An EXpanded View on the Climatology of Atmospheric Rivers Impacting the Southern Appalachian Mountains

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Outline

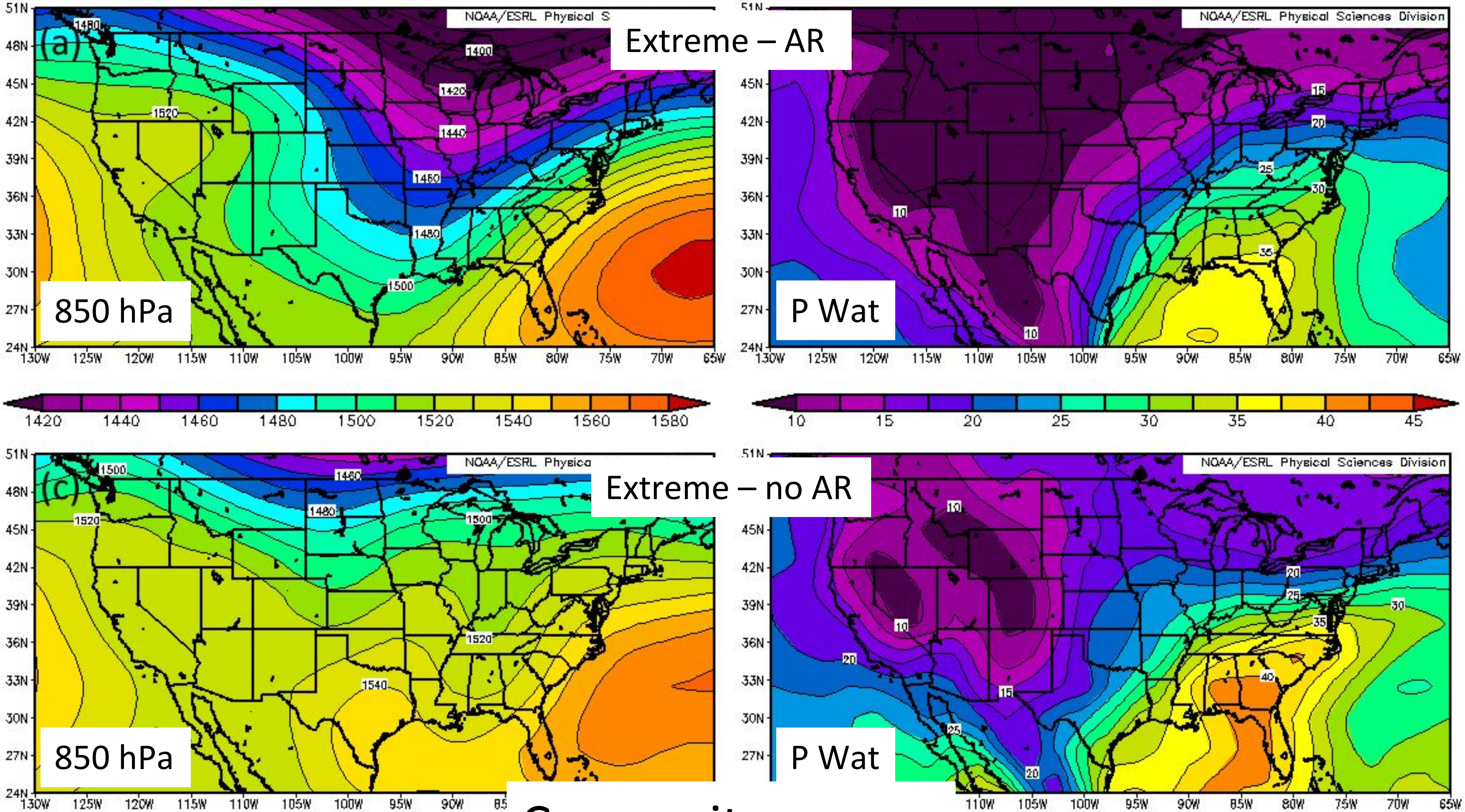
- Background
- Expanded view
    - atmospheric rivers and two river basins in the southern Appalachian Mountains (1 July 2009 – 30 June 2017)
        - Pigeon and Coweeta River Basins
    - further back in time (4 June 1936 – 30 June 2009)
        - Coweeta River Basin
    - mud slides and debris flows
        - Super Rain Time Clusters [SRTCs]
- Summary
- Future work

Background

- Background
  - A 5-year study of rainfall observations at high elevations (Duke GSMRGN) in the southern Appalachian Mountains (Pigeon River Basin, PRB) showed Atmospheric Rivers (ARs) were responsible for
    - just over half of the extreme (top 2.5%) rainfall events in the PRB
    - societal hazards (minor-to-major flooding and/or storm reports) in 73% of the AR-influenced extreme rainfall events
    - non-hazard conditions for 75 – 88% of ARs detected during the study period

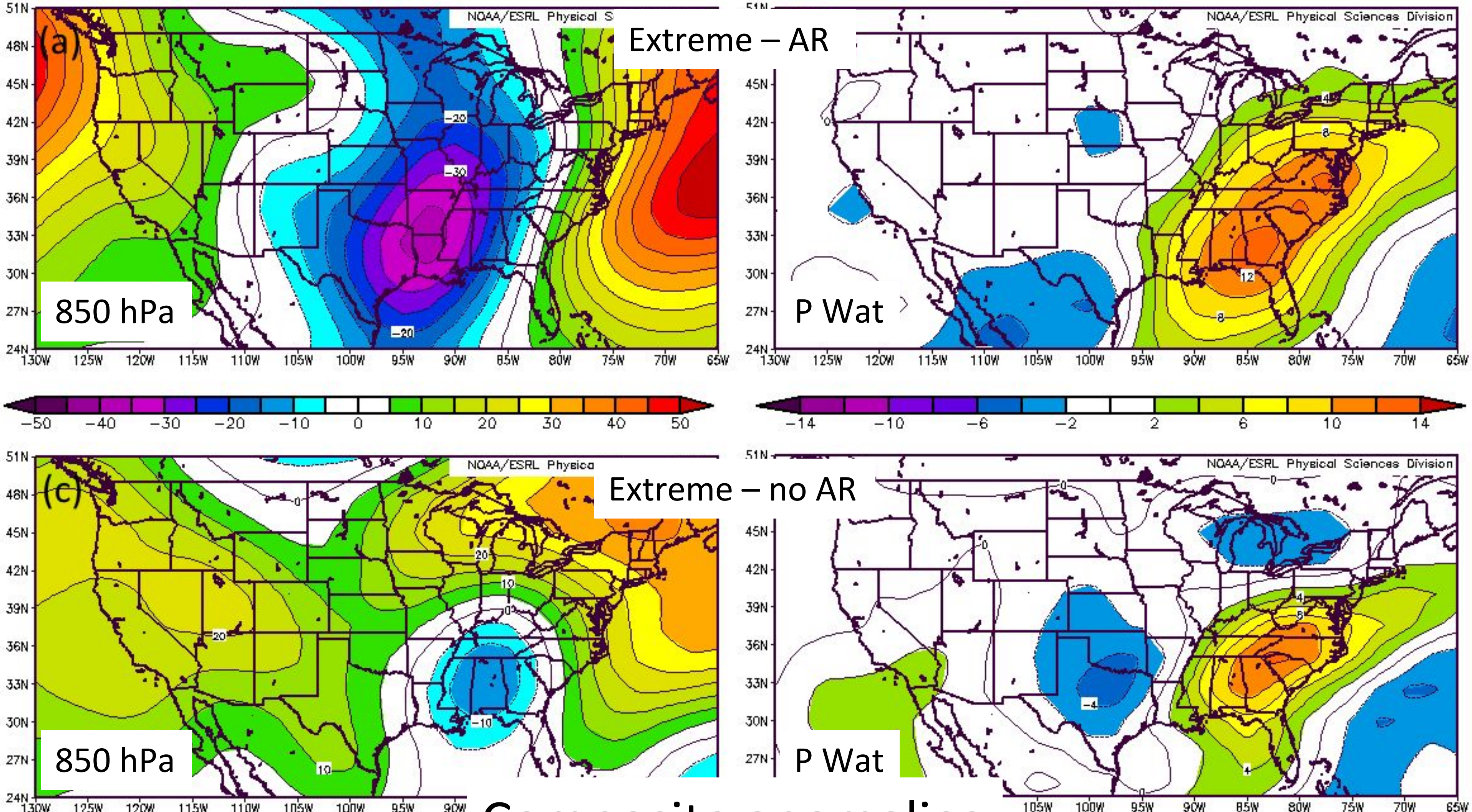
Miller et al. (2018)

Background



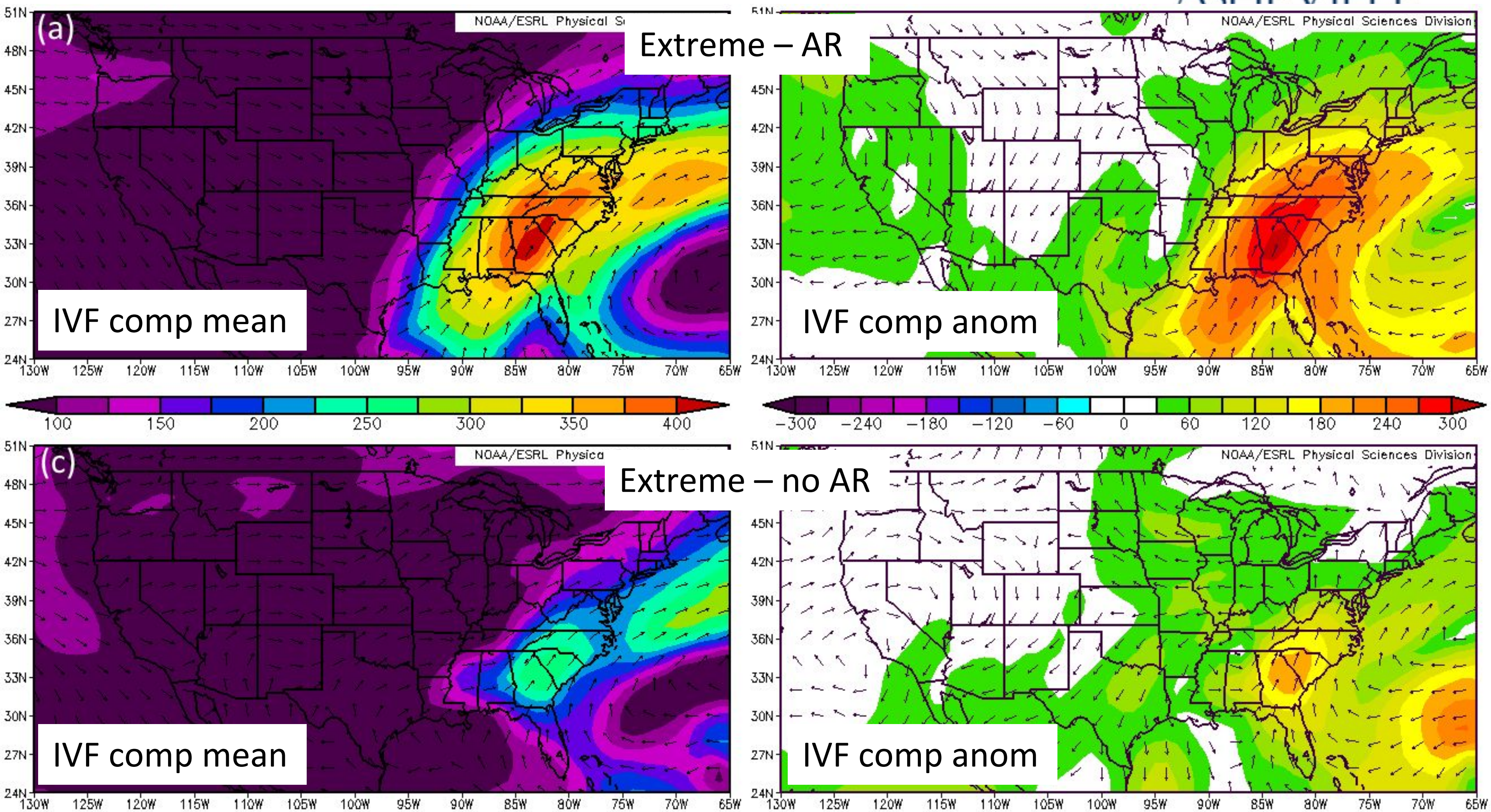
Composite means

Background



Composite anomalies

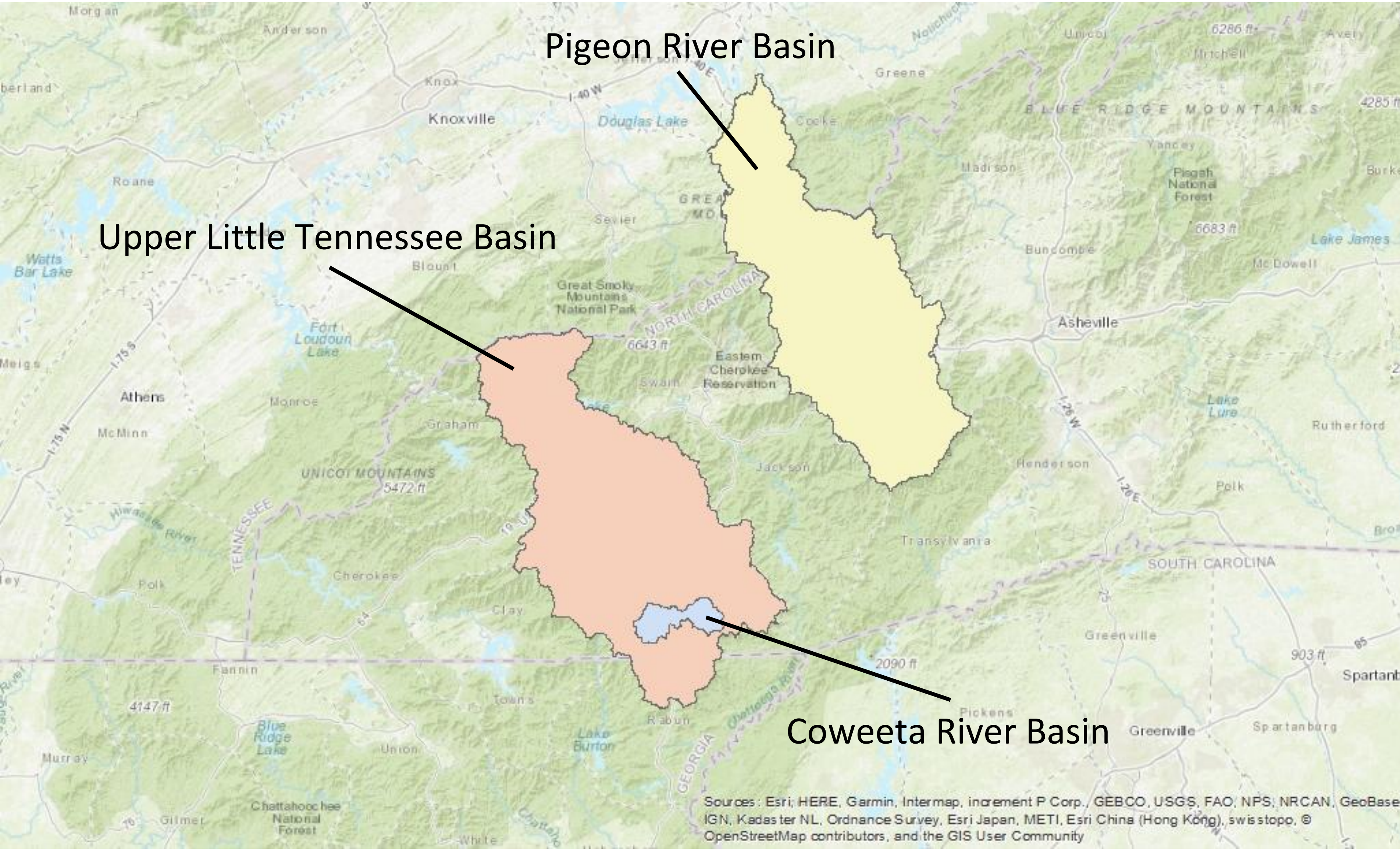
Background



(a)
NOAA/ESRL Physical Sciences Division
Extreme – AR
IVF comp mean
IVF comp anom
100
150
200
250
300
350
400
−300
−240
−180
−120
−60
0
60
120
180
240
300
(c)
Extreme – no AR
IVF comp mean
IVF comp anom
130W 125W 120W 115W 110W 105W 100W 95W 90W 85W 80W 75W 70W 65W
24N 27N 30N 33N 36N 39N 42N 45N 48N 51N

Expanded view – two river basins

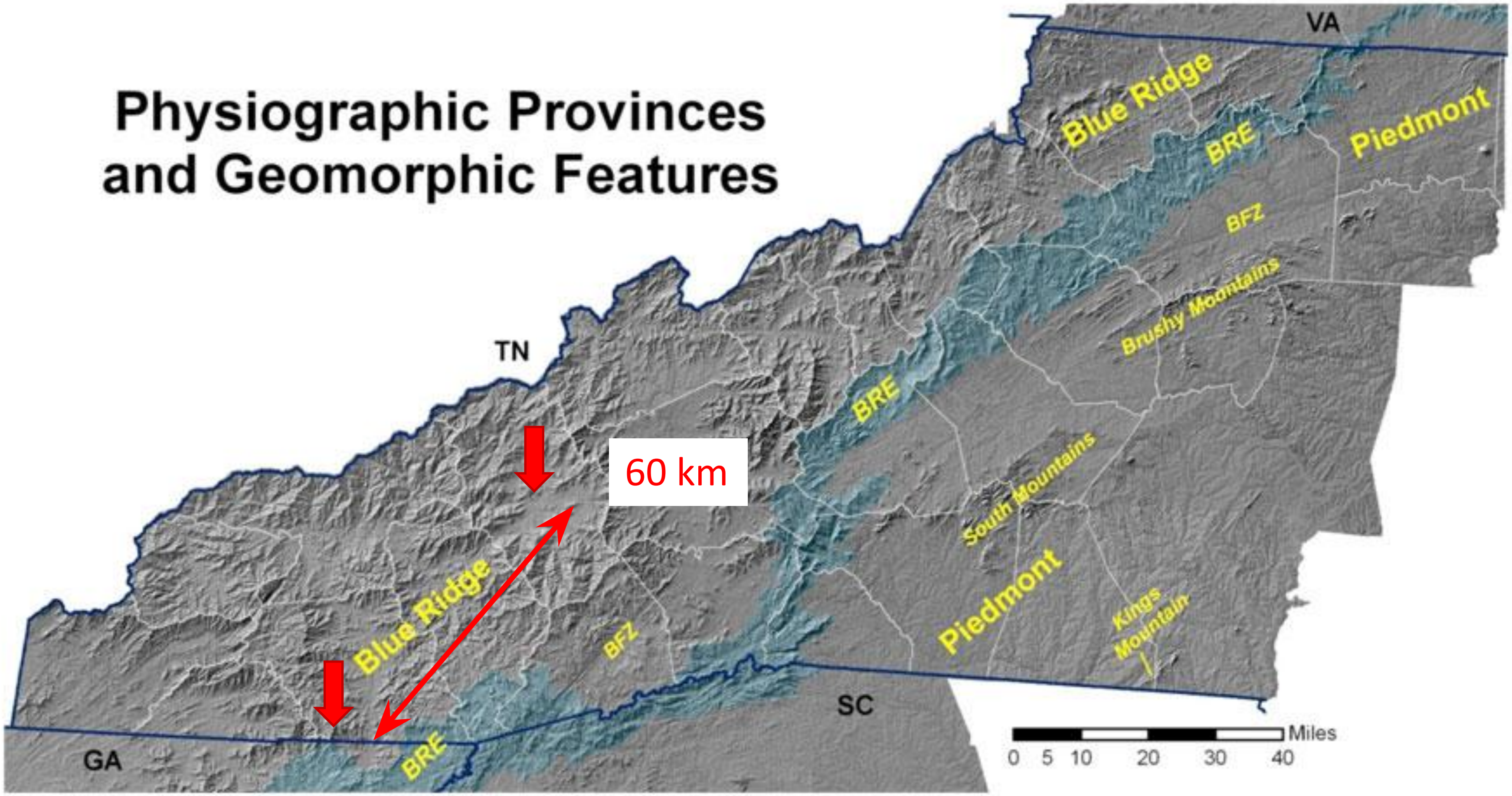
- Methodology
  - Examine rainfall observations from two river basins in the southern Appalachian Mountains (PRB and Coweeta River Basin, CRB) over an 8-yr study period [1 July 2009 to 30 June 2017]
  - Investigate the impact of ARs on observed rainfall in the two basins over the study period, looking for systematic differences between rainfall patterns of the basins


Pigeon River Basin
Upper Little Tennessee Basin
Coweeta River Basin
Knoxville
Asheville
Douglas Lake
Great Smoky Mountains National Park
NORTH CAROLINA
SOUTH CAROLINA
TENNESSEE
GEORGIA
BLUE RIDGE MOUNTAINS
UNICOI MOUNTAINS
Eastern Cherokee Reservation
Pisgah National Forest
Chattahoochee National Forest
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Expanded view – two river basins

- Motivation
  - “The PRB (Haywood County, NC) is displaced north and west from the prominent southeast-facing slope, the Blue Ridge escarpment. Of interest will be to investigate AR-influenced events appearing to have favorable synoptic weather patterns with an ‘underperforming’ number of societal hazard reports… It is hypothesized during these events that the synoptic forcing was too weak … to overcome the limits forced by suppression of precipitation by orography upwind of the PRB.”

Miller et al. (2018)



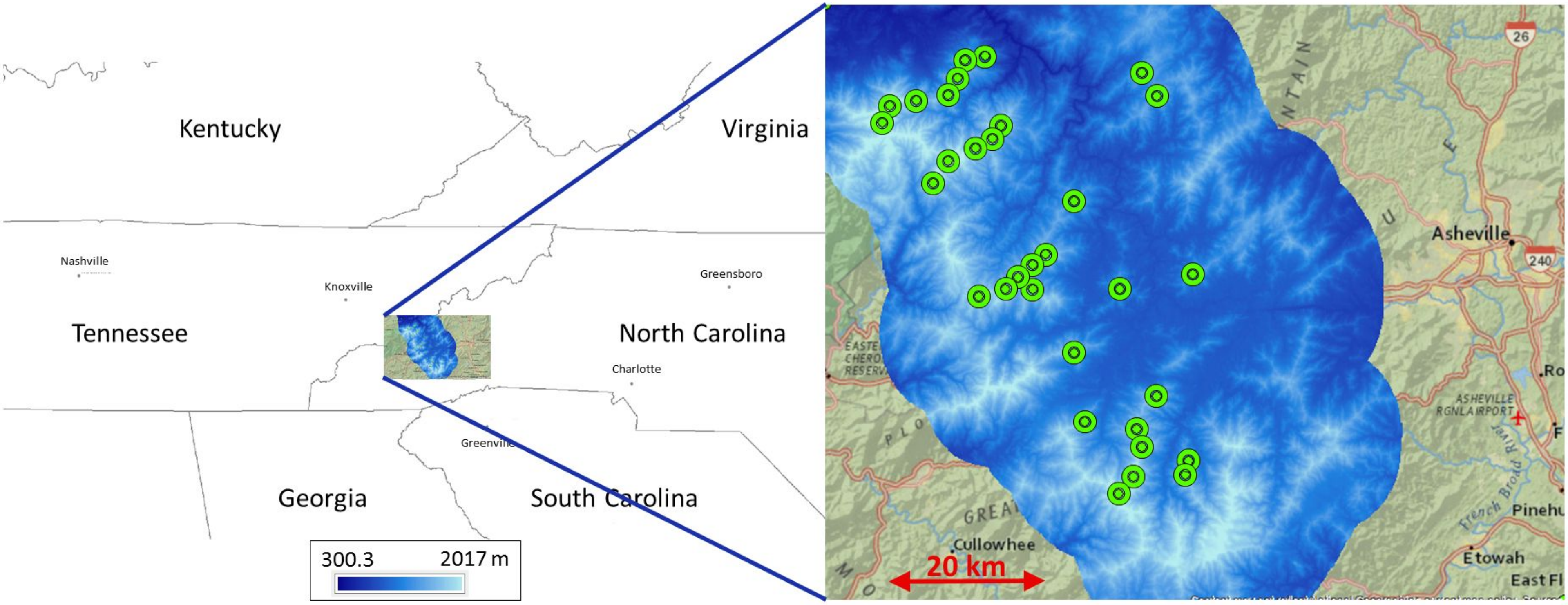
http://www.wncvitalityindex.org/topography/mountain-topography-and-geomorphology

Expanded view – two river basins

- Methodology
  - <u>Pigeon River Basin</u> – displaced north and west of the Blue Ridge escarpment
  - <u>Coweeta River Basin</u> – adjacent to the Blue Ridge escarpment

Expanded view – two river basins

- Pigeon River Basin



[Miller et al. (2018)](#)

Area = 1823 km^2

Expanded vie

- Duke GSMRGN

TABLE 1. Location and elevation of the 32 tipping-bucket rain gauges composing the Duke GSMRGN.

Rain gauge No.	Lat (N)	Lon (W)	Elev (m)
RG001	35°23.8′	82°54.7′	1156
RG002	35°25.5′	82°58.2′	1731
RG003	35°23.0′	82°54.9′	1609
RG004	35°22.0′	82°59.4′	1922
RG005	35°24.5′	82°57.8′	1520
RG008	35°22.9′	82°58.4′	1737
RG010	35°27.3′	82°56.8′	1478
RG100	35°35.1′	83°04.3′	1495
RG101	35°34.5′	83°05.2′	1520
RG102	35°33.8′	83°06.2′	1635
RG103	35°33.2′	83°07.0′	1688
RG104	35°33.2′	83°05.2′	1587
RG105	35°38.0′	83°02.4′	1345
RG106	35°25.9′	83°01.7′	1210
RG107	35°34.0′	82°54.4′	1359
RG108	35°33.2′	82°59.3′	1277
RG109	35°29.7′	83°02.4′	1500
RG110	35°32.8′	83°08.8′	1563
RG111	35°43.7′	82°56.8′	1394
RG112	35°45.0′	82°57.8′	1184
RG300	35°43.5′	83°13.0′	1558
RG301	35°42.3′	83°15.3′	2003
RG302	35°43.2′	83°14.8′	1860
RG303	35°45.7′	83°09.7′	1490
RG304	35°40.2′	83°10.9′	1820
RG305	35°41.4′	83°07.9′	1630
RG306	35°44.7′	83°10.2′	1536
RG307	35°39.0′	83°11.9′	1624
RG308	35°43.8′	83°10.9′	1471
RG309	35°40.9′	83°09.0′	1604
RG310	35°42.1′	83°07.3′	1756
RG311	35°45.9′	83°08.4′	1036

Δ = 967 m

Miller et al. (2018)

Expanded v

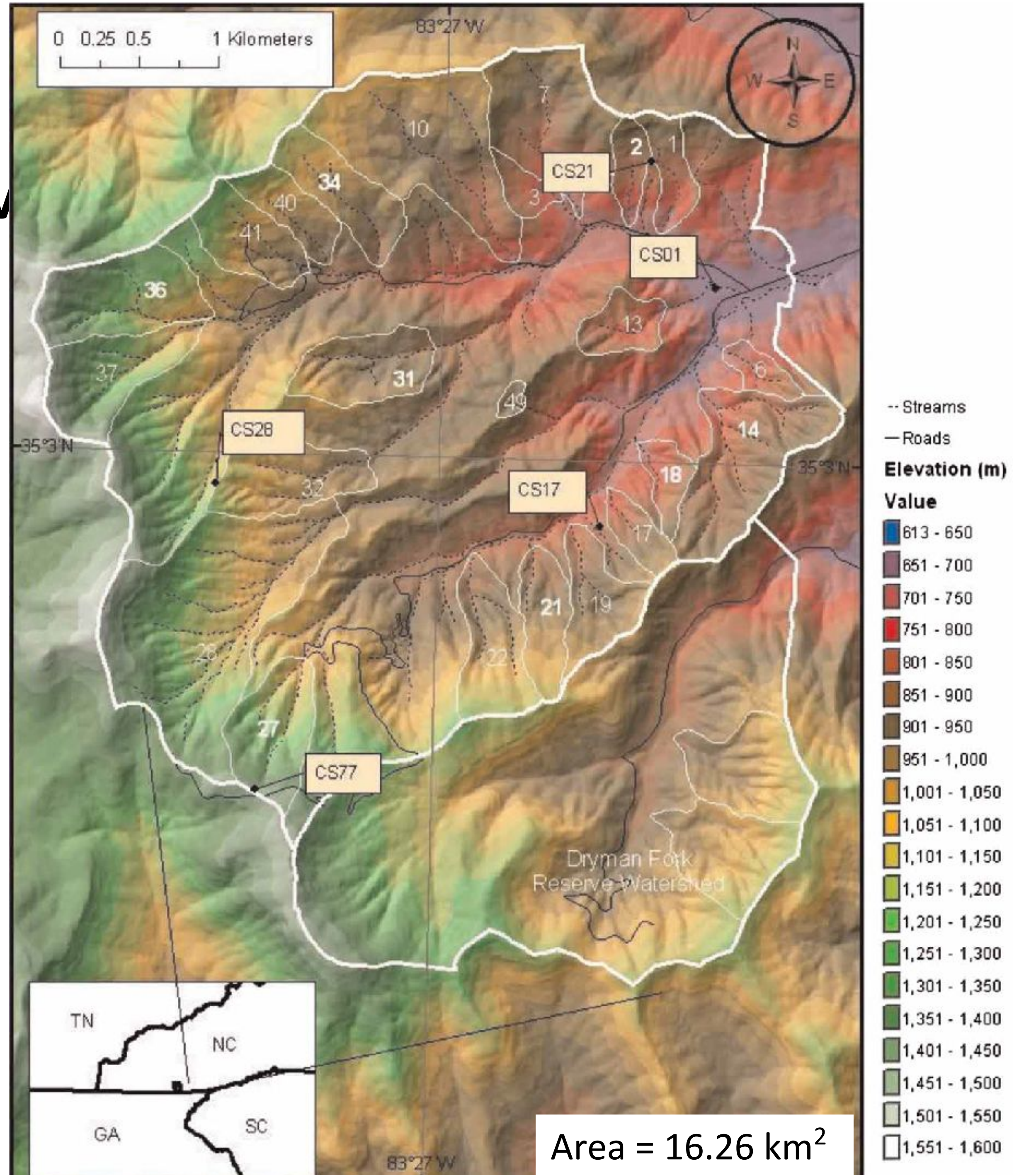
- Coweeta H. L.

Long

Term

Ecological

Research (LTER)



Laseter et al. (2012)

Expanded view – two river basins

- Recording rain gauges – Coweeta H. L.

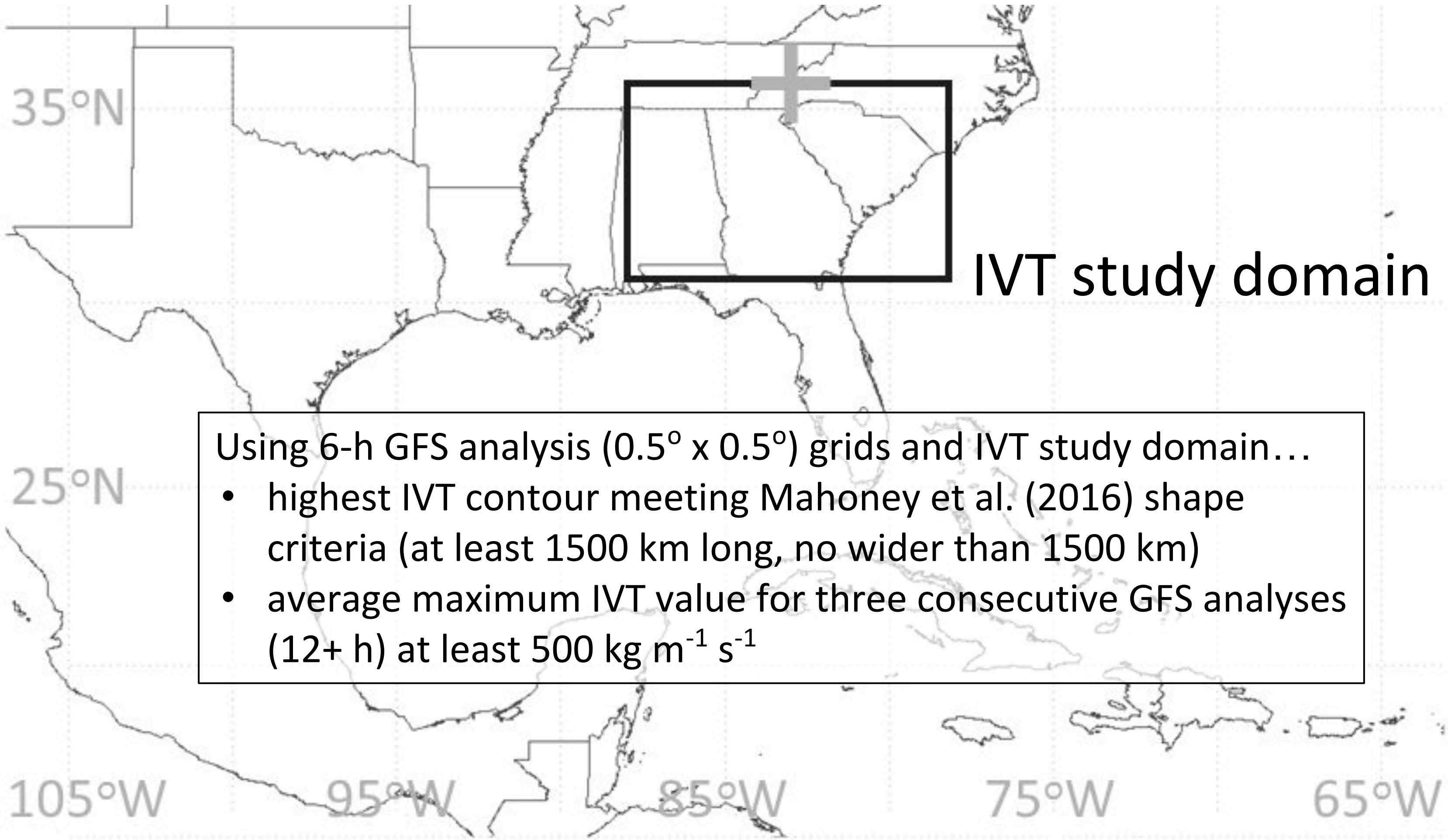
Table 2 | Location, elevation and date of first record of all paired recording and standard rain gages (RRG and SRG, respectively)

Gage or Station	SRG	Location (lat/long)	Elevation (m)	Date of first record	Aspect
RRG06	19	35°03′37.48/83°25′48.36	687	6/4/1936	Valley bottom
RRG05	02	35°03′37.77/83°27′53.98	1,144	6/4/1936	SE-facing
RRG20	20	35°03′53.37/83°26′29.18	740	11/5/1962	Stream bottom
RRG31	31	35°01′57.89/83°28′05.24	1,366	11/1/1958	High elevation gap
RRG40	13	35°03′44.77/83°27′22.18	961	11/10/1942	S-facing
RRG41	41	35°03′19.11/83°25′43.32	776	5/1/1958	N-facing
RRG45	12	35°02′50.19/83°27′31.11	1,001	6/1/1942	Low elevation gap
RRG55	55	35°02′23.59/83°27′19.32	1,035	11/5/1990	N-facing
RRG96	96	35°02′43.33/83°26′14.63	894	11/1/1943	N-facing

Δ = 679 m

Laseter et al. (2012)

Expanded view – two river basins

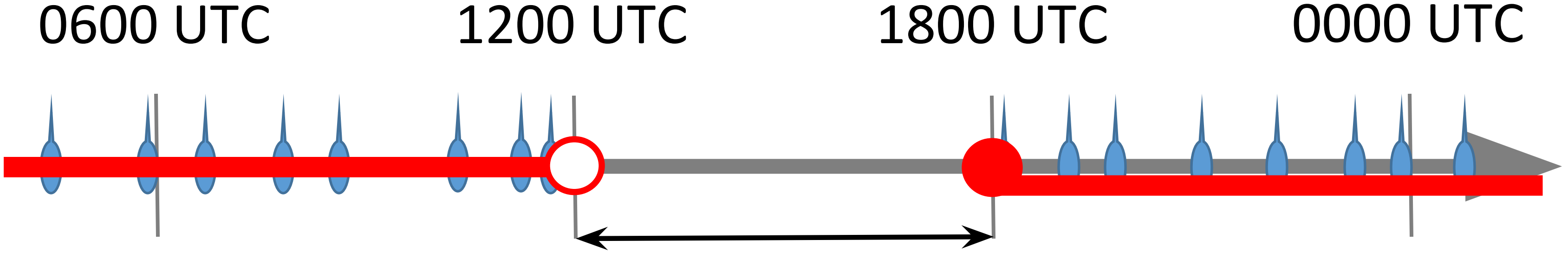


Using 6-h GFS analysis ($0.5^{o} \times 0.5^{o}$) grids and IVT study domain…

- highest IVT contour meeting Mahoney et al. (2016) shape criteria (at least 1500 km long, no wider than 1500 km)
- average maximum IVT value for three consecutive GFS analyses (12+ h) at least 500 kg m^{-1} s^{-1}

Expanded view – two river basins

- Methodology



$\Delta t =$
6-h

Expanded view – two river basins

- Results
  - Seasonal count of number of ARs impacting the IVT study domain using available 11463 GFS 6-h analysis periods of the 8-yr study (of 11688 maximum 6-h periods; 98.1% of a complete archive).

Meteorological season	AR events	6-h periods	Avg duration (h)
Winter (DJF)	73	519	42.66
Spring (MAM)	41	344	50.34
Summer (JJA)	14	142	60.86
Autumn (SON)	40	289	43.35
Total/avg	168	1294	49.30

Expanded view – two river basins

- Results

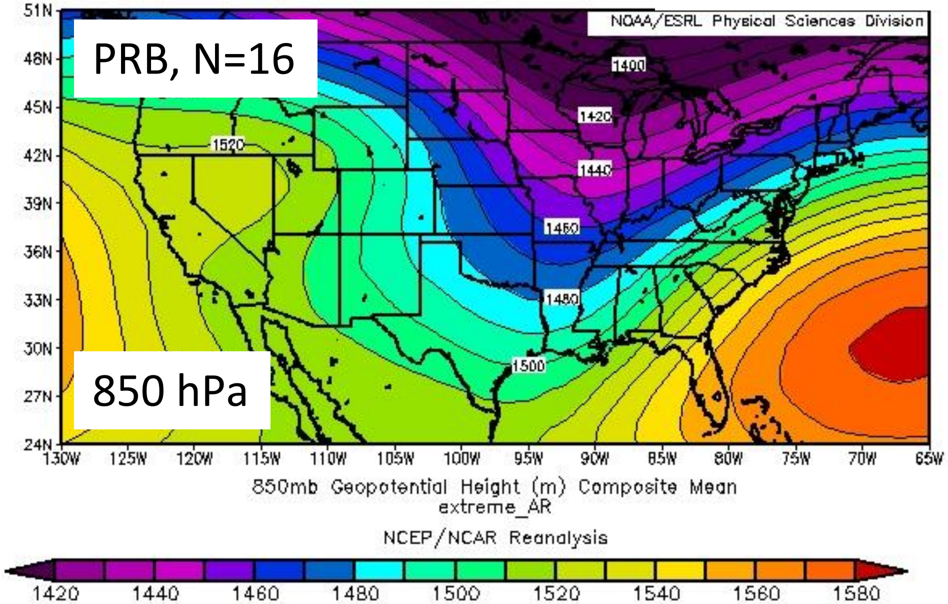
Number of <u>extreme</u> (top 2.5%) <u>rain events</u> of the 8-yr study [1 July 2009 – 30 June 2017].

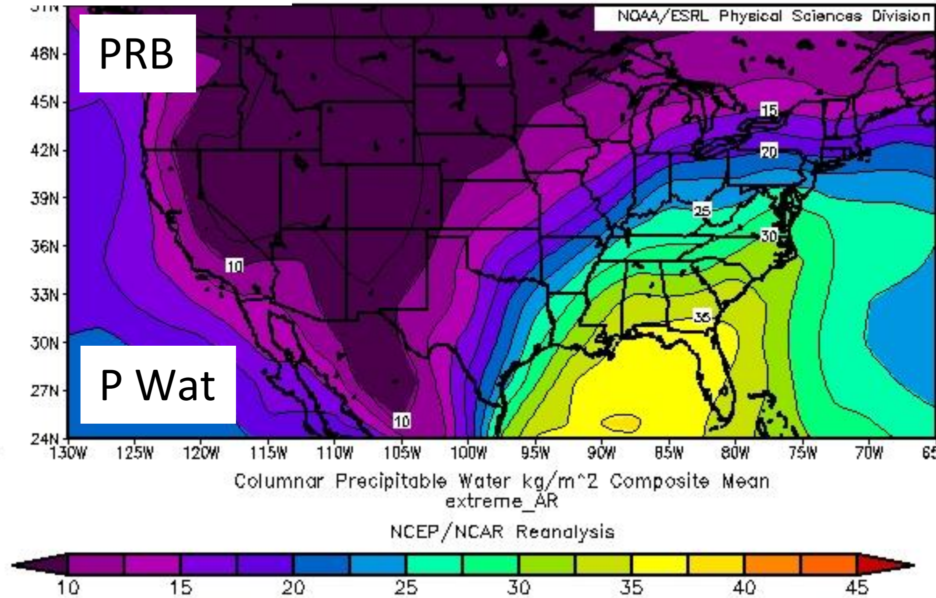
River basin	AR-influenced	TC-influenced	NOT AR- or TC-influenced	Total
Pigeon	19 (44.2%) {1464-h}	3 (7.0%) {Ida, Lee, Andrea}	21 (48.8%)	43
Coweeta	18 (75.0%) {1260-h}	2 (8.3%) {Ida, Lee}	4 (16.7%)	24

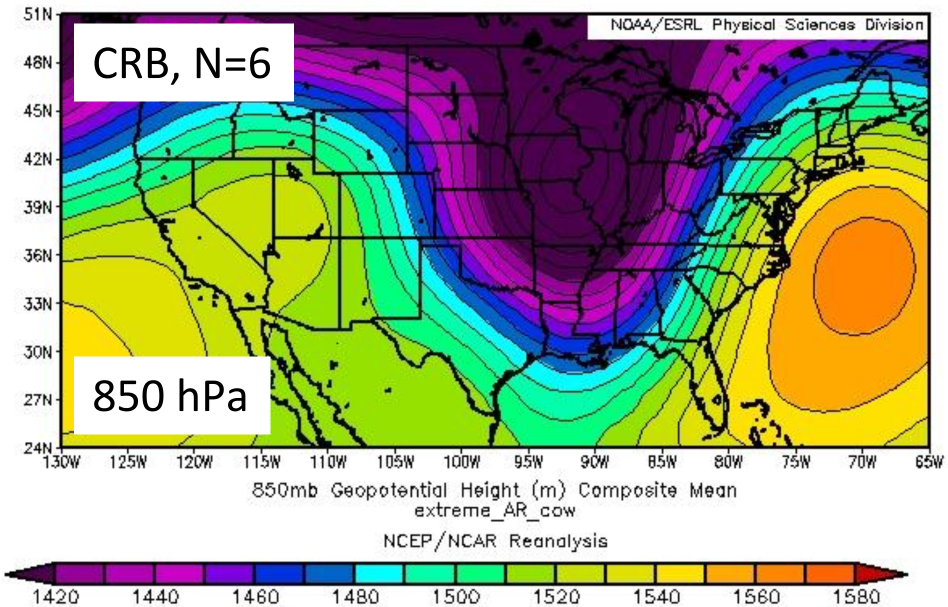
Expanded view – two river basins

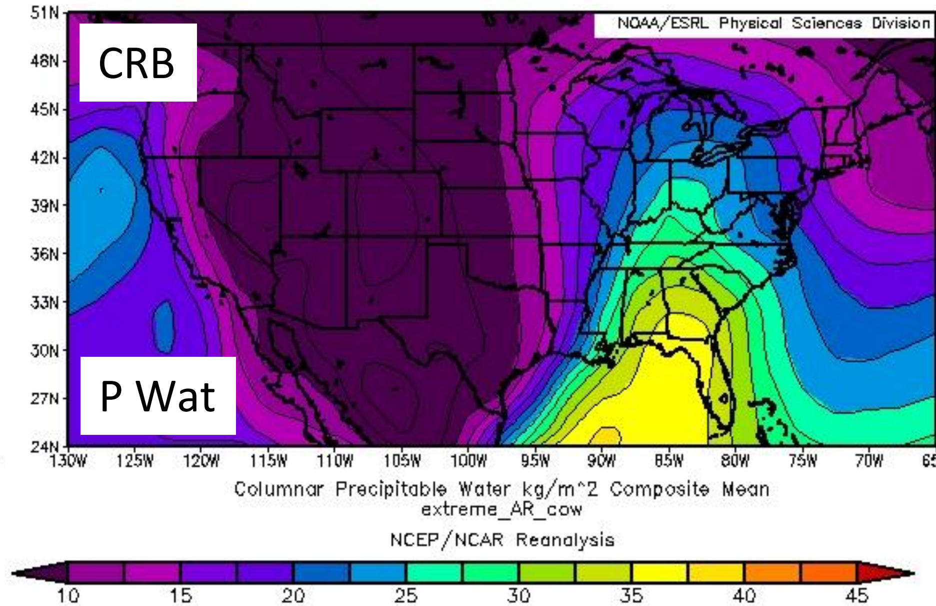
- Results
  - Seven rainfall events qualify as extreme in the Coweeta River Basin and less-than-extreme in the Pigeon R.B.
    - Five events = AR influenced (5 Feb 2012, 28 Nov 2011, 14 Oct 2014, 18 Nov 2015, and 3 Feb 2016)
    - One event = near-AR influenced (16 Apr 2011, 417 kg m^{-1} s^{-1})
    - One event = squall line and severe weather (26 Oct 2010)
  - Examination of geopotential height and precipitable water composite means and anomalies of
    - six AR or near-AR influenced extreme rainfall events (CRB)
    - 16 AR influenced extreme rainfall events (PRB, Miller et al. 2018)

Composite means

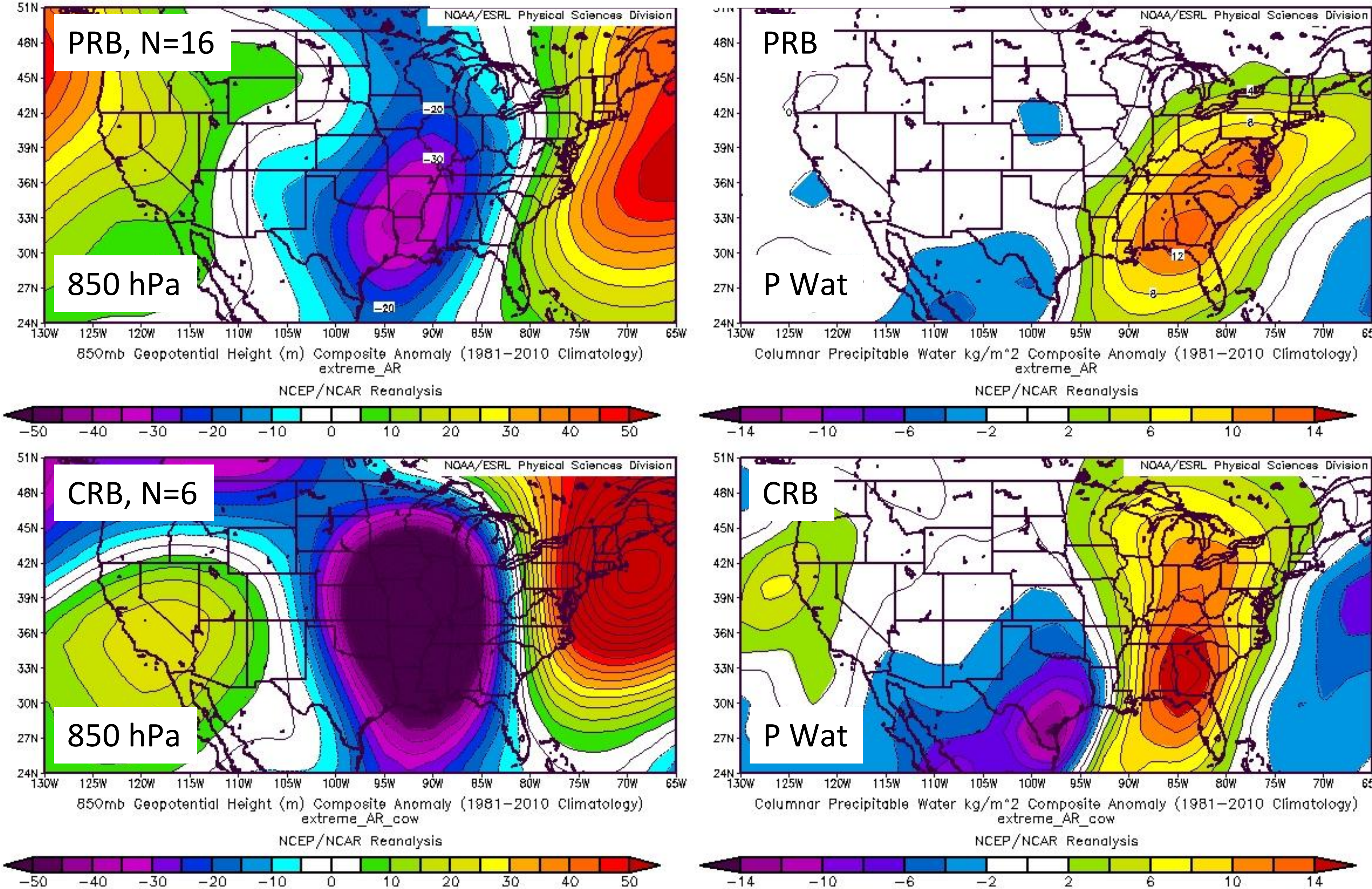


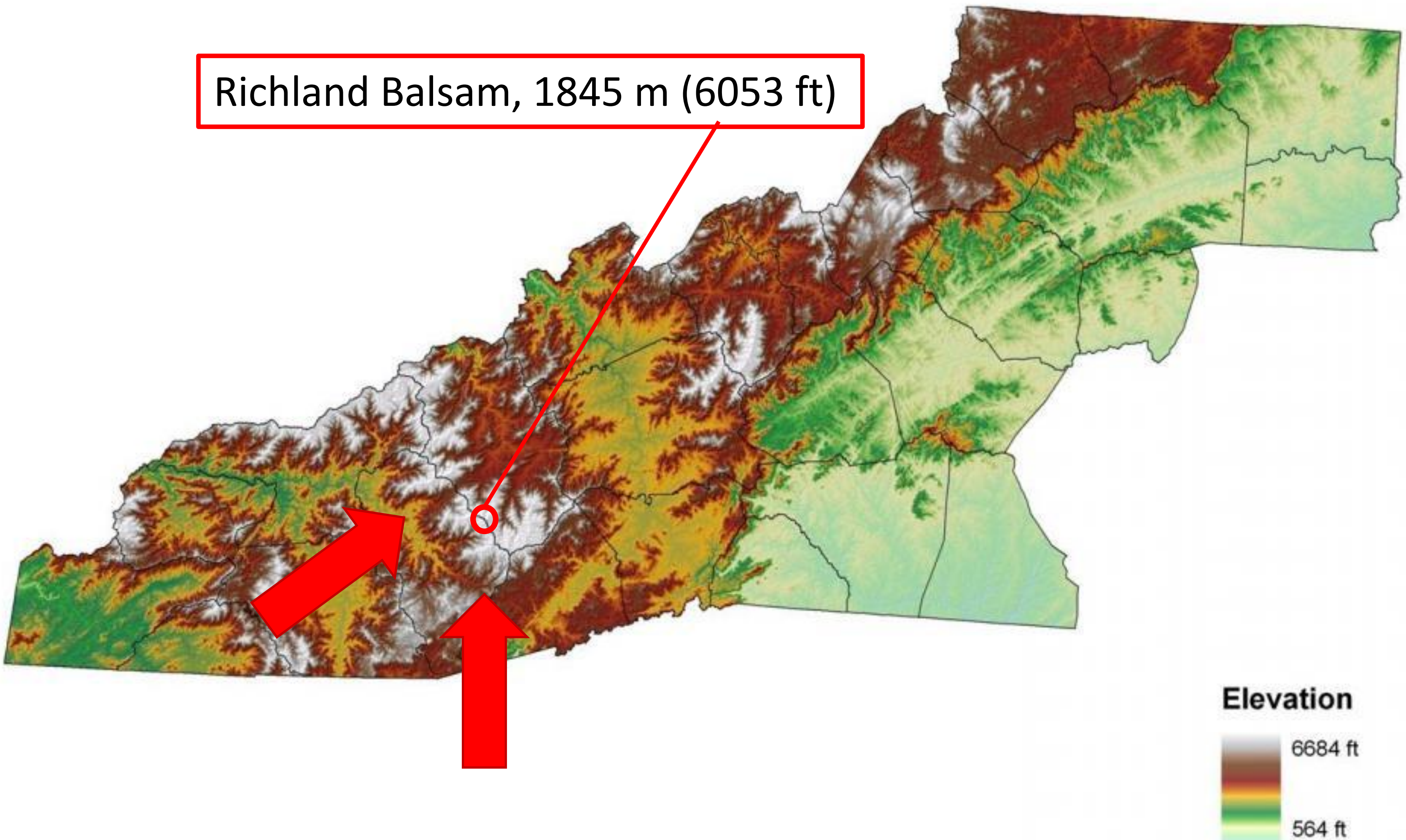






Composite anomalies





http://www.wncvitalityindex.org/topography/mountain-topography-and-geomorphology

Expanded view – two river basins

- Results
  - Disagreement between two river basins on 'extreme' events
    - Much smaller record (8-yr [v. 82-yr]) in the Pigeon River Basin
    - Difference in position relative to the Blue Ridge escarpment
    - Relative landform homogeneity of the Coweeta River Basin; 8-9 [32] gauges spread over 16.26 km^2 [1823 km^2, PRB]
  - Composite weather AR pattern differences
    - Southwesterly flow favors extreme events in the PRB
    - Southerly flow inhibits extreme events in the PRB

Expanded view – further back in time

- Methodology
  - Is the recent rainfall record of the Coweeta RB consistent with the ‘distant’ past?
    - Rainfall observations in the CRB extend back to <u>June 1936</u>
  - Reliable means of detecting ARs in the ‘distant’ past
    - Remote sensing of lower atmospheric moisture is ‘recent’
    - Surface weather observations at Coweeta also date back to June 1936
    - Operational weather soundings

Expanded view – further back in time

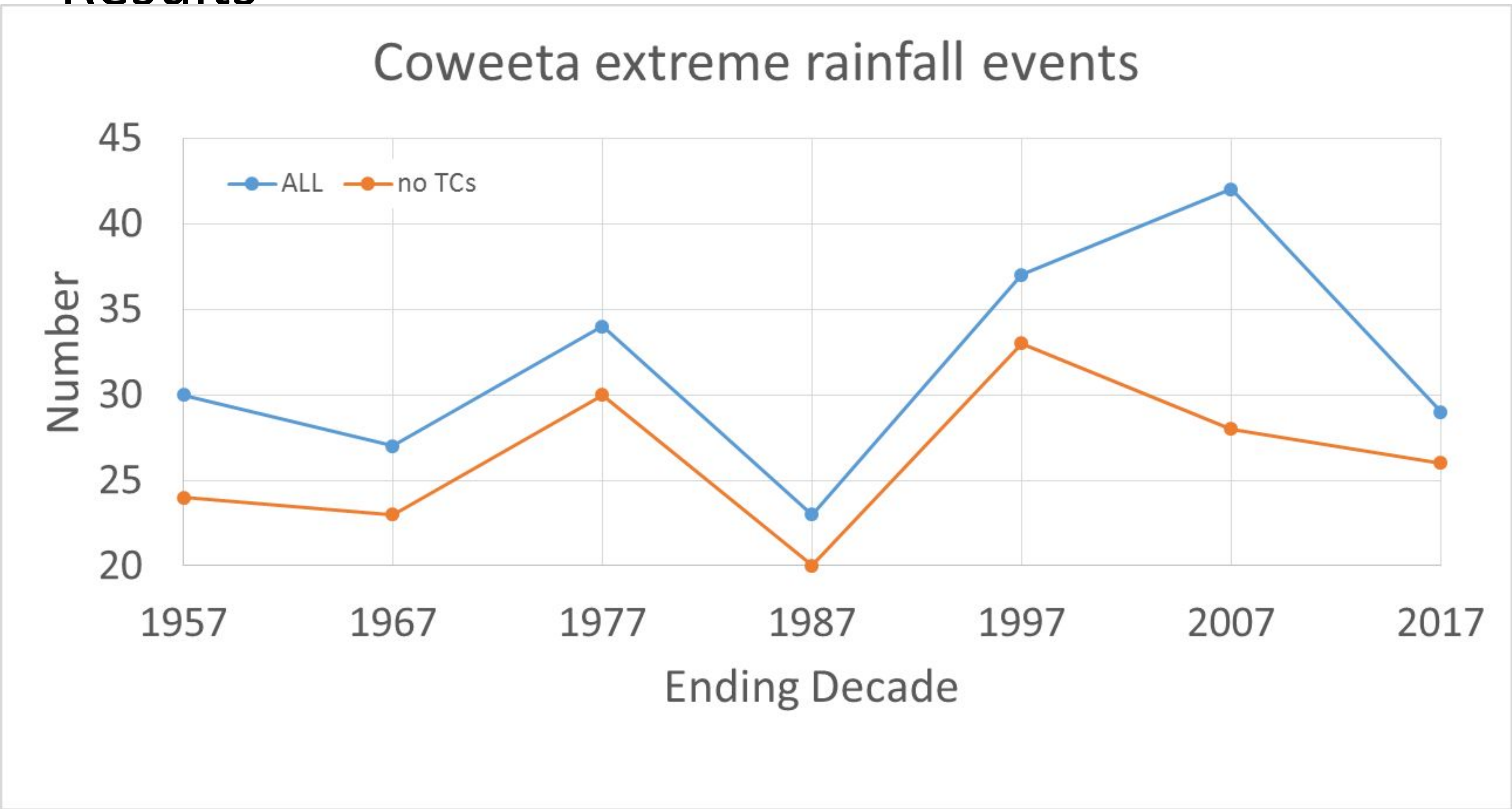
- Results

Seasonal <u>extreme</u> rain events observed by the Coweeta Hydrologic Laboratory gauge network coincident with 6-h analysis periods of the 82-yr study.

Meteorological season	Rain events	6-h periods	Total per gauge accum. (mm)	Avg duration (h)	Event avg per gauge accum. (mm)
Winter (DJF)	59	581	7697.71	59.08	130.47
Spring (MAM)	50	417	6349.67	50.04	126.99
Summer (JJA)	43	512	7004.51	71.44	162.90
Autumn (SON)	89	801	12616.91	54.00	141.76
Total/avg	241	2311	33668.80	58.64	139.70 (5.5 in)

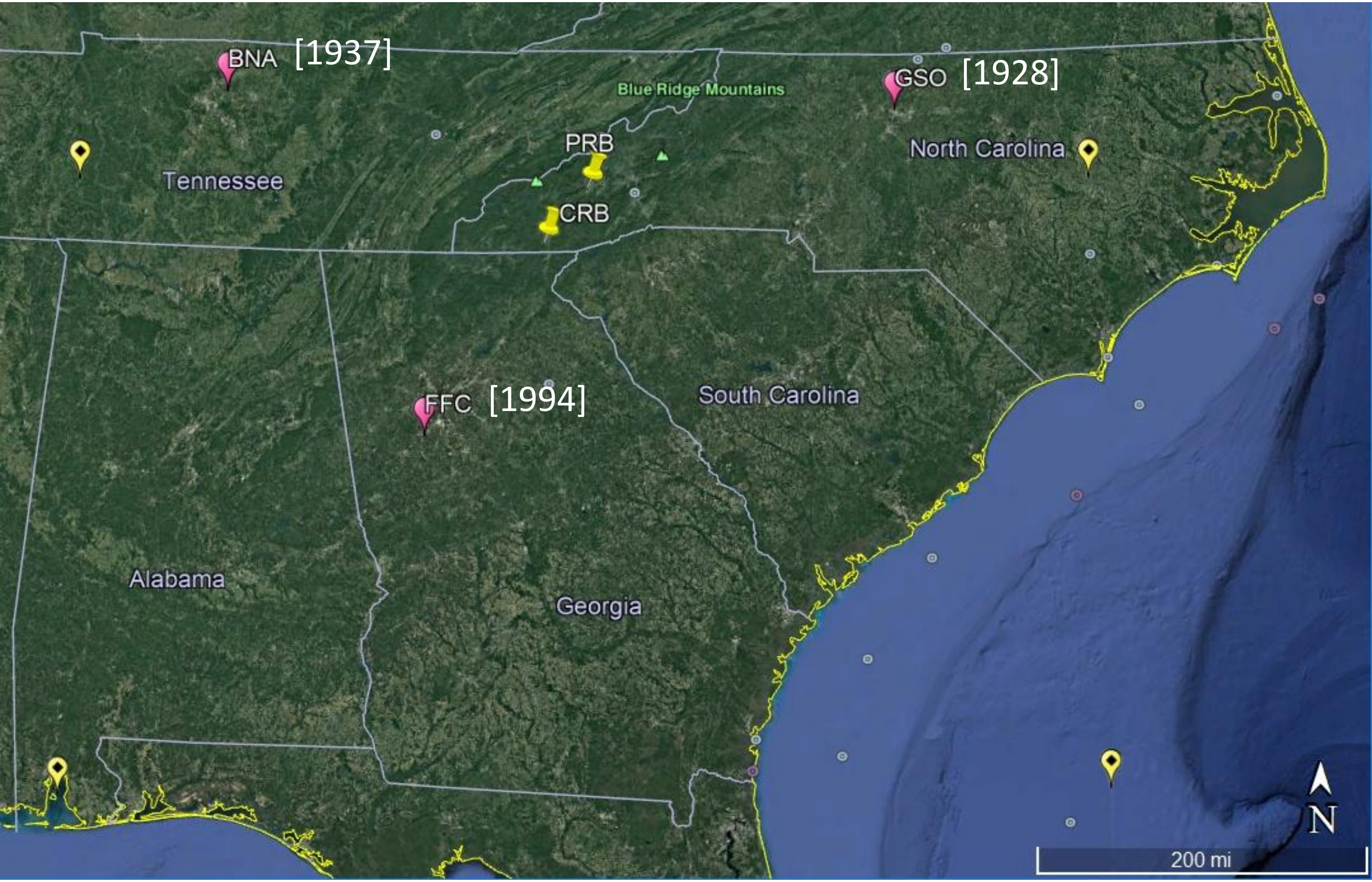
Expanded view – further back in time

- Results



Expanded view – further back in time

- Methodology
  - AR detection in the ‘distant’ past
    - Coweeta surface weather observations at the LTER climate stations
      - Too influenced by local orography to be representative of lower tropospheric IVT
    - Operational weather soundings…
      - Average IVT, maximum IVT, geostrophic thickness (850-500 hPa layer) advection, other?



BNA [1937]
GSO [1928]
Blue Ridge Mountains
PRB
CRB
Tennessee
North Carolina
South Carolina
FFC [1994]
Alabama
Georgia
N
200 mi

Expanded view – further back in time

- Results

  Number of <u>extreme</u> (top 2.5%) <u>rain events</u> in the Coweeta River Basin of two study periods.

since…	AR-influenced	TC-influenced	NOT AR- or TC-influenced	Total
4 Jun 1936	TBD	43 (17.8%)	TBD	241
1 Sep 1994	TBD	20 (24.1%)	TBD	83

Expanded view – mud slides, debris flows

- Motivation
  - "It is acknowledged that the degree to which rainfall amount contributes to flooding can be modulated by soil type and moisture conditions and was one reason for a lack of one-to-one correspondence between rainfall intensity and the degree of reported flooding."

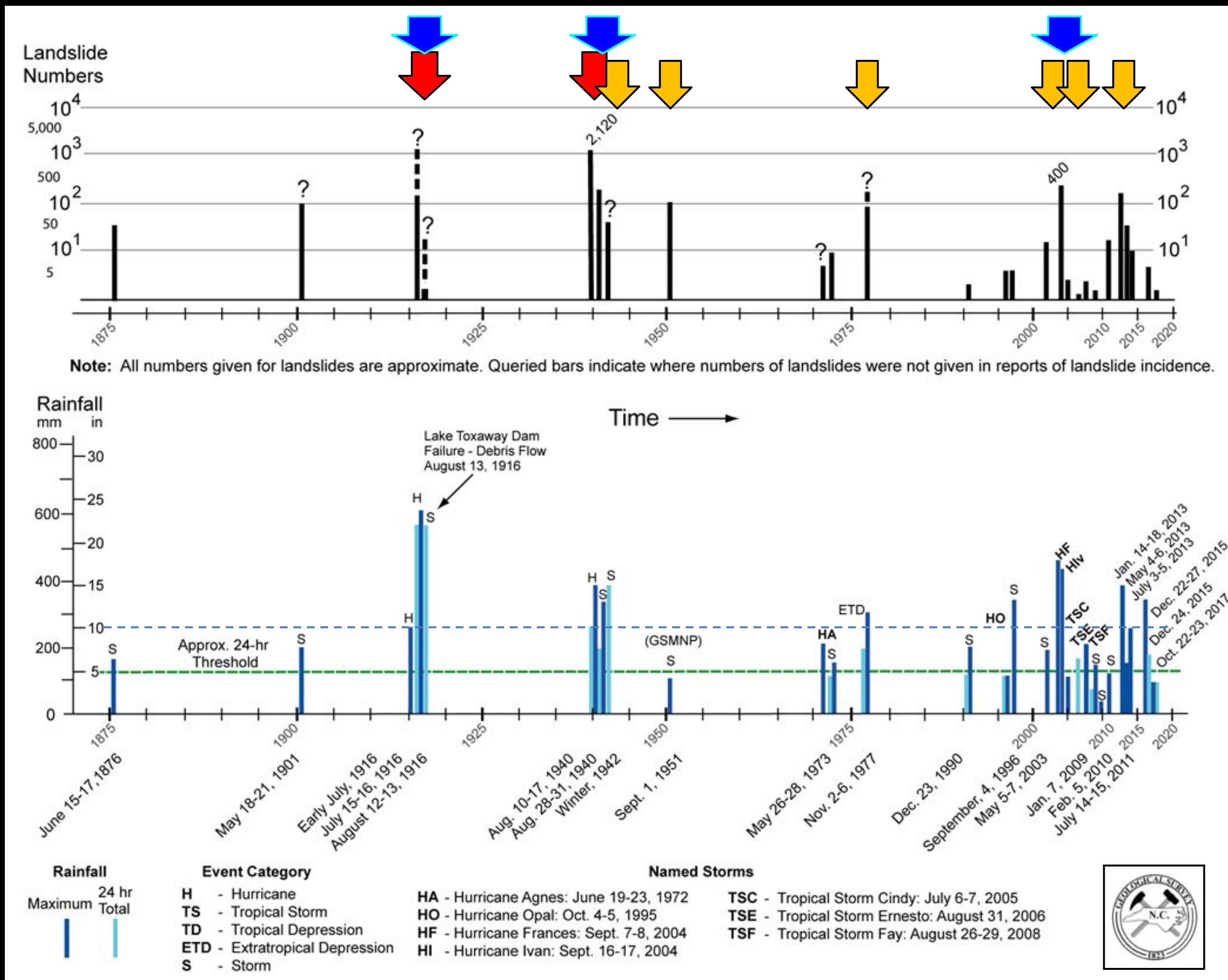
Miller et al. (2018)

Expanded view – mud slides, debris flows

- Methodology
  - Combine
    - Rainfall observations at the Coweeta Hydrologic Laboratory to detect Super Rain Time Clusters [SRTCs]
    - North Carolina Geodetic Survey landslide database

  to examine AR (and longer time scale event) influences on creating conditions favorable for mud slides, debris flows, and rock slides

Landslide Events and Rainfall Recurring Weather Patterns



Average Frequency 1876-2017 141 years

6 events: 100s of landslides
Avg. Frequency = 23.5 yr

2 events: 1000s of landslides
Avg. Frequency = 70.5 yr

8 events: 100s-1000s of landslides
Avg. Frequency = 17.5 yr

30 total recorded landslide events
Avg. Frequency = 4.7 yr

1916-2017 101 years

Back-to-Back Storm Events
8-12 days apart 1916, 1940, 2004

3 - Two-Storm Events
Avg. Frequency 33.7 yr

Rainfall Amounts

- ≥3 inches / 24 hours
  Periods of high antecedent moisture
  Landslides on some modified slopes
- ≥5 inches / 24 hours
  Scattered landslides:
  Modified and Unmodified Slopes
- ≥10 inches / 24 hours
  Widespread landslides:
  Modified and Unmodified Slopes

[1] Excludes major landslide events on I-40 not coincident with landslides events elsewhere in western NC

[2] NCGS begins tracking landslide events in western NC.

R. Wooten

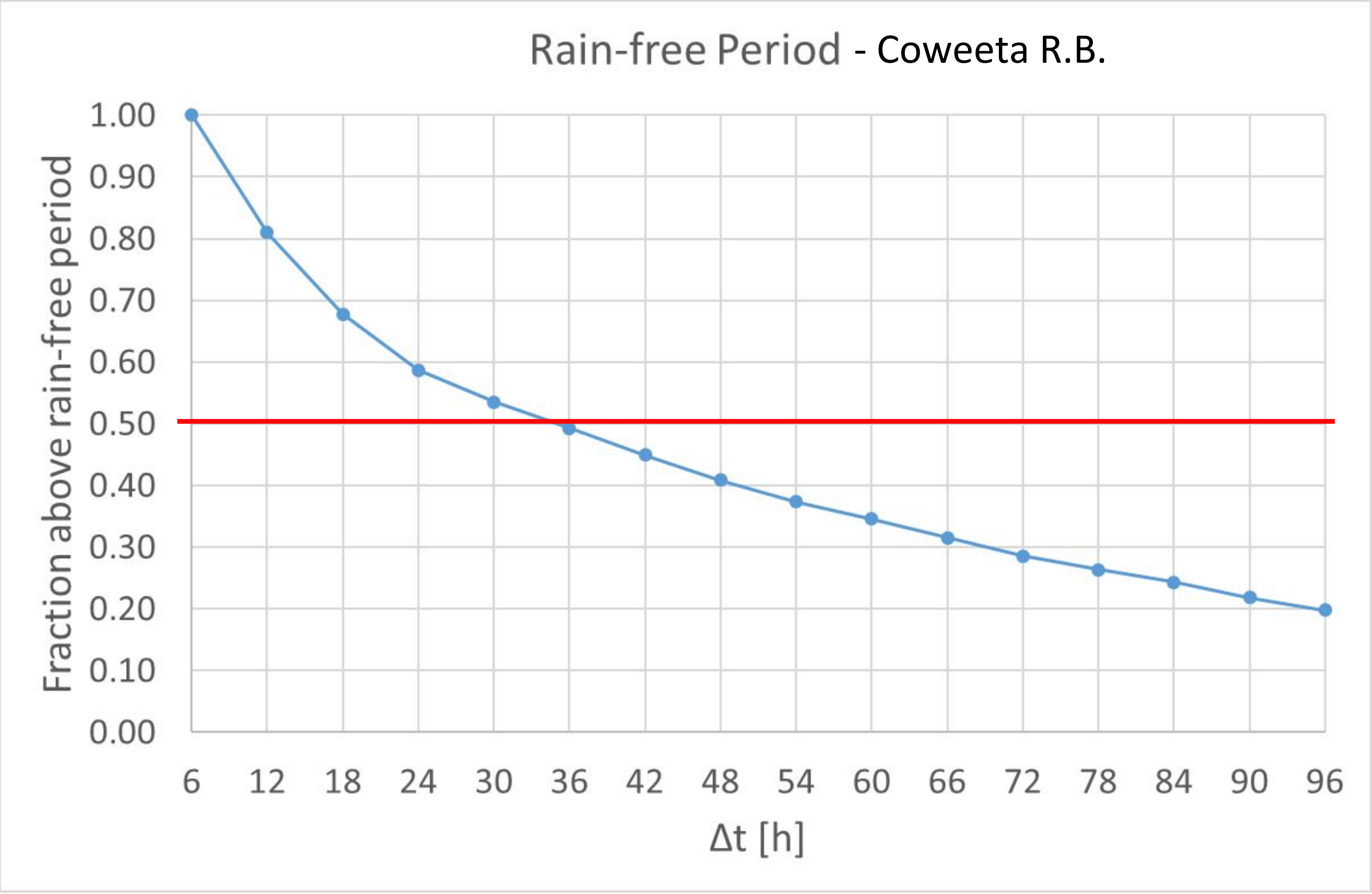
Expanded view – mud slides, debris flows

- Methodology
  - Recent (NOT TC-influenced) mud slide/debris flow events of western NC

Expanded view – mud slides, debris flows

Date	Description	AR	Extreme event
23 October 2009	Chimney Rock	Yes	No
25 October 2009	I-40 rock slide	Yes	No
5 February 2010	Ghost Town	Yes	CRB
14-15 July 2011	GSMNP – training convection	No	No
14 November 2012	Chimney Rock	No	No
14-18 January 2013	Western NC	Yes [2]	CRB and PRB
29-30 January 2013	Western NC	Yes [2]	CRB and PRB
27-28 April 2013	Western NC	No	No
4-5 May 2013	Western NC	No	No
4-5 July 2013	Western NC	Yes	CRB and PRB
27 July 2013	Western NC	No	No

Expanded view – mud slides, debris flows

- 

Expanded view – mud slides, debris flows

- Methodology
  - Longer time-scale precipitation events [SRTCs]

Δt =
30-h

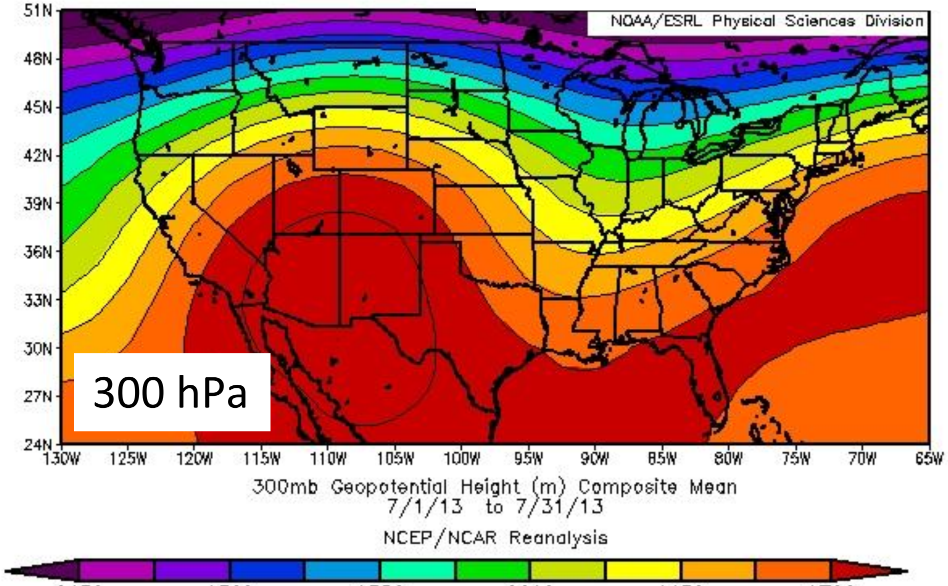
Expanded view – mud slides, debris flows

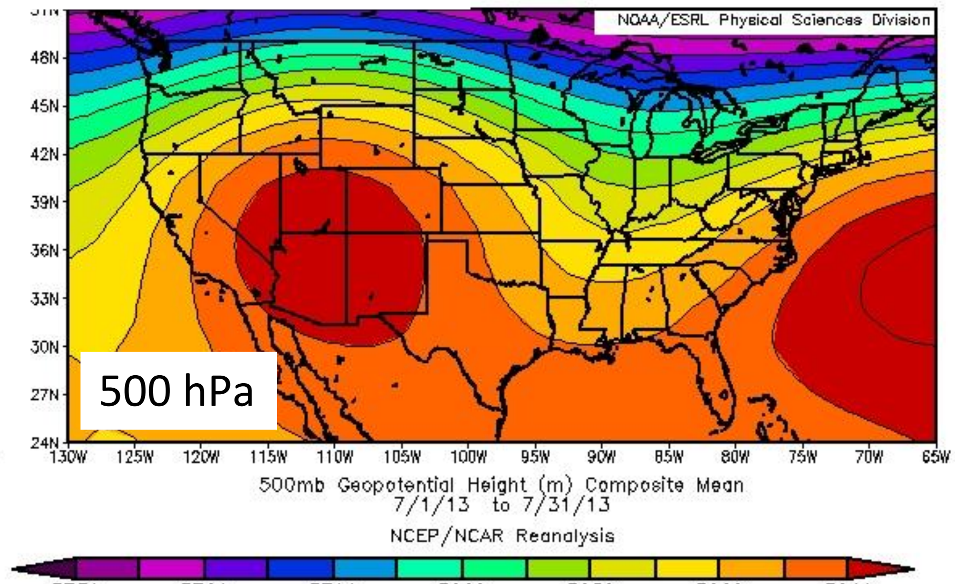
- Results
  - Recent (NOT TC-influenced) mud slide/debris flow events of western NC

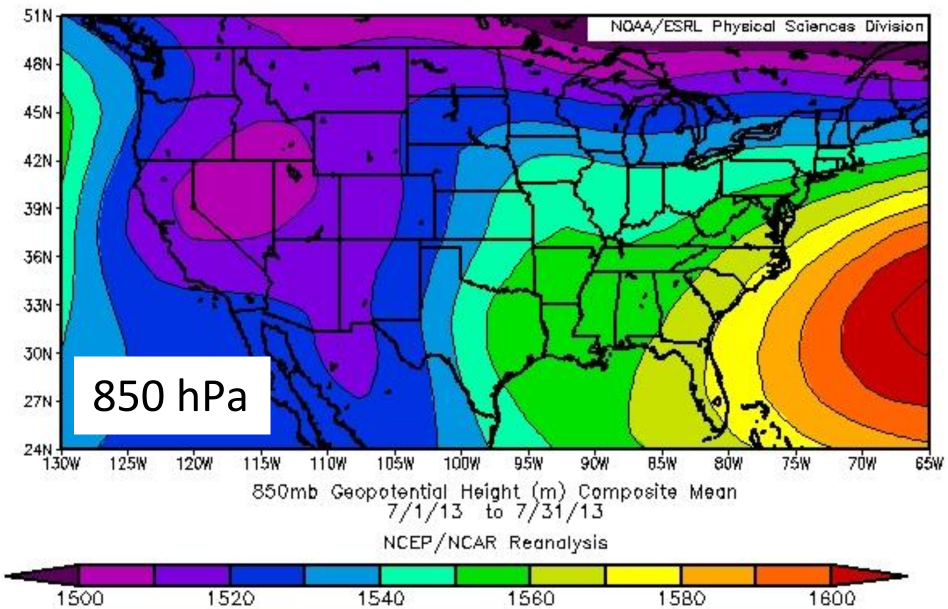
Date	Description	AR	SRTC ranking (CRB)
23 October 2009	Chimney Rock	Yes	9%
25 October 2009	I-40 rock slide	Yes	9%
14 November 2012	Chimney Rock	No	44%
27-28 April 2013	Western NC	No	12%
4-5 May 2013	Western NC	No	10%
27 July 2013*	Western NC	No	2.5% (extreme)

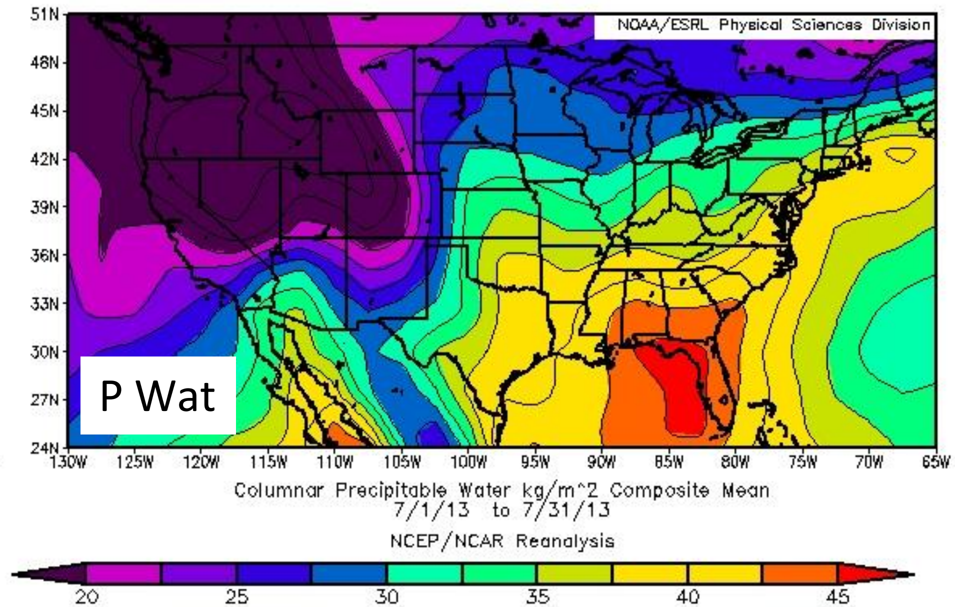
*Top-ranked extra-tropical SRTC event

Composite means – July 2013

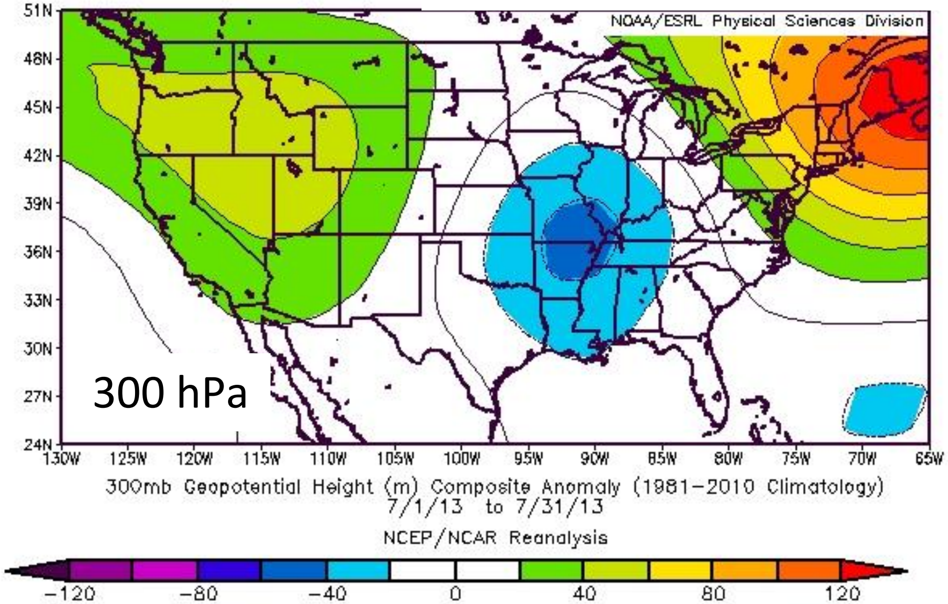


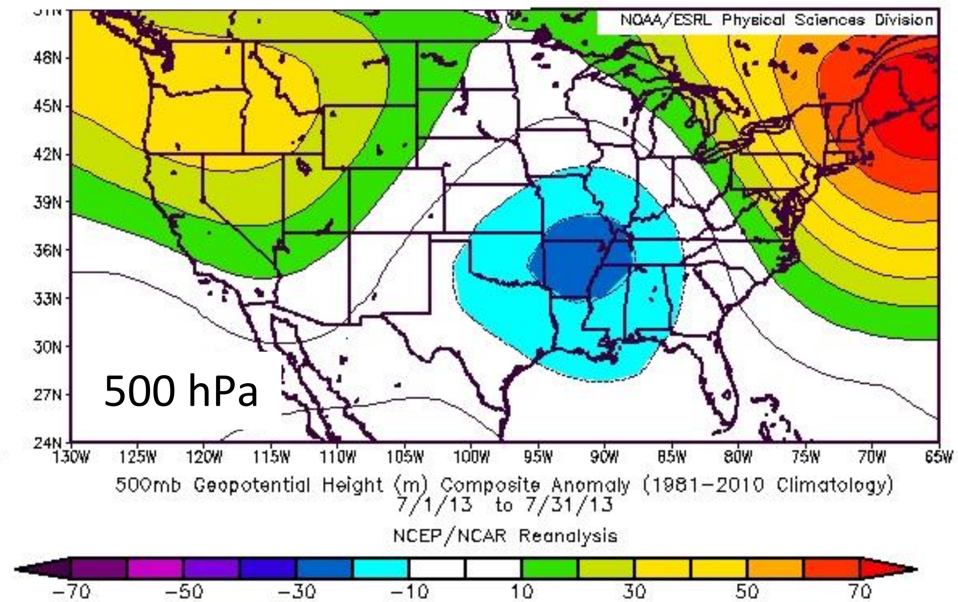


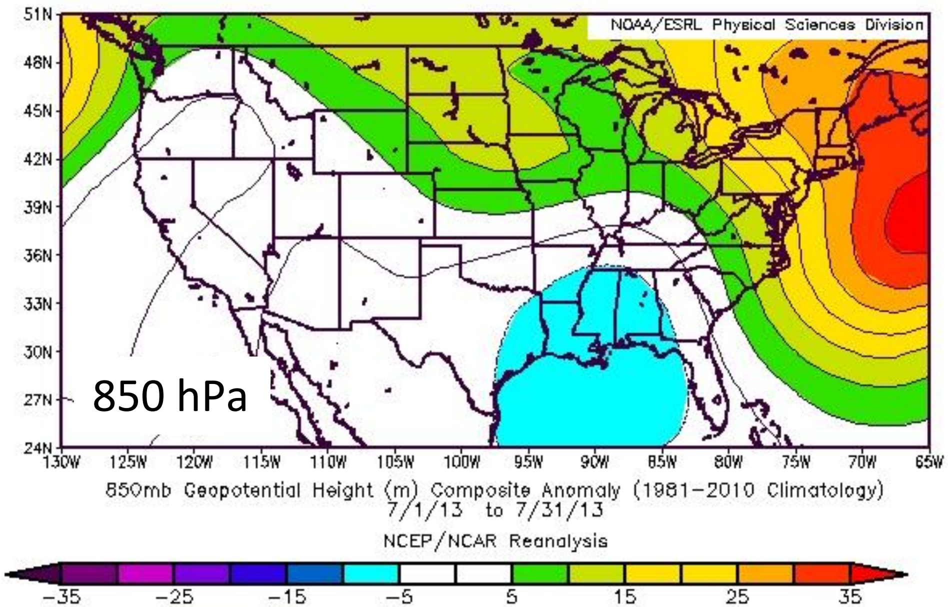


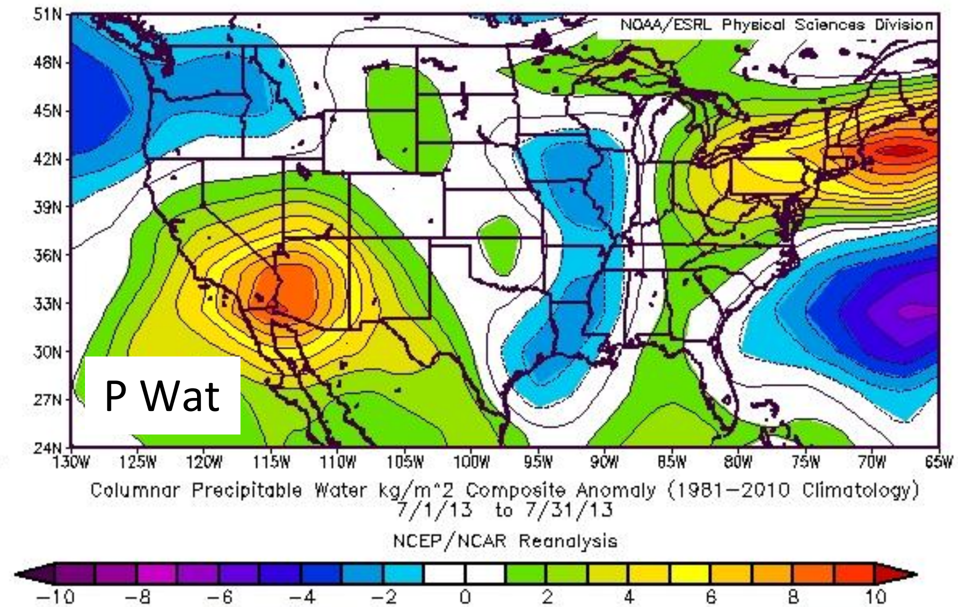


Composite anomalies – July 2013

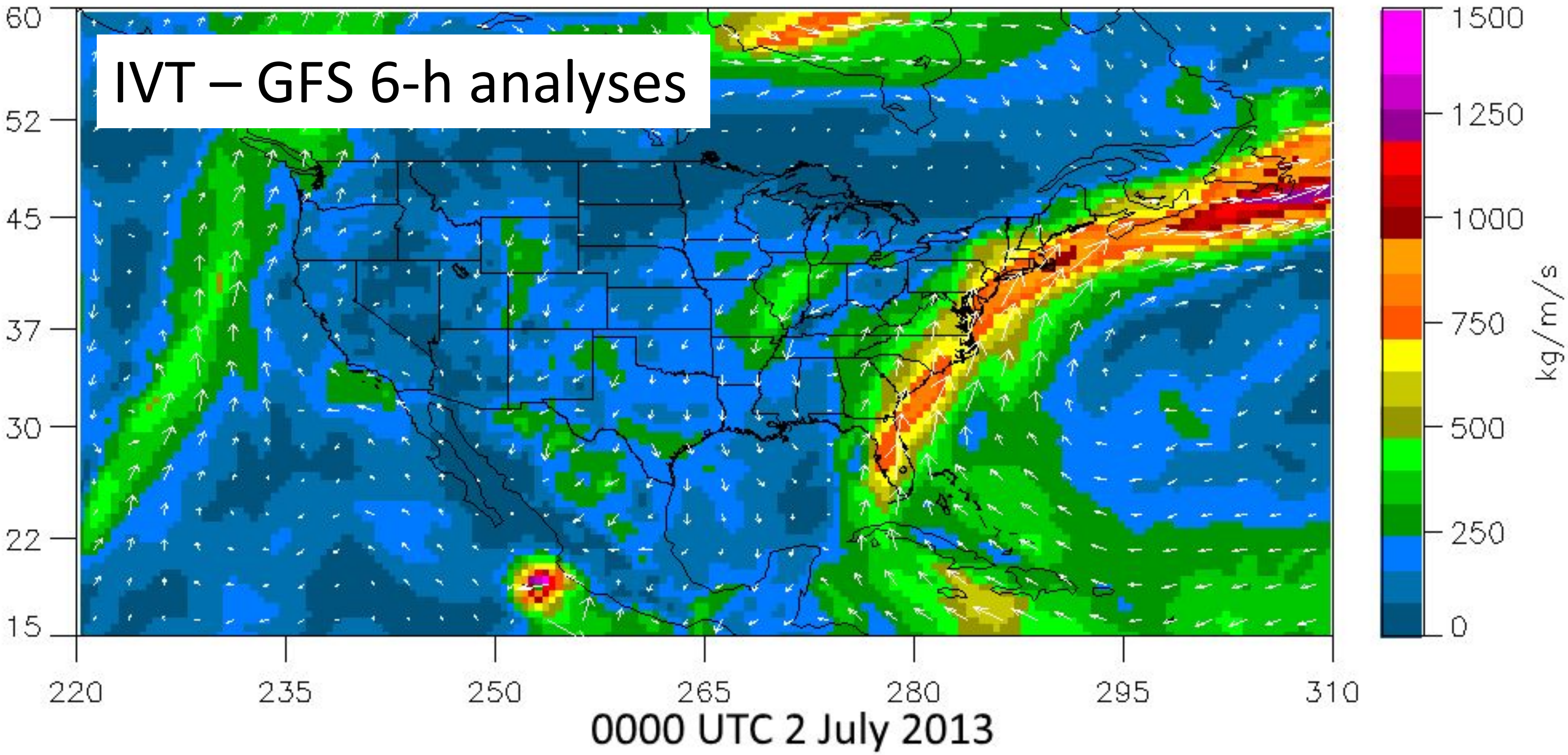








Expanded view – mud slides, debris flows



Expanded view – mud slides, debris flows

- Results
  - 6 of 11 recent landslides were directly linked with an AR
    - 4 of 6 qualified as an extreme rainfall event in the PRB or CRB
  - 6 recent landslides associated with non-extreme rainfall events
    - 1 event qualified as an extreme SRTC in the CRB (July 2013)
  - Hypothesis
    - Diabatic heating (LHR) attributable to a strong AR at the beginning of July 2013 strengthened a downstream ridge (Bermuda High), leading to a strong SRTC

Summary

- Expanded view
  - atmospheric rivers of two river basins in the southern Appalachian Mountains (1 July 2009 – 30 June 2017)
    - Proximity to the Blue Ridge escarpment and local orography show different ‘favored’ large-scale low-level wind directions during extreme rainfall events
      - Implications for AR category ratings (“one size” fits all?)
  - further back in time (4 June 1936 – 30 June 2009)
    - Most extreme rainfall events happen in the cool season, while warm season events have greatest mean duration and intensity
    - No apparent decadal trend in extreme events
  - mud slides and debris flows (1937 - 2017)
    - ARs and SRTCs are linked to some landslides, but link isn’t strong enough to utilize for prediction (have neglected other factors, e.g., soil type)

Future work

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- Expanded view
  - atmospheric rivers of two river basins in the southern Appalachian Mountains (1 July 2009 – 30 June 2017)
    - Link to societal hazards near the Coweeta River Basin
  - further back in time (4 June 1936 – 30 June 2009)
    - CRB non-AR events more often linked to mesoscale convective systems (26 Oct 2010)?
    - Fine tune operational weather soundings-based method of detecting ARs to determine their contribution to extreme events
  - mud slides and debris flows (1937 - 2017)
    - Expand search for AR/SRTC link to a larger number of landslides
    - How many strong SRTCs were led by an AR of at least moderate strength?
    - Are ARs responsible for contributing to a large-scale weather regime shift more favorable for landslides?

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Extras

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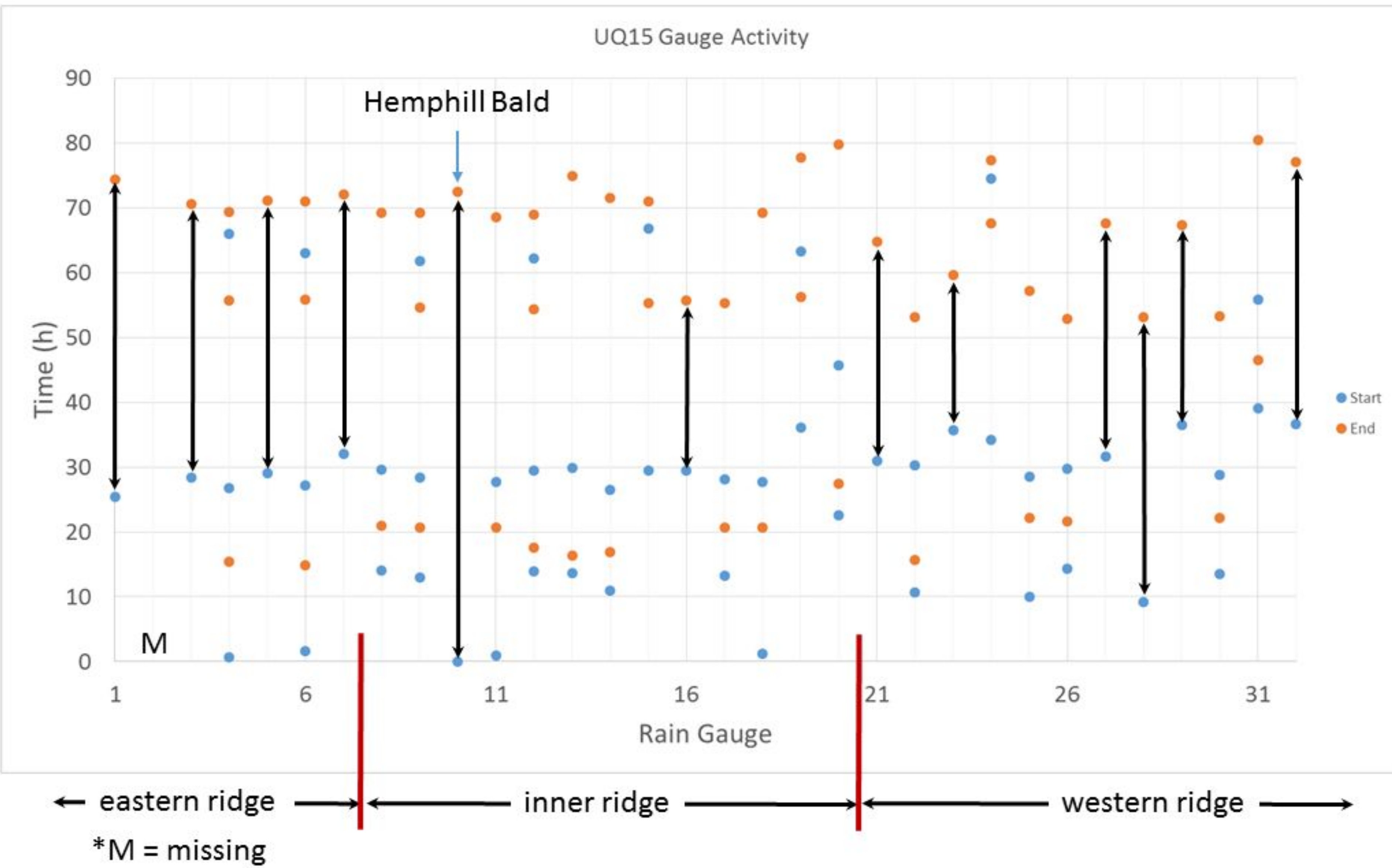
UQ15 Gauge Activity
Hemphill Bald
Time (h)
Rain Gauge
Start
End
M
90
80
70
60
50
40
30
20
10
0
1
6
11
16
21
26
31
eastern ridge
inner ridge
western ridge
*M = missing

Expanded view – two river basins

- Results
  - Yearly count of number of ARs impacting the IVT study domain using available 11463 GFS 6-h analysis periods of the 8-yr study.

Period	AR events	6-h periods	Avg duration (h)
Jul 2009 – Jun 2010	27	153	34.00
Jul 2010 – Jun 2011	18	108	36.00
Jul 2011 – Jun 2012	17	117	41.29
Jul 2012 – Jun 2013	23	164	42.78
Jul 2013 – Jun 2014	22	178	48.55
Jul 2014 – Jun 2015	19	120	37.89
Jul 2015 – Jun 2016	26	197	45.46
Jul 2016 – Jun 2017	16	114	42.75
Total/avg	168/21	1151	41.11

Expanded view – further back in time

- Results

  Seasonal rain events observed by the Coweeta Hydrologic Laboratory gauge network coincident with 6-h analysis periods of the 82-yr study.

Meteorological season	Rain events	6-h periods	Total per gauge accum. (mm)	Avg duration (h)	Event avg per gauge accum. (mm)
Winter (DJF)	2126	7469	46994.91	21.08	22.10
Spring (MAM)	2415	7224	43946.98	17.95	18.20
Summer (JJA)	3207	8036	41788.15	15.03	13.03
Autumn (SON)	1874	5989	39154.85	19.18	20.89
Total/avg	9622	28718	171884.89	18.31	17.86 (0.7 in)