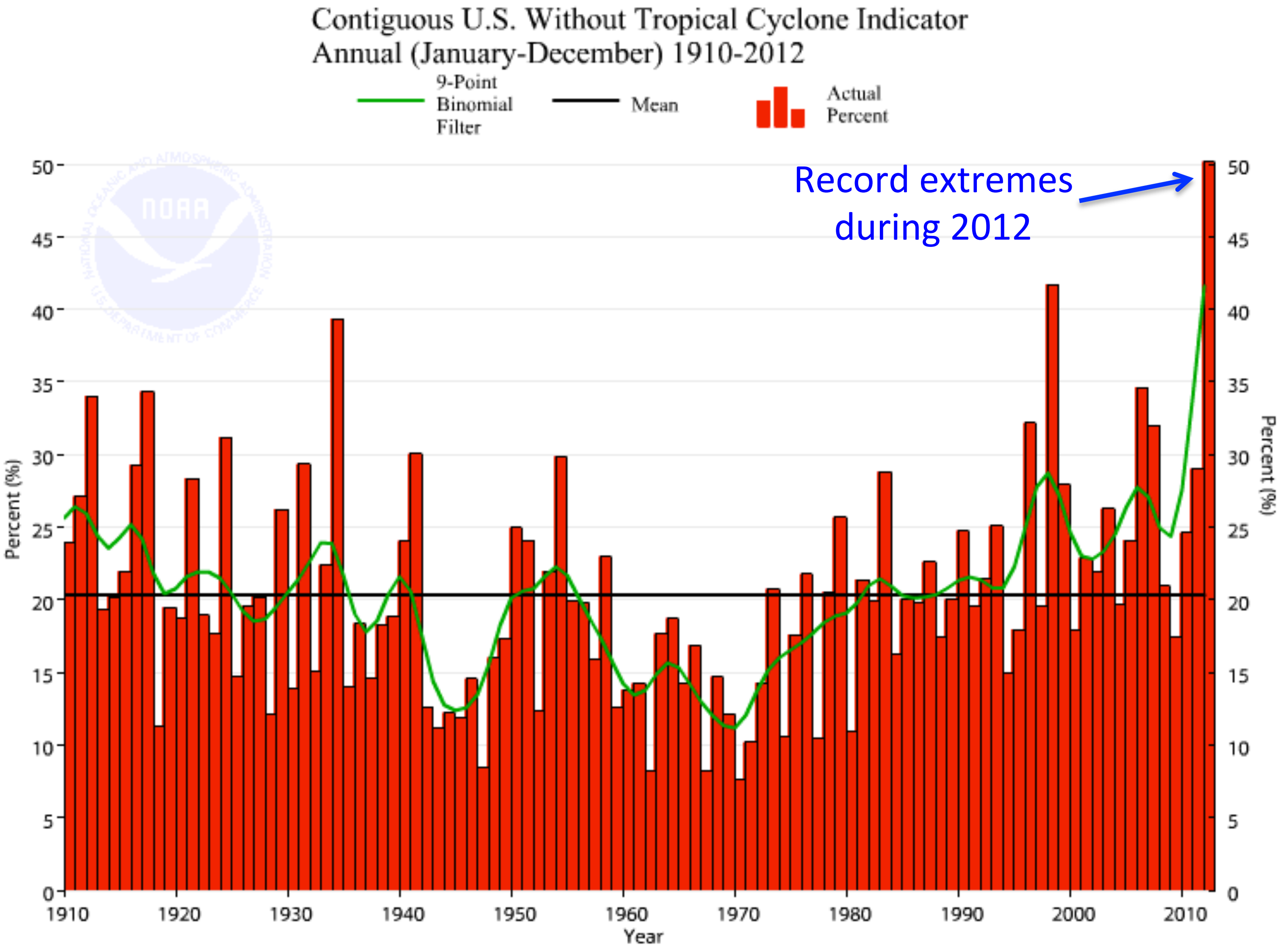
Relating Extreme Weather Events to Large-Scale Meteorological Patterns: Is the Glass half full or half empty?

Steve Vavrus
Center for Climatic Research
University of Wisconsin

U. S. Climate Extremes Index



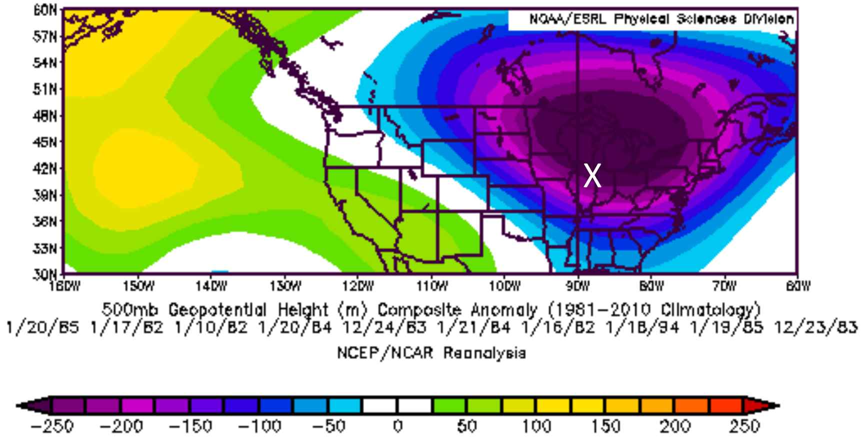
Contiguous U.S. Without Tropical Cyclone Indicator
Annual (January-December) 1910-2012

Record extremes during 2012

Upper-air Circulation Anomalies during Extreme Weather (Chicago)

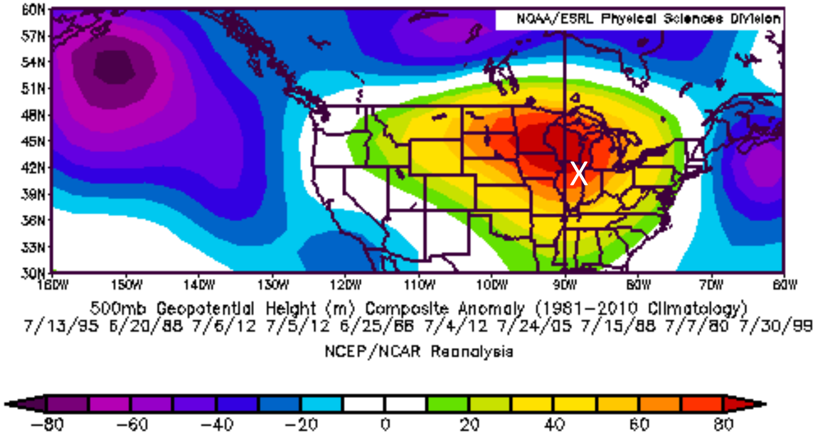
High-Amplitude Wave Patterns

10 Coldest Days



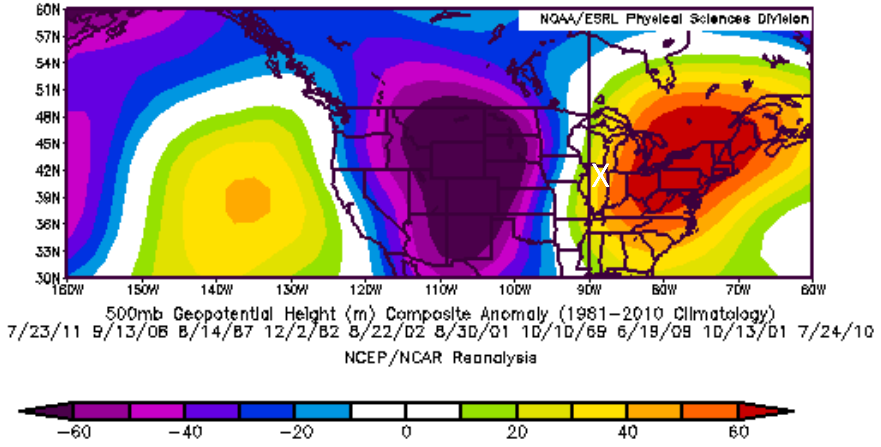
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
1/20/85 1/17/82 1/10/82 1/20/84 12/24/83 1/21/84 1/16/82 1/18/94 1/19/85 12/23/83
NCEP/NCAR Reanalysis

10 Hottest Days



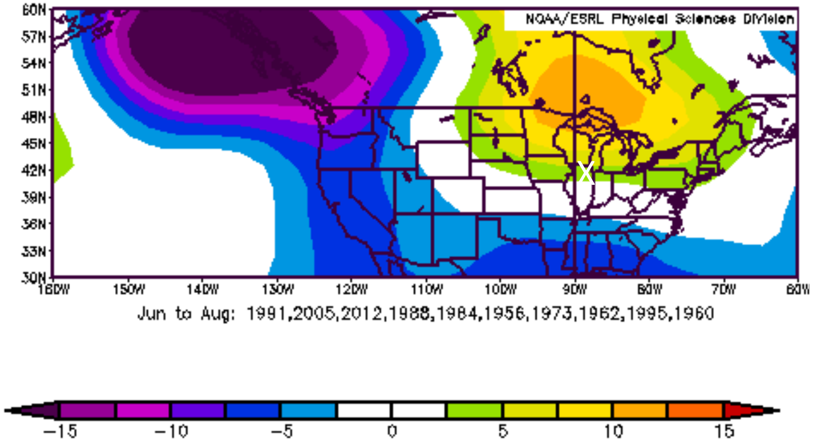
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/13/95 6/20/88 7/6/12 7/5/12 6/25/88 7/4/12 7/24/05 7/15/88 7/7/80 7/30/99
NCEP/NCAR Reanalysis

10 Wettest Days



500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/23/11 9/13/08 8/14/87 12/2/82 8/22/02 8/30/01 10/10/69 6/19/09 10/13/01 7/24/10
NCEP/NCAR Reanalysis

10 Driest Summers

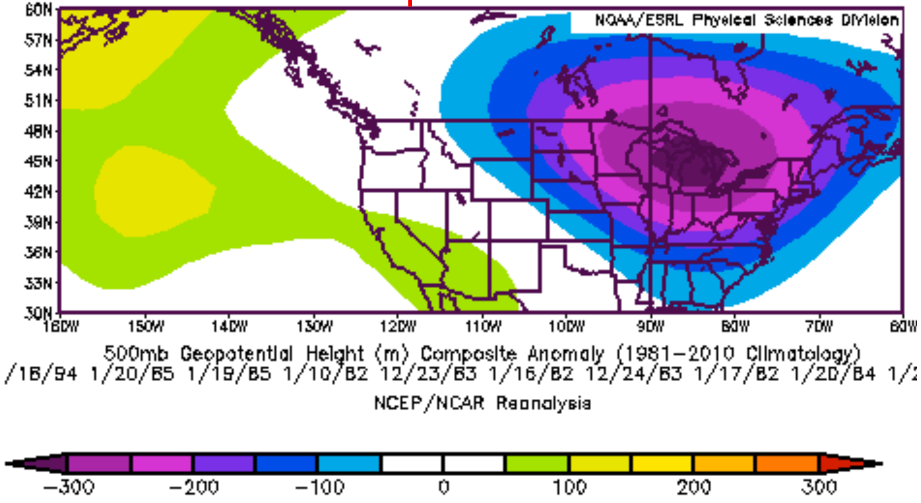


Jun to Aug: 1991,2005,2012,1988,1984,1956,1973,1962,1995,1960

Chicago's 10 Coldest Days

500 hPa Anomalies (m)

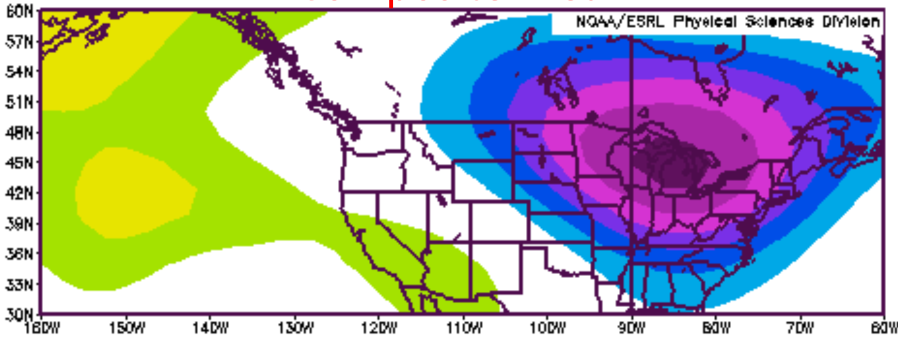
Composite Mean



Chicago’s 10 Coldest Days

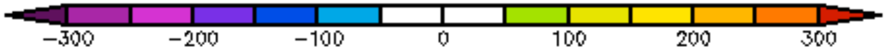
500 hPa Anomalies (m)

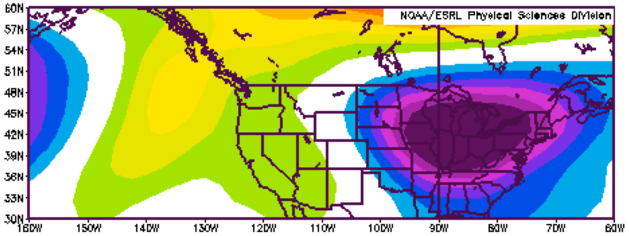
Composite Mean



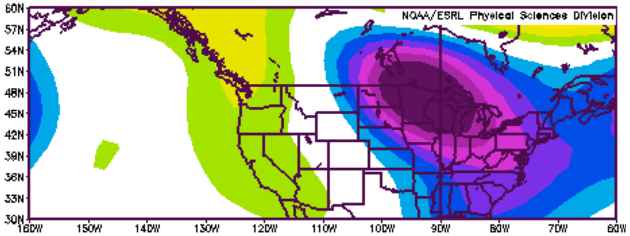
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
/16/94 1/20/85 1/19/85 1/10/82 12/23/83 1/16/82 12/24/83 1/17/82 1/20/84 1/

NCEP/NCAR Reanalysis

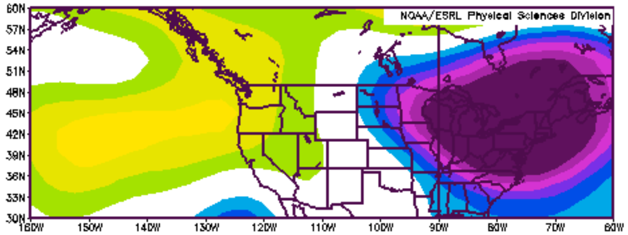




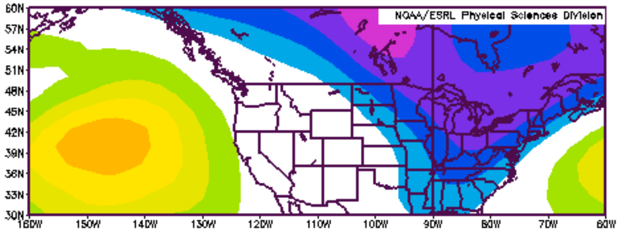
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
1/20/85



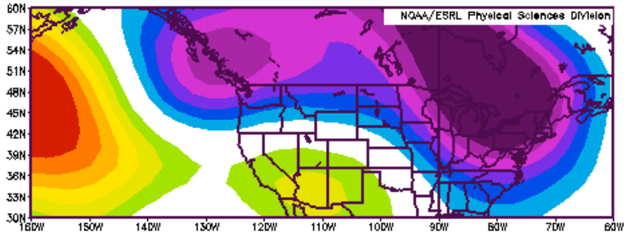
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
1/19/85



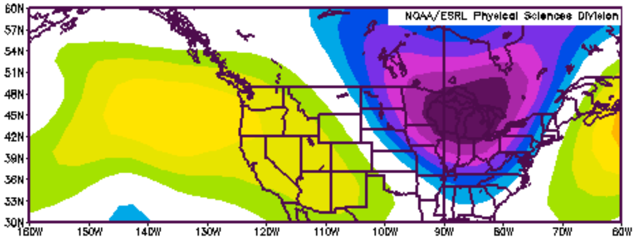
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
1/10/82



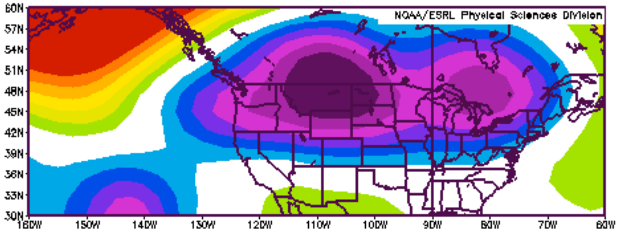
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
1/21/84



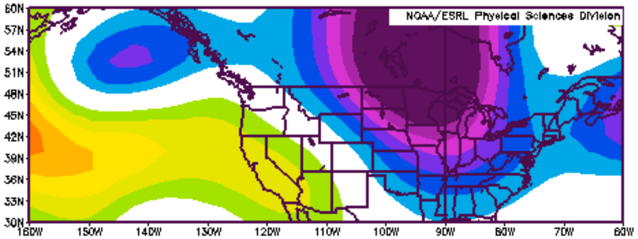
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
1/17/82



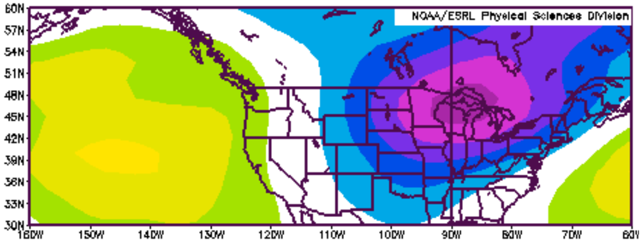
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
1/16/94



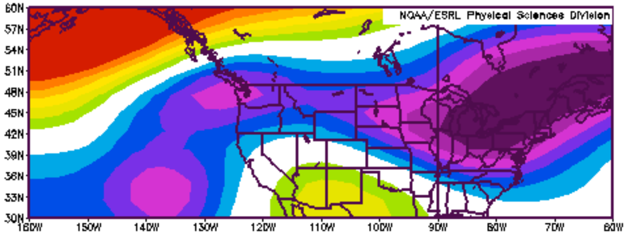
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
12/23/83



500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
1/16/82



500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
1/20/84

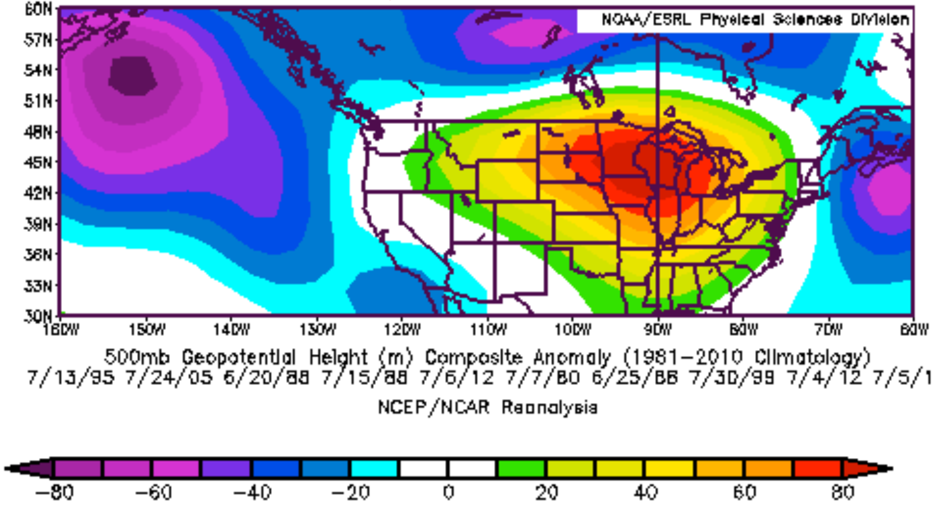


500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
12/24/83

Chicago’s 10 Hottest Days

500 hPa Anomalies (m)

Composite Mean

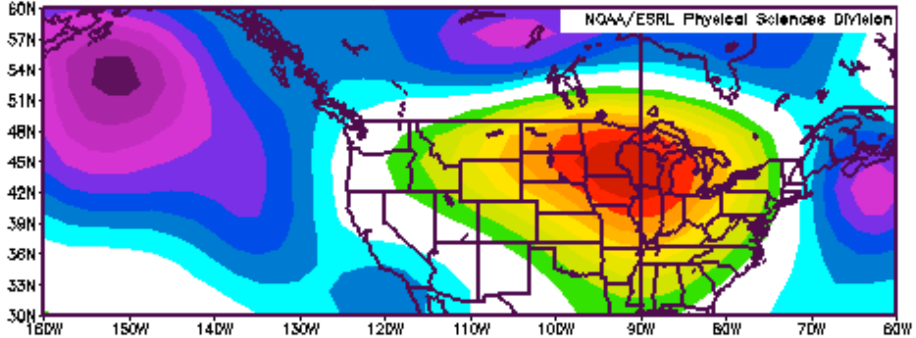


500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/13/95 7/24/05 6/20/88 7/15/88 7/6/12 7/7/80 6/25/88 7/30/99 7/4/12 7/5/1
NCEP/NCAR Reanalysis

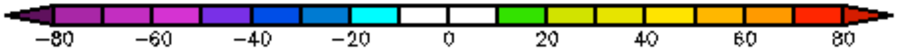
Chicago’s 10 Hottest Days

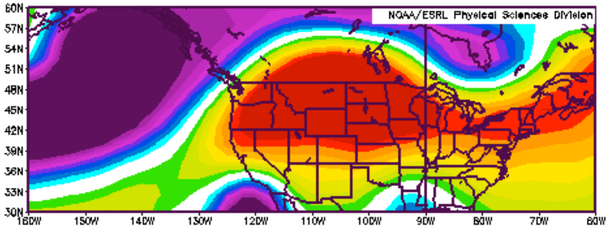
500 hPa Anomalies (m)

Composite Mean

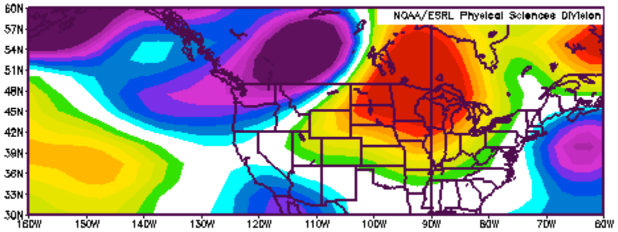


500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/13/95 7/24/05 6/20/88 7/15/88 7/6/12 7/7/80 6/25/88 7/30/99 7/4/12 7/5/1
NCEP/NCAR Reanalysis

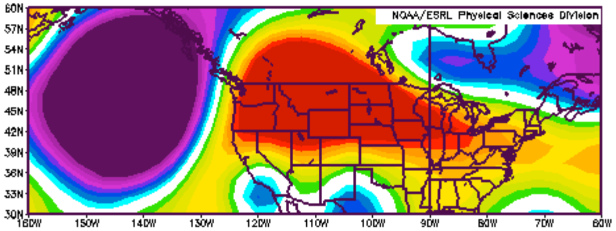




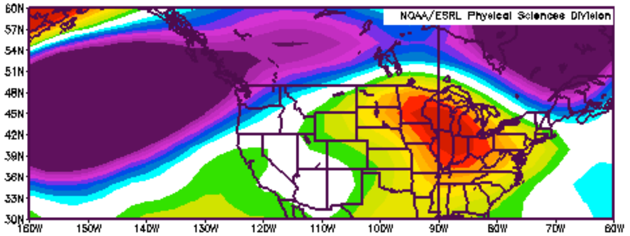
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
6/20/88



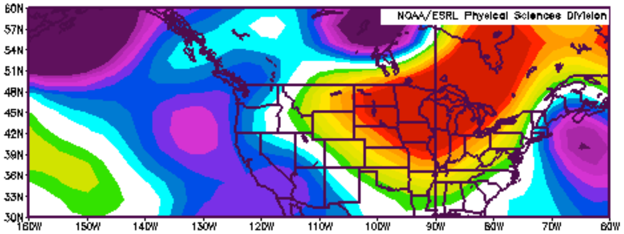
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/4/12



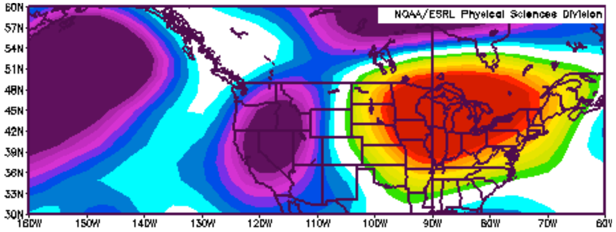
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
6/25/88



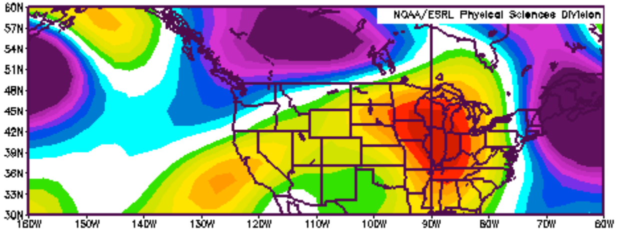
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/15/88



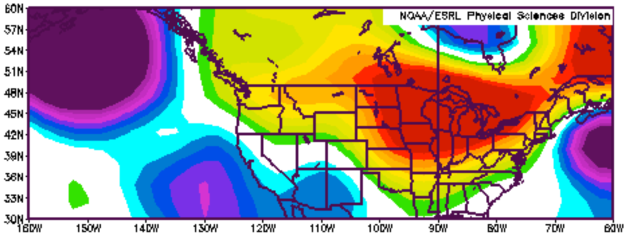
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/5/12



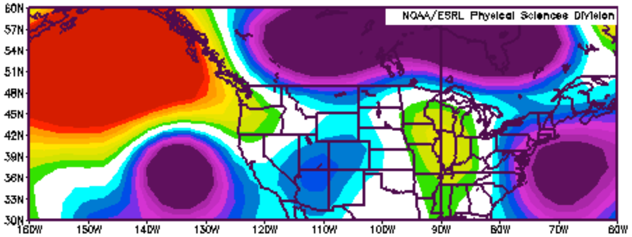
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/13/95



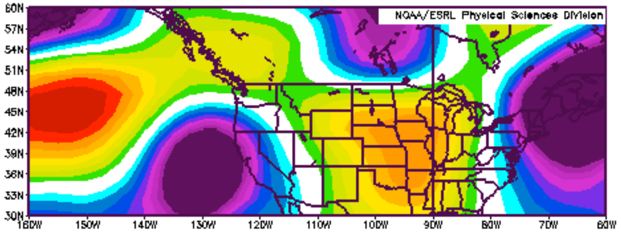
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/24/05



500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/6/12



500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/30/99

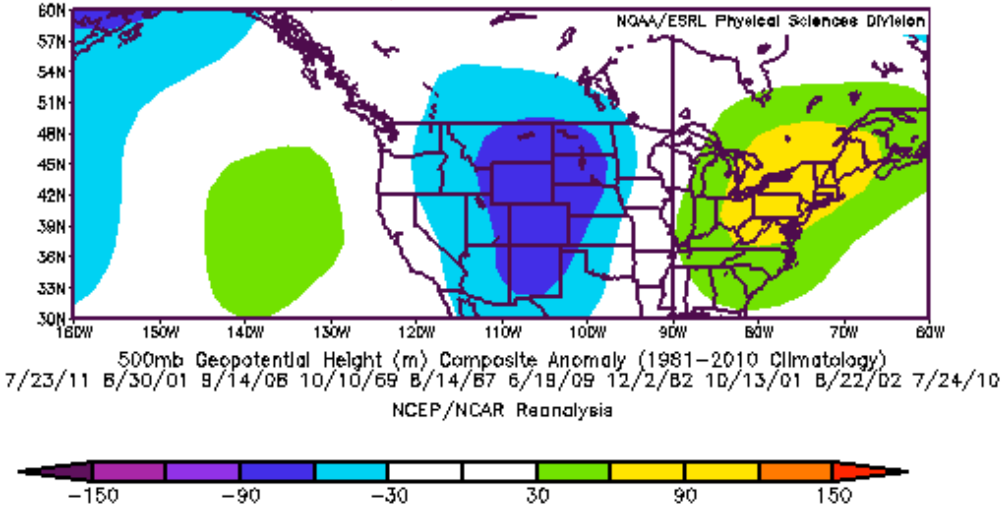


500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/7/80

Chicago’s 10 Wettest Days

500 hPa Anomalies (m)

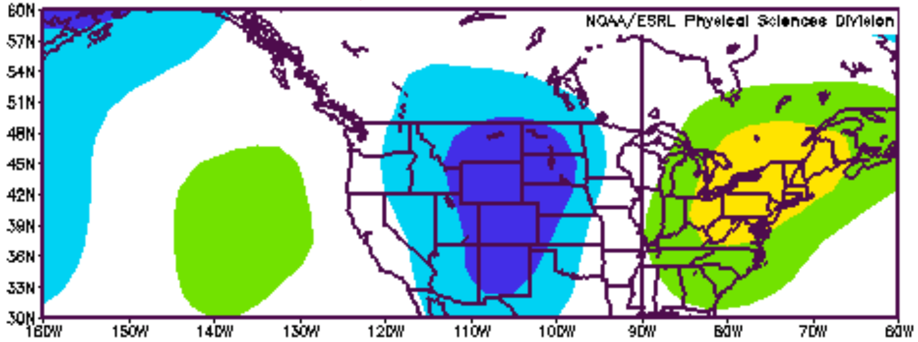
Composite Mean



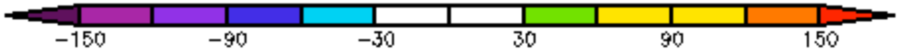
Chicago's 10 Wettest Days

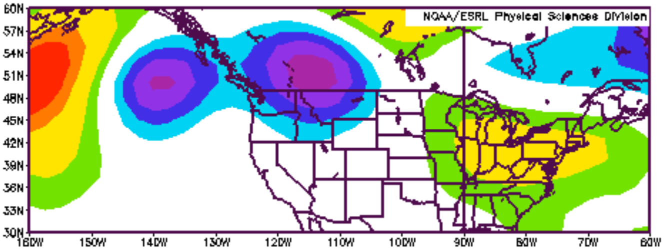
500 hPa Anomalies (m)

Composite Mean

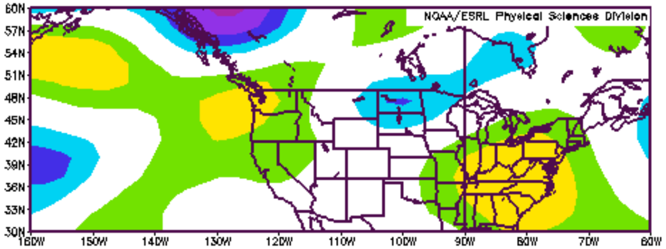


500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/23/11 8/30/01 9/14/06 10/10/69 8/14/87 6/19/09 12/2/82 10/13/01 8/22/02 7/24/10
NCEP/NCAR Reanalysis

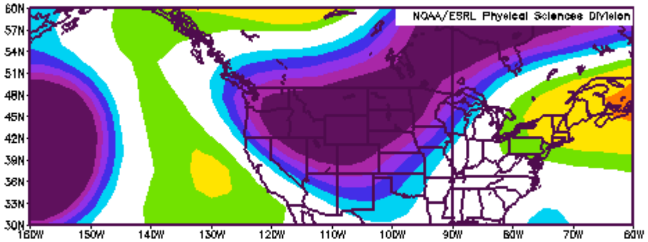




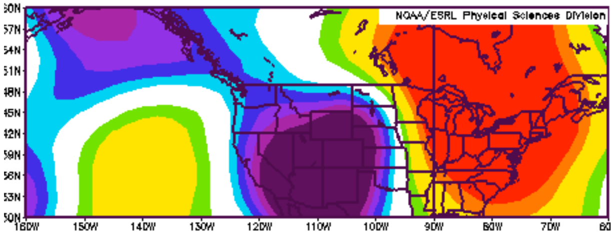
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/23/11



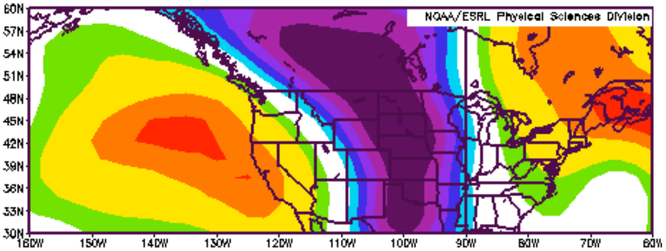
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
7/24/10



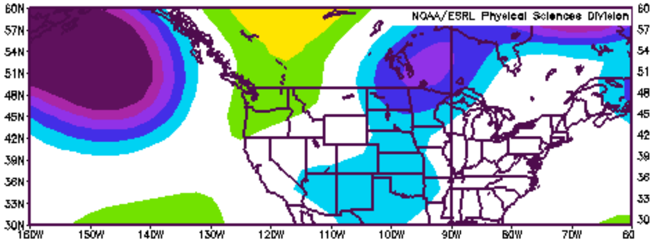
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
10/10/69



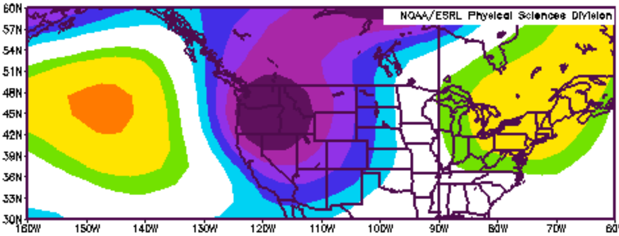
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
12/2/82



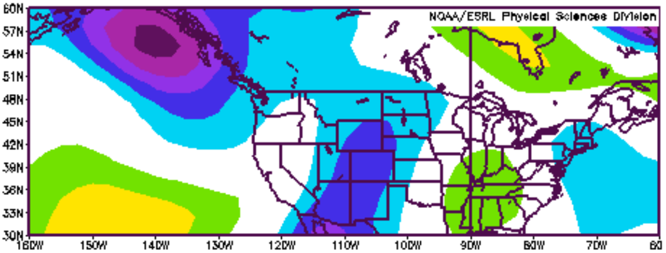
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
10/13/01



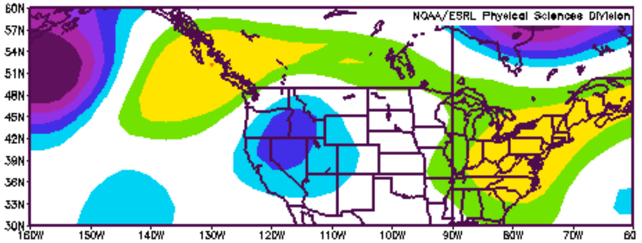
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
8/30/01



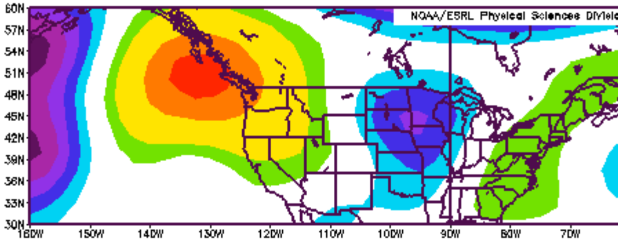
500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
8/14/87



500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
6/19/09



500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
8/22/02

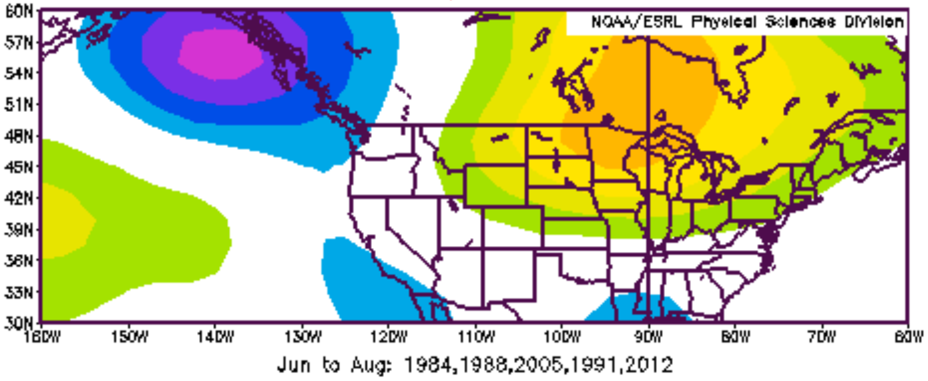


500mb Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
9/14/06

Chicago's 5 Driest Summers

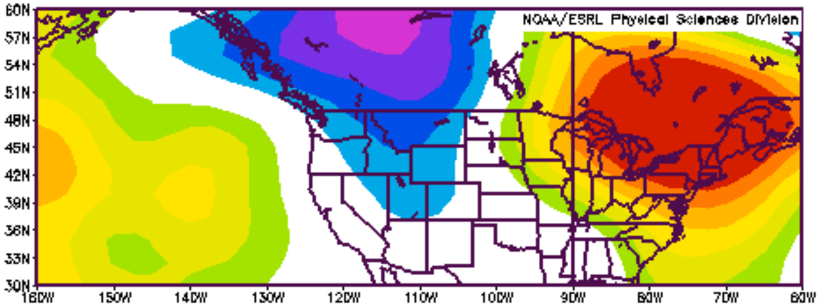
500 hPa Anomalies (m)

Composite Mean

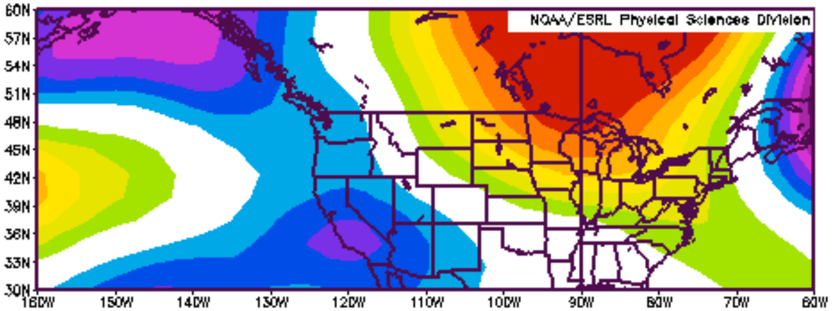


Chicago’s 5 Driest Summers

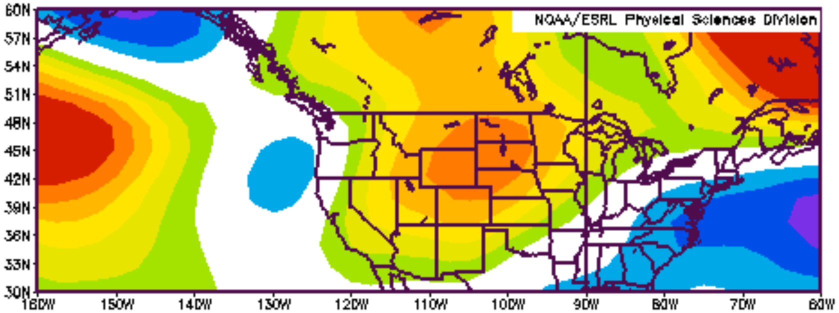
500 hPa Anomalies (m)



Jun to Aug: 2005

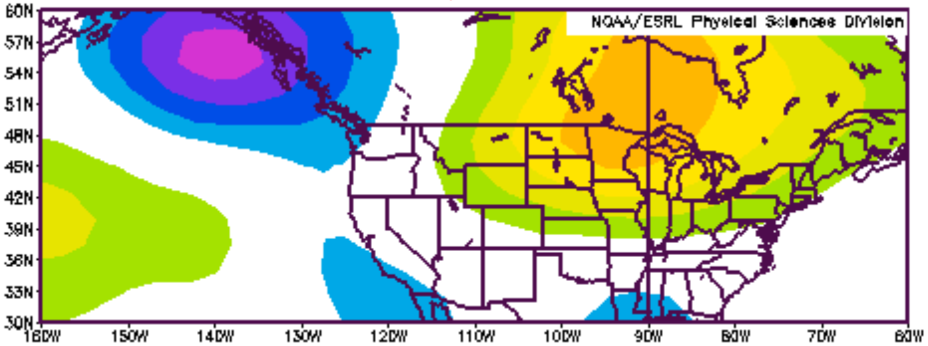


Jun to Aug: 1991

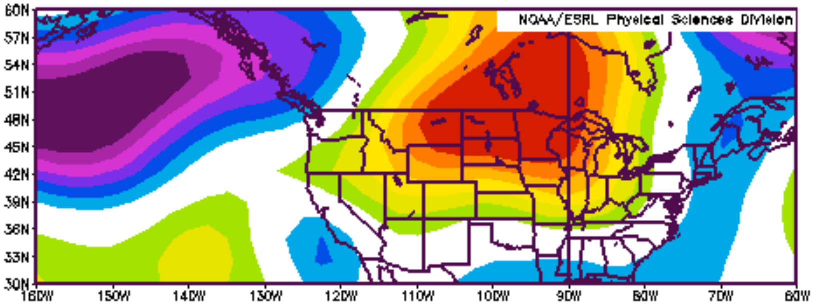


Jun to Aug: 2012

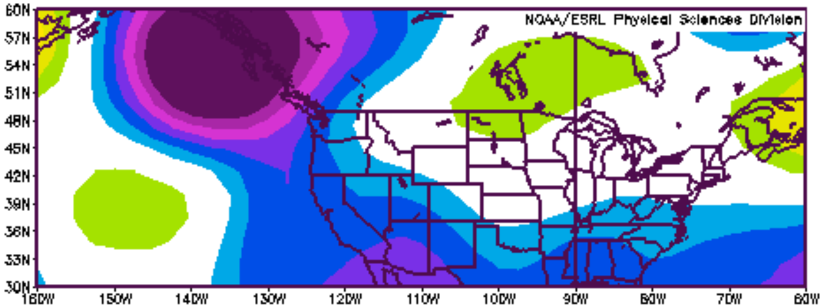
Composite Mean



Jun to Aug: 1984,1988,2005,1991,2012

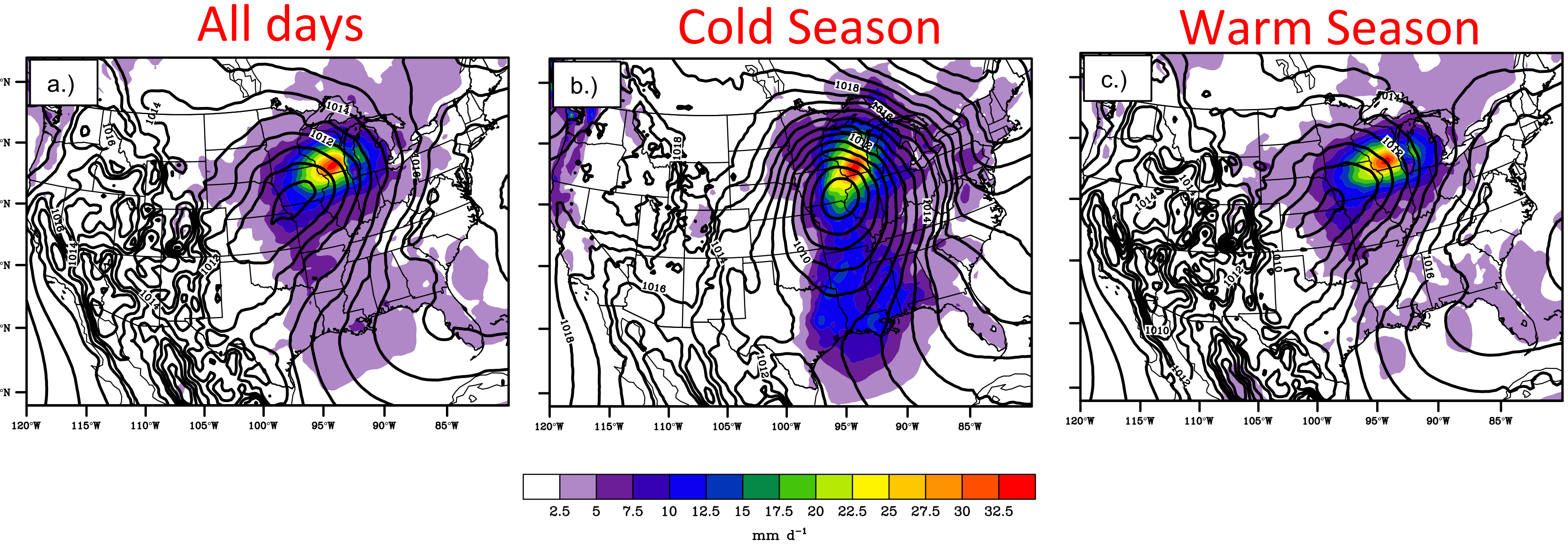


Jun to Aug: 1988



Jun to Aug: 1984

SLP and Precipitation on wettest 1% of days in Madison, WI
North American Regional Reanalysis 1981-2000



All days

Cold Season

Warm Season

Holman and Vavrus
J. Hydromet., 2012

Simulated SLP and Precipitation on wettest 1% of days in Madison, WI: 20th Century

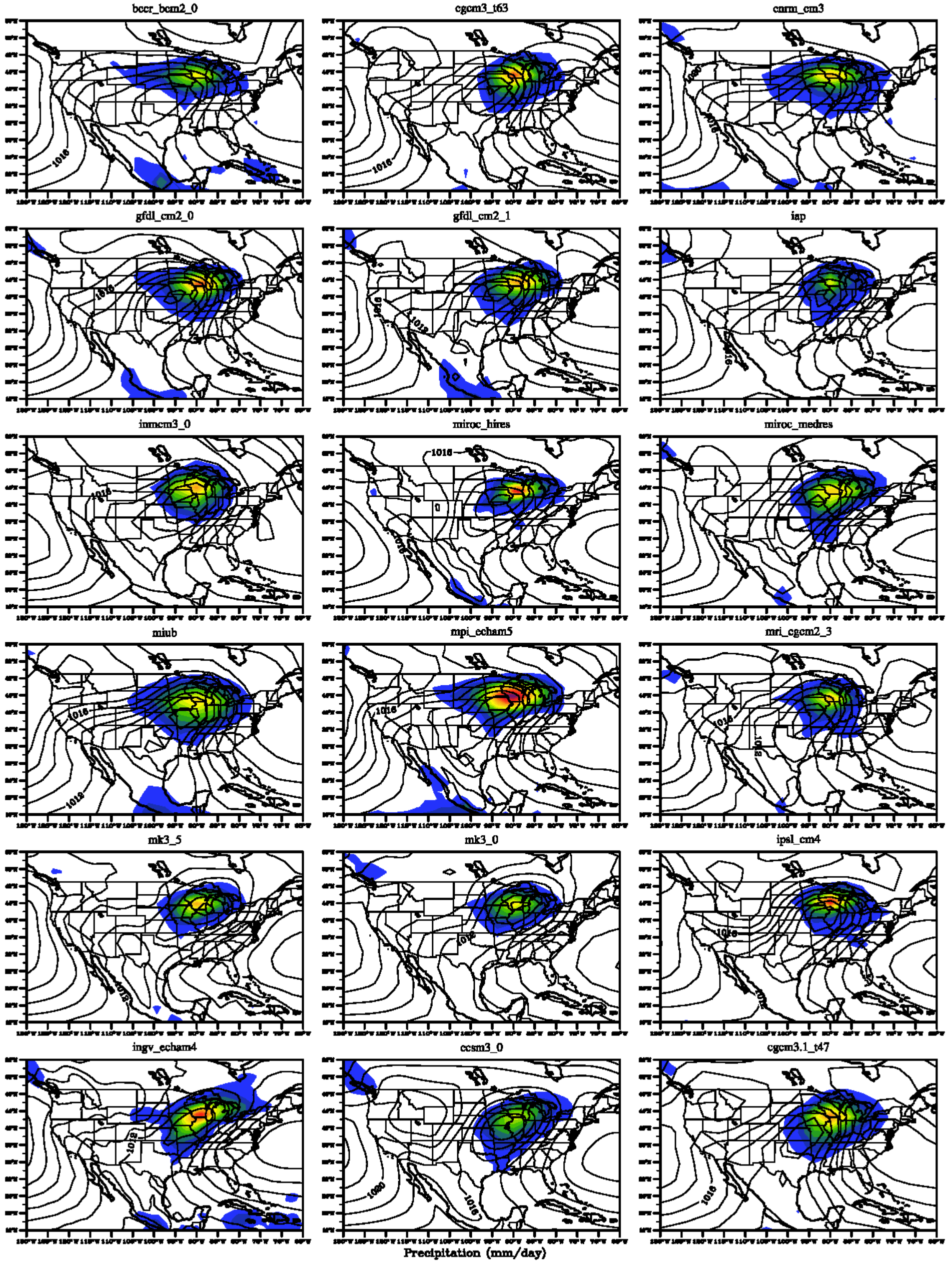


FIGURE 3.13: Late twentieth century (1981-2000) spatial composites of daily precipitation (mm/day) and sea-level pressure (hPa, contoured every 2hPa) during the wettest 1% of days for

Holman and Vavrus
J. Hydromet., 2012

Simulated SLP and Precipitation on wettest 1% of days in Madison, WI: 21st Century

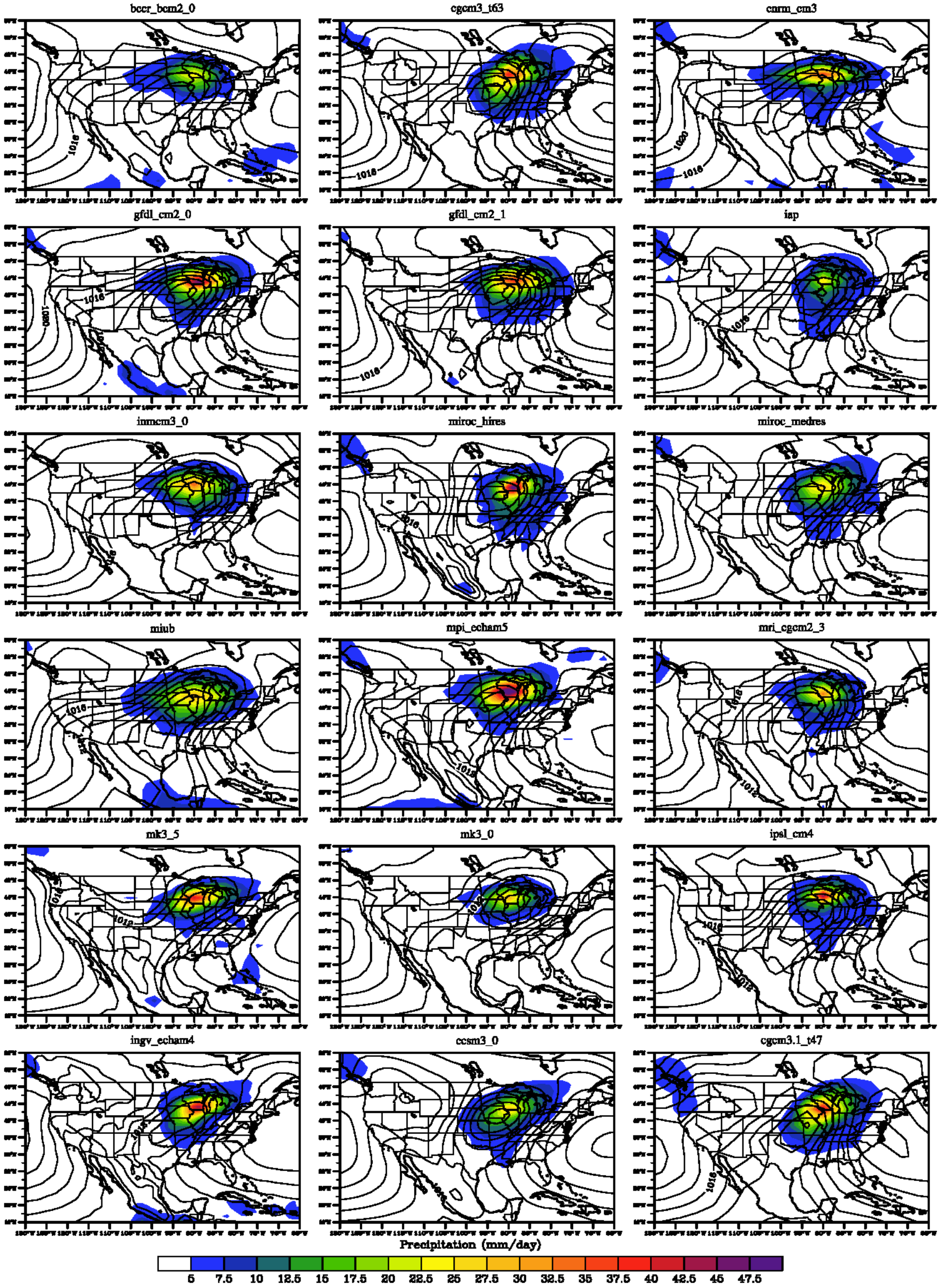
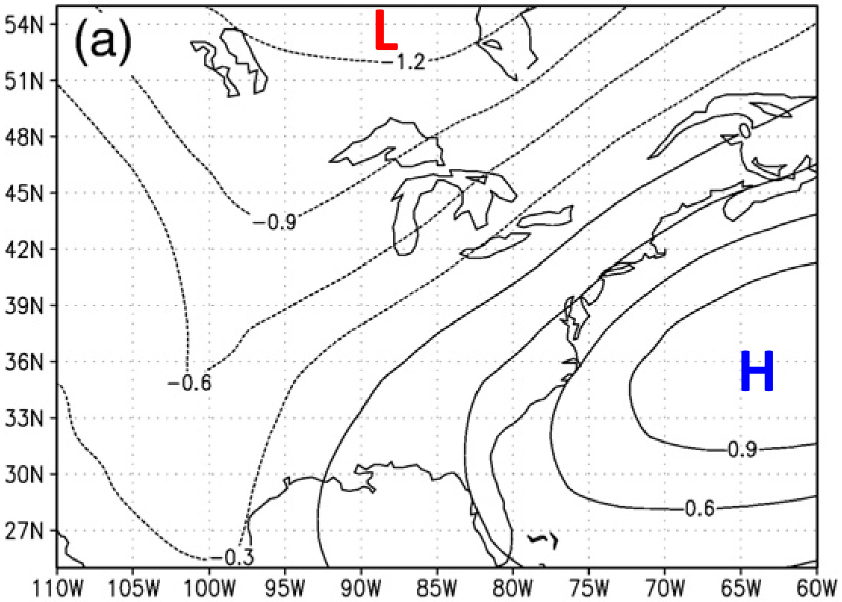
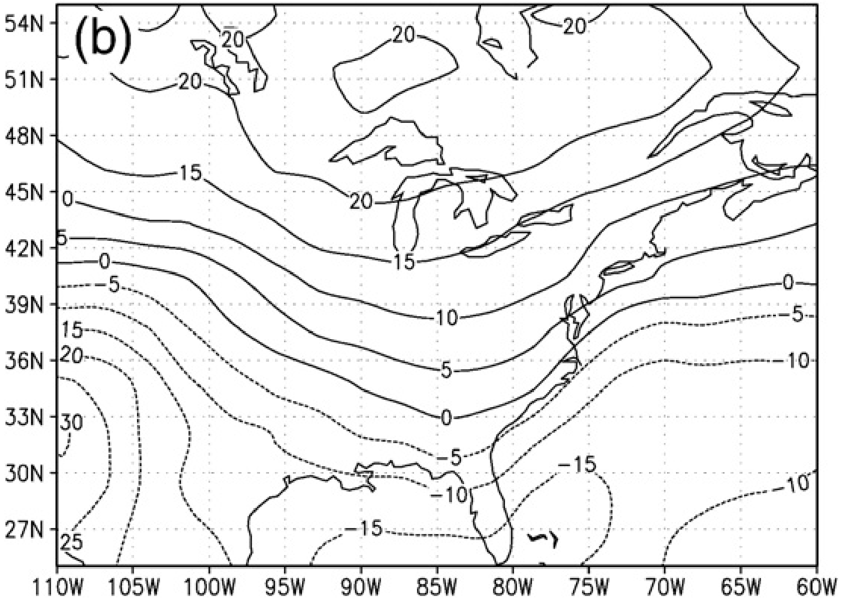


FIGURE 3.14: Same as Fig 3.13 except for the late twenty-first century (2081-2100).

Synoptic Pattern related to Projected Climate Change Springtime Precipitation (mid-21st Century, A1B)



SLP Response (hPa)

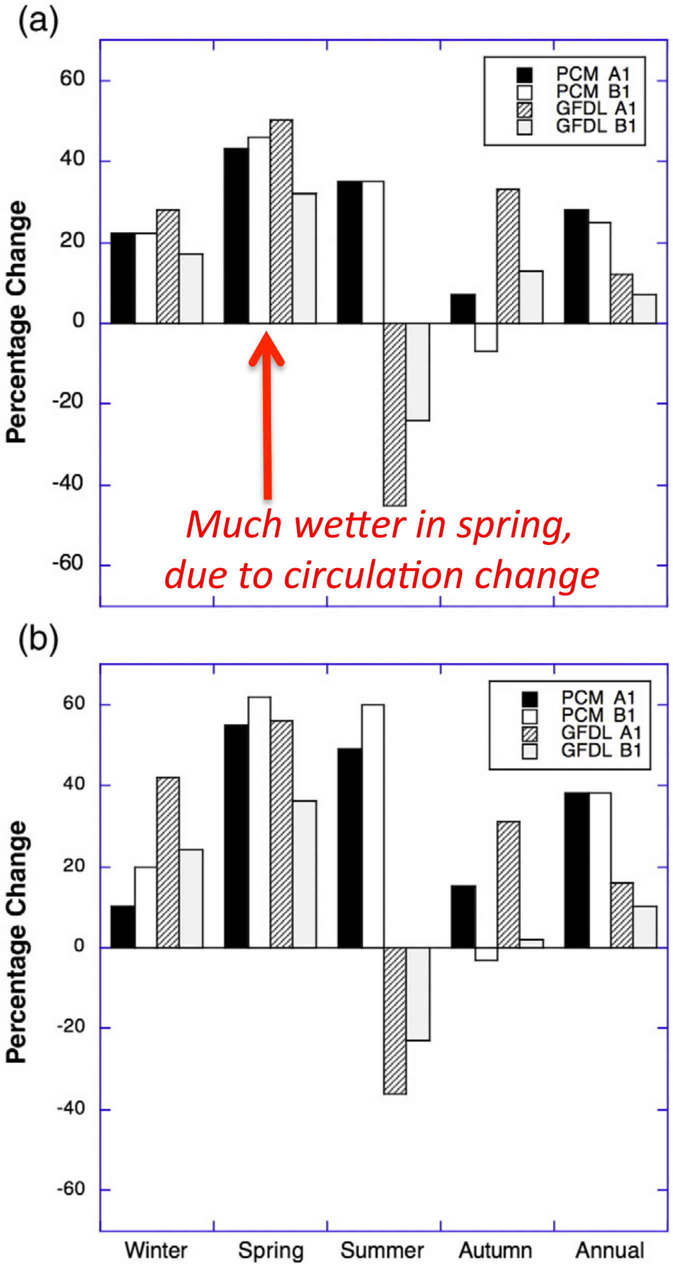


Precipitation Change (%)

Relationship between Changes in Mean and Extreme Precipitation (Chicago, late 21st Century)

Mean Precipitation

Extreme Precipitation
(wettest 5% of days)



Much wetter in spring,
due to circulation change

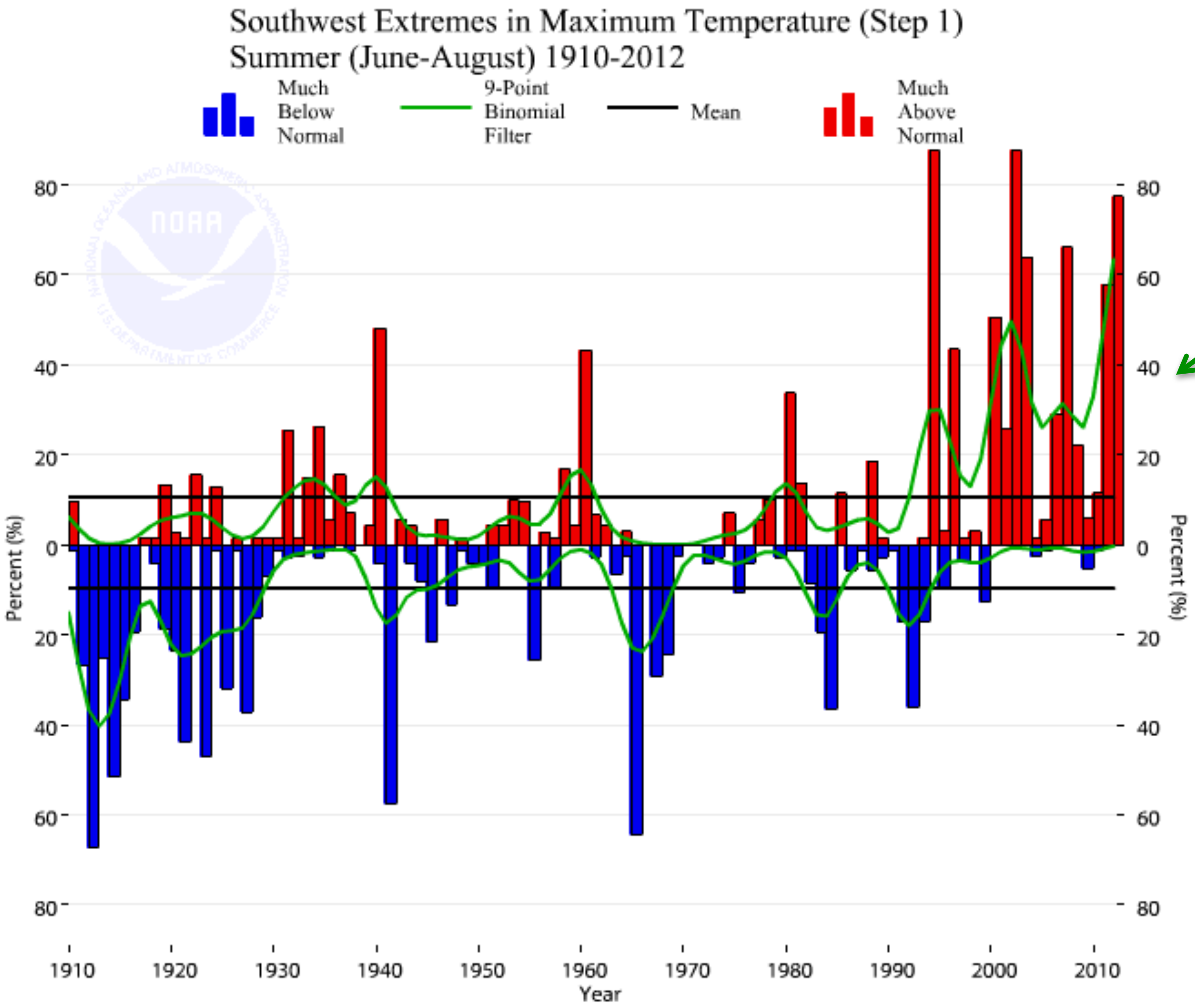
Increased heavy precipitation mirrors mean changes in every season

Vavrus and van Dorn, JGLR 2010

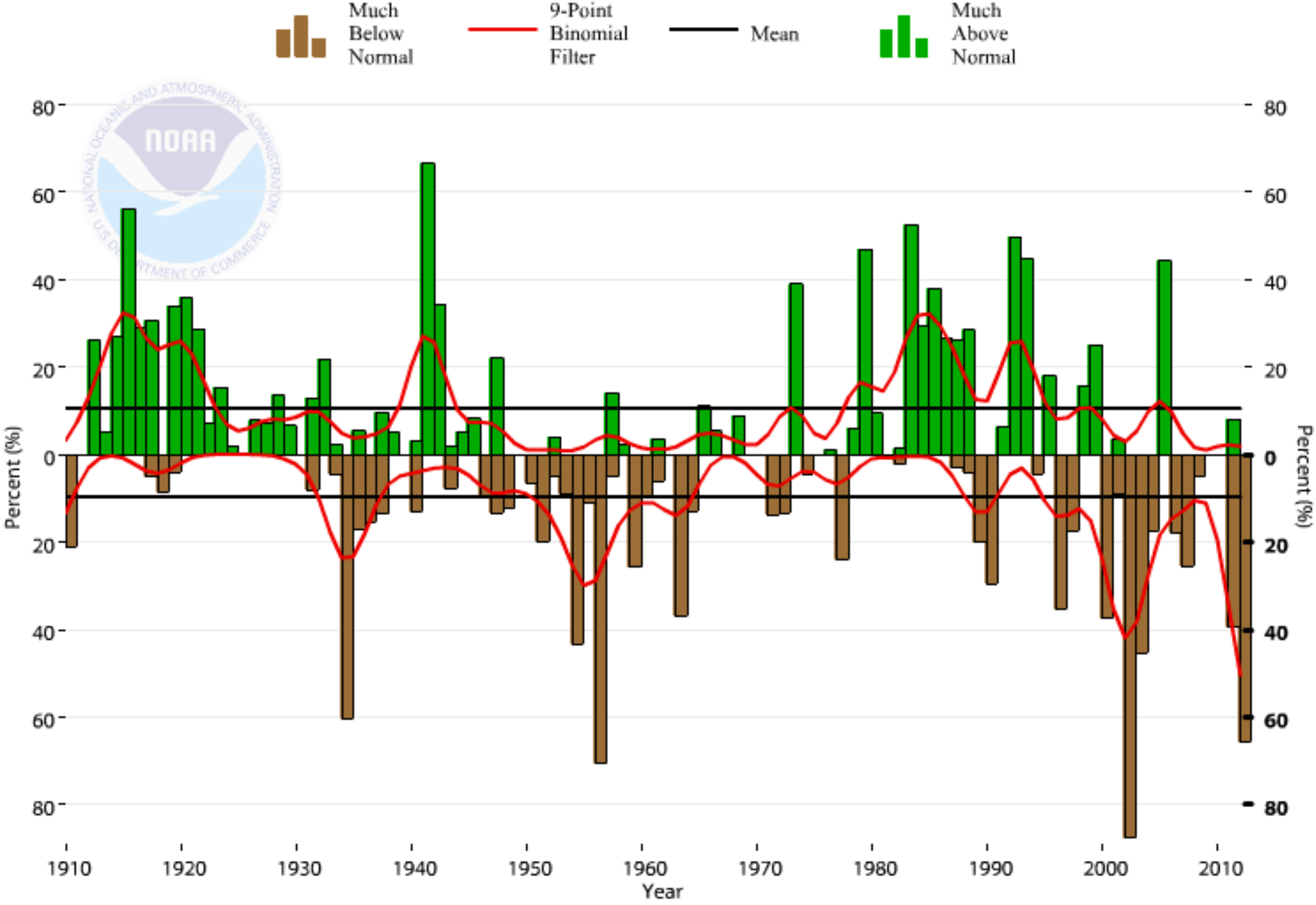
Back to the present day climate. . . .

U. S. Climate Extremes Index

Summer Daily Maximum Temperature (Southwestern U. S.)

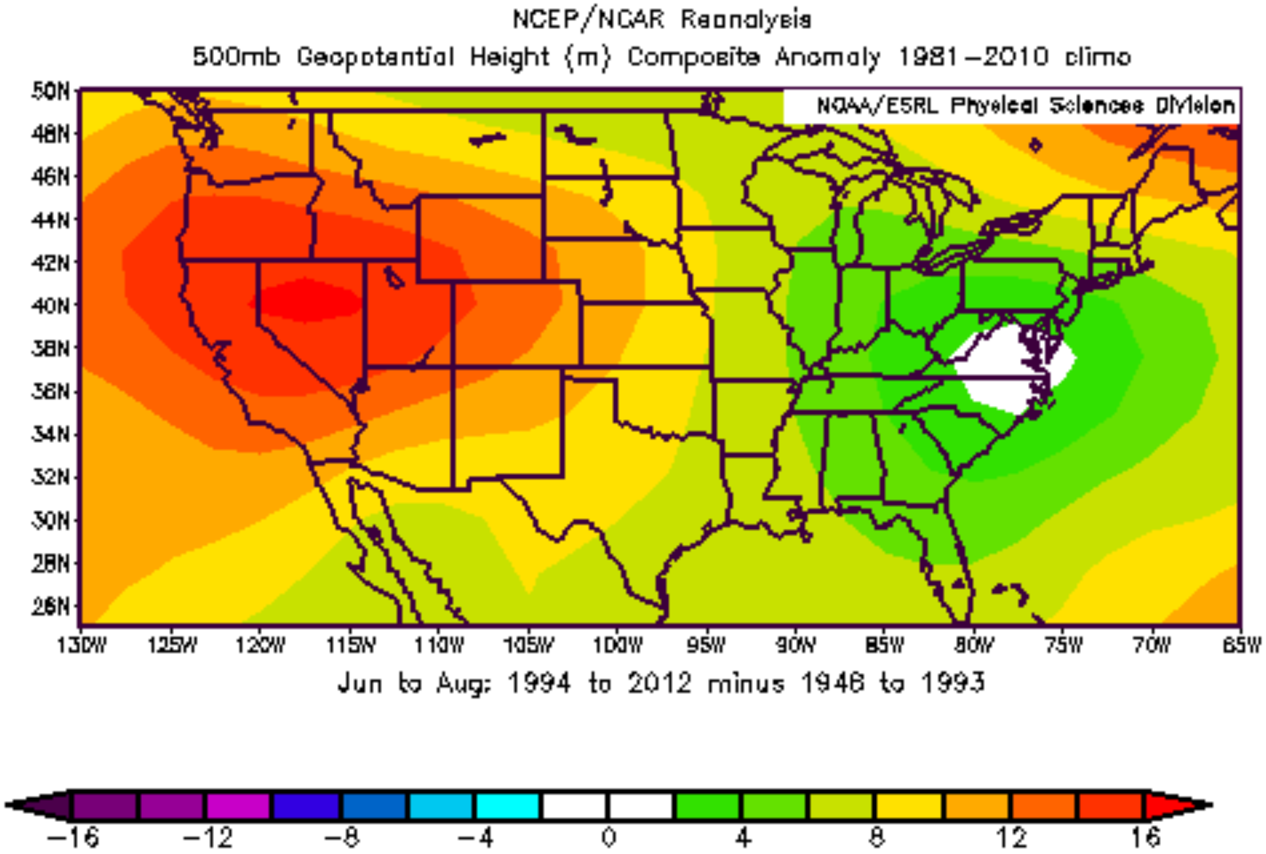


Recent trend: hotter summers


Southwest Extremes in PDSI (Step 3)
Summer (June-August) 1910-2012

Summer Circulation Change since mid-1990s

500 hPa anomaly (post-1994 minus pre-1994)



Synoptic Evolution of Extreme Cold-Air Outbreaks (CAOs)

Midwestern CAOs

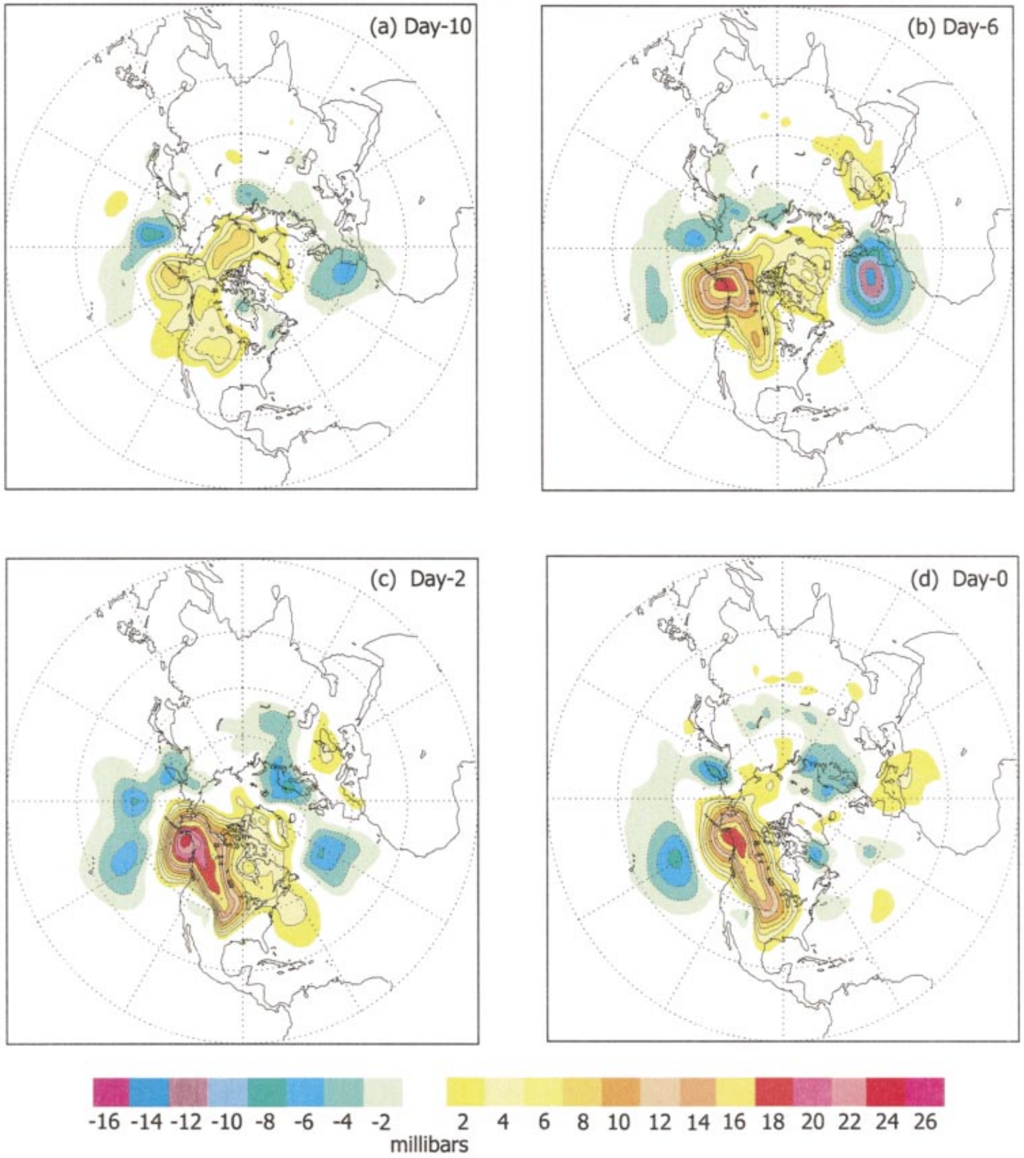
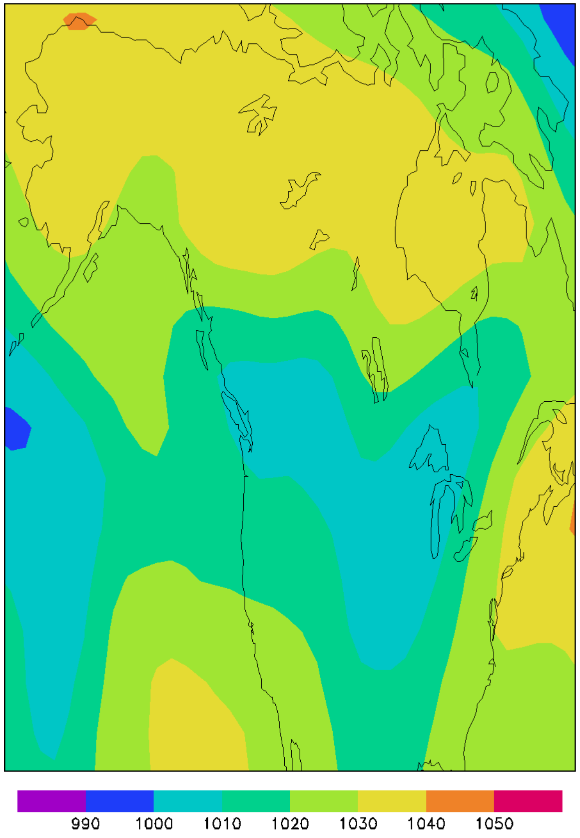


FIG. 7. SLP anomaly composites for (a) 10 days, (b) 6 days, (c) 2 days, and (d) 0 days prior to the dates of the 10 cold events in the Midwest (MW) region. Numbers below color bar denote the lower limit of each 2-mb range of magnitudes. Unshaded areas have magnitudes smaller than 2 mb.

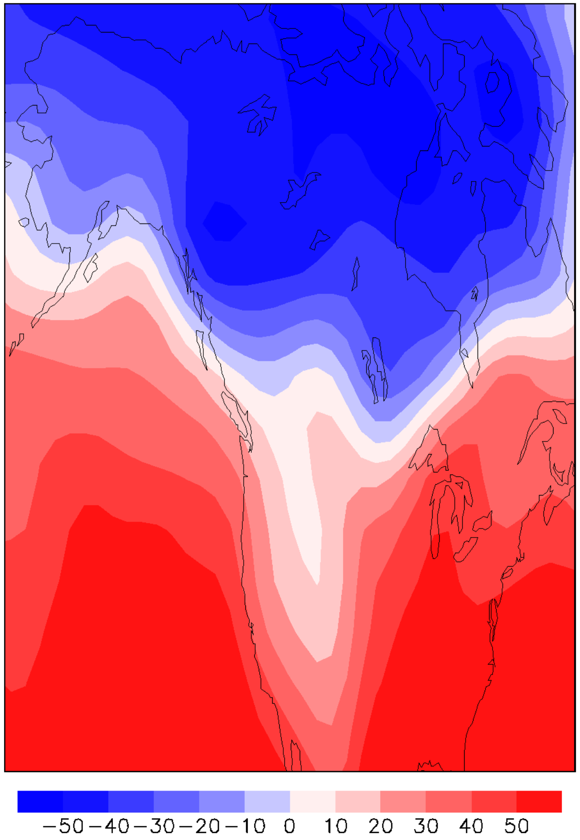
Walsh et al.
J Climate (2001)

CSM Simulation of a CAO (February 24 - March 8)

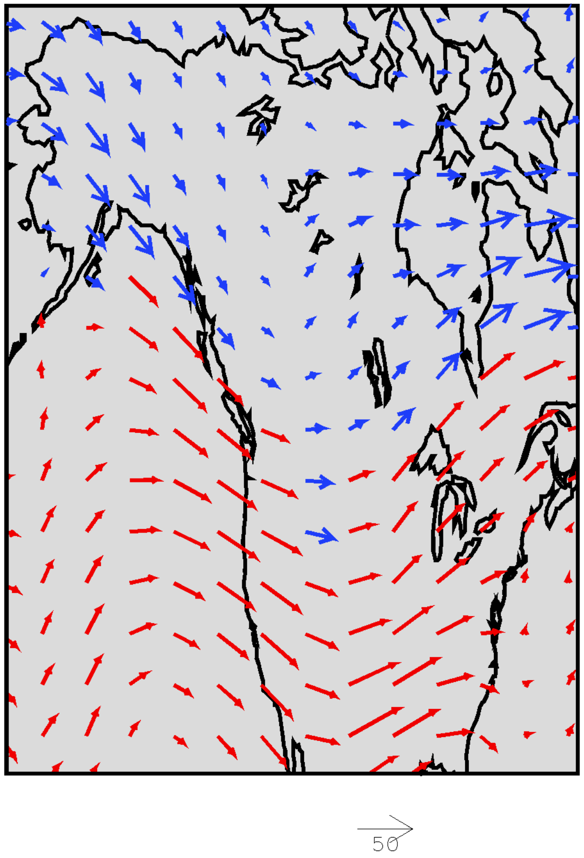
Day 1 SLP



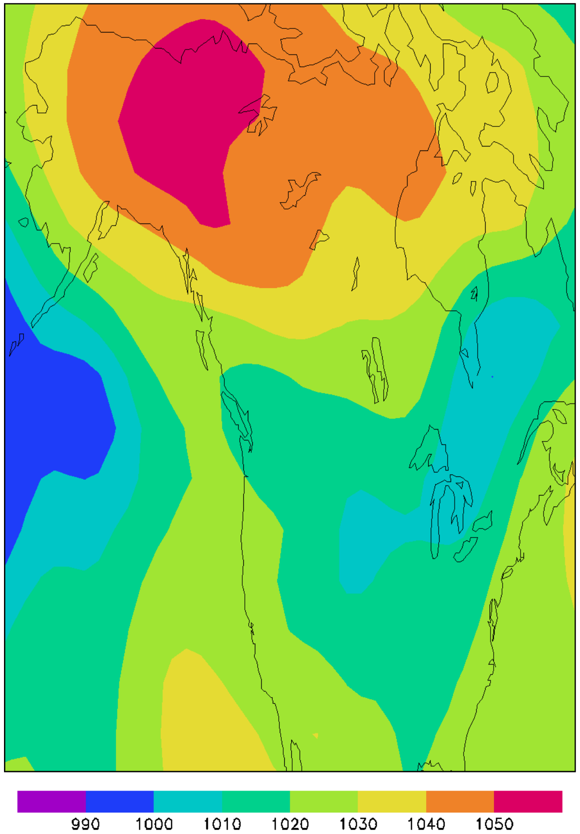
Day 1 Temperature



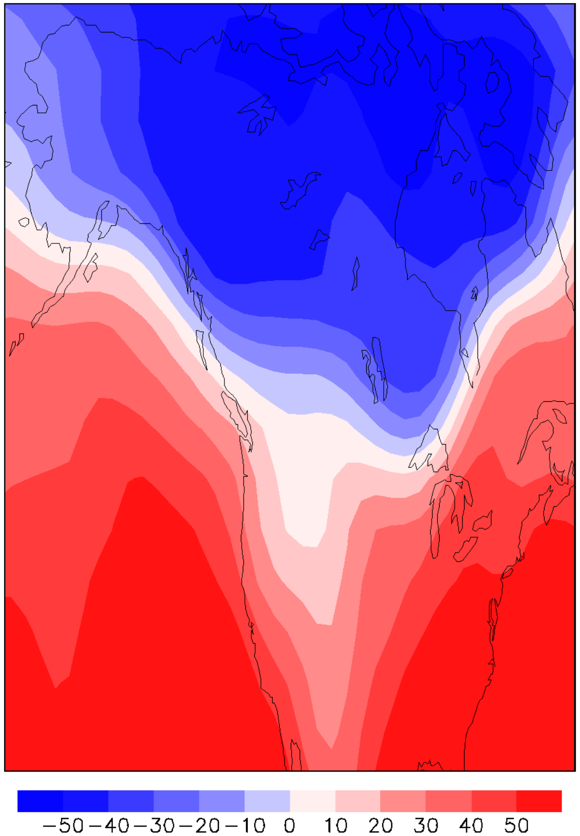
Day 1 500 hPa Wind



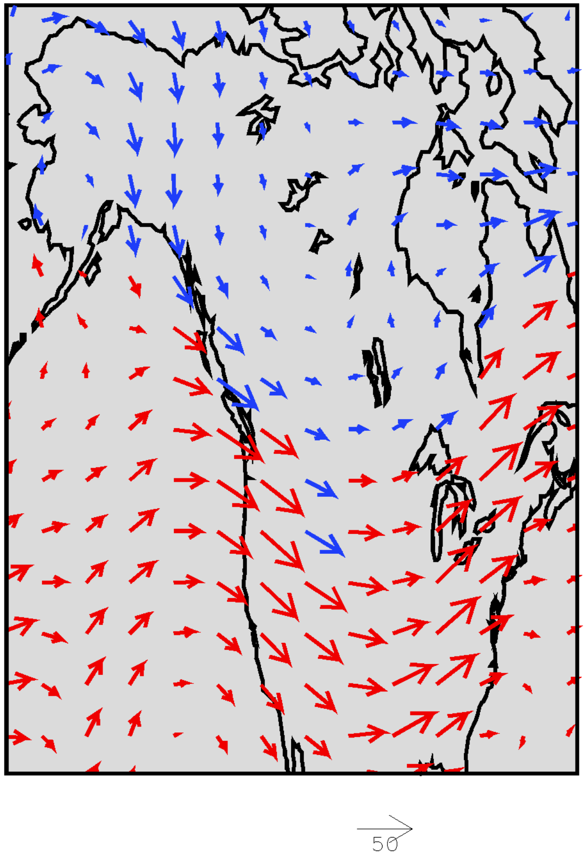
Day 2 SLP



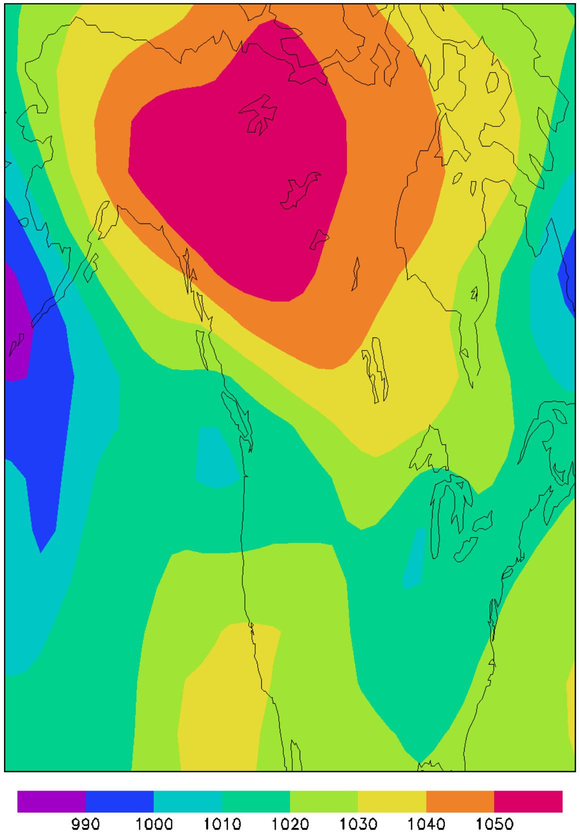
Day 2 Temperature



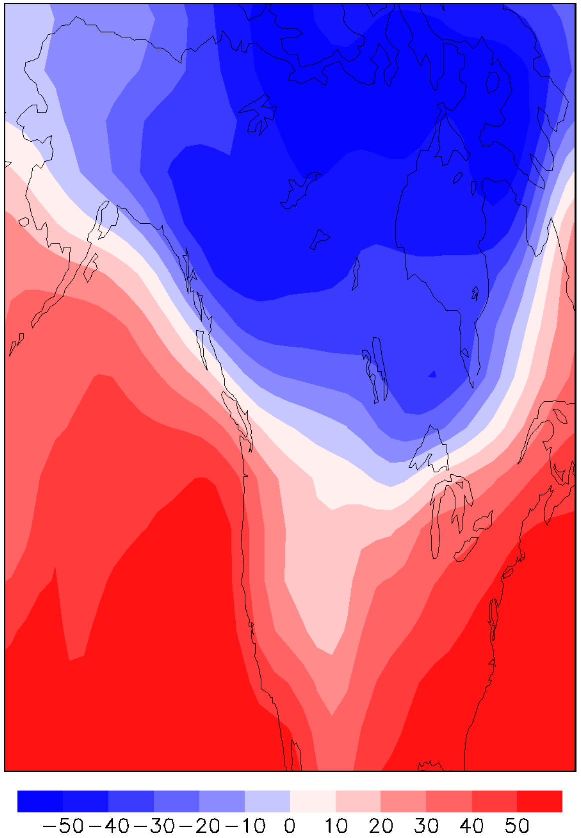
Day 2 500 hPa Wind



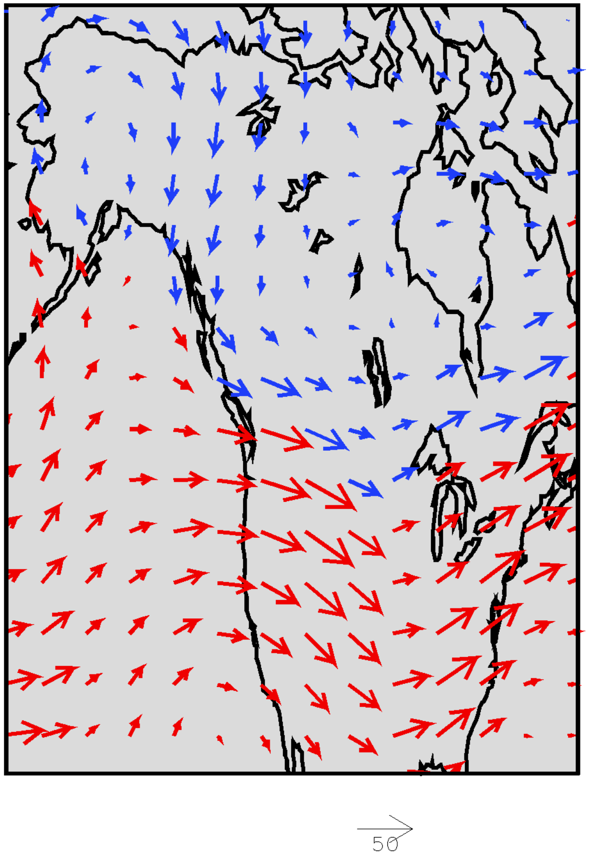
Day 3 SLP



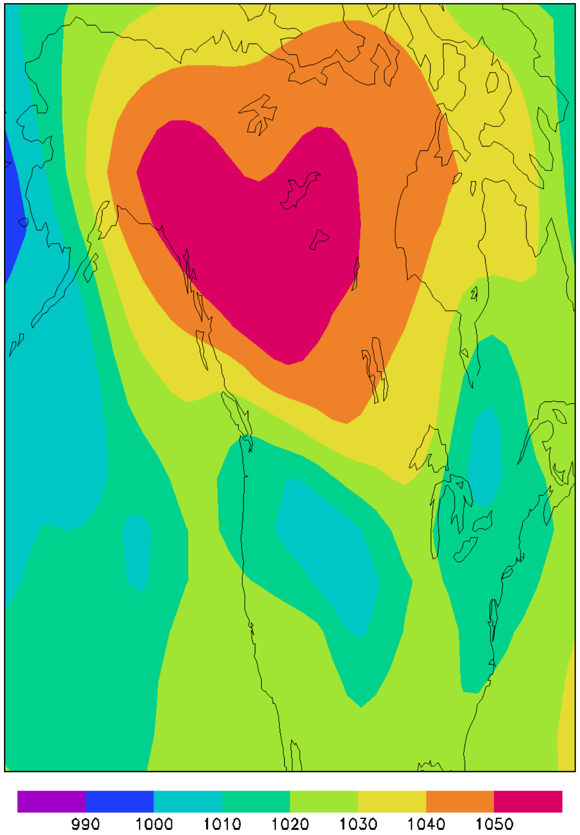
Day 3 Temperature



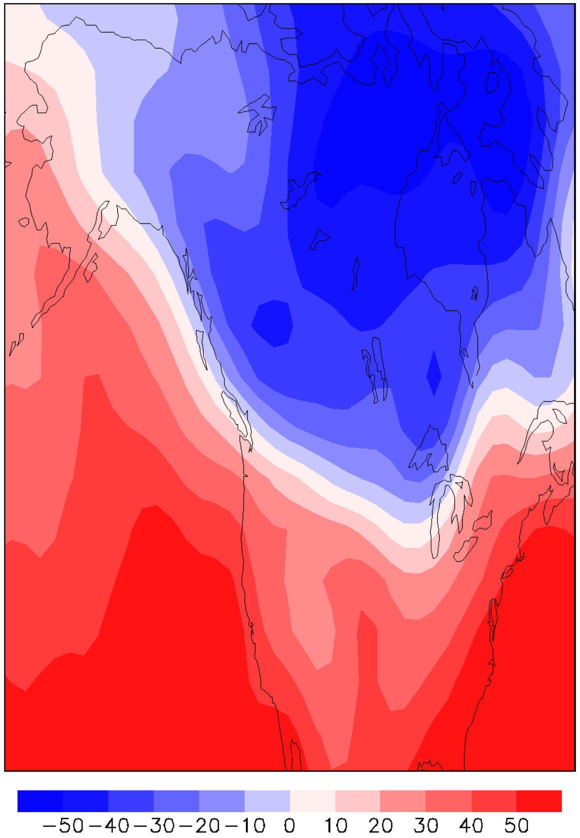
Day 3 500 hPa Wind



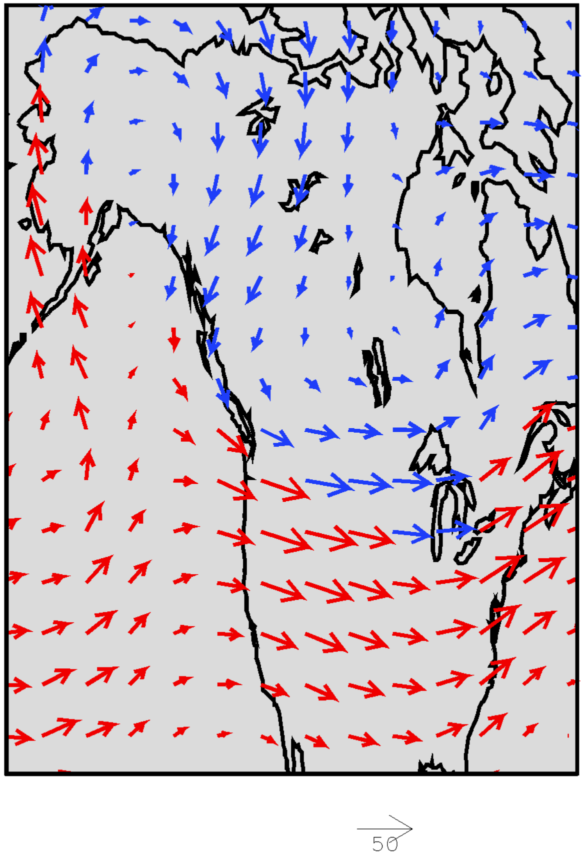
Day 4 SLP



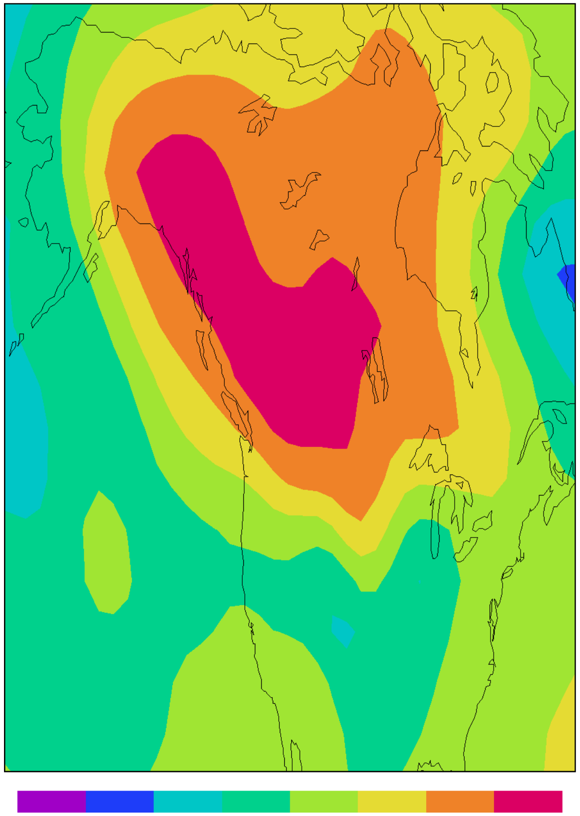
Day 4 Temperature



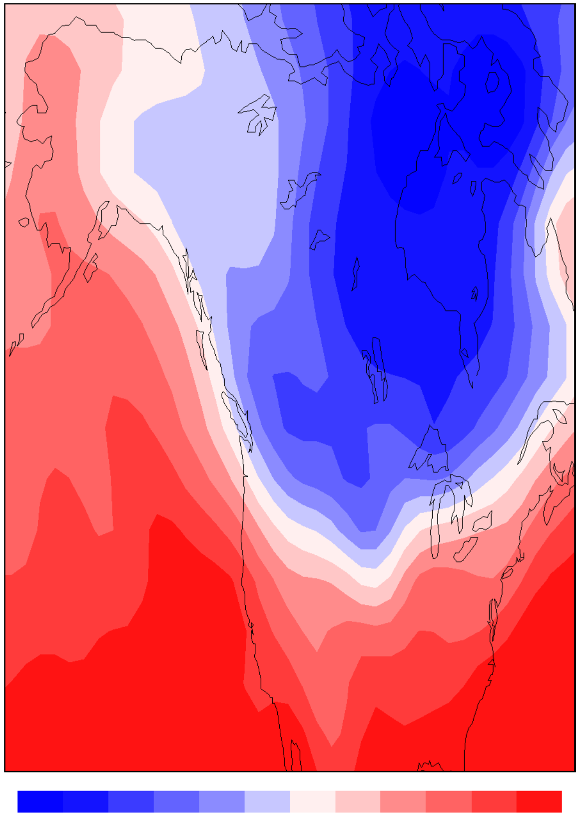
Day 4 500 hPa Wind



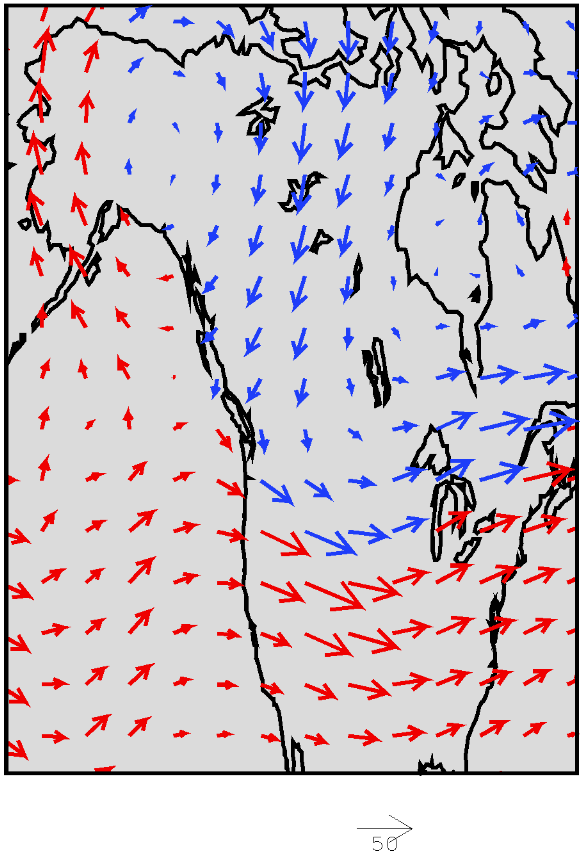
Day 5 SLP



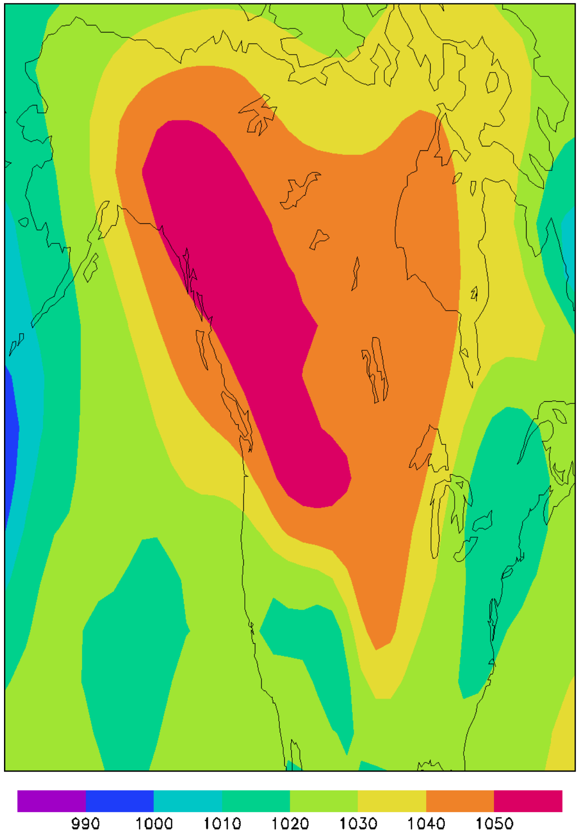
Day 5 Temperature



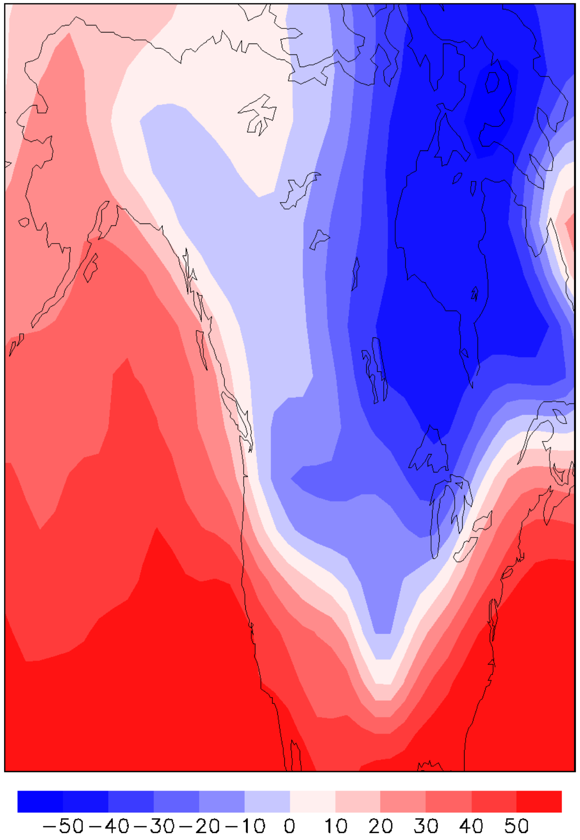
Day 5 500 hPa Wind



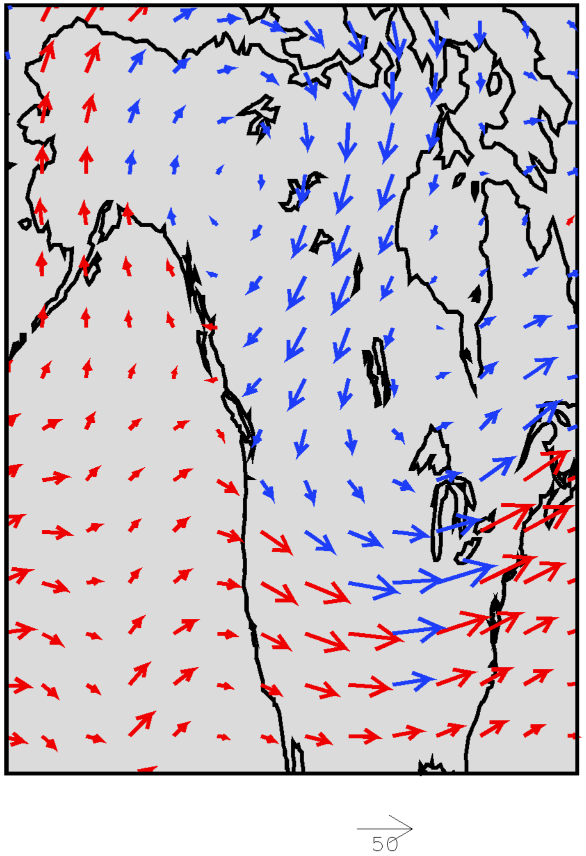
Day 6 SLP

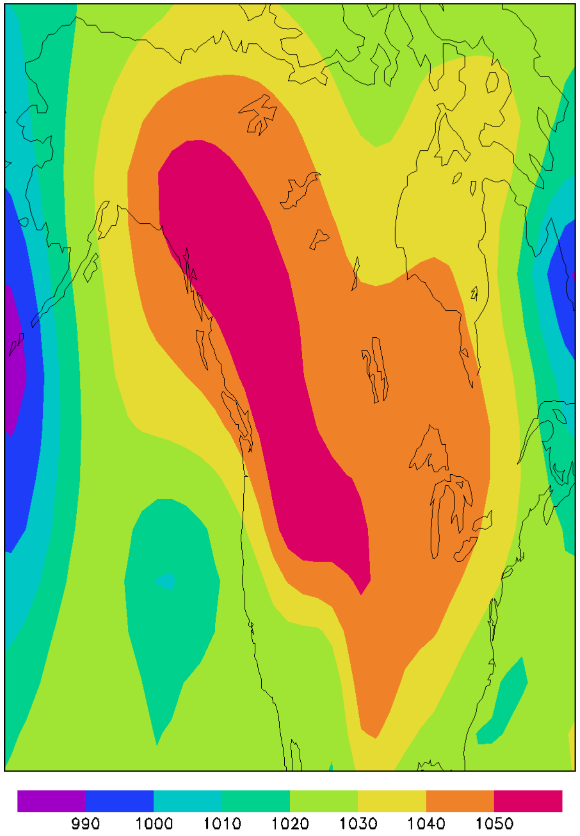


Day 6 Temperature

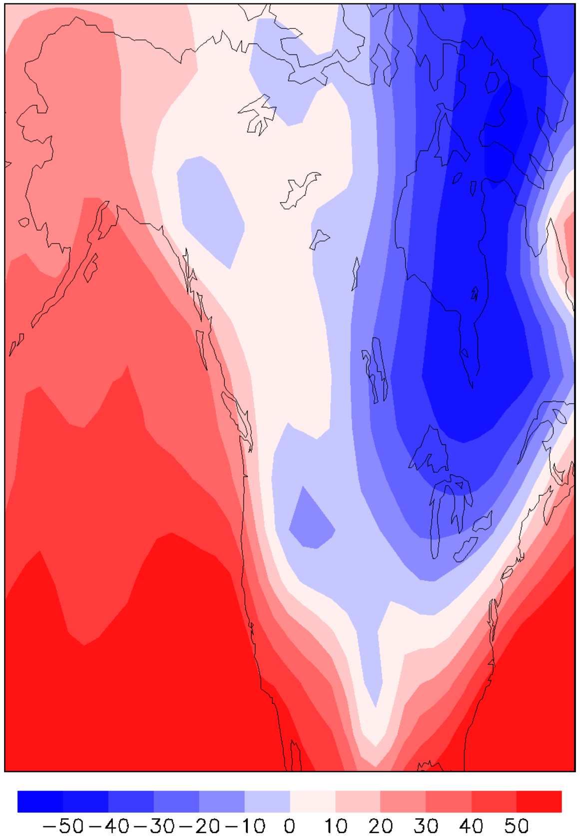


Day 6 500 hPa Wind

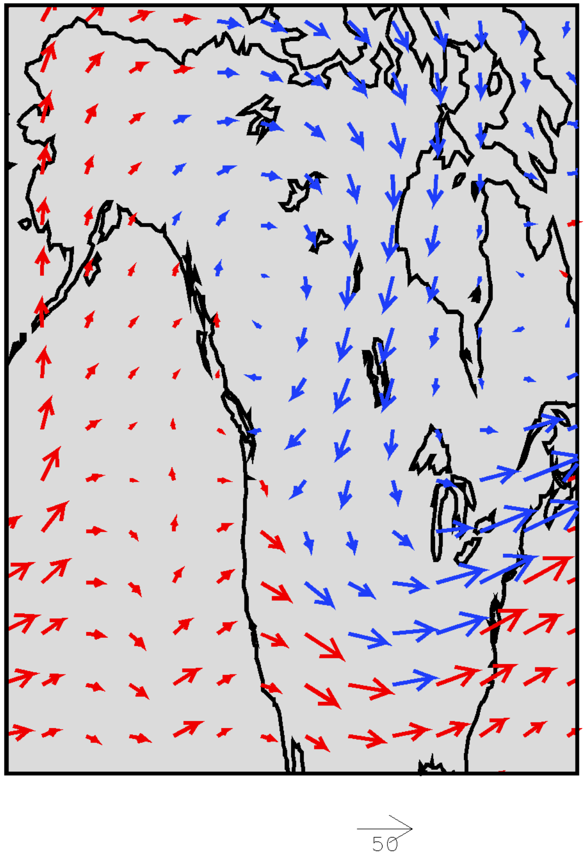




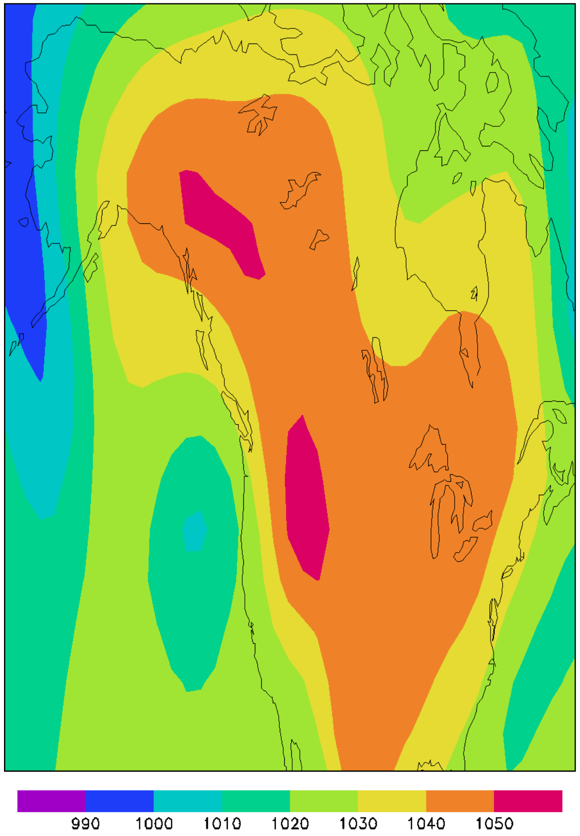
Day 7 SLP

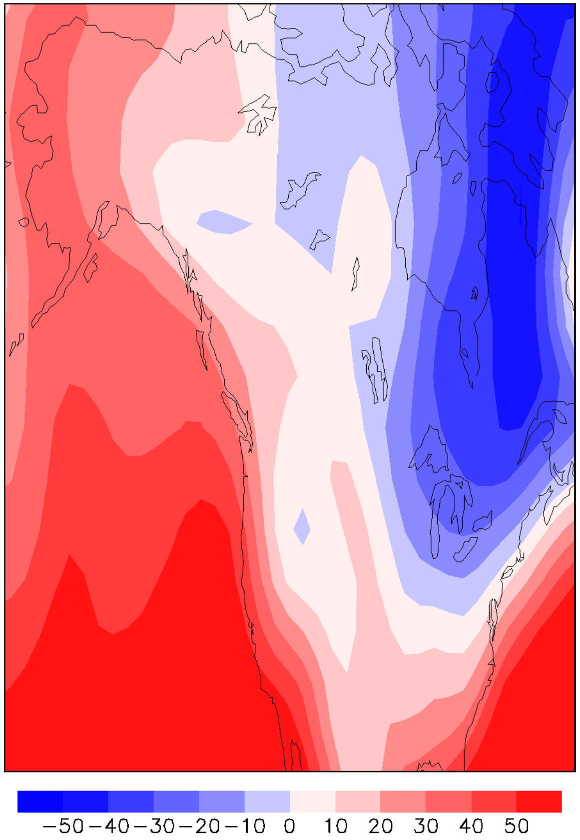


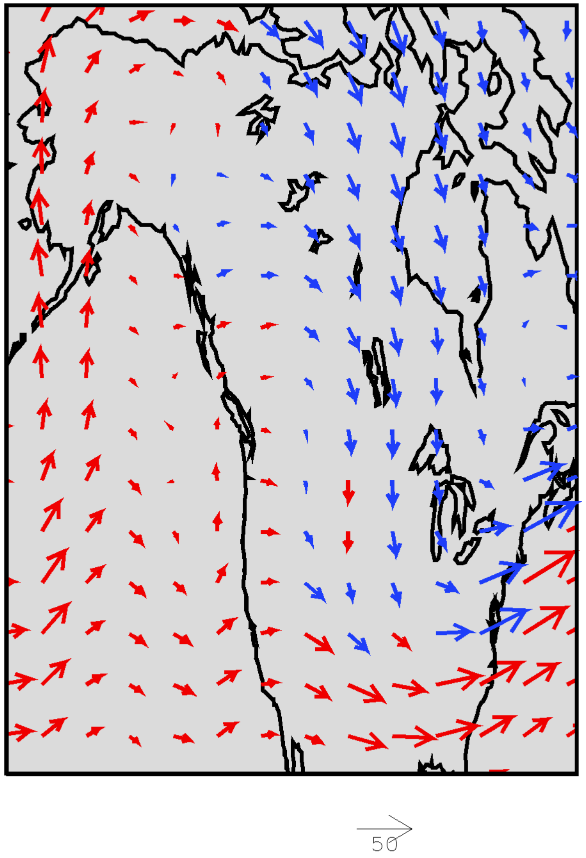
Day 7 Temperature



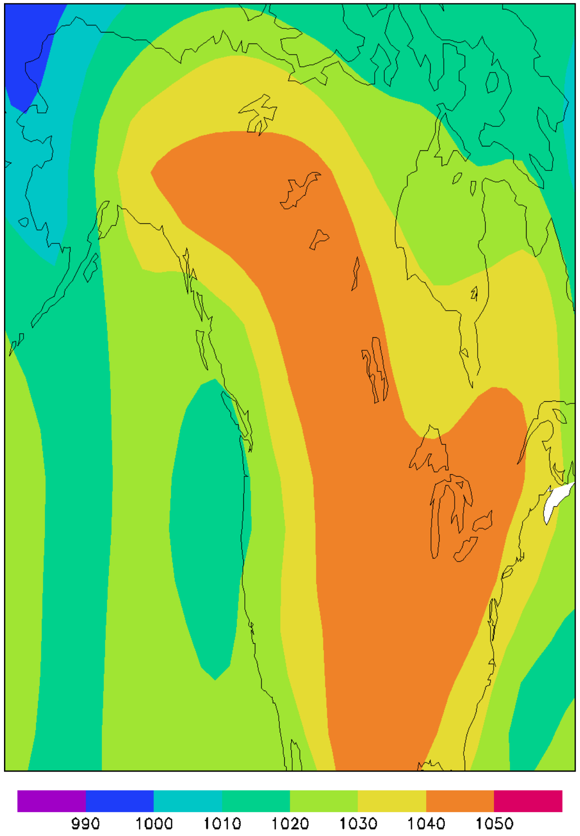
Day 7 500 hPa Wind


Day 8 SLP

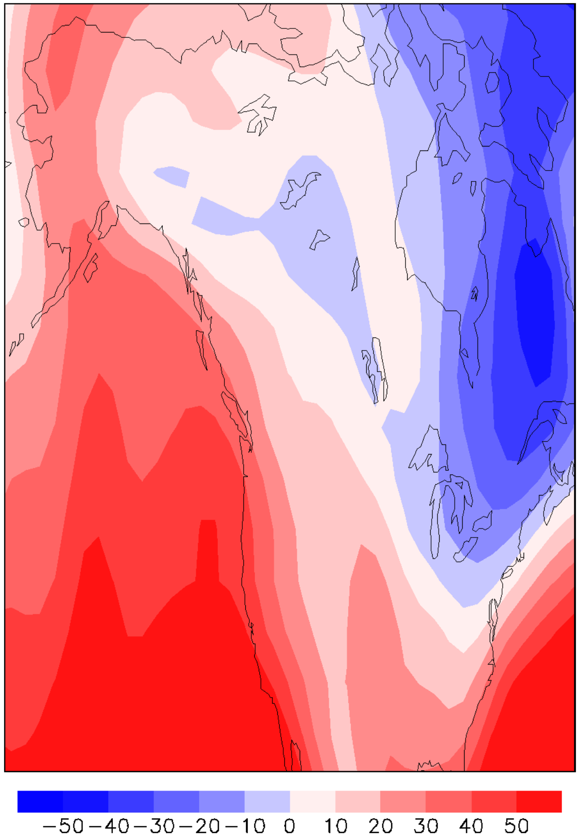

Day 8 Temperature


Day 8 500 hPa Wind

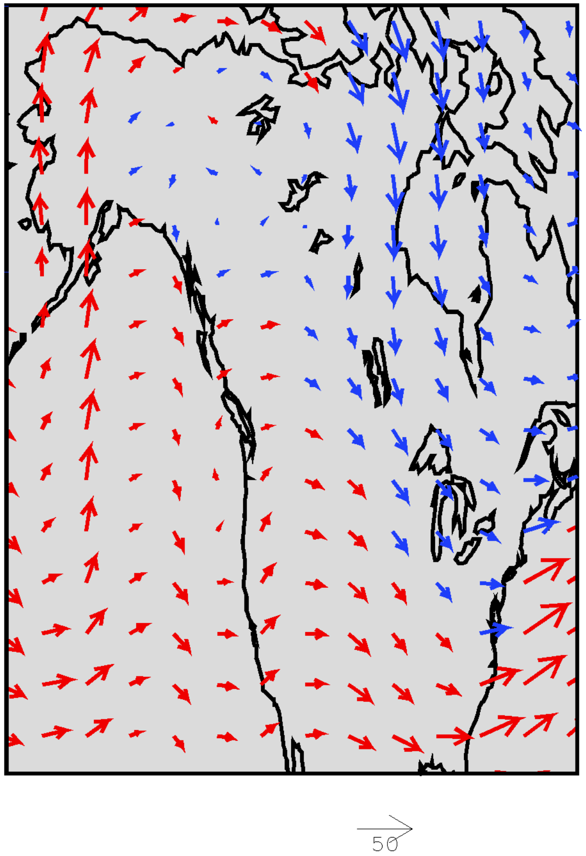
Day 9 SLP



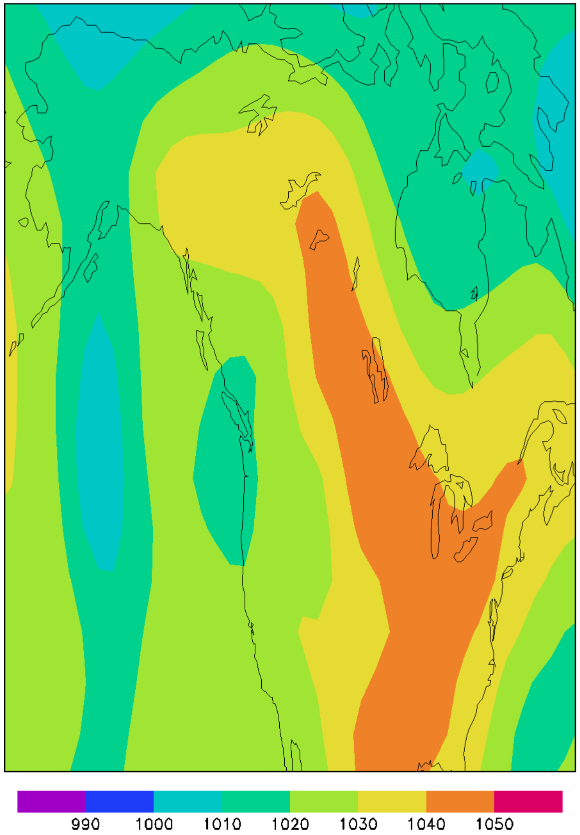
Day 9 Temperature



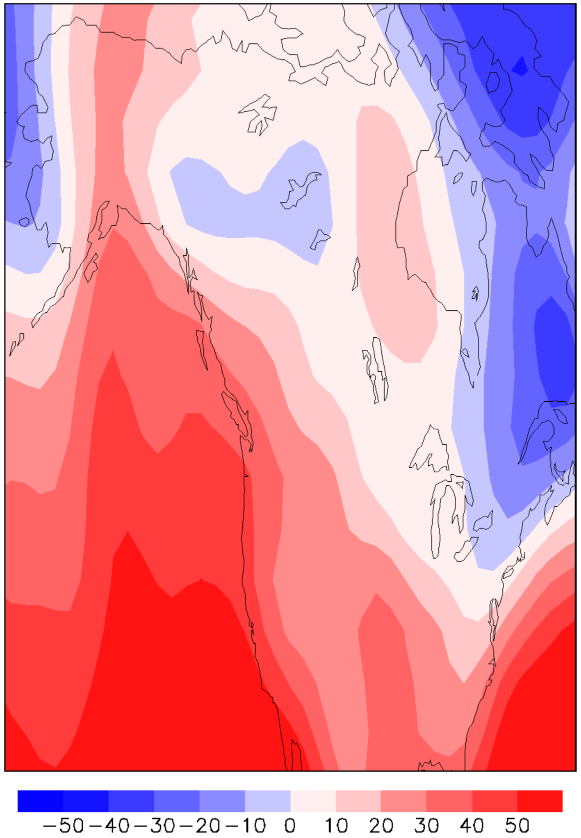
Day 9 500 hPa Wind



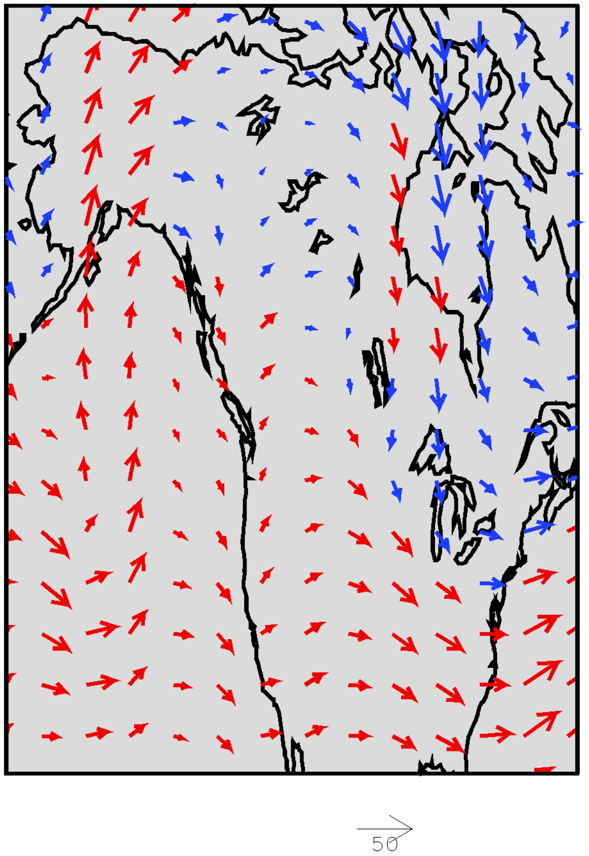
Day 10 SLP

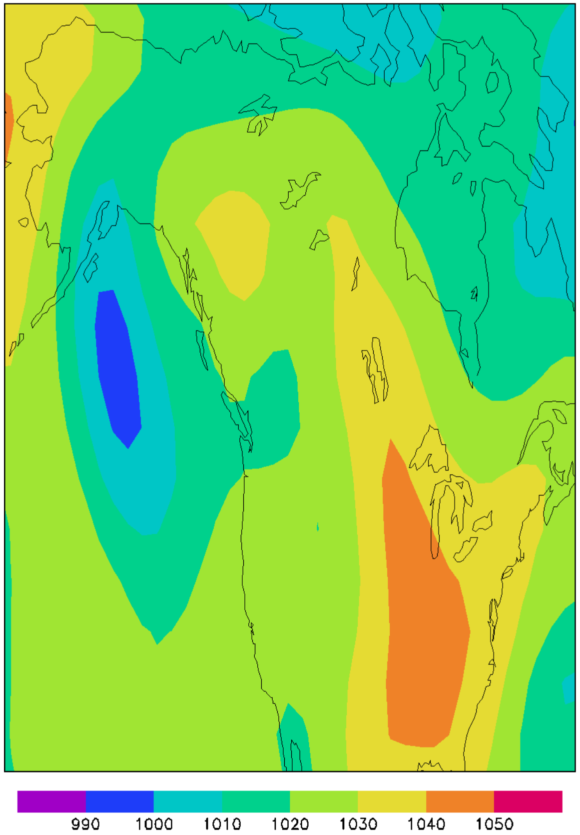


Day 10 Temperature

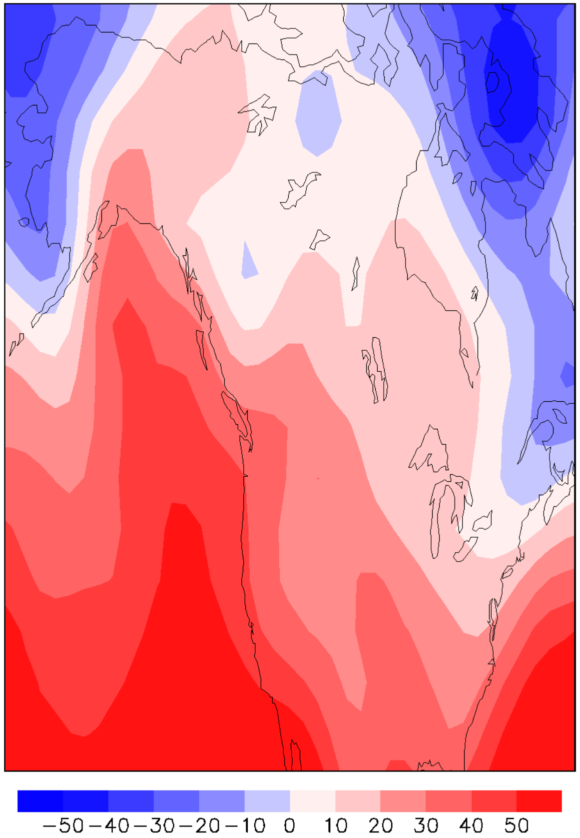


Day 10 500 hPa Wind

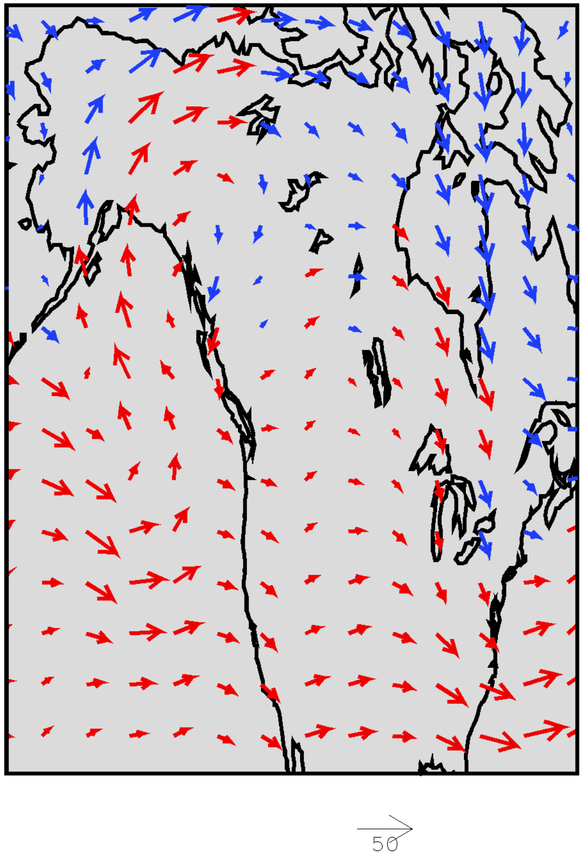




Day 11 SLP

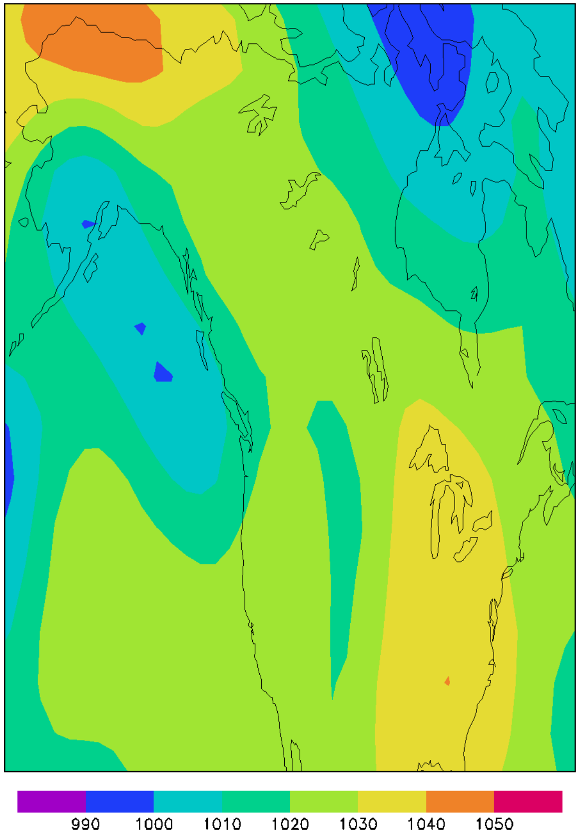


Day 11 Temperature

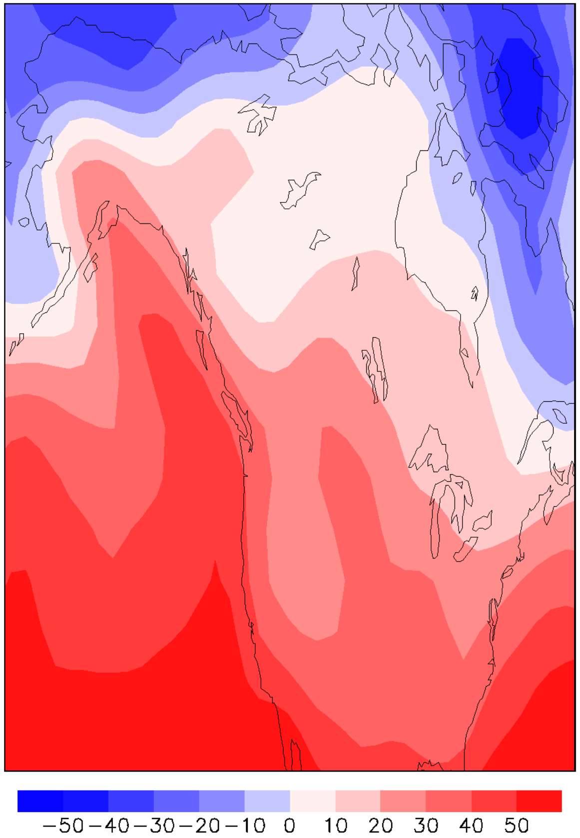


Day 11 500 hPa Wind

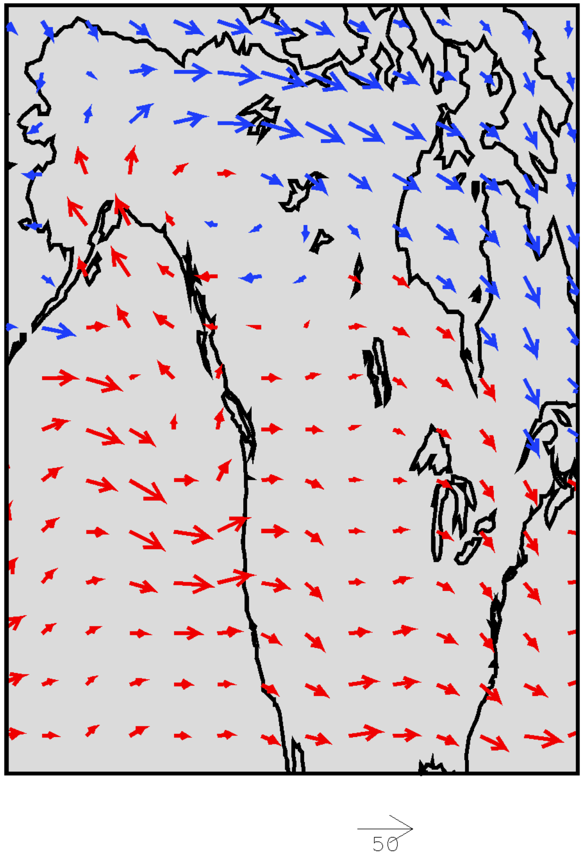
Day 12 SLP



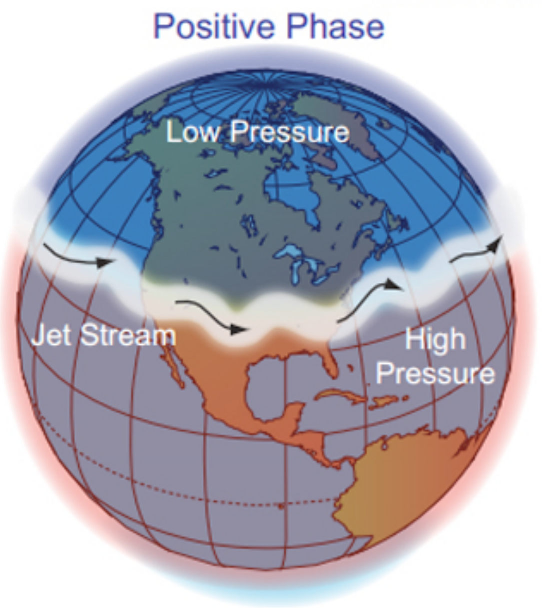
Day 12 Temperature



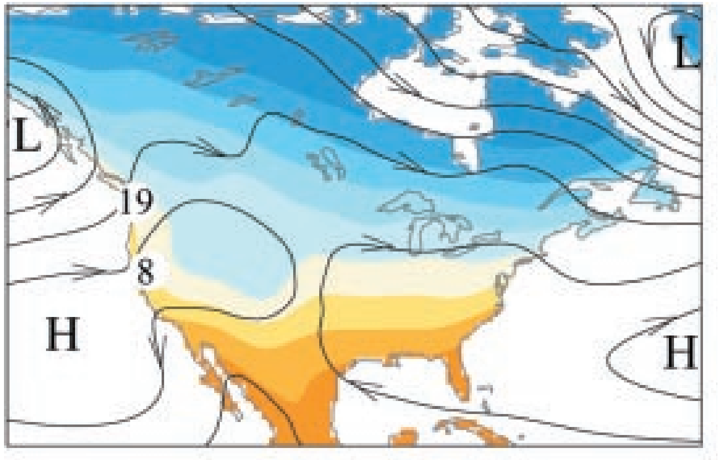
Day 12 500 hPa Wind



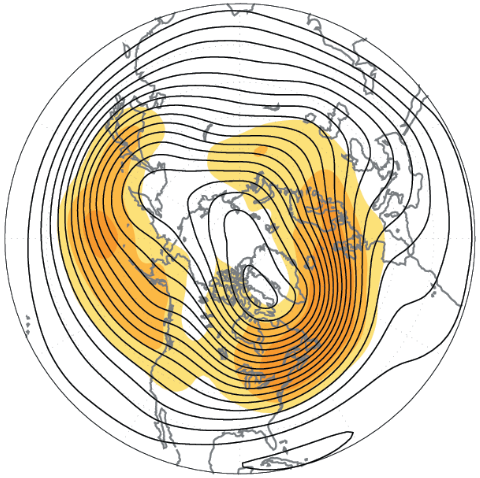
Role of the Arctic Oscillation in Extreme Cold-air Outbreaks



Surface Response in + AO (SLP)



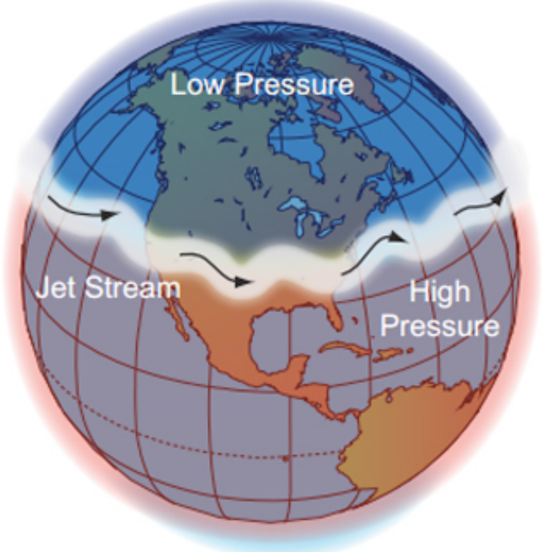
Response Aloft in + AO (Z500)



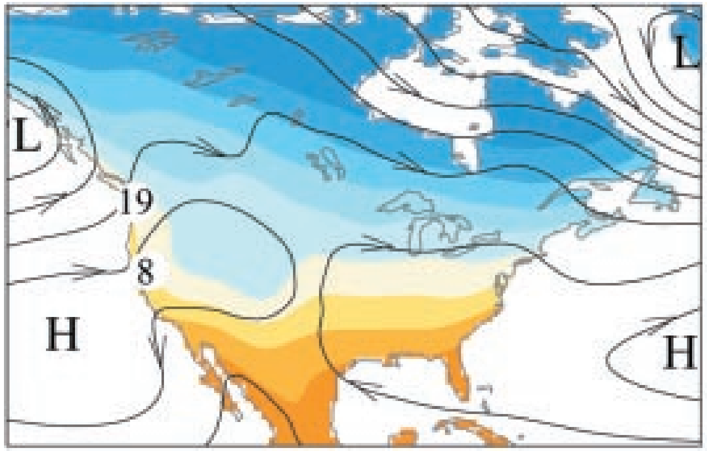
Thompson and Wallace
Science, 2002

Role of the Arctic Oscillation in Extreme Cold-air Outbreaks

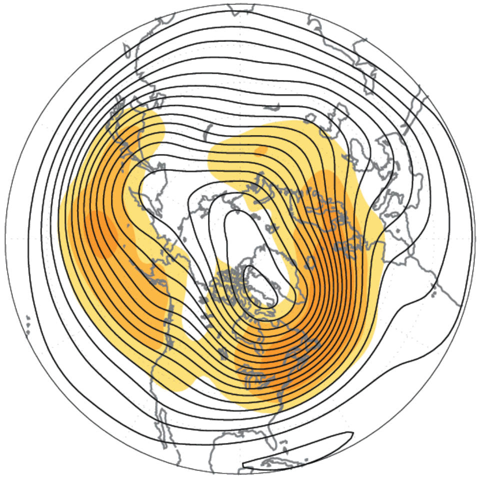
Positive Phase



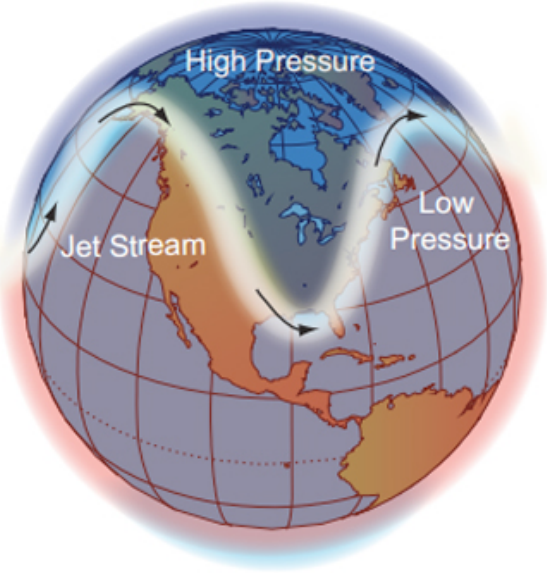
Surface Response in + AO (SLP)



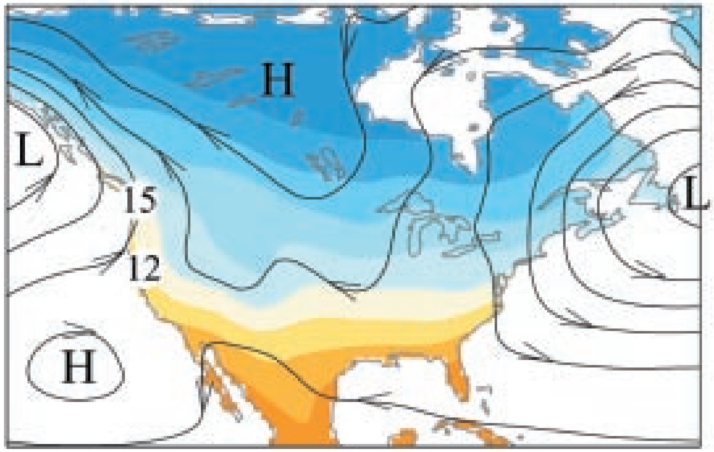
Response Aloft in + AO (Z500)



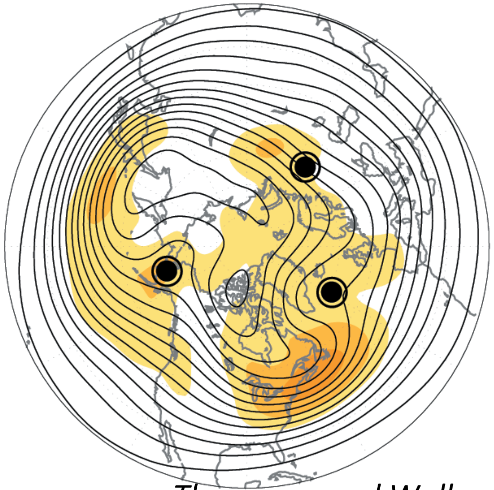
Negative Phase



Surface Response in - AO (SLP)



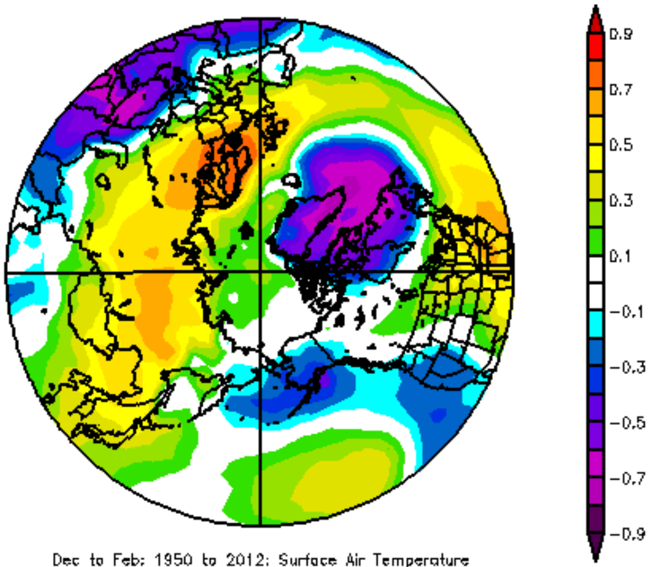
Response Aloft in + AO (Z500)



Thompson and Wallace
Science, 2001

Arctic Oscillation Effect on Winter Temperature

Mean Surface Temperatures



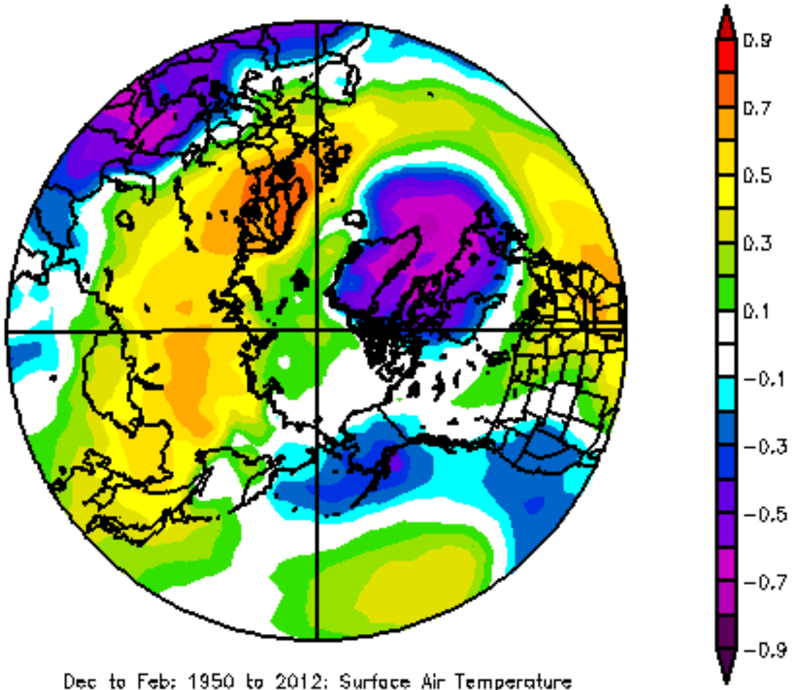
Dec to Feb: 1950 to 2012: Surface Air Temperature
Seasonal Correlation w/ Dec to Feb AO
NCEP/NCAR Reanalysis

NOAA/ESRL Physical Sciences Division

Cold winters typical in AO negative phase over mid-high latitude land

Arctic Oscillation Effect on Winter Temperature

Mean Surface Temperatures



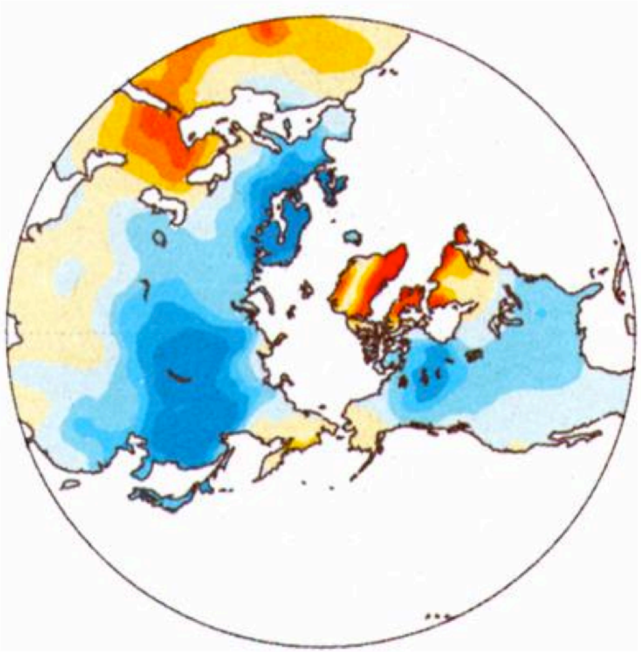
Dec to Feb: 1950 to 2012: Surface Air Temperature
Seasonal Correlation w/ Dec to Feb AO

NCEP/NCAR Reanalysis

NOAA/ESRL Physical Sciences Division

Cold winters typical in AO negative phase over mid-high latitude land

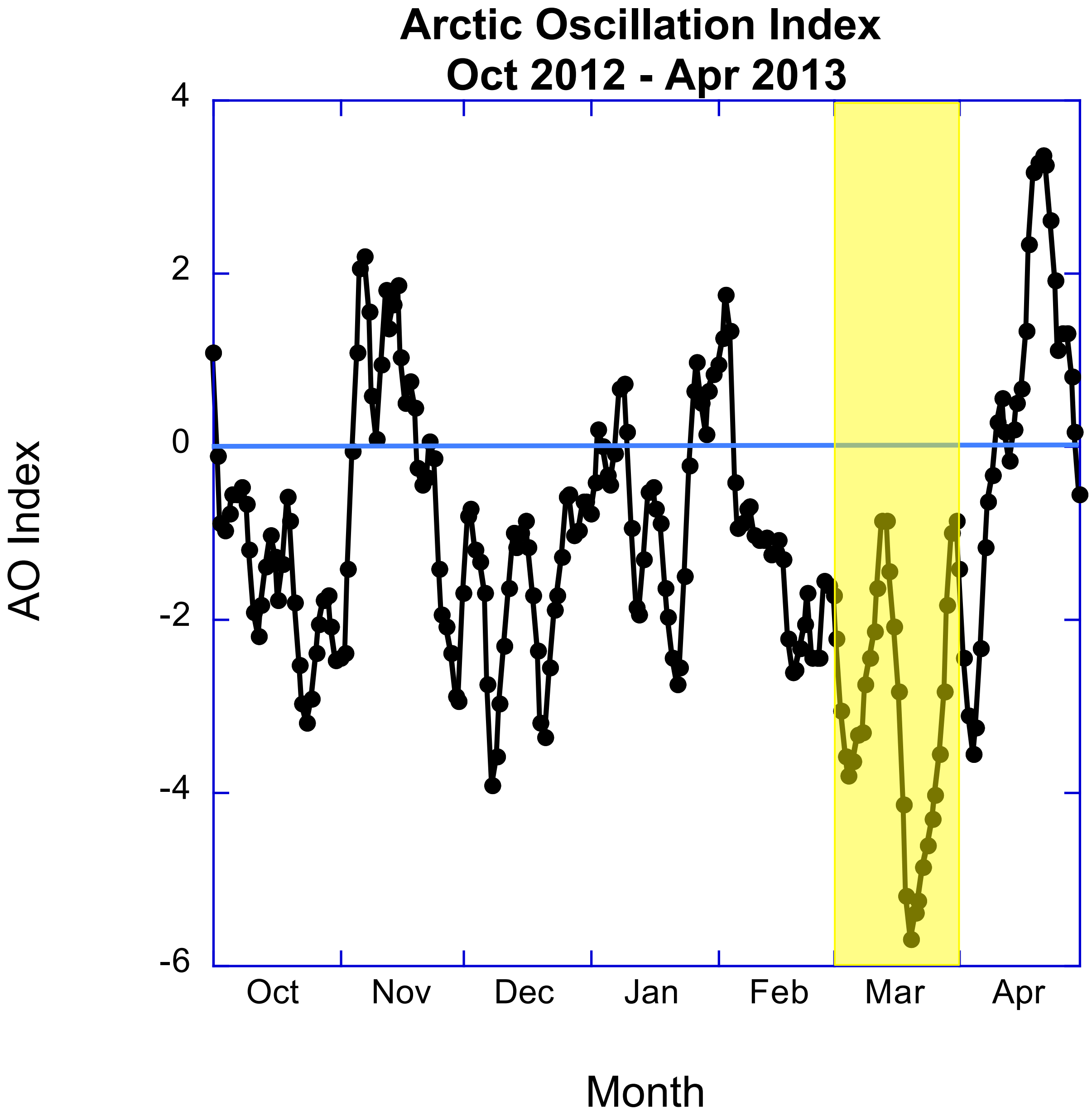
Extreme Surface Temperatures



Daily Cold Extremes:
Neg AO/Pos AO

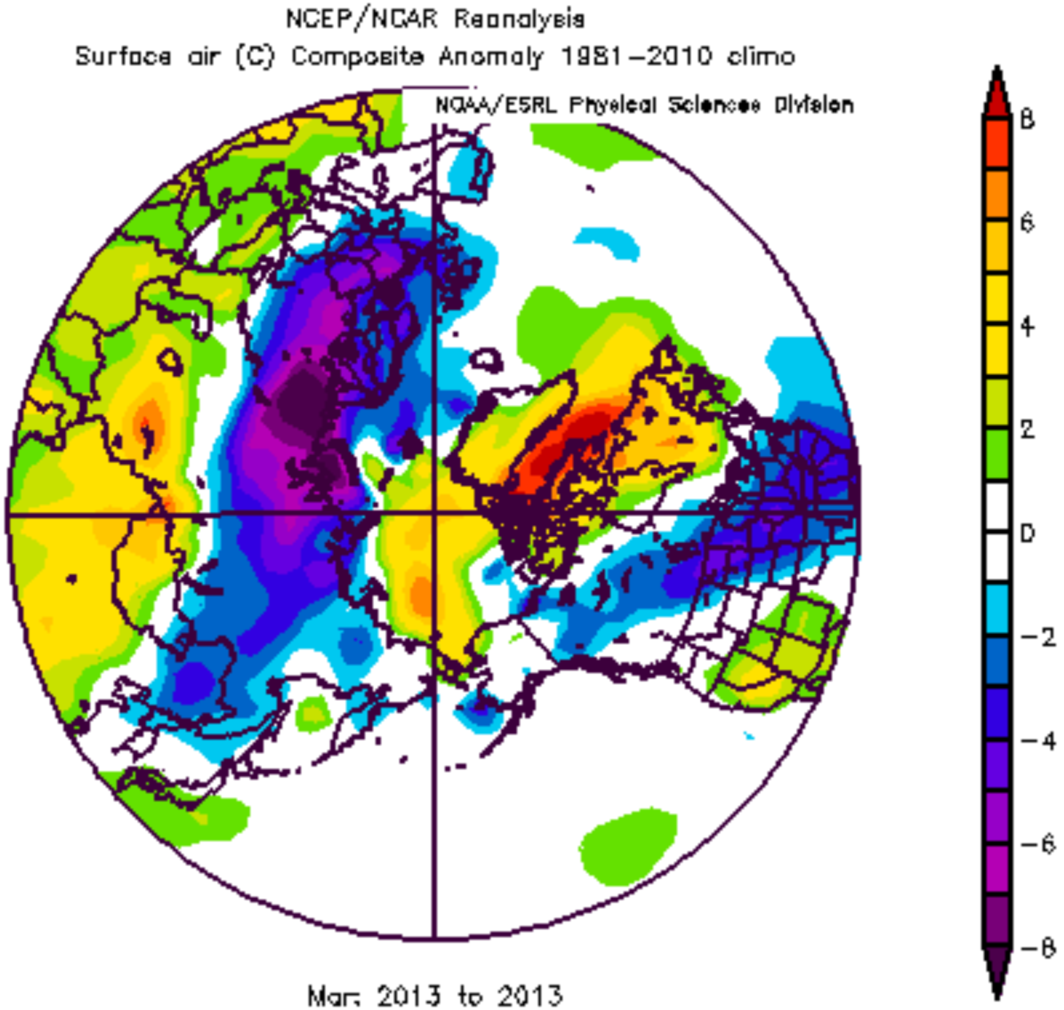
Thompson and Wallace
Science, 2001

Fig. 4. The signature of the NAM in the frequency of occurrence of cold events (daily minimum temperature <1.5 SD below the climatological mean) based on 6-hourly JFM data, 1958–1997, from the NCEP/NCAR Reanalysis (*10*). (Top) The ratios of the number of cold events in the low NAM–index sample to the number of cold events in the high NAM–index sample. (Bottom) As in the top panel, but for the ratios attributable to shifts in mean temperature (*19*). Shading is drawn for ratios ± 2:1, 3:1, 4:1, and 6:1. Blue shading indicates more cold events under low index conditions.

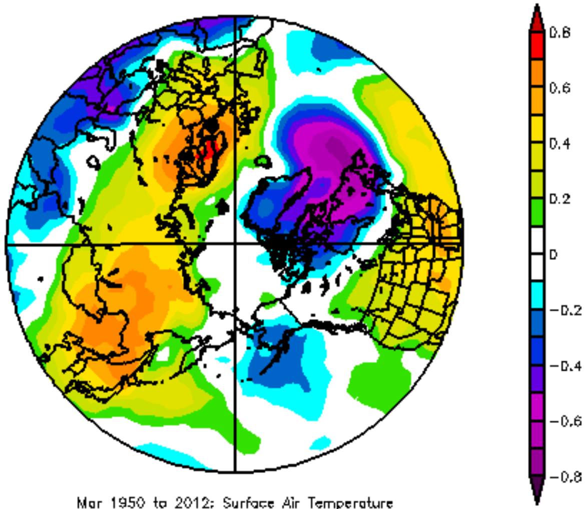


Record low March
AO index (-3.2)

March 2013 Surface Temperature Anomalies

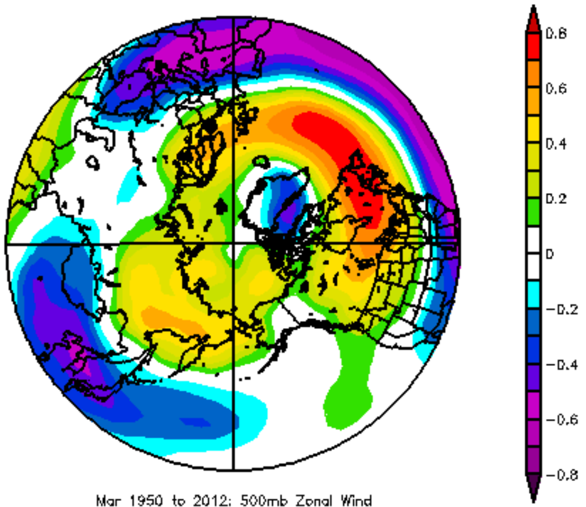


March AO Correlations with Tsfc, 500mb U, 500mb V



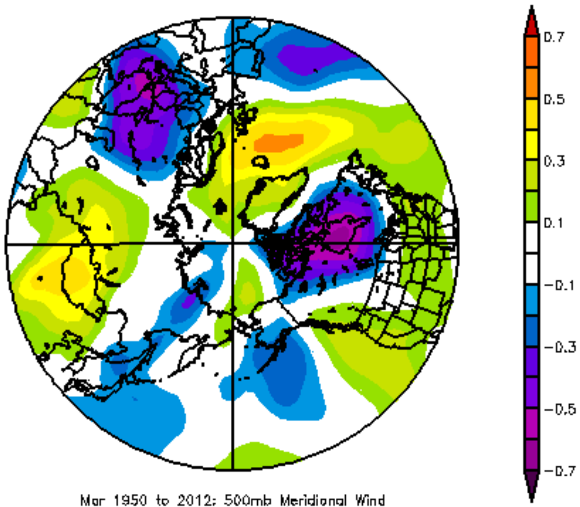
Mar 1950 to 2012: Surface Air Temperature
Seasonal Correlation w/ Mar AO
NCEP/NCAR Reanalysis

NOAA/ESRL Physical Sciences Division



Mar 1950 to 2012: 500mb Zonal Wind
Seasonal Correlation w/ Mar AO
NCEP/NCAR Reanalysis

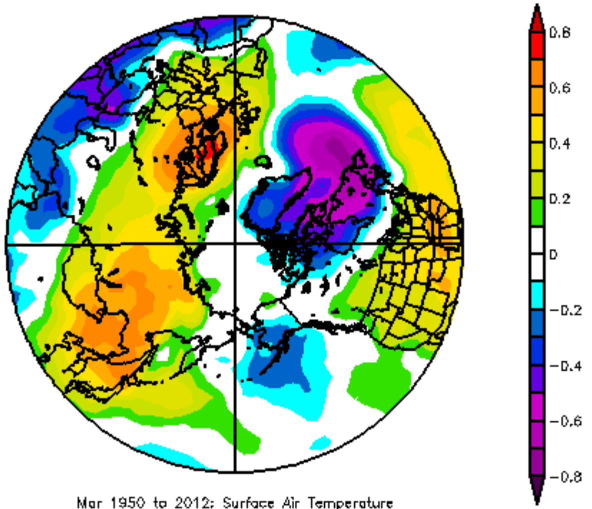
NOAA/ESRL Physical Sciences Division



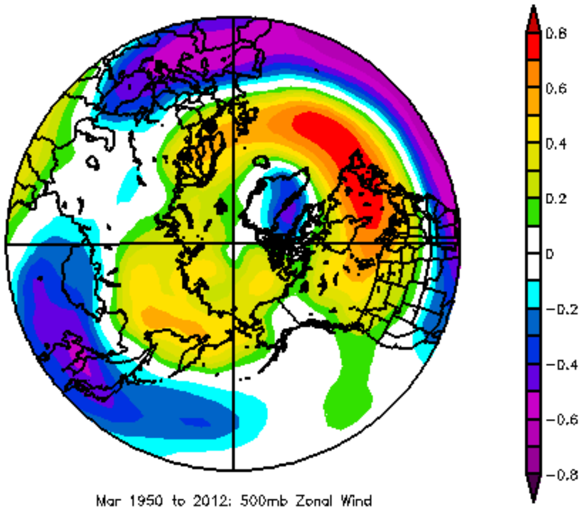
Mar 1950 to 2012: 500mb Meridional Wind
Seasonal Correlation w/ Mar AO
NCEP/NCAR Reanalysis

NOAA/ESRL Physical Sciences Division

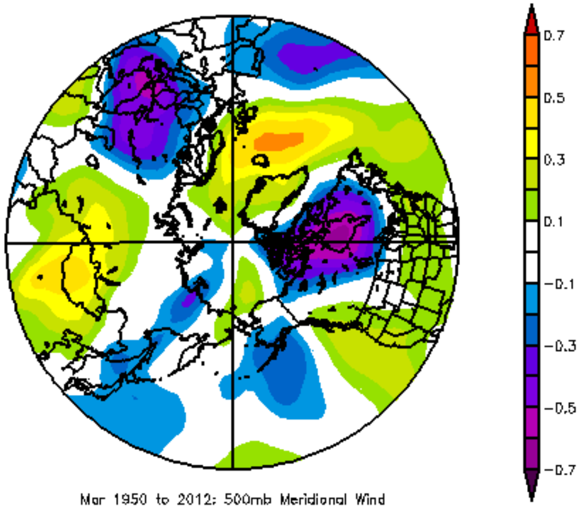
March AO Correlations with Tsfc, 500mb U, 500mb V



Mar 1950 to 2012: Surface Air Temperature
Seasonal Correlation w/ Mar AO
NCEP/NCAR Reanalysis
NOAA/ESRL Physical Sciences Division



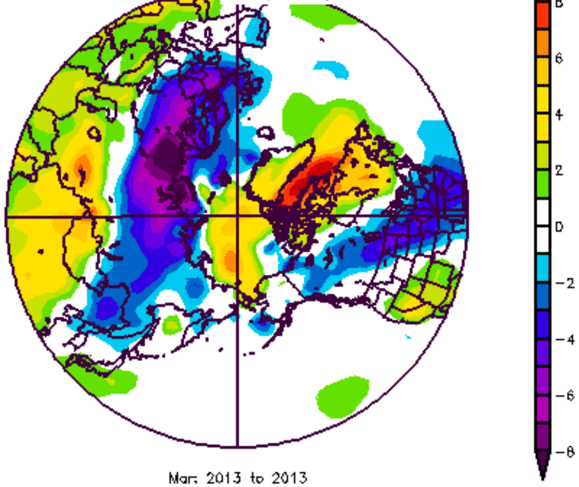
Mar 1950 to 2012: 500mb Zonal Wind
Seasonal Correlation w/ Mar AO
NCEP/NCAR Reanalysis
NOAA/ESRL Physical Sciences Division



Mar 1950 to 2012: 500mb Meridional Wind
Seasonal Correlation w/ Mar AO
NCEP/NCAR Reanalysis
NOAA/ESRL Physical Sciences Division

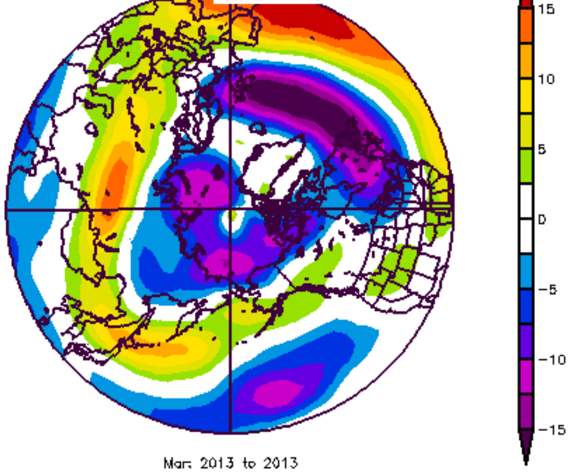
March 2013 anomalies of Tsfc, 500mb U, 500mb V

NCEP/NCAR Reanalysis
Surface air (C) Composite Anomaly 1981–2010 climo
NOAA/ESRL Physical Sciences Division



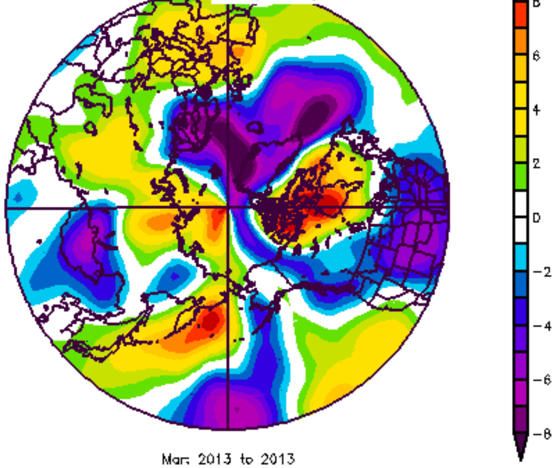
Mar: 2013 to 2013

NCEP/NCAR Reanalysis
500mb Zonal Wind (m/s) Composite Anomaly 1981–2010 climo
NOAA/ESRL Physical Sciences Division



Mar: 2013 to 2013

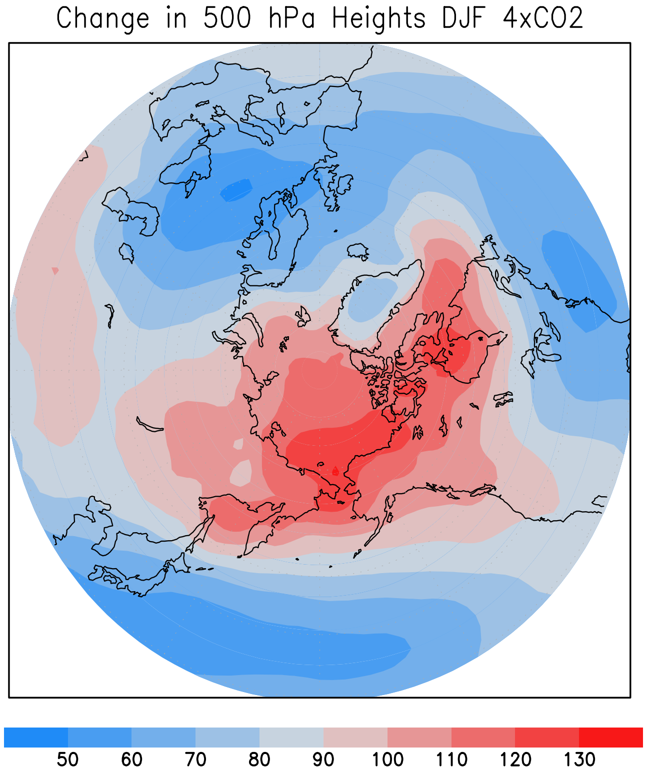
NCEP/NCAR Reanalysis
500mb Meridional Wind (m/s) Composite Anomaly 1981–2010 climo
NOAA/ESRL Physical Sciences Division



Mar: 2013 to 2013

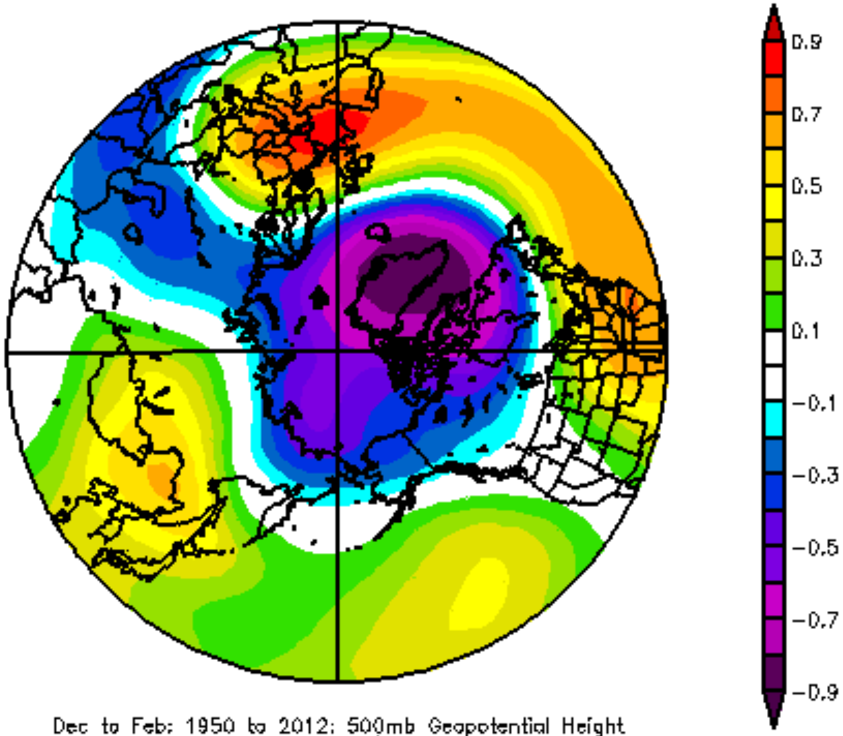
Projected Winter Changes resemble Negative Phase of AO

Future Height Changes Aloft



Present-day AO Relationship

(500 hPa Heights)



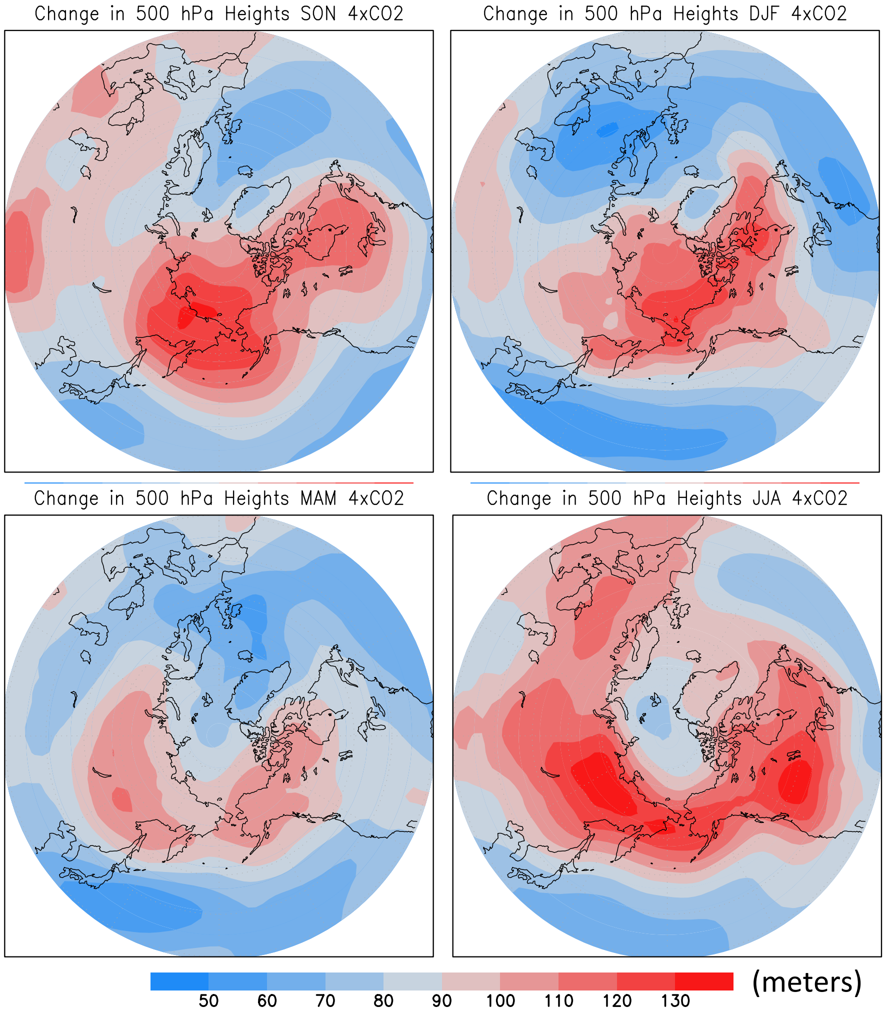
Dec to Feb: 1950 to 2012: 500mb Geopotential Height
Seasonal Correlation w/ Dec to Feb AO

NCEP/NCAR Reanalysis

Should we expect slower and more meandering (AO-like) circulation pattern in future?

Upper-air Circulation Response in CCSM4's 4xCO$_2$ Simulation

500 hPa Heights by Season



Autumn-Winter ridging largely over Arctic Ocean

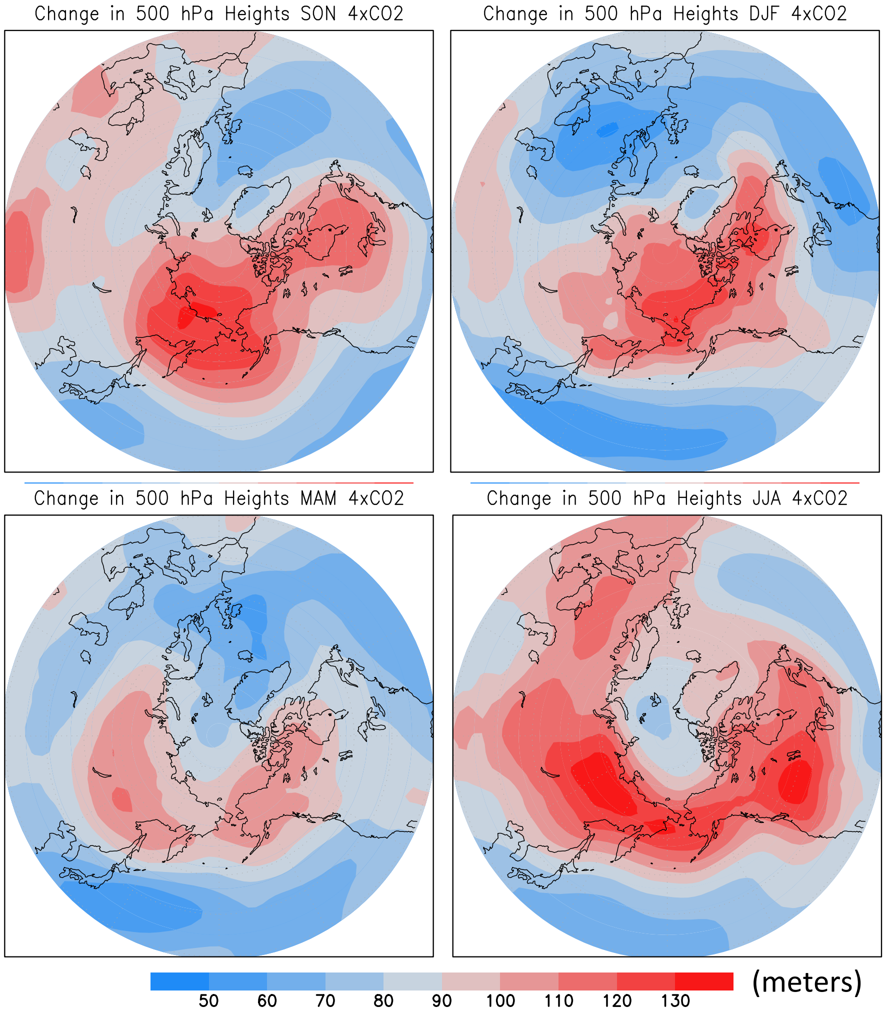
(sea ice loss)

Spring-Summer ridging over high-latitude land

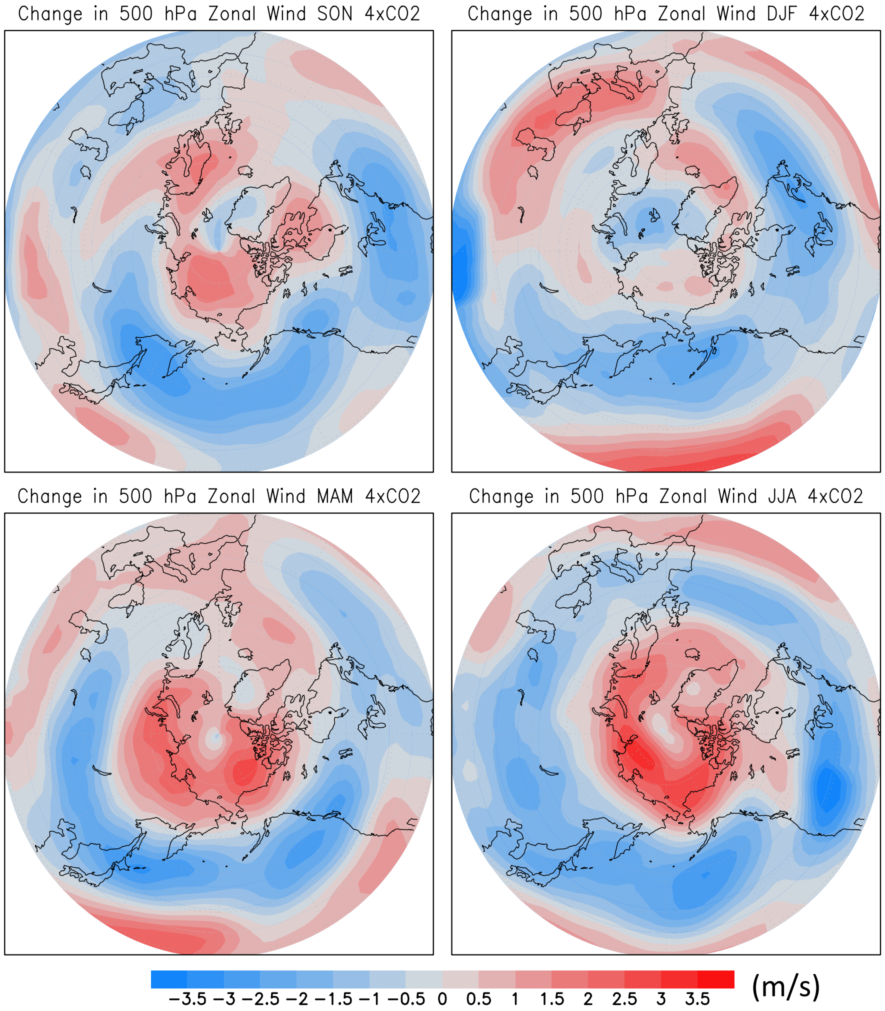
(snow cover loss,
lower land heat capacity)

Upper-air Circulation Response in CCSM4's 4xCO$_2$ Simulation

500 hPa Height Changes by Season



500 hPa Zonal Wind Changes by Season



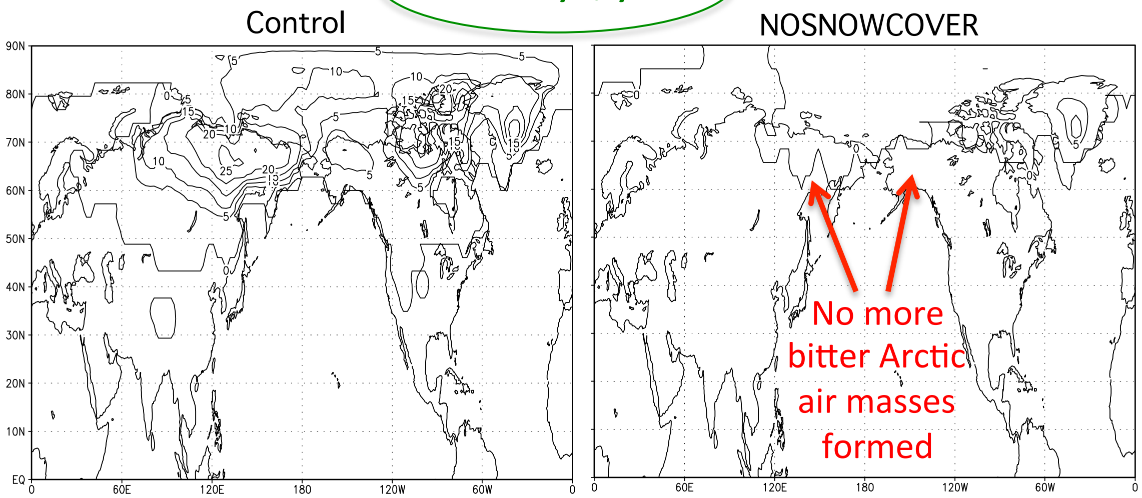
Weakened westerlies on equatorward side of ridging

Large-Scale Meteorological Patterns (LSMPs) are clearly important for regulating extreme weather, but they aren’t the only show in town.

We need to also recognize the strong thermodynamic role played by surface boundary conditions, such as snow cover and soil moisture. . . .

Role of Snow Cover in Extreme Cold-Air Outbreaks (CAOs)

CCSM3 Simulation with terrestrial snow cover suppressed



-40° days/year

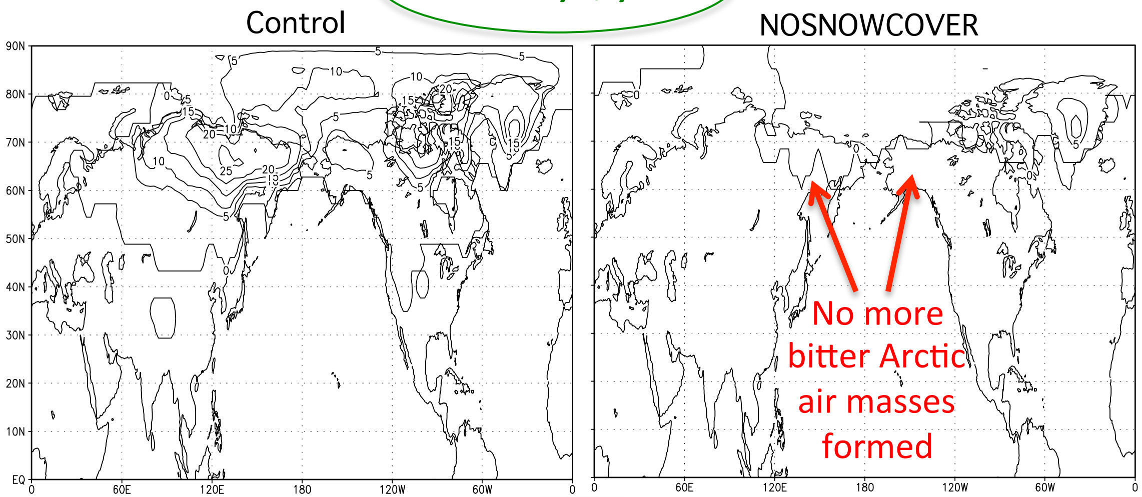
No more bitter Arctic air masses formed

Vavrus, 2007
Climate Dynamics

Role of Snow Cover in Extreme Cold-Air Outbreaks (CAOs)

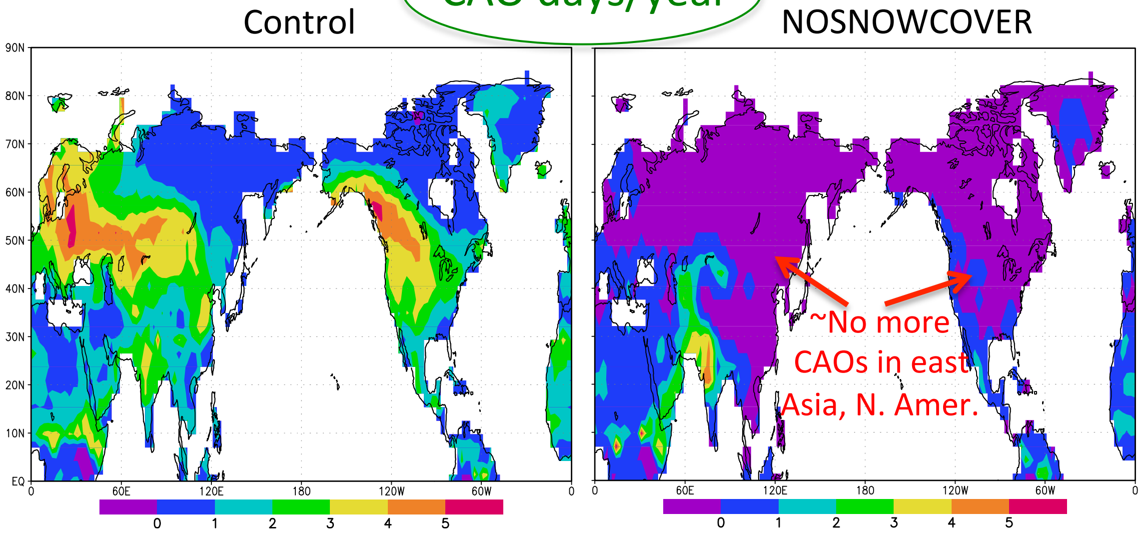
CCSM3 Simulation with terrestrial snow cover suppressed

-40° days/year



No more bitter Arctic air masses formed

CAO days/year



~No more CAOs in east Asia, N. Amer.

Vavrus, 2007
Climate Dynamics

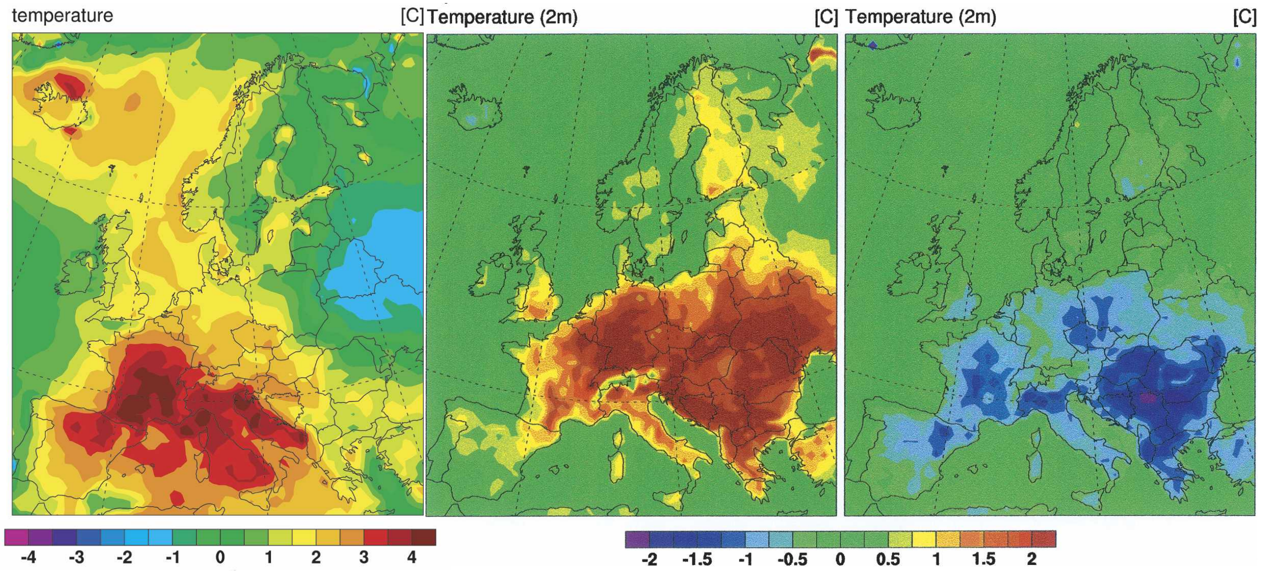
Role of Soil Moisture in Extreme Heat Wave: Europe 2003

Surface Temperature Anomalies

Control Run

-25% Spring Soil Moisture

+25% Spring Soil Moisture



Fischer et al.
J. Climate 2007

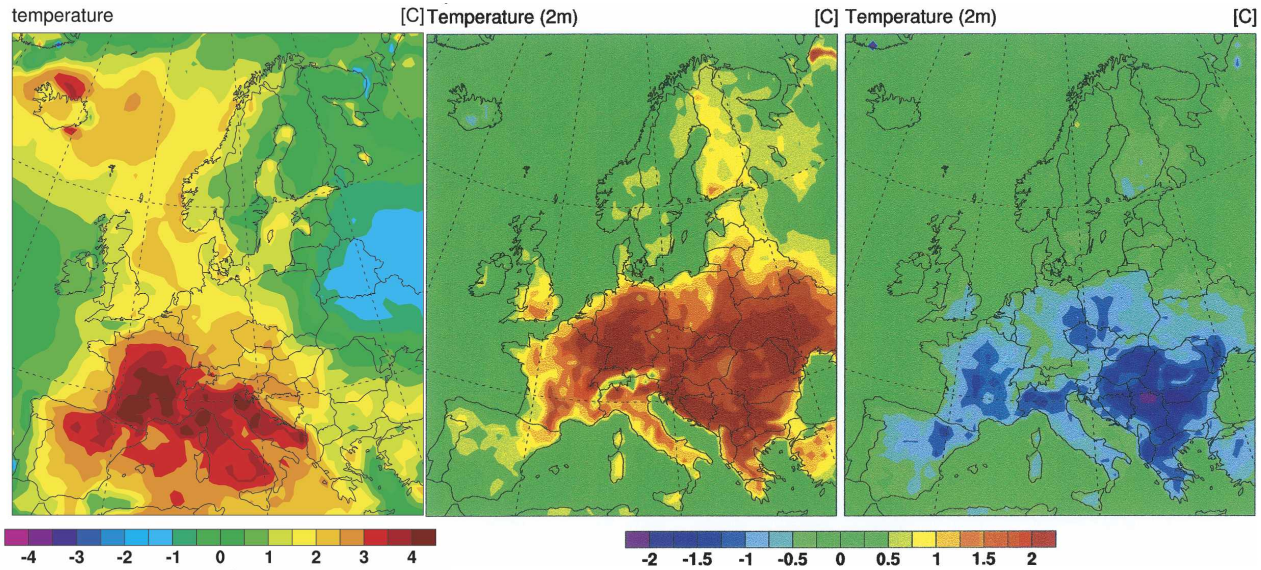
Role of Soil Moisture in Extreme Heat Wave: Europe 2003

Control Run

-25% Spring Soil Moisture

+25% Spring Soil Moisture

Surface Temperature Anomalies

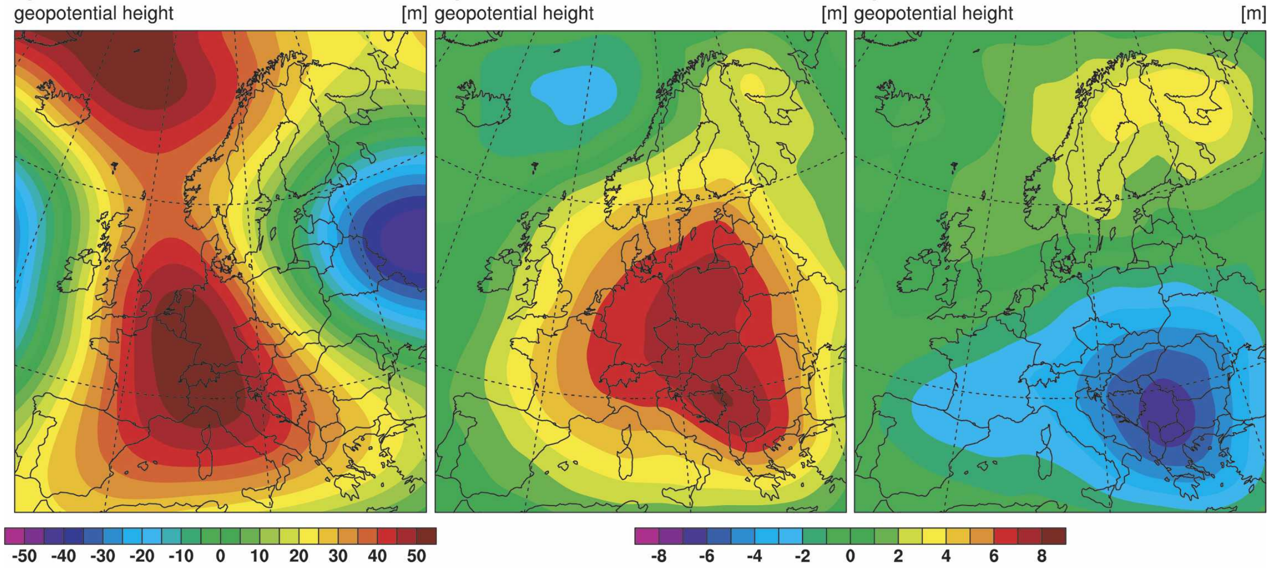


Control Run

-25% Spring Soil Moisture

+25% Spring Soil Moisture

500 hPa Height Anomalies



Fischer et al.
J. Climate 2007

Relating Extreme Weather Events to LSMPs:
Is the Glass half full or half empty?

1. We can identify the typical LSMPs associated with extreme weather, which provides useful knowledge for diagnosing the events.

- *Half full if only a few patterns are associated with particular types of extreme events*
- *Half full if we can understand the causes of the overriding LSMPs (otherwise half empty)*

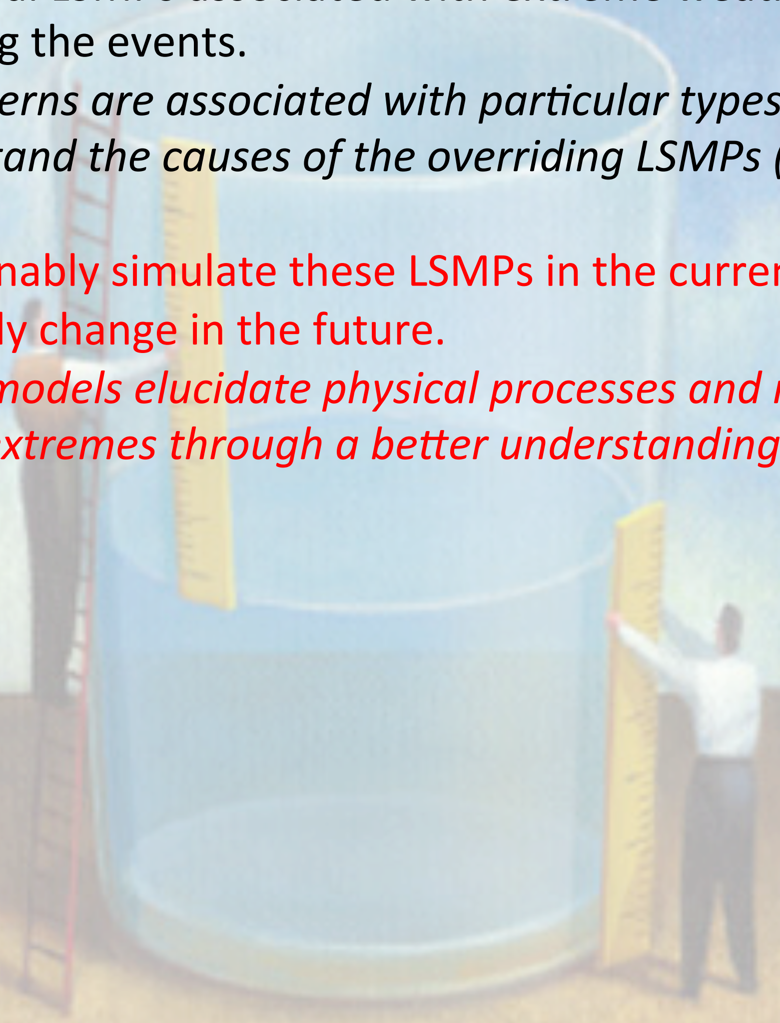
Relating Extreme Weather Events to LSMPs:
Is the Glass half full or half empty?

1. We can identify the typical LSMPs associated with extreme weather, which provides useful knowledge for diagnosing the events.

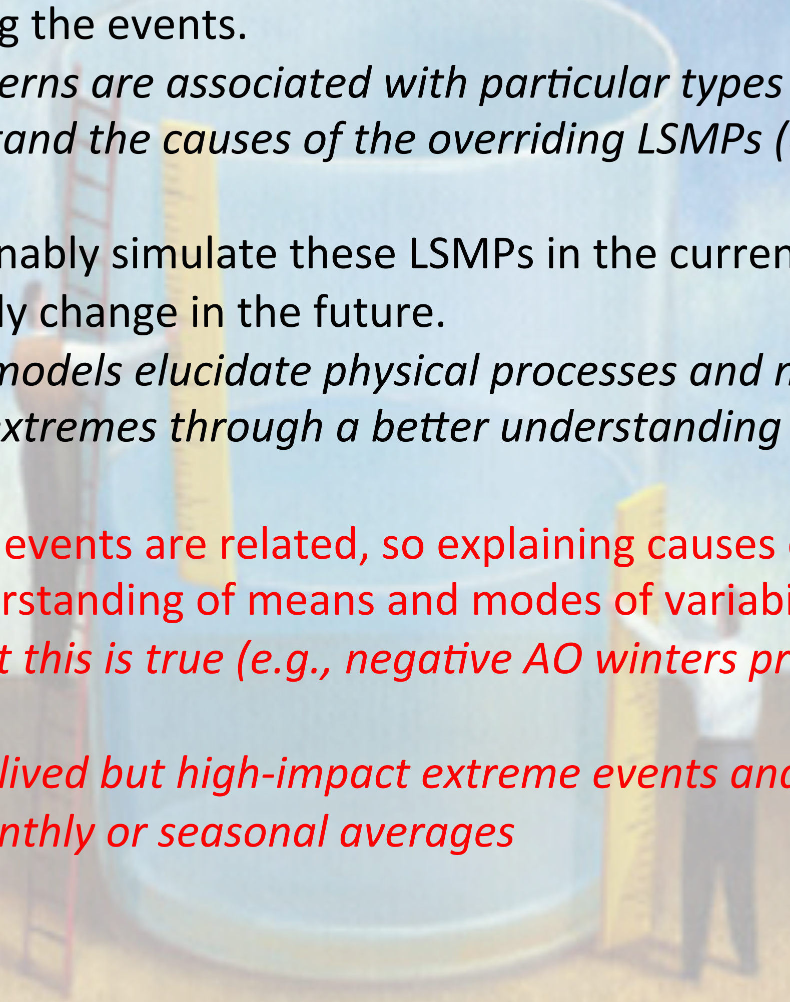
- *Half full if only a few patterns are associated with particular types of extreme events*
- *Half full if we can understand the causes of the overriding LSMPs (otherwise half empty)*

2. Climate models can reasonably simulate these LSMPs in the current climate and suggest that patterns won’t fundamentally change in the future.

- *Half full on both counts: models elucidate physical processes and may promote understanding of future extremes through a better understanding of present-day events*



Relating Extreme Weather Events to LSMPs:
Is the Glass half full or half empty?



1. We can identify the typical LSMPs associated with extreme weather, which provides useful knowledge for diagnosing the events.

- *Half full if only a few patterns are associated with particular types of extreme events*
- *Half full if we can understand the causes of the overriding LSMPs (otherwise half empty)*

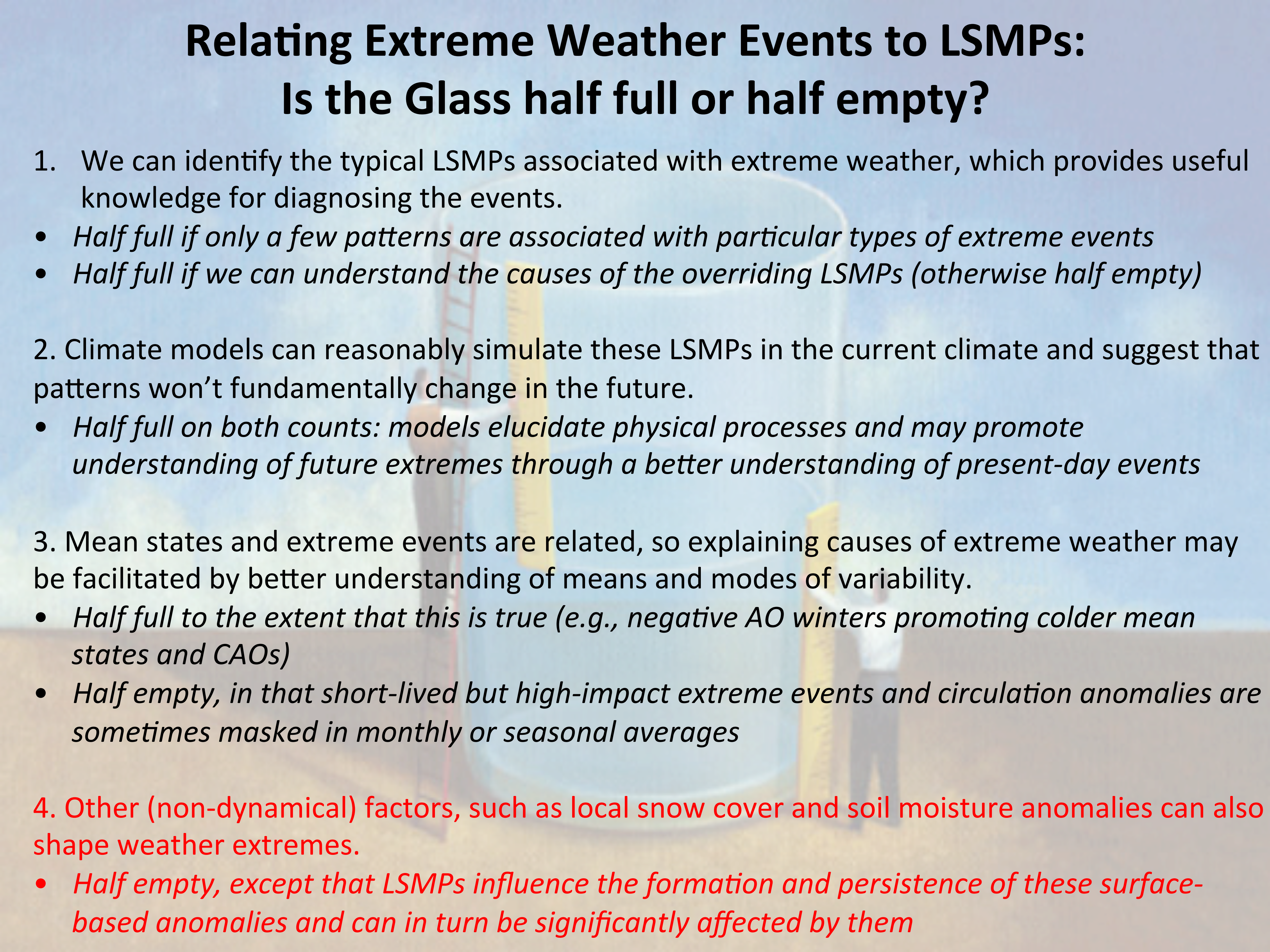
2. Climate models can reasonably simulate these LSMPs in the current climate and suggest that patterns won't fundamentally change in the future.

- *Half full on both counts: models elucidate physical processes and may promote understanding of future extremes through a better understanding of present-day events*

3. Mean states and extreme events are related, so explaining causes of extreme weather may be facilitated by better understanding of means and modes of variability.

- *Half full to the extent that this is true (e.g., negative AO winters promoting colder mean states and CAOs)*
- *Half empty, in that short-lived but high-impact extreme events and circulation anomalies are sometimes masked in monthly or seasonal averages*

Relating Extreme Weather Events to LSMPs:
Is the Glass half full or half empty?



1. We can identify the typical LSMPs associated with extreme weather, which provides useful knowledge for diagnosing the events.

- *Half full if only a few patterns are associated with particular types of extreme events*
- *Half full if we can understand the causes of the overriding LSMPs (otherwise half empty)*

2. Climate models can reasonably simulate these LSMPs in the current climate and suggest that patterns won't fundamentally change in the future.

- *Half full on both counts: models elucidate physical processes and may promote understanding of future extremes through a better understanding of present-day events*

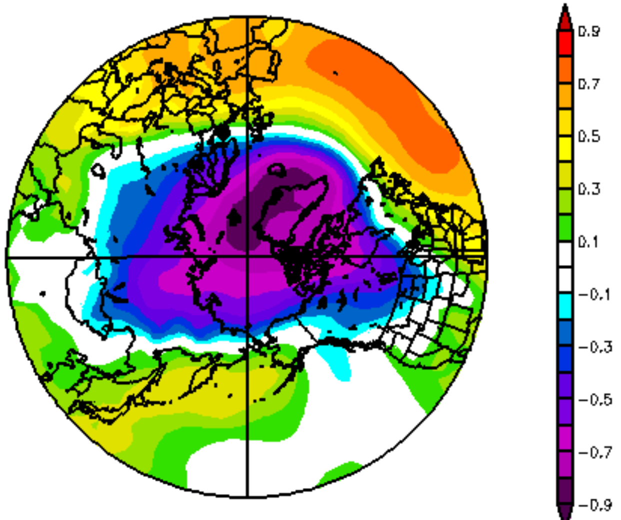
3. Mean states and extreme events are related, so explaining causes of extreme weather may be facilitated by better understanding of means and modes of variability.

- *Half full to the extent that this is true (e.g., negative AO winters promoting colder mean states and CAOs)*
- *Half empty, in that short-lived but high-impact extreme events and circulation anomalies are sometimes masked in monthly or seasonal averages*

4. Other (non-dynamical) factors, such as local snow cover and soil moisture anomalies can also shape weather extremes.

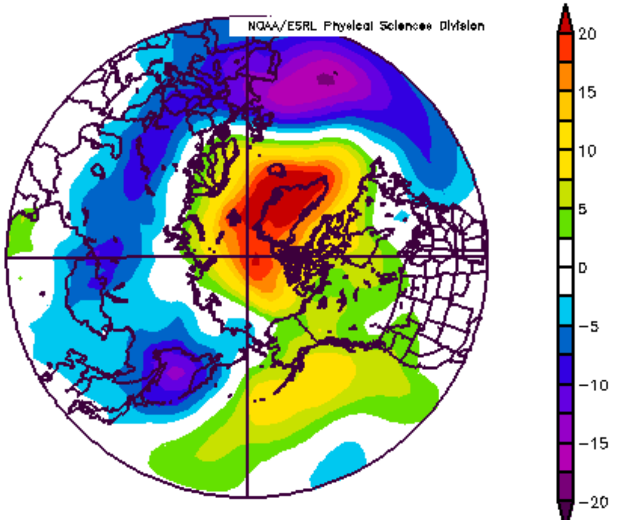
- *Half empty, except that LSMPs influence the formation and persistence of these surface-based anomalies and can in turn be significantly affected by them*

March AO Correlations with SLP



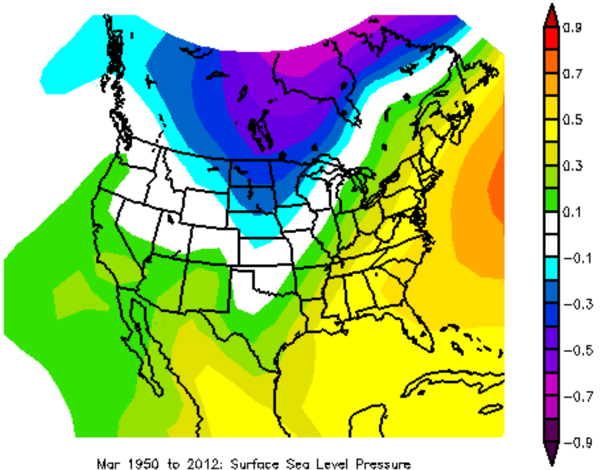
Mar 1950 to 2012: Surface Sea Level Pressure
Seasonal Correlation w/ Mar AO
NCEP/NCAR Reanalysis
NOAA/ESRL Physical Sciences Division

March 2013 SLP Anomaly



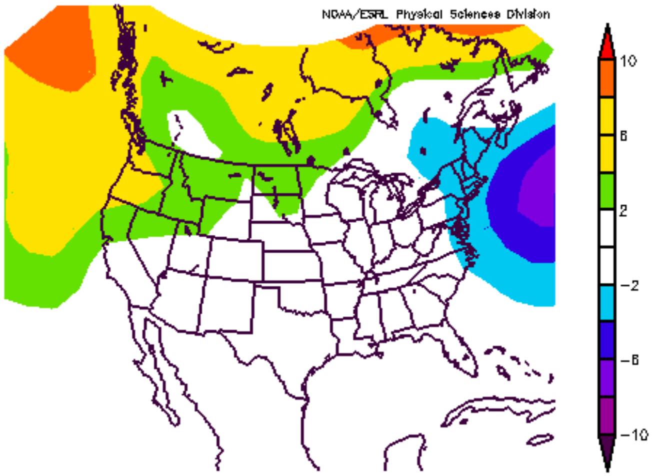
Sea Level Pressure (mb) Composite Anomaly (1981−2010 Climatology)
3/1/13 to 3/23/13
NCEP/NCAR Reanalysis

March AO Correlations with SLP



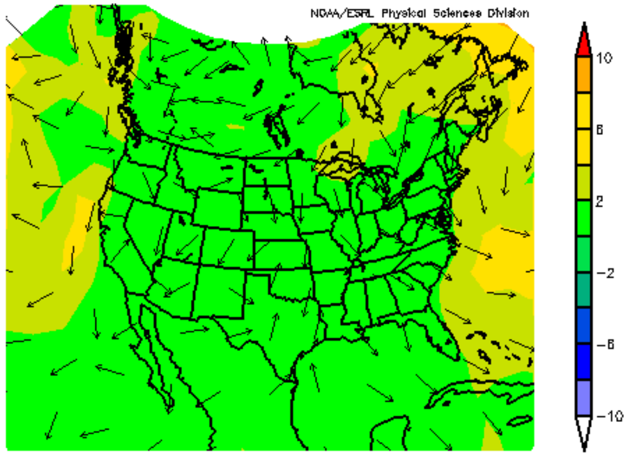
Mar 1950 to 2012: Surface Sea Level Pressure
Seasonal Correlation w/ Mar AO
NCEP/NCAR Reanalysis
NOAA/ESRL Physical Sciences Division

March 2013 SLP Anomaly



Sea Level Pressure (mb) Composite Anomaly (1981−2010 Climatology)
3/1/13 to 3/23/13
NCEP/NCAR Reanalysis

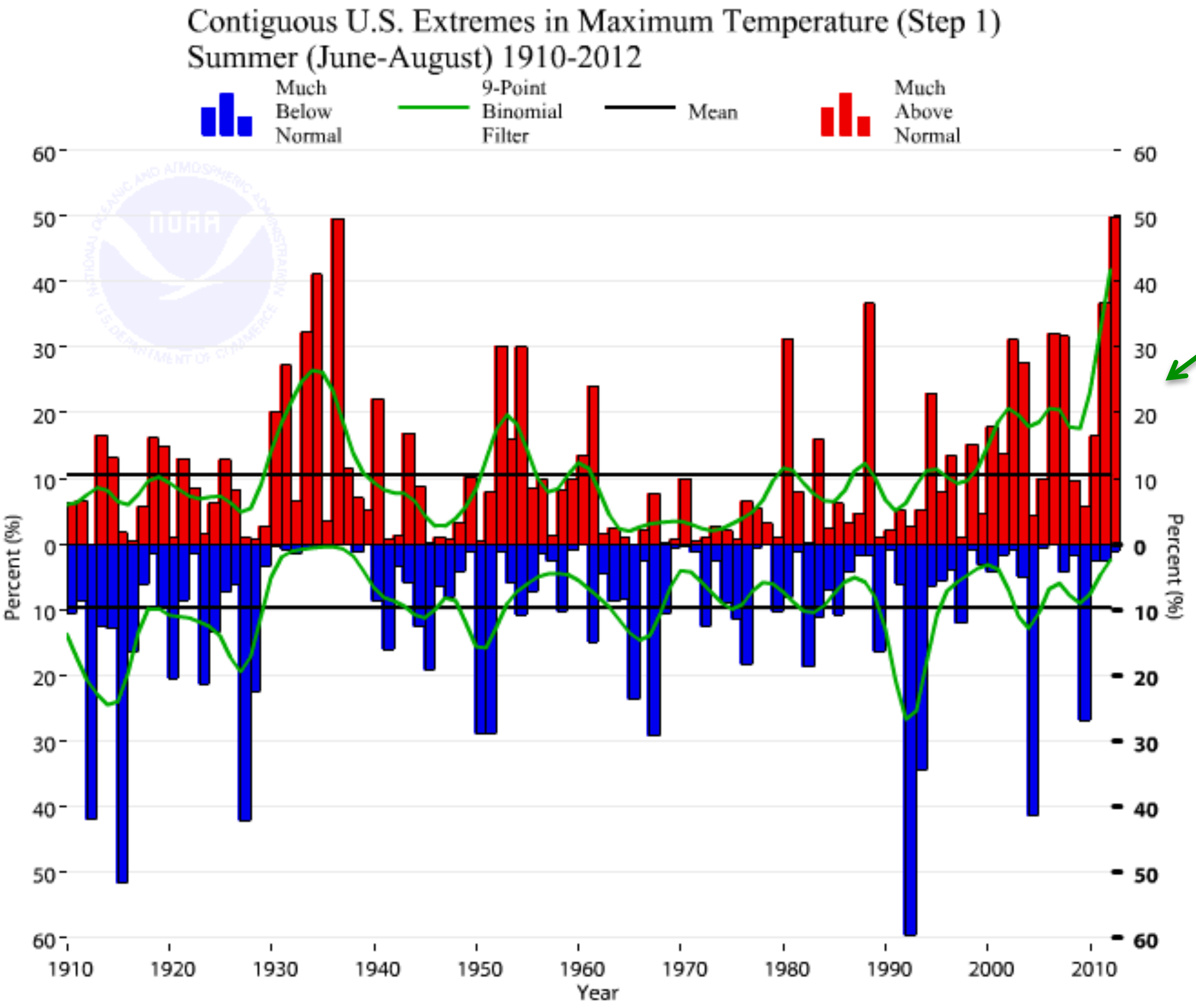
March 2013 Sfc Wind Anomaly



Surface Vector Wind (m/s) Composite Anomaly (1981−2010 Climatology)
3/1/13 to 3/23/13
NCEP/NCAR Reanalysis

U. S. Climate Extremes Index

Summer Daily Maximum Temperature (Continental U. S.)

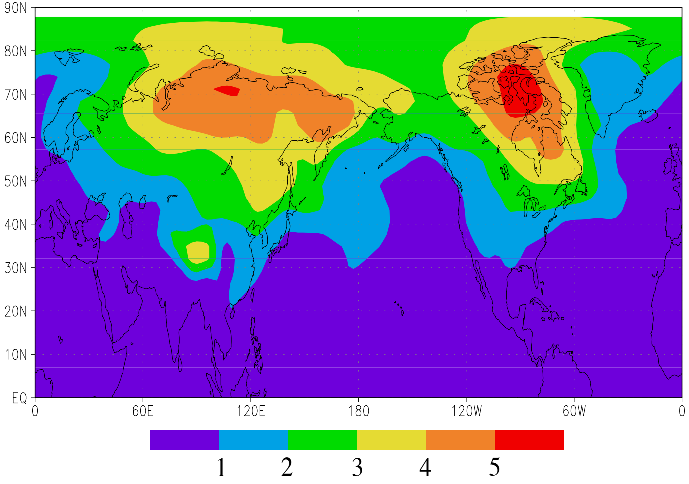


Recent trend: hotter summers

Role of Snow Cover in Extreme Cold-Air Outbreaks (CAOs)

CCSM3 Simulation with terrestrial snow cover suppressed

Annual Average



Increase in Air Temperature without Snow Cover

Vavrus, 2007
Climate Dynamics

Synoptic Evolution of Extreme Cold-Air Outbreaks (CAOs)

Midwestern CAOs

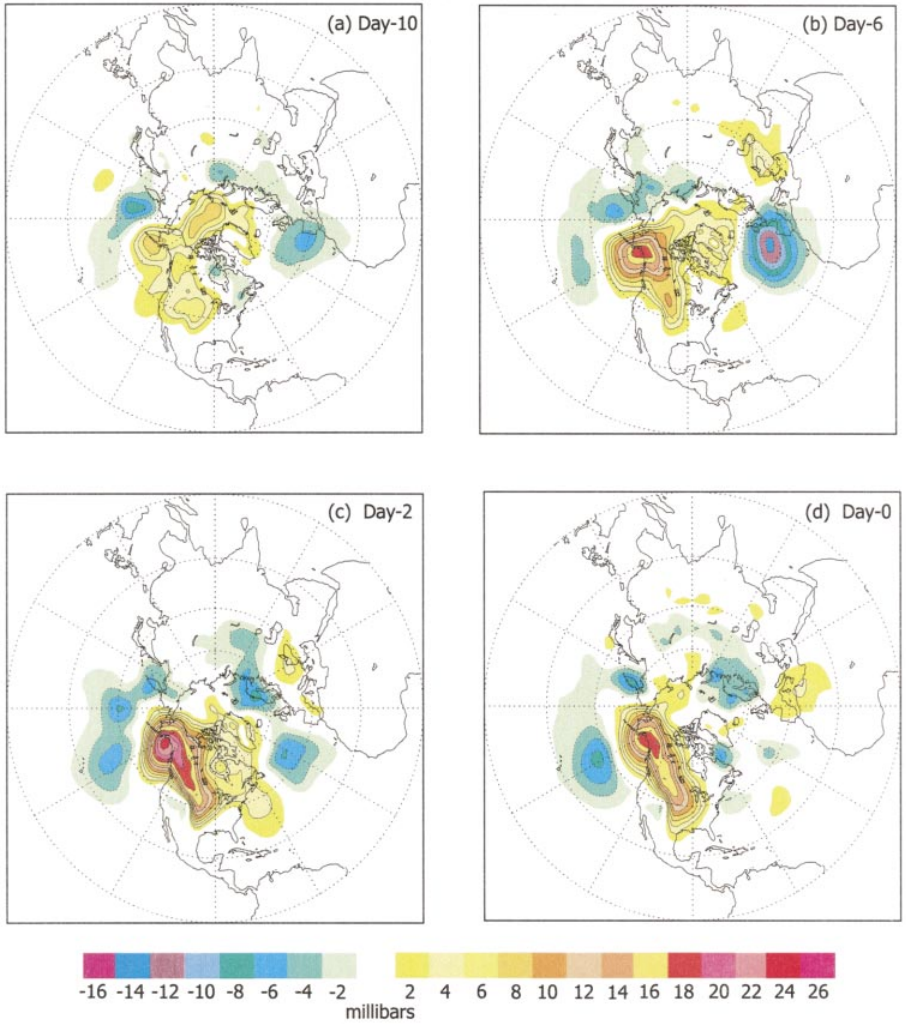
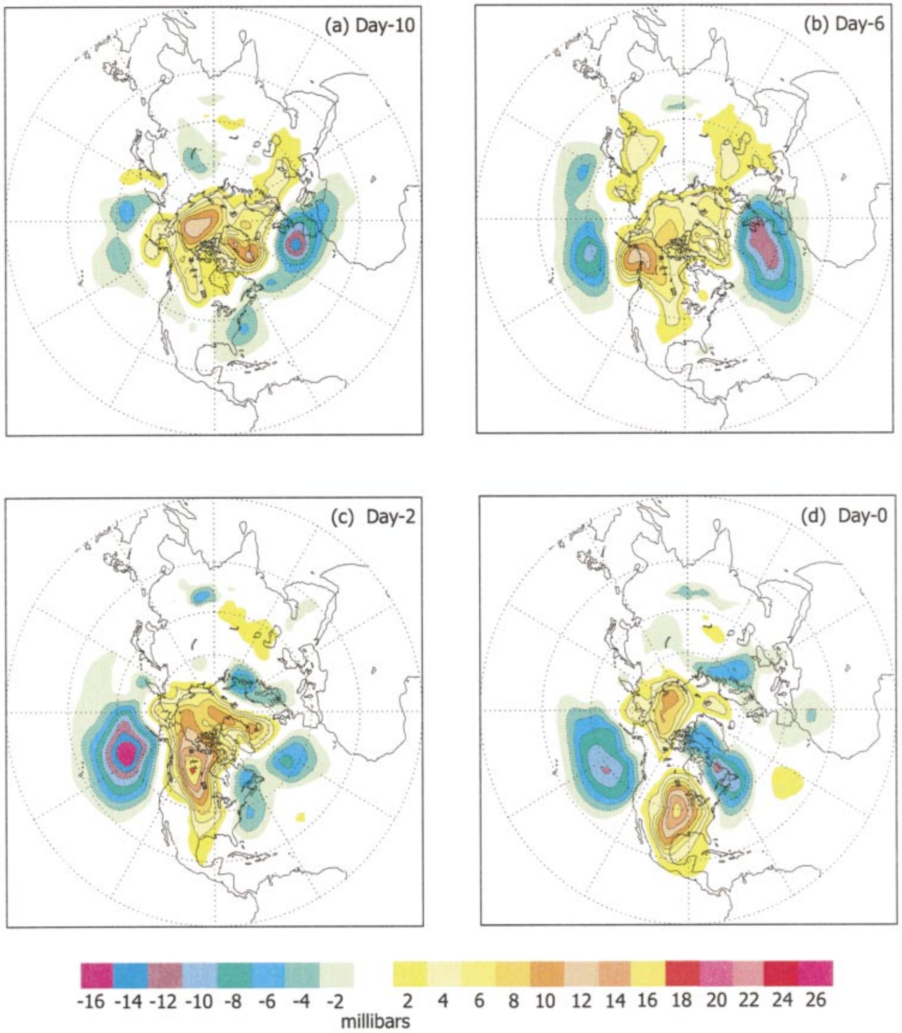


FIG. 7. SLP anomaly composites for (a) 10 days, (b) 6 days, (c) 2 days, and (d) 0 days prior to the dates of the 10 cold events in the Midwest (MW) region. Numbers below color bar denote the lower limit of each 2-mb range of magnitudes. Unshaded areas have magnitudes smaller than 2 mb.

East Coast CAOs



Walsh et al.
J Climate (2001)