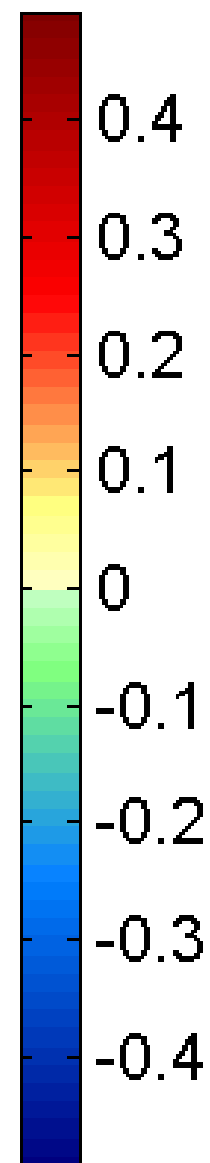
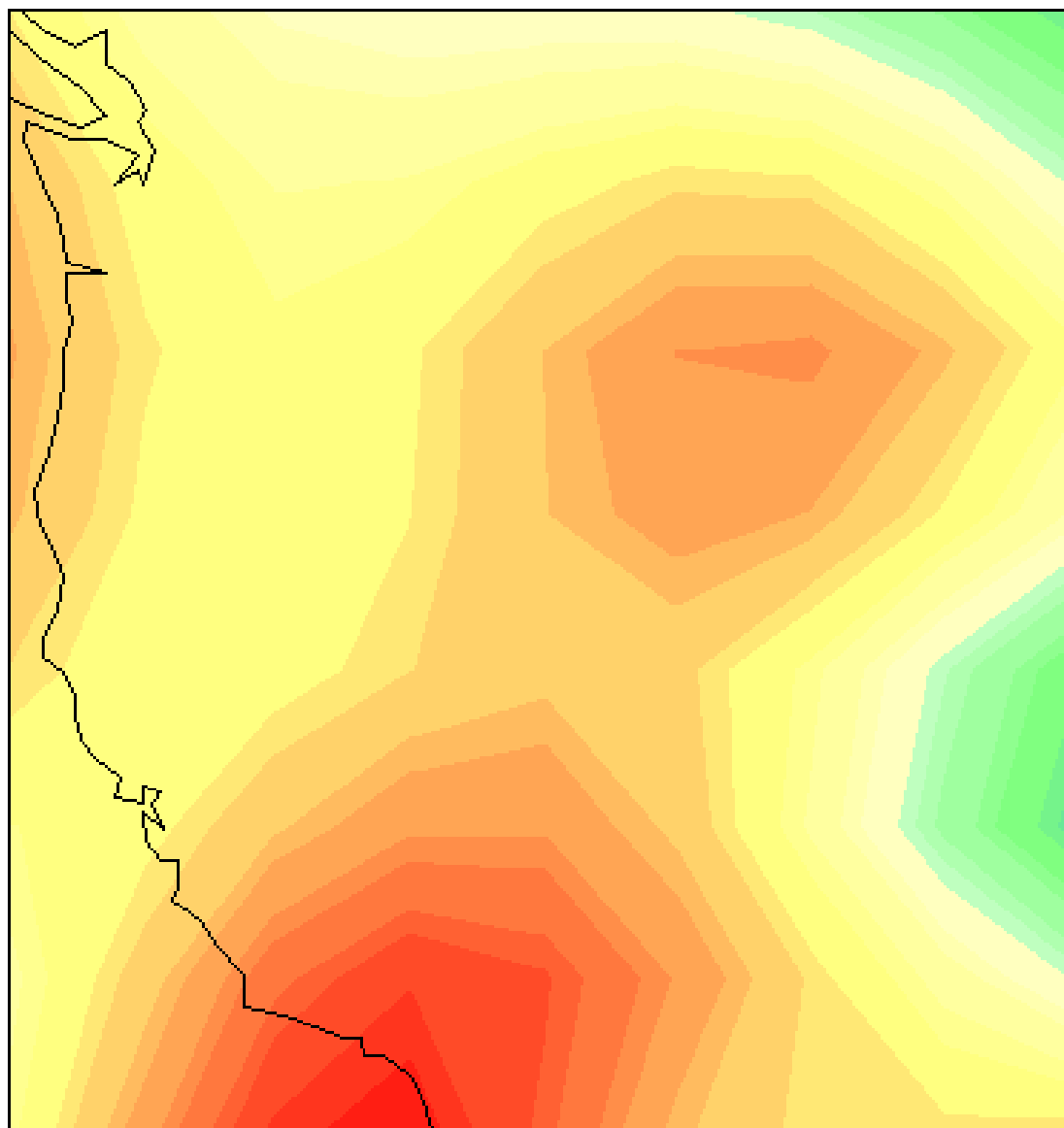
Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

JJA 3000ft



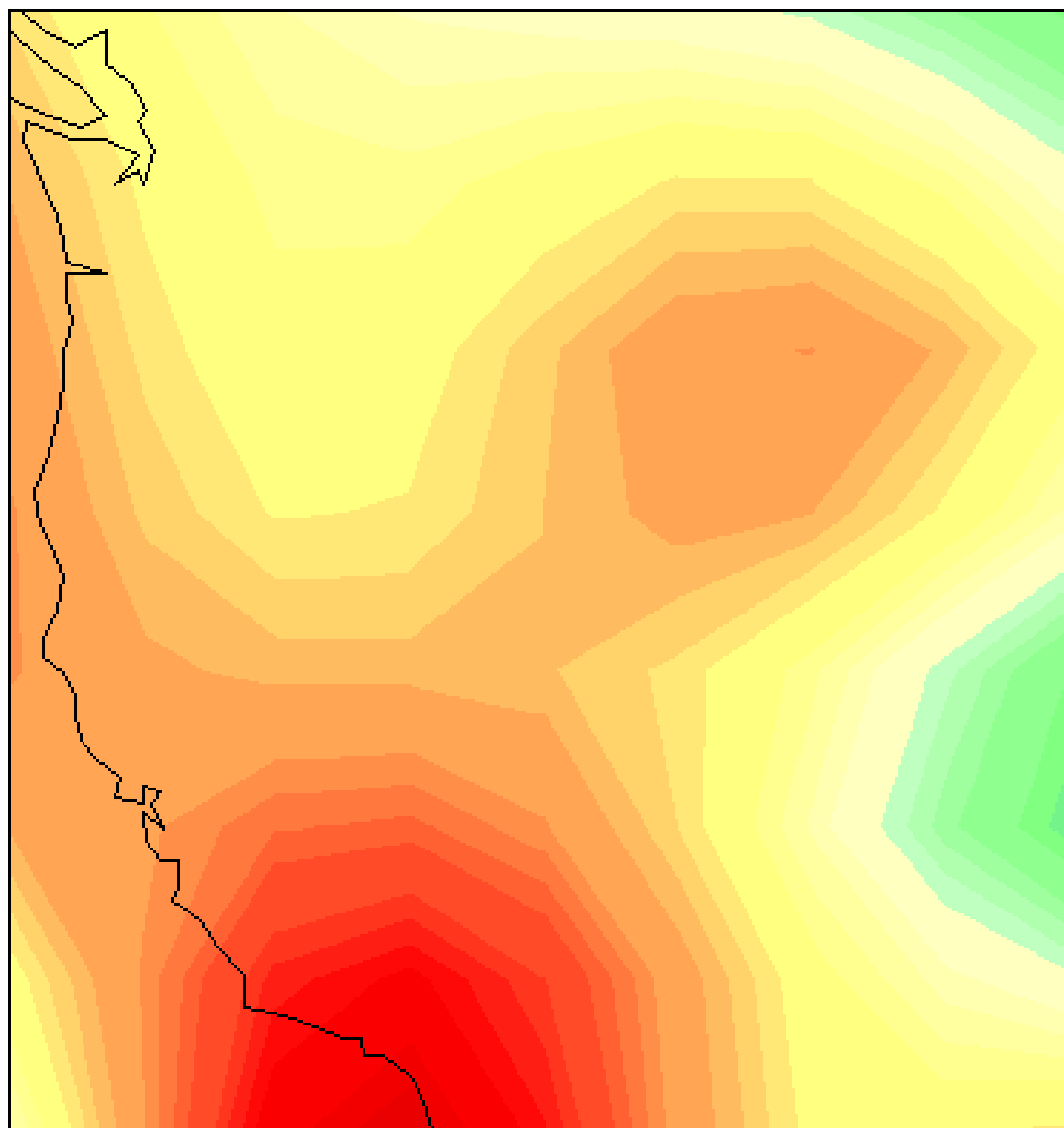
Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

JJA 4000ft



Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

0.4

0.3

0.2

0.1

0

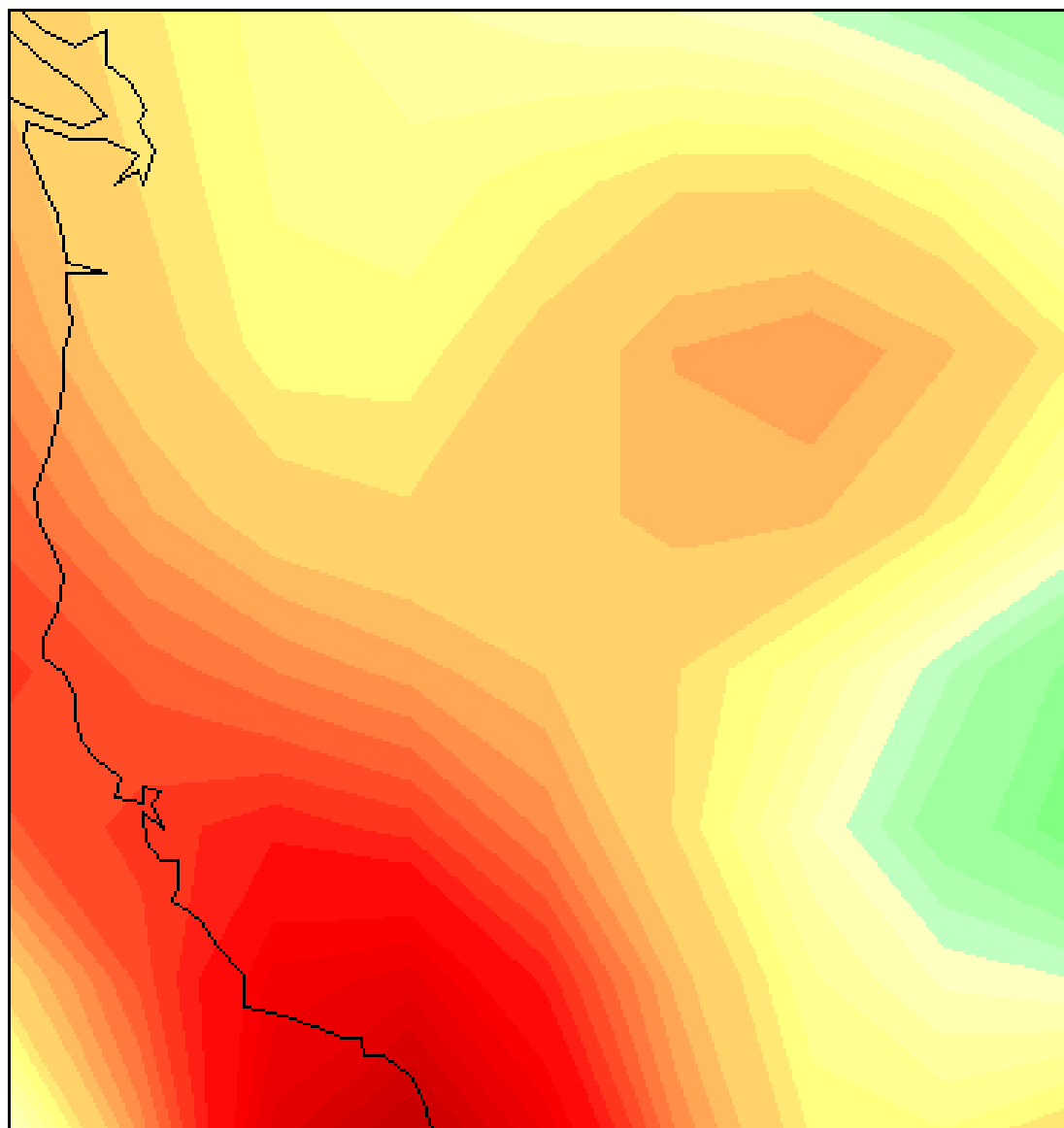
-0.1

-0.2

-0.3

-0.4

JJA 5000ft



Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

0.4

0.3

0.2

0.1

0

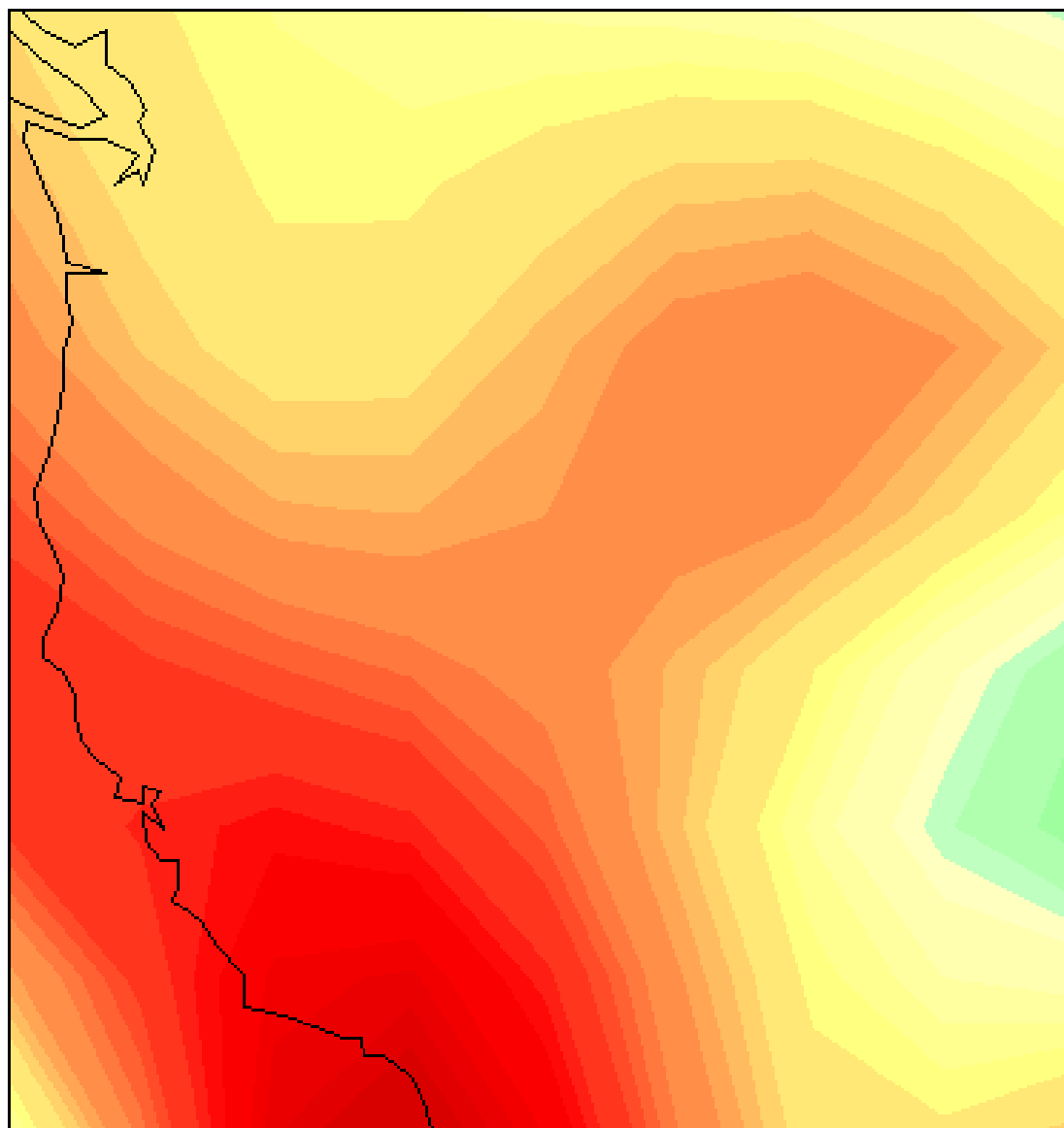
-0.1

-0.2

-0.3

-0.4

JJA 6000ft



Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

0.4

0.3

0.2

0.1

0

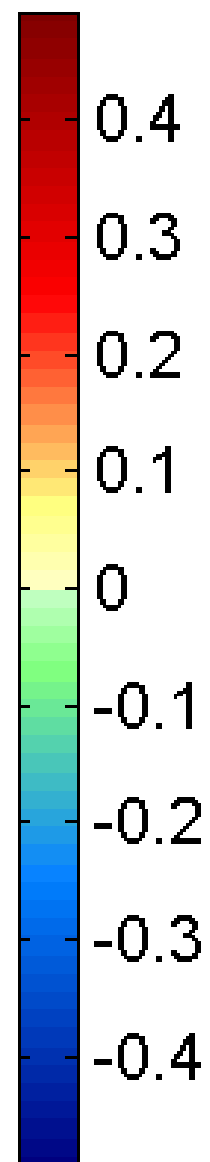
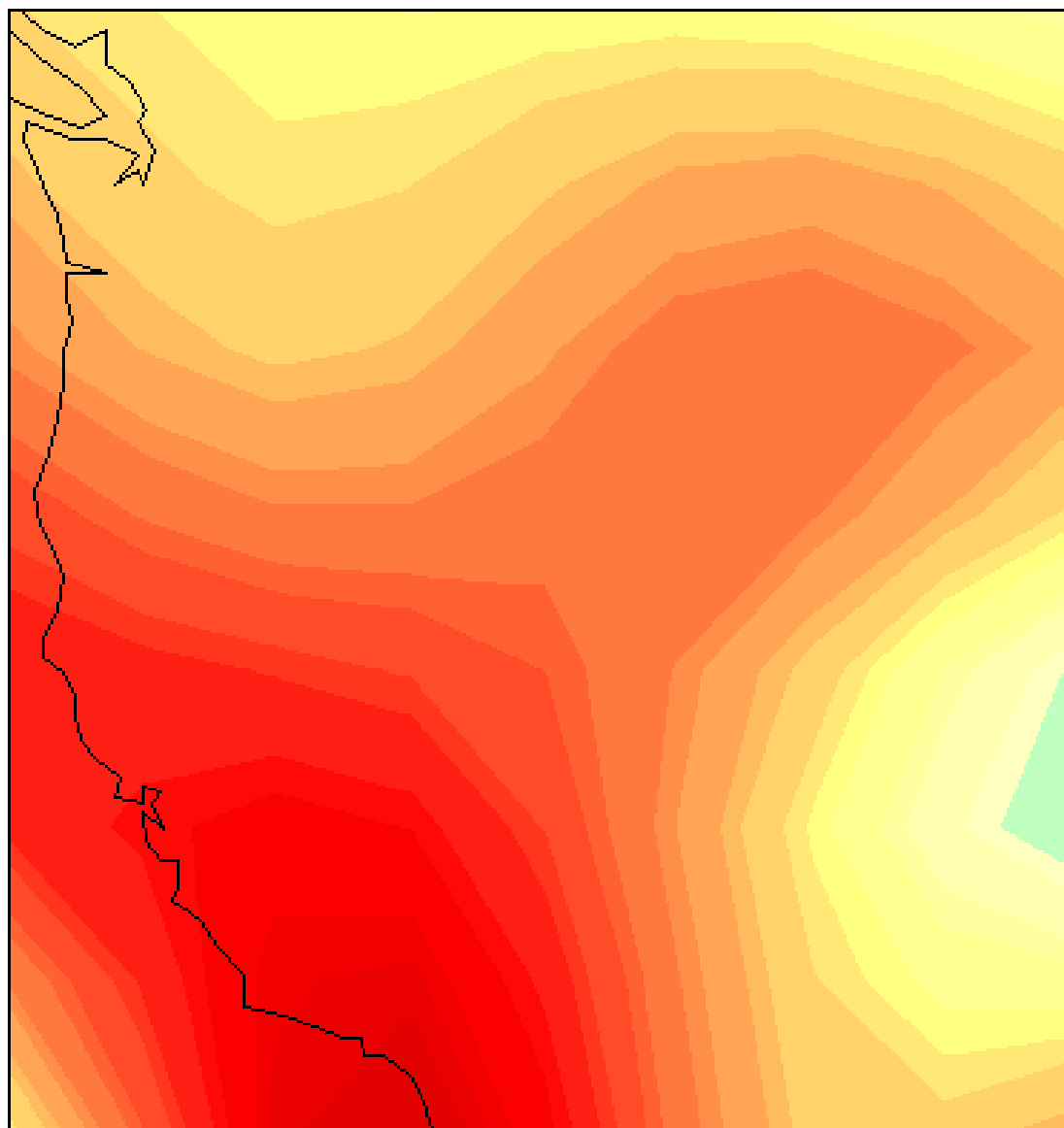
-0.1

-0.2

-0.3

-0.4

JJA 7000ft



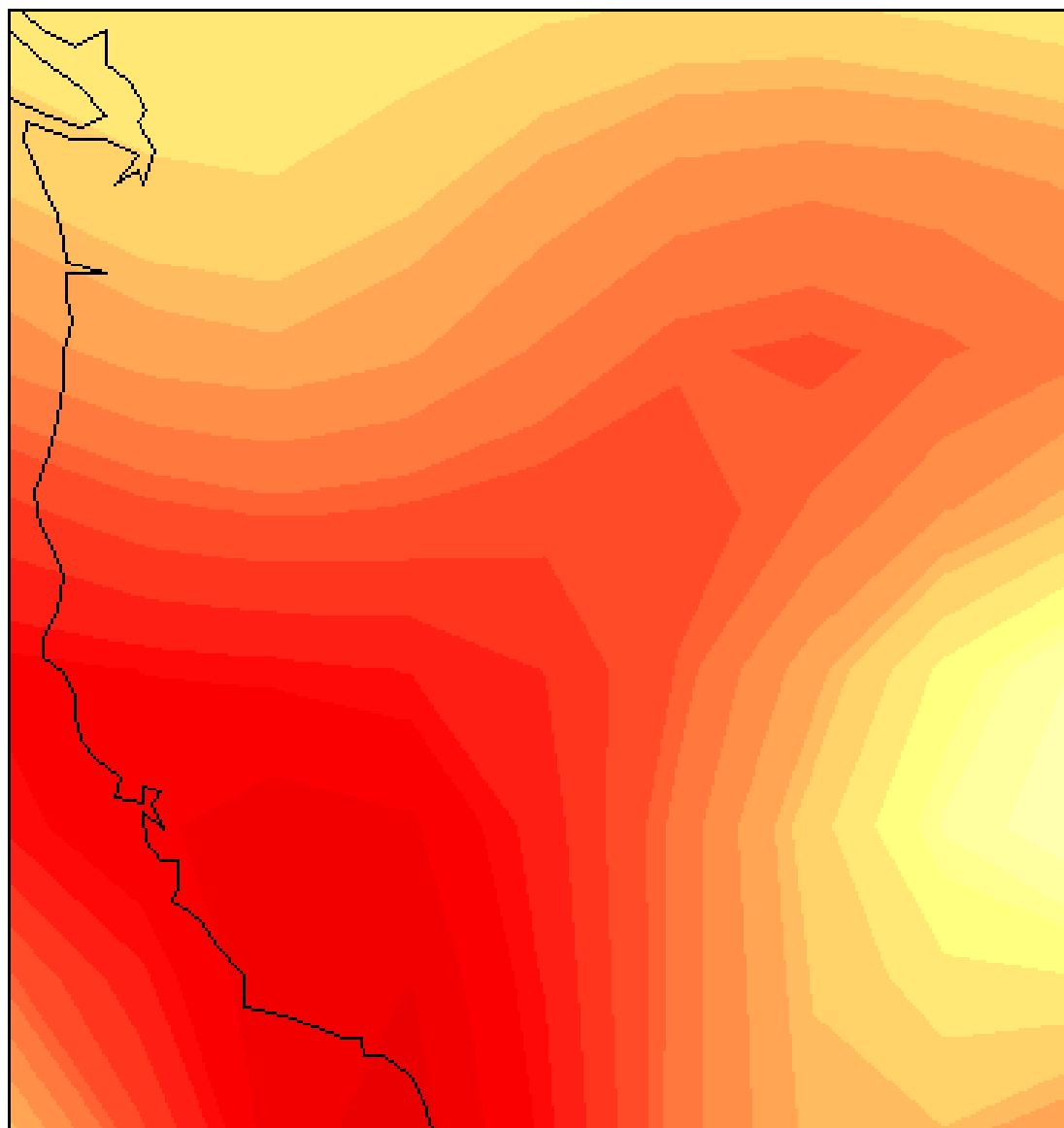
Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

JJA 8000ft



Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

0.4

0.3

0.2

0.1

0

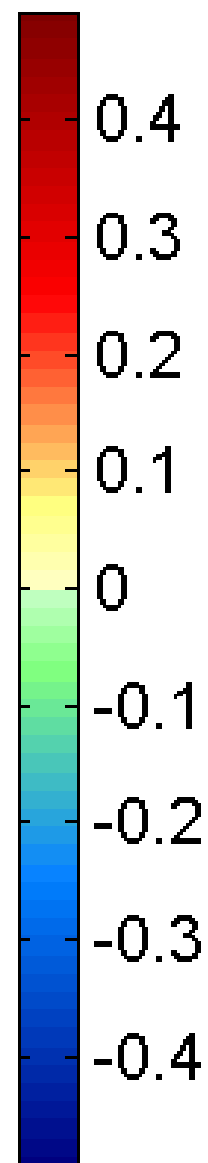
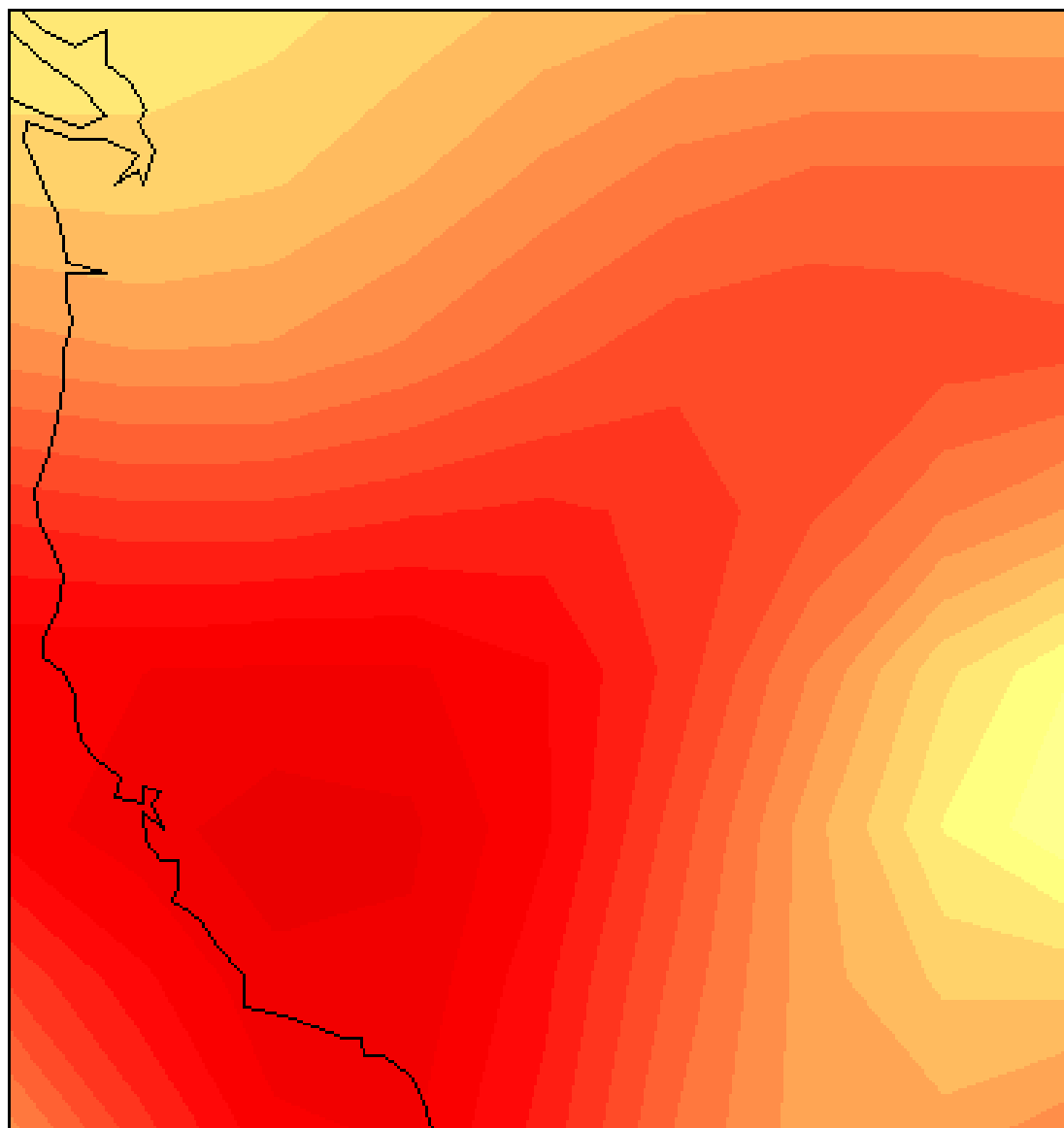
-0.1

-0.2

-0.3

-0.4

JJA 9000ft



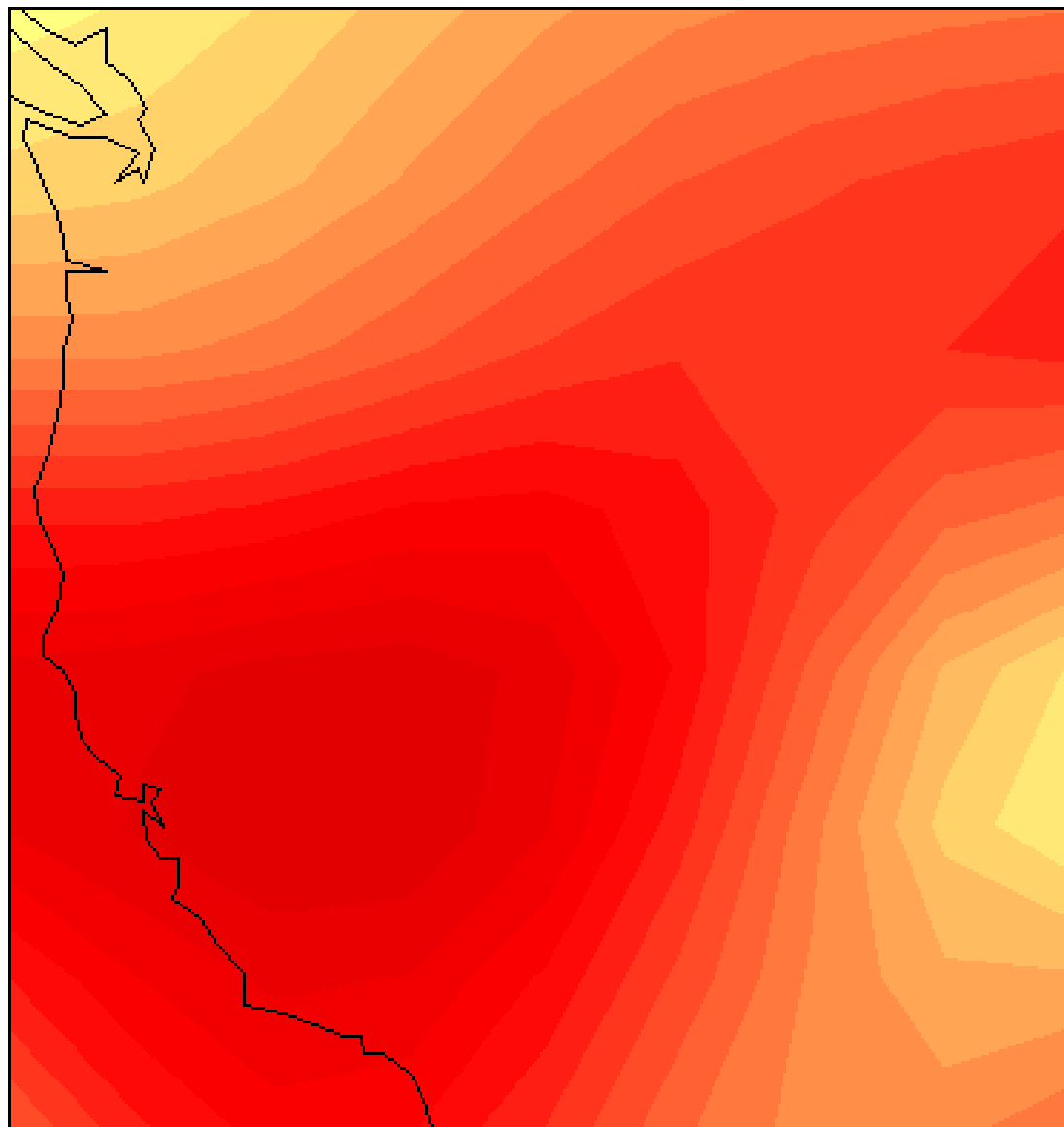
Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

JJA 10000ft



Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

0.4

0.3

0.2

0.1

0

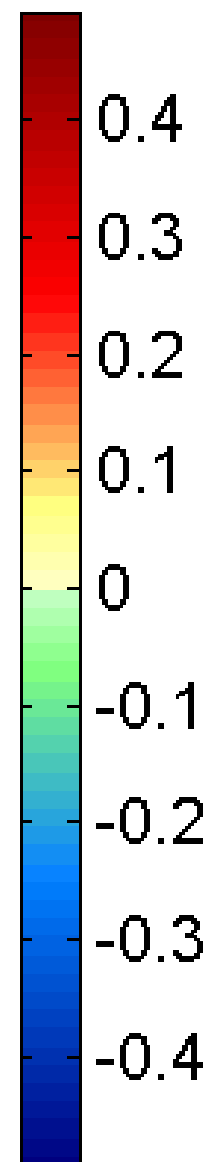
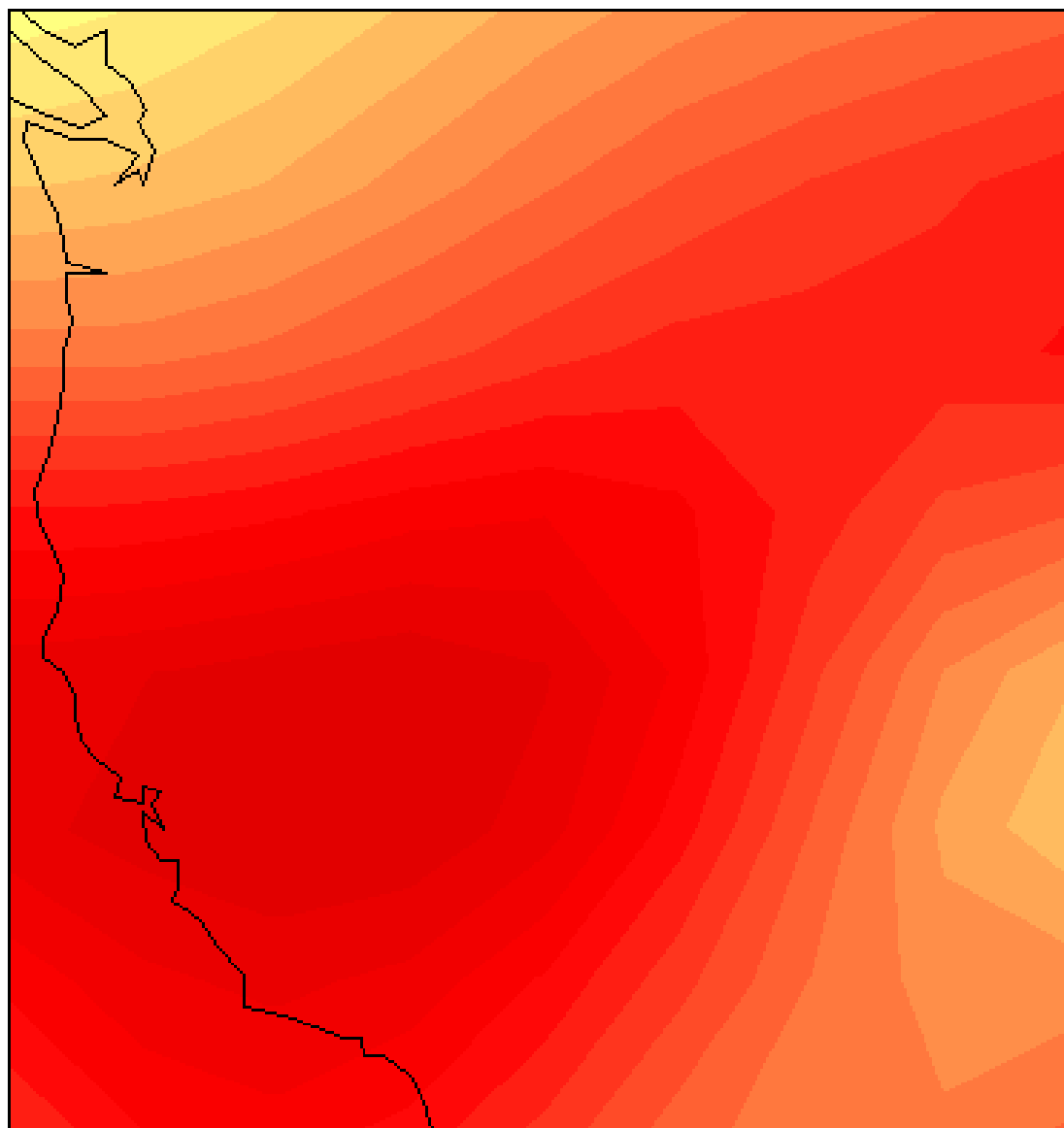
-0.1

-0.2

-0.3

-0.4

JJA 11000ft



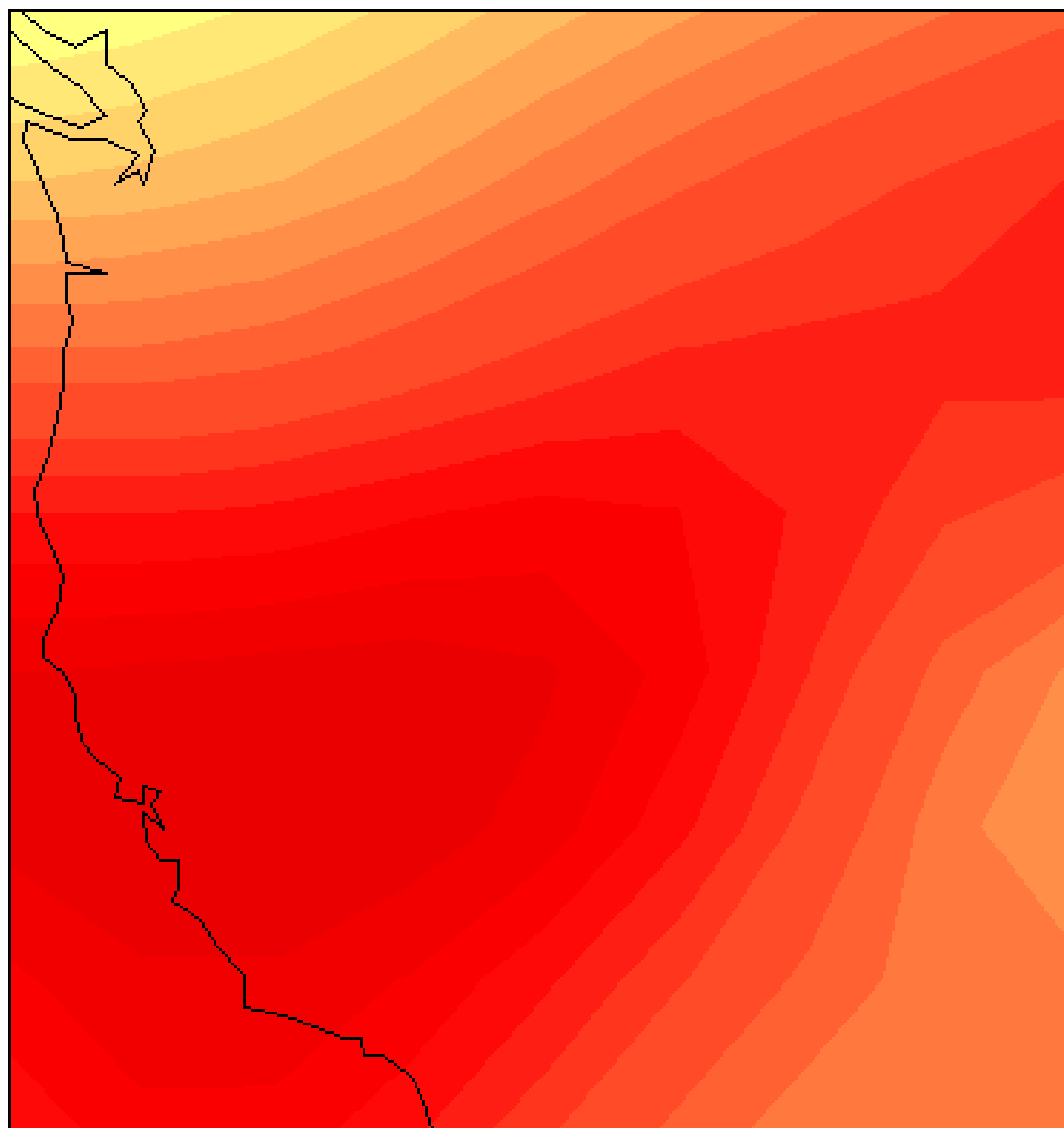
Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

JJA 12000ft



Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

0.4

0.3

0.2

0.1

0

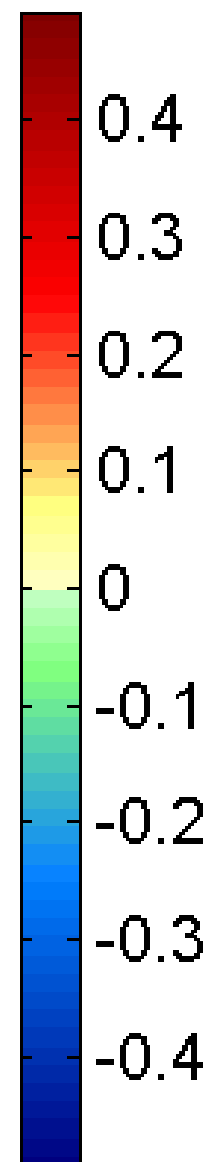
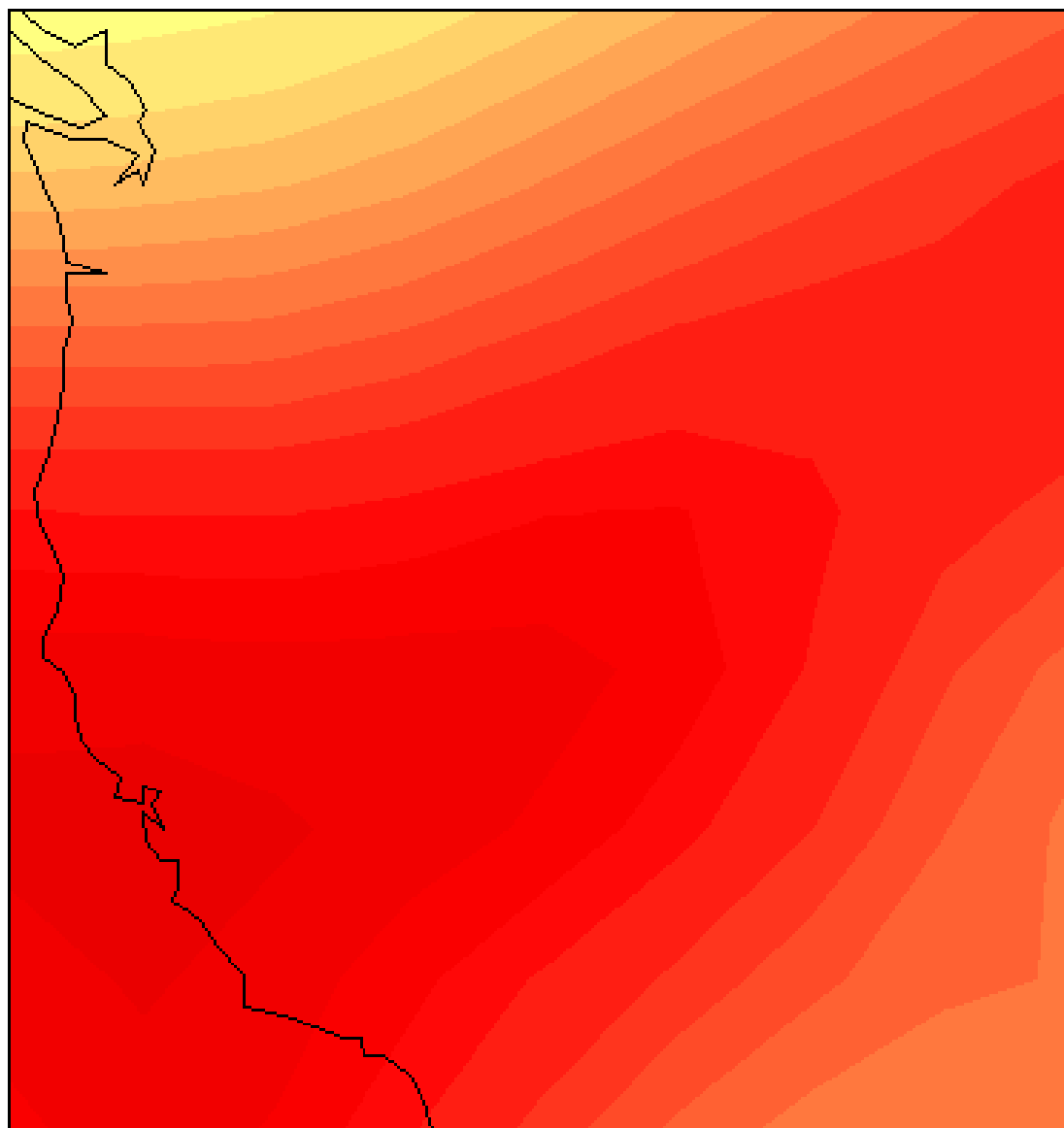
-0.1

-0.2

-0.3

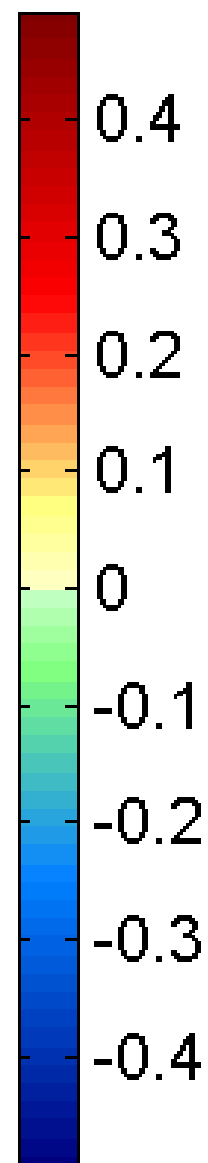
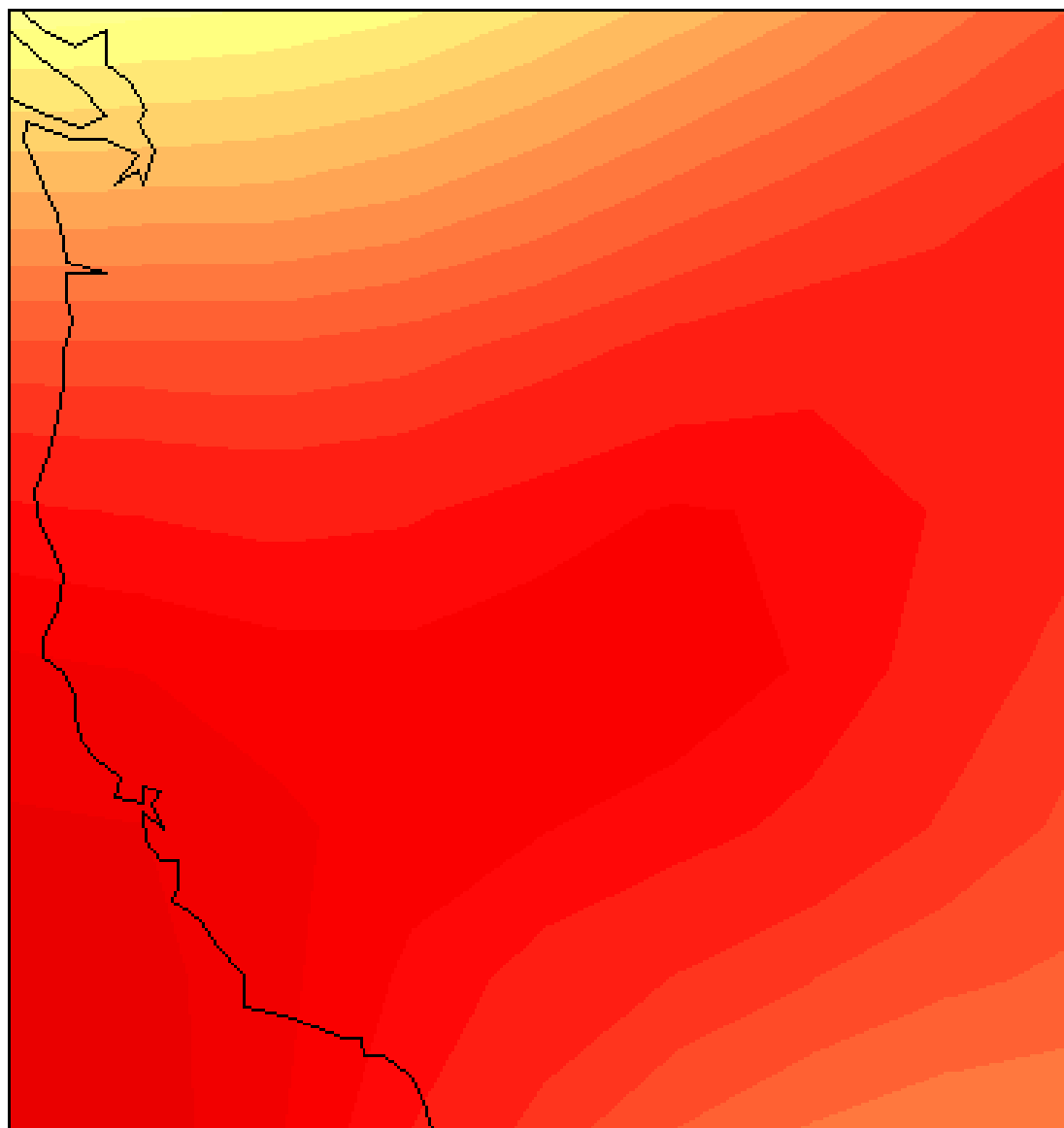
-0.4

JJA 13000ft



Summer
(JJA)
Trend in
temperature.
1949-2007.
NCEP
Reanalysis
Units
Deg C /
Decade

JJA 14000ft



Summer
(JJA)
Trend in
temperature.

1949-2007.

NCEP
Reanalysis

Units
Deg C /
Decade

JJA Western US Temperature Trends (1958-2007)

Summer
(JJA)
Trend in
temperature.

1949-2007.

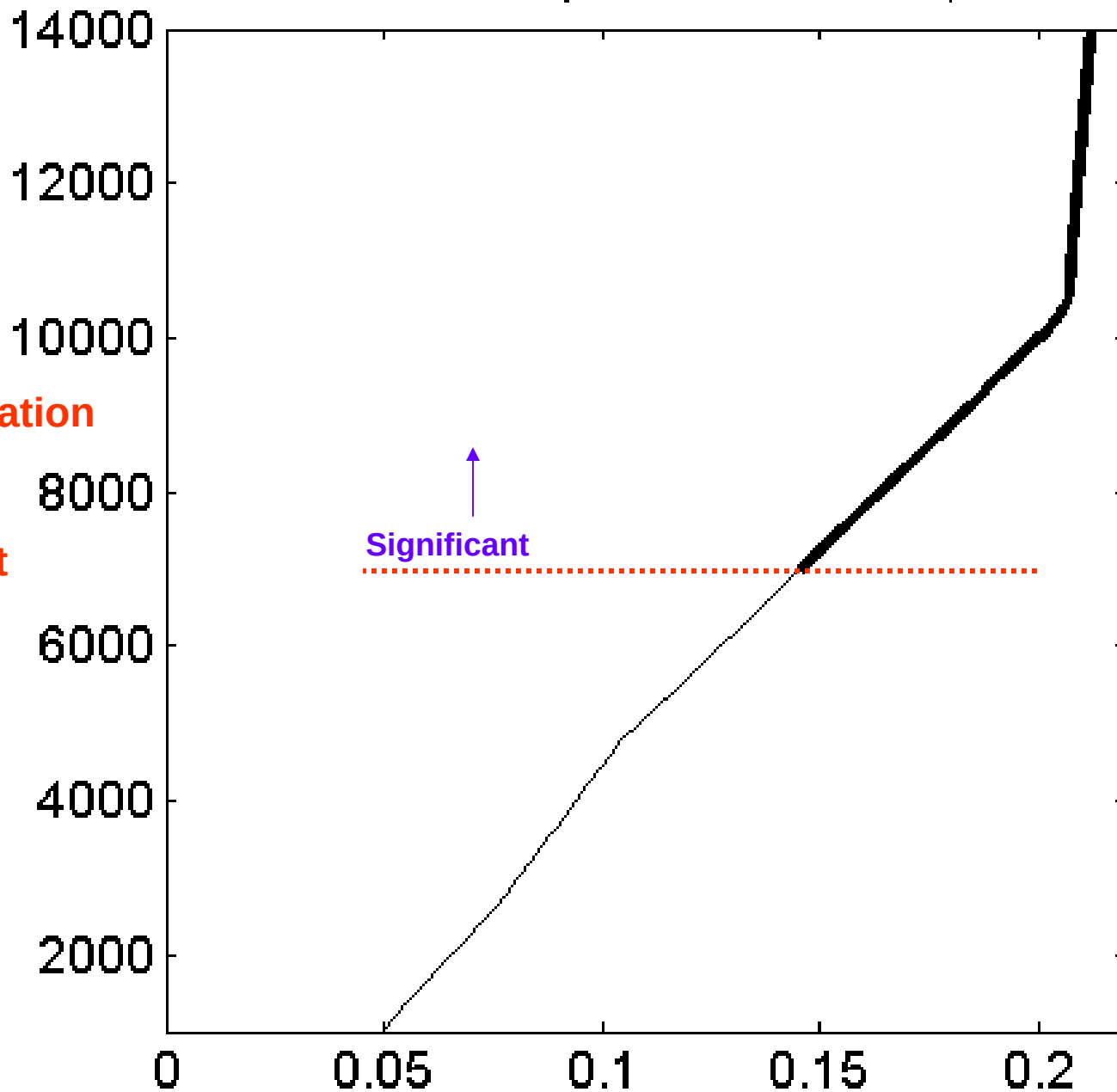
NCEP
Reanalysis

Elevation

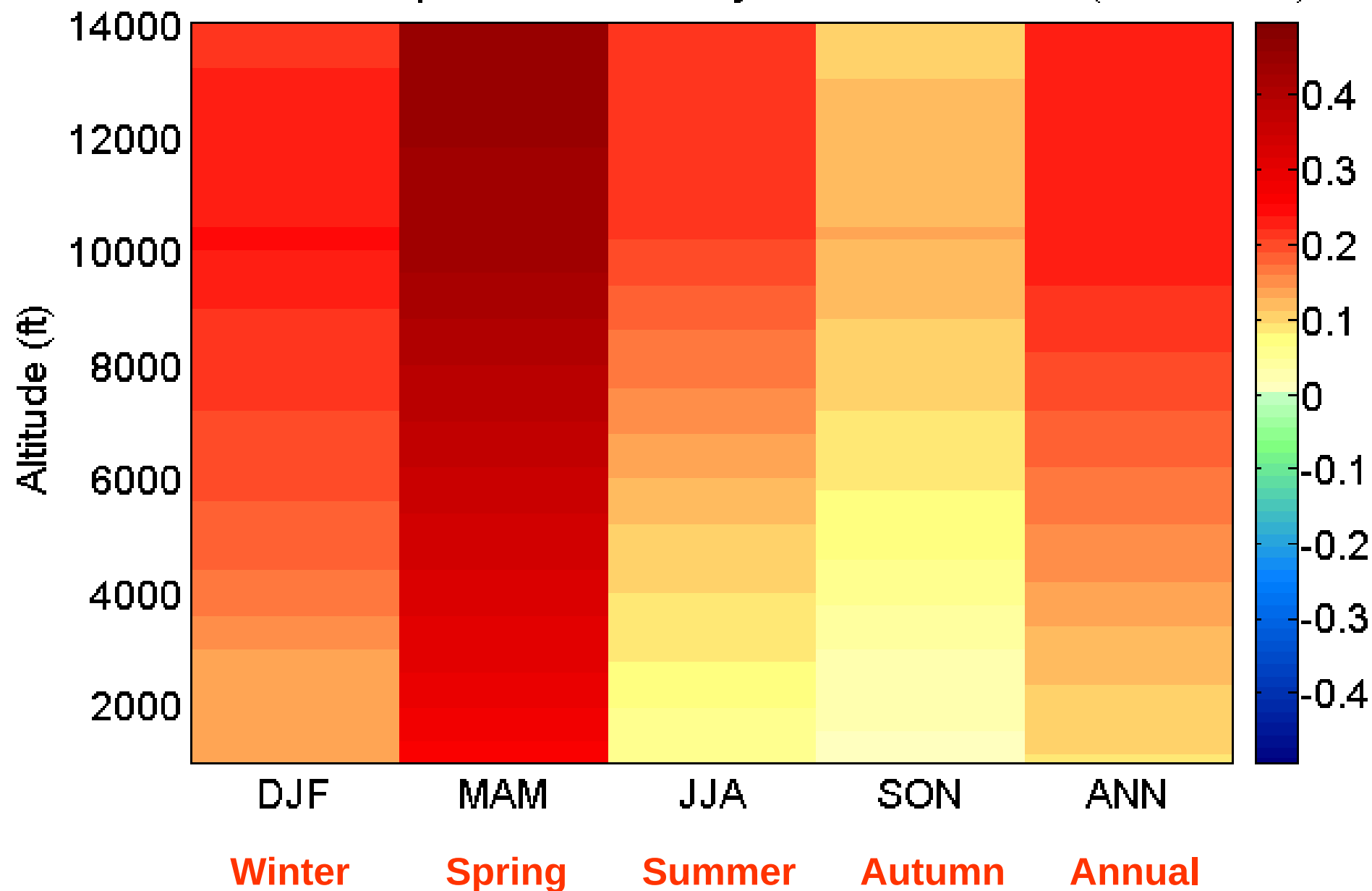
Feet

Significant

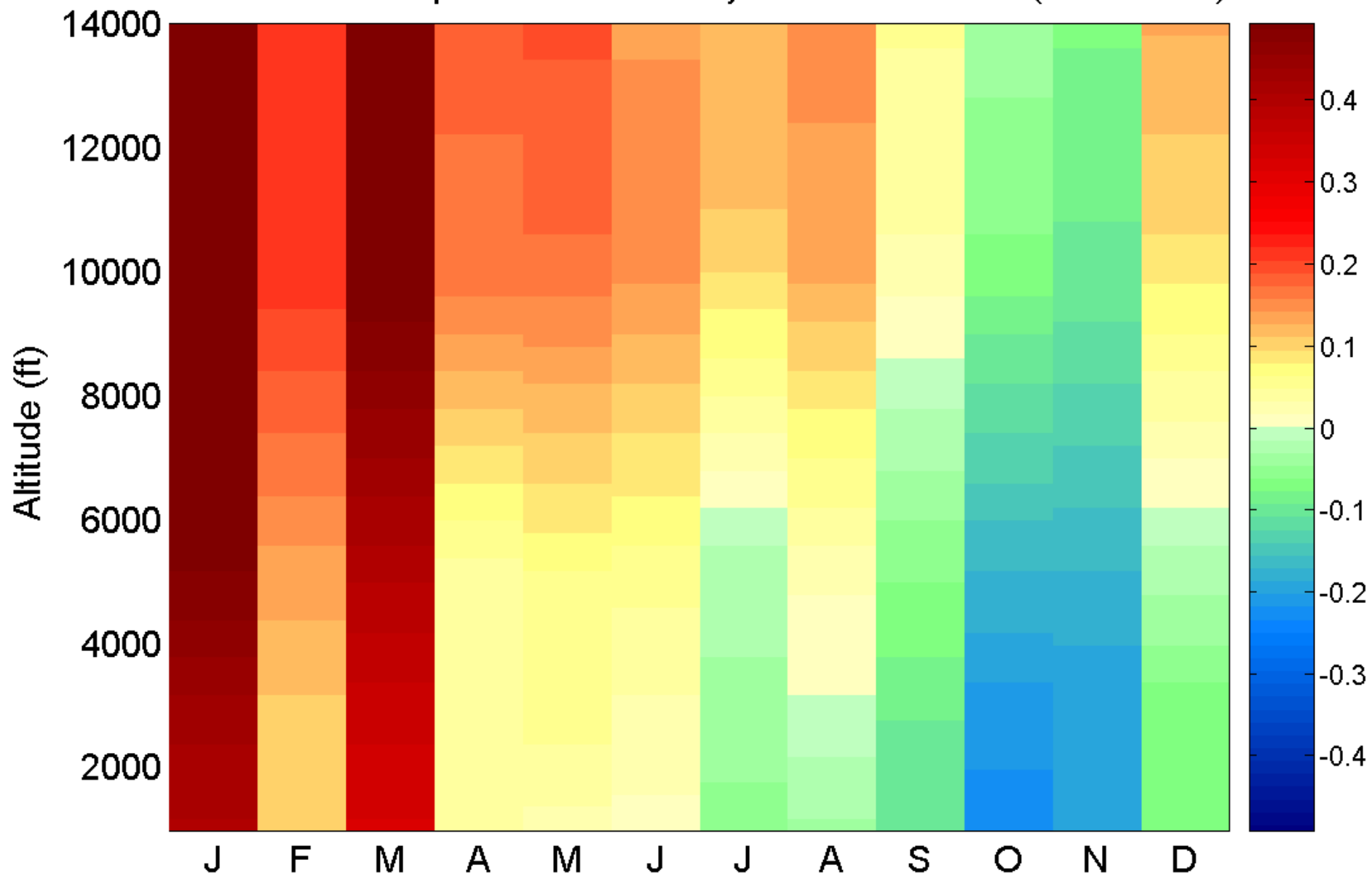
Degrees C / Decade



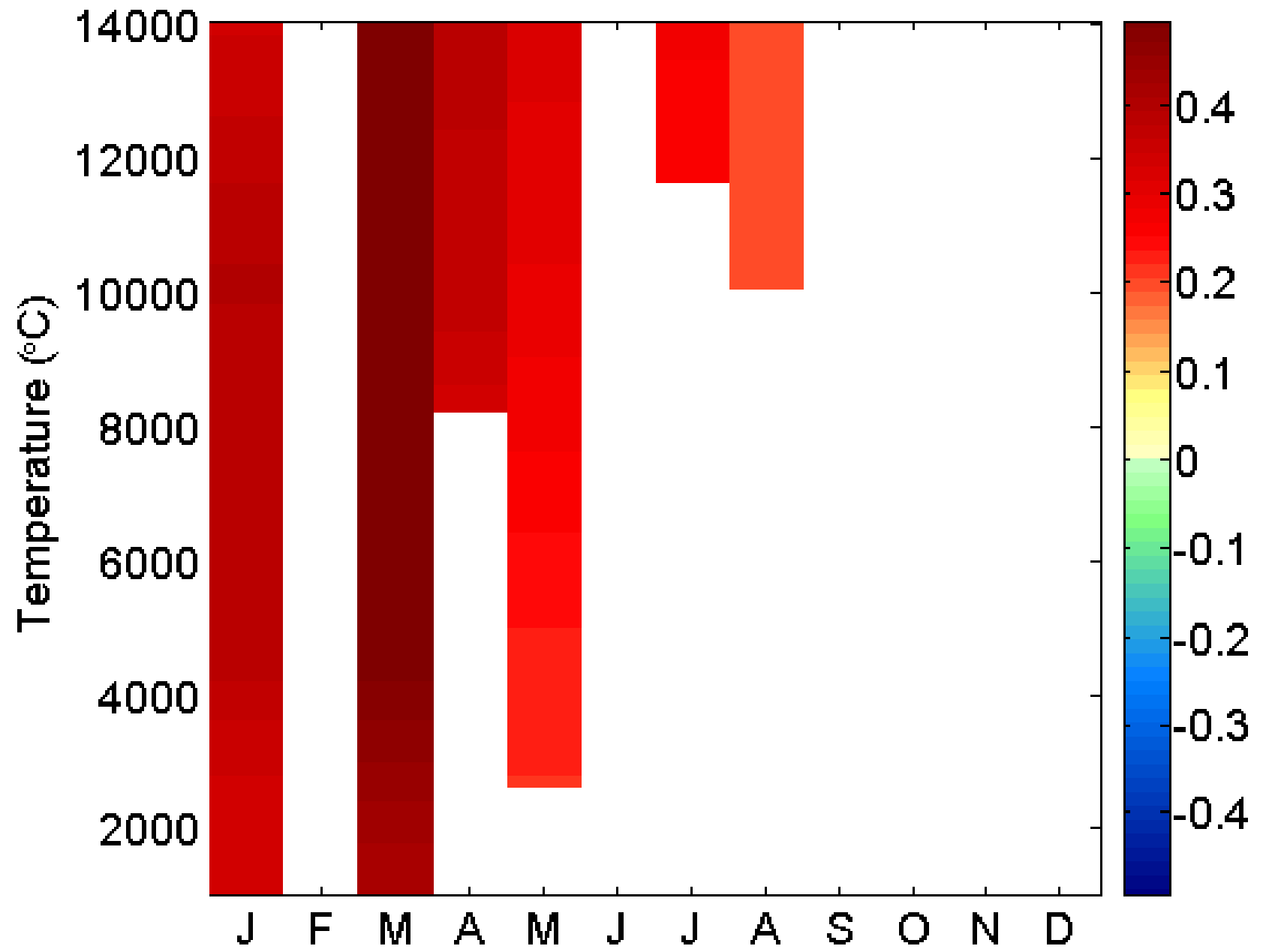
Western US Temperature Trends by Season & Altitude (1958-2007)



Western US Temperature Trends by Month & Altitude (1949-2007)



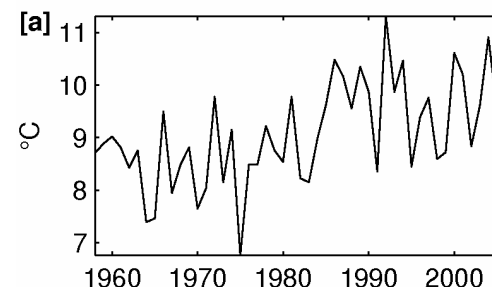
Western US Temperature Trends by Elevation (1958-2007) ... Kendall-Tau Significant



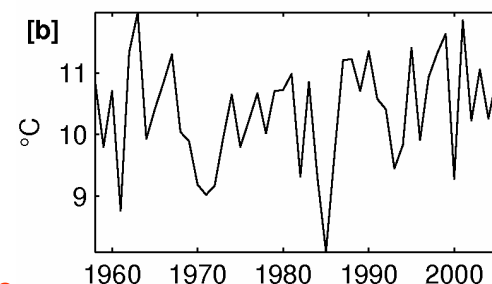
The Asymmetric Warming of Western US Spring and Autumn

Linear Trend per decade 1958-2006

Winter	+0.26	Deg C / Decade
Spring	+0.28	
Summer	+0.16	
Autumn	+0.07	



Spring
+0.28



Autumn
+0.07

Models project similar warming for Spring and Autumn

Observations show much faster warming in Spring compared to Autumn

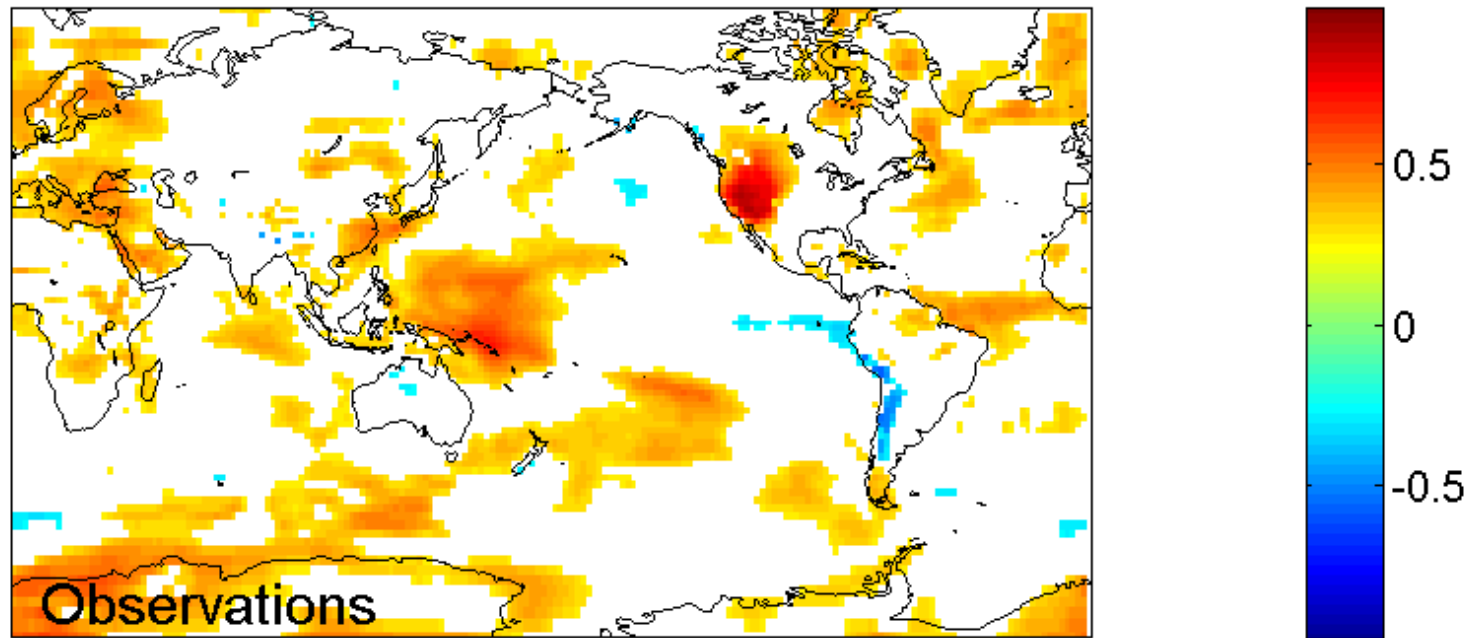
Changes in circulation patterns through time:

In Spring: Reinforce warming

In Autumn: Counteract warming

Abatzoglou, J. T., and K.T. Redmond, 2007. Asymmetry between trends in spring and autumn temperature and circulation regimes over western North America. Geophys. Res. Lett., Vol. 34, No. 18, L1880810.1029/2007GL030891 21 September 2007

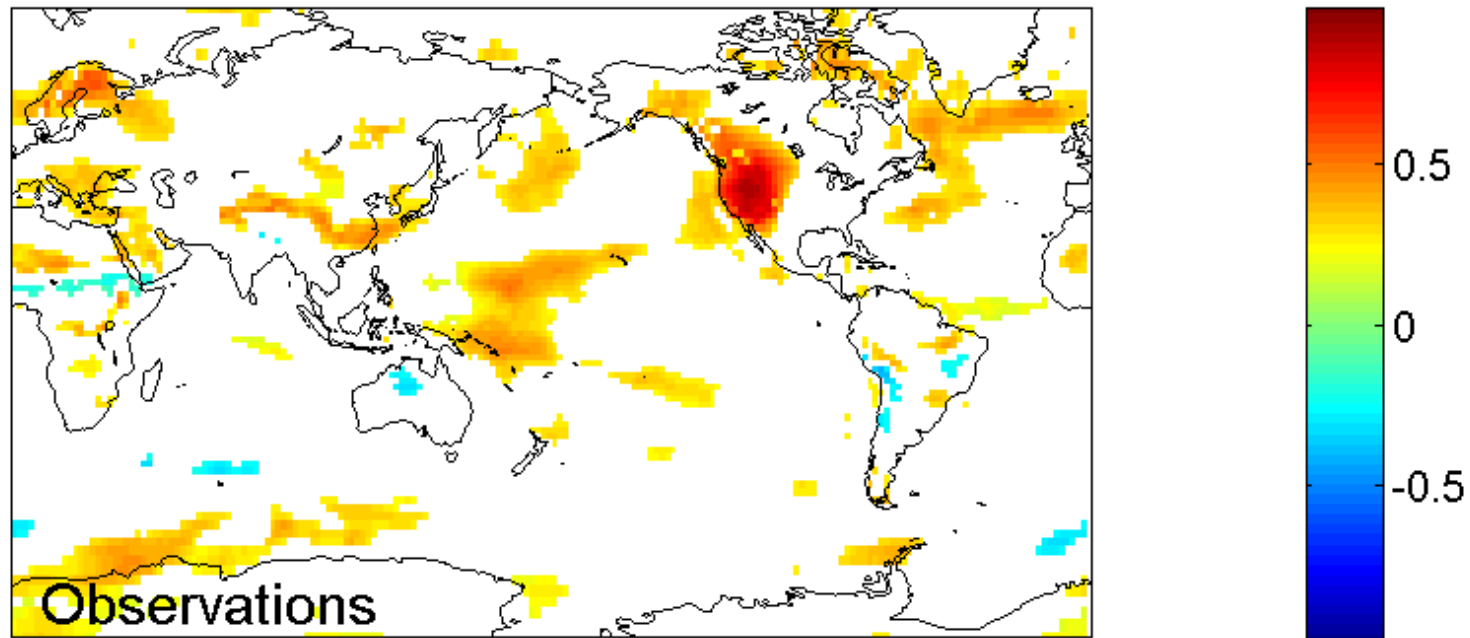
When summer is warm in the West, where else is it warm ?



Regression of summer mean air temperature on western
U.S. summer mean air temperature, 1949-2007.

Standardized time series. No time series filtering.

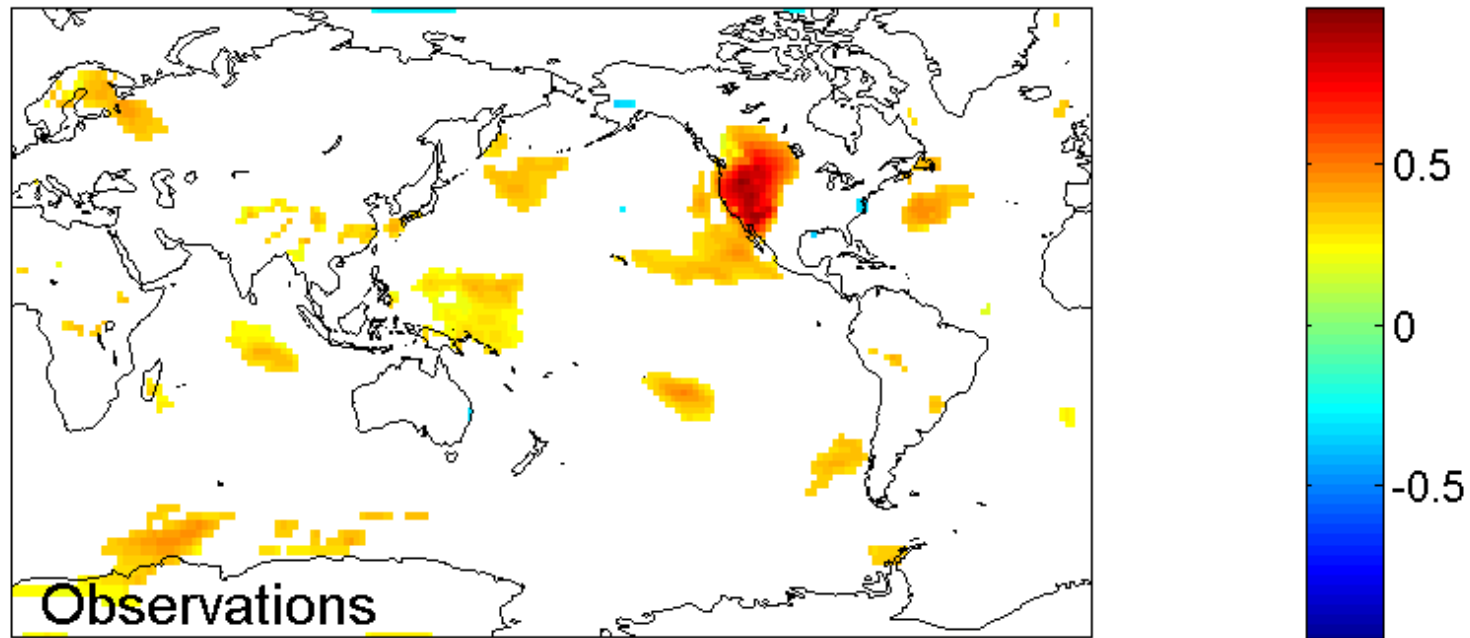
When summer is warm in the West, where else is it warm ?



Regression of summer mean air temperature on western U.S. summer mean air temperature, 1949-2007.

Standardized time series. Linear detrending applied.

When a year is warm in the West, where else is it warm ?

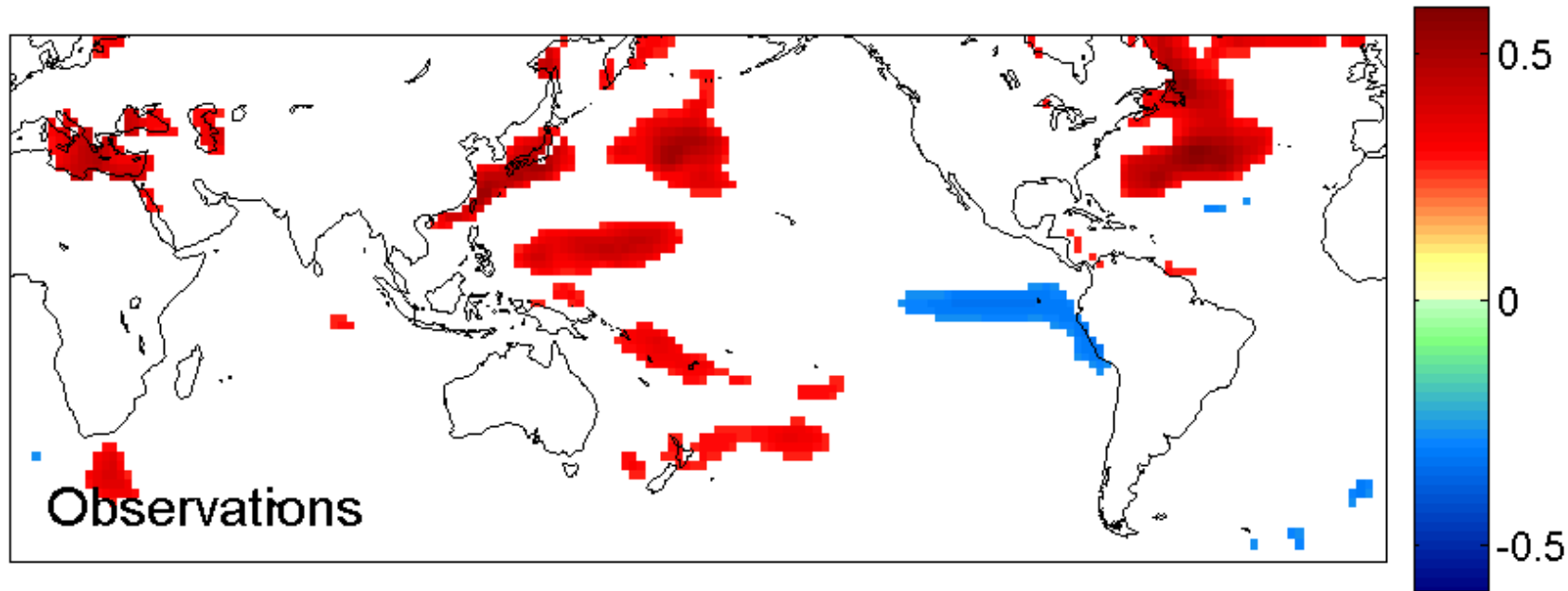


**Regression of summer mean air temperature on western
U.S. summer annual mean air temperature, 1949-2007.**

Standardized time series.

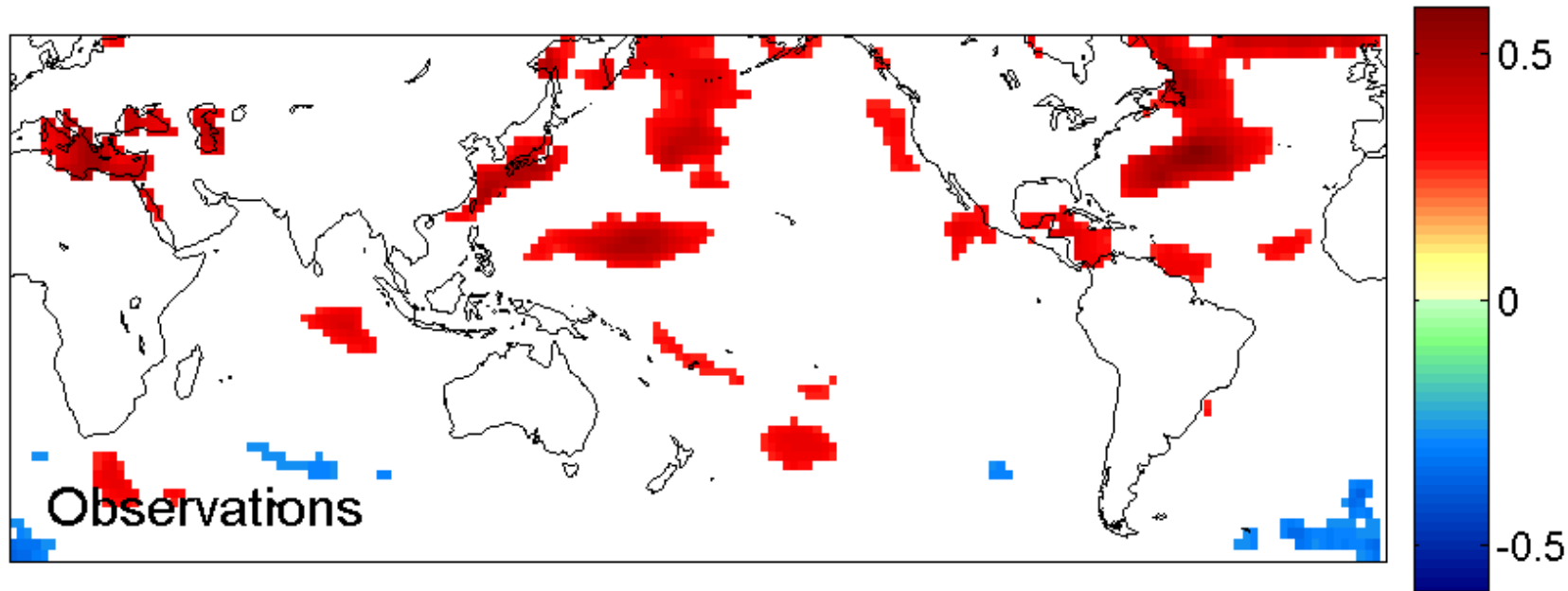
Highpass filter. Variability on 1 to 30 year time scale.

When summer is warm in the West, where is the ocean warm ?



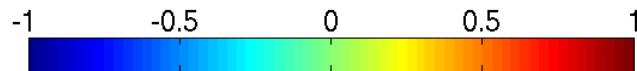
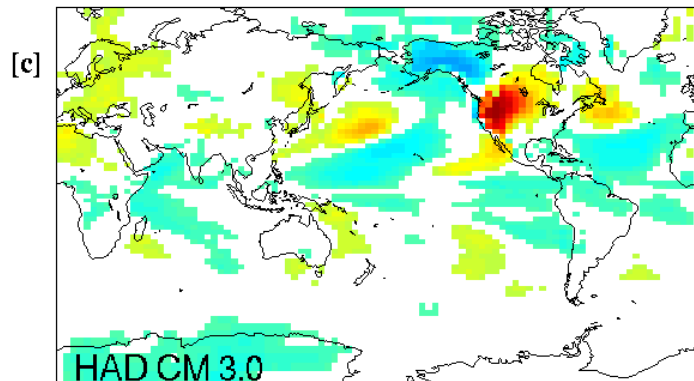
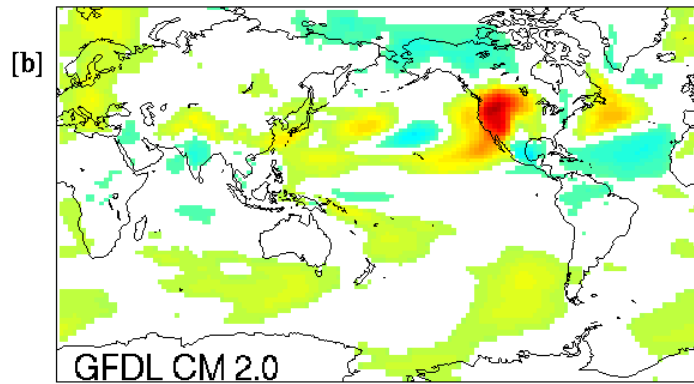
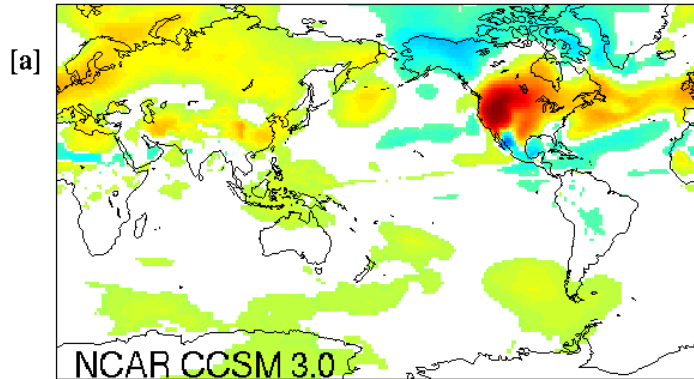
**Correlation of summer mean western U.S. temperature and global
sea surface temperature, 1949-2007, significant at 95 % level.
No filtering.**

When summer is warm in the West, where is the ocean warm ?



**Correlation of summer mean western U.S. temperature and global
sea surface temperature, 1949-2007, significant at 95 % level.
Linearly detrended time series.**

All frequencies (no bandpass)



Regression:

**500 year
model runs**

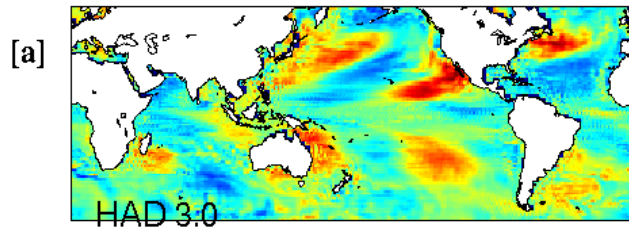
**Western US
annual
temperatures**

&

**Global annual
surface air
temperatures**

**Units are
standardized.**

Highpass (1 – 30 years)

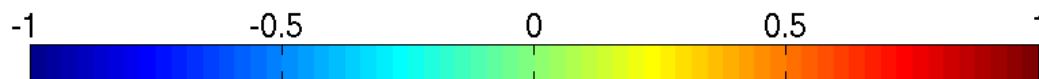
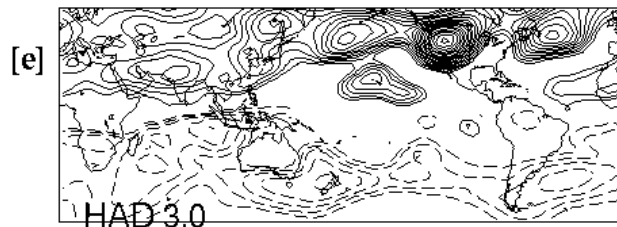
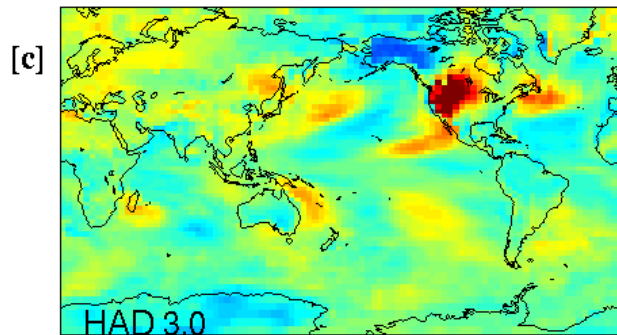


Regression

Western US Annual Temperature
and Hadley model

Standardized units

500 model years.

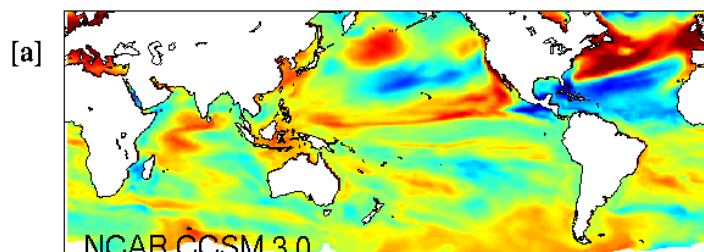


Annual
SST

Surface
T air
2 meter

300 mb
Stream-
function

Highpass (1 – 30 years)

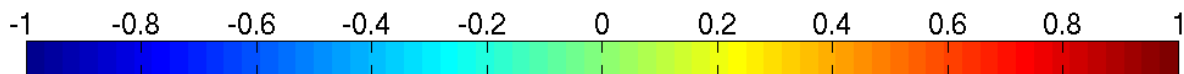
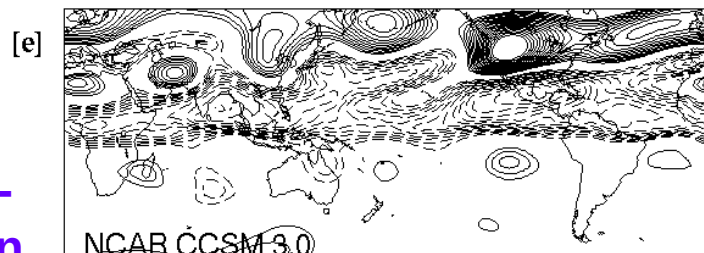
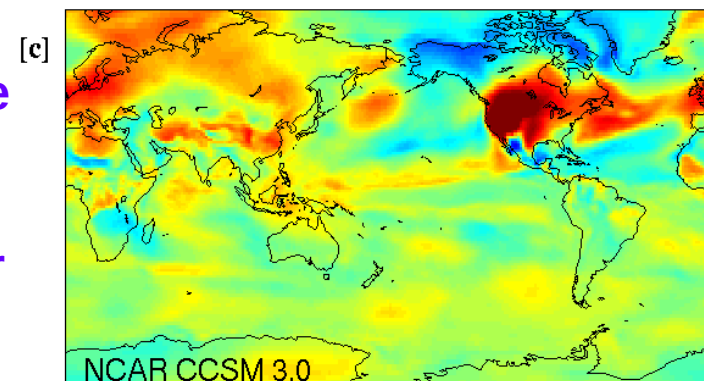


Regression

Western US Annual Temperature
and NCAR CCSM model

Standardized units.

500 model years.

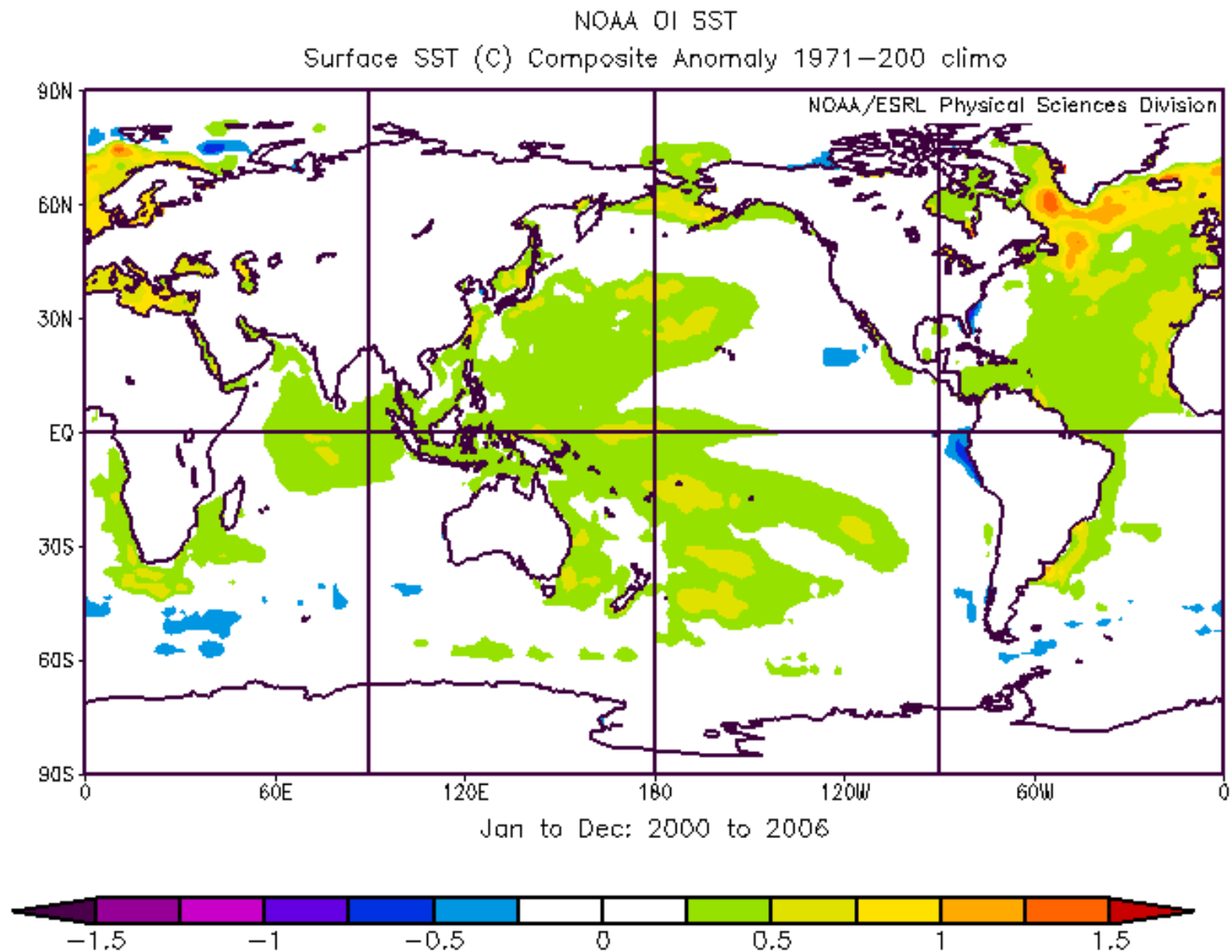


Annual
SST

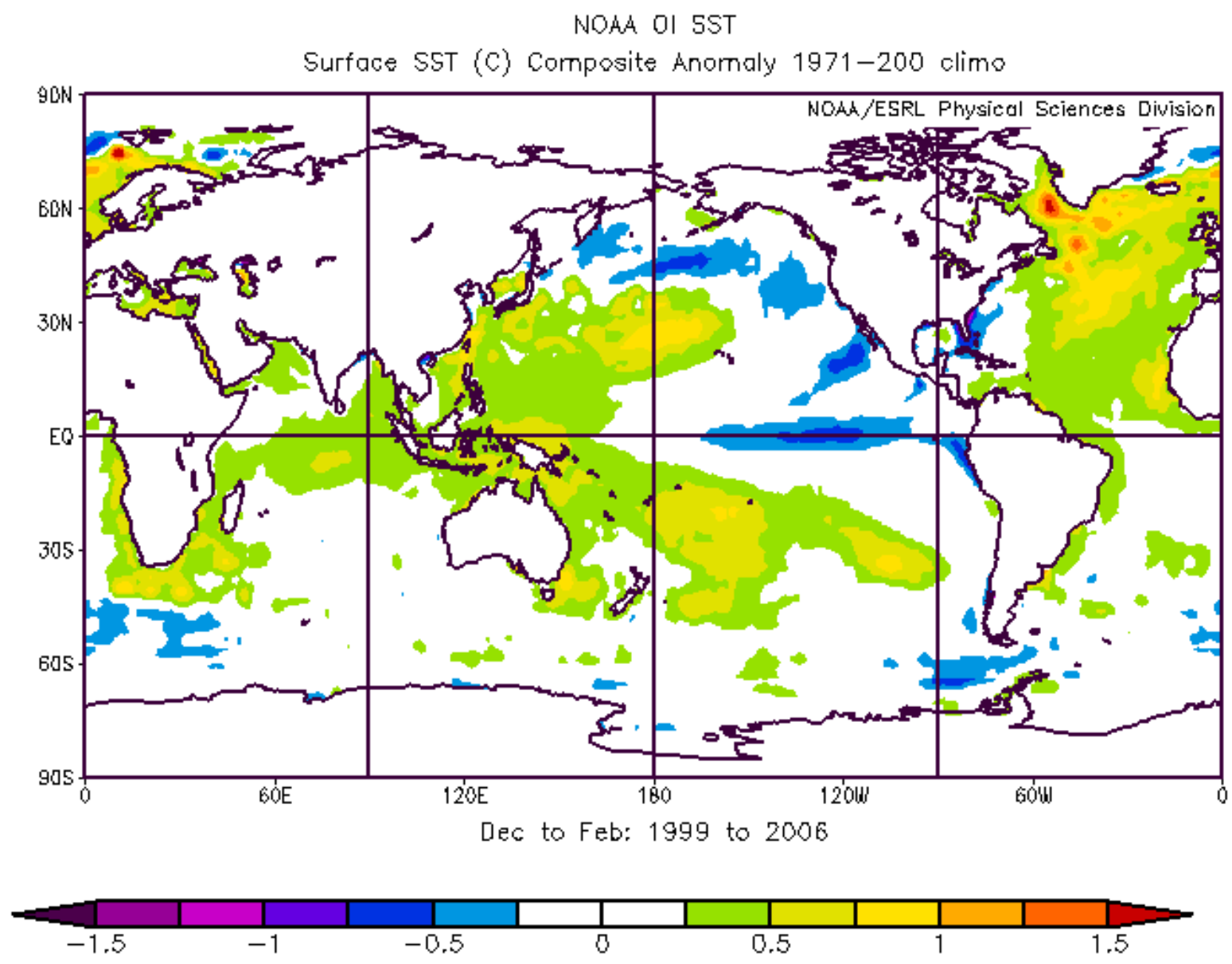
Surface
T air
2 meter

300 mb
Stream-
function

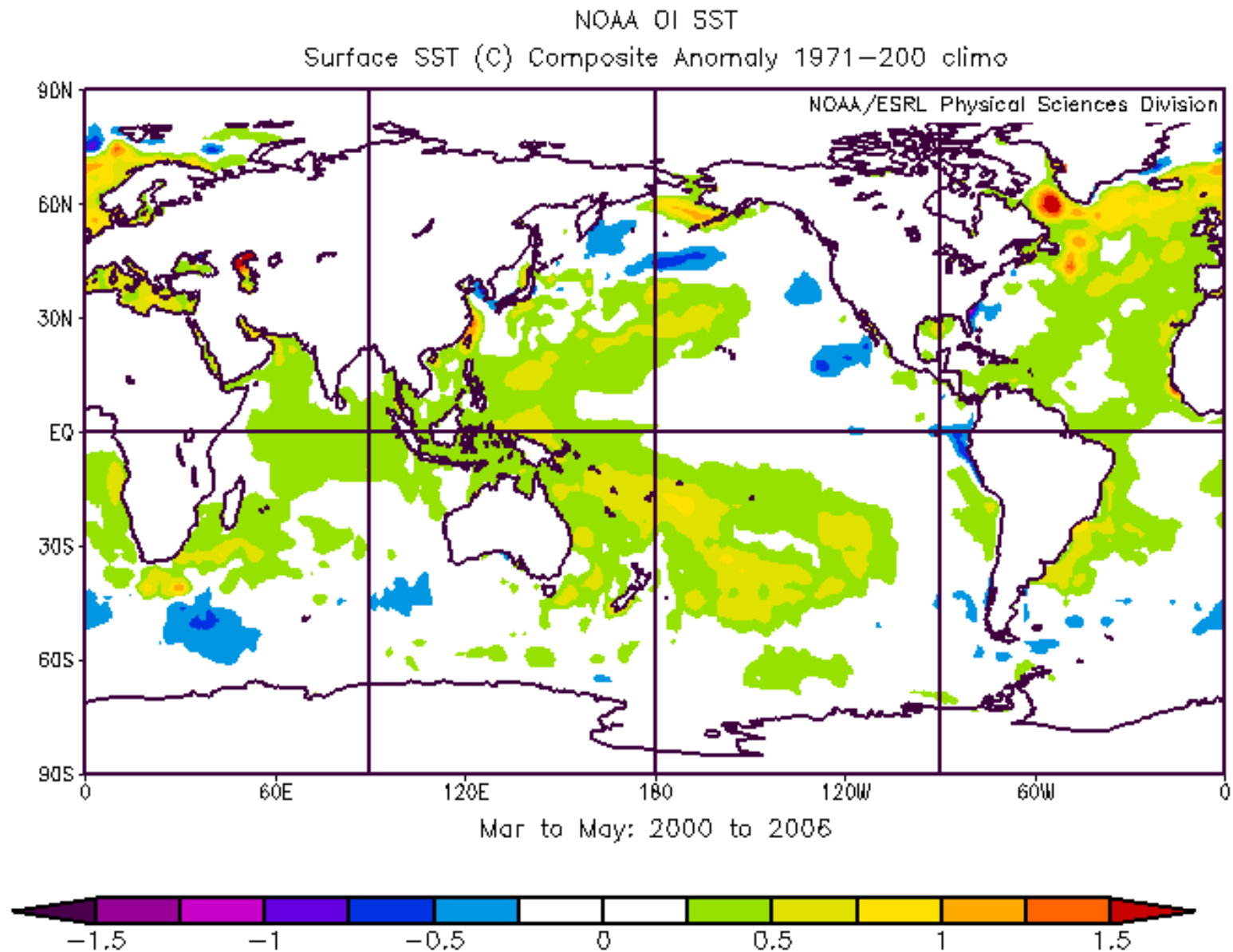
SST Departure from Climatology, Annual Jan-Dec, for 7 years 2000-2006.



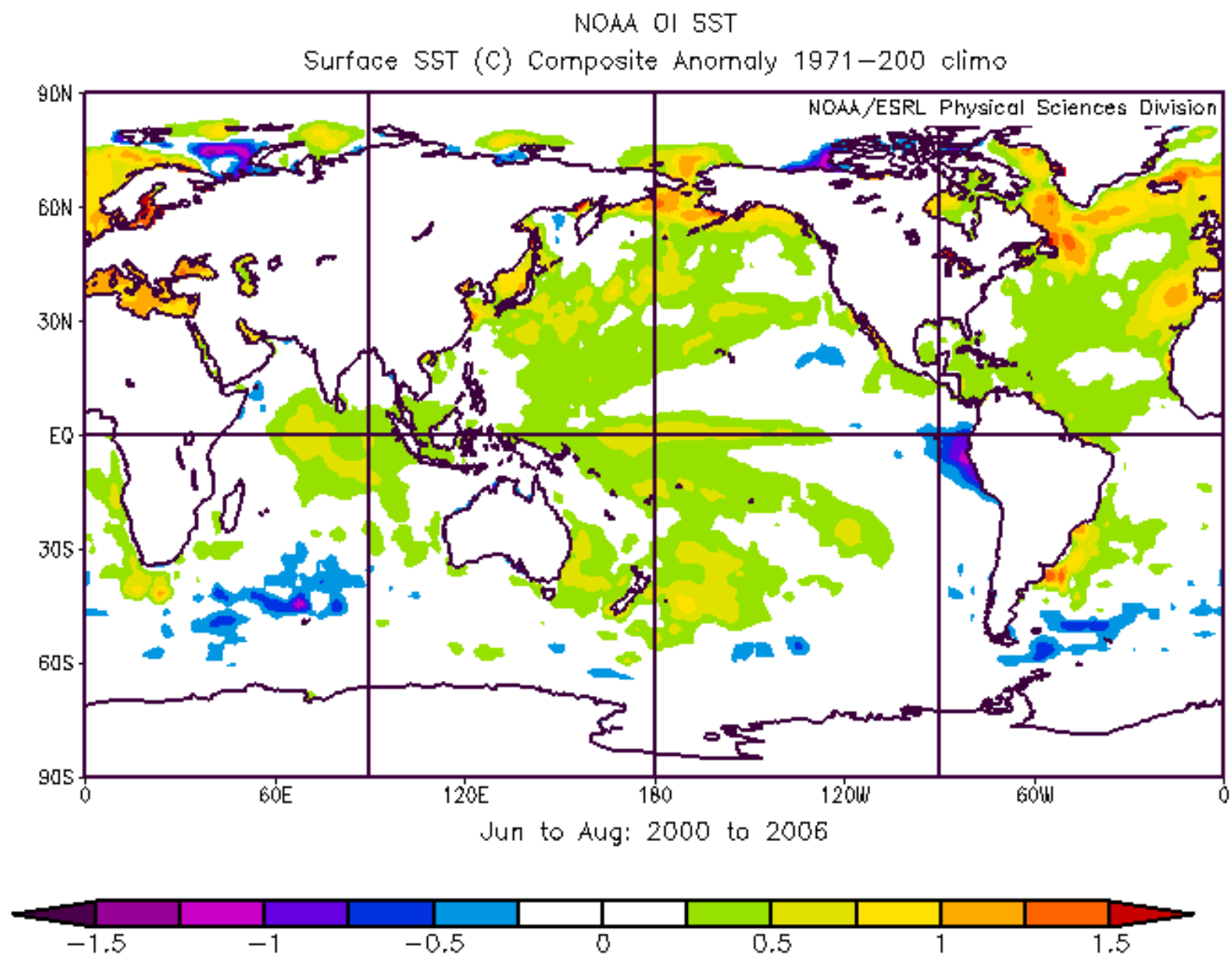
SST Departure from Climatology, Winter DJF, for 7 years 1999/2000 - 2005/2006.



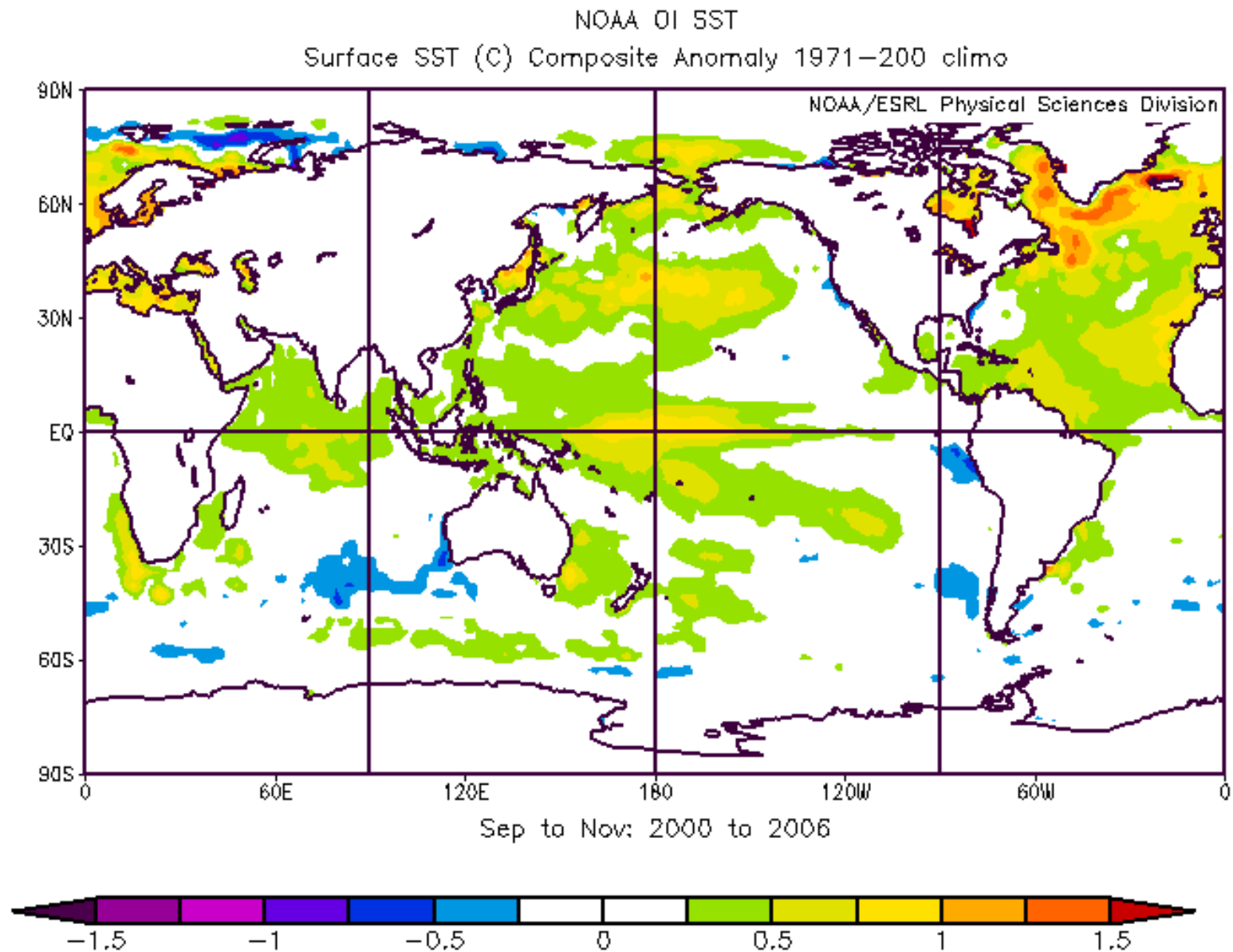
SST Departure from Climatology, Spring MAM, for 7 years 2000-2006.



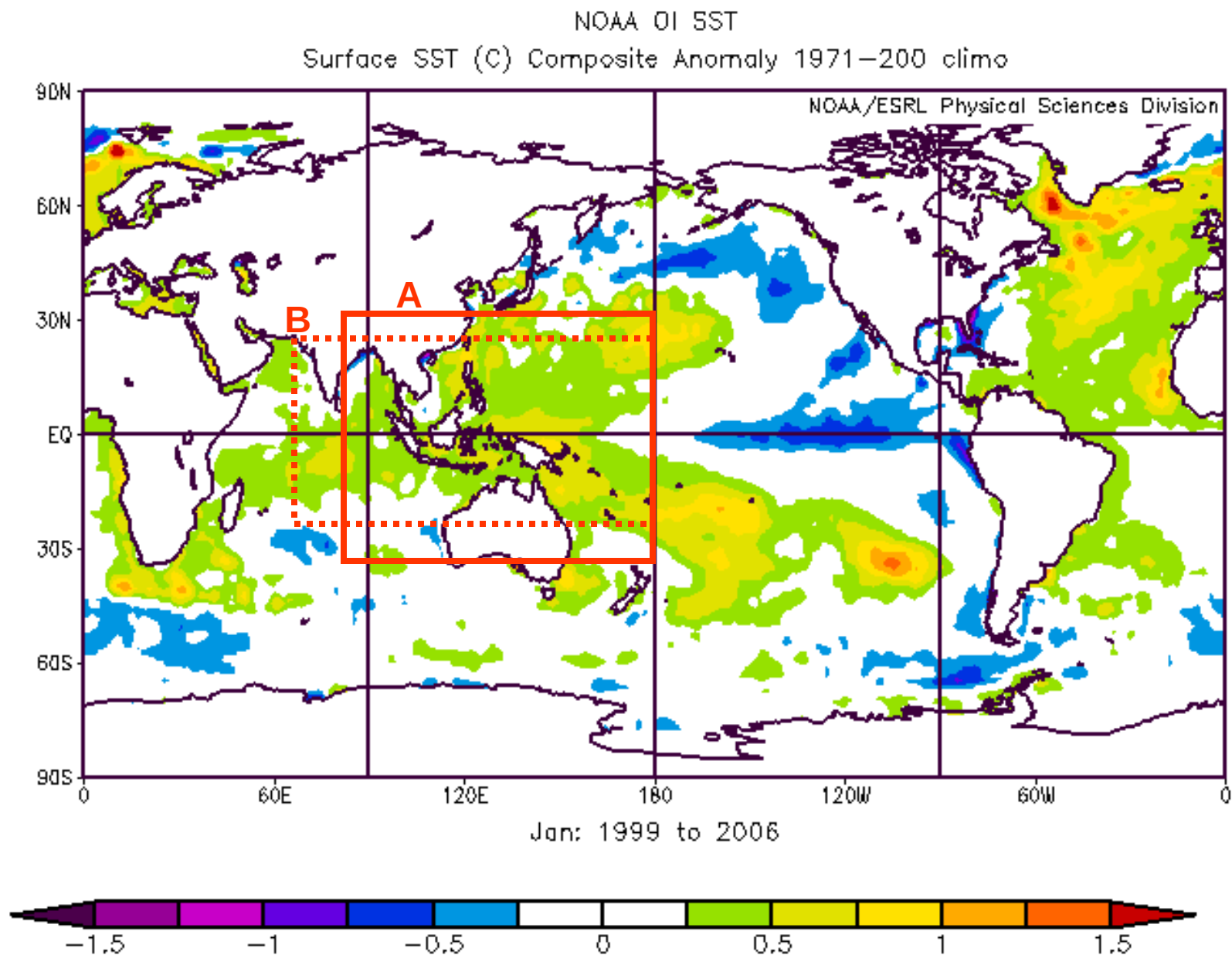
SST Departure from Climatology, Summer JJA, for 7 years 2000-2006.



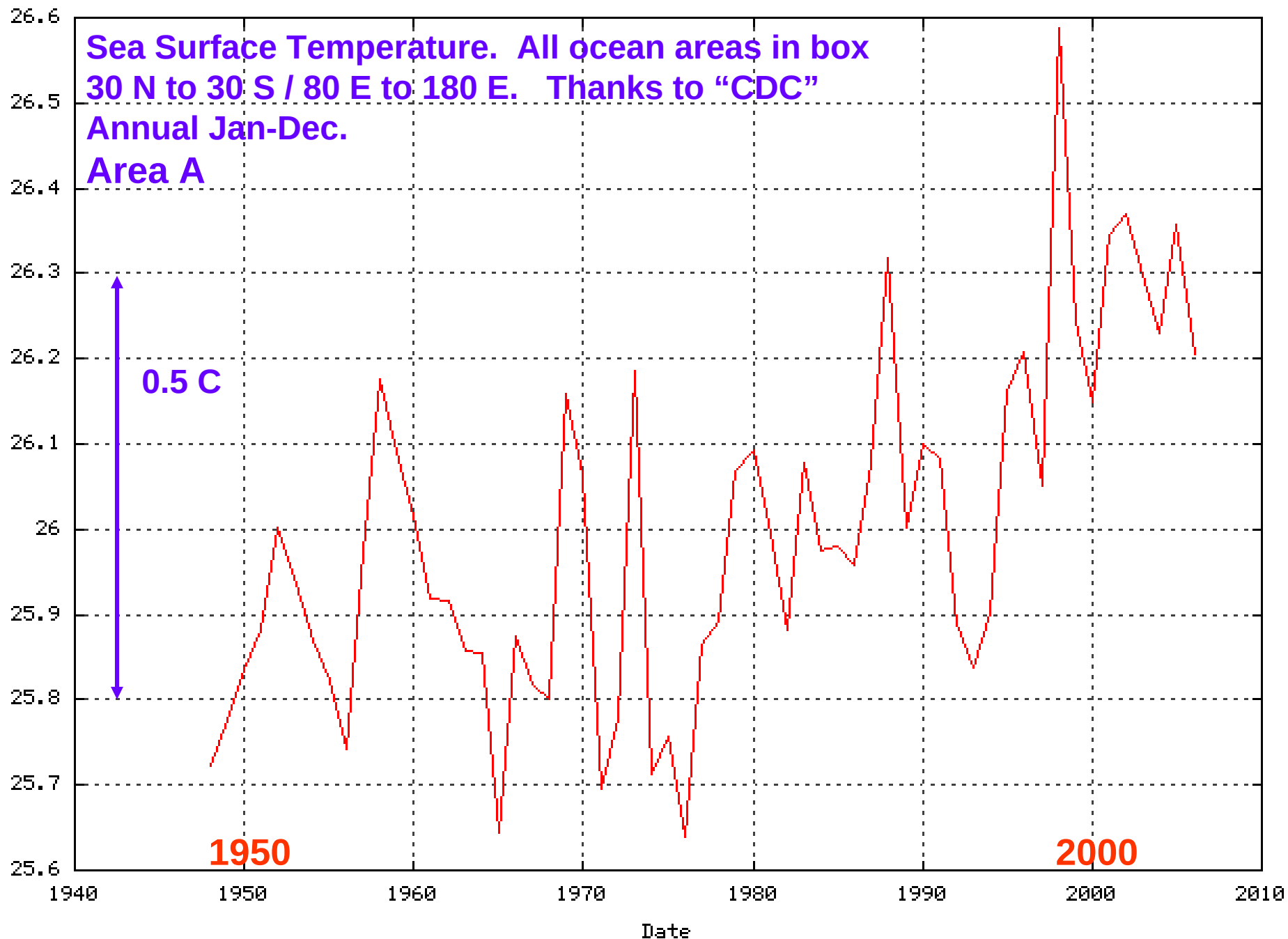
SST Departure from Climatology, Autumn SON, for 7 years 2000-2006.



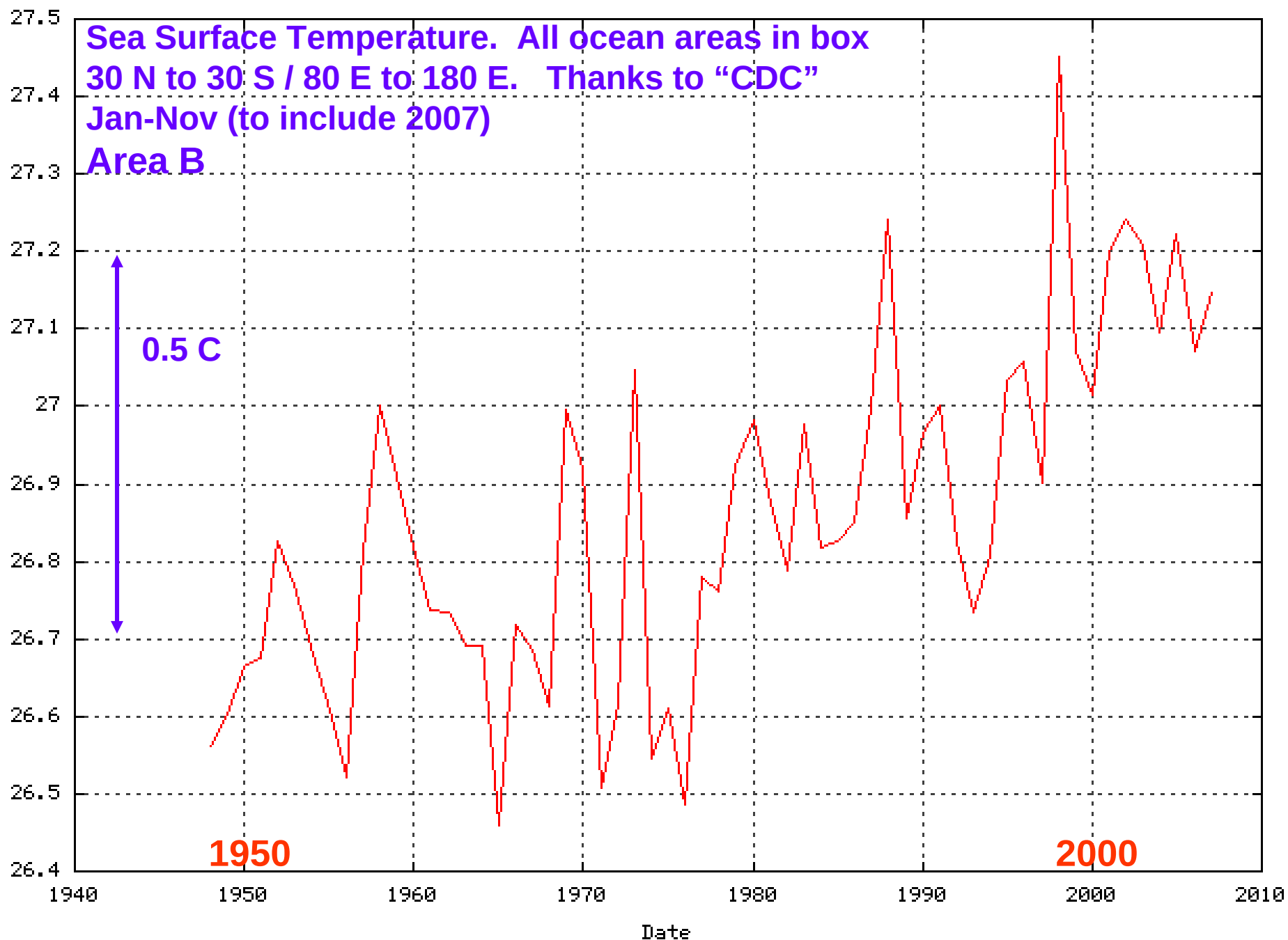
SST Departure from Climatology, Annual Jan-Dec, for 8 years 1999-2006.



SST (NCEP Reanalysis) Jan to Dec:30N to -30S and 80E to 180E averaged



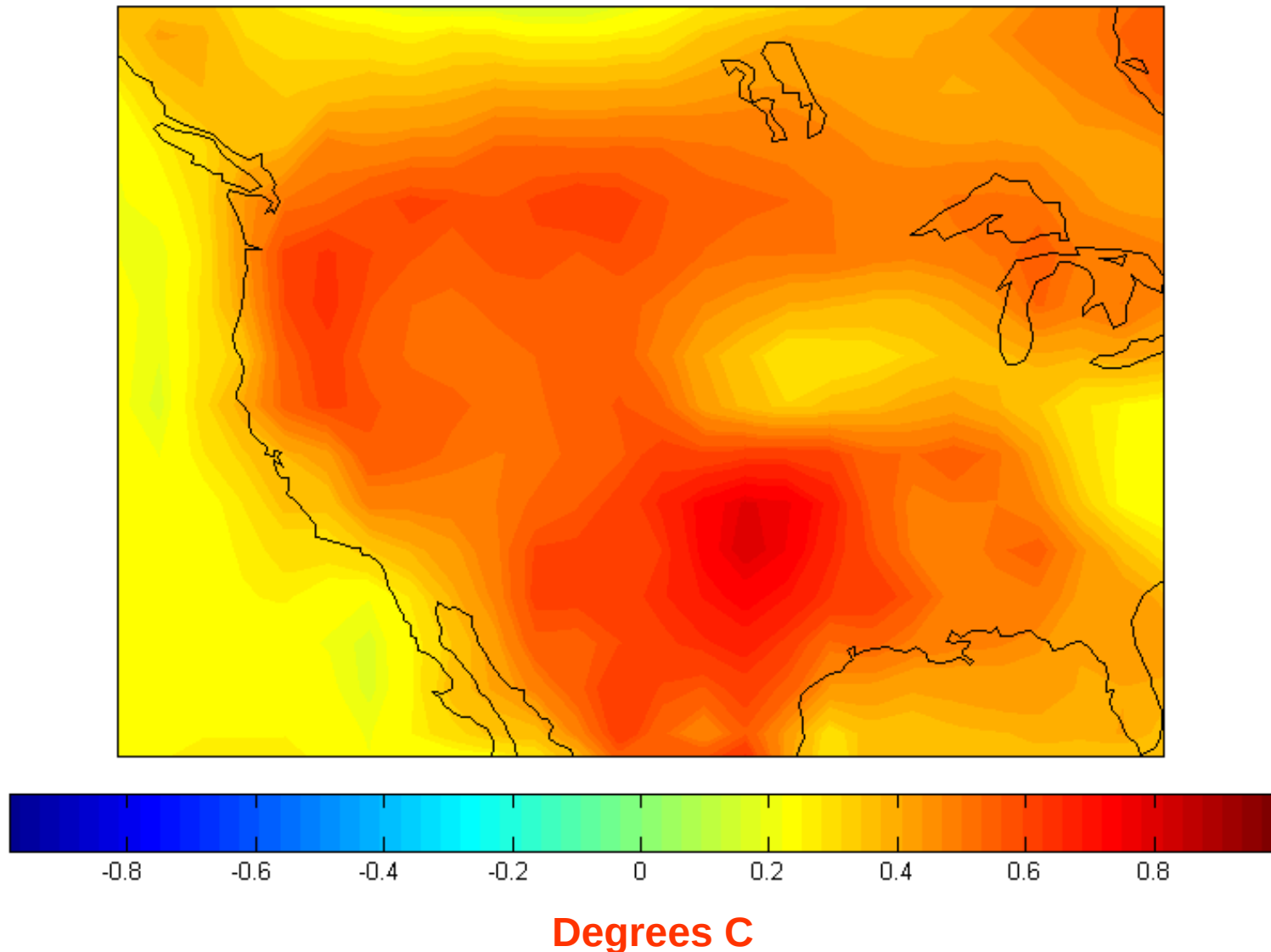
SST (NCEP Reanalysis) Jan to Nov:25N to -25S and 60E to 180E averaged



9 models x 3 scenarios = 27 “opinions”

Anomaly expectations for recent years. Summer.

MultiModel Ensemble JJA Temperature difference 2000-2007 minus 1971-2000



Mt Warren (12327 ft) Toward South. July 2000.

Mt Warren



View looking south up Deer Cr (NB: beautiful Pleistocene Rock Glacial cyn), a tributary of Lundy Cyn (note also limber pines at left foreslope (one of our sites). 7/00

Photo: Connie Millar

Mt Warren Summit Station 12,327 ft



**Mt Warren Toward North
Dunderberg Peak 12374'
a GLORIA Site**



Thanks !

Conclusions

Western temperature history similar to global temperature history, last 115 years

Western United States temperature has risen for about the last 30 years
Since about the mid-to-late 1970s

Warming more prevalent in the western half of the United States

Especially warm in recent years about 1999 / 2000 thru 2006 (and into 2007)
Temperature seemed to jump up around the turn of the millenium

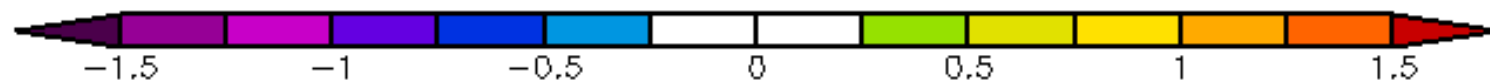
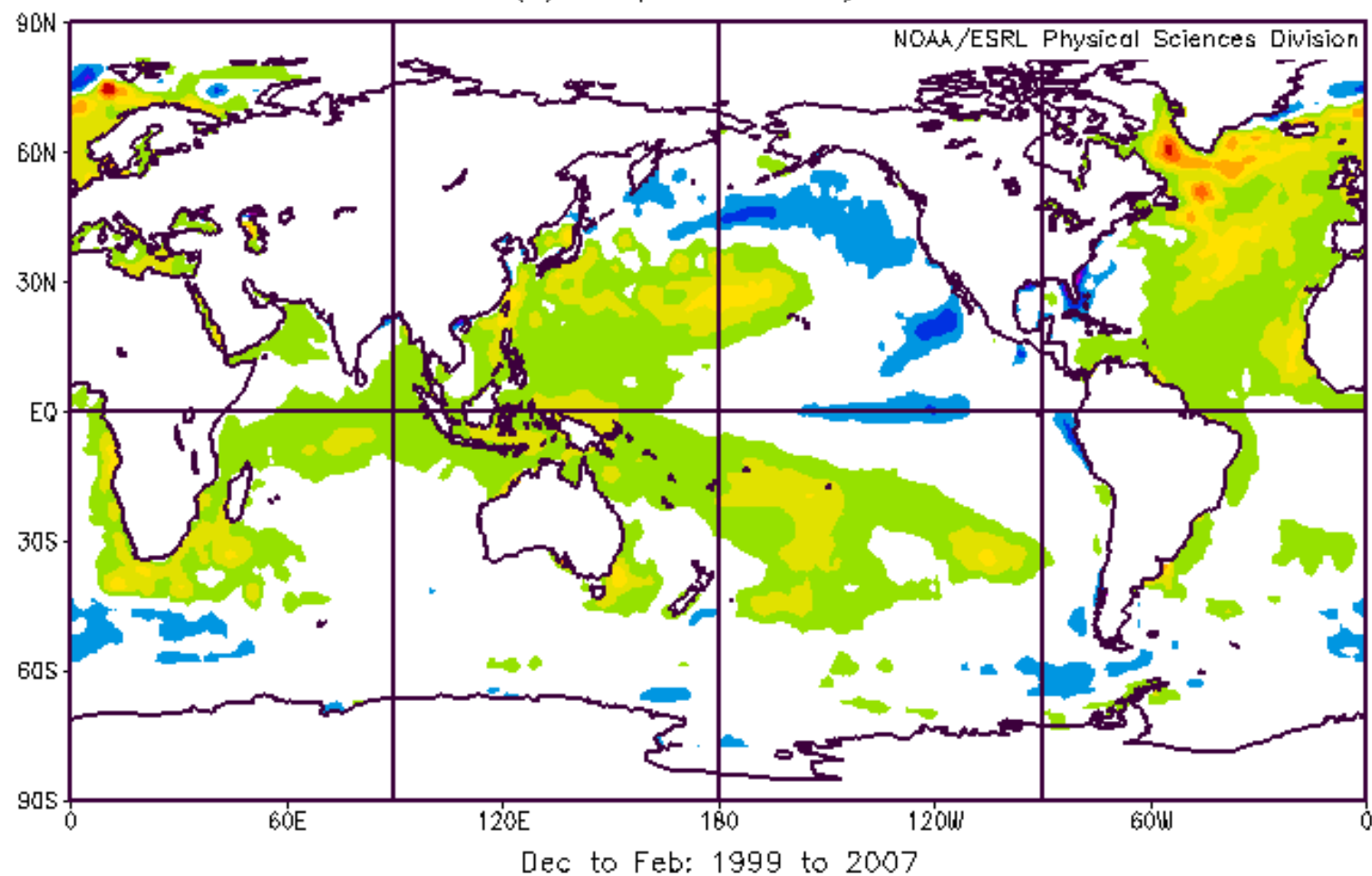
Spring shows more warming than autumn

Greater warming at higher elevations than lower elevations, in free atmosphere
All months

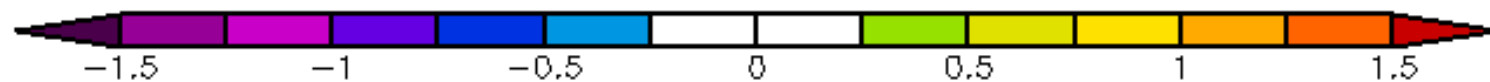
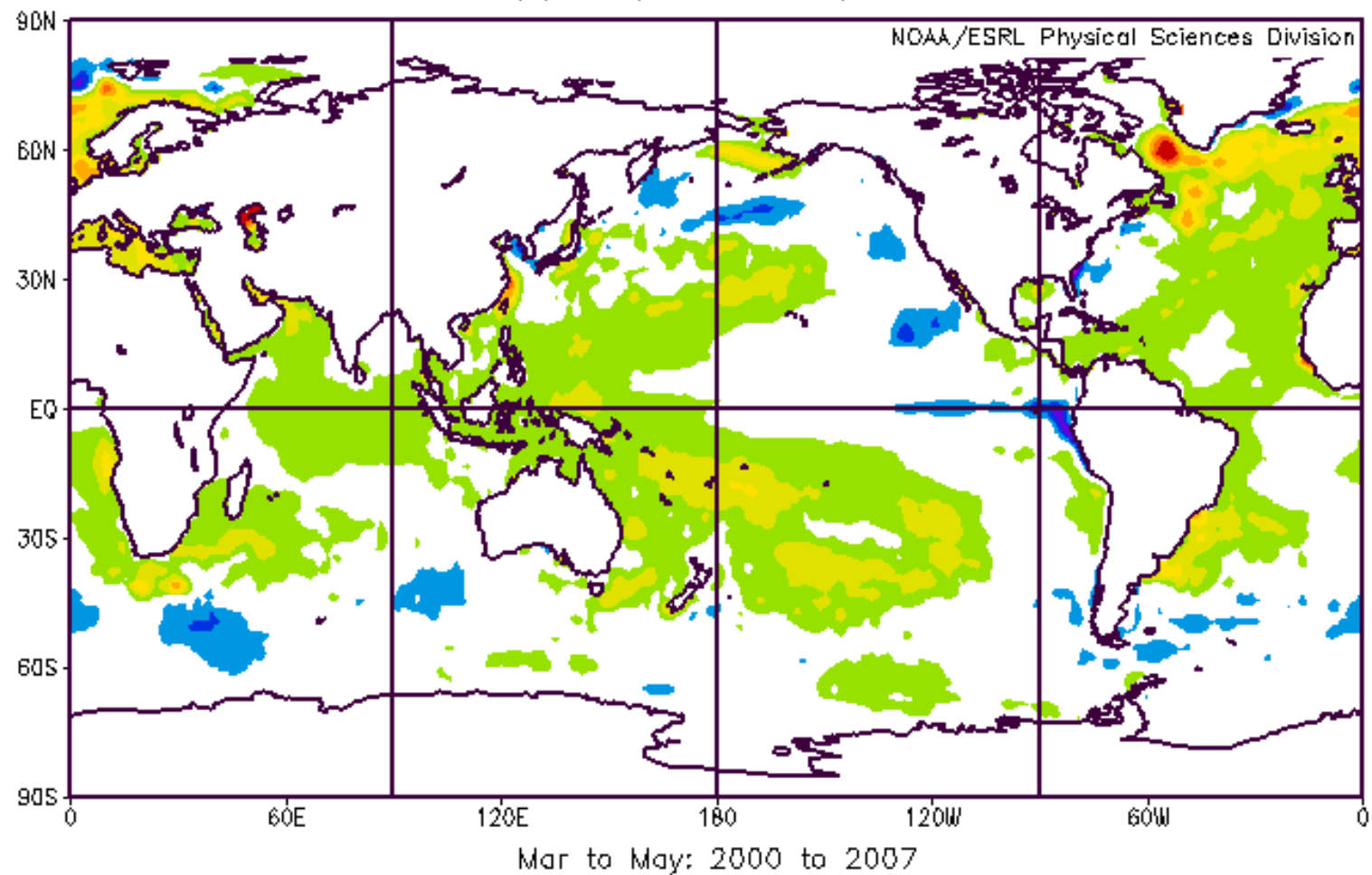
Recent western warming appears to be related to western Pacific warming.

Supplements and Discards

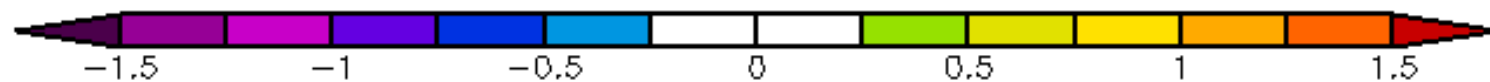
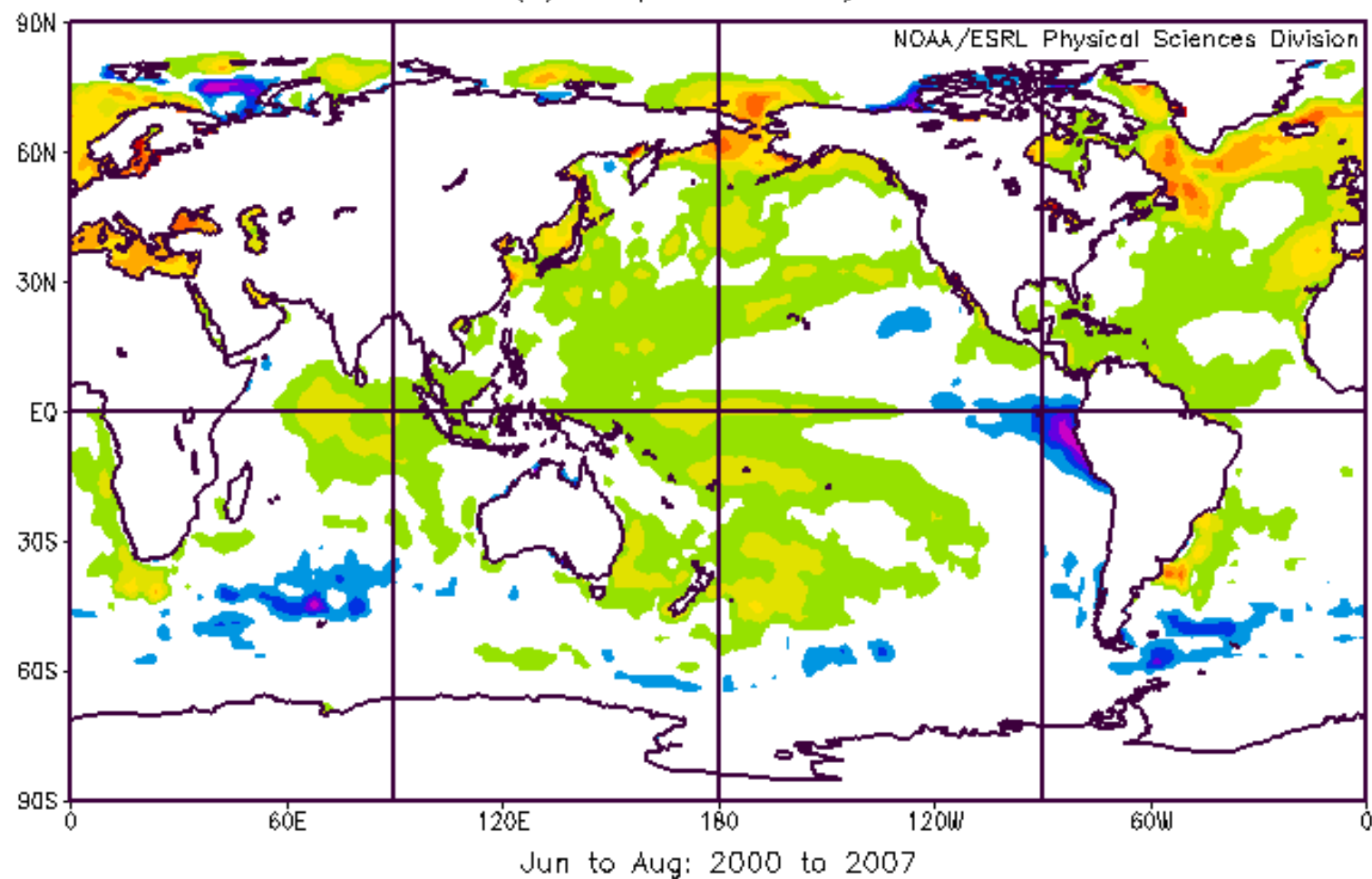
NOAA OI SST
Surface SST (C) Composite Anomaly 1971-200 climo



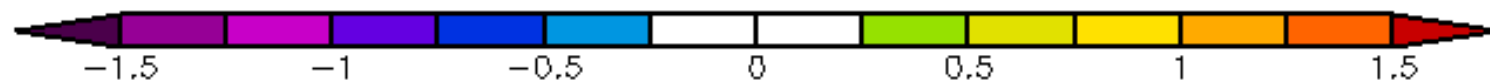
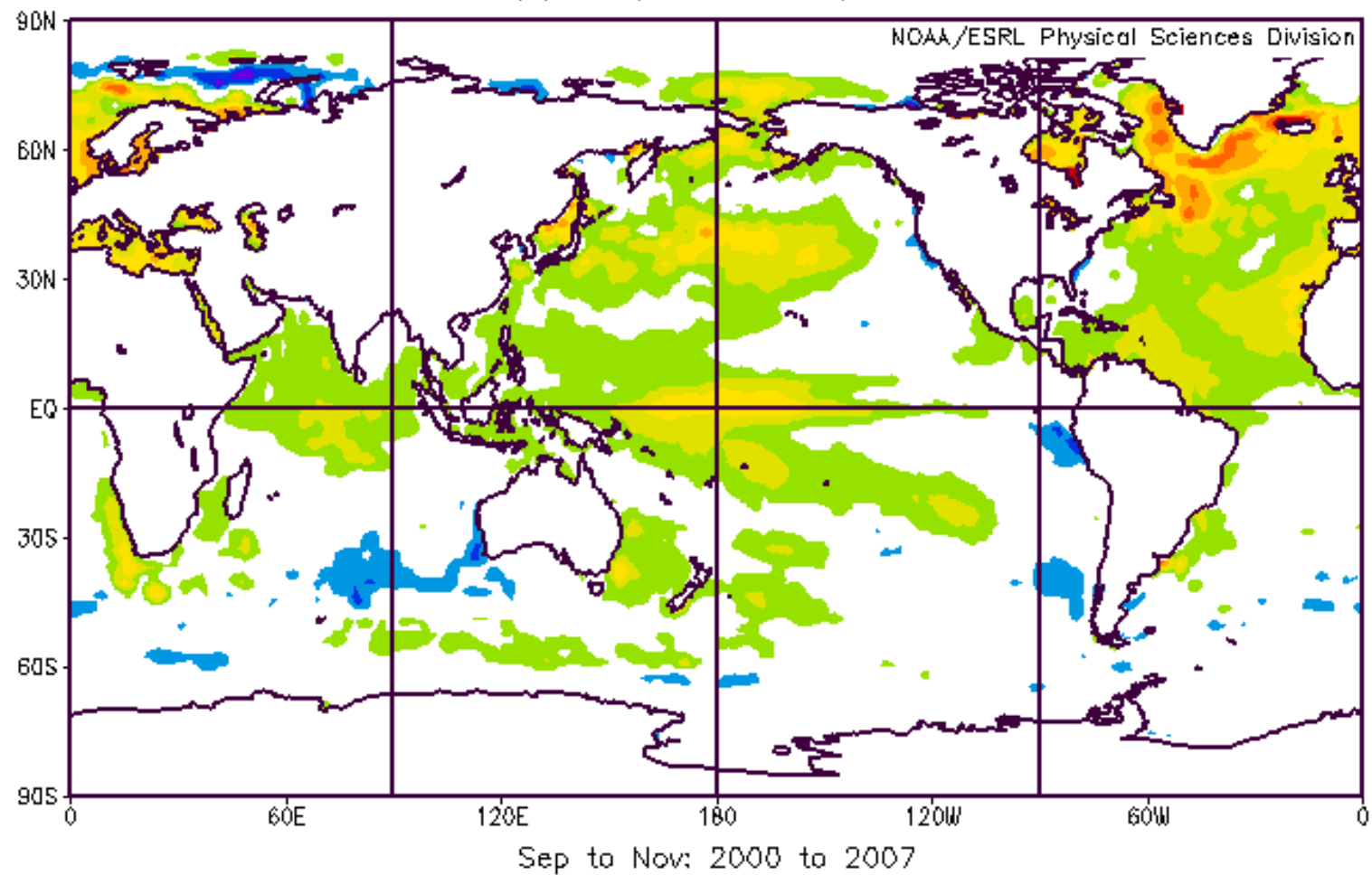
NOAA OI SST
Surface SST (C) Composite Anomaly 1971-200 climo



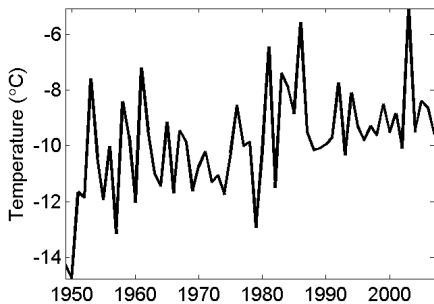
NOAA OI SST
Surface SST (C) Composite Anomaly 1971-200 climo



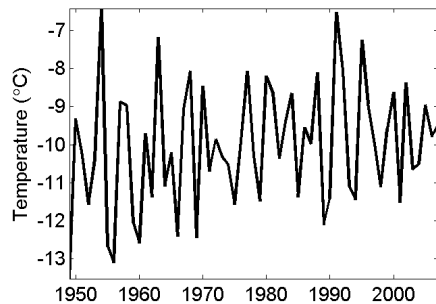
NOAA OI SST
Surface SST (C) Composite Anomaly 1971–200 climo



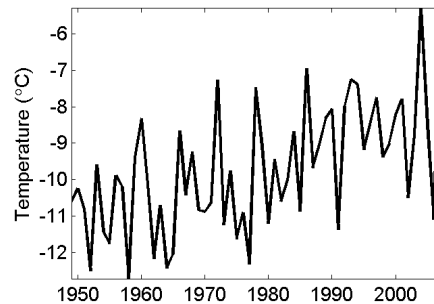
Western US 12,000 ft, JAN



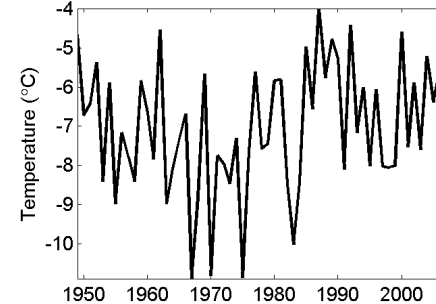
Western US 12,000 ft, FEB



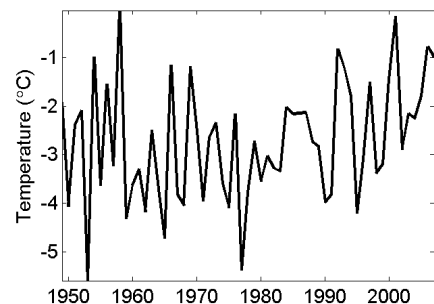
Western US 12,000 ft, MAR



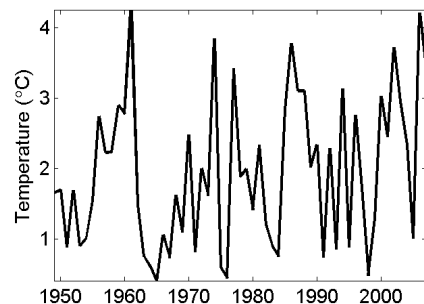
Western US 12,000 ft, APR



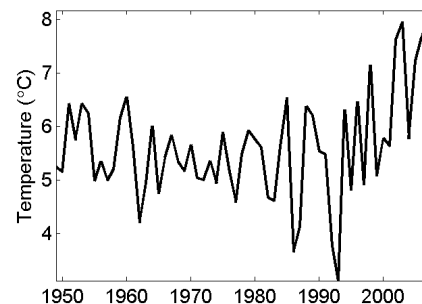
Western US 12,000 ft, MAY



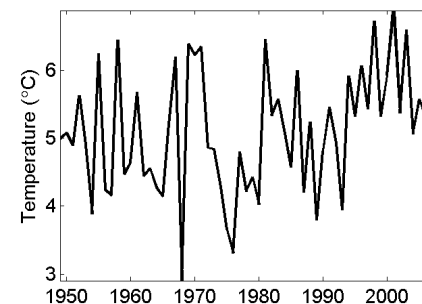
Western US 12,000 ft, JUN



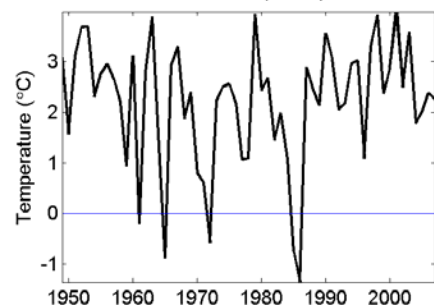
Western US 12,000 ft, JUL



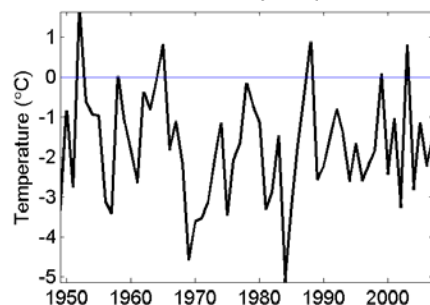
Western US 12,000 ft, AUG



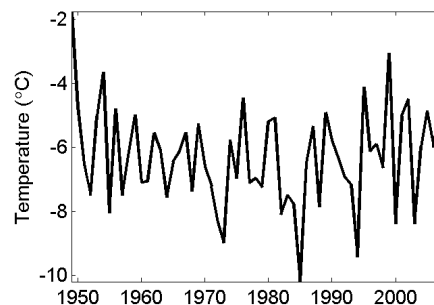
Western US 12,000 ft, SEP



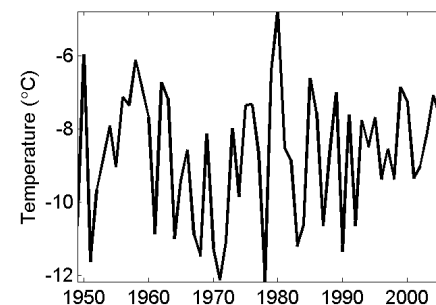
Western US 12,000 ft, OCT



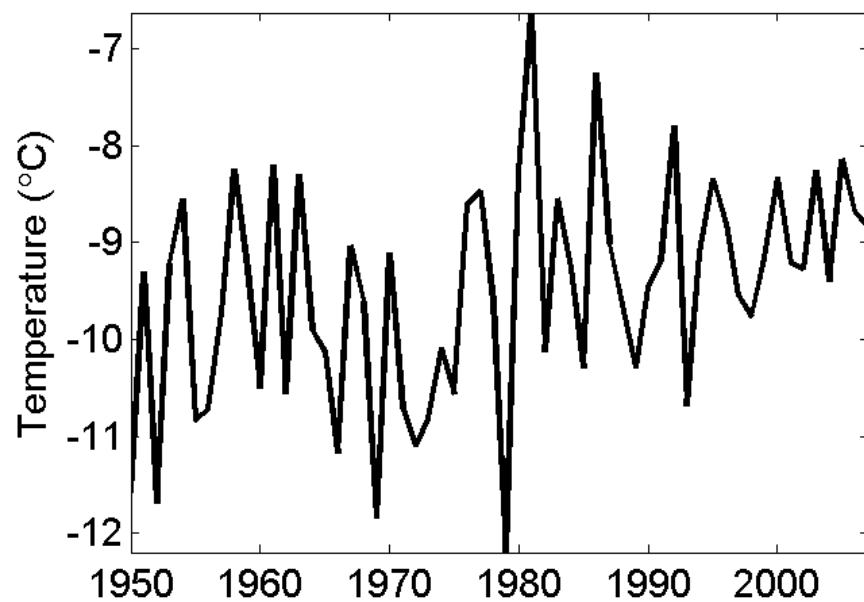
Western US 12,000 ft, NOV



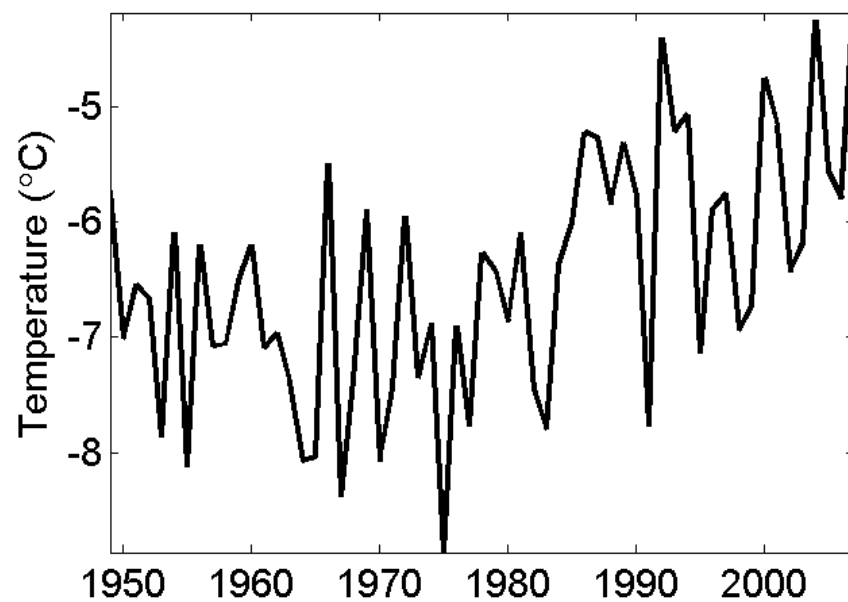
Western US 12,000 ft, DEC



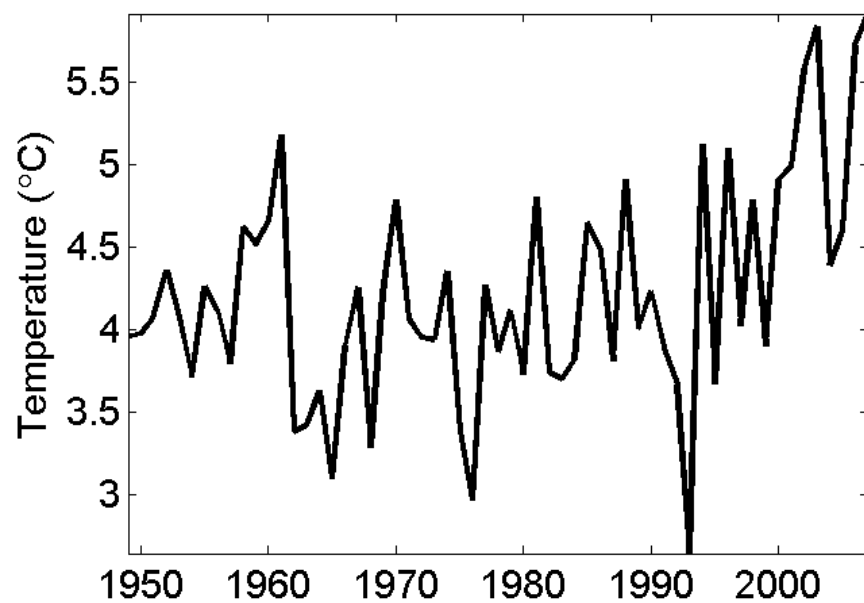
Western US 12,000 ft, DJF



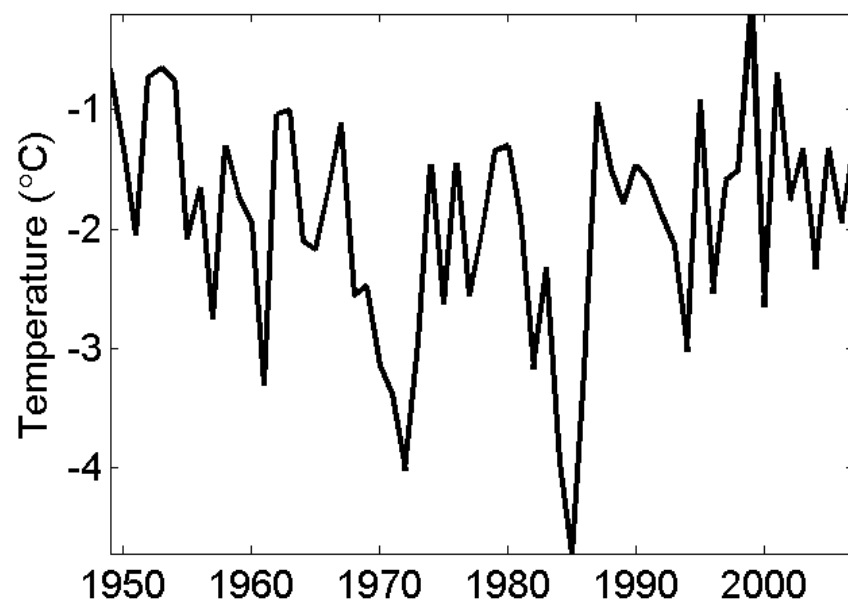
Western US 12,000 ft, MAM



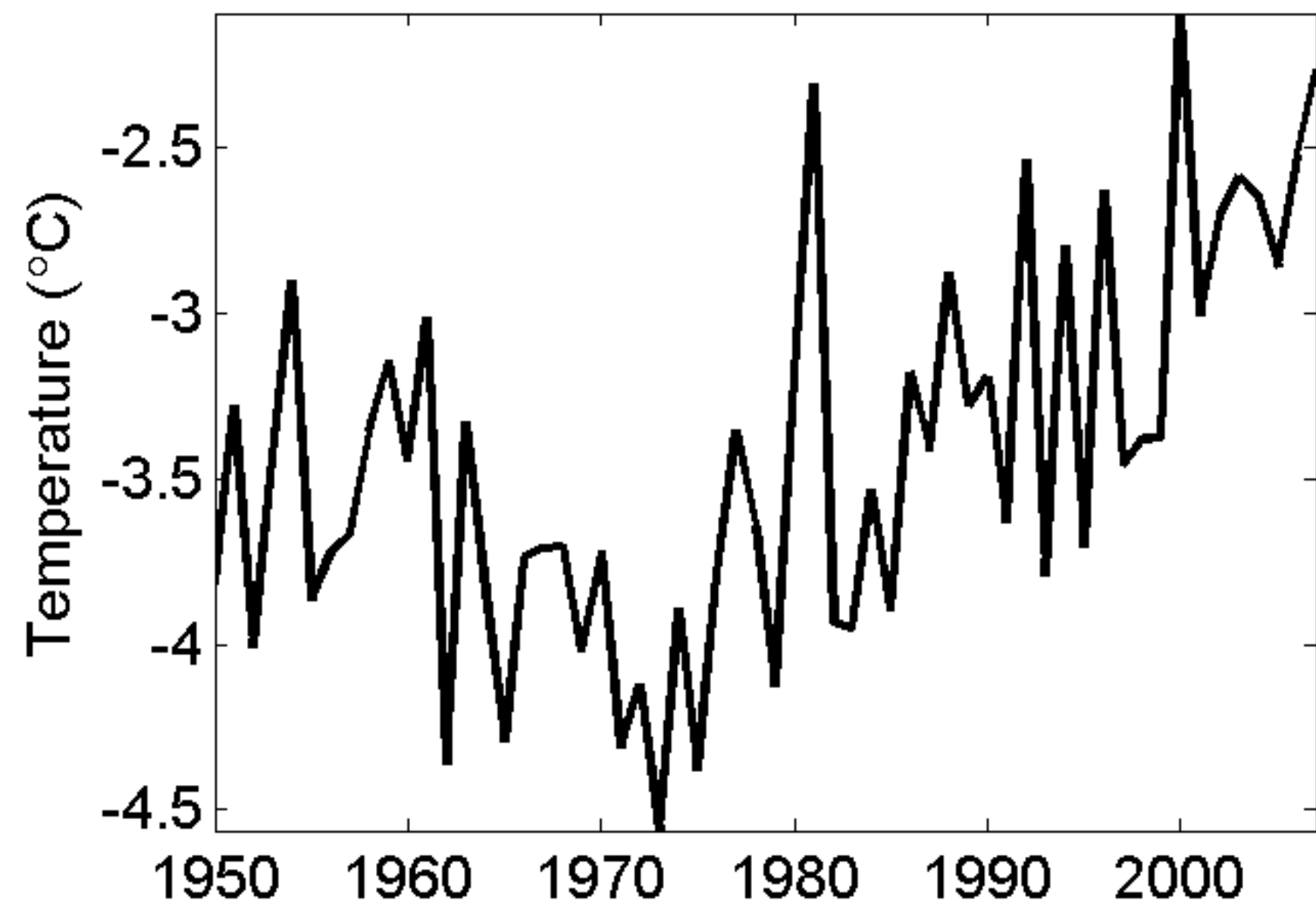
Western US 12,000 ft, JJA

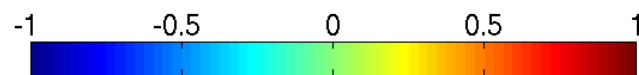
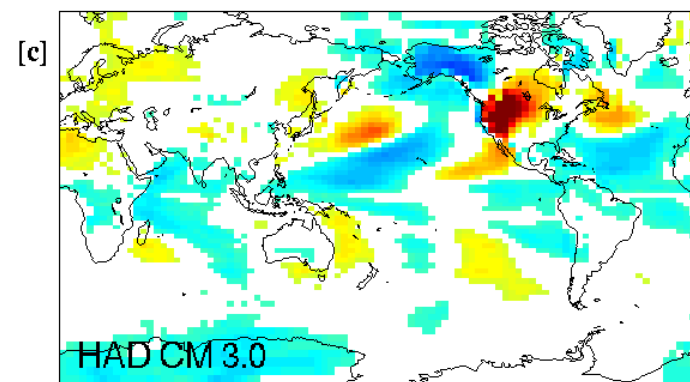
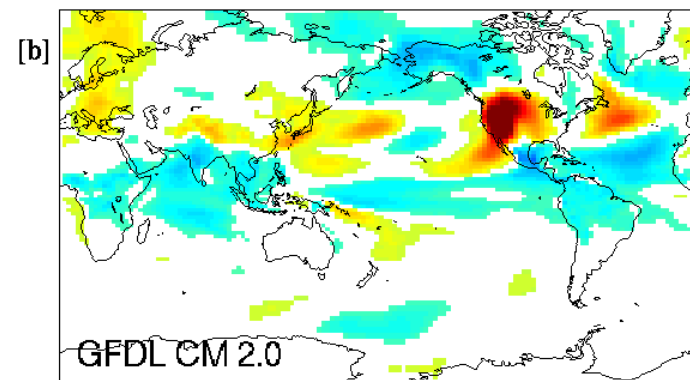
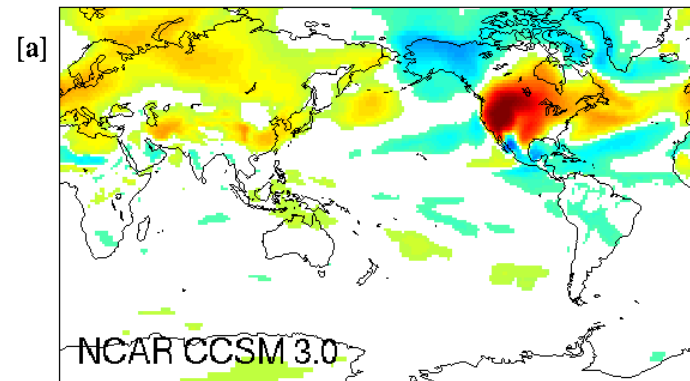


Western US 12,000 ft, SON

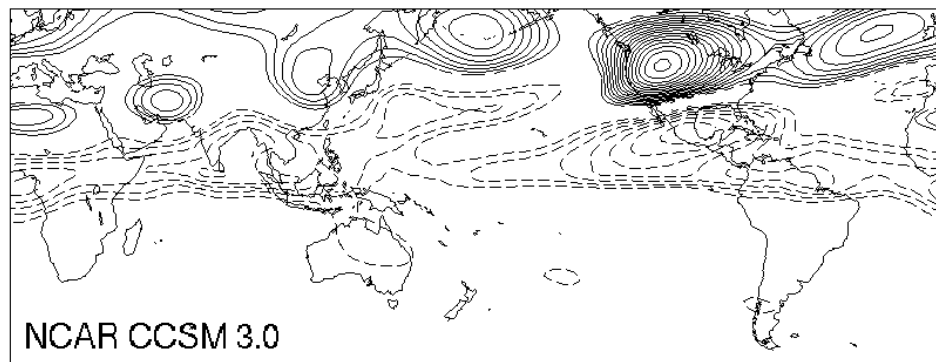


Western US 12,000 ft, ANN

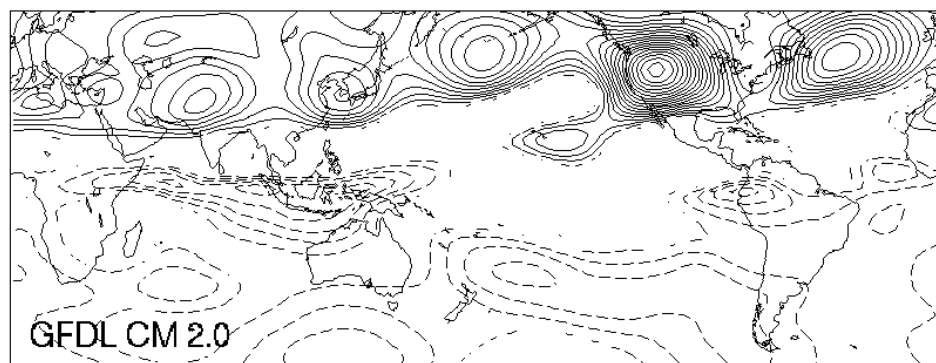




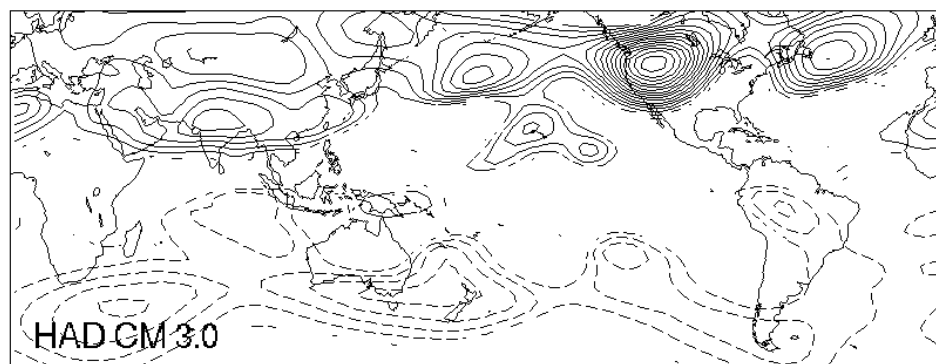
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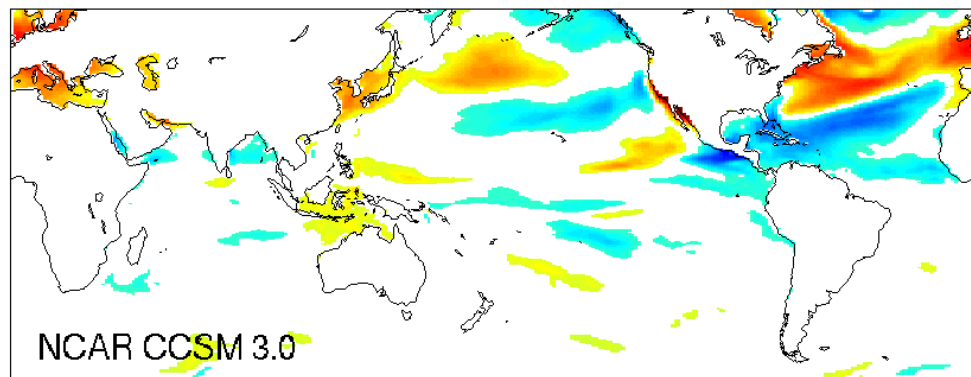
[b]



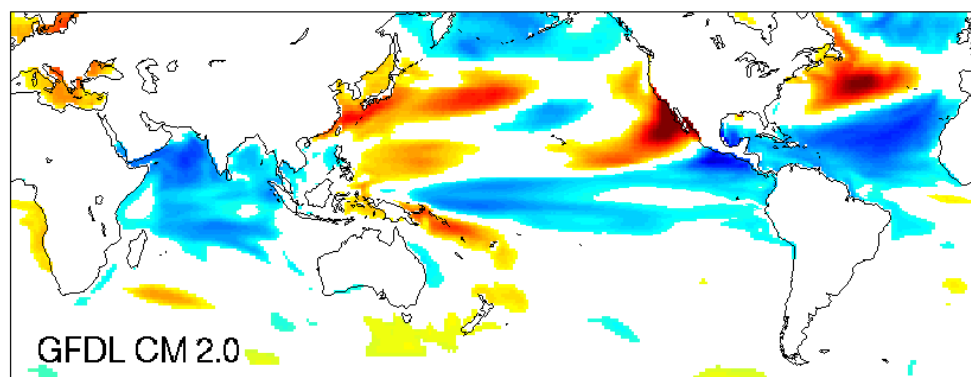
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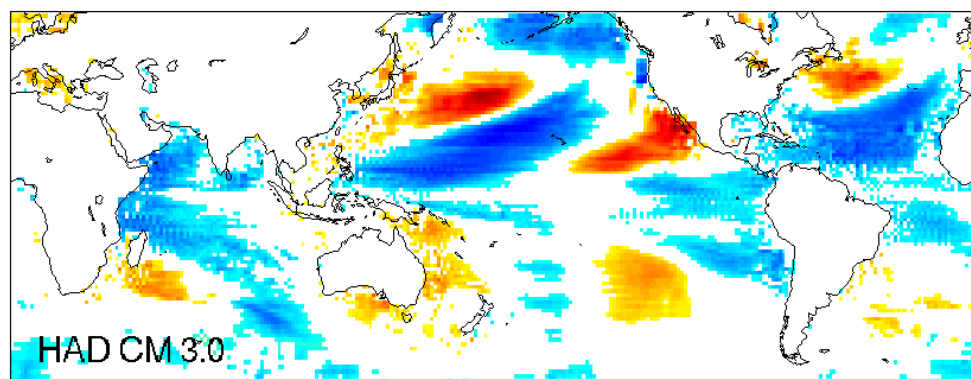
[a]



[b]



[c]



-0.4

-0.2

0

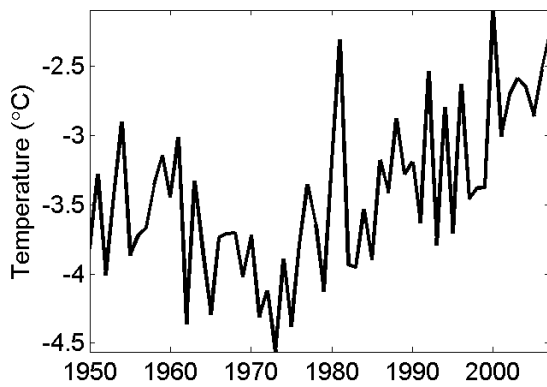
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0.4

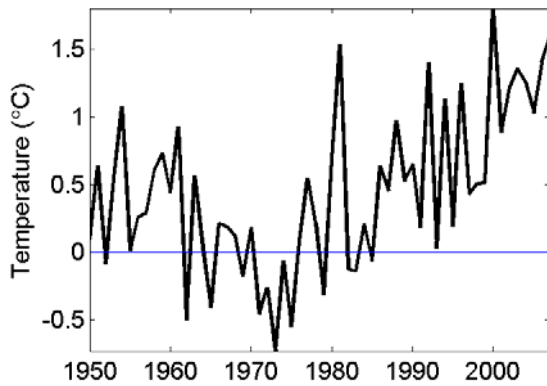
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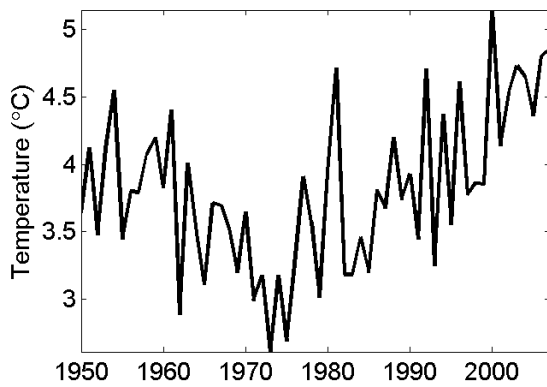
Western US 12,000 ft, ANN

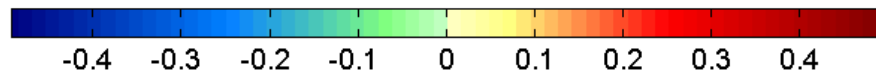
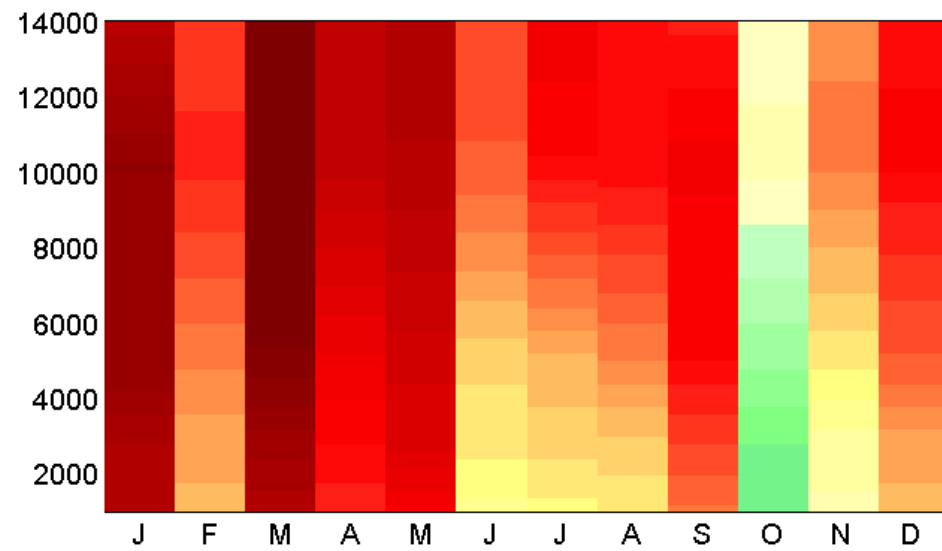
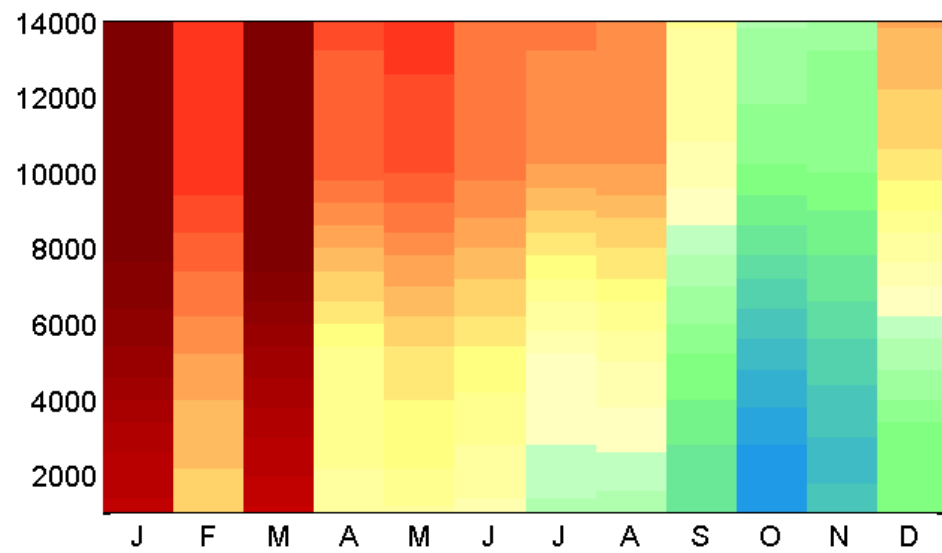


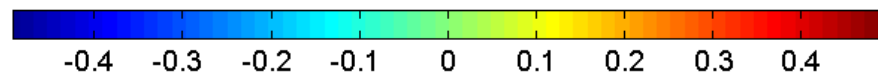
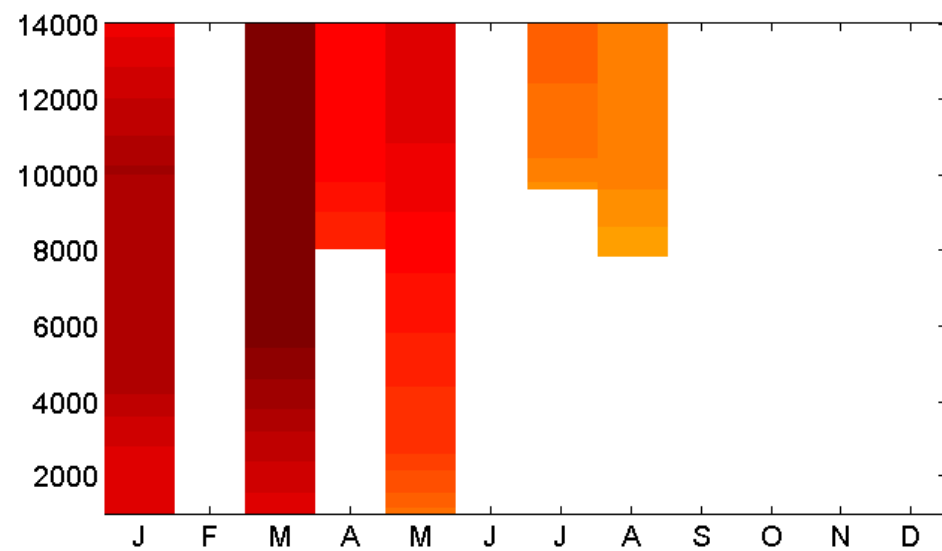
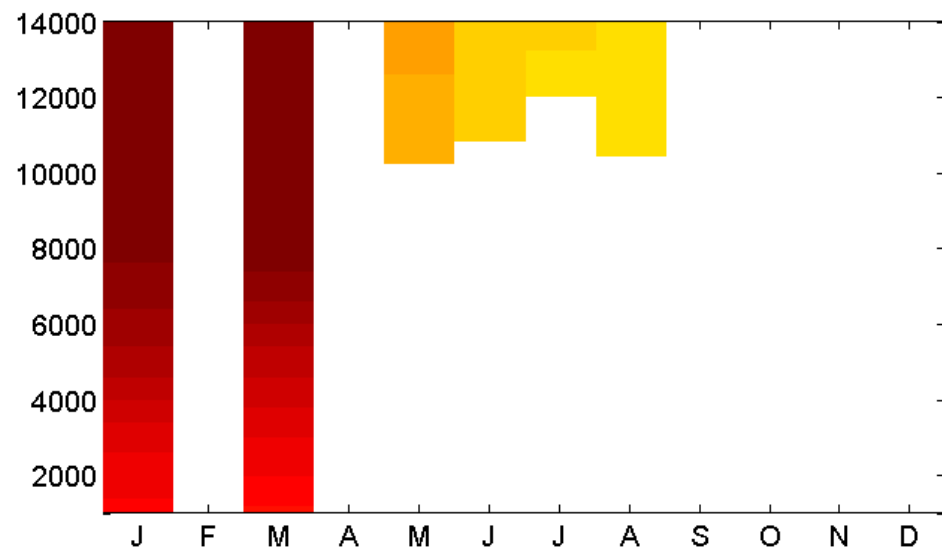
Western US 10,000 ft, ANN

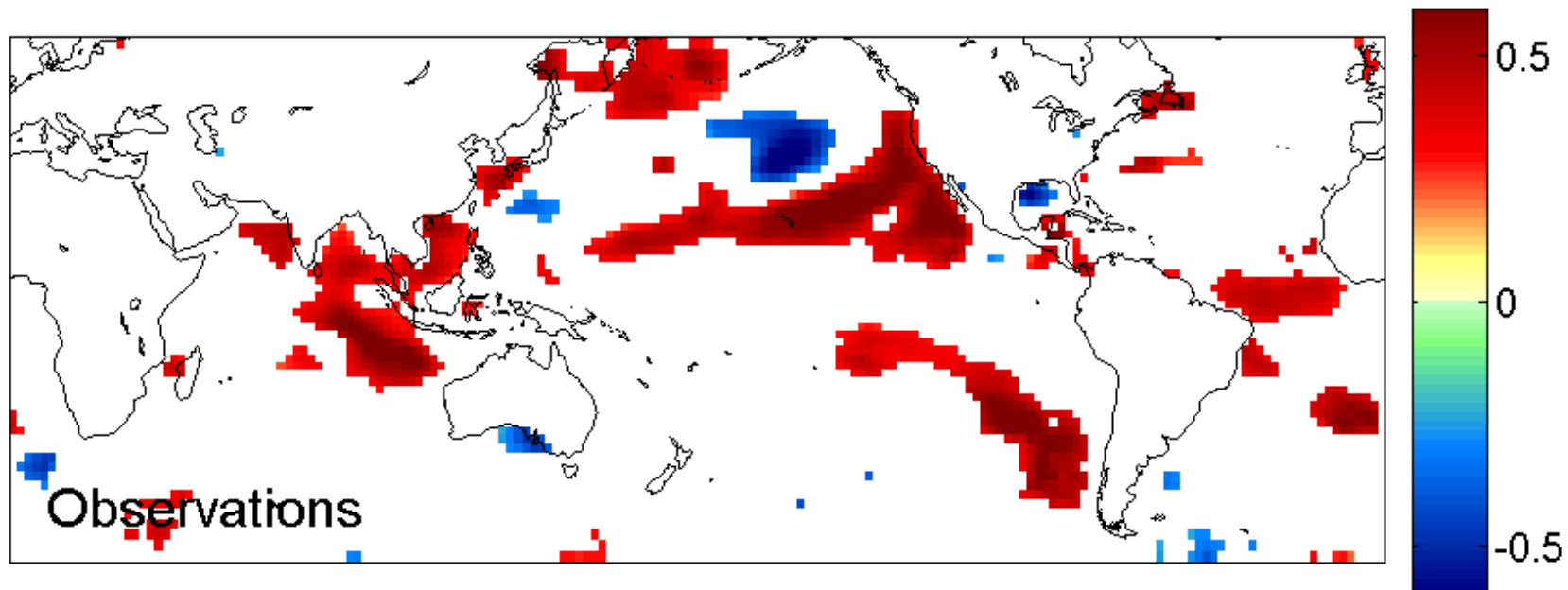


Western US 8,000 ft, ANN

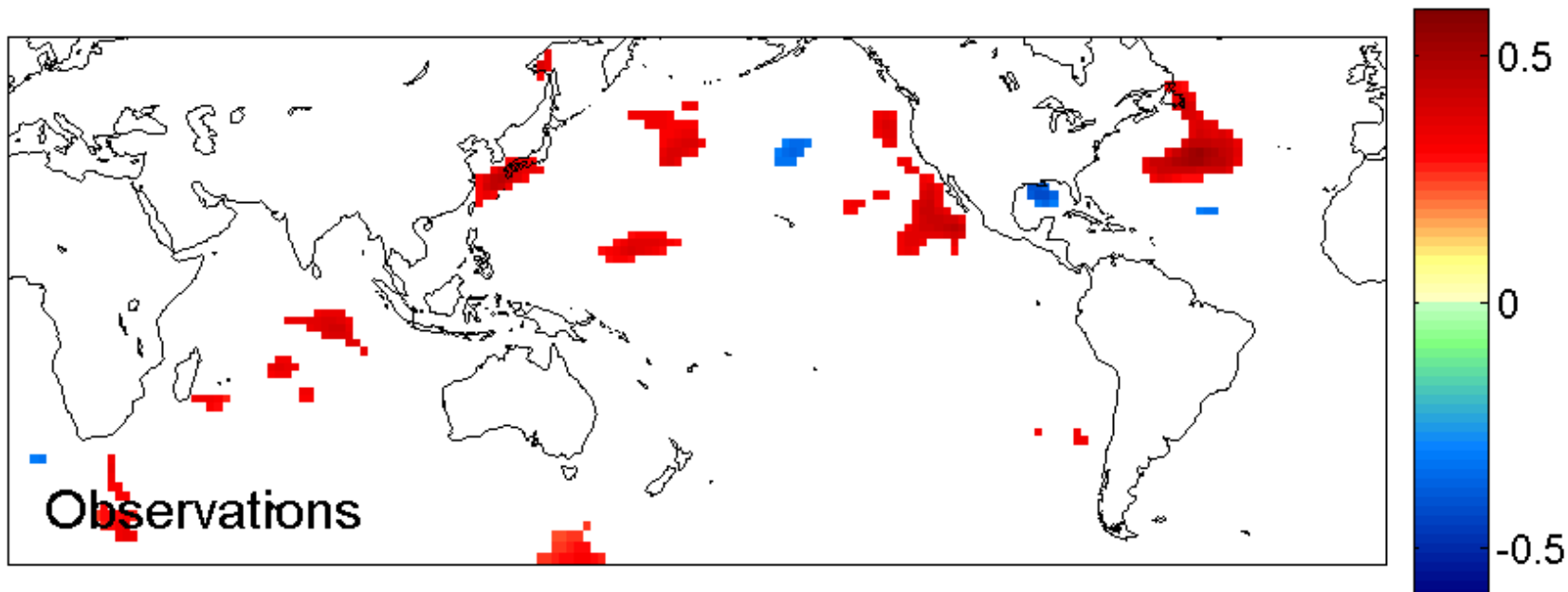






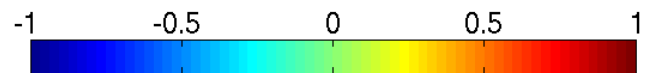
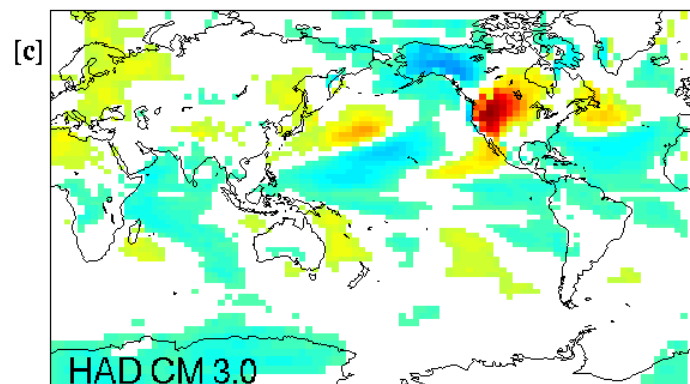
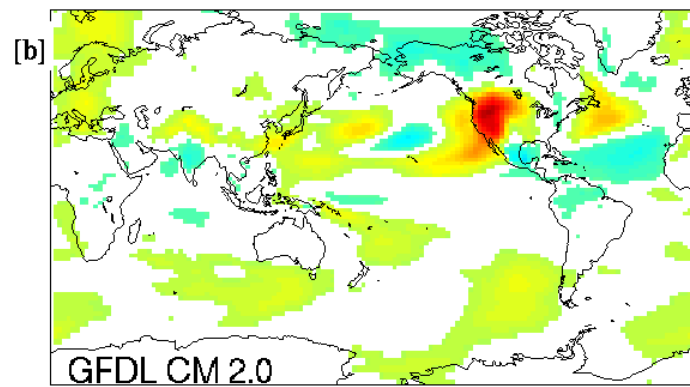
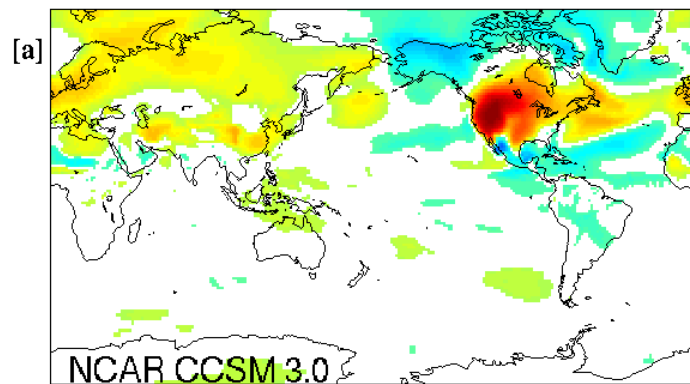


**Correlation of summer mean western U.S. temperature and global sea surface temperature, 1949-2007, significant at ___ level.
Bandpass filtered time series, 5-30 years.**

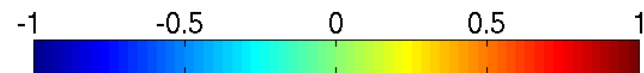
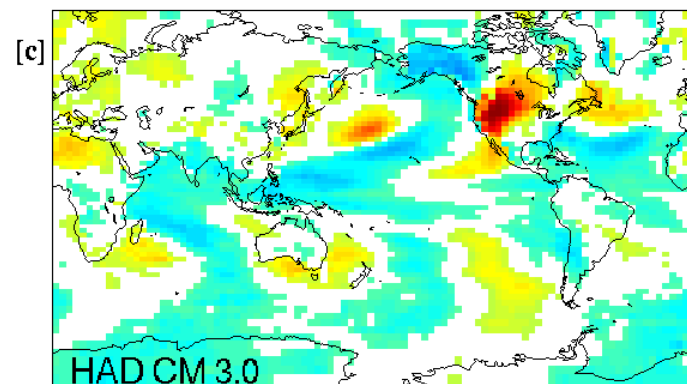
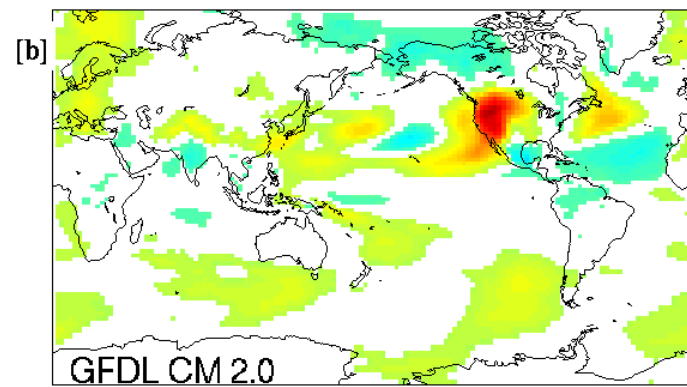
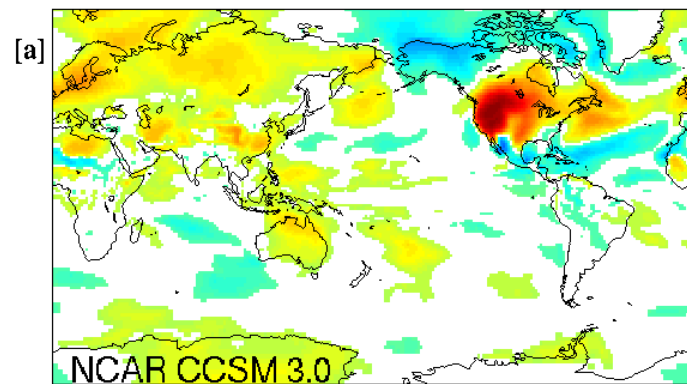


Correlation of summer mean western U.S. temperature and global sea surface temperature, 1949-2007, significant at ___ level. Highpass filter, 30 years and higher.

Highpass 30 year +



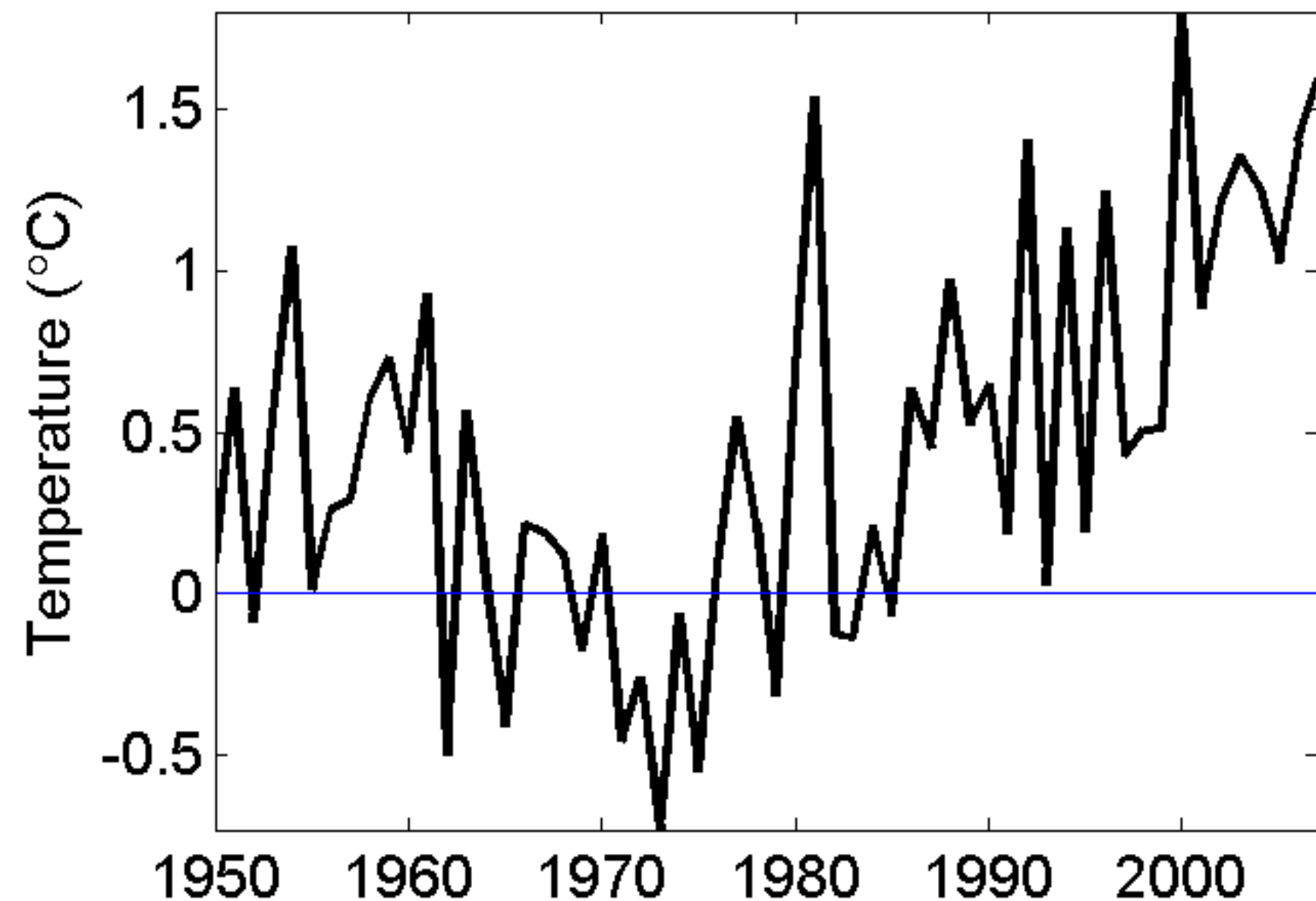
Bandpass 5-30 years

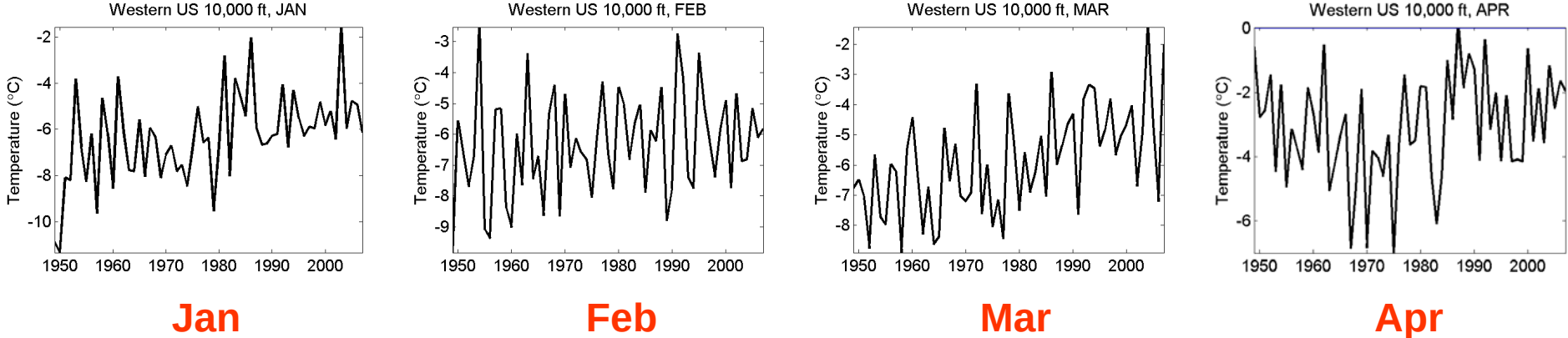


Fixed
Elevation

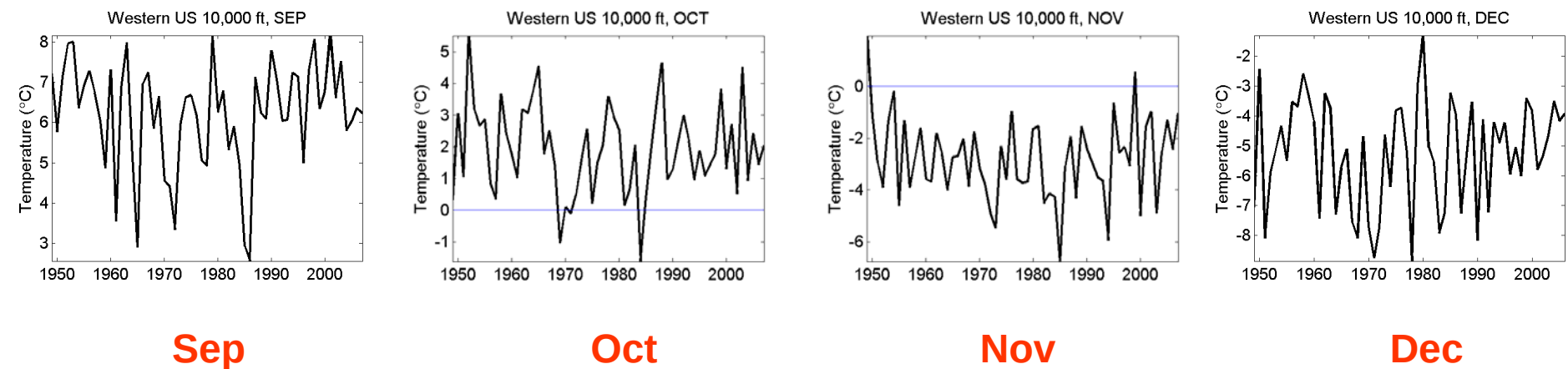
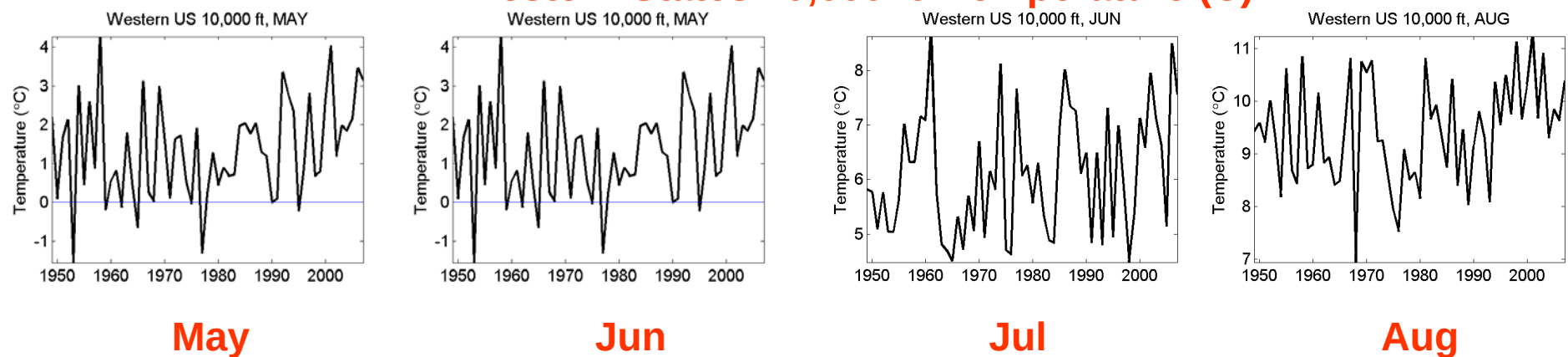
Western US 10,000 ft, ANN

32.5 – 50 N
105 – 125 W

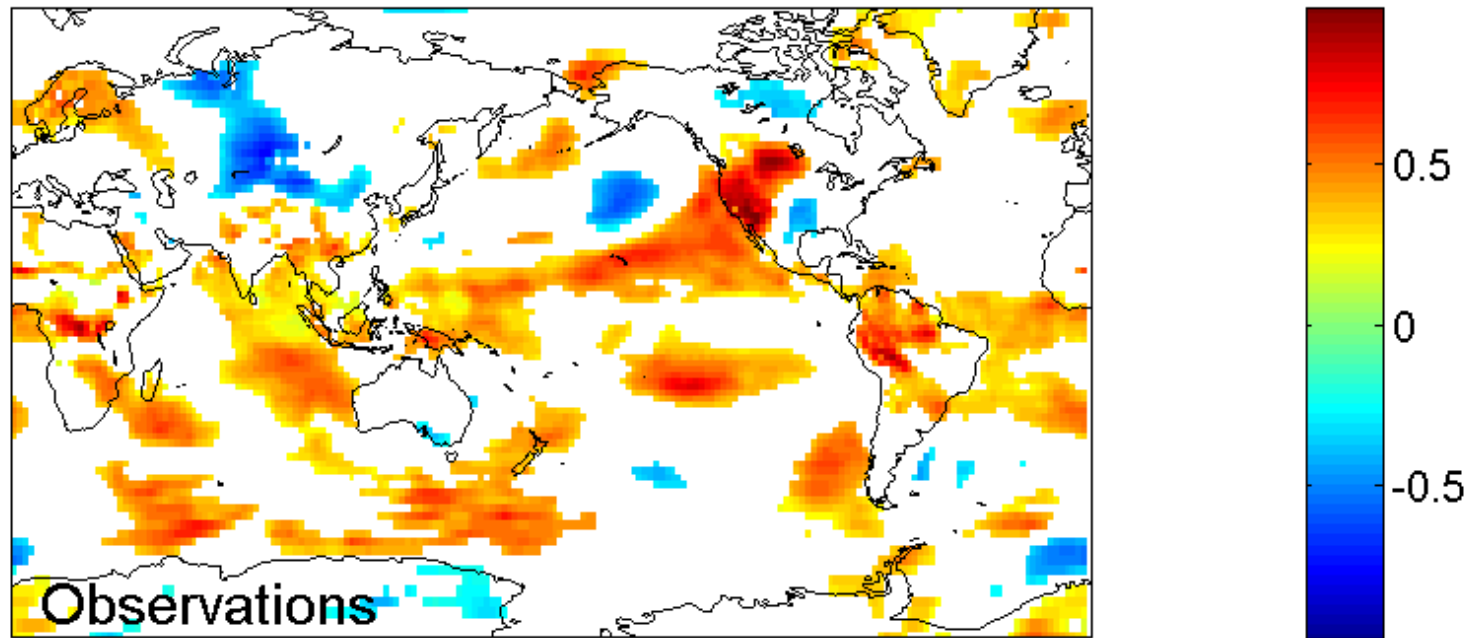




Western States 10,000 ft Temperature (C)



When summer is warm in the West, where else is it warm ?



**Regression of summer mean air temperature on western
U.S. summer mean air temperature, 1949-2007.**

Standardized time series.

Bandpass filtered to allow 5-30 year variability.