Investigation of Atmospheric Rivers Impacting the Pigeon River Basin of the Southern Appalachian Mountains

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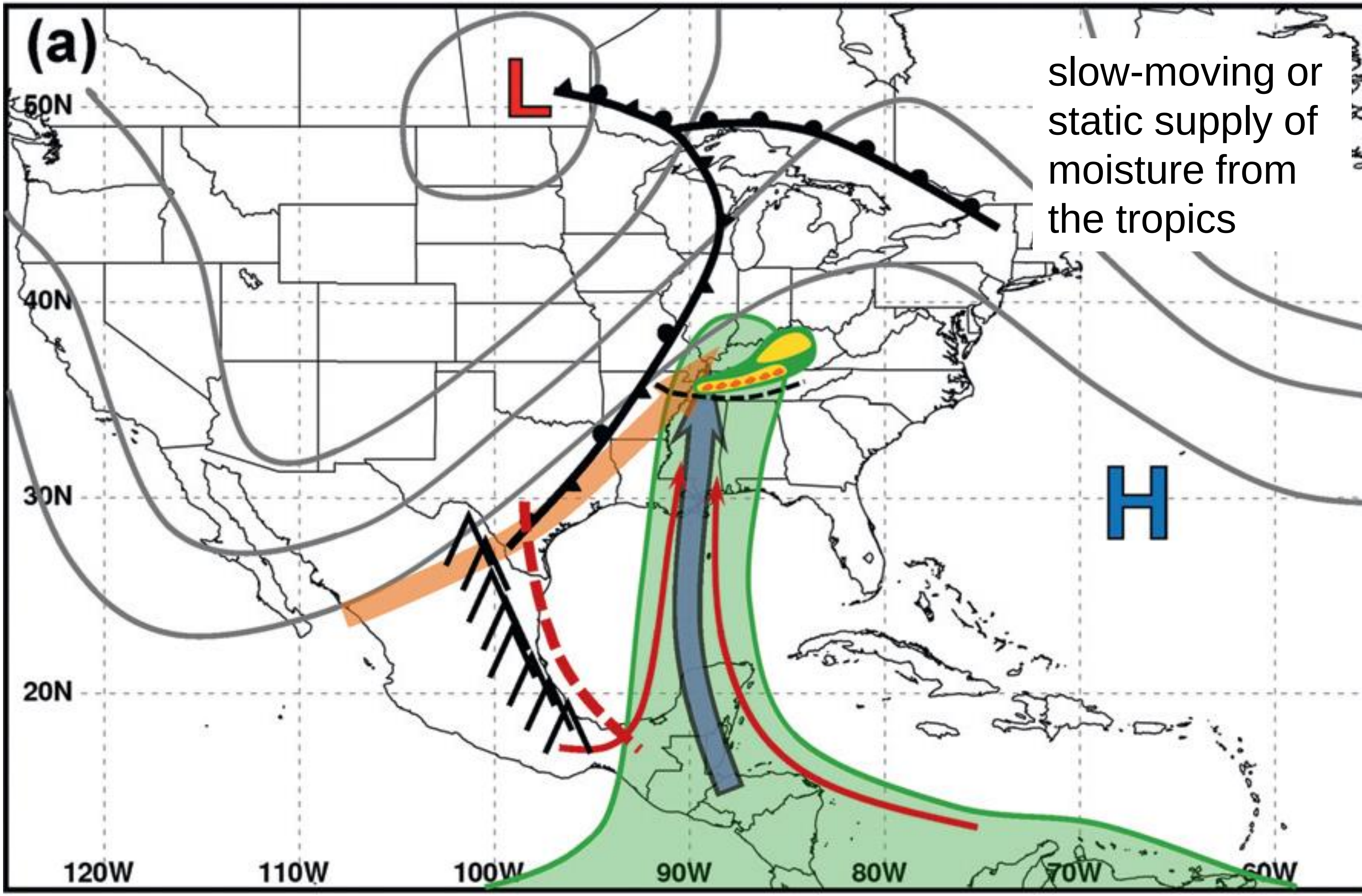
Outline

- Atmospheric Rivers
  - Background
    - southeastern U.S.
  - Purpose of COMET GOES-R Partners Project
  - Methodology
  - Results
  - Future work

Background

- southeastern U.S.

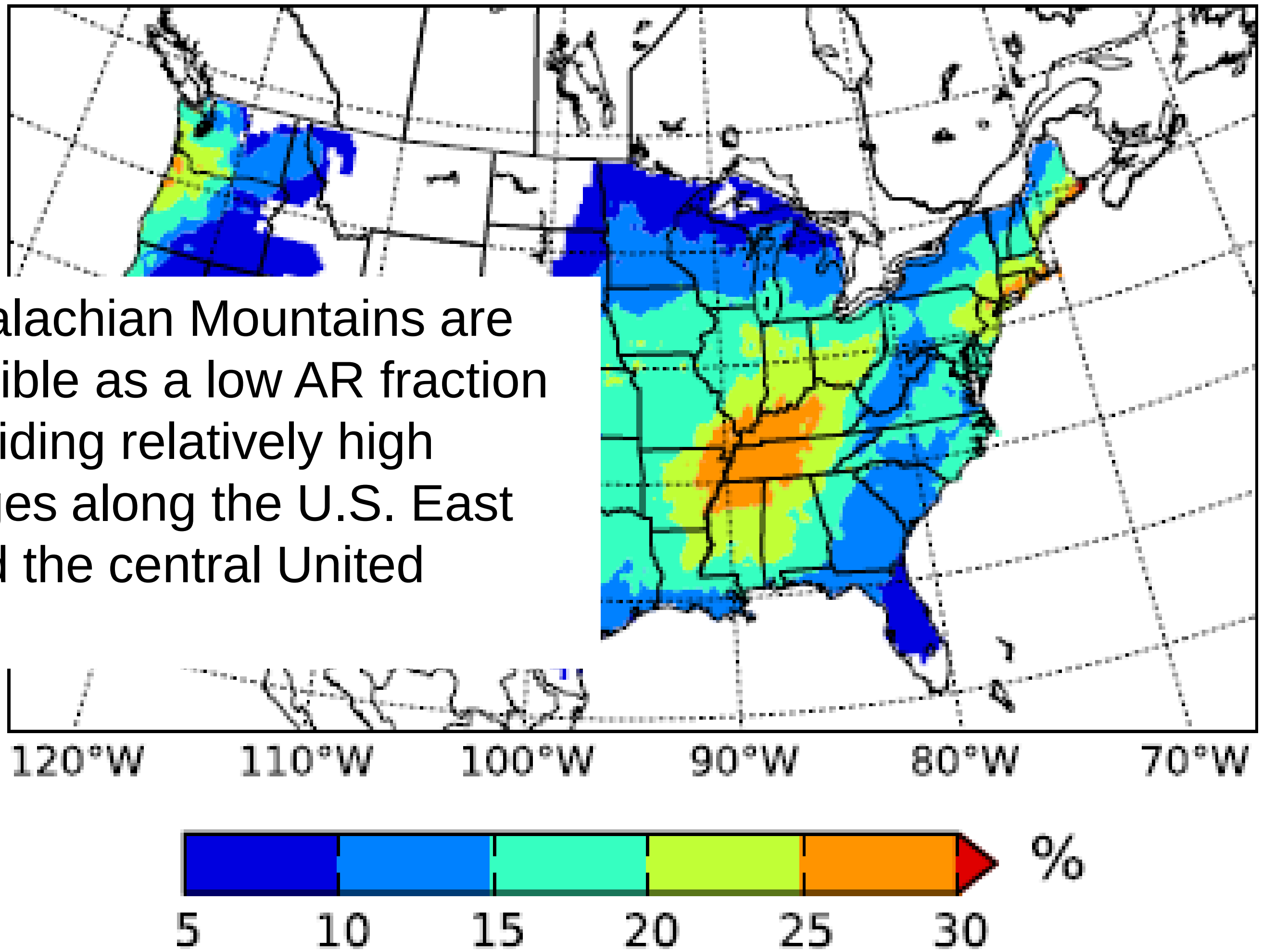


slow-moving or static supply of moisture from the tropics

1 – 2 May 2010

Moore et al. (2012)

Climatology in SE U.S.



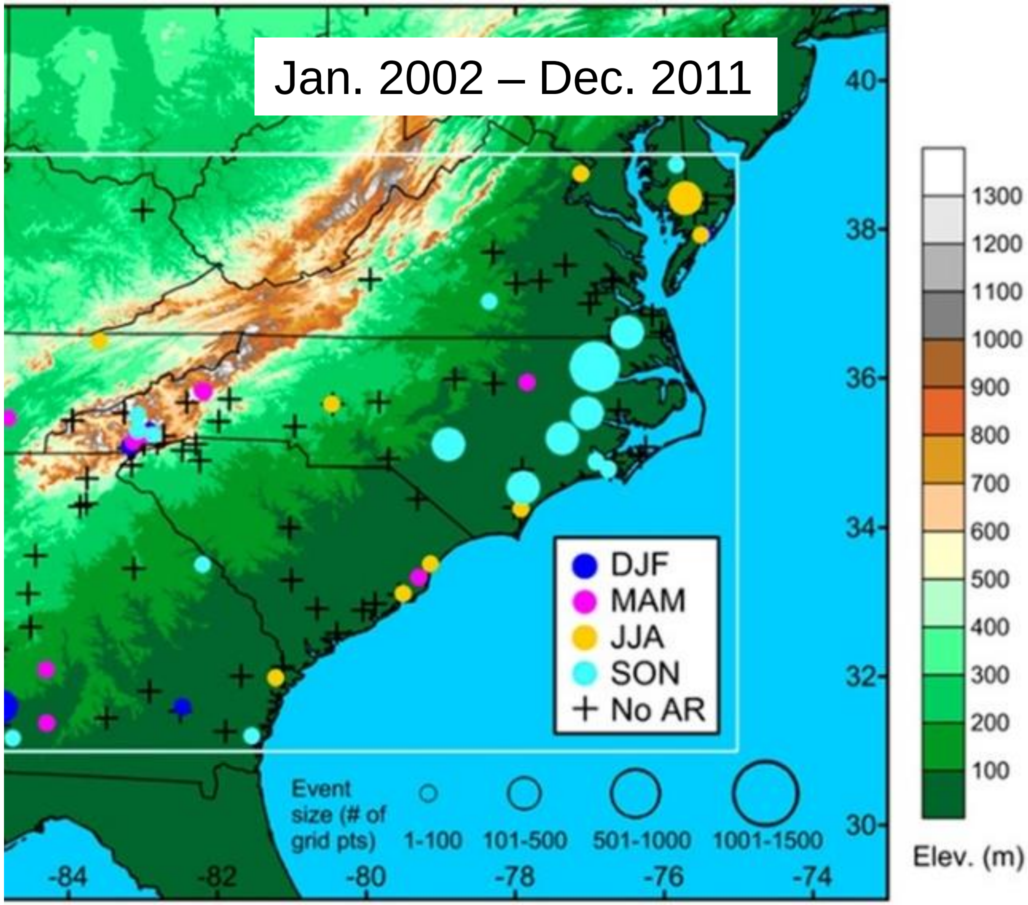
"The Appalachian Mountains are clearly visible as a low AR fraction region dividing relatively high percentages along the U.S. East Coast and the central United States."

Lavers and Villarini (2015)

Background

S.E. U.S. (SEUS) findings…

- IVT ~500 kg m^{-1} s^{-1} reasonable threshold for defining ARs
- clear connection between ARs and heavy precipitation events in non-summer months
- AR conditions in SEUS have a less direct influence on heavy precipitation relative to the U.S. west coast



Mahoney et al. (2016)

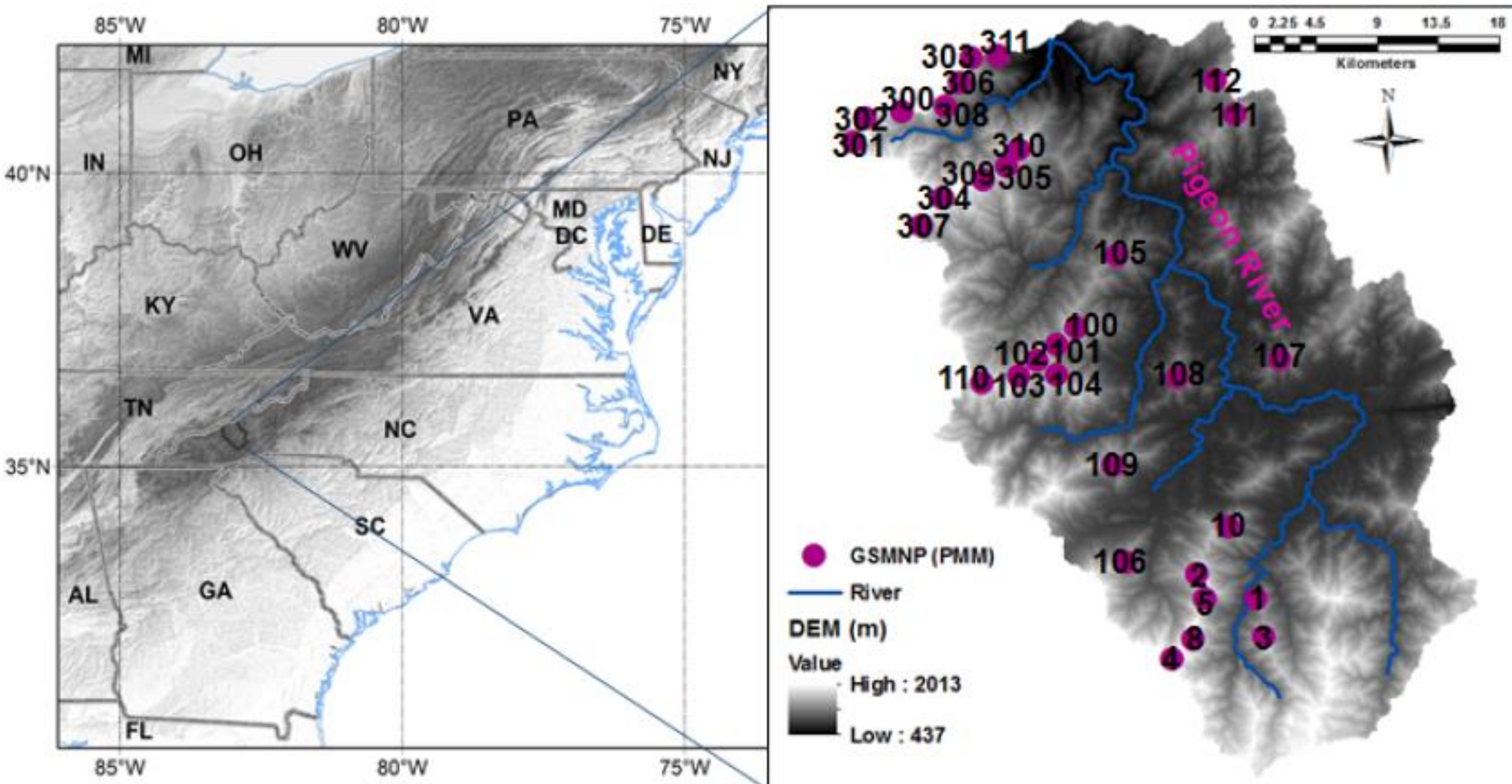
Purpose

- Do Atmospheric Rivers impact the southern Appalachians?
  - Are they responsible for flooding events?
  - Are they detectable by today's GOES sounder observations?
  - Will they be detectable by tomorrow's GOES-R sounder observations?

http://www.goes-r.gov/users/comet/goes_r/abi/print.php.htm

Methodology

Duke University Great Smoky Mountain Rain Gauge Network



Duan et al. (2015)

Methodology

32 gauges

Table 1. Inventory of long-term raingauges in the Pigeon River basin including the Great Smoky Mountains National Park (GSMNP) in the southern Appalachians used in this study.

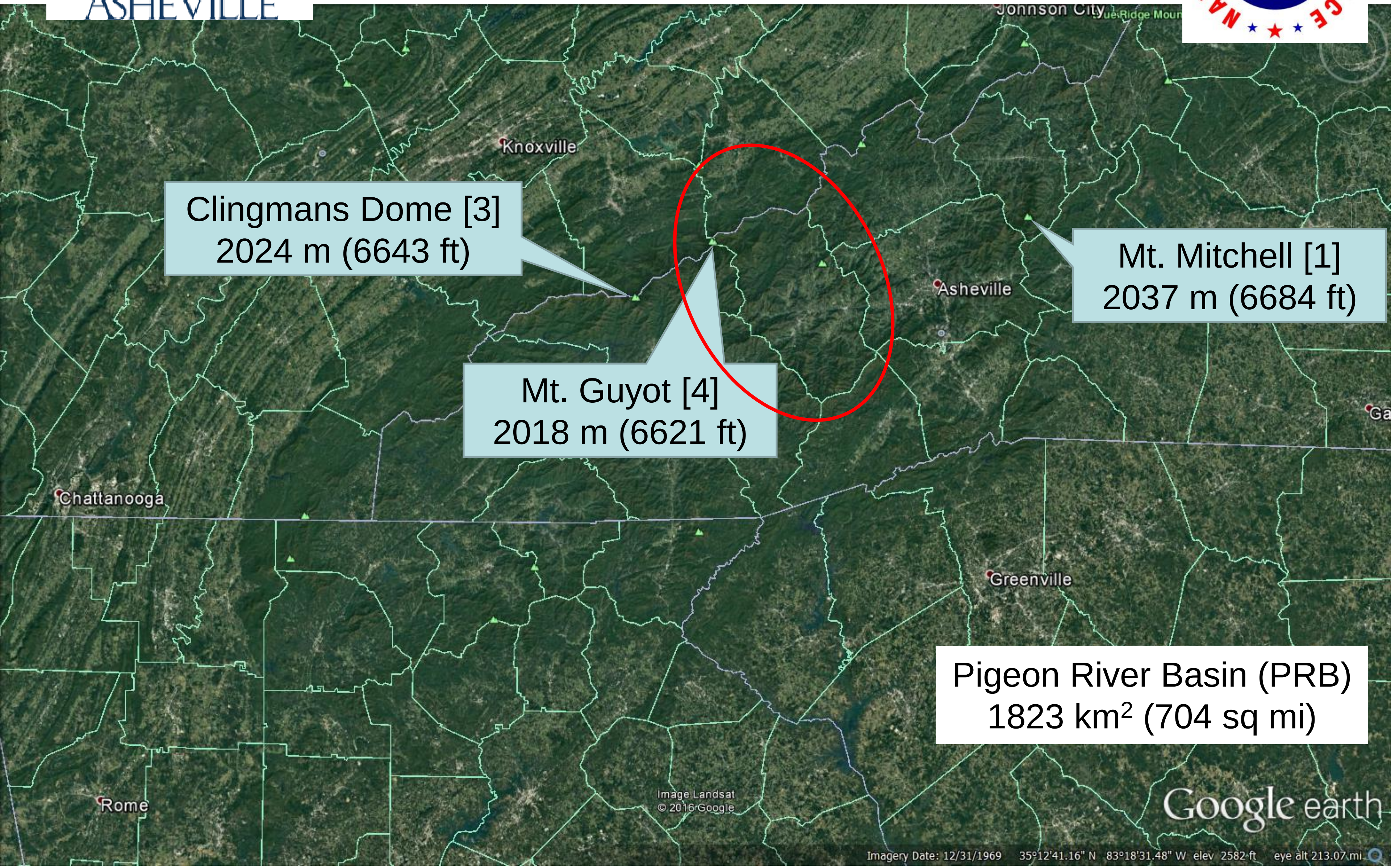
Raingauge	Latitude	Longitude	Elevation (m)	Series
RG001	35.4	−82.91	1156	
RG002	35.43	−82.97	1731	
RG003	35.38	−82.92	1609	
RG004	35.37	−82.99	1922	RG0XX eastern ridge
RG005	35.41	−82.96	1520	
RG008	35.38	−82.97	1737	
RG010	35.46	−82.95	1478	
RG100	35.59	−83.07	1495	
RG101	35.58	−83.09	1520	
RG102	35.56	−83.1	1635	
RG103	35.55	−83.12	1688	
RG104	35.55	−83.09	1587	
RG105	35.63	−83.04	1345	
RG106	35.43	−83.03	1210	RG1XX inner ridge
RG107	35.57	−82.91	1359	
RG108	35.55	−82.99	1277	
RG109	35.5	−83.04	1500	
RG110	35.55	−83.15	1563	
RG111	35.73	−82.95	1394	
RG112	35.75	−82.96	1184	
RG300	35.73	−83.22	1558	
RG301	35.71	−83.26	2003	
RG302	35.72	−83.25	1860	
RG303	35.76	−83.16	1490	
RG304	35.67	−83.18	1820	
RG305	35.69	−83.13	1630	
RG306	35.75	−83.17	1536	RG3XX western ridge
RG307	35.65	−83.2	1624	
RG308	35.73	−83.18	1471	
RG309	35.68	−83.15	1604	
RG310	35.7	−83.12	1756	
RG311	35.77	−83.14	1036	

Duan et al. (2015)

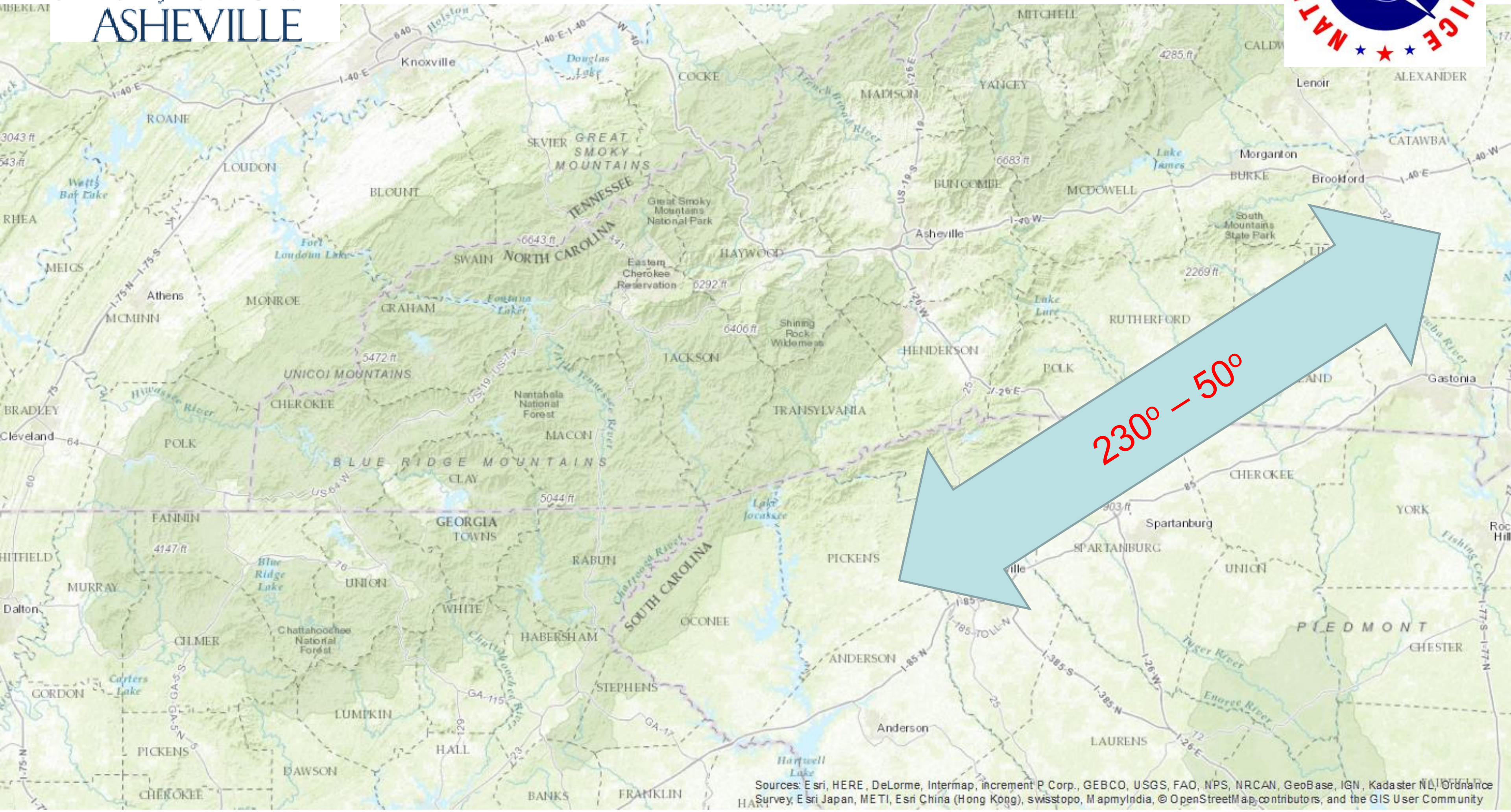
University of North Carolina Asheville

Southern Appalachians

National Weather Service



Southern Appalachians



Methodology

- Synoptically-forced rainfall events
  - rainfall parameter [RP]
    - RP = number of tips x dt [hours]
  - event start/finish
    - time between tips is greater than six hours
  - at each rain gauge location
    - rank RP values for every event
  - two sizes of tipping buckets (0.1 & 1.0 mm)
    - normalize [NRP] individually at each site

      $NRP = RP/RP_{max}$

Methodology

- Sustained rainfall events (continued)
  - combine results at ALL gauges
    - events between gauges are considered a single event if start/finish time at one gauge falls within ONE hour of the finish/start at a different gauge
  - at least 27 (of 32) rain gauges reporting in order to qualify as an event
  - rank upper-quartile (UQ) and above median (AM) events
    - top 15** of each category selected for in-depth analysis

Methodology

Integrated vapor transport (IVT)…

$$-\int_{p_o}^{p} (q\mathbf{V})\frac{dp}{g}, \qquad (1)$$

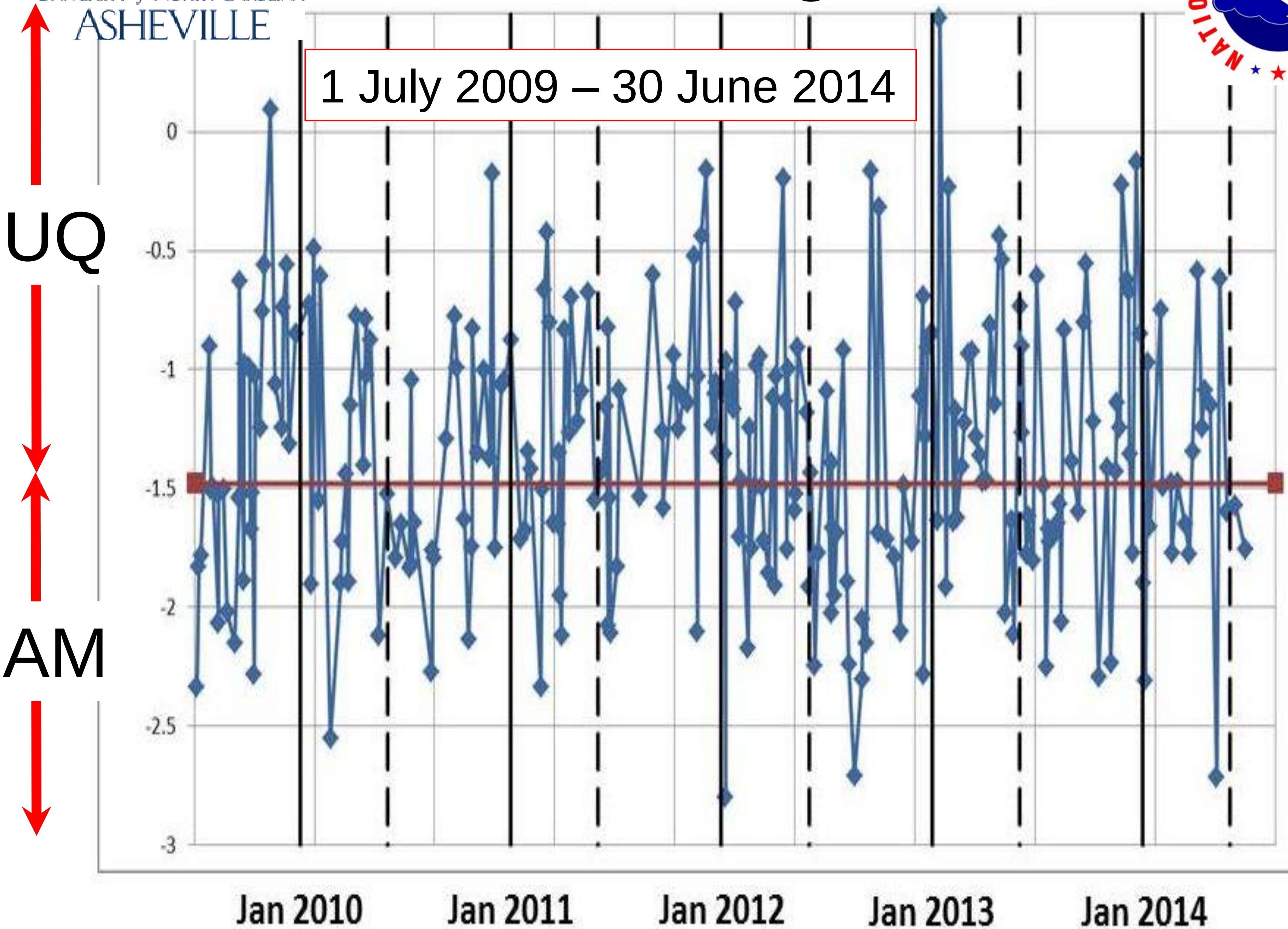
where q is the specific humidity, $\mathbf{V}$ is the horizontal wind, p_o is 1000 hPa, p is 300 hPa, and g is the acceleration due to gravity.

Moore et al. (2012)

Results

- High elevation GSM Rain Gauge Network

Rain Gauge Obs



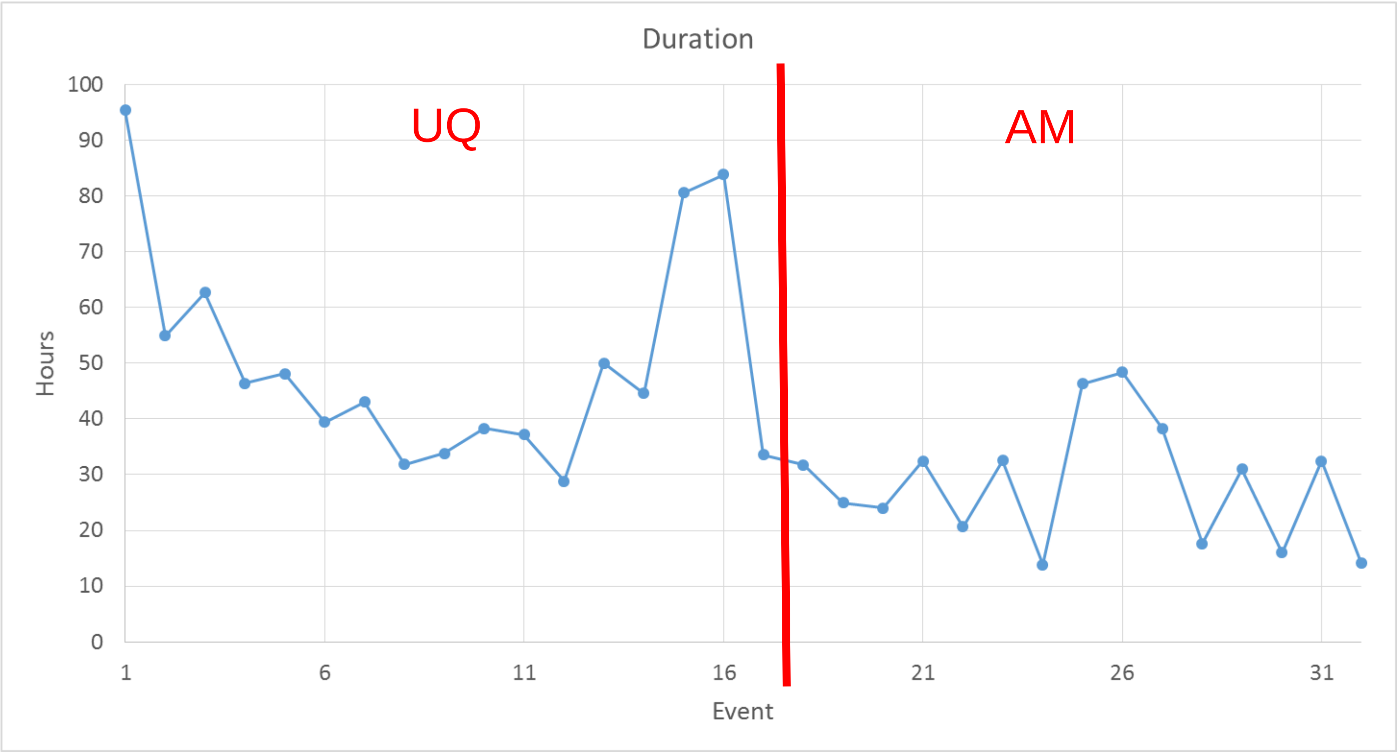
	Starting			(EDT)			Ending			(EDT)					
Case	Year	Month	Day	Hour	Minute	Second	Year	Month	Day	Hour	Minute	Second	Δt (h)	#gauges	Score
AM15	2009	9	16	4	34	39	2009	9	16	18	46	48	14.20	31	0.0289853
AM14	2011	8	13	10	27	35	2011	8	14	18	54	20	32.45	30	0.0293127
AM13	2009	8	12	0	40	30	2009	8	12	16	41	34	16.02	31	0.0298383
AM12	2010	5	30	23	34	49	2010	6	1	6	31	59	30.95	32	0.0299490
AM11	2012	5	9	3	33	49	2012	5	9	21	11	55	17.64	30	0.0300439
AM10	2009	10	9	17	6	14	2009	10	11	7	21	44	38.26	31	0.0303231
AM09	2009	8	20	12	8	22	2009	8	22	12	31	47	48.39	31	0.0312183
AM08	2009	7	29	21	7	4	2009	7	31	19	24	49	46.30	32	0.0313731
AM07	2011	2	24	21	33	7	2011	2	25	11	25	24	13.87	32	0.0314135
AM06	2012	3	12	5	39	49	2012	3	13	14	10	53	32.52	29	0.0319821
AM05	2009	8	1	19	54	54	2009	8	2	16	34	21	20.66	31	0.0320535
AM04	2012	2	29	1	33	17	2012	3	1	9	58	20	32.42	30	0.0320562
AM03	2014	2	4	19	32	56	2014	2	5	19	33	2	24.00	29	0.0321463
AM02	2012	11	12	3	51	19	2012	11	13	4	49	53	24.97	32	0.0325865
AM01	2013	7	13	22	39	55	2013	7	15	6	24	34	31.74	27	0.0326067
UQ17	2013	9	24	22	44	12	2013	9	26	8	19	44	33.59	31	0.2793404
UQ16	2013	5	2	21	15	57	2013	5	6	9	5	4	83.81	32	0.2875626
UQ15	2011	11	14	11	36	24	2011	11	17	20	7	24	80.51	31	0.2994687
UQ14	2010	1	23	19	50	27	2010	1	25	16	23	18	44.55	31	0.3213153
UQ13	2013	4	27	2	20	33	2013	4	29	4	17	38	49.95	32	0.3636338
UQ12	2011	11	27	20	29	48	2011	11	29	1	21	14	28.85	31	0.3656741
UQ11	2011	3	5	6	28	10	2011	3	6	19	38	23	37.17	31	0.3752993
UQ10	2012	10	1	0	28	20	2012	10	2	14	44	55	38.28	31	0.4803601
UQ09	2013	1	29	17	15	6	2013	1	31	3	3	29	33.81	32	0.5803836
UQ08	2013	11	25	21	56	46	2013	11	27	5	45	18	31.80	32	0.6008443
UQ07	2012	4	17	13	10	38	2012	4	19	8	12	3	43.02	32	0.6391015
UQ06	2010	11	29	14	50	19	2010	12	1	6	13	15	39.38	32	0.6697140
UQ05	2012	9	17	4	7	8	2012	9	19	4	12	53	48.09	31	0.6854642
UQ04	2011	12	5	19	39	8	2011	12	7	18	1	33	46.38	32	0.6894096
UQ03	2013	12	21	4	24	58	2013	12	23	19	5	45	62.68	31	0.7404496
UQ02	2009	11	10	2	58	57	2009	11	12	9	50	42	54.86	31	1.2410330
UQ01	2013	1	13	20	8	10	2013	1	17	19	27	30	95.32	32	3.0153080

AM

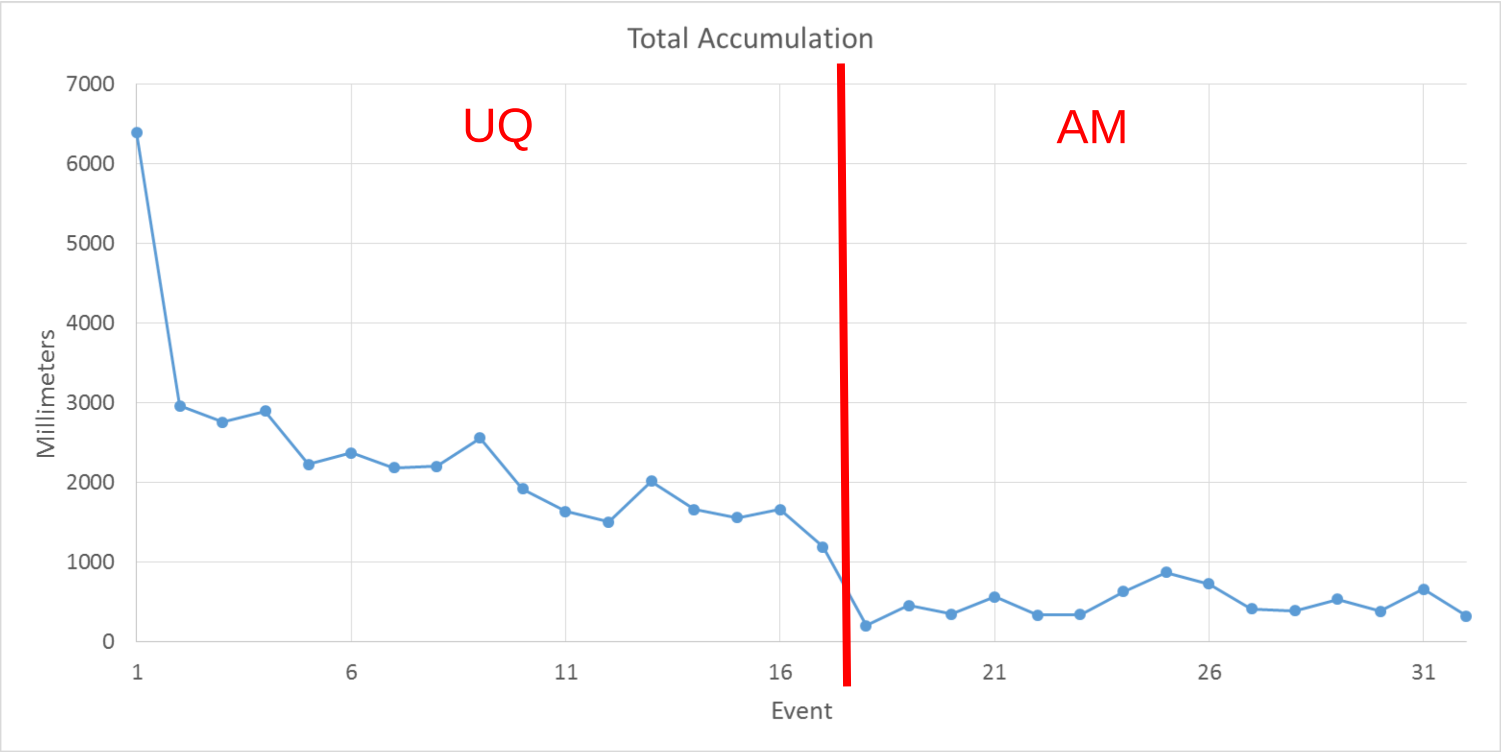
UQ

non-summer events

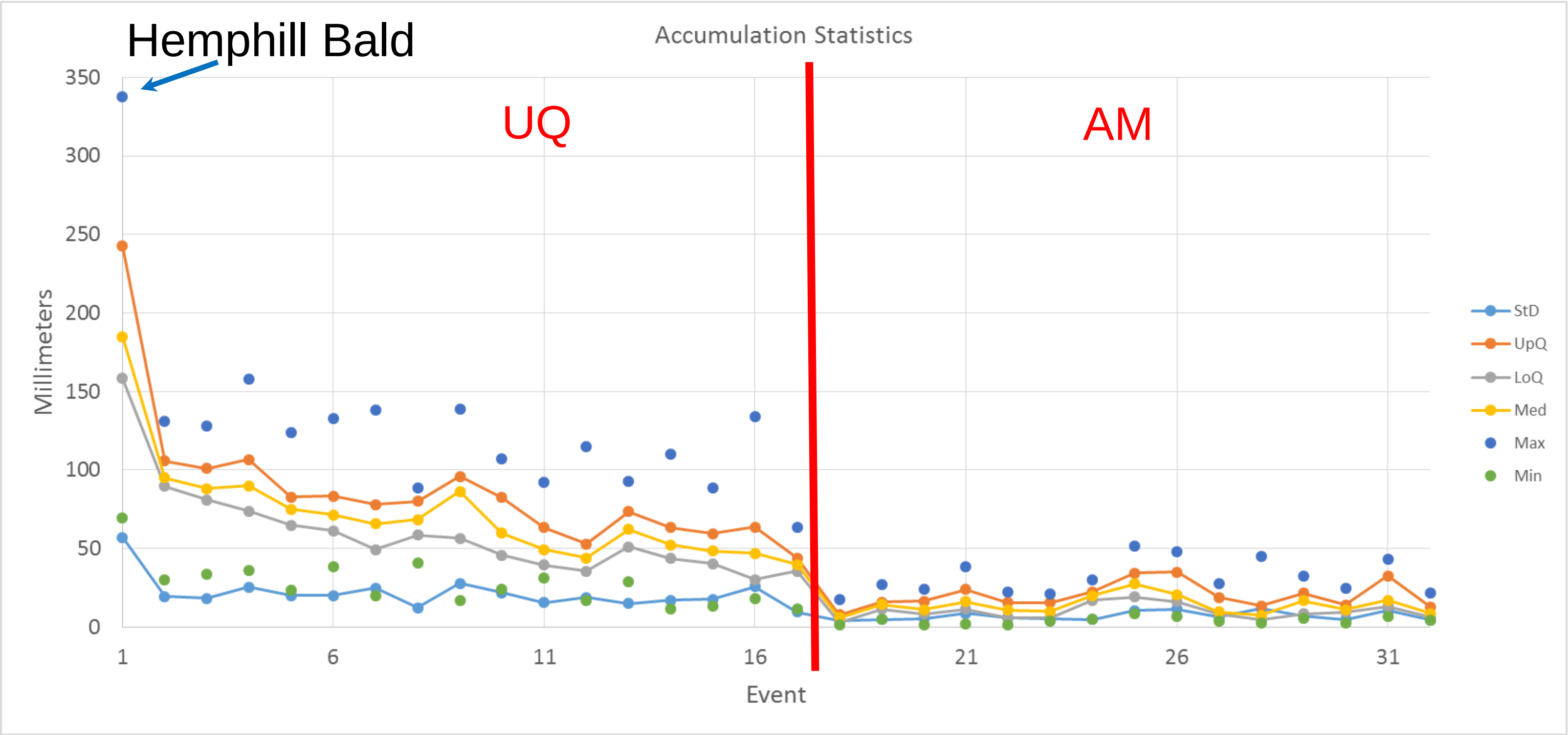
Rain Gauge Obs



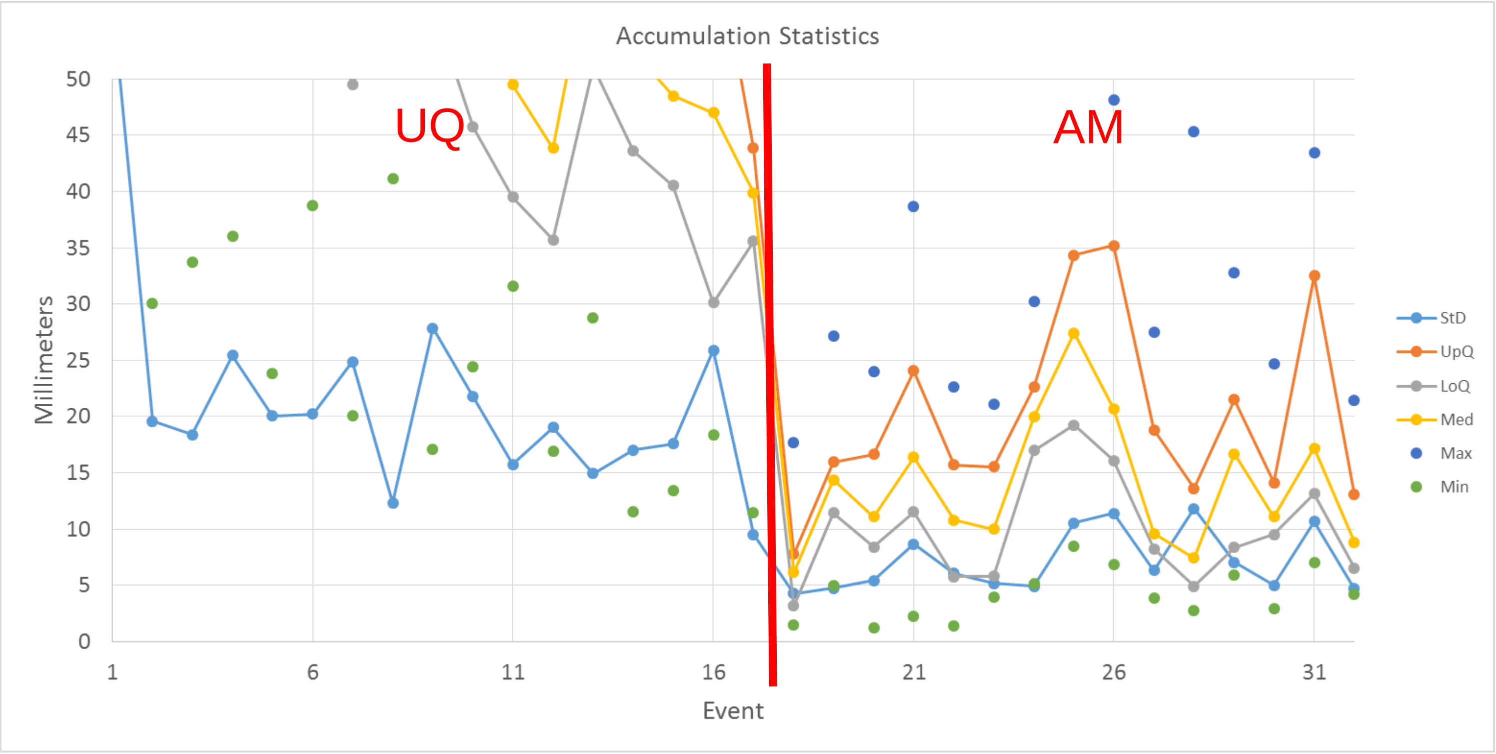
Rain Gauge Obs



Rain Gauge Obs



Rain Gauge Obs



Analysis Questions

- Do Atmospheric Rivers impact the southern Appalachians?
  - Are they responsible for flooding events?
  - Are they detectable by today's GOES sounder observations? Will they be detectable by tomorrow's GOES-R sounder observations?
  - What atmospheric fields beyond satellite observations are useful in their detection?

Methodology for determining whether or not an AR was involved in a particular case study...

- Does 500 hPa map show enhanced southerly (jet) winds over the SE US?
    - likely to occur in the presence of a deep (meridional) trough
        - strong low-level winds (~850 hPa level)

- Does 850 hPa map show a cyclone located upstream of the SE US?
    - likely to draw air parcels at low levels from the GoM and/or the Atlantic Ocean
    - favorable location for ascent given usual QG theory (warm air advection)

- Does HYSPLIT EDAS-based trajectory indicate parcels ending at the PRB at 1.5, 2.2, and 3.0 km AGL being drawn from over the GoM and/or Atlantic Ocean?
    - bonus if parcels show red (1.5 km), blue (2.2 km), and green (3.0 km) trajectories oriented clockwise near/at the endpoint
        - indicative of warm air advection

- Confirm that AR is possible given the surface pressure map [e.g., warm air advection]?

*Note: AR-spotting methodology did NOT at all involve looking at TPW or IWV maps, although the SPC upper-air 850 hPa level map did have shading indicative of low-level atmospheric vapor.

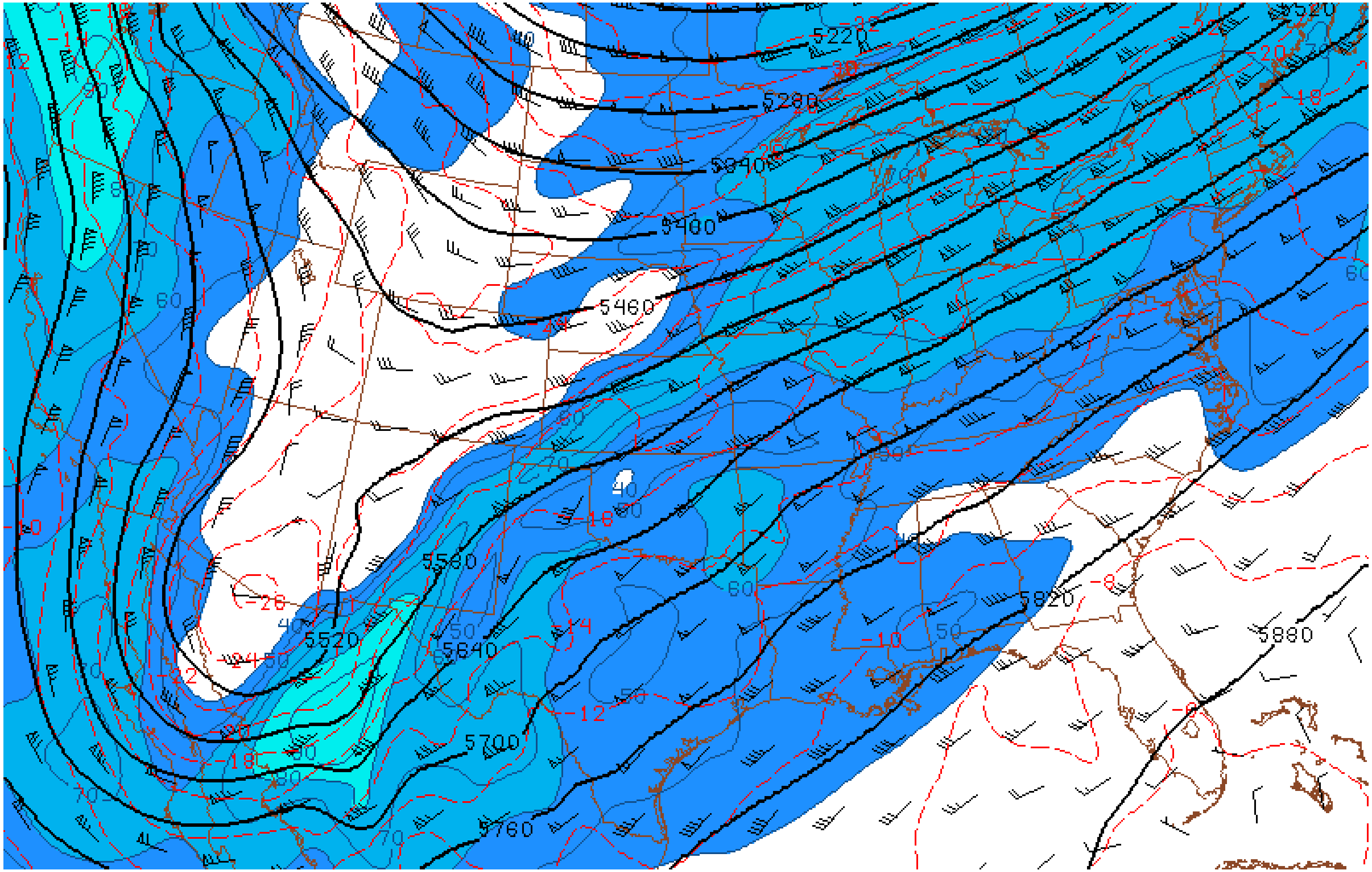
	Starting			(EDT)					
Case	Year	Month	Day	Hour	Minute	Δt (h)	USGS gauge	Storm Data	AR
AM15	2009	9	16	4	34	14.20	None	Flooding (TN)	No
AM14	2011	8	13	10	27	32.45	None	Flooding (NC)*	No
AM13	2009	8	12	0	40	16.02	None	None	No
AM12	2010	5	30	23	34	30.95	None	Flooding (NC)	Possible
AM11	2012	5	9	3	33	17.64	None	None	No
AM10	2009	10	9	17	6	38.26	None	None	Possible
AM09	2009	8	20	12	8	48.39	None	Flooding (NC)*	No
AM08	2009	7	29	21	7	46.30	None	None	No
AM07	2011	2	24	21	33	13.87	Action stage	None	Possible
AM06	2012	3	12	5	39	32.52	Action stage	None	Possible
AM05	2009	8	1	19	54	20.66	None	Flooding (NC)*	No
AM04	2012	2	29	1	33	32.42	None	None	Possible
AM03	2014	2	4	19	32	24.00	Action stage	None	Possible
AM02	2012	11	12	3	51	24.97	None	None	Possible
AM01	2013	7	13	22	39	31.74	Action stage	Flooding (NC)	No
UQ17	2013	9	24	22	44	33.59	None	None	No
UQ16	2013	5	2	21	15	83.81	Moderate flooding	Flooding (NC)	No
UQ15	2011	11	14	11	36	80.51	None	None	Possible
UQ14	2010	1	23	19	50	44.55	Major flooding	Flooding (NC)	Possible
UQ13	2013	4	27	2	20	49.95	Action stage	Flooding (TN)	No
UQ12	2011	11	27	20	29	28.85	Moderate flooding	Flooding (NC)	Possible
UQ11	2011	3	5	6	28	37.17	Minor flooding	Flooding (NC)	Possible
UQ10	2012	10	1	0	28	38.28	None	Flooding (TN)	Possible
UQ09	2013	1	29	17	15	33.81	Major flooding	Flooding (NC)	Possible
UQ08	2013	11	25	21	56	31.80	Minor flooding	None	Possible
UQ07	2012	4	17	13	10	43.02	Action stage	None	Possible
UQ06	2010	11	29	14	50	39.38	Minor flooding	Flooding (TN, NC)	Possible
UQ05	2012	9	17	4	7	48.09	Minor flooding	Flooding (TN, NC)	Possible
UQ04	2011	12	5	19	39	46.38	Major flooding	Flooding (TN)	Possible
UQ03	2013	12	21	4	24	62.68	Moderate flooding	Flooding (NC)	Possible
UQ02	2009	11	10	2	58	54.86	Moderate flooding	Flooding (NC)	No
UQ01	2013	1	13	20	8	95.32	Major flooding	Flooding (TN, NC)	Possible

*mesoscale

Results

- Case study examples

500 hPa level Geo Ht / Temp / WS



40 60 80 100 120 140

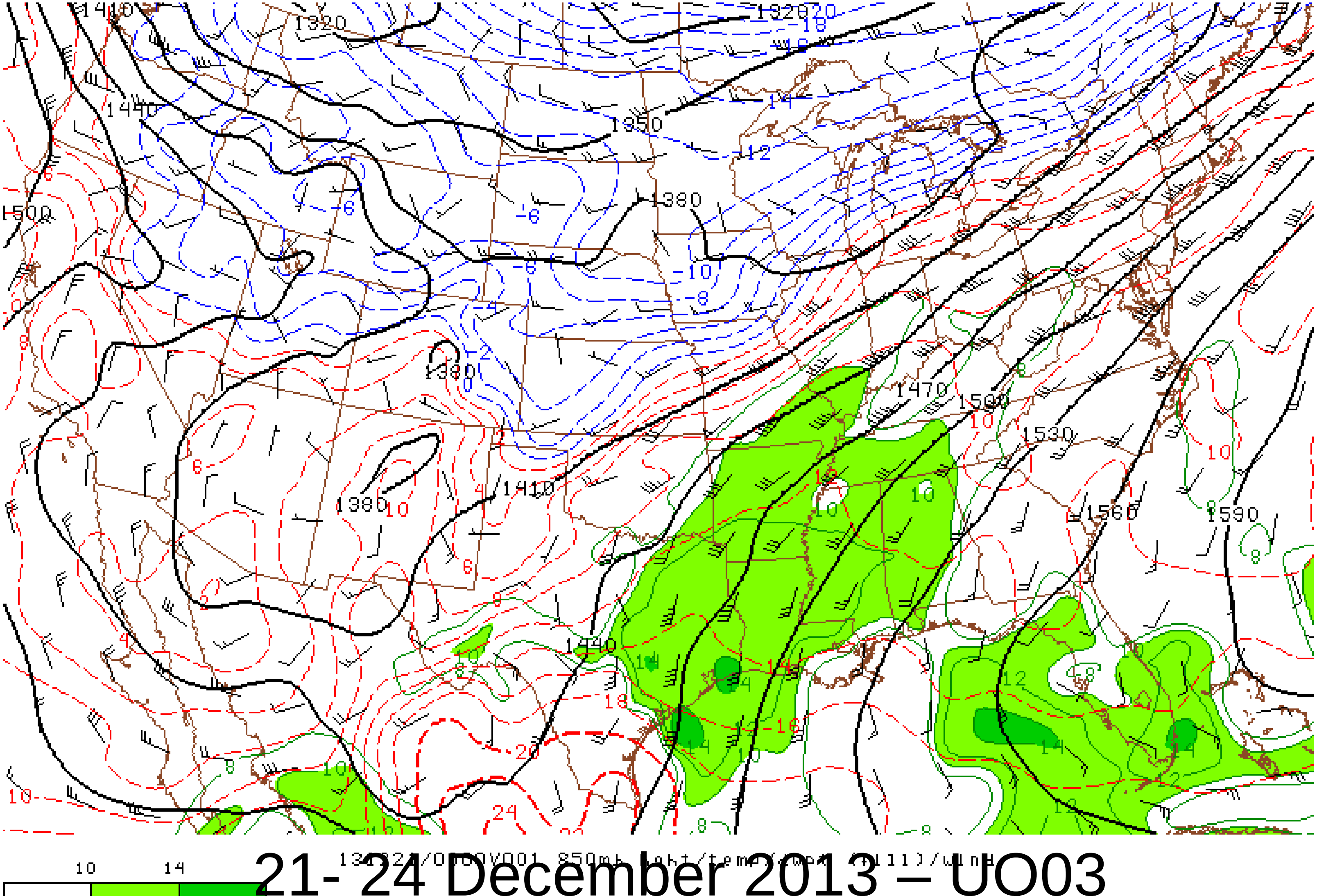
131221/0000V001 500mb hght/temp/wind

21- 24 December 2013 – UQ03

(moderate flooding)

NOAA - SPC

850 hPa level Geo Ht / Temp / Td

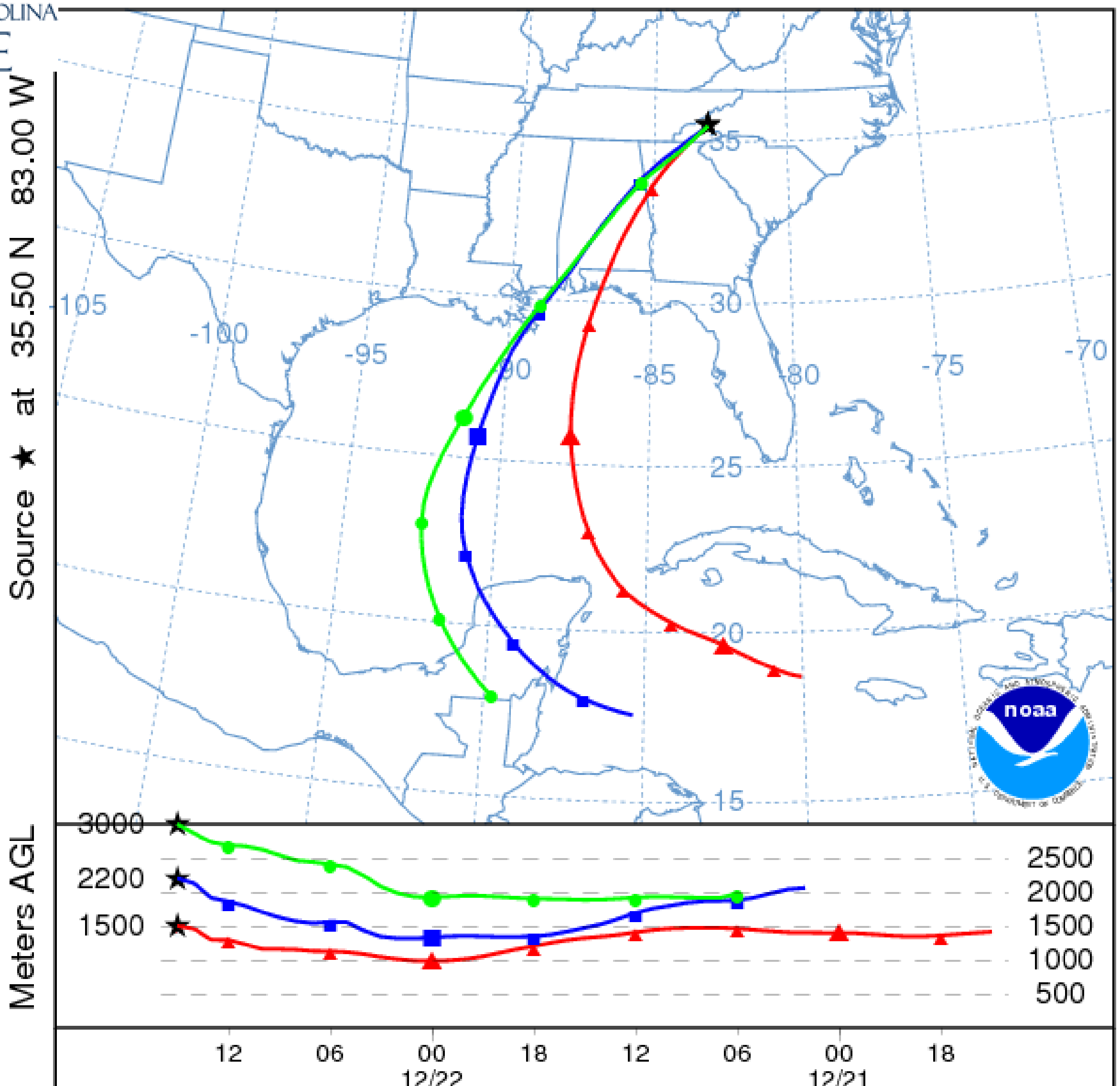


21- 24 December 2013 – UQ03

(moderate flooding)

NOAA - SPC

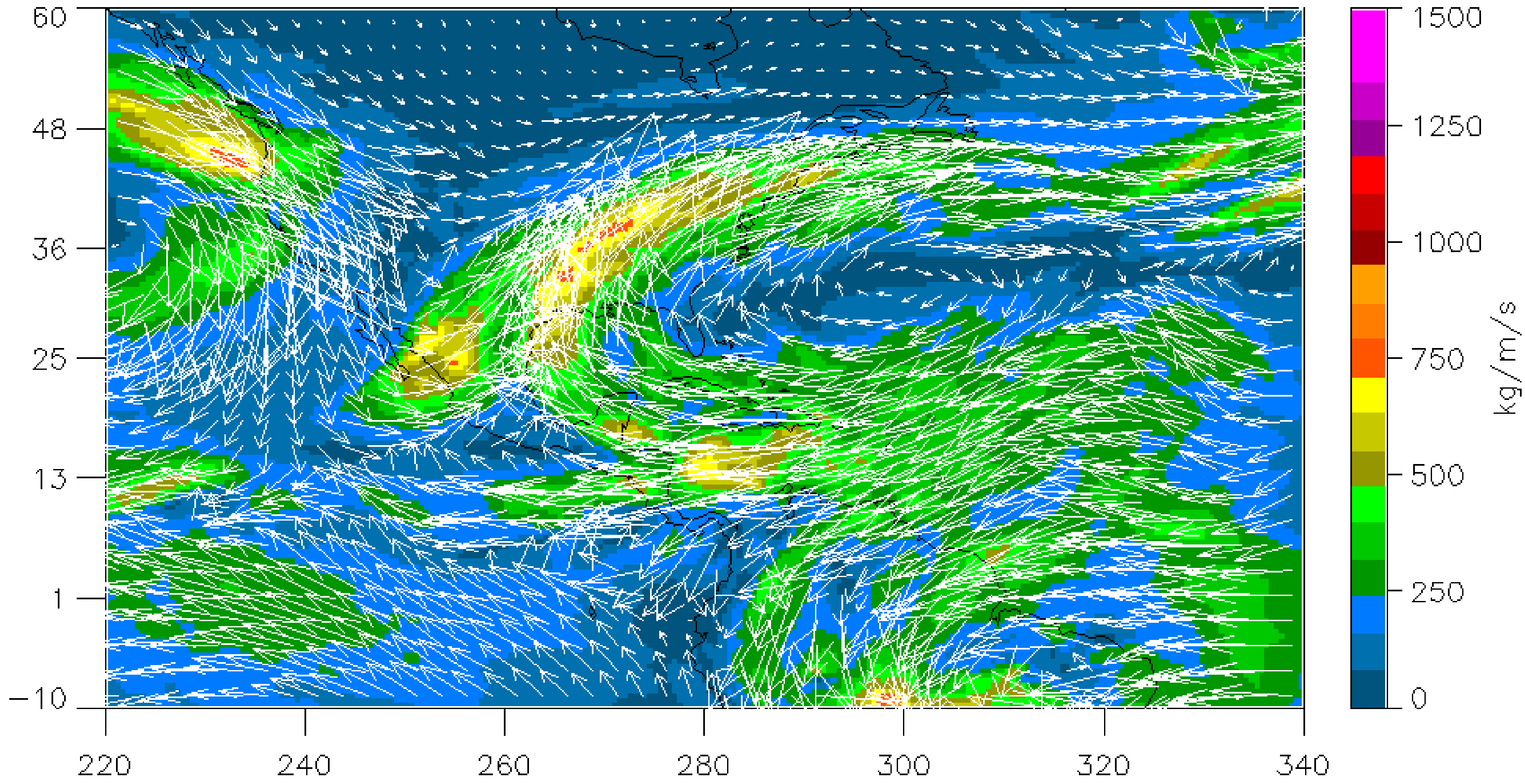
NOAA HYSPLIT MODEL
Backward trajectories ending at 1500 UTC 22 Dec 13
EDAS Meteorological Data



Job ID: 112174 Job Start: Thu Jul 14 19:15:45 UTC 2016
Source 1 lat.: 35.500000 lon.: -83.000000 hgts: 1500, 2200, 3000 m AGL

Trajectory Direction: Backward Duration: 48 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 16 Dec 2013 - EDAS40

Integrated Vapor Transport



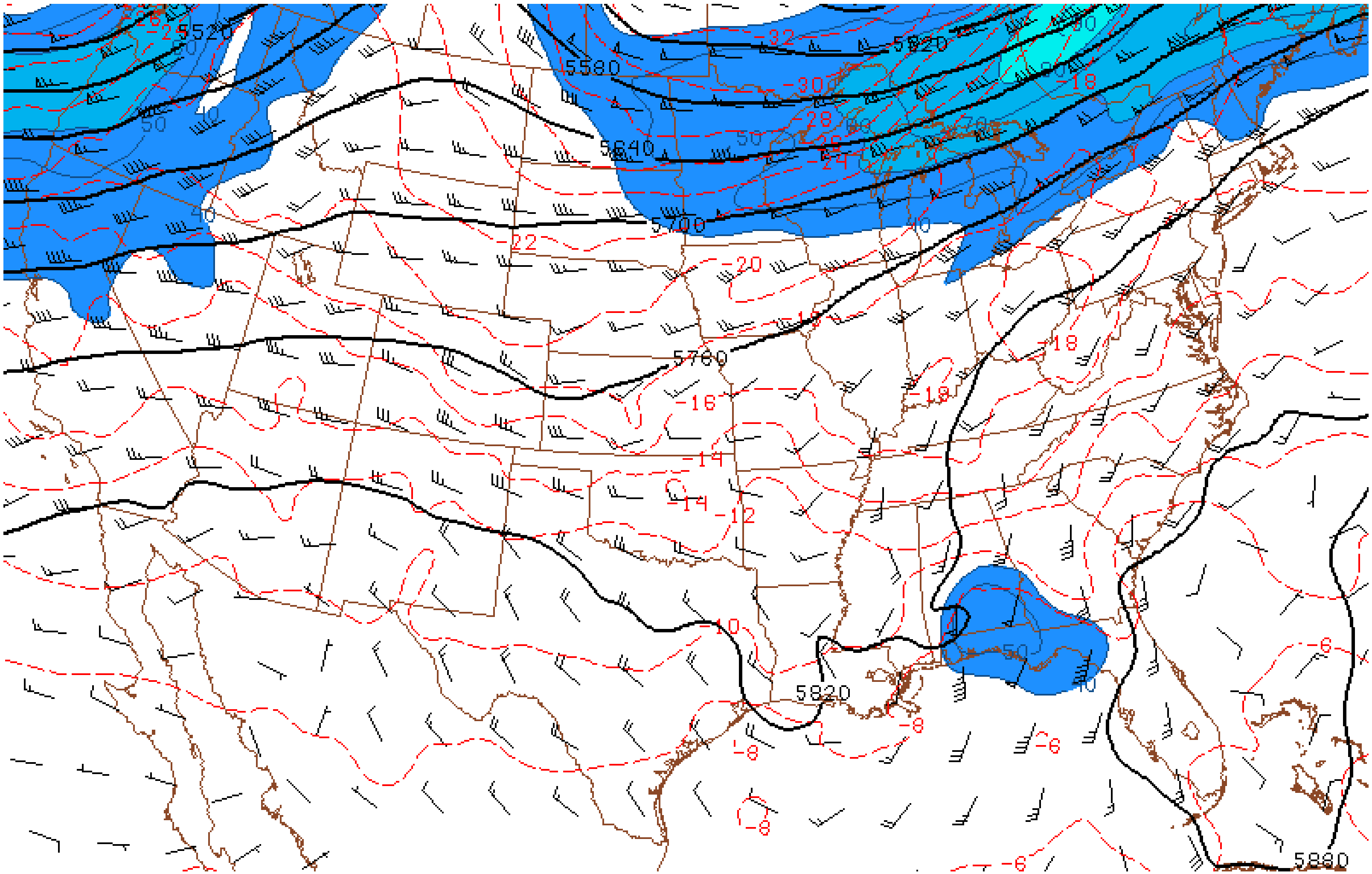
0000 UTC 21- 0600 UTC 24 December 2013 – UQ03

GFS gridded analyses

(moderate flooding)

NOAA - NOMADS

500 hPa level Geo Ht / Temp / WS

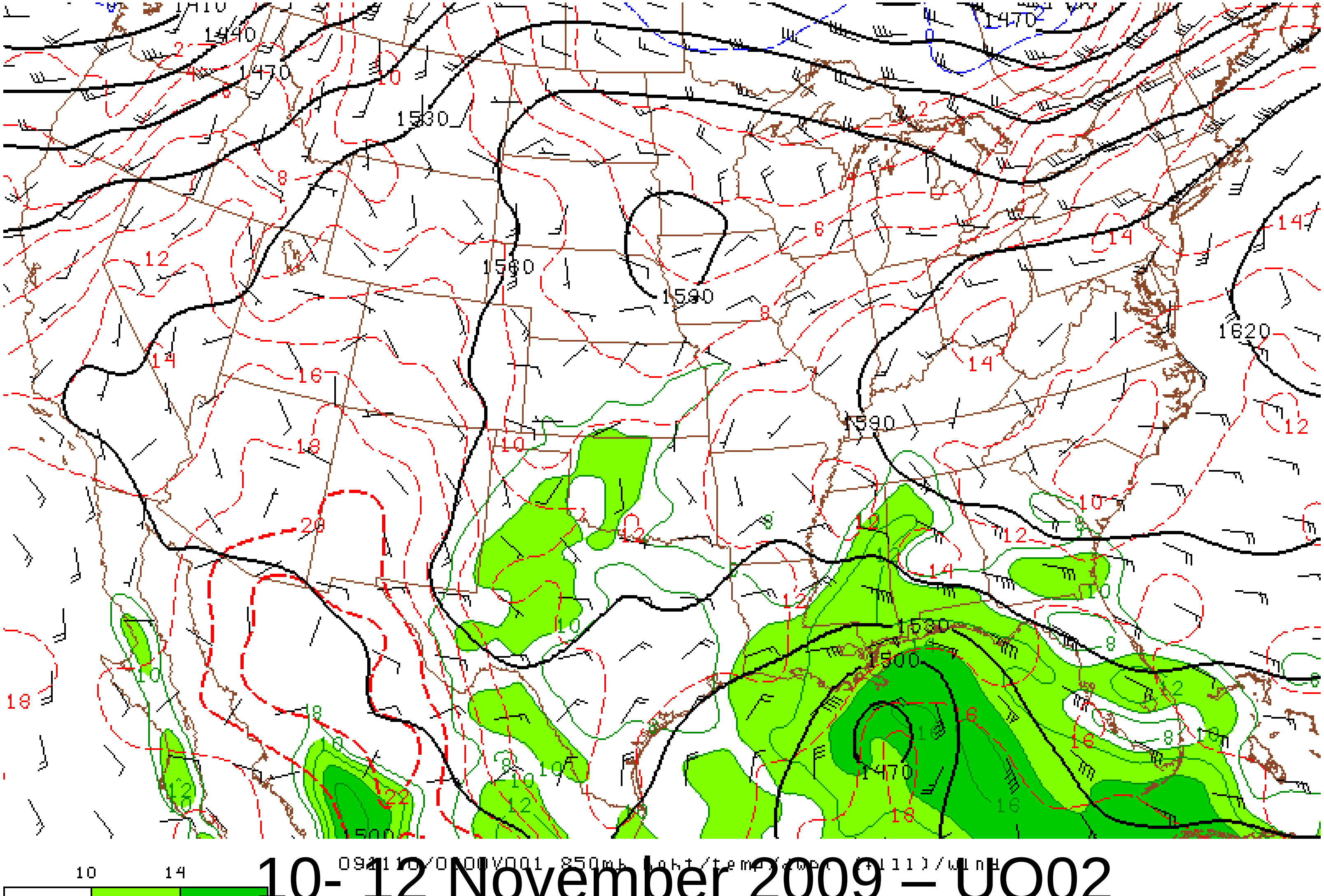


10- 12 November 2009 – UQ02

(moderate flooding)

NOAA - SPC

850 hPa level Geo Ht / Temp / Td



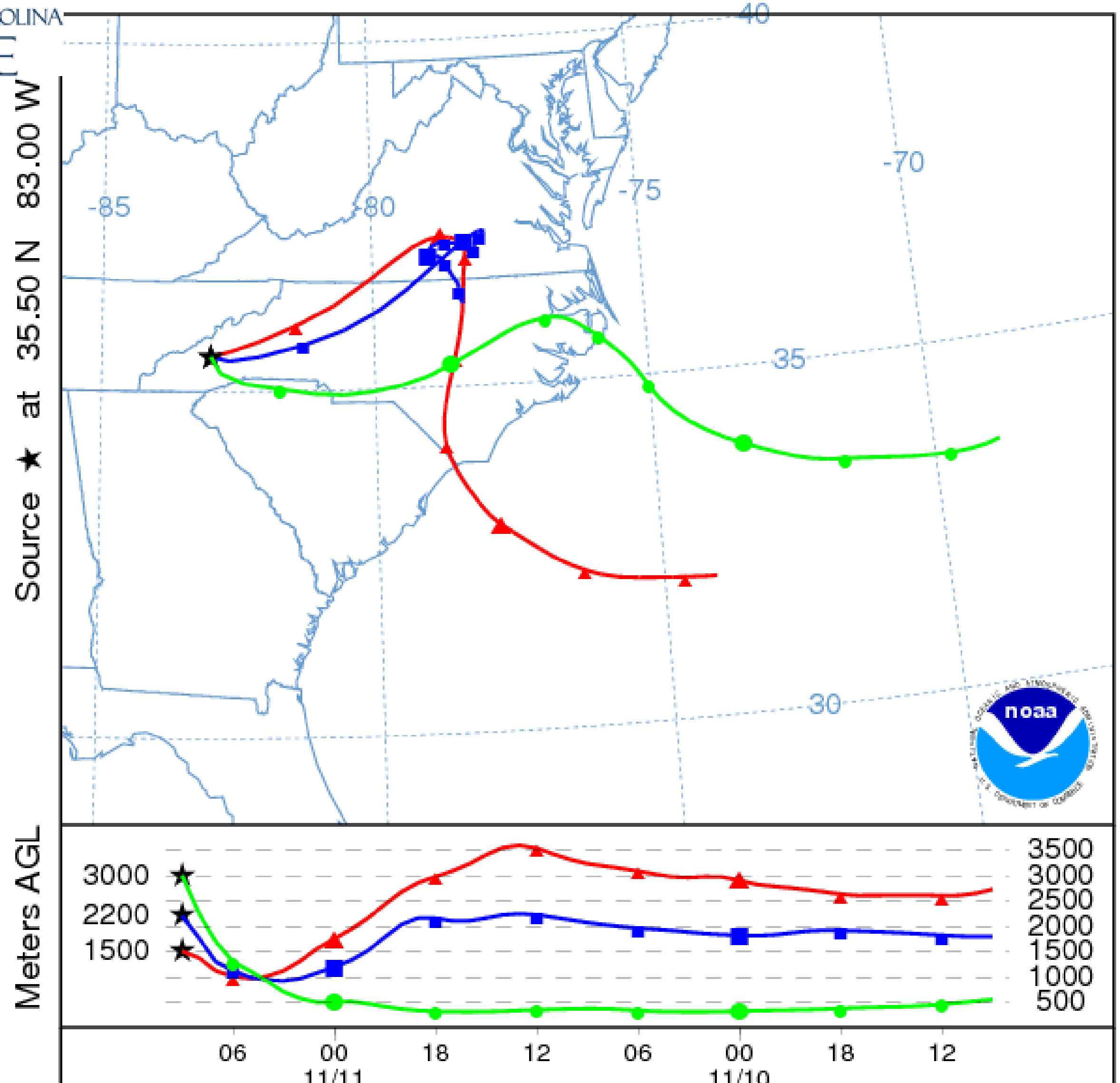
10- 12 November 2009 – UQ02

(moderate flooding)

NOAA - SPC

University of North Carolina Asheville

NOAA HYSPLIT MODEL
Backward trajectories ending at 0900 UTC 11 Nov 09
EDAS Meteorological Data



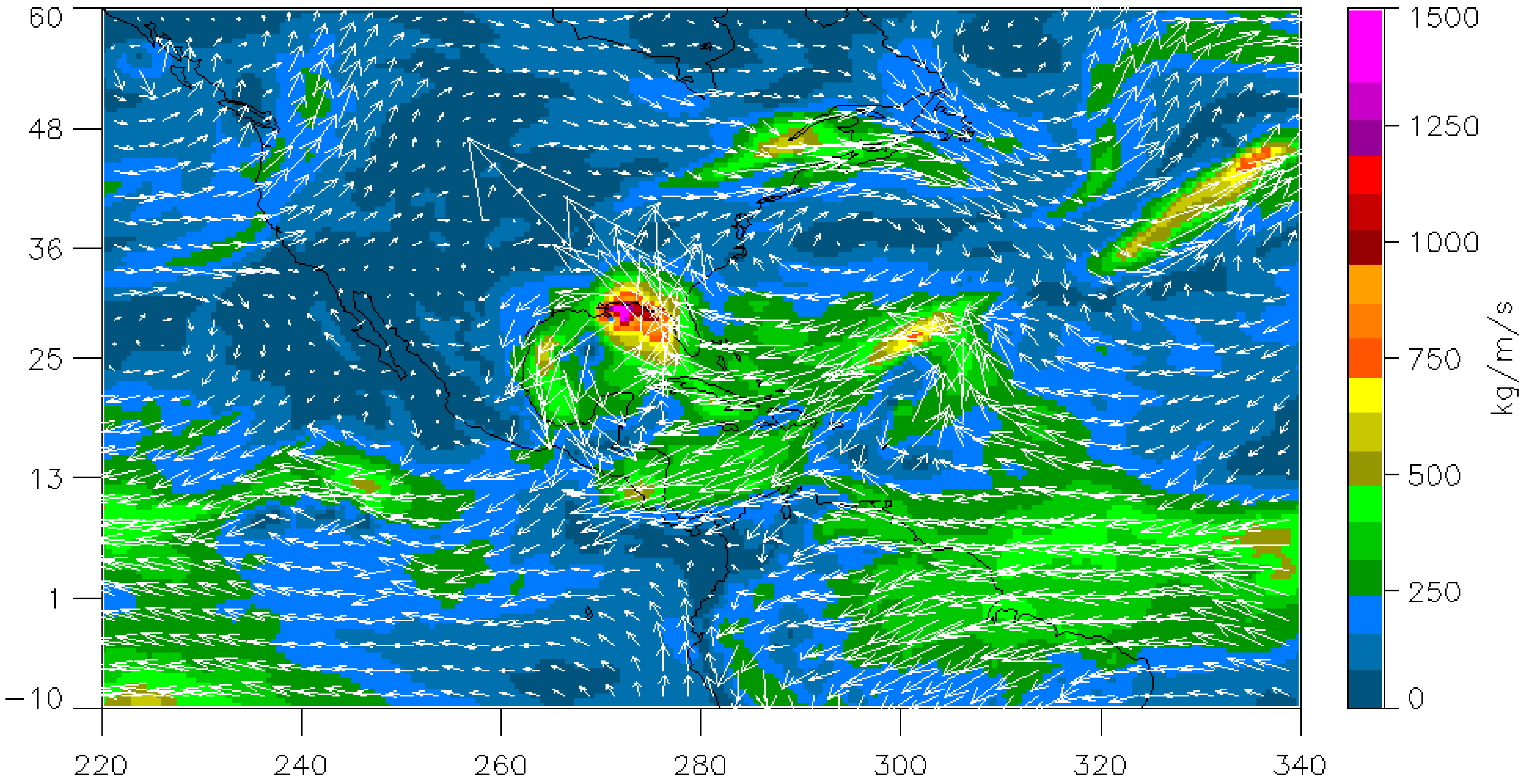
Job ID: 110409 Job Start: Thu Jul 14 18:12:29 UTC 2016
Source 1 lat.: 35.500000 lon.: -83.000000 hgts: 1500, 2200, 3000 m AGL

Trajectory Direction: Backward Duration: 48 hrs
Vertical Motion Calculation Method: Model Vertical Velocity
Meteorology: 0000Z 1 Nov 2009 - EDAS40

NATIONAL WEATHER SERVICE

noaa

Integrated Vapor Transport



0000 UTC 10- 1200 UTC 12 November 2009 – UQ02

(moderate flooding)

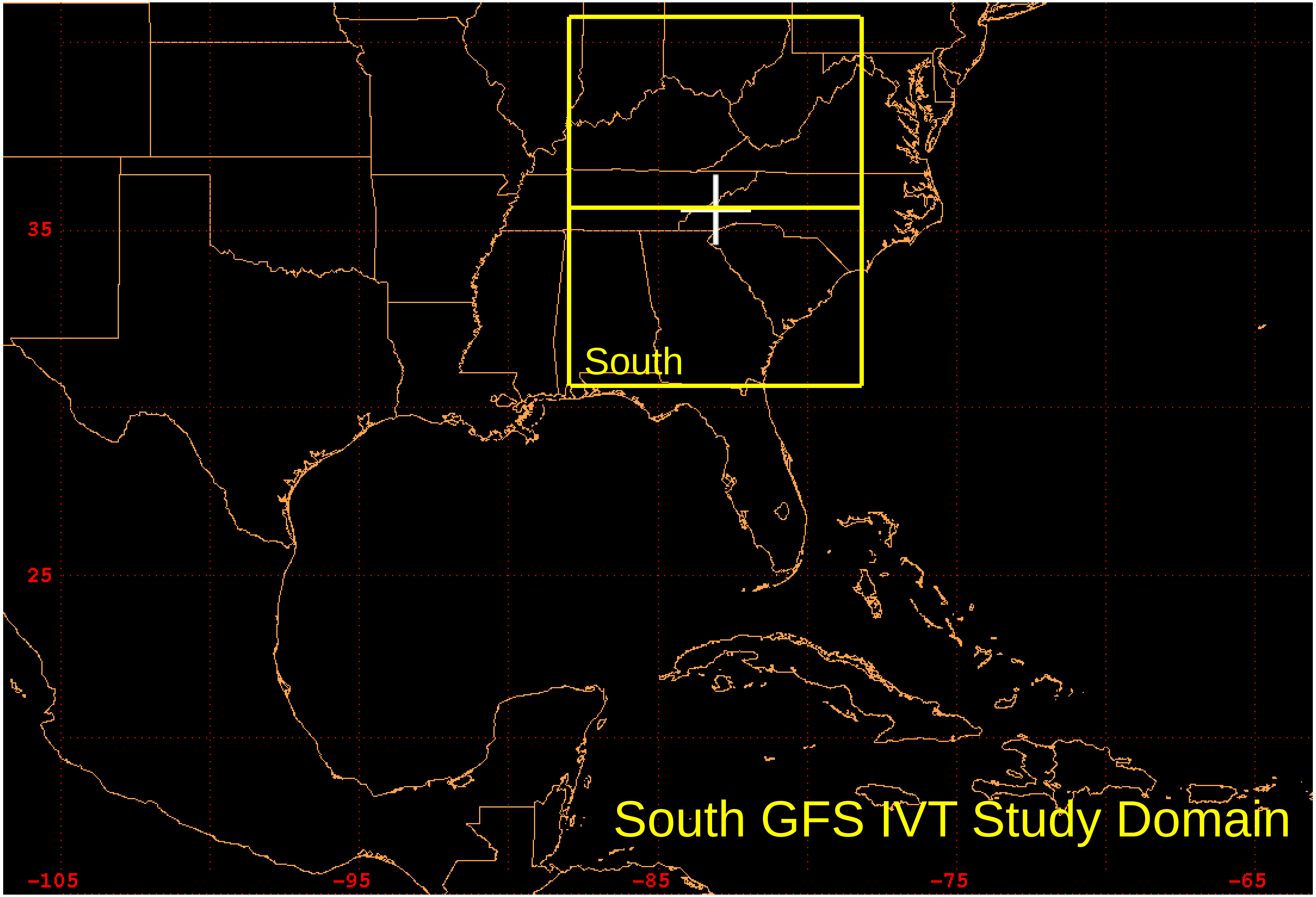
GFS gridded analyses

NOAA - NOMADS

Results

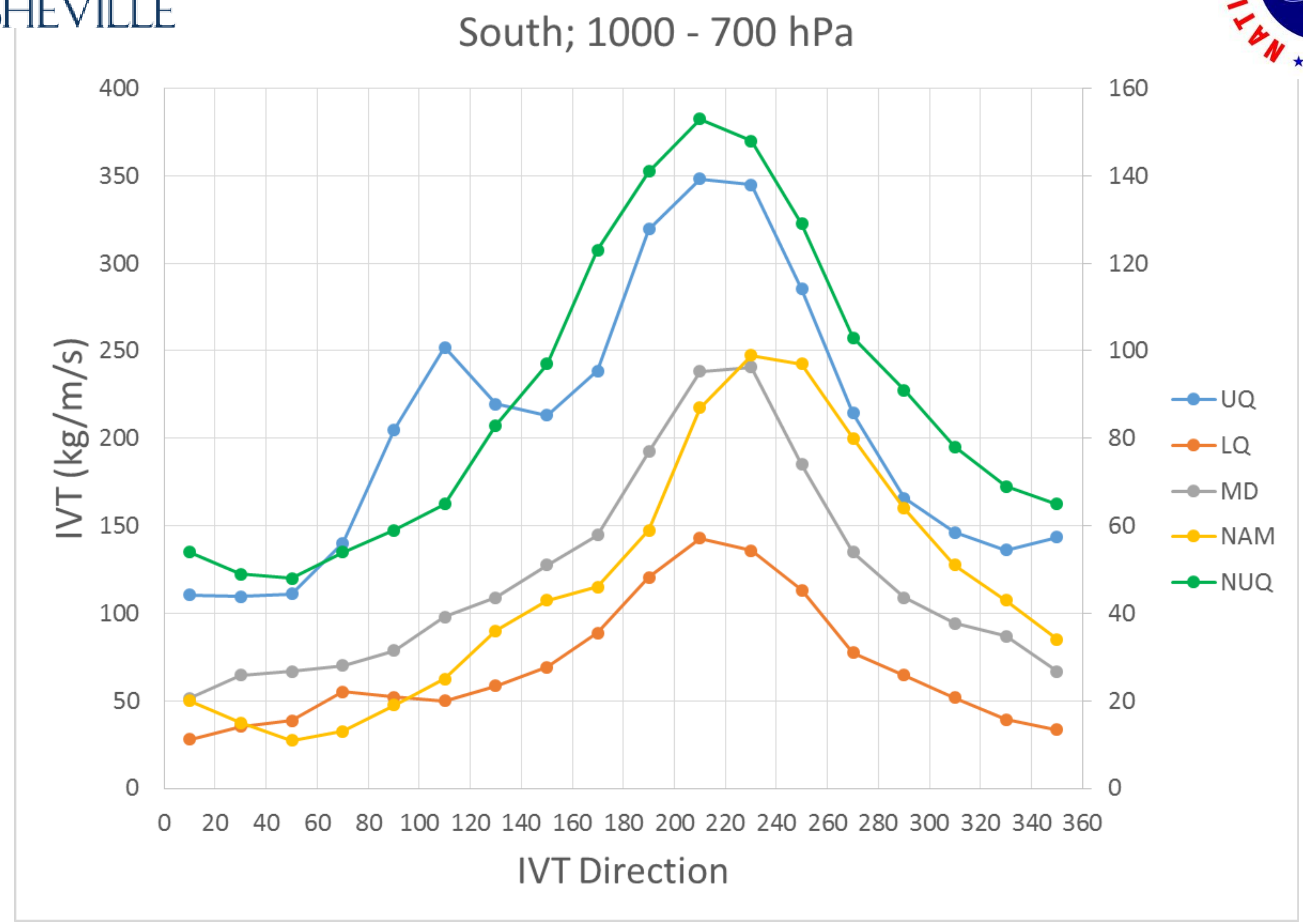
- GFS analysis-based IVT
  - 0.5^o x 0.5^o

GFS IVT Results



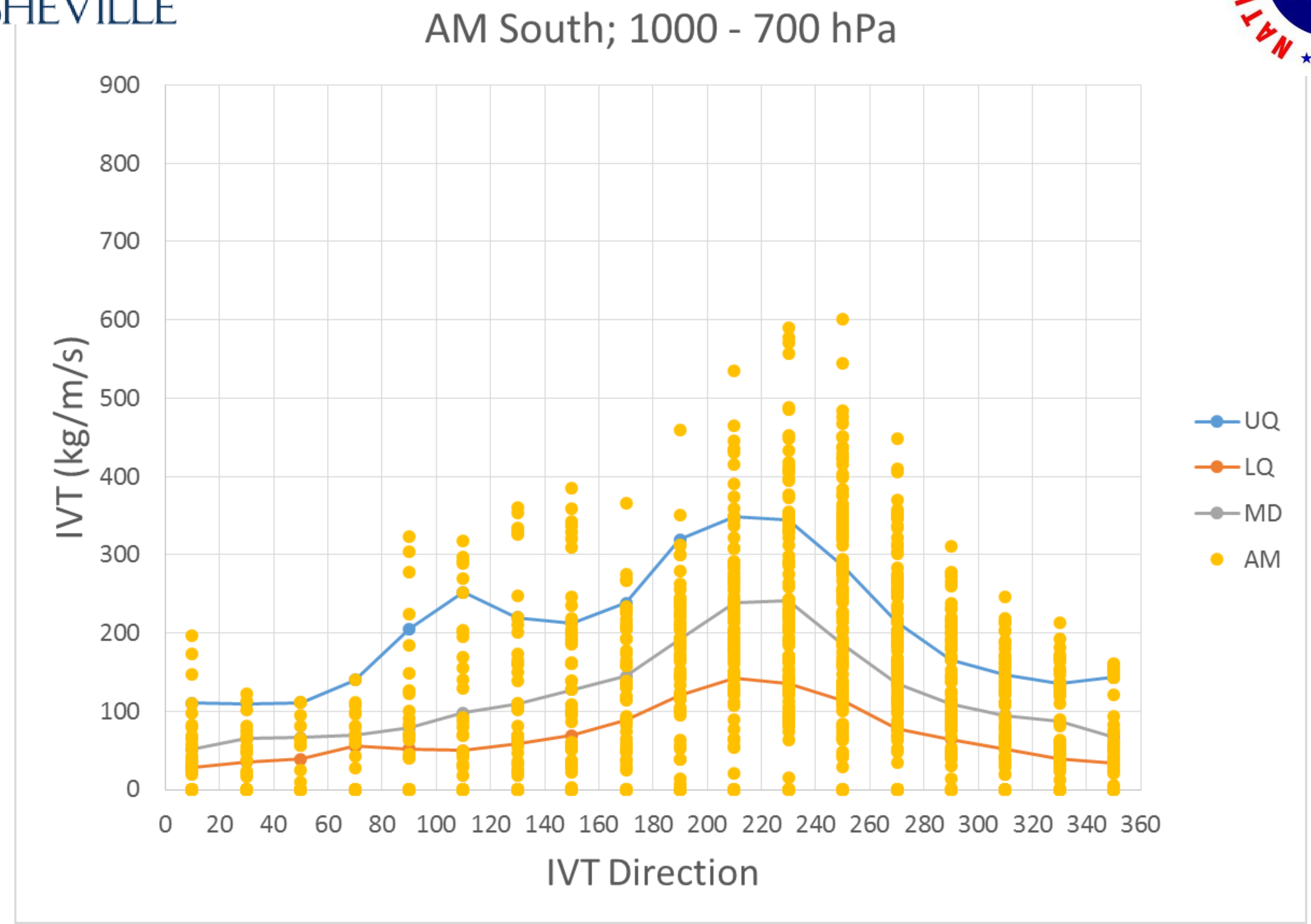
		Starting			(EDT)			#GFS grid points	GFS event Σ IVT	
	Case	Year	Month	Day	Hour	Minute	Δt (h)	IVT ≥ 500 $kg\ m^{-1}\ s^{-1}$	($kg\ m^{-1}\ s^{-1}$)	AR
	AM15	2009	9	16	4	34	14.20	51	141568	No
	AM14	2011	8	13	10	27	32.45	20	19279	No
	AM13	2009	8	12	0	40	16.02	10	7249	No
	AM12	2010	5	30	23	34	30.95	7	286995	Possible
	AM11	2012	5	9	3	33	17.64	64	31449	No
	AM10	2009	10	9	17	6	38.26	716	117446	Possible
AM	**AM09**	2009	8	20	12	8	48.39	198	109145	No
	AM08	2009	7	29	21	7	46.30	1204	66945	No
	AM07	2011	2	24	21	33	13.87	473	164982	Possible
	AM06	2012	3	12	5	39	32.52	44	183553	Possible
	AM05	2009	8	1	19	54	20.66	356	44215	No
	AM04	2012	2	29	1	33	32.42	830	130844	Possible
	AM03	2014	2	4	19	32	24.00	501	223208	Possible
	AM02	2012	11	12	3	51	24.97	85	218196	Possible
	AM01	2013	7	13	22	39	31.74	457	506492	No
	UQ17	2013	9	24	22	44	33.59	0	107645	No
	UQ16	2013	5	2	21	15	83.81	115	659672	No
	UQ15	2011	11	14	11	36	80.51	1023	336253	Possible
	UQ14	2010	1	23	19	50	44.55	705	463696	Possible
	UQ13	2013	4	27	2	20	49.95	138	242312	No
	UQ12	2011	11	27	20	29	28.85	577	419234	Possible
	UQ11	2011	3	5	6	28	37.17	"msg"	"msg"	Possible
	UQ10	2012	10	1	0	28	38.28	907*	501387*	Possible
UQ	**UQ09**	2013	1	29	17	15	33.81	845	525936	Possible
	UQ08	2013	11	25	21	56	31.80	653	369902	Possible
	UQ07	2012	4	17	13	10	43.02	0	145435	Possible
	UQ06	2010	11	29	14	50	39.38	927	546644	Possible
	UQ05	2012	9	17	4	7	48.09	807	397522	Possible
	UQ04	2011	12	5	19	39	46.38	689	387974	Possible
	UQ03	2013	12	21	4	24	62.68	1516	708028	Possible
	UQ02	2009	11	10	2	58	54.86	413	425881	No
	UQ01	2013	1	13	20	8	95.32	1330	561286	Possible

GFS IVT Results



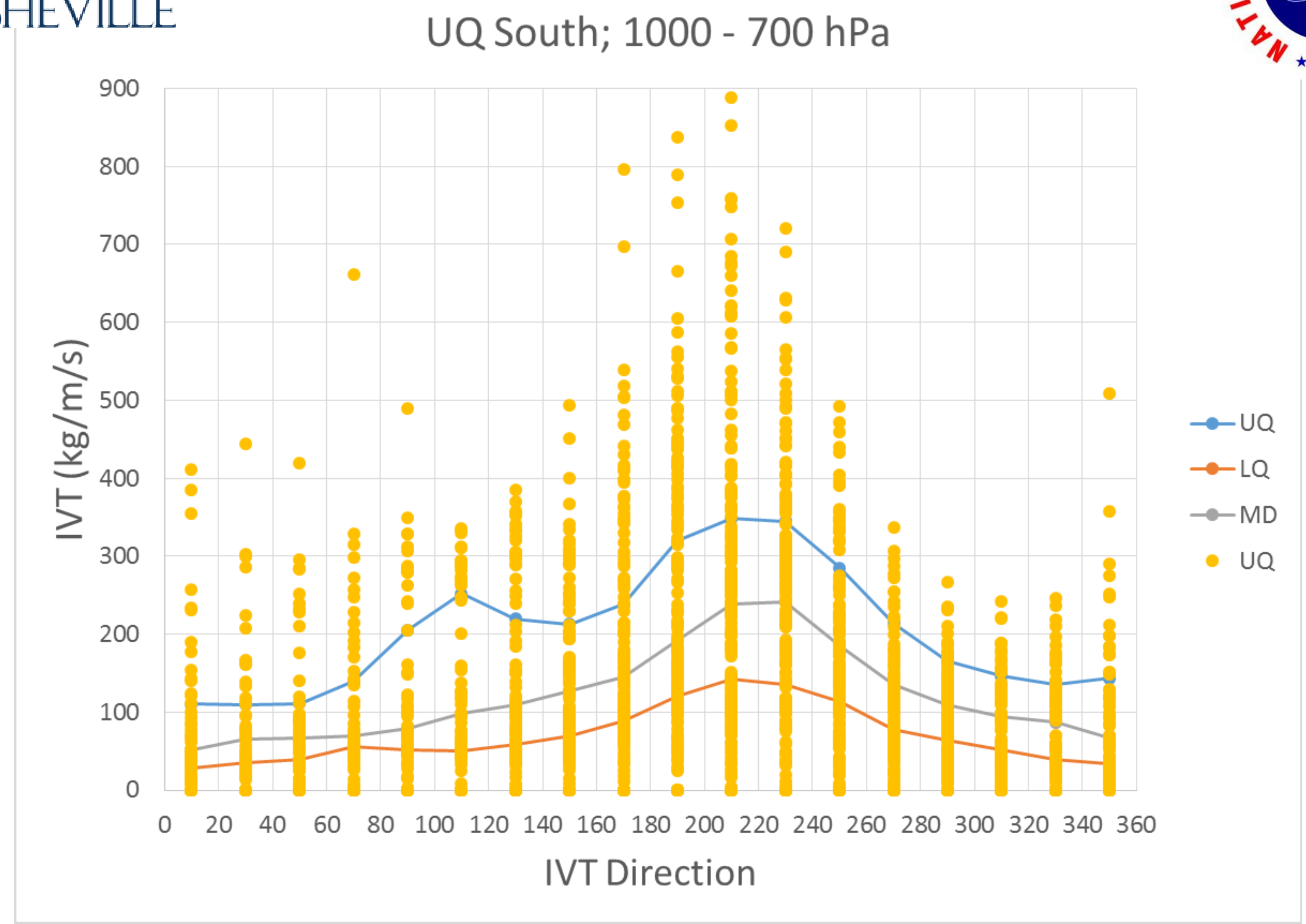
GFS IVT Results

AM

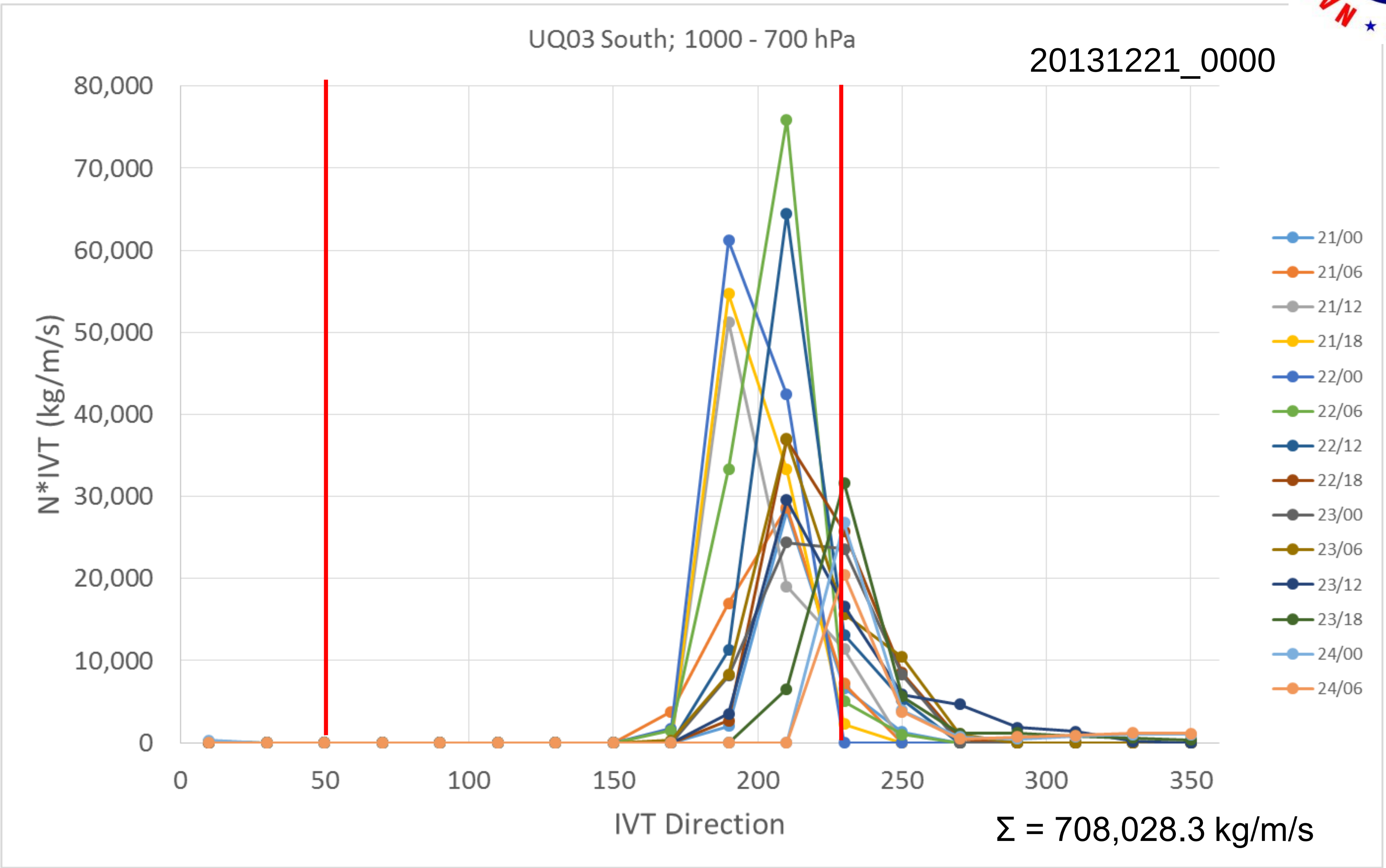


GFS IVT Results

UQ

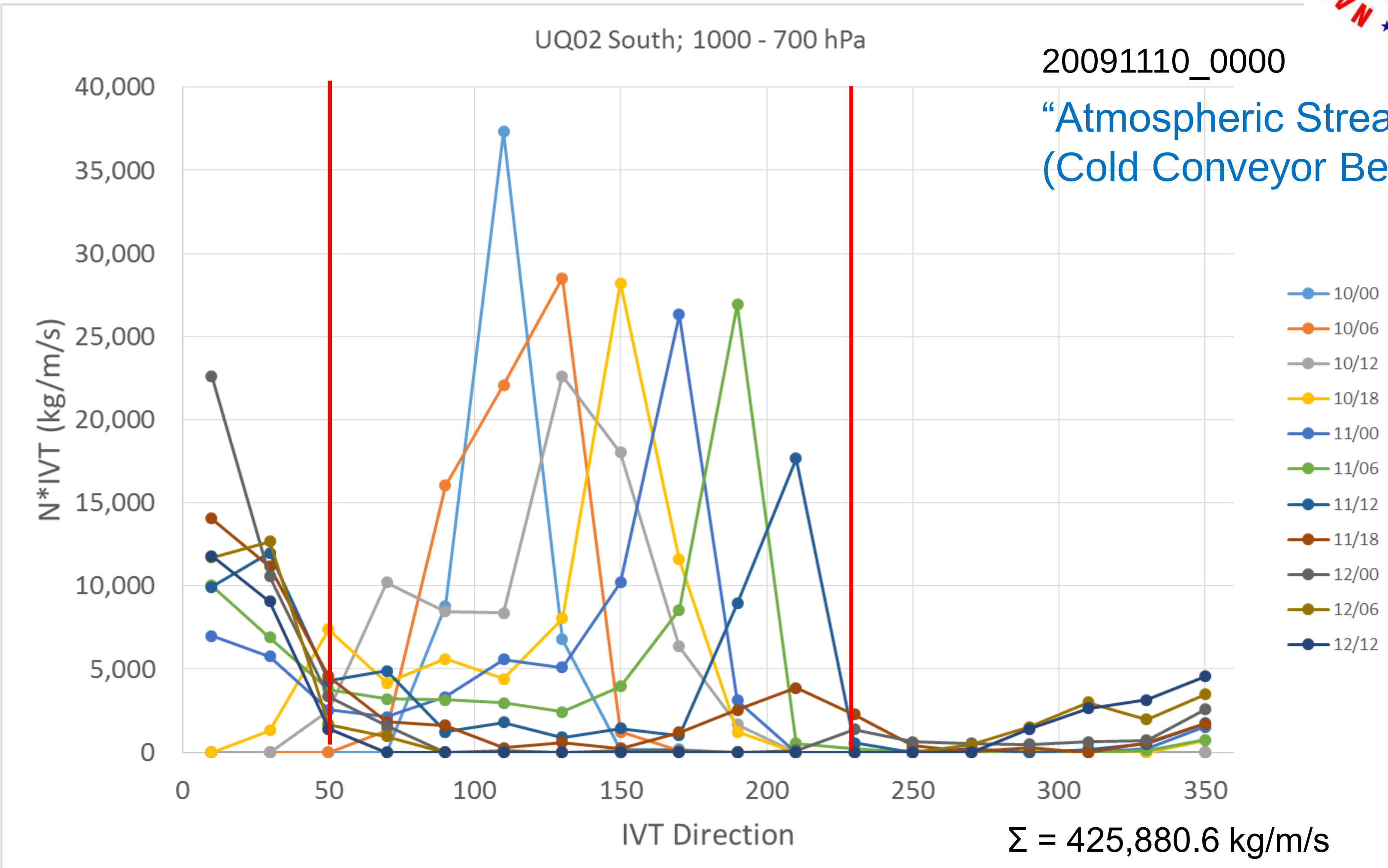


GFS IVT Results



0000 UTC 21- 0600 UTC 24 December 2013 – UQ03

GFS IVT Results

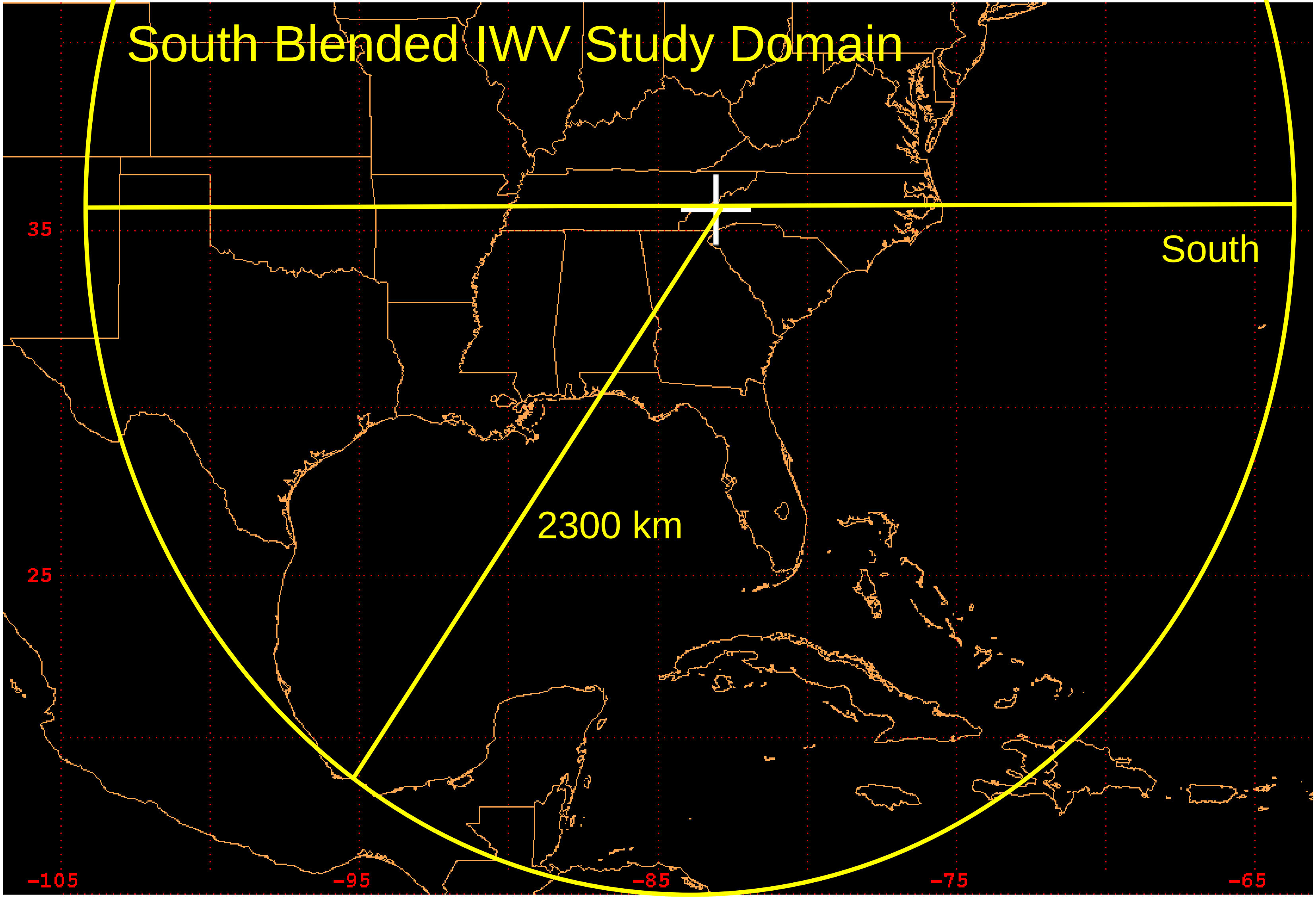


0000 UTC 10- 1200 UTC 12 November 2009 – UQ02

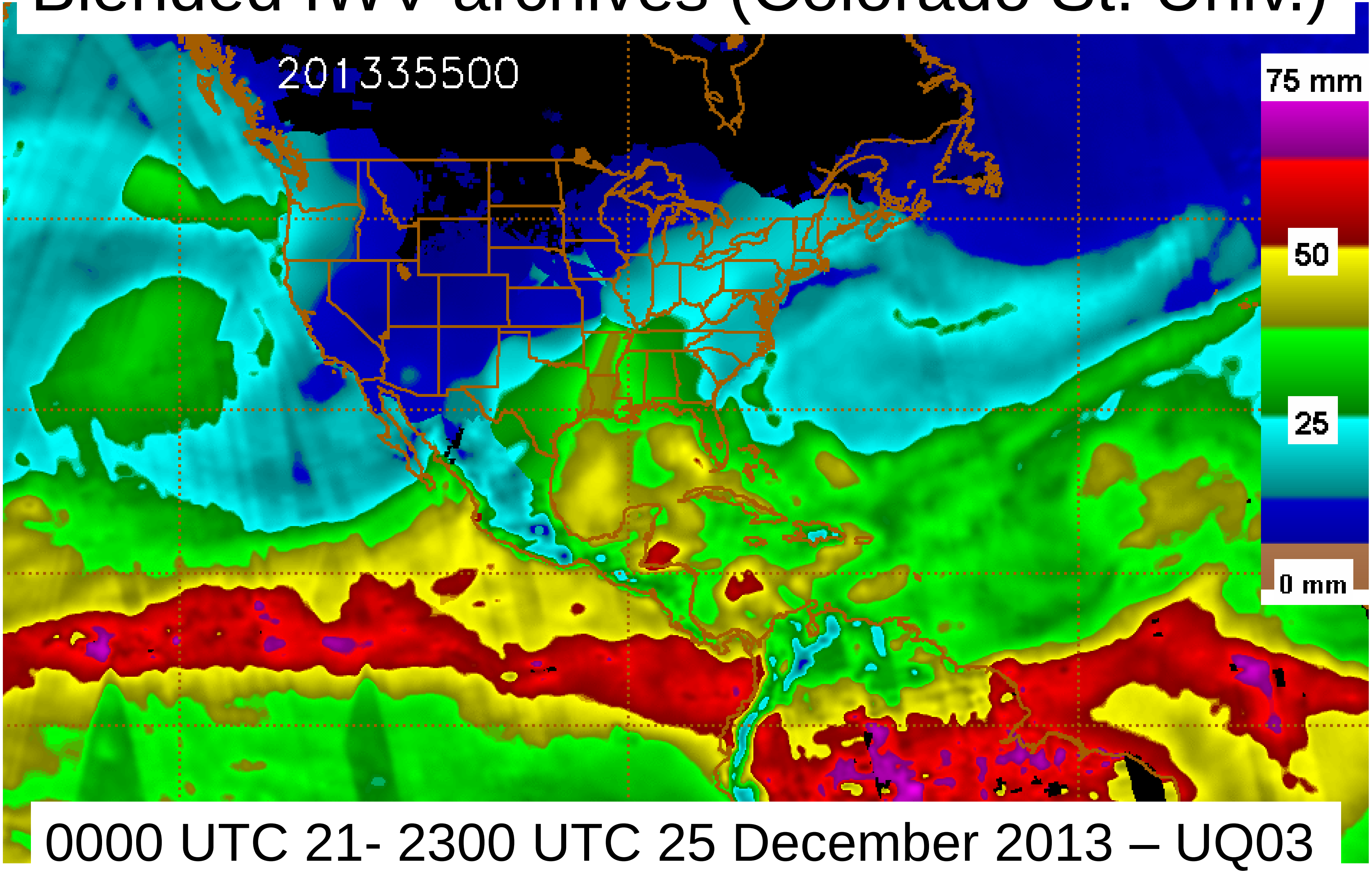
Results

- Satellite observations
  - Blended IWV (CIRA-Colorado State University); 16 km x 16 km grid

Satellite Obs



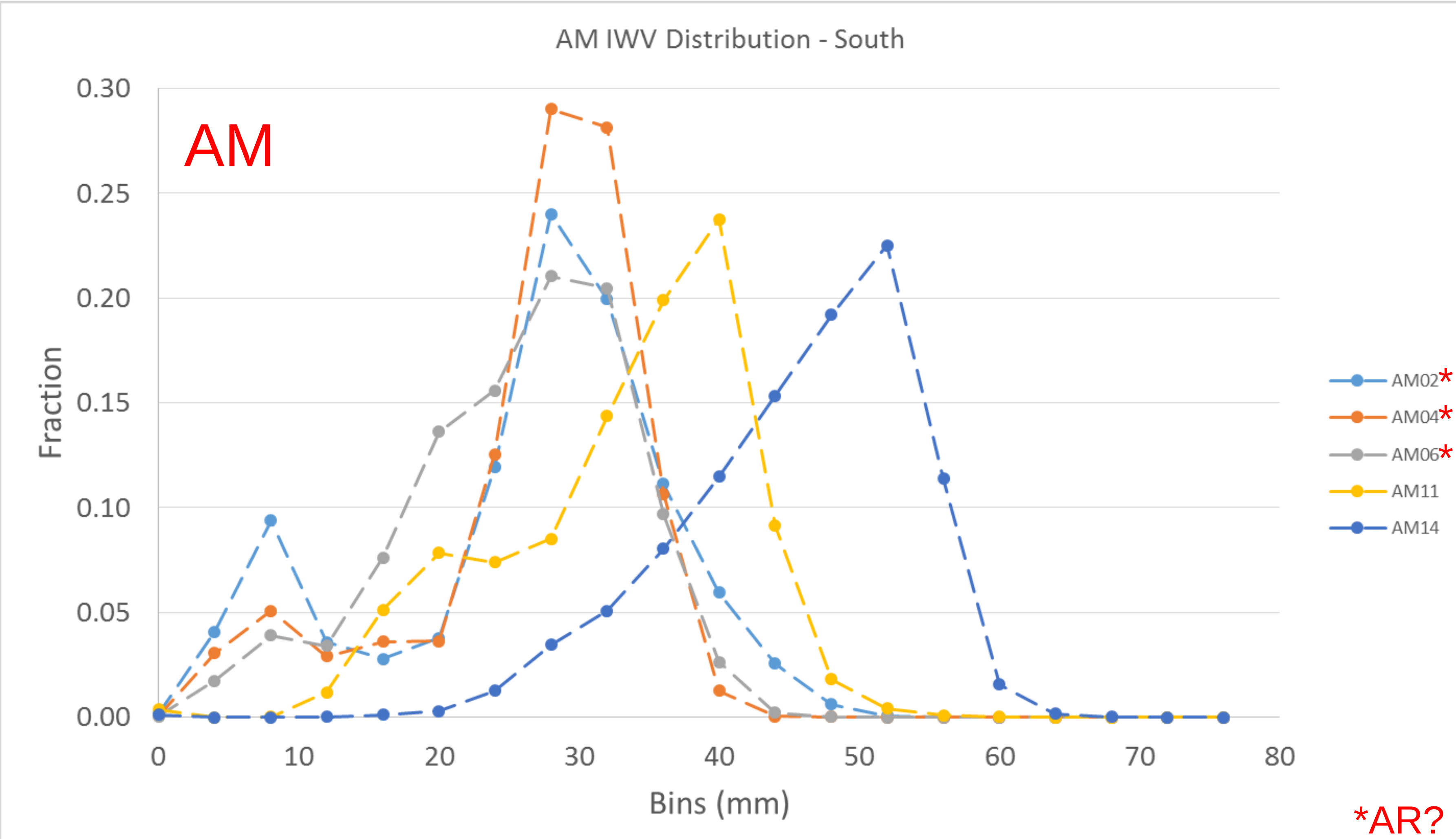
Blended IWV archives (Colorado St. Univ.)



0000 UTC 21- 2300 UTC 25 December 2013 – UQ03

(355) (359)

Satellite Obs

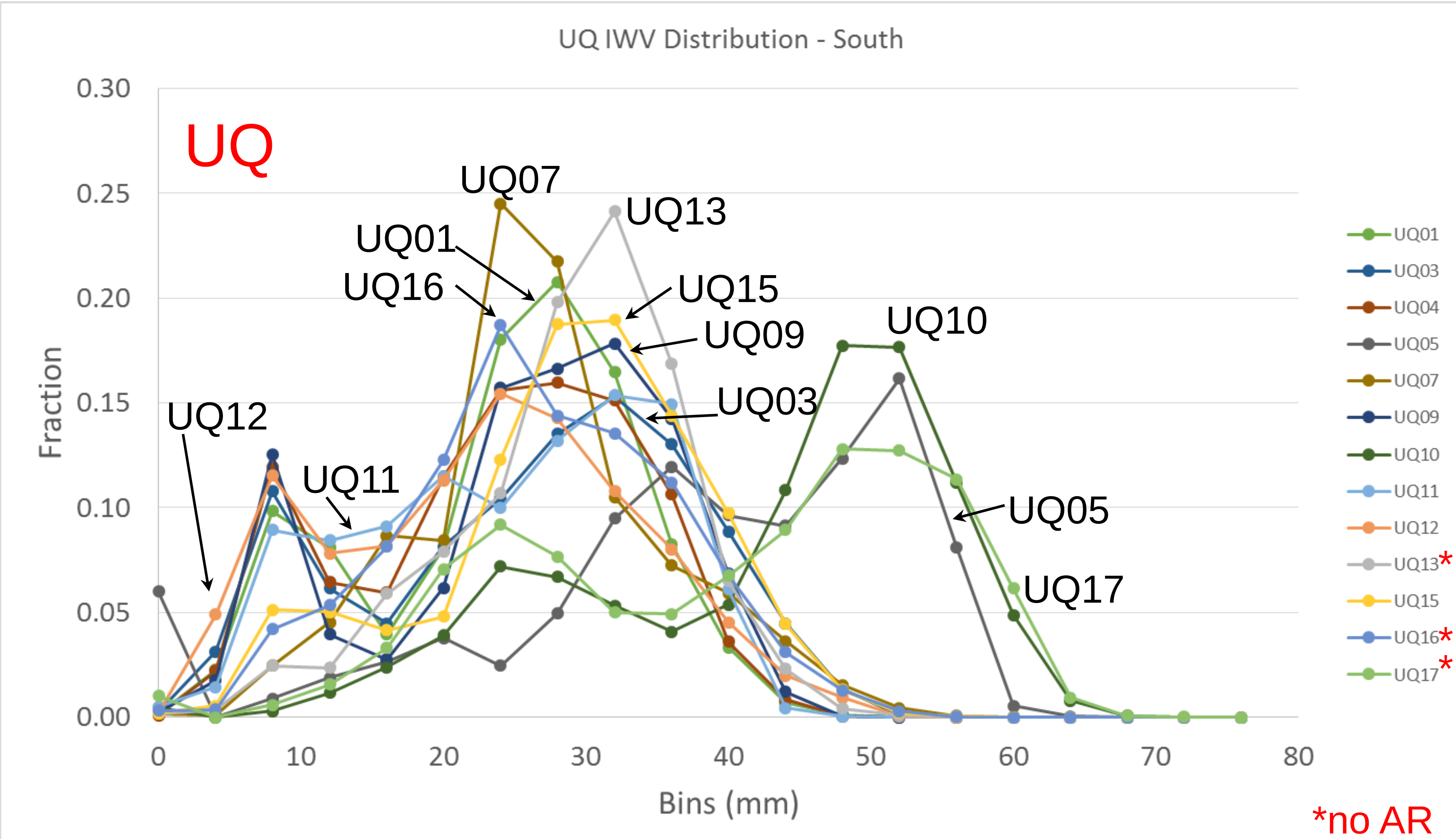


Blended IWV archives (Colorado St. Univ.)

		Starting			(EDT)					
	Case	Year	Month	Day	Hour	Minute	Δt (h)	USGS gauge	Storm Data	AR
	AM15	2009	9	16	4	34	14.20	None	Flooding (TN)	No
	AM14	2011	8	13	10	27	32.45	None	Flooding (NC)*	No
	AM13	2009	8	12	0	40	16.02	None	None	No
	AM12	2010	5	30	23	34	30.95	None	Flooding (NC)	Possible
	AM11	2012	5	9	3	33	17.64	None	None	No
	AM10	2009	10	9	17	6	38.26	None	None	Possible
AM	**AM09**	2009	8	20	12	8	48.39	None	Flooding (NC)*	No
	AM08	2009	7	29	21	7	46.30	None	None	No
	AM07	2011	2	24	21	33	13.87	Action stage	None	Possible
	AM06	2012	3	12	5	39	32.52	Action stage	None	Possible
	AM05	2009	8	1	19	54	20.66	None	Flooding (NC)*	No
	AM04	2012	2	29	1	33	32.42	None	None	Possible
	AM03	2014	2	4	19	32	24.00	Action stage	None	Possible
	AM02	2012	11	12	3	51	24.97	None	None	Possible
	AM01	2013	7	13	22	39	31.74	Action stage	Flooding (NC)	No
	UQ17	2013	9	24	22	44	33.59	None	None	No
	UQ16	2013	5	2	21	15	83.81	Moderate flooding	Flooding (NC)	No
	UQ15	2011	11	14	11	36	80.51	None	None	Possible
	UQ14	2010	1	23	19	50	44.55	Major flooding	Flooding (NC)	Possible
	UQ13	2013	4	27	2	20	49.95	Action stage	Flooding (TN)	No
	UQ12	2011	11	27	20	29	28.85	Moderate flooding	Flooding (NC)	Possible
	UQ11	2011	3	5	6	28	37.17	Minor flooding	Flooding (NC)	Possible
	UQ10	2012	10	1	0	28	38.28	None	Flooding (TN)	Possible
UQ	**UQ09**	2013	1	29	17	15	33.81	Major flooding	Flooding (NC)	Possible
	UQ08	2013	11	25	21	56	31.80	Minor flooding	None	Possible
	UQ07	2012	4	17	13	10	43.02	Action stage	None	Possible
	UQ06	2010	11	29	14	50	39.38	Minor flooding	Flooding (TN, NC)	Possible
	UQ05	2012	9	17	4	7	48.09	Minor flooding	Flooding (TN, NC)	Possible
	UQ04	2011	12	5	19	39	46.38	Major flooding	Flooding (TN)	Possible
	UQ03	2013	12	21	4	24	62.68	Moderate flooding	Flooding (NC)	Possible
	UQ02	2009	11	10	2	58	54.86	Moderate flooding	Flooding (NC)	No
	UQ01	2013	1	13	20	8	95.32	Major flooding	Flooding (TN, NC)	Possible

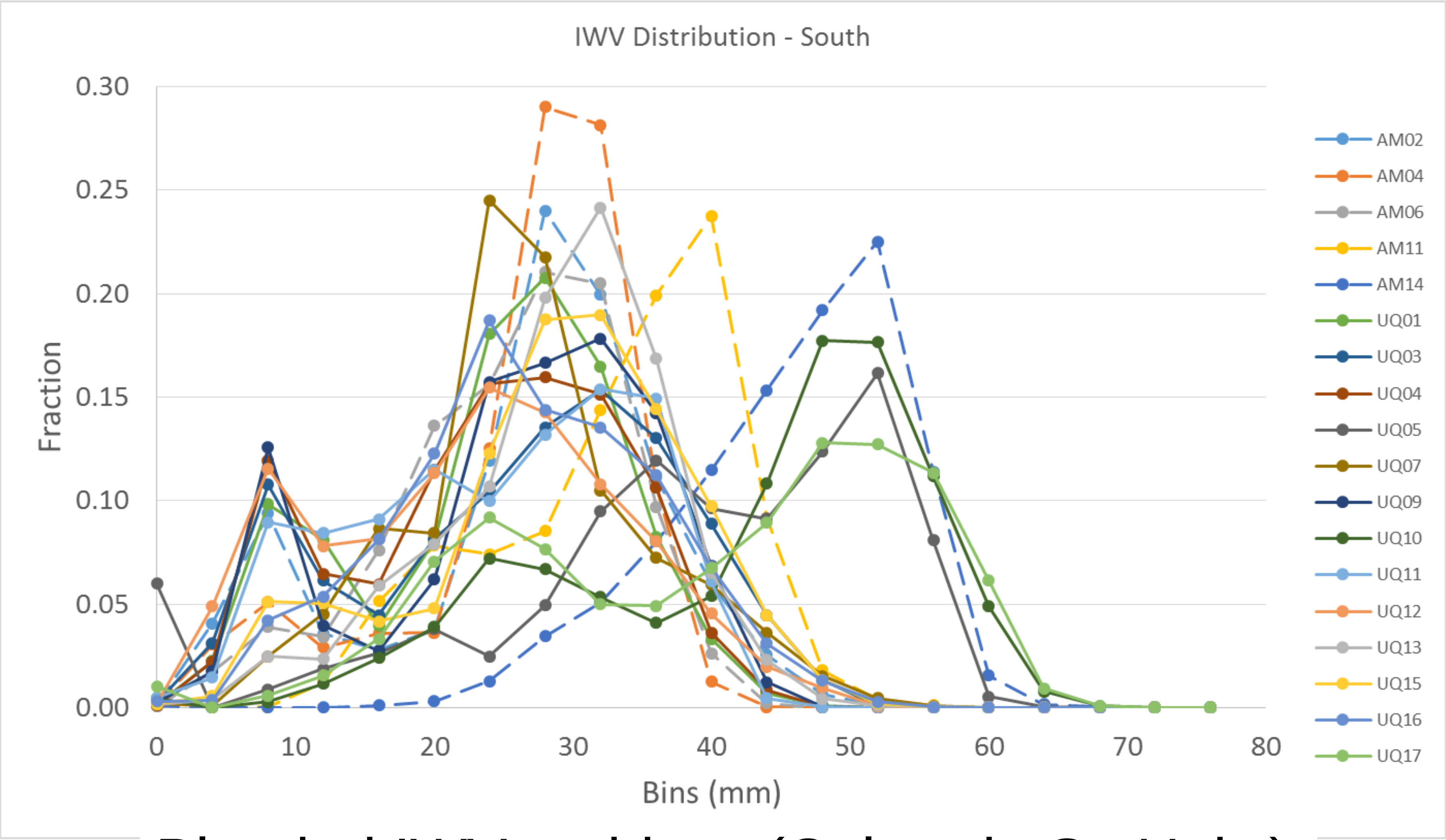
*mesoscale

Satellite Obs



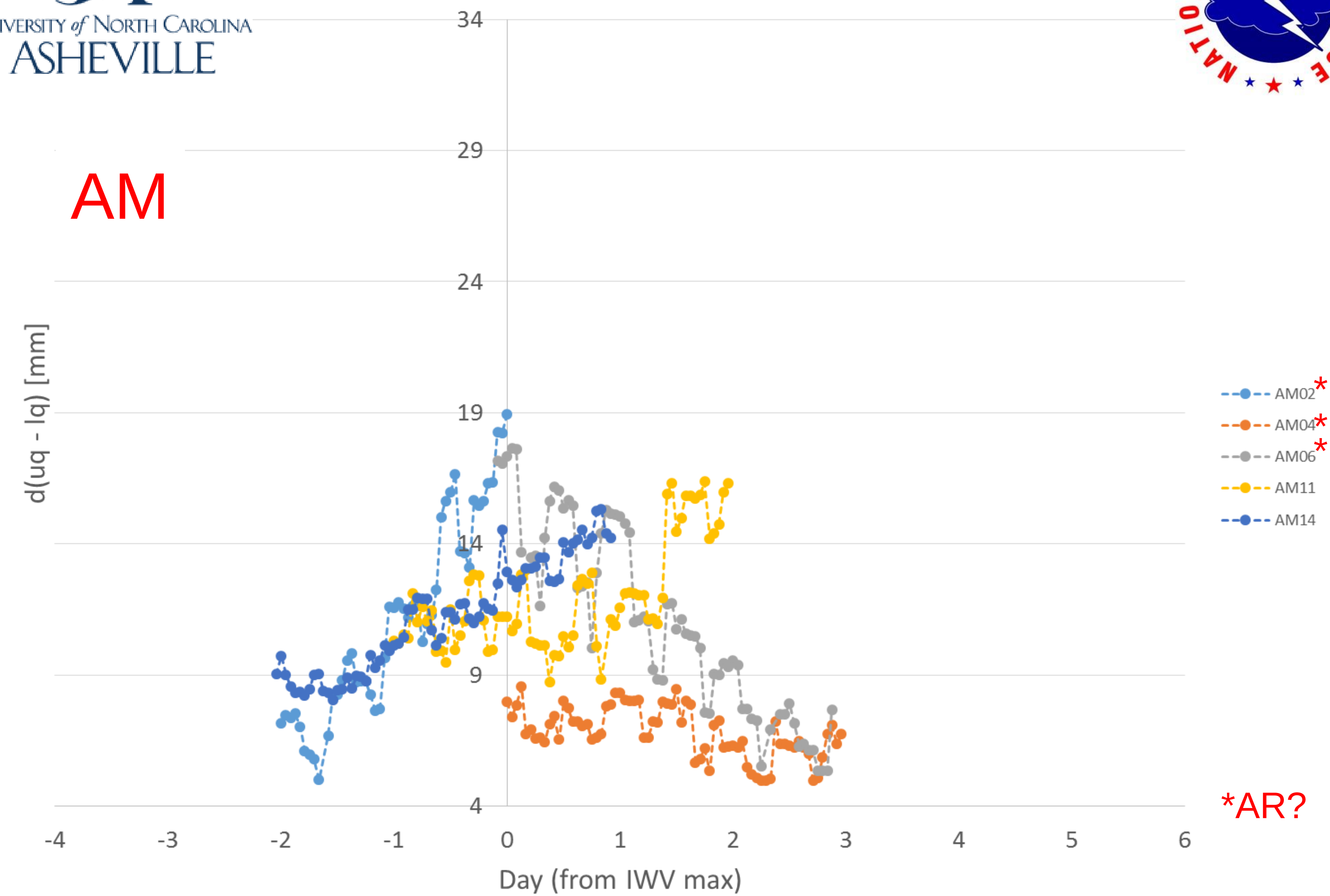
Blended IWV archives (Colorado St. Univ.)

Satellite Obs

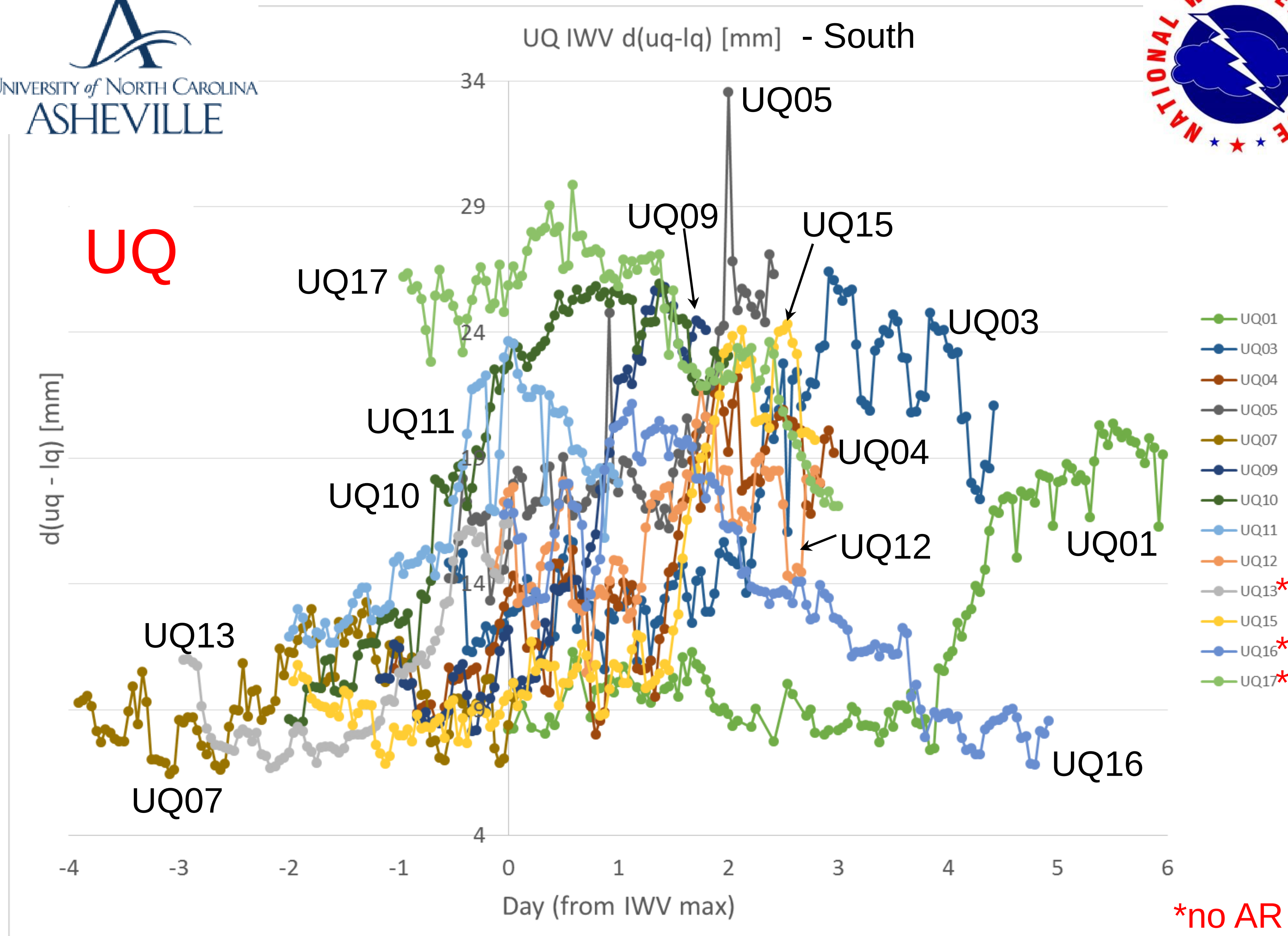


Blended IWV archives (Colorado St. Univ.)

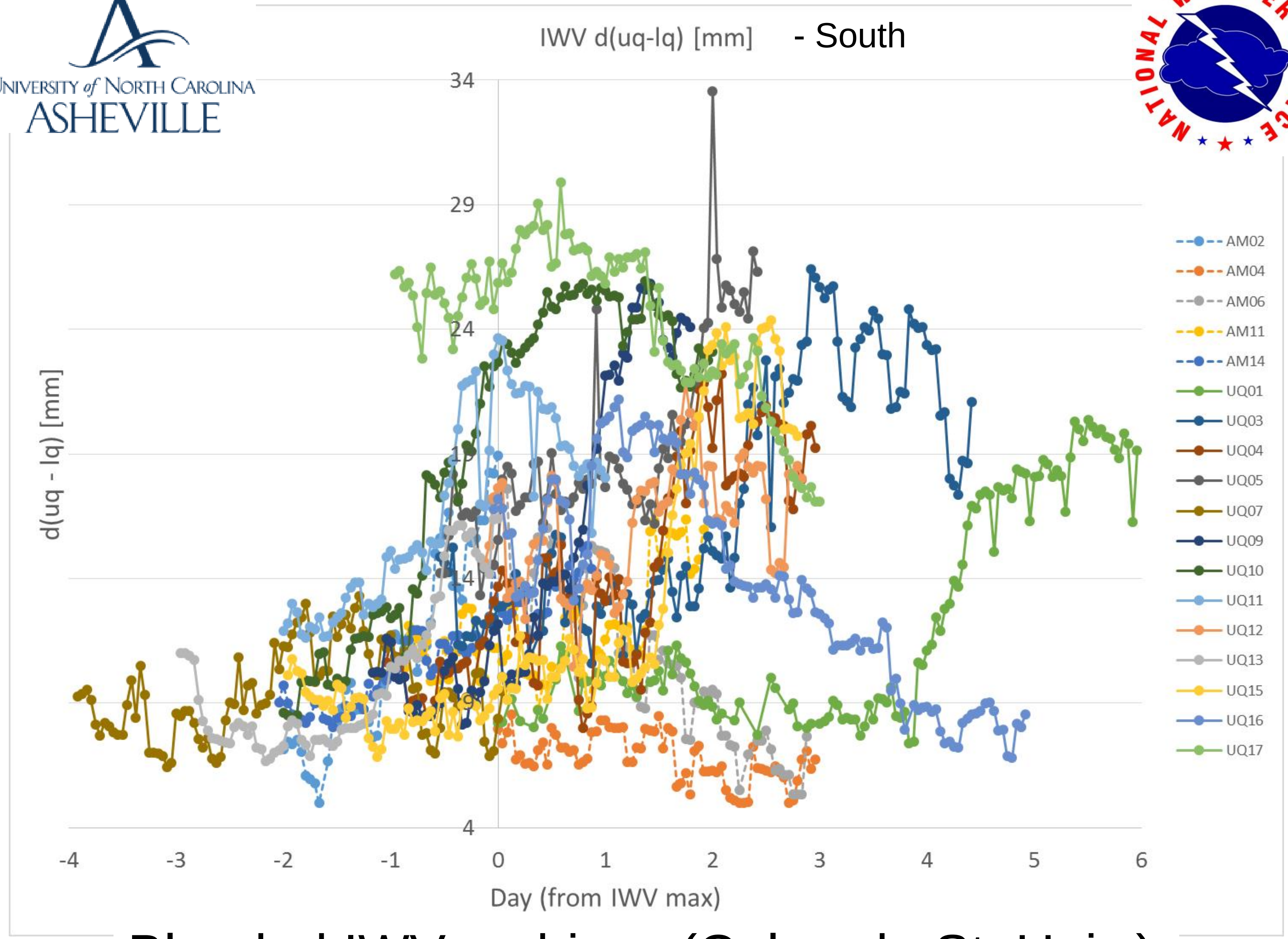
AM IWV d(uq-lq) [mm] - South



Blended IWV archives (Colorado St. Univ.)



Blended IWV archives (Colorado St. Univ.)



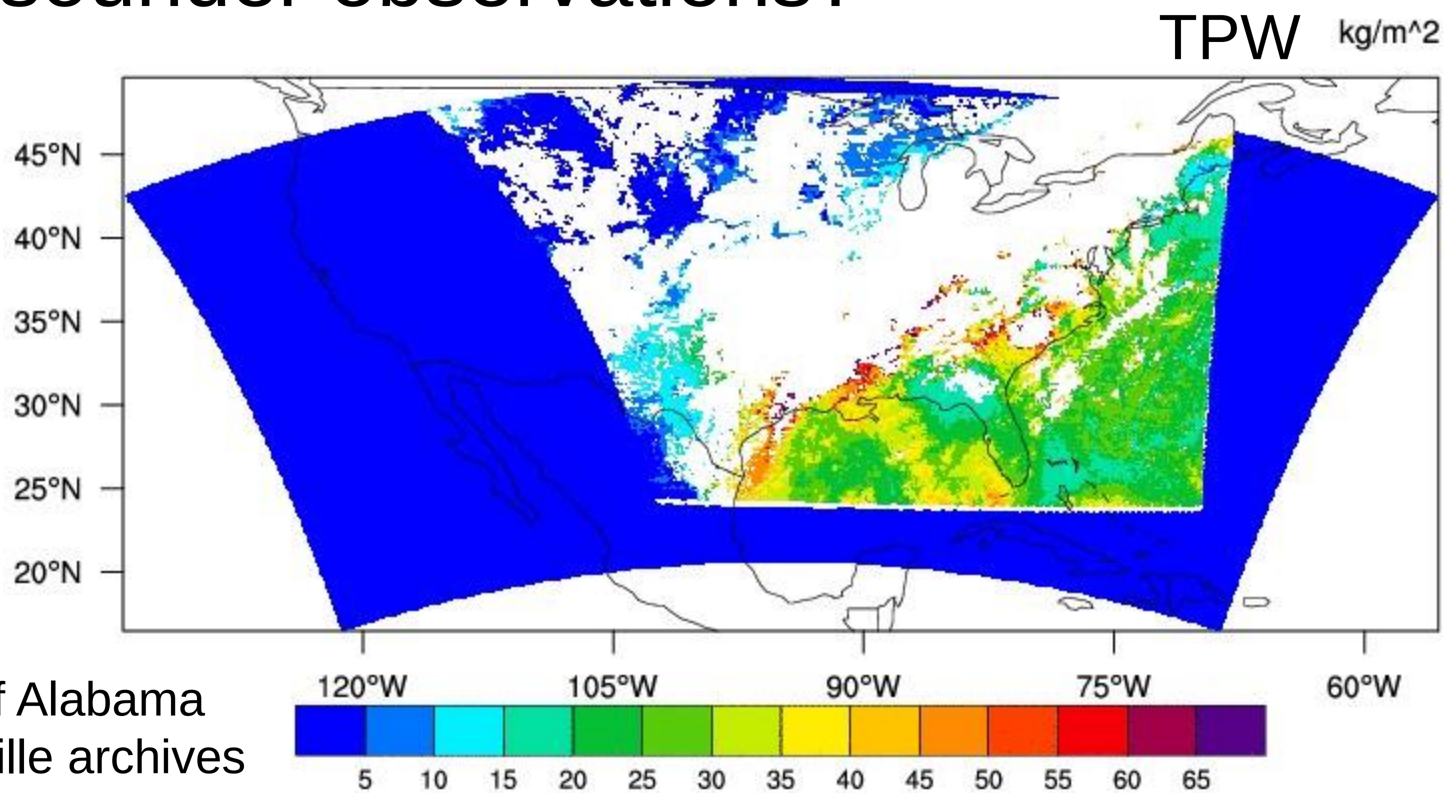
Blended IWV archives (Colorado St. Univ.)

Results

- Satellite observations
  – GOES Sounder TPW (University of Alabama – Huntsville)

Satellite Obs

- Are ARs detectable by today's GOES sounder observations?



Univ. of Alabama Huntsville archives

1200 UTC 5 – 1200 UTC 7 December 2011 – UQ04

Answers to Analysis Questions

- Do Atmospheric Rivers impact the southern Appalachians? 7/15 – AM, 13/17 – UQ
  - Are ARs responsible for flooding events?
    - Storm Data; 1/7 – AM, 11/13 – UQ
    - USGS River Gauge; 0/7 – AM, 10/13 – UQ
  - Are they detectable by today's GOES sounder observations?
    - IR cloud contamination problem

Answers to Analysis Questions

- Do Atmospheric Rivers impact the southern Appalachians?
  - Will they be detectable by tomorrow's GOES-R sounder observations?
    - blended IWV approach suggests multi-spectral abilities of GOES-R should improve AR detection
    - IWV d[UQ-LQ] shows promise (10 mm UQ-LQ spread increase over a period of 24-h or less)

Answers to Analysis Questions

- Do Atmospheric Rivers impact the southern Appalachians?
  - What atmospheric fields beyond satellite observations are useful in their detection?
    - favorable HYSPLIT flow/high climatological IWV values
    - strong Integrated Vapor Transport (IVT)
    - direction of IVT; SE to SSW is best
    - long duration IVT
    - strong upper level forcing & large-scale ascent

Future Work

- Will ARs be detectable by tomorrow's GOES-R sounder observations?
  - Current launch schedule; November 2016
- AR climatology as observed by the Duke GSM Rain Gauge Network (3-yr continuation study)

http://www.goes-r.gov/users/comet/goes_r/abi/print.php.htm

Acknowledgements

COMET GOES-R Partners Project
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Near Purchase Knob, credit: Michael Goldsbury

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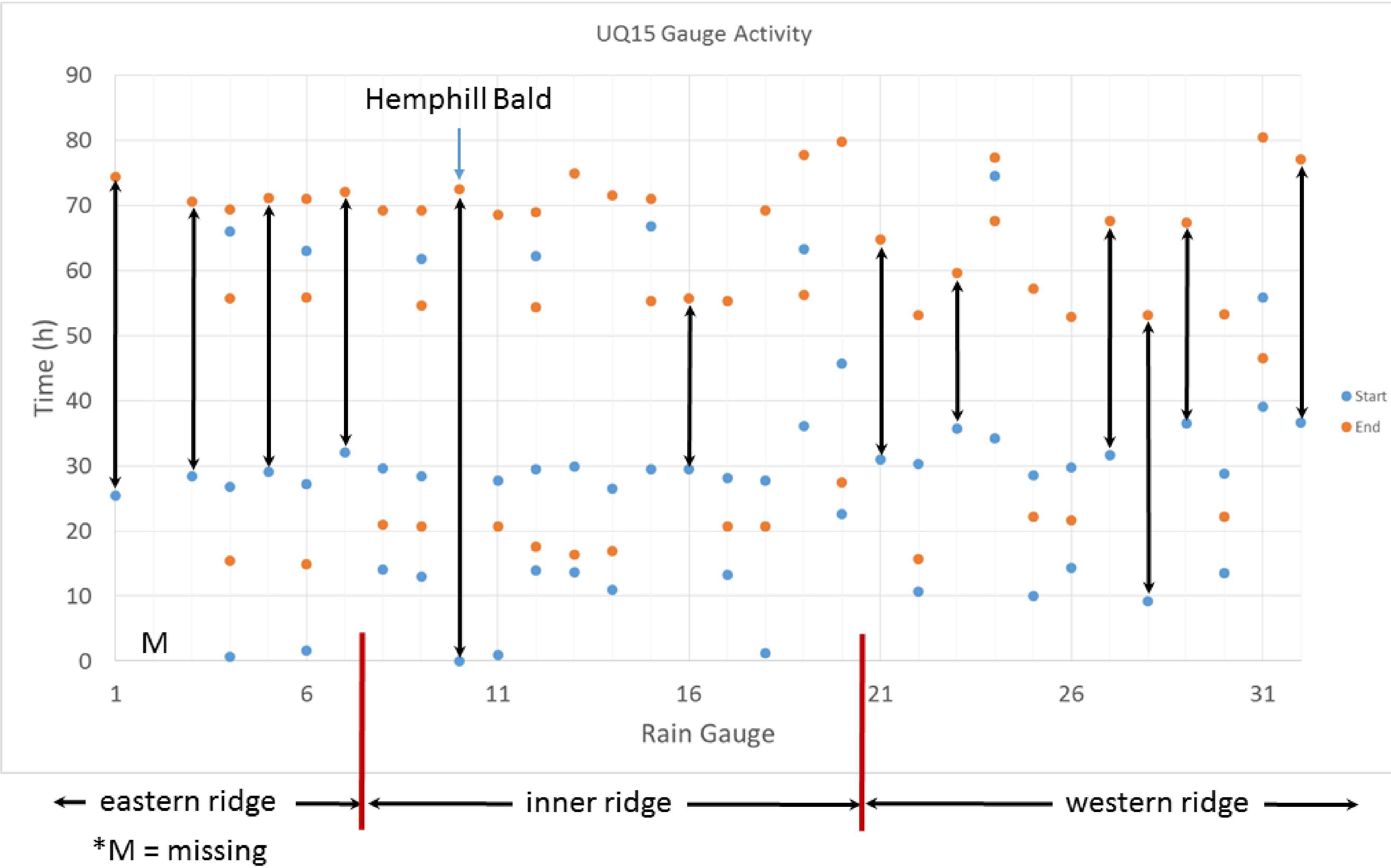

UQ15 Gauge Activity
Hemphill Bald
90
80
70
60
50
40
30
20
10
0
Time (h)
M
1
6
11
16
21
26
31
Rain Gauge
Start
End
eastern ridge
inner ridge
western ridge
*M = missing

Rain Gauge Obs