On the Synoptic-Scale Mechanisms of Extreme Precipitation Events:

The role of the anticyclone and a dynamically based index

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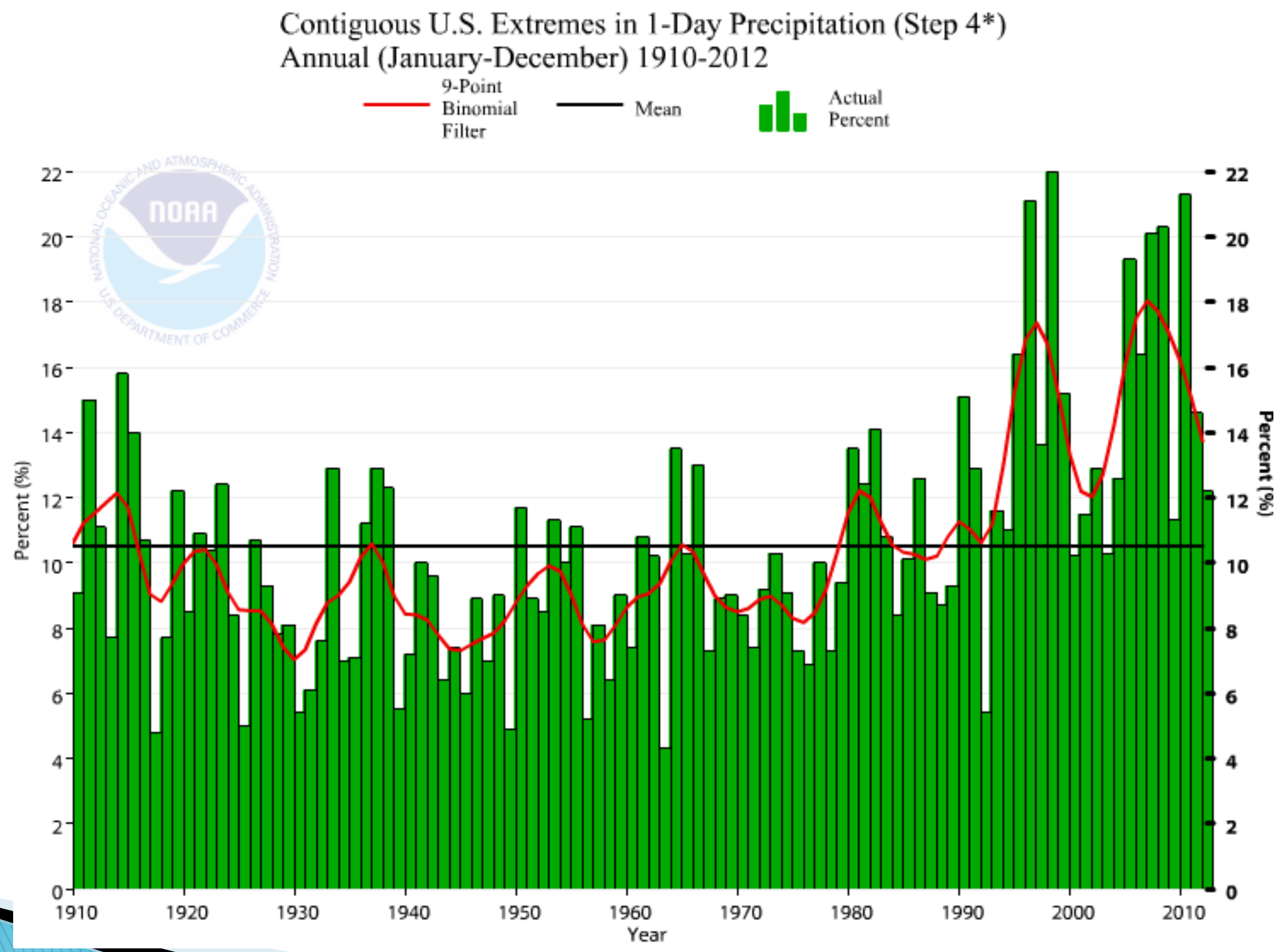
Outline

- **Motivation**
- **Synoptic-scale precursors and characteristics of extreme/heavy precipitation events**
- **Synoptic evolution of the June 2013 Alberta Flood**
- **Research questions, the Extreme Precipitation Index (EPI), and future work**

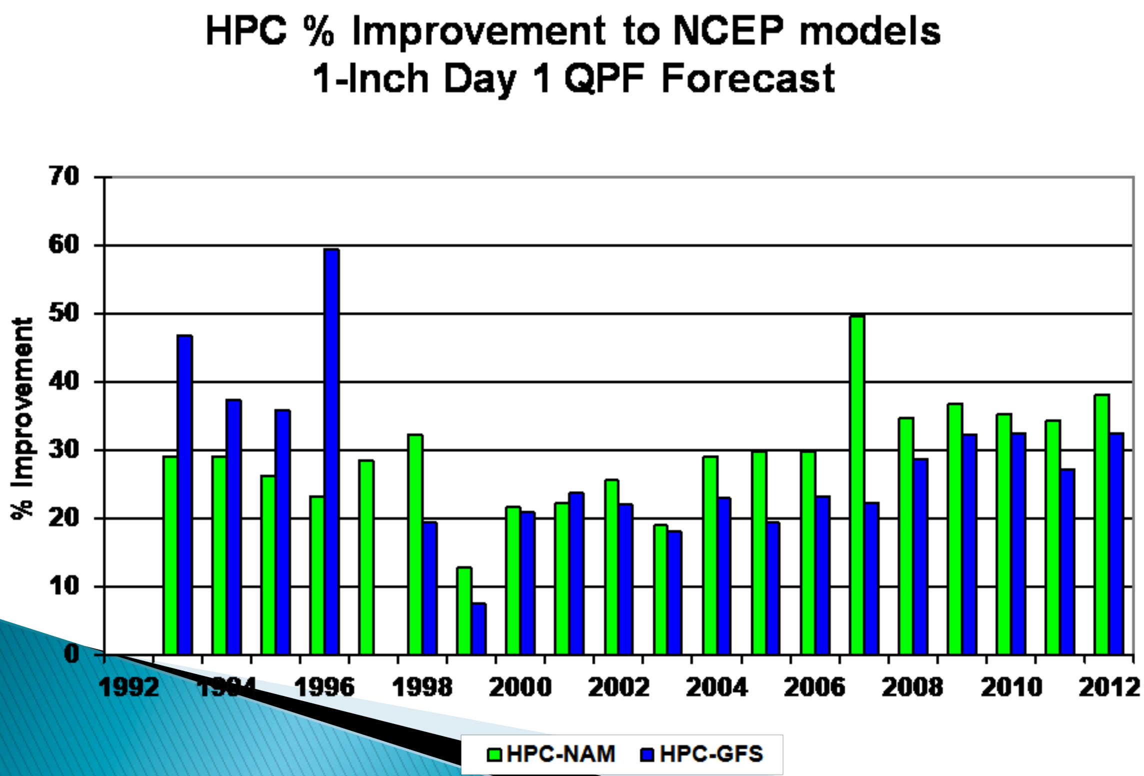
U.S. Climate Extremes Index: 1-Day Precip



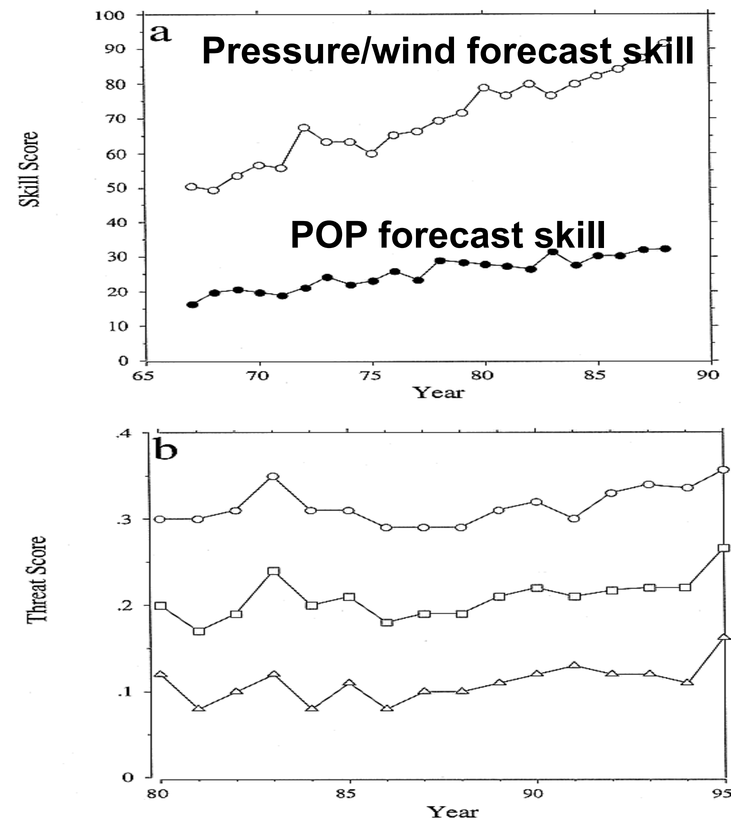
Source: NOAA/NCDC

Extreme/Heavy Events: Predictability

- **Numerical forecast models do not handle extreme/heavy precipitation events particularly well**
  - **Mass field (pressure/wind) forecast skill exceeds Quantitative Precipitation Forecast (QPF) skill**



...rce: NWS Weather Prediction Center



Source: Roebber and Bosart (1998)

Research Objectives

- Increase understanding of the synoptic-dynamic precursors and characteristics of extreme/heavy precipitation events
- Develop a user-friendly, dynamically-based index to diagnose extreme precipitation events

Desired result:

- Aid the human forecaster in QPF, assuming that the mass fields are well predicted by numerical models

Warm-season Heavy Precipitation Events

- Focus: Heavy warm-season precipitation events at Montreal, QC
  - Previous work: Cool-season events (Montreal, QC; Burlington, VT; St. John's, NL)
    - Sisson and Gyakum (2004); Milrad et al. (2009); Milrad et al. (2010a,b)
- June-November heavy (top 10%) precipitation events
- Precipitation data
  - Environment Canada 6-hourly precipitation
- Synoptic typing and synoptic-dynamic analysis
  - NCEP/DOE Reanalysis-2: 2.5° horizontal resolution

Milrad, S. M., E. H. Atallah, J. R. Gyakum, and G. Dookhie, 2013: Synoptic-scale precursors and typing of warm-season precipitation events at Montreal, Quebec. *Wea. Forecasting*, submitted.

Synoptic Typing of Heavy Events

- Closer examination of heavy event (top 10%) dynamics
- Synoptic-scale vs. mesoscale ascent mechanisms
- Partitioning methodology: Based on Q-vector components and the Q-vector form of the QG omega equation

$$(\nabla^2{}_p + \frac{f_o{}^2}{\sigma}\frac{\partial^2}{\partial p^2})\omega = -2\nabla_p \bullet \mathbf{Q}$$

Milrad, S. M., E. H. Atallah, J. R. Gyakum, and G. Dookhie, 2013: Synoptic-scale precursors and typing of warm-season precipitation events at Montreal, Quebec. *Wea. Forecasting*, submitted.

Synoptic Typing

- Partitioning methodology (via Keyser et al. 1988)
  - Q_s and Q_n are the along- and across-isentrope components of the Q-vector
  - $\nabla_p \cdot Q_s < 0$: Represents synoptic-scale forcing for ascent
  - $\nabla_p \cdot Q_n < 0$: Represents mesoscale forcing for ascent
- Event types based on threshold values of $\nabla_p \cdot Q_s$ and $\nabla_p \cdot Q_n$

Milrad, S. M., E. H. Atallah, J. R. Gyakum, and G. Dookhie, 2013: Synoptic-scale precursors and typing of warm-season precipitation events at Montreal, Quebec. *Wea. Forecasting*, submitted.

Synoptic Typing

- **4 heavy event types identified**

Type	Description		
A	Cyclone	<< 0	< 0
B	Warm front	~ 0	< 0 (isotherms east-west)
C	Cold front	~ 0	< 0 (isotherms north-south)
D	Convective	~ 0	~ 0

Q_s divergence Q_n divergence

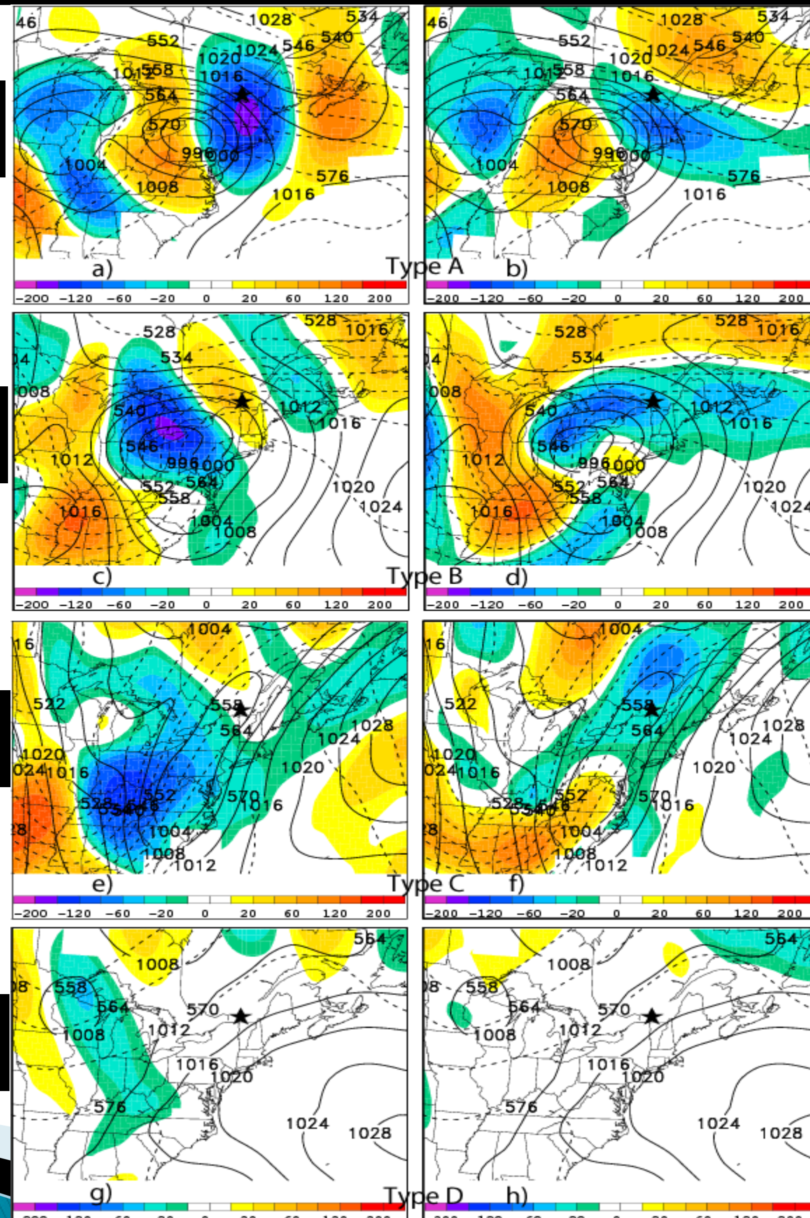
Cool colors indicate convergence (ascent)

Type A: Cyclone

Type B: Warm Front

Type C: Cold Front

Type D: Convective



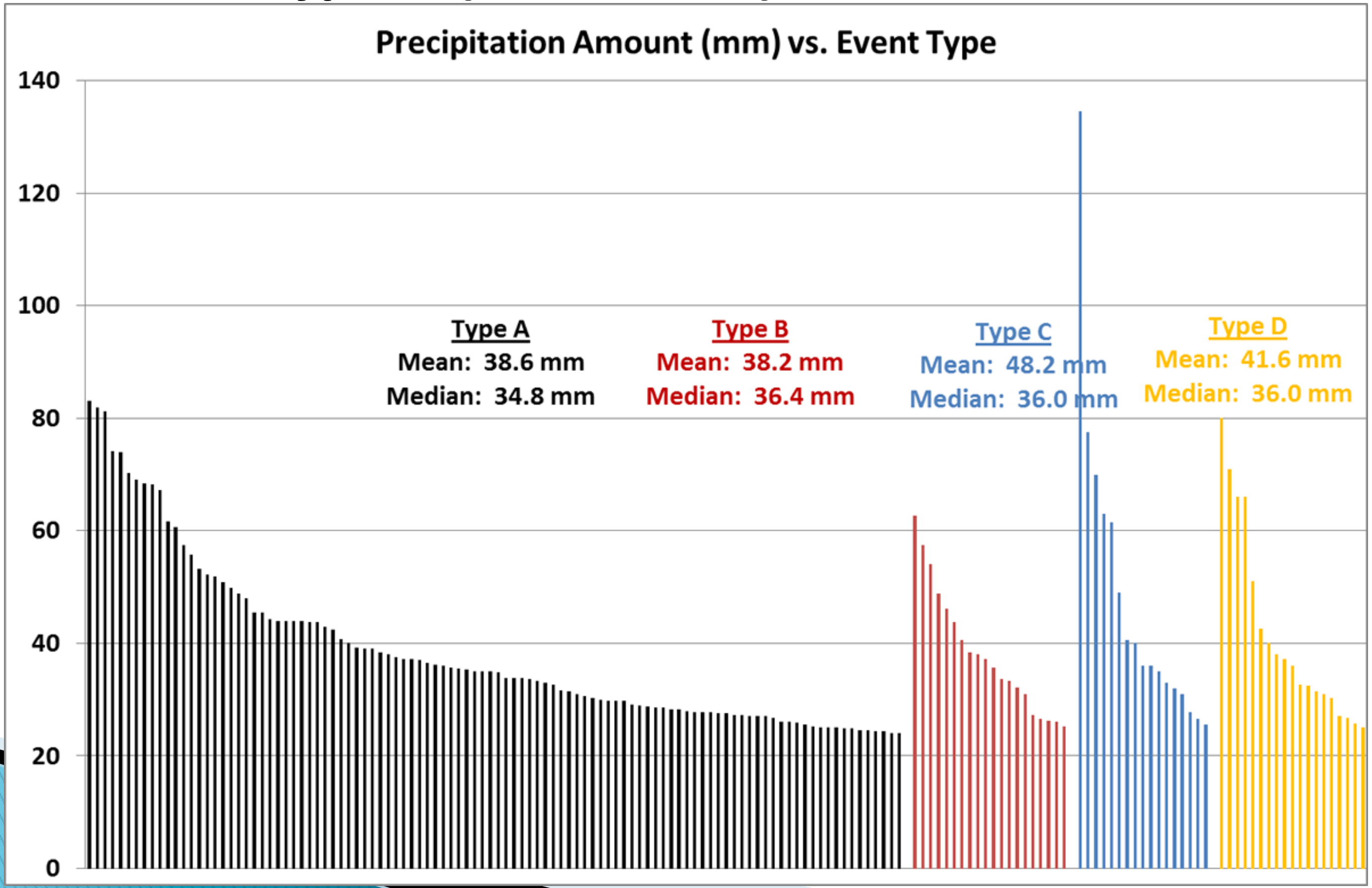
Synoptic Typing

Type A (cyclone): 103 cases

Type B (warm frontal): 20 cases

Type C (cold frontal): 17 cases

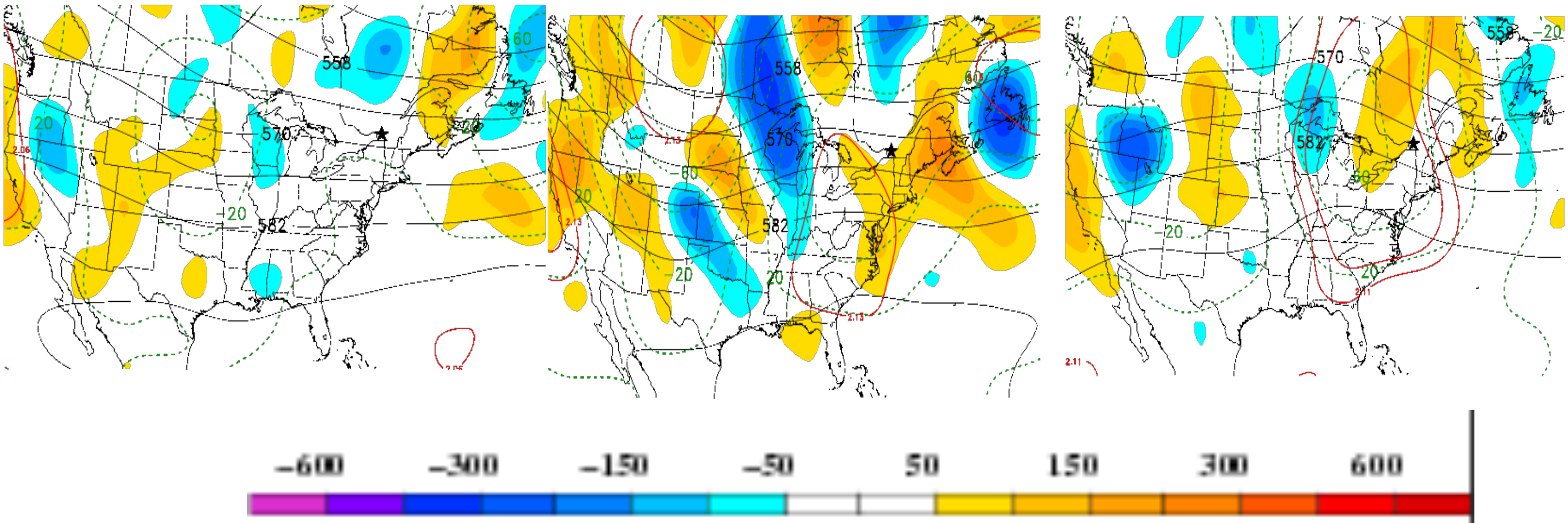
Type D (convective): 19 cases



Synoptic-Dynamic Analysis: 500 mb Height

Animations every 6 hours from t = -48 h to t = 0 h (time of heaviest precipitation)

Type A: Cyclone Type C: Cold front Type D: Convective



1000-500 mb layer-averaged Q_s divergence (shaded, cool colors convergent)

500 mb composite geopotential height (dam, solid)

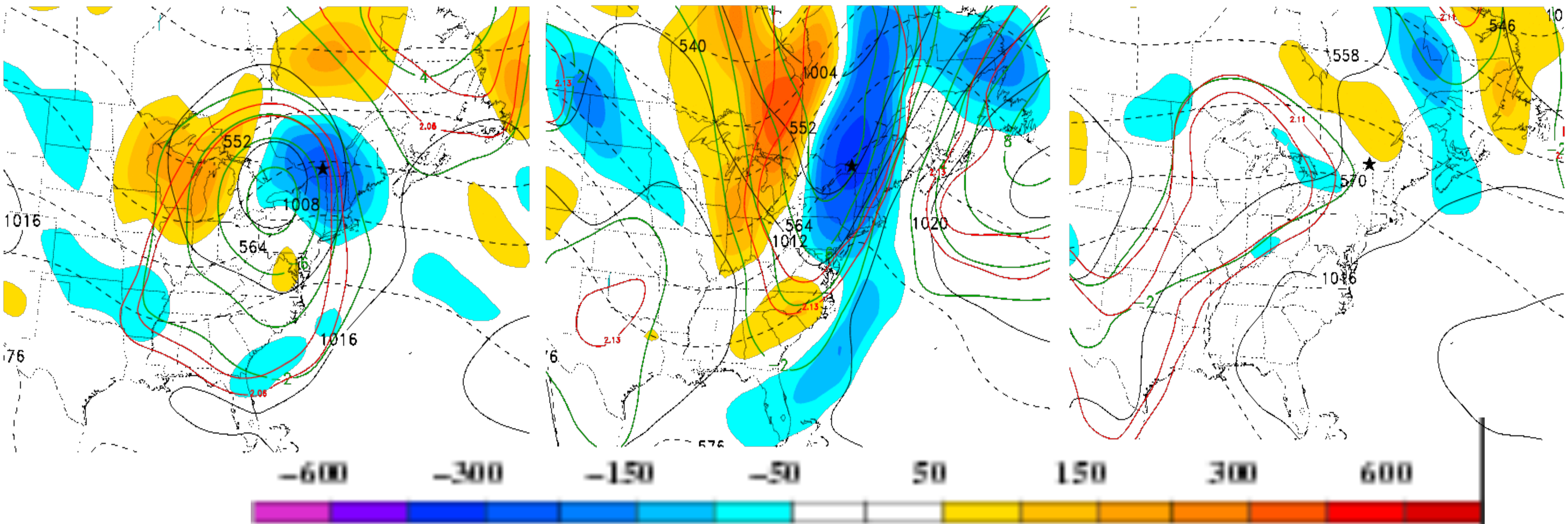
500 mb geopotential height composite anomalies (m, green dashed)

Statistical significance at 95% (outer solid red) and 99% (inner solid red)

Synoptic-Dynamic Analysis: MSLP

At t = 0 h (time of heaviest precipitation)

Type A: Cyclone | **Type C: Cold front** | **Type D: Convective**



1000-500 mb layer-averaged Q_n divergence (shaded, cool colors convergent)

Composite MSLP (mb, solid)

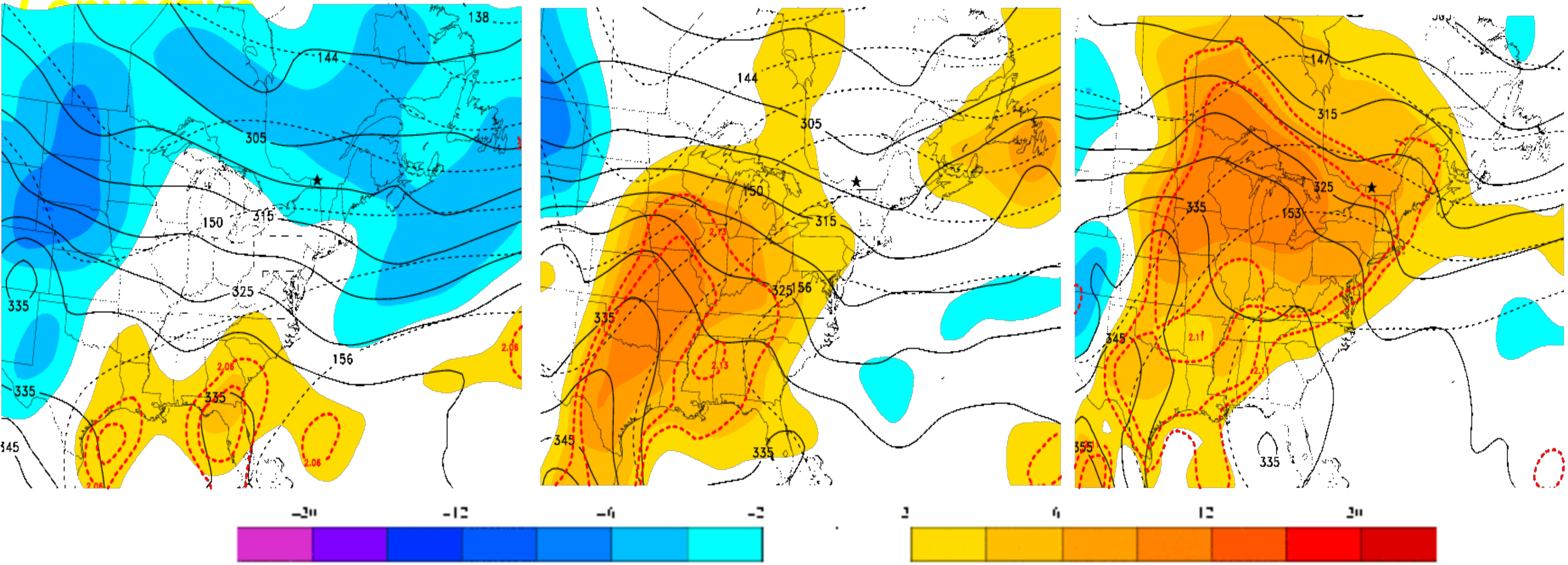
MSLP composite anomalies (mb, green dashed)

Statistical significance at 95% (outer solid red) and 99% (inner solid red)

Synoptic-Dynamic Analysis: 850 Equiv. Pot. Temp. (θ_e)

Animations every 6 hours from t = -48 h to t = 0 h (time of heaviest precipitation)

Type A: Cyclone **Type C: Cold front** **Type D: Convective**



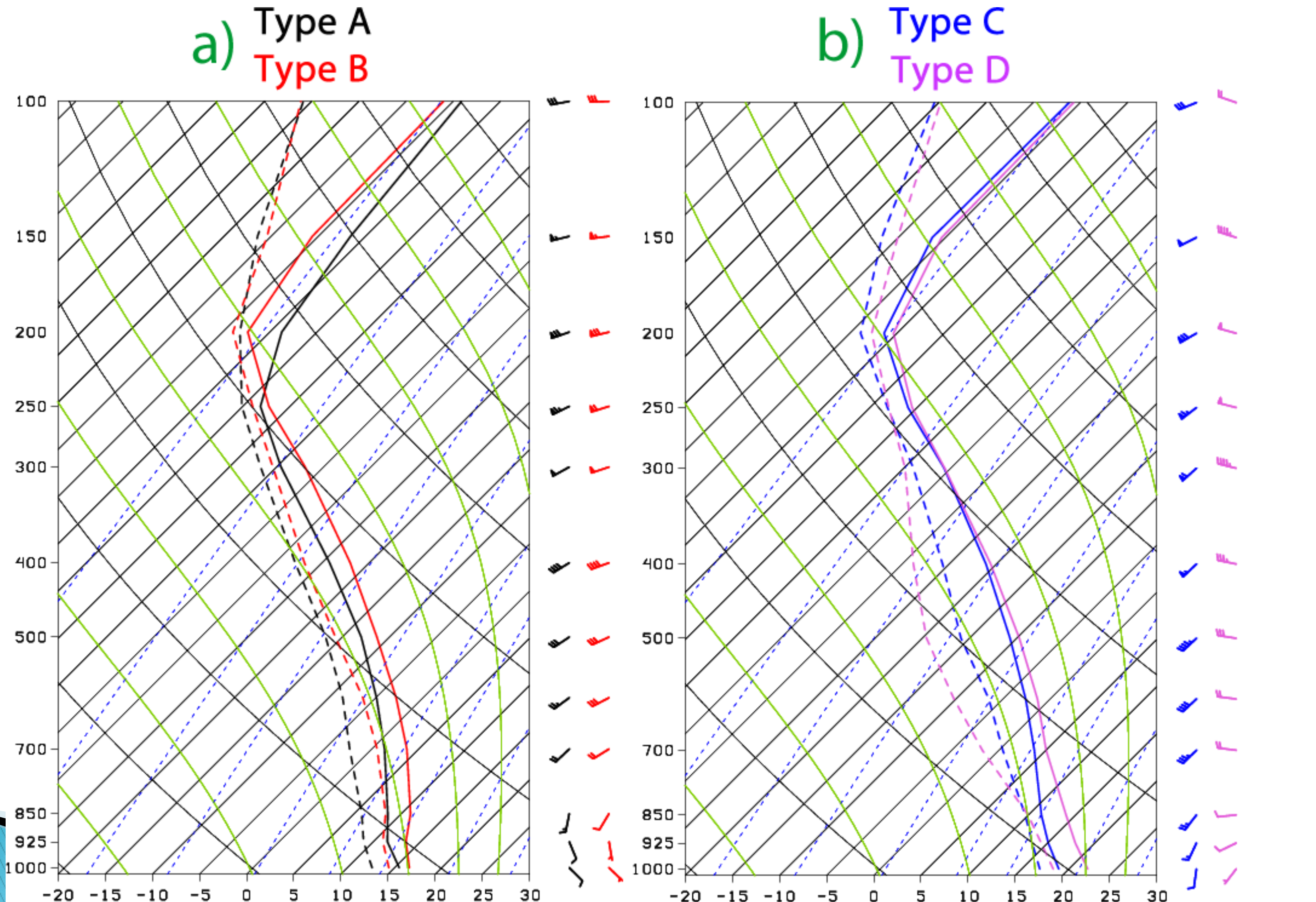
850 mb θ_e composite anomalies (K, shaded)

850 mb composite θ_e (K, solid)

700 mb composite geopotential height (dam, dashed)

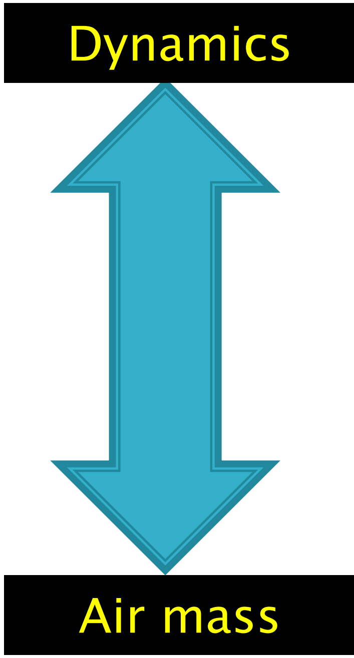
Statistical significance at 95% (outer solid red) and 99% (inner solid red)

Synoptic-Dynamic Analysis: Soundings



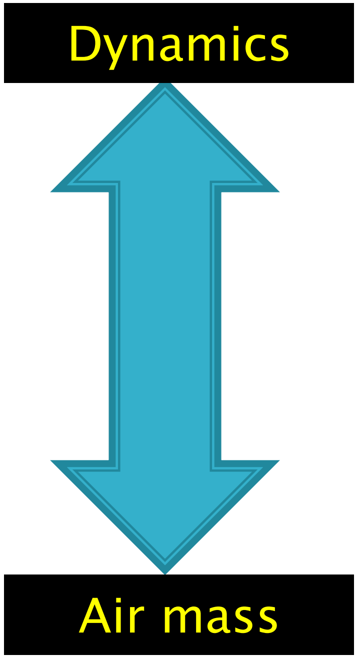
Pathways to Heavy Precipitation

- Cyclone (Type A)
  - Strong upstream trough/MSLP cyclone
  - Synoptic-scale QG forcing for ascent
  - Relatively slow-developing Gulf/Atlantic high-θ_e transport
- Cold front (Type C)
  - Very anomalous trough-ridge couplet
  - Cyclone track to north of Montreal
  - Extensive high-θ_e air transport from Gulf
  - Steep lapse rates/low static stability
- Convective (Type D)
  - In-situ anomalous ridge
  - Weak shortwave trough w/in ridge environment
  - Steep lapse rates/low static stability
  - Warm, humid air mass: Conditioning in U.S. Plains?



Key Take-Home Points/Questions

- **Cyclones are important (e.g., Pfahl and Wernli 2012), but so is the downstream anticyclone**
    - **Moisture transport**
    - **Warm, unstable air mass**
- **A cyclone is not required to produce an extreme precipitation event**
    - **Air mass characteristics: Moisture, stability**
    - **More common in the warm season?**



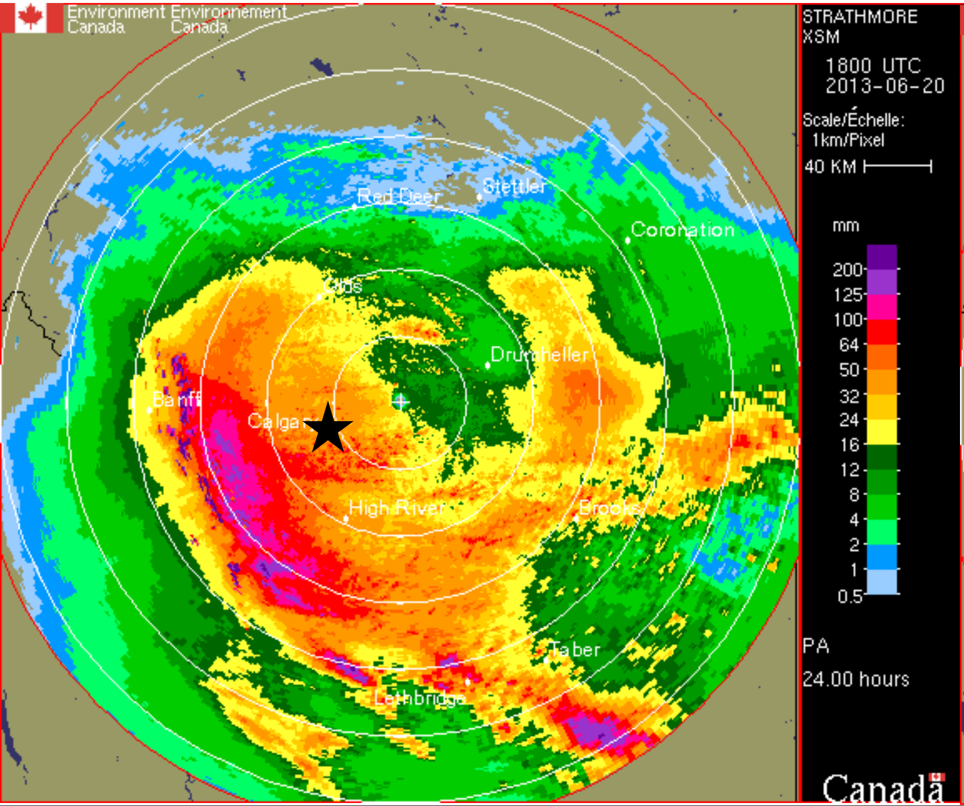
Alberta Flood of June 2013

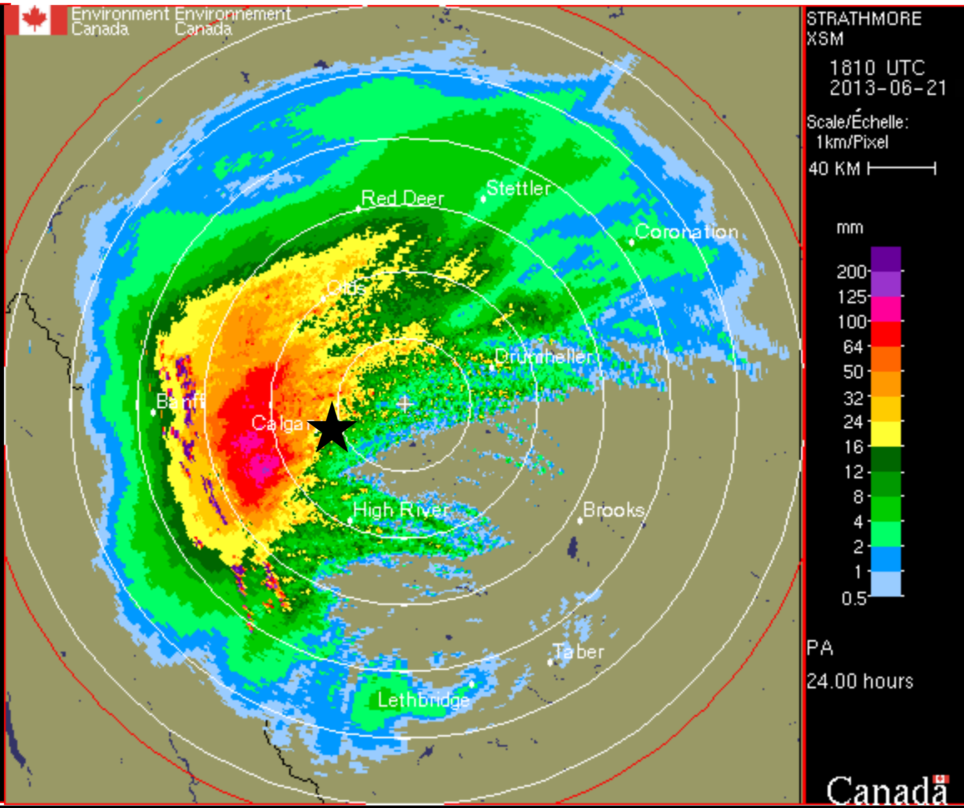
- Heavy rain (June 19-21) in AB foothills
  - 200+ mm (1800 UTC 19 June – 1800 UTC 21 June)
  - Flowed downstream/downhill through Bow River Basin
  - Worst flooding in Calgary, AB history

- Objective: Synoptic evolution of an extreme precipitation event

http://www.huffingtonpost.ca/2013/07/22/alberta-flooding-before-after-video_n_3636314.html

Precipitation totals

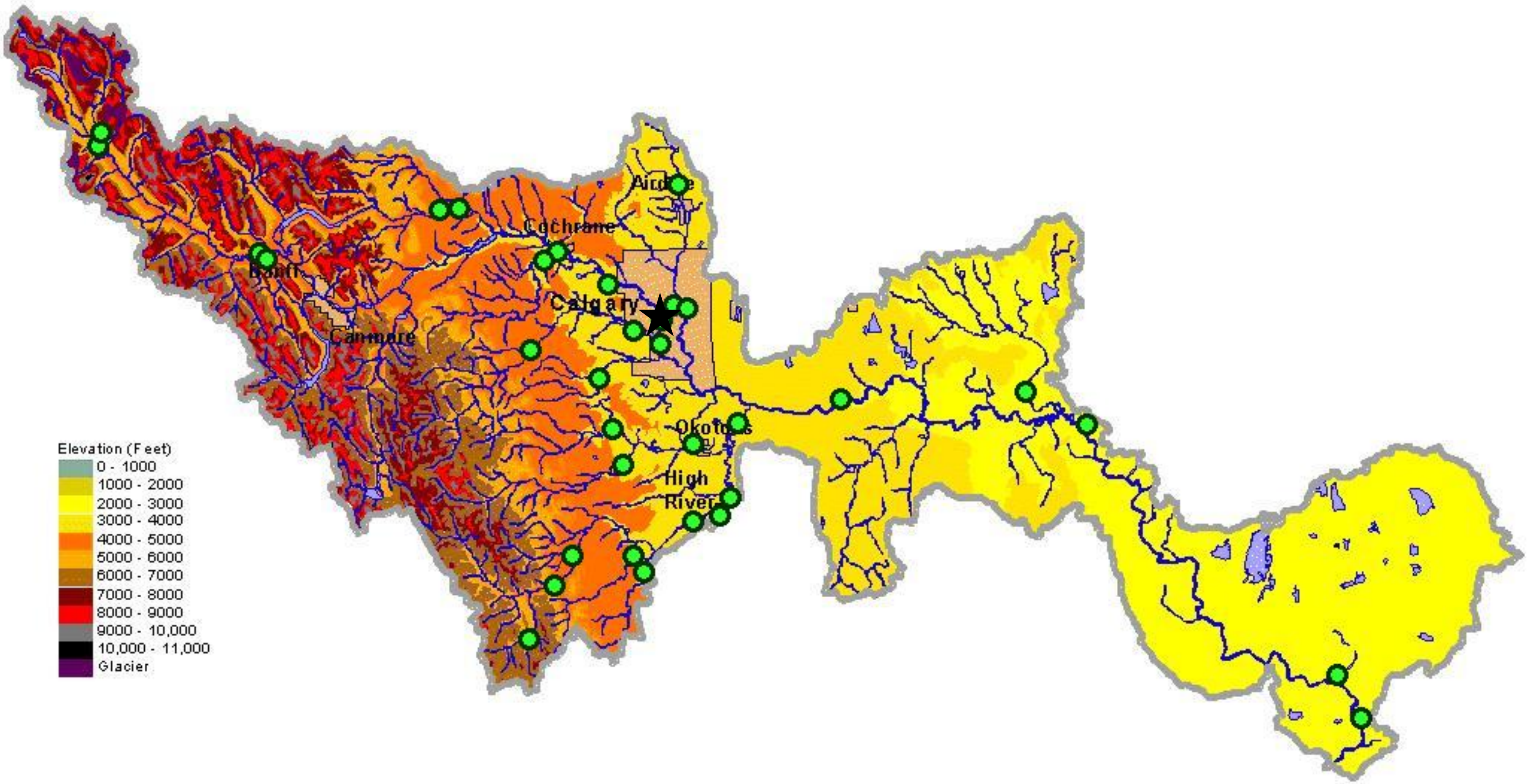




24-h radar-based accumulation

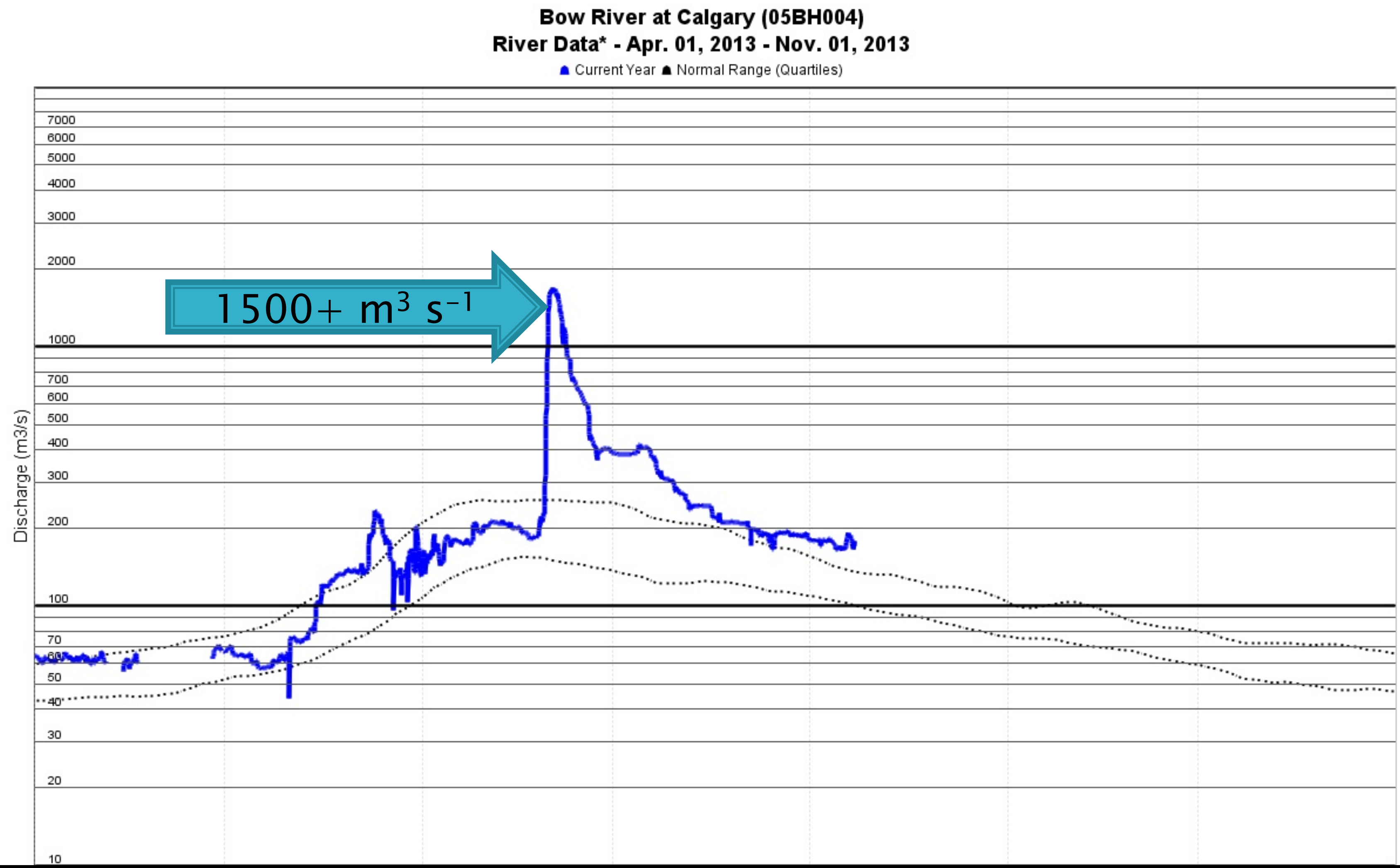
1800 UTC 19 June-1800 UTC 20 June　　1800 UTC 20 June-1800 UTC 21 June

Hydrology



Airdrie
Cochrane
Banff
Calgary
Canmore
Okotoks
High River
Elevation (Feet)
0 - 1000
1000 - 2000
2000 - 3000
3000 - 4000
4000 - 5000
5000 - 6000
6000 - 7000
7000 - 8000
8000 - 9000
9000 - 10,000
10,000 - 11,000
Glacier

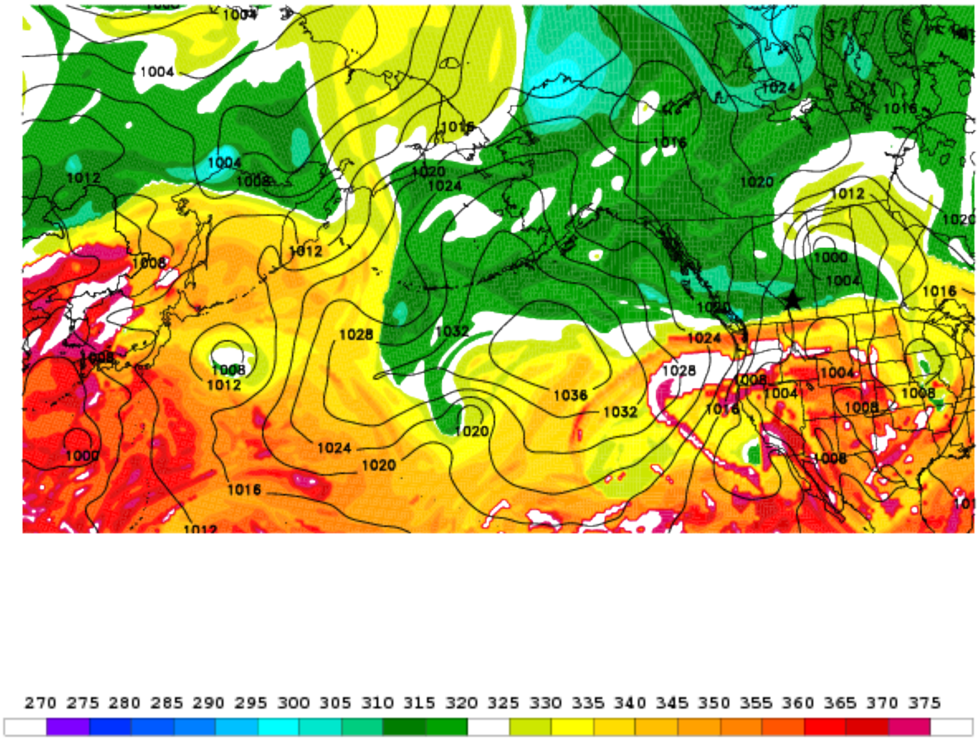
Hydrology

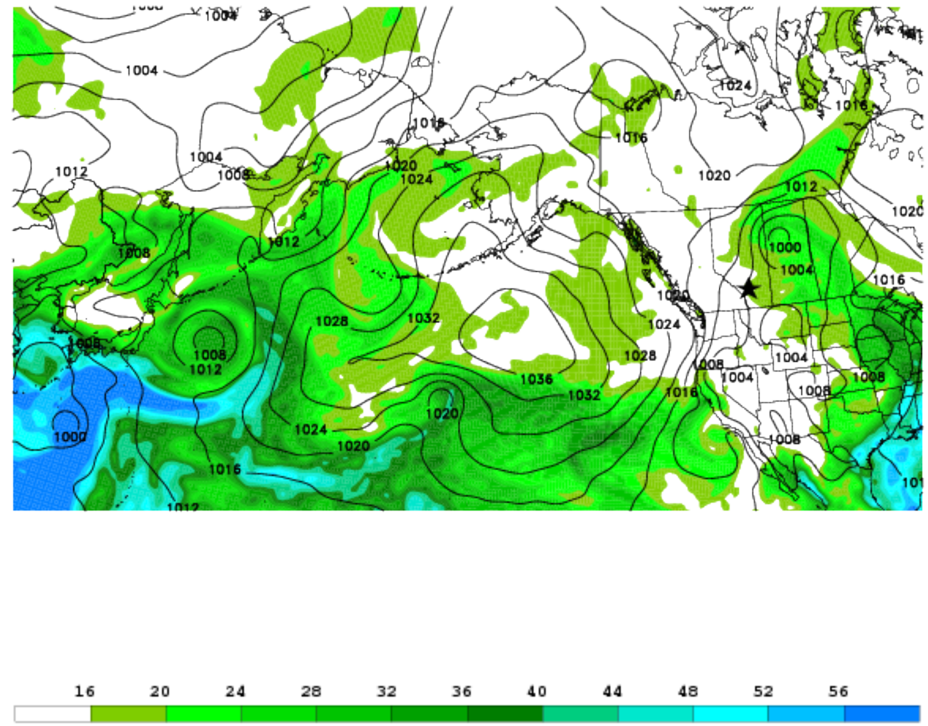


Streamflow (Bow River at Calgary)

Synoptic Evolution: CFSR (0.5° Global)

t = -240 h (0000 UTC 10 June)



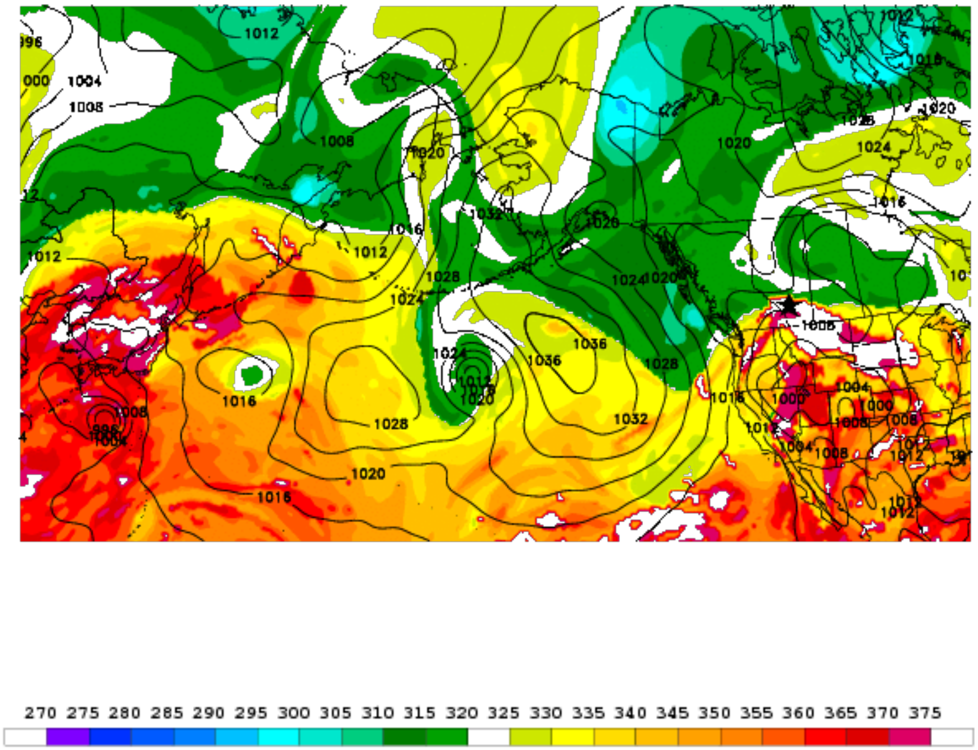


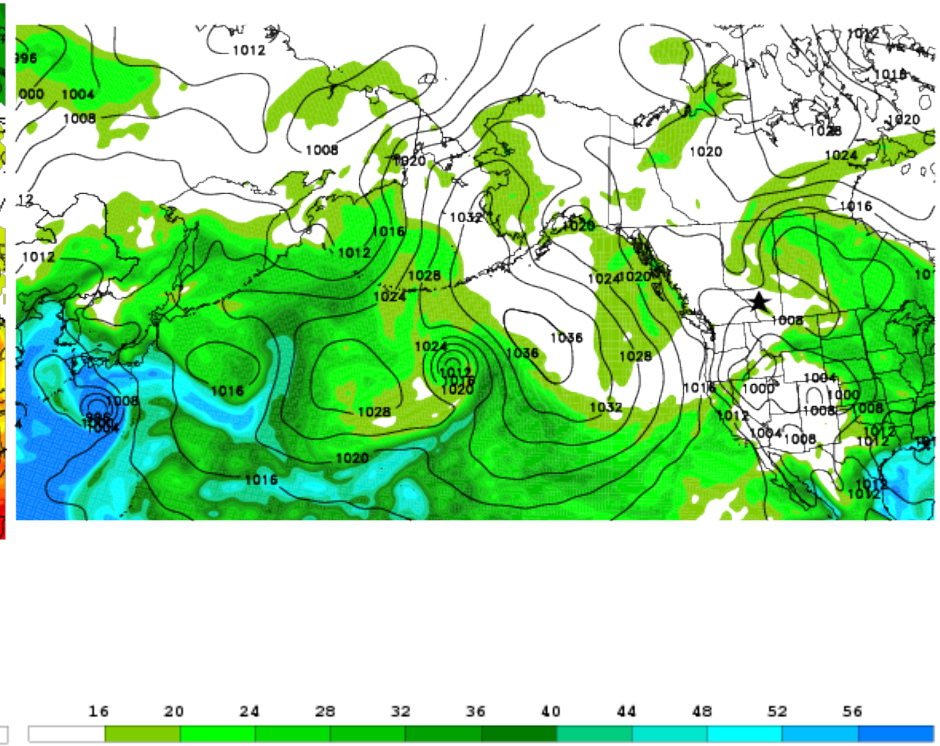
θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

Precipitable Water (mm, shaded)
MSLP (mb, solid)

Synoptic Evolution: CFSR (0.5° Global)

t = -216 h (0000 UTC 11 June)



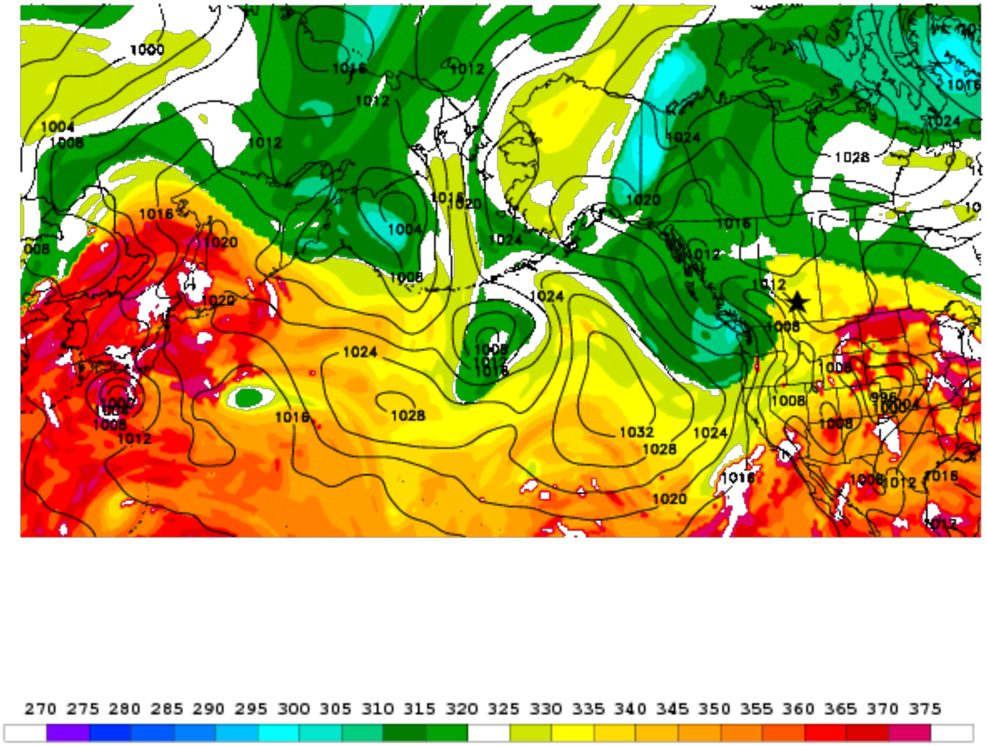


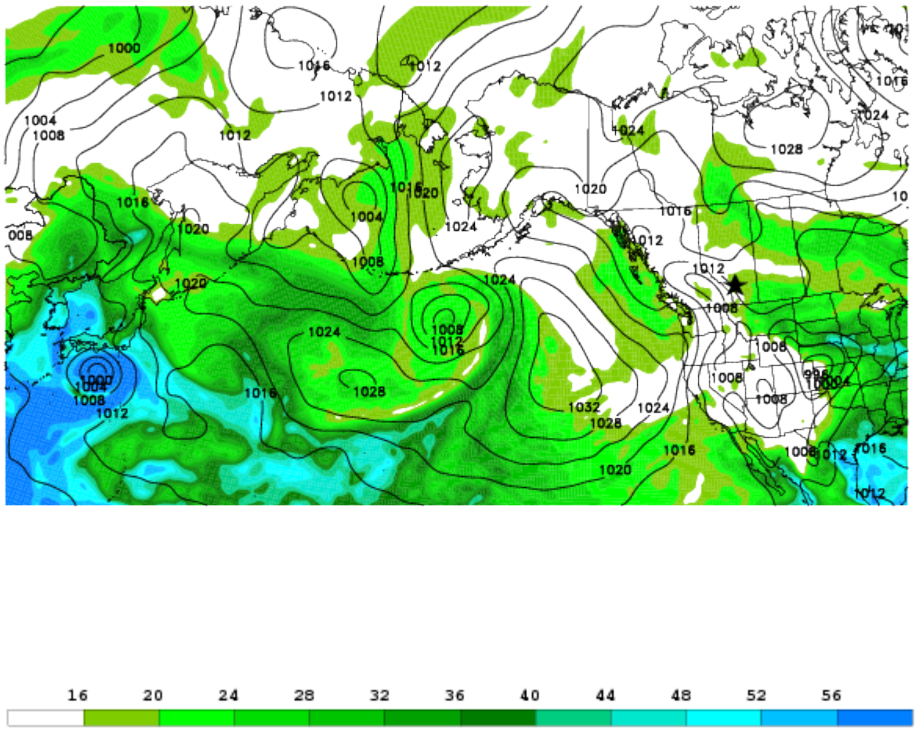
θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

Precipitable Water (mm, shaded)
MSLP (mb, solid)

Synoptic Evolution: CFSR (0.5° Global)

t = -192 h (0000 UTC 12 June)



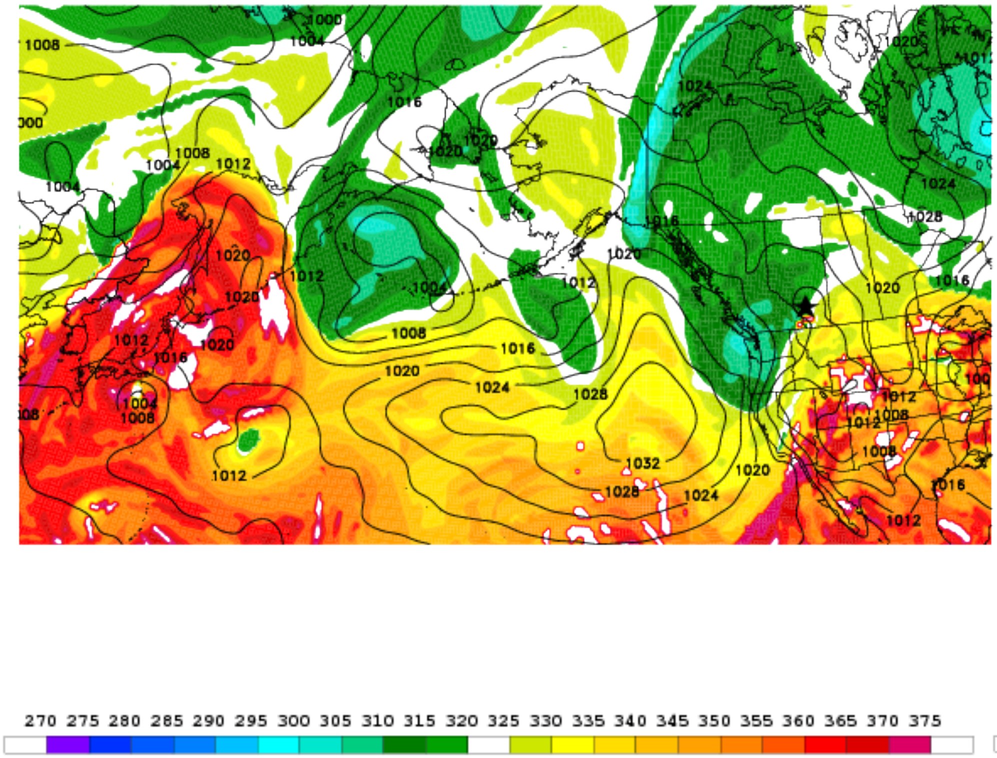


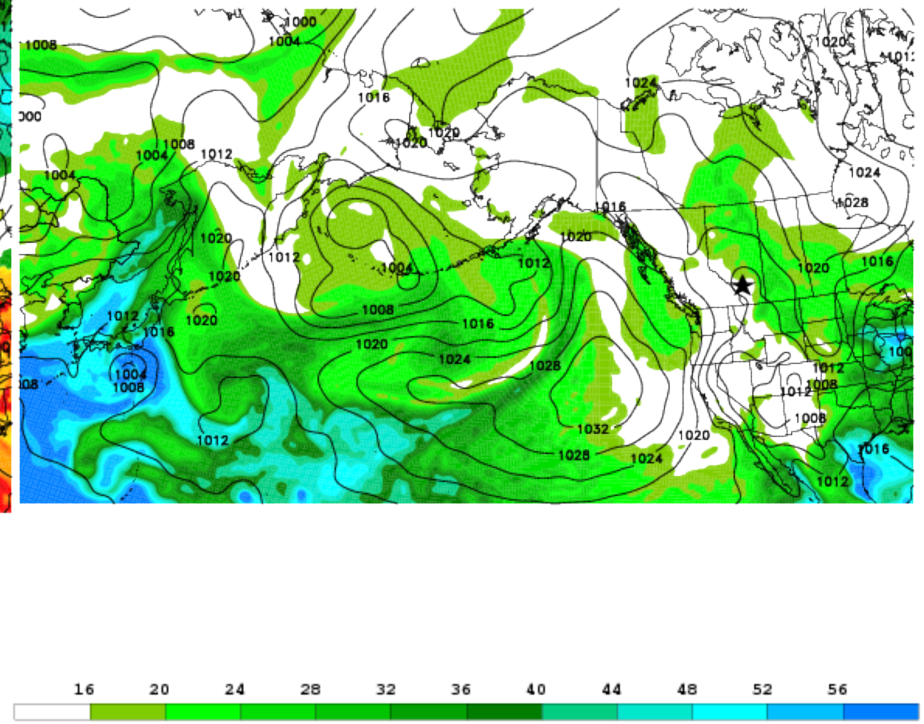
θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

Precipitable Water (mm, shaded)
MSLP (mb, solid)

Synoptic Evolution: CFSR (0.5° Global)

t = -168 h (0000 UTC 13 June)



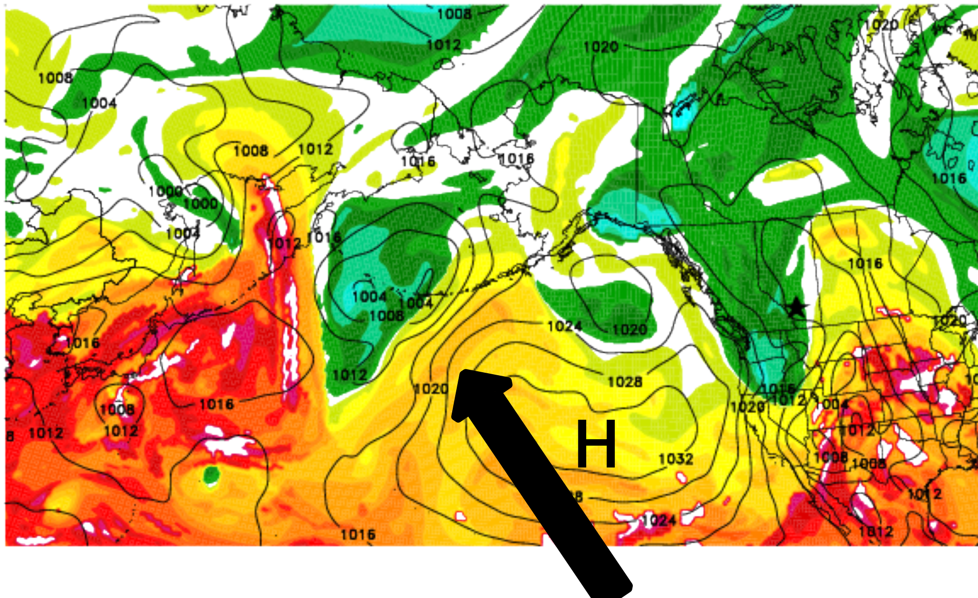


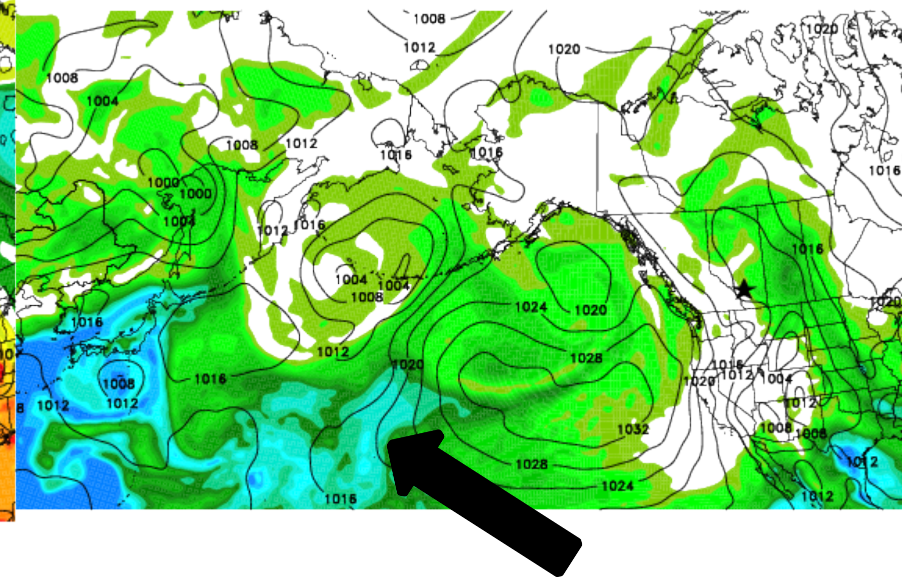
θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

Precipitable Water (mm, shaded)
MSLP (mb, solid)

Synoptic Evolution: CFSR (0.5° Global)

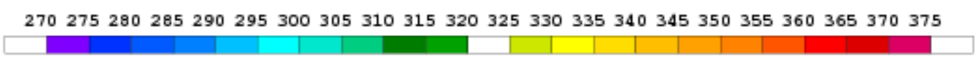
t = -144 h (0000 UTC 14 June)

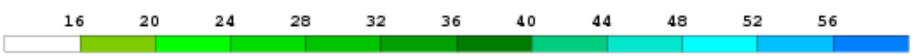




Start of Atmospheric River

Subtropical Moisture Reservoir



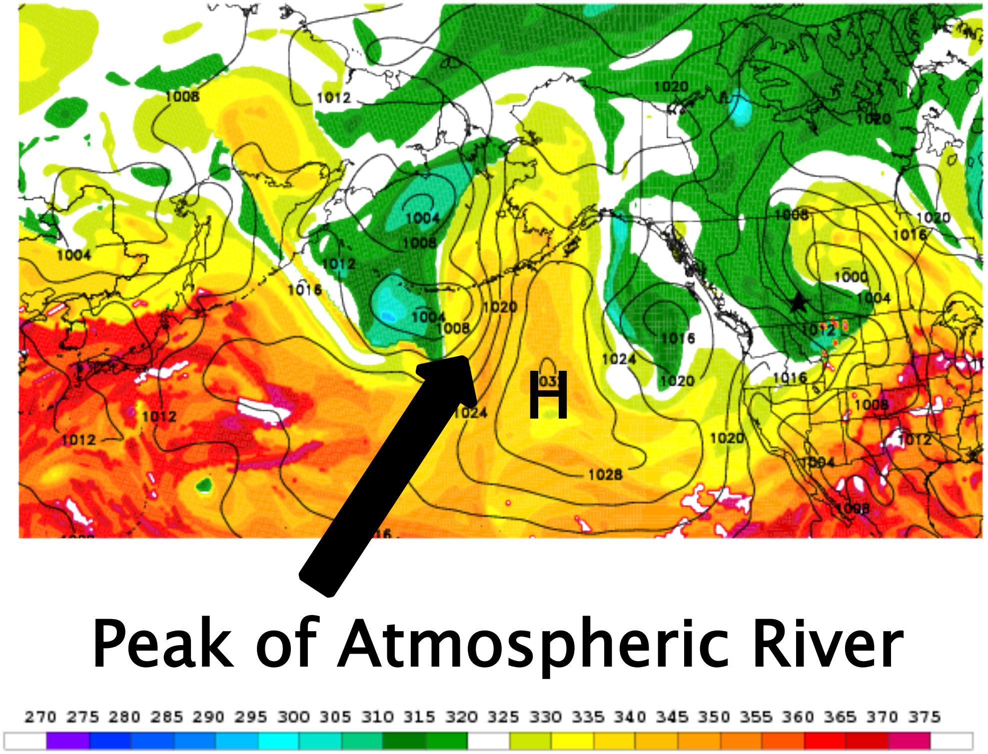


θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

Precipitable Water (mm, shaded)
MSLP (mb, solid)

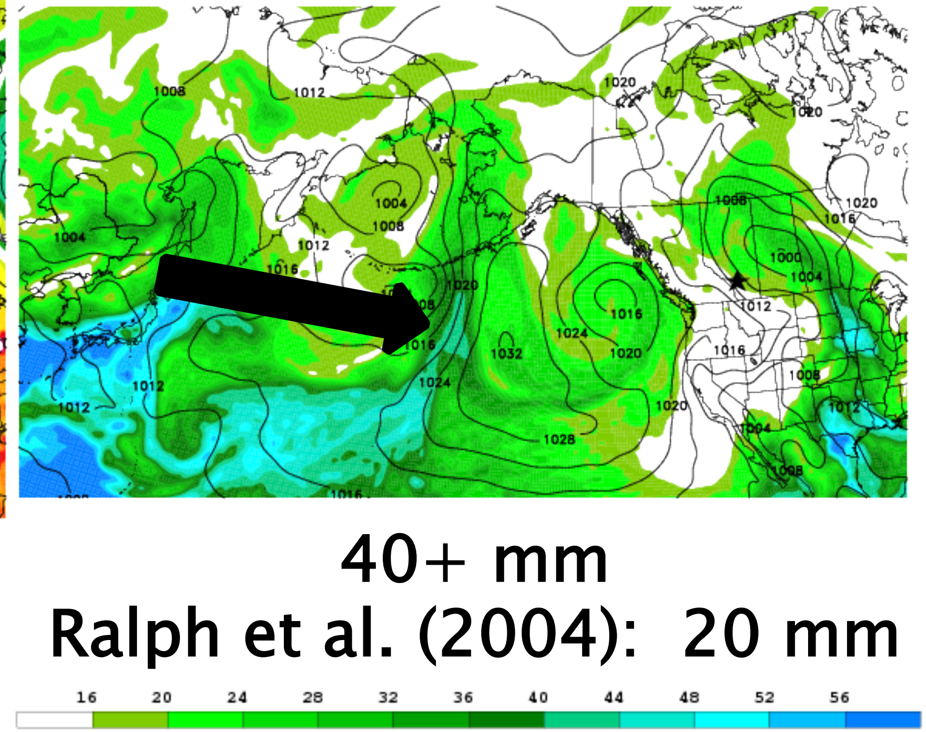
Synoptic Evolution: CFSR (0.5° Global)

t = -120 h (0000 UTC 15 June)



Peak of Atmospheric River

θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

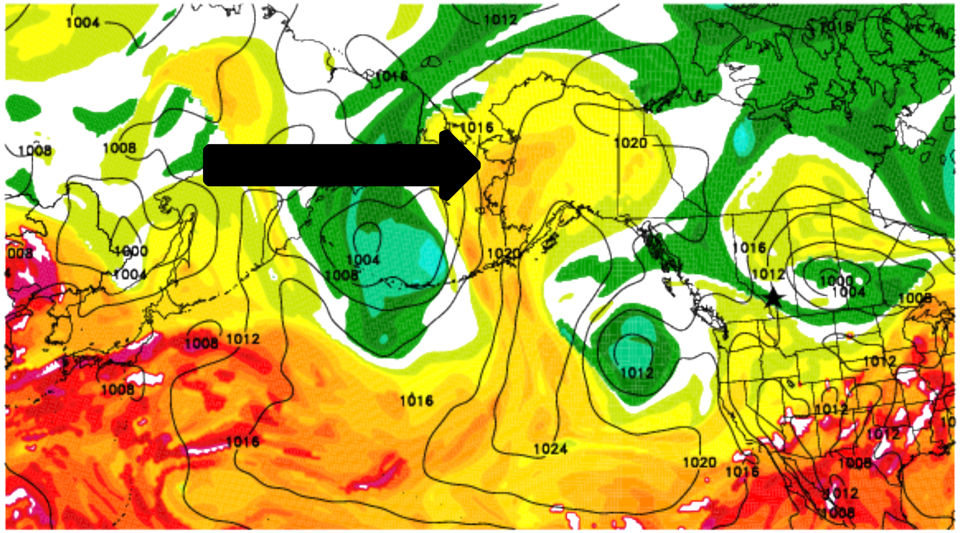


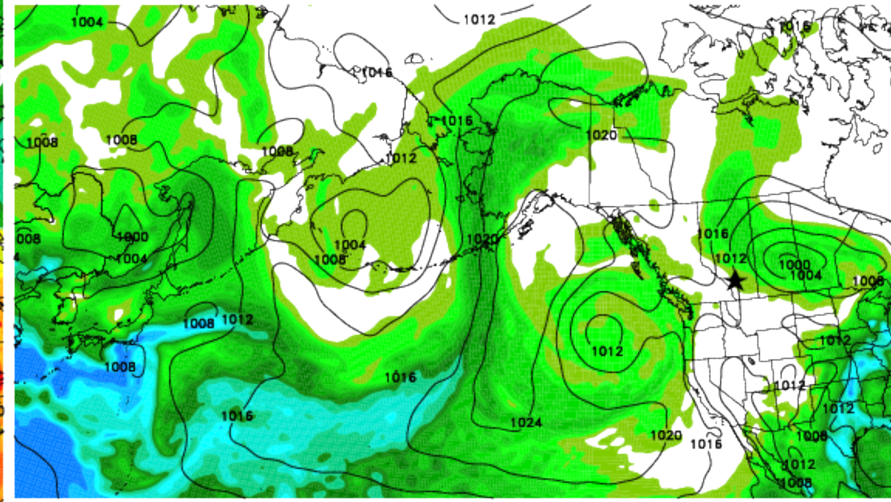
40+ mm
Ralph et al. (2004): 20 mm

Precipitable Water (mm, shaded)
MSLP (mb, solid)

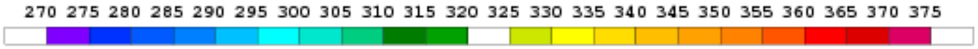
Synoptic Evolution: CFSR (0.5° Global)

t = -96 h (0000 UTC 16 June)





Alaskan Ridge/heat wave

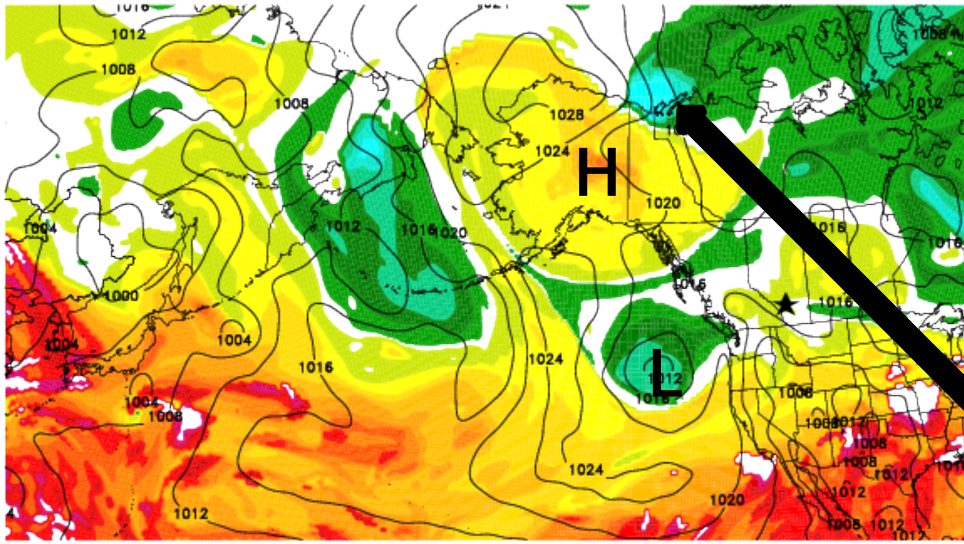


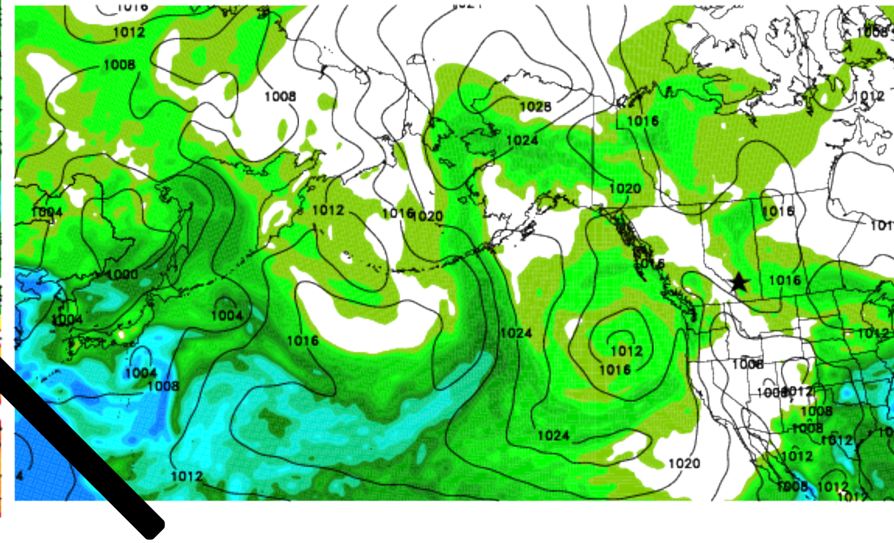
θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

Precipitable Water (mm, shaded)
MSLP (mb, solid)

Synoptic Evolution: CFSR (0.5° Global)

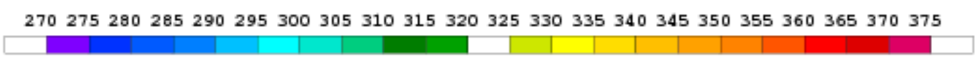
t = -72 h (0000 UTC 17 June)

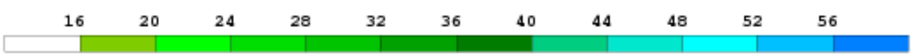




East Pacific Rex Block

Cyclonic DT Disturbance

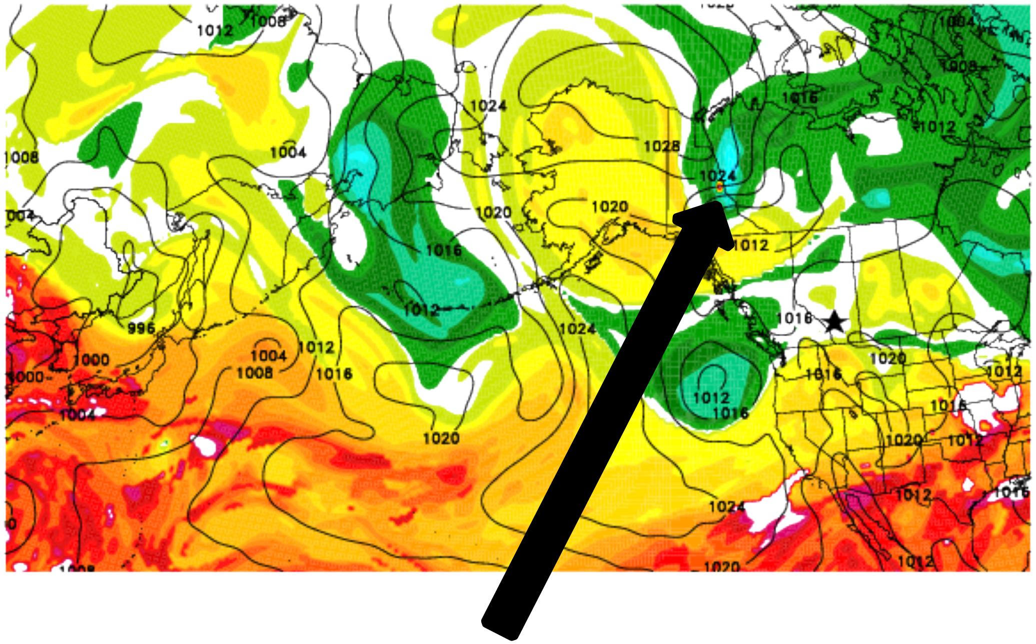




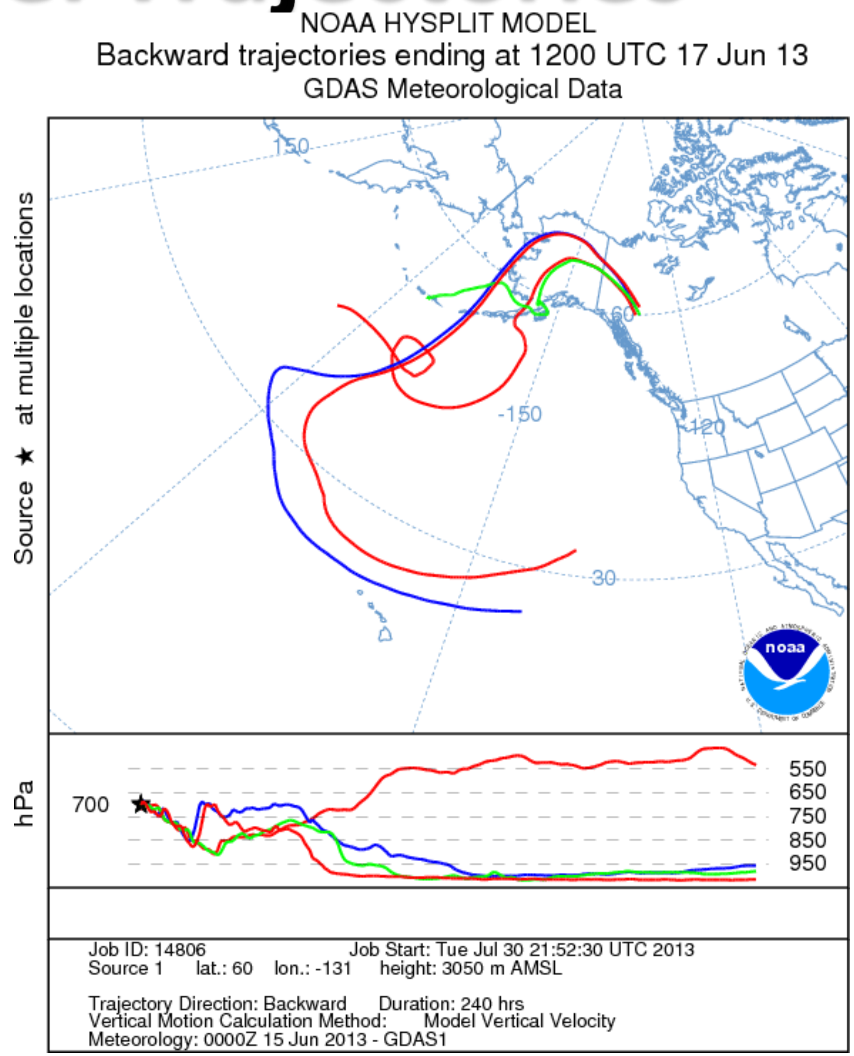
θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

Precipitable Water (mm, shaded)
MSLP (mb, solid)

Backward Air Parcel Trajectories

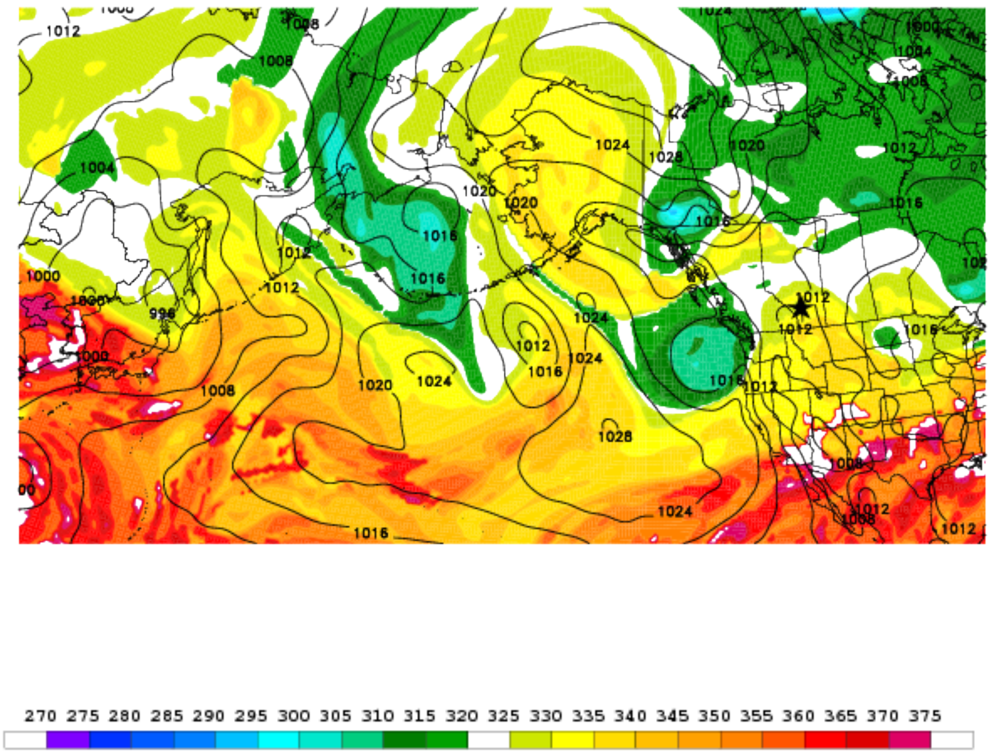


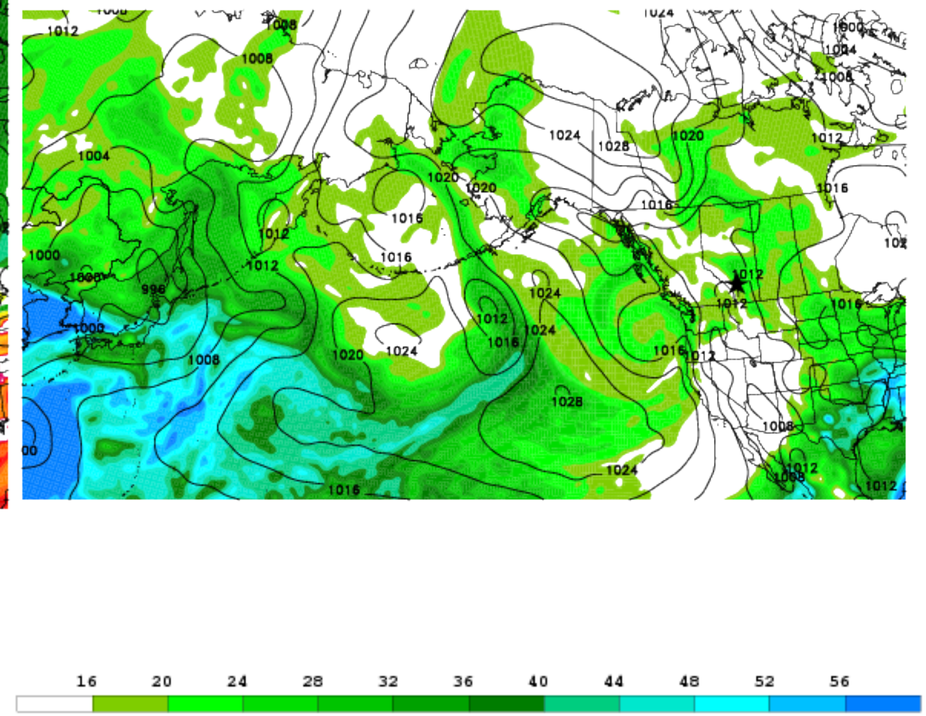
Cyclonic DT Disturbance



Synoptic Evolution: CFSR (0.5° Global)

t = -48 h (0000 UTC 18 June)



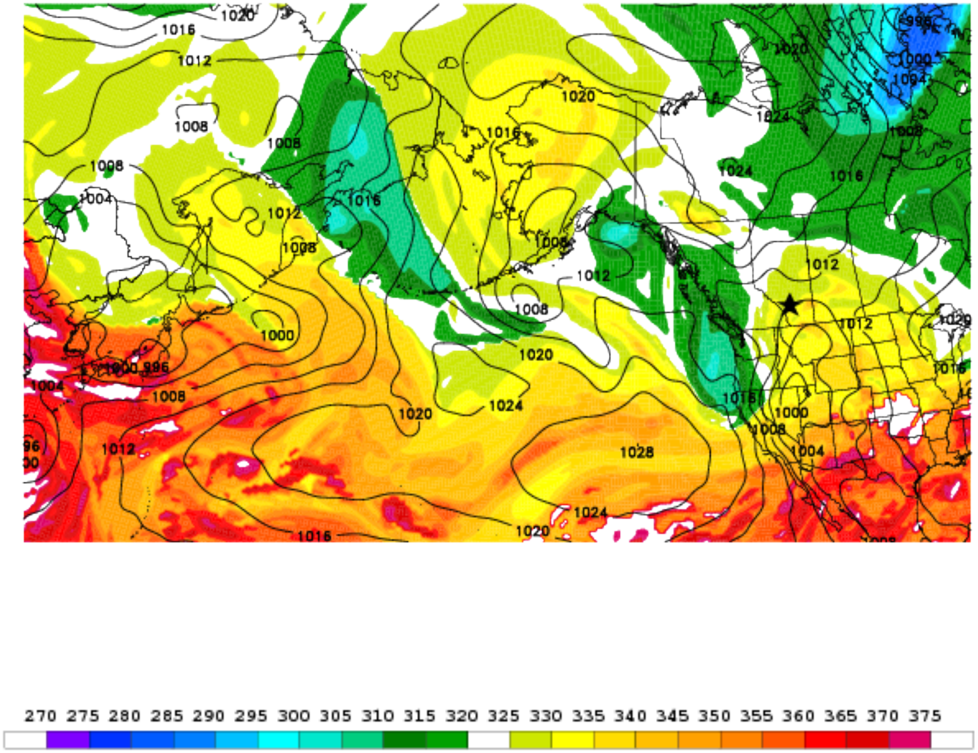


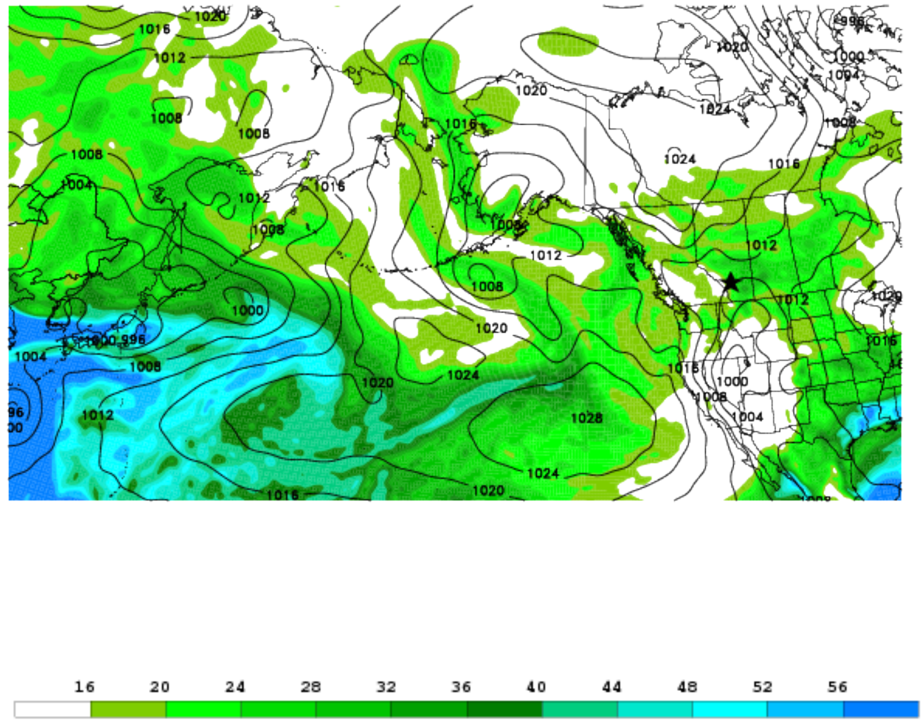
θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

Precipitable Water (mm, shaded)
MSLP (mb, solid)

Synoptic Evolution: CFSR (0.5° Global)

t = -24 h (0000 UTC 19 June)



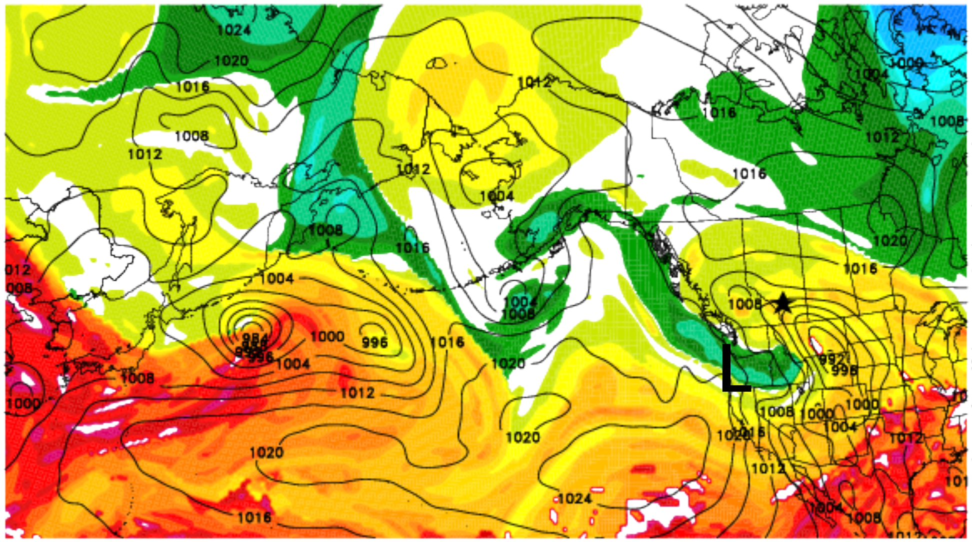


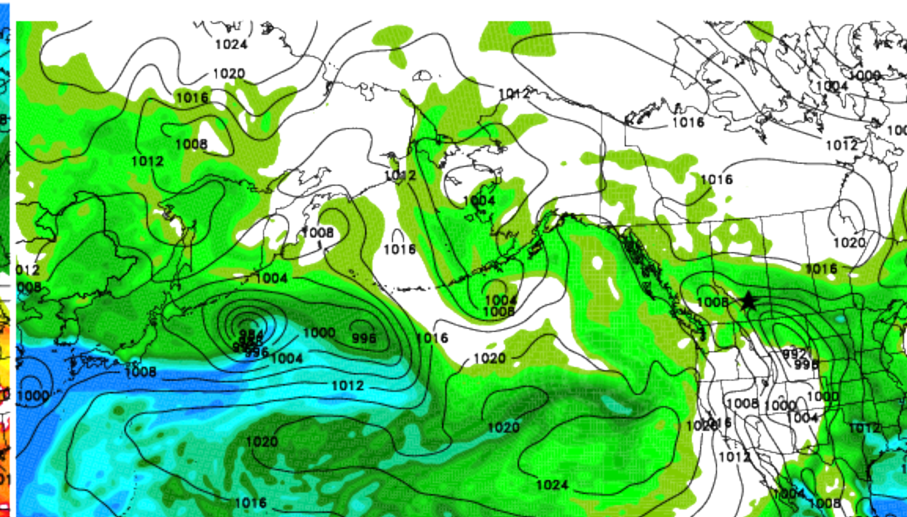
θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

Precipitable Water (mm, shaded)
MSLP (mb, solid)

Synoptic Evolution: CFSR (0.5° Global)

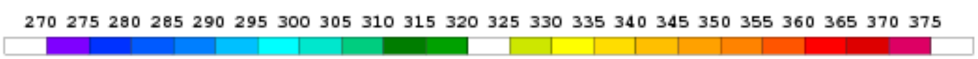
t = 0 h (0000 UTC 20 June)

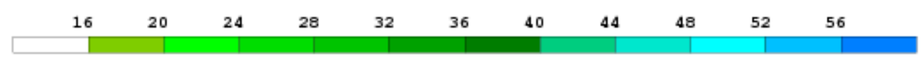




West Coast Cutoff Low

Easterly Upslope Flow



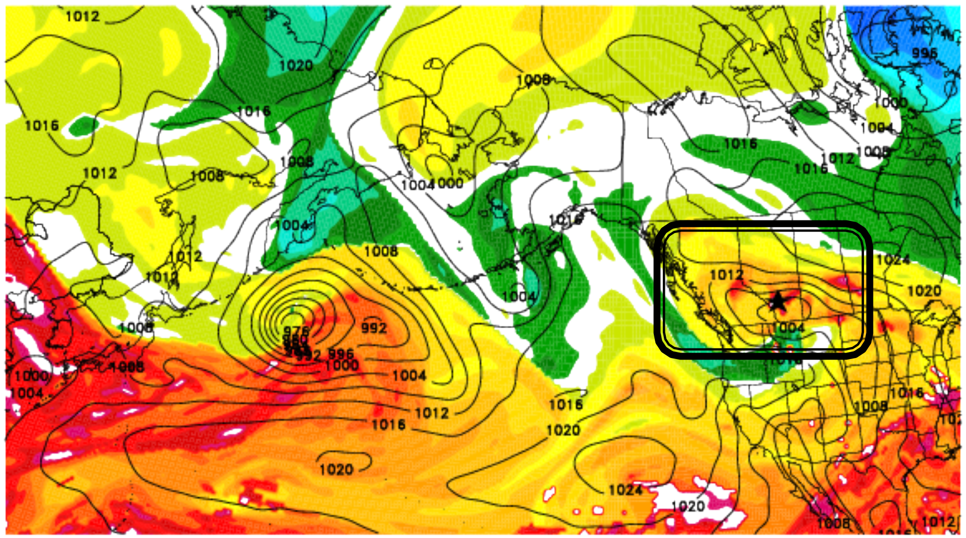


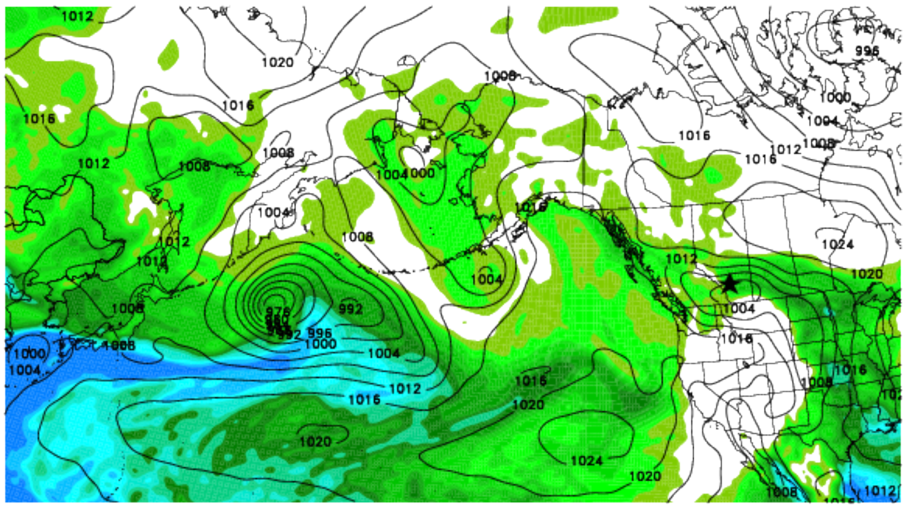
θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

Precipitable Water (mm, shaded)
MSLP (mb, solid)

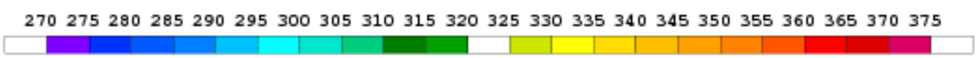
Synoptic Evolution: CFSR (0.5° Global)

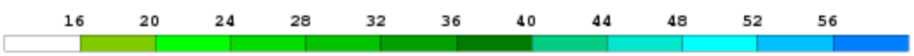
t = +12 h (1200 UTC 20 June)





Diabatic PV Generation





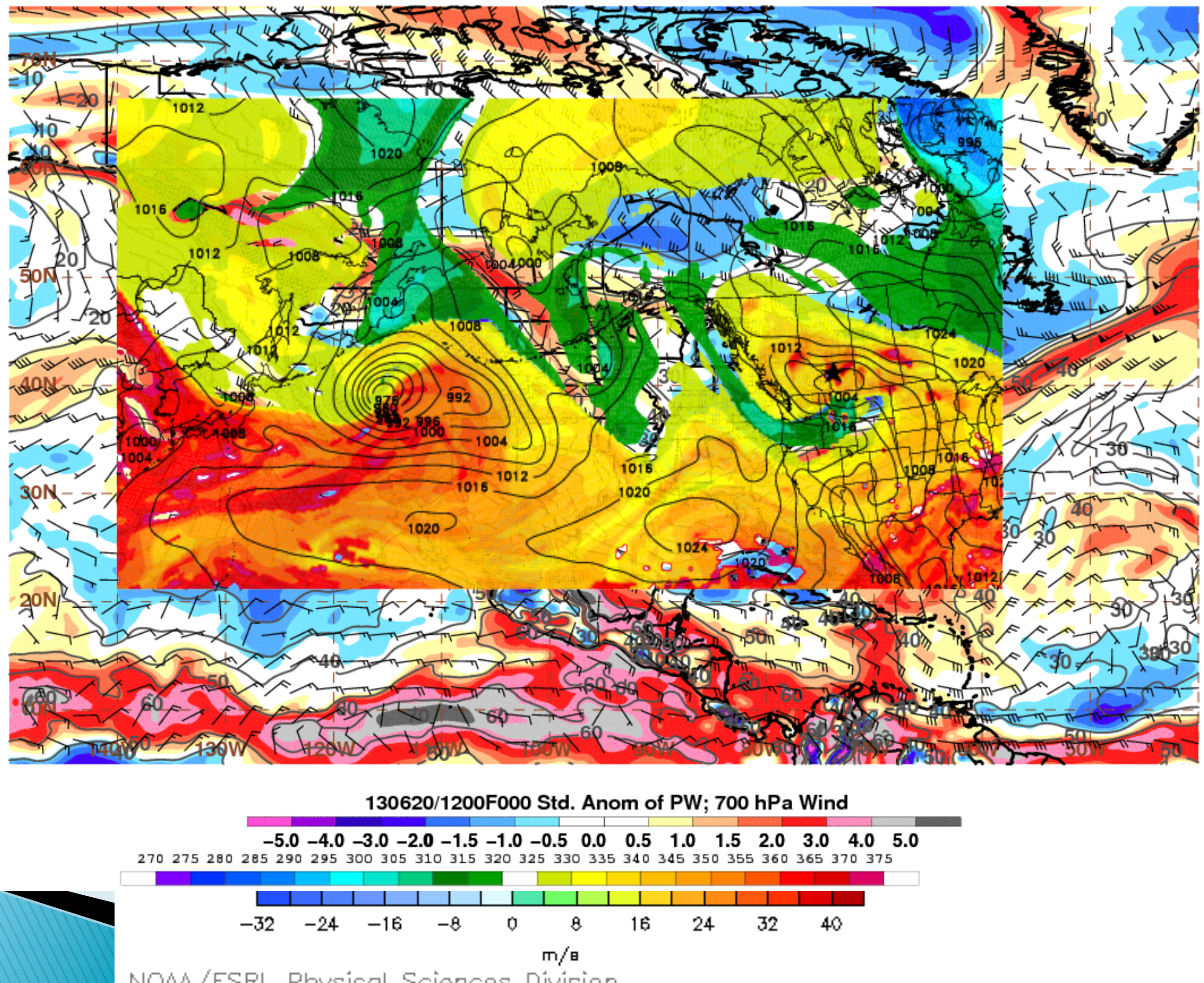
θ (K, shaded) on the DT (2 PVU surface)
MSLP (mb, solid)

Precipitable Water (mm, shaded)
MSLP (mb, solid)

Synoptic Evolution: Recap

- Synoptic waveguide starts at t = -240 h over East Asia (Hovmoller 45°N)
  - Downstr
- Strong sul
  - Atmosph
- Alaskan R
  - Record h
  - East Paci
- Cyclonic D
  - "Kicks" w
- Anomalou
- In-situ dia

Courtesy: SUNY-Albany

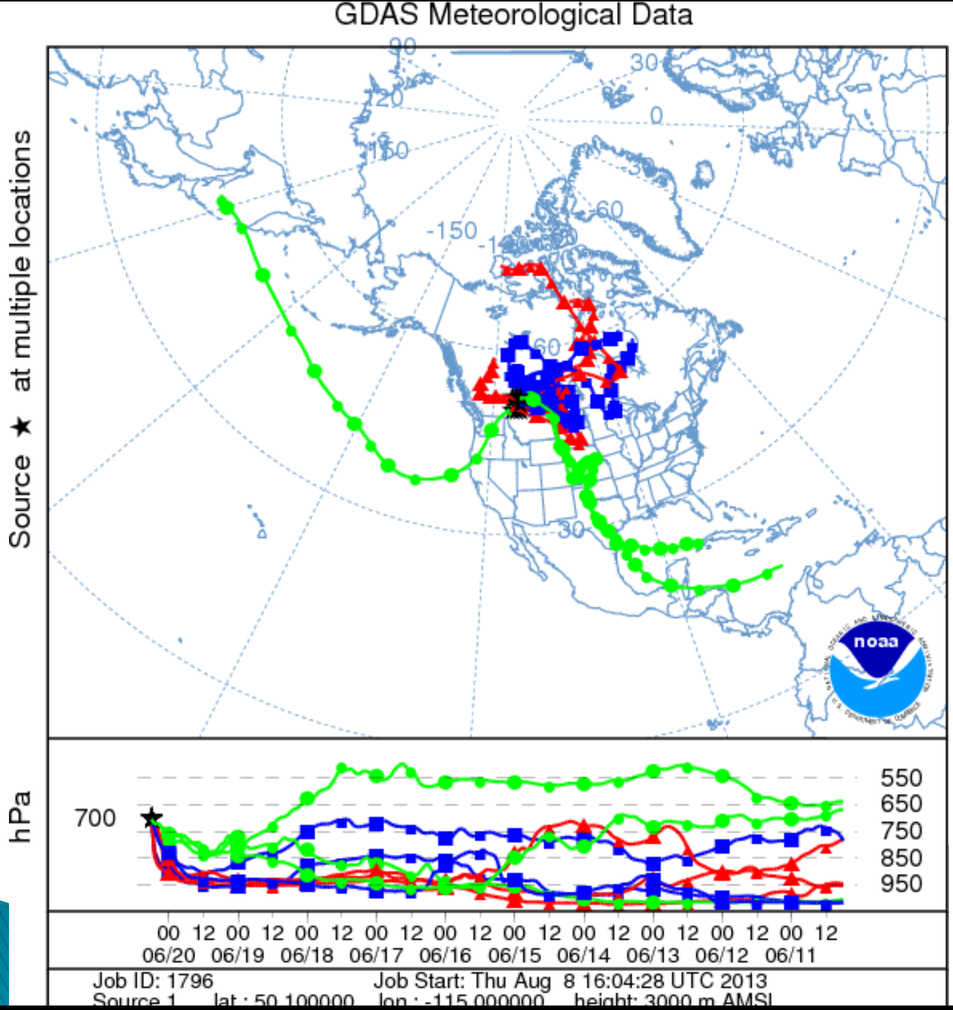


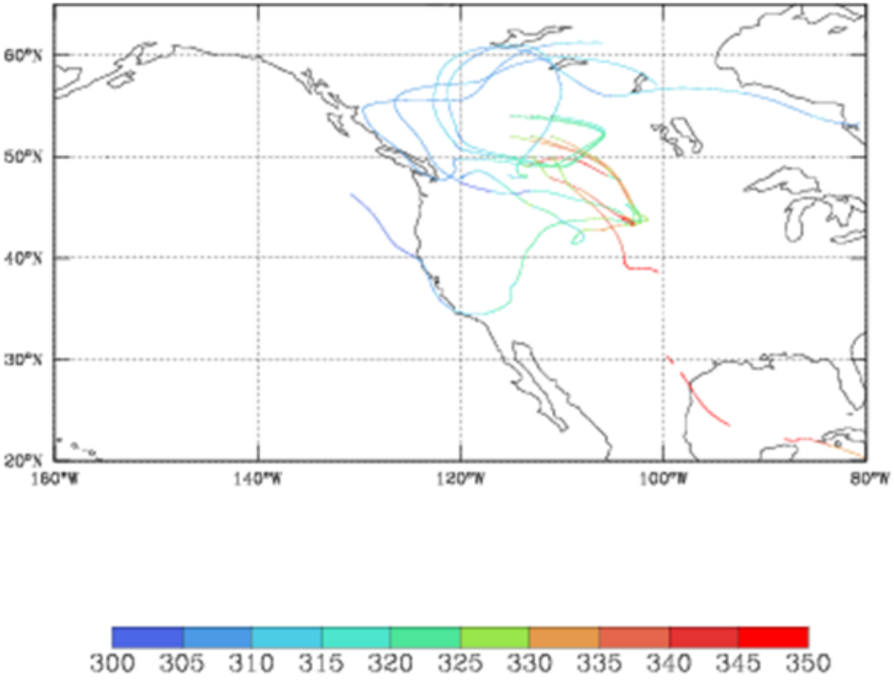
Air Mass Characteristics

- **For extreme precipitation events, high-θ_e air often appears to originate in the U.S. Plains, not directly from the Gulf of Mexico**
  - **Milrad et al. (2010a, 2013), Milrad and Kelly (2013)**
  - **In-situ air mass "conditioning"**

Air Mass Characteristics

10-day (240-h) Backward air parcel trajectories starting from t = + 6 h





Pressure Coordinates

Θ_e as scalar tracer

Research Questions

- **If slow-moving, meridional wave patterns are becoming more frequent in a warming world (e.g., Francis and Vavrus 2012), will synoptic evolutions similar to that of the Alberta flood follow?**
  - Downstream Rossby wave development
  - High-latitude (50+°N) atmospheric rivers
  - Alaskan Ridge
  - Rex Blocks
- **How do we quantify the role of the anticyclone in extreme precipitation events?**
  - Trough-ridge couplets
  - Moisture transport
  - Air mass establishment

Research Questions

- Air mass "conditioning"
  - Is it unique to the U.S. Plains?
  - Will it become more frequent under climate change?
- Diabatic upper-level ridge generation
  - Extreme precipitation event → latent heat release → diabatic ridge development/enhancement → more blocking patterns?
- Predictability
  - Models continue to struggle with QPF
  - How can we better use mass fields (high forecast skill) to help predict an extreme precipitation event?

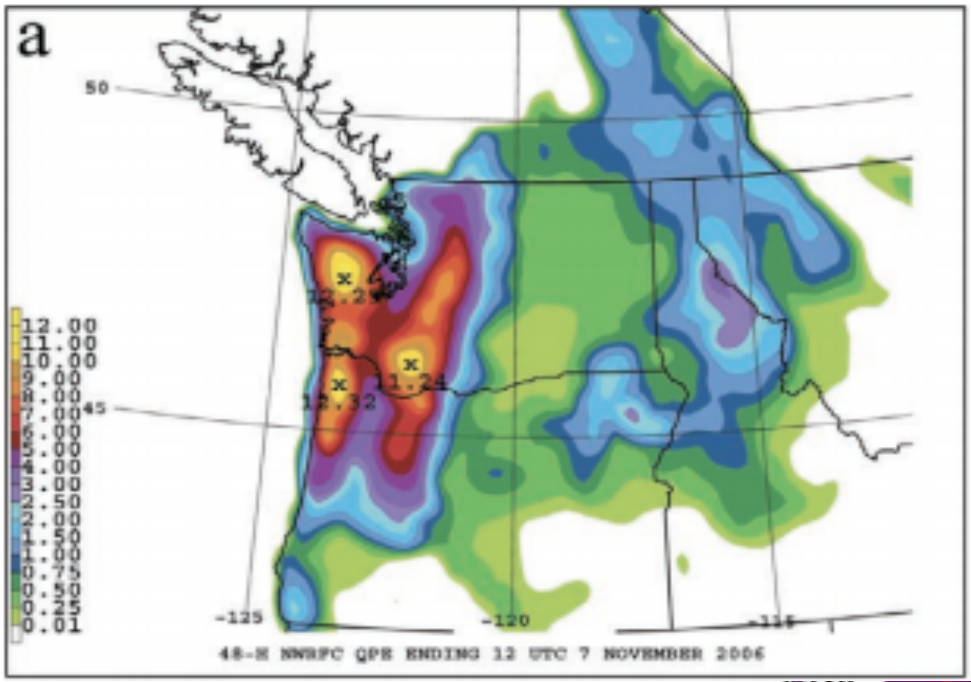
Diagnosing Extreme Precipitation

- One major contribution to the quantification of extreme precipitation events is the use of standardized anomalies
  - Hart and Grumm (2001), Grumm and Hart (2001), Junker et al. (2009)
  - $N = X - \mu / \sigma$
  - X: Value of a variable (e.g. 500 mb height)
  - µ: Daily mean value for that grid point
  - σ: Standard deviation from daily mean
  - Each M is a mass-weighted mean-anomaly for height, temperature, wind and humidity

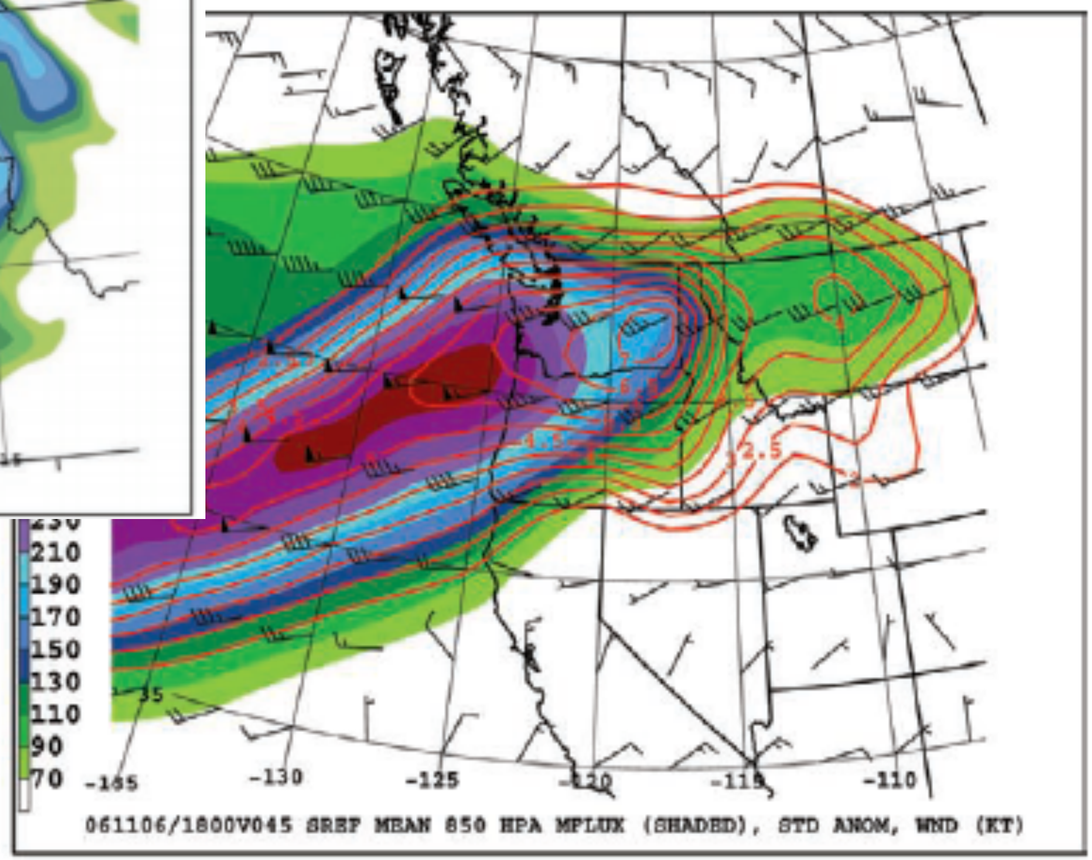
$$M_{\mathrm{TOTAL}} = (M_{\mathrm{HEIGHT}} + M_{\mathrm{TEMP}} + M_{\mathrm{WIND}} + M_{\mathrm{MOIST}})/4$$

Standardized Anomalies

48 -hour Rainfall



SREF 850 hPa moisture flux (shaded) and std. anom. (red)



From Junker et al. (2009)

Standardized Anomalies

- Limitation
  - In general, only one standardized anomaly field is plotted at a time
- Standardized anomaly rankings certainly identify many past extreme *storms*
- Question: Does an all-encompassing (M_{total}) standardized anomaly fully describe the potential for an extreme *precipitation* event?
  - Do height, temperature, wind, and specific humidity fully capture synoptic-scale and mesoscale forcing for ascent and static stability?

The Extreme Precipitation Index (EPI)

- **From the notes of Fred Sanders and the tribute monograph (Gyakum 2008):**
  - $$P = -\frac{1}{g}\int \omega \left(\frac{dr_s}{dp} \right)_{ma} dp$$

Precipitation Rate

Vertical Motion

Change in saturated mixing ratio with height along the moist adiabat

- **Ingredients within the equation**
  - **Lift**
  - **Temperature of the air mass**
  - **Static stability of the air mass (implicit within ω)**

The Extreme Precipitation Index (EPI)

- **Ingredients within the equation**
  - **Lift**
  - **Temperature of the air mass**
  - **Static stability of the air mass (implicit within ω)**

- **Most 'value for the dollar' with both greater ascent (in a less stable air mass, implicit in ω) AND a warmer air mass, represented by dr_s/dp**
  - $$P = -\frac{1}{g}\int \omega \left(\frac{dr_s}{dp}\right)_{ma} dp$$

Precipitation Rate | Vertical Motion | Change in saturated mixing ratio with height along the moist adiabat

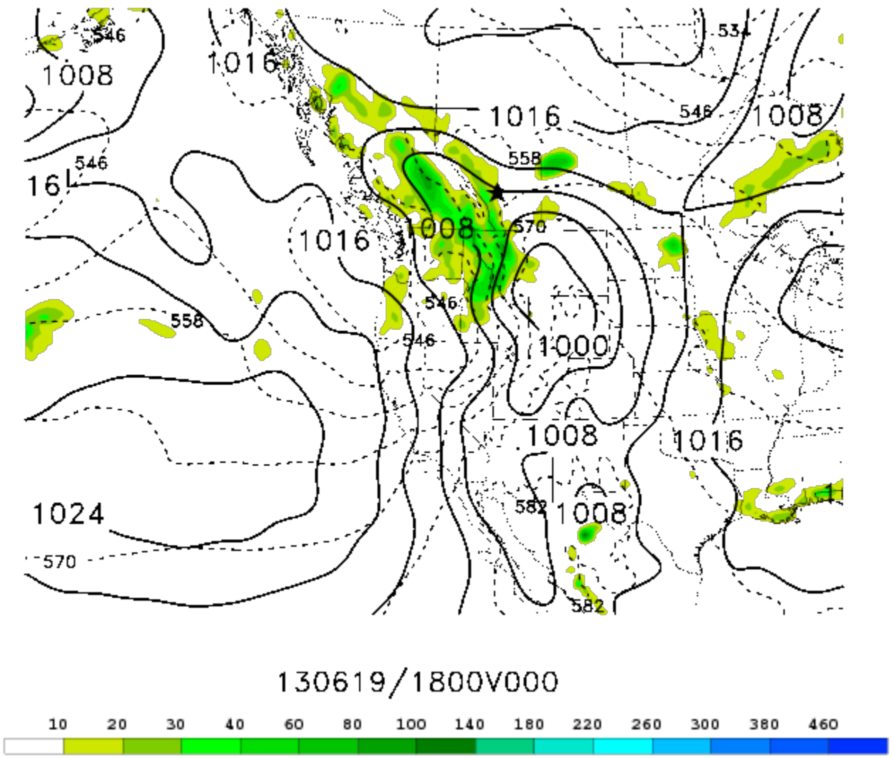
EPI in Practice: Lift

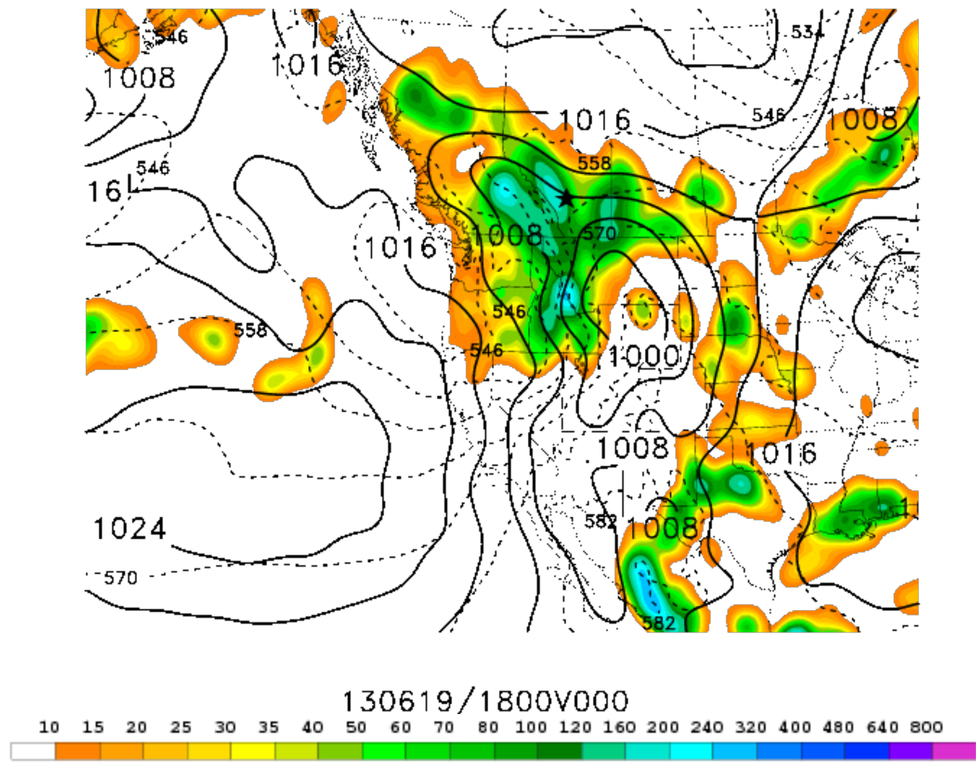
- Tested two different methodologies for representing lift
  - Explicit vertical motion (ω): "EPI1"
  - 850-500 hPa layer-averaged Q-vector divergence (proxy for vertical motion): "EPI2"
- Result:
  - Using ω seems to produce too many spurious EPI maxima (compared to precipitation observations)

$$P = -\frac{1}{g}\int \omega \left(\frac{dr_s}{dp}\right)_{ma} dp$$

EPI in Practice: Alberta Flood

Animations from t = - 6 h (1800 UTC 19 June) to t = +18 h (1800 UTC 20 June)



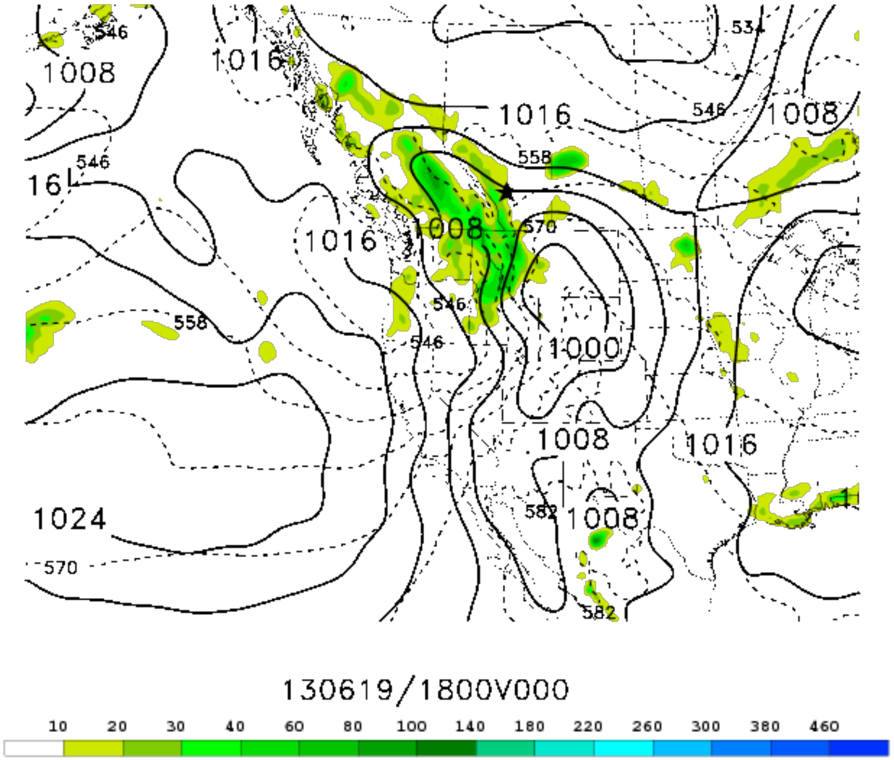


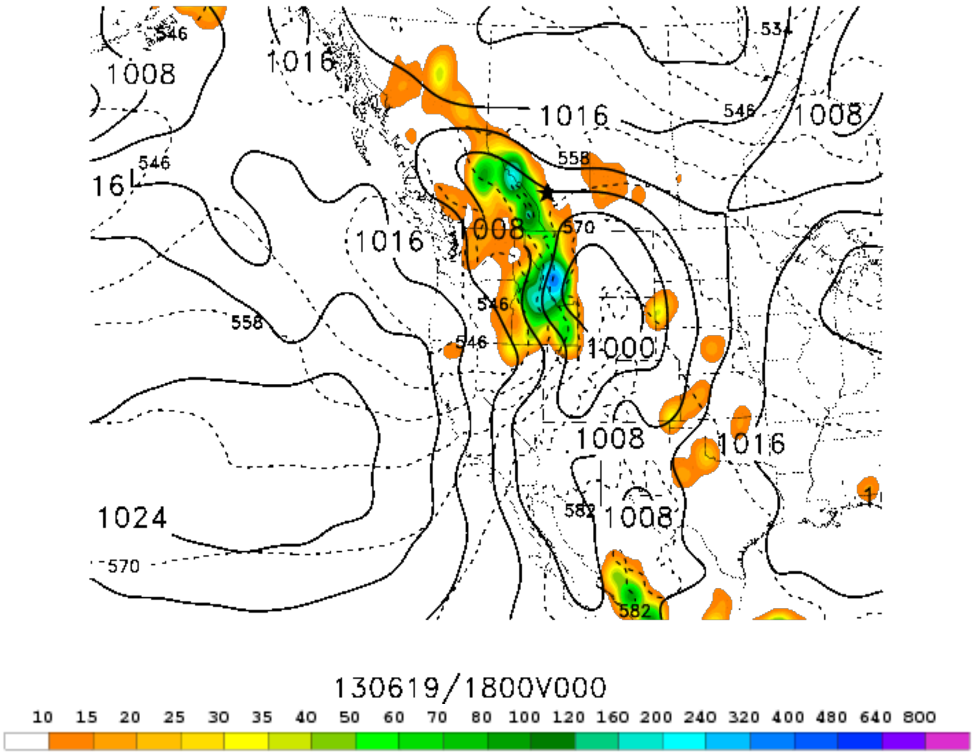
CFSR 6-h Precipitation Rate (mm/day)
MSLP (mb, solid)
1000-500 mb thickness (dam, dashed)

EPI1 (explicit ω)
MSLP (mb, solid)
1000-500 mb thickness (dam, dashed)

EPI in Practice: Alberta Flood

Animations from t = - 6 h (1800 UTC 19 June) to t = +18 h (1800 UTC 20 June)





CFSR 6-h Precipitation Rate (mm/day)
MSLP (mb, solid)
1000-500 mb thickness (dam, dashed)

EPI2 (Q-vector divergence)
MSLP (mb, solid)
1000-500 mb thickness (dam, dashed)

EPI in Practice: Air Mass

Q-vector approach

- **Integrated saturation mixing ratio along the moist adiabat over the entire troposphere**

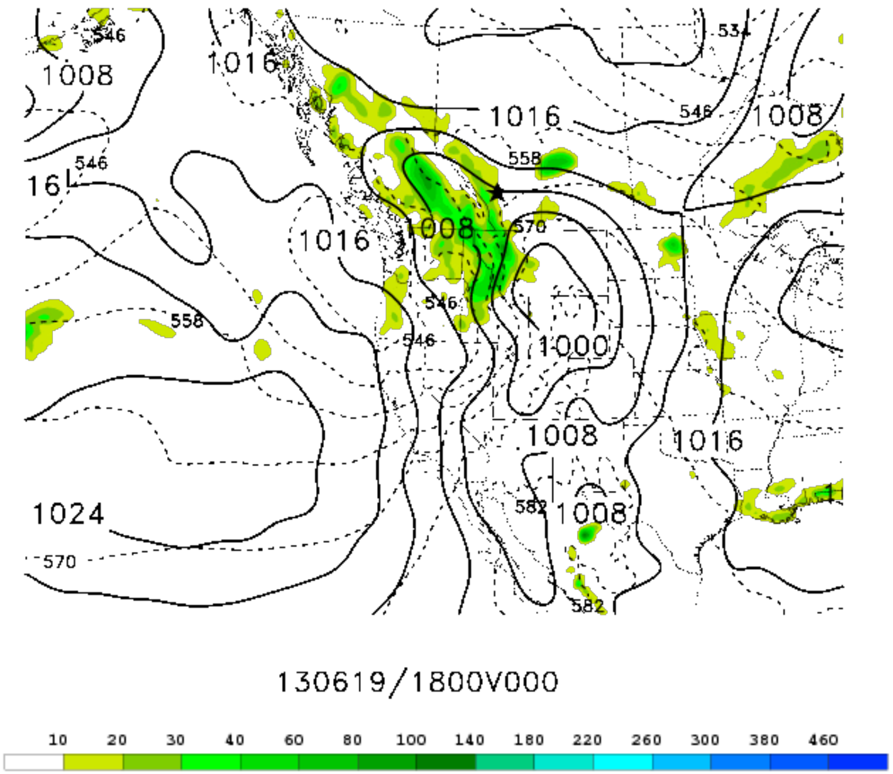
- **Divide ("normalize") by stability**
  - **Helps to account for seasonal differences**
  - **Tested two methods:**
    - $d\theta/dp$ (static stability) → "EPI2"
    - $d\theta_e/dp$ ("effective" static stability) → "EPI3"
      - e.g, Durran and Klemp (1982)

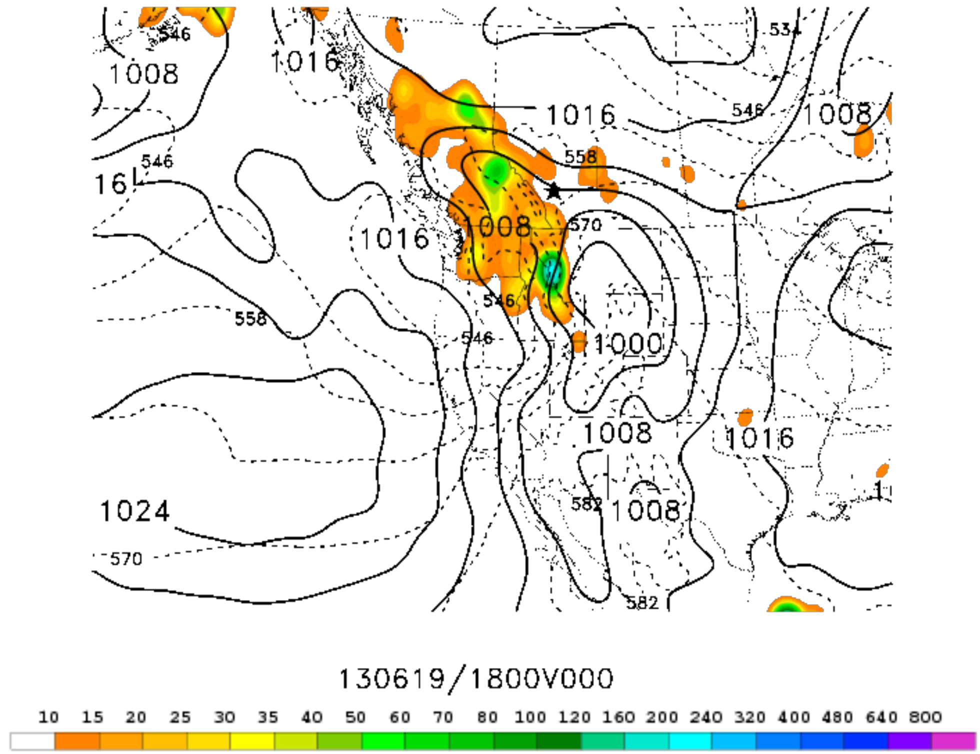
$$P = -\frac{1}{g}\int \omega \left(\frac{dr_s}{dp}\right)_{ma} dp$$

EPI = (Lift * air mass) / stability

EPI in Practice: Alberta Flood

Animations from t = - 6 h (1800 UTC 19 June) to t = +18 h (1800 UTC 20 June)





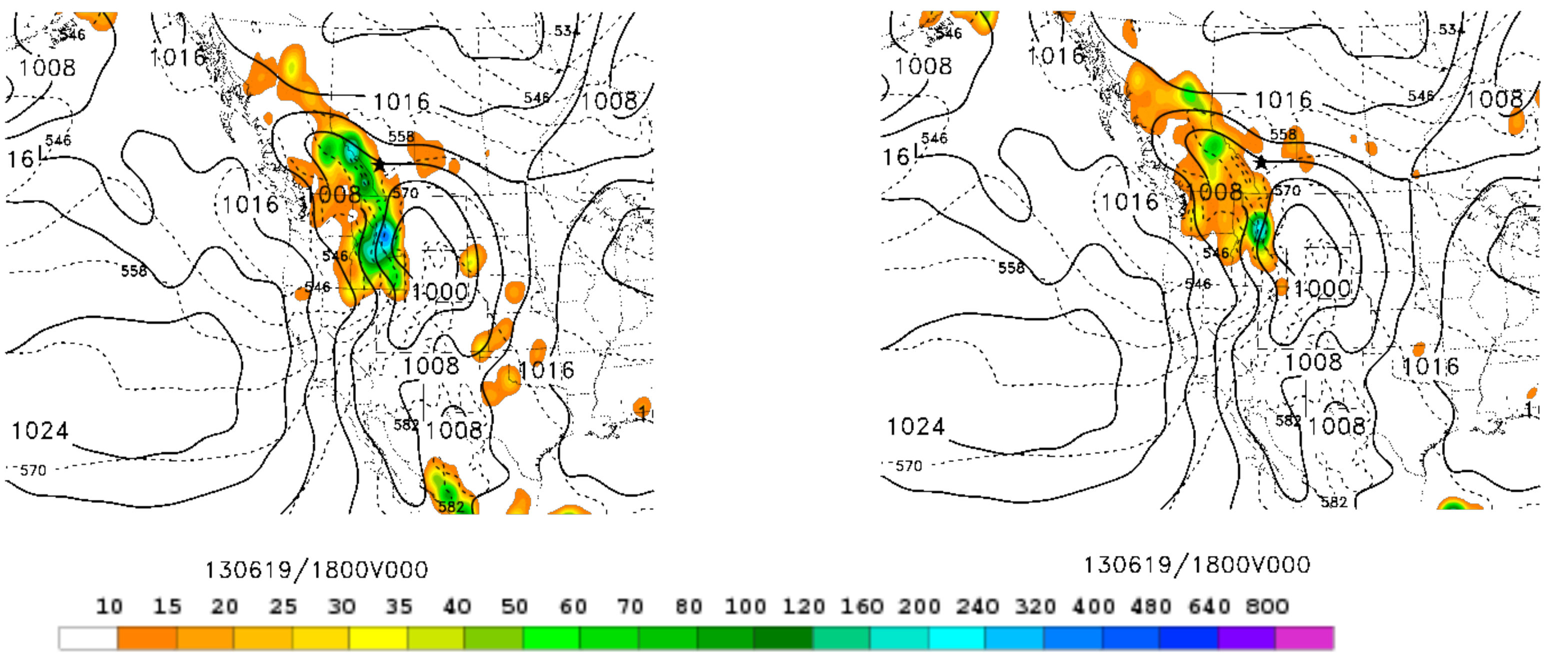
CFSR 6-h Precipitation Rate (mm/day)
MSLP (mb, solid)
1000-500 mb thickness (dam, dashed)

EPI3 (Q-vec divergence + eff. Static stab.)
MSLP (mb, solid)
1000-500 mb thickness (dam, dashed)

EPI in Practice: Air Mass

- **Preliminary Result:**
  - **"Effective" static stability method more precise in heavy events**

Animations from t = - 6 h (1800 UTC 19 June) to t = +18 h (1800 UTC 20 June)



EPI2 (Q-vec divergence + static stab.)
MSLP (mb, solid)
1000-500 mb thickness (dam, dashed)

EPI3 (Q-vec divergence + eff. static stab.)
MSLP (mb, solid)
1000-500 mb thickness (dam, dashed)

EPI: Preliminary Results

- Mid-latitude precipitation events
  - Serves as a good qualitative proxy for precipitation based on the dynamics of the model/reanalysis
  - Use of effective static stability: $d\theta_e/dp$
- Extratropical Transition (ET) of tropical cyclones
  - Replicates shift of precipitation from symmetric to asymmetric
    - Left-of-track in intensifying ETs (e.g. Sandy 2012, Irene 2011)
    - Right-of-track in decaying ETs (e.g. Isabel 2003)

Extreme Precipitation: Future Work

- Evaluating EPI skill vs. QPF skill
- Implementing the EPI operationally
  - Another tool based on mass fields (e.g., standardized anomalies), not parameterizations
- Using EPI to help identify trends in extreme precipitation
  - Mass fields in climate simulations

Thank you

Questions?

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