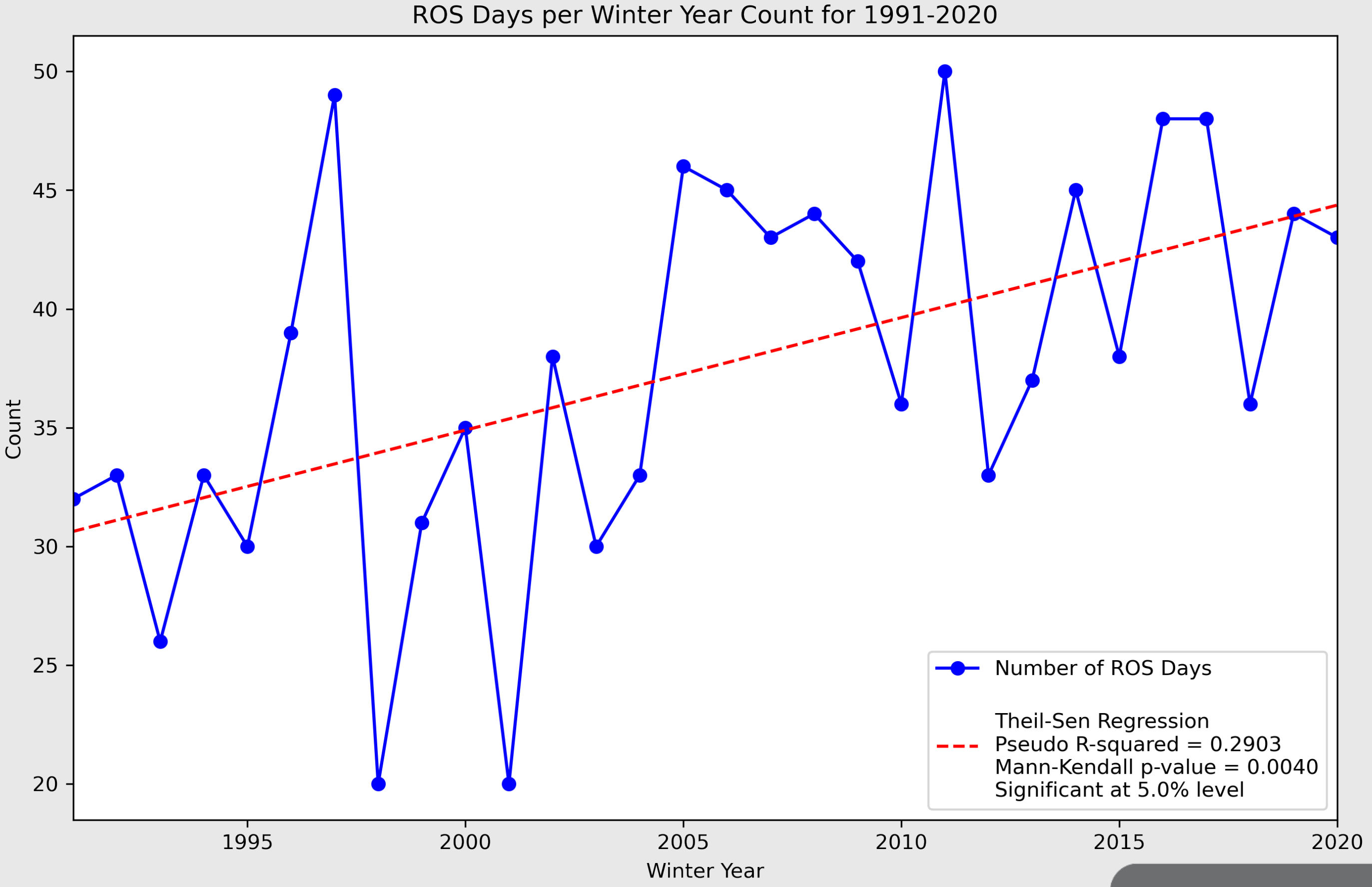
# December 2023 ROS Case Study

Laura Wilson

# Overall ROS Trends

## FROM LARGER ROS PAPER:

- Frequency of Mount Washington ROS Events is increasing w/ time



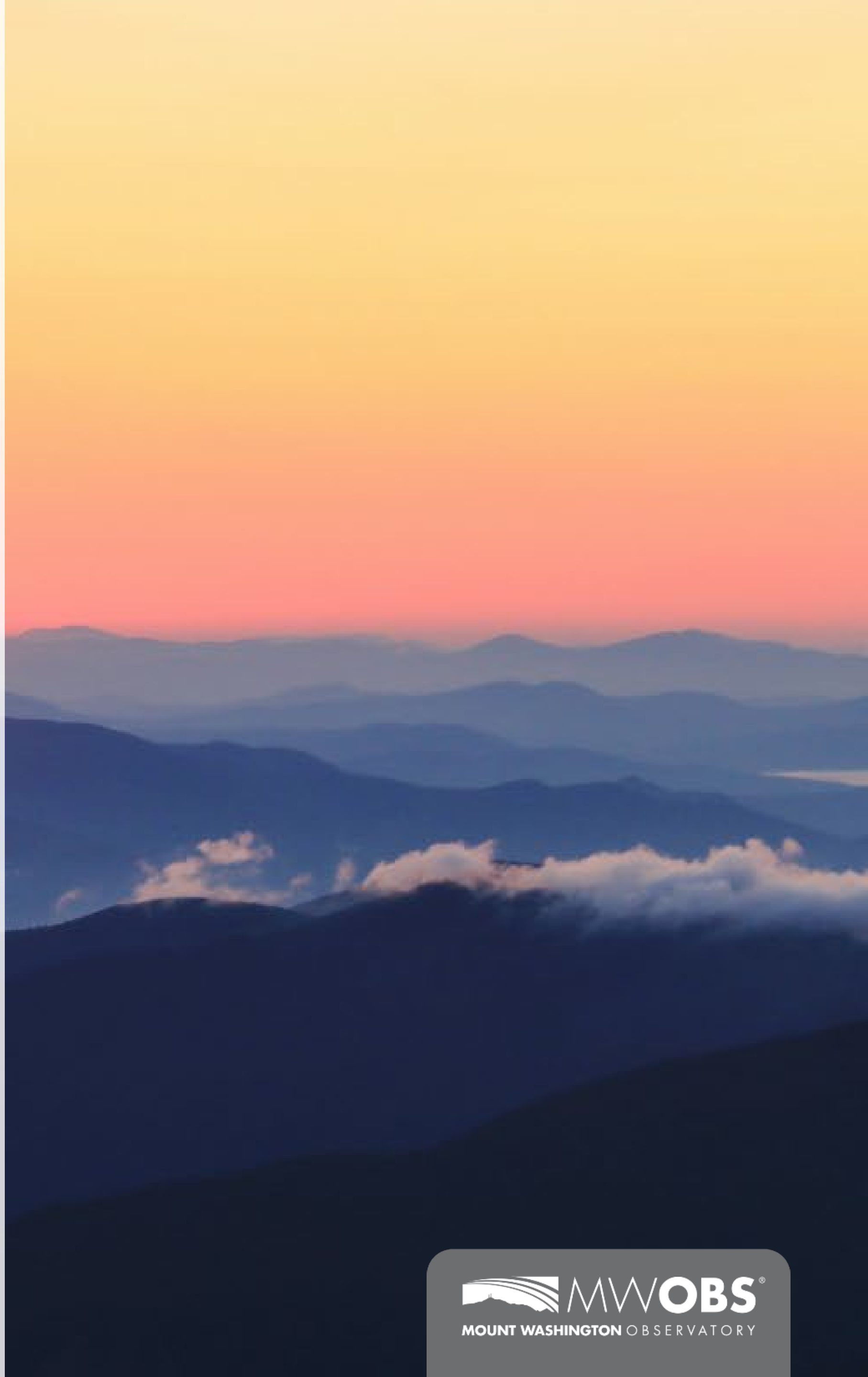
**This event serves as an example of the potential size and impact of future ROS events; even those falling on relatively thin snowpacks**

# How will anthropogenic climate change impact climate and weather?

**Globally:**
- Increasing hot extremes, decreasing cold extremes
- More abrupt shifts in regional weather patterns
- Increasing variability and intensity of global water cycle
  - Increases in very wet and very dry weather and climate events (Pörtner 2023)

**Regionally:**
- Intense warming in the Northeast (1870-2005) (Brown et al 2010)
- Increased heat waves, decreasing snowpack, and more extreme flooding/droughts (Young and Young 2021)

**Mount Washington:**
- 0.1°C of warming/decade since 1935
  - Faster in the winter (0.14°C/decade (Murray et al.)



# Why do ROS events matter?

## And why is it important to understand their development?

## History of Highly Impactful ROS Floods:

- South Saskatchewan and Elk River Basin (2015) (Pomeroy et al 2016)
  - Costliest natural disaster in Canadian history
  - 100,000 person evacuation
  - Water levels reached highest peak in 60 years
- Oroville Dam Disaster (2017) (Vahedifard et al. 2017)
  - Damaged the tallest dam in North America
  - 200,000 person evacuation
  - Increased sediment damage to adjacent dams
- Pennsylvania ROS Flood (1996) (Kroczynski 2004)
  - Largest midwinter flood in the state's history
- Many of the most damaging storms in the Sierra Nevada have been ROS events (Kattleman 1996)
  - Uncertainties in runoff forecasting impedes flood mitigation

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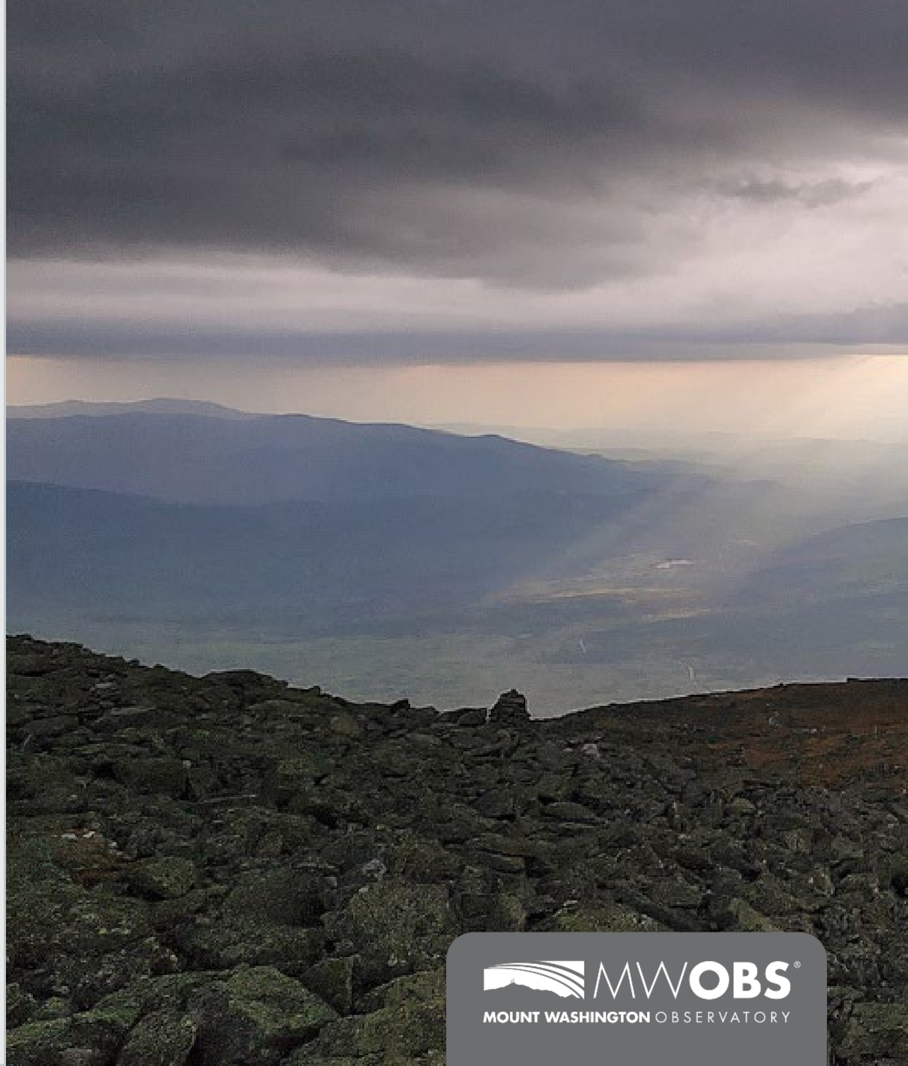
# So, what contributes to ROS flooding?

## Major Factors:

- Rainfall intensity and duration
  - Compounded by melting energy from liquid precipitation (Kattelman 1996)
- Snowmelt contributions – snow cover extent and depth (Rössler et al. 2013)
  - Dependent on snowpack conditioning
    - Can generally hold up to ~10% SWE
    - Ice layers impede runoff and can double holding capacity

## Snowpack Depth:

- Thick Snowpacks:
  - Precipitation generated runoff potentially reduced by higher holding capacity
- Thin Snowpacks:
  - Lower holding capacity
  - Greater runoff amplifying potential for precipitation induced snowmelt



# Study Area:

## Mount Washington and Adjacent Subbasins

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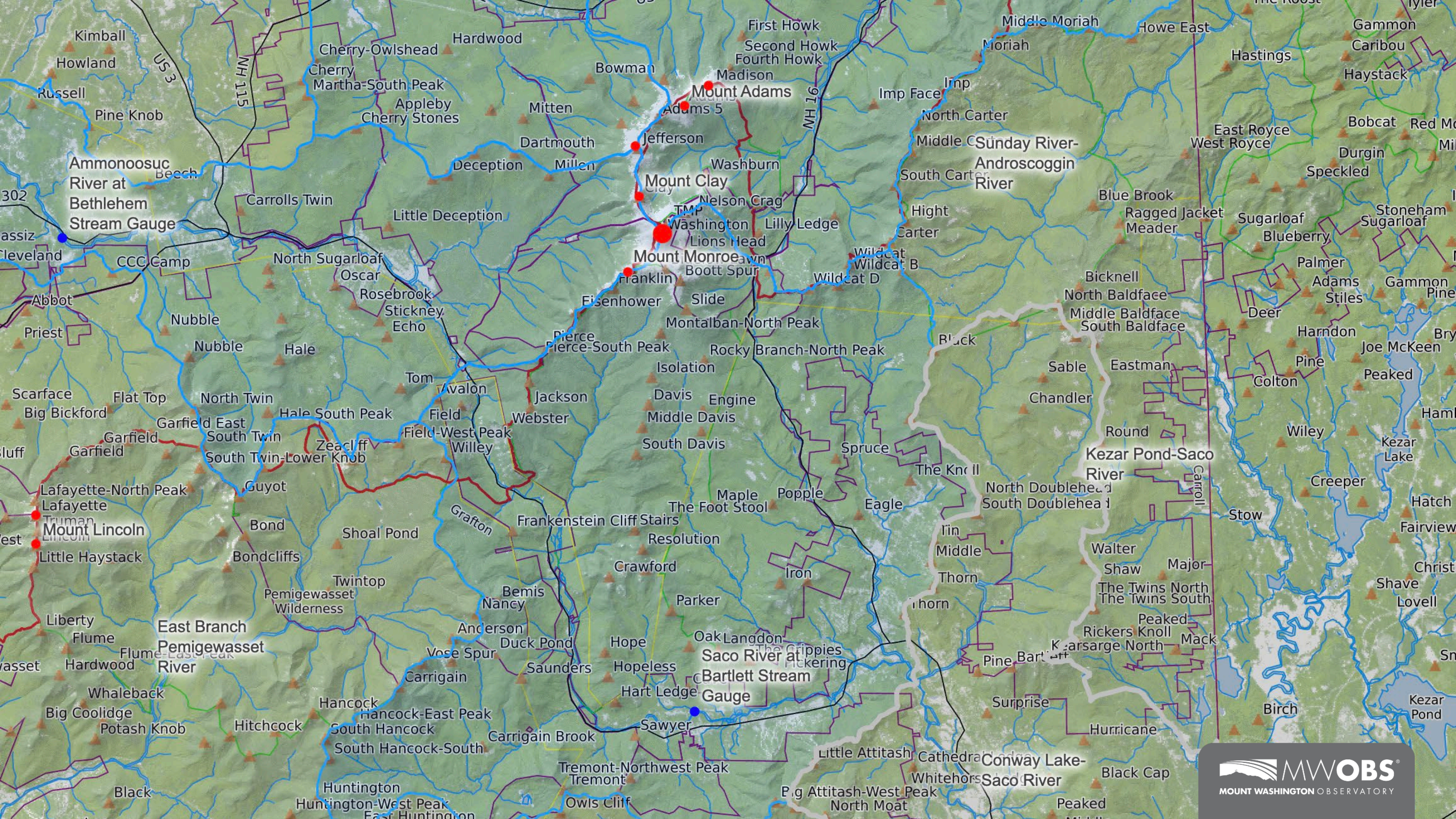
# Mount Washington:

- Intersection between three watersheds
    - Headwaters Ammonoosuc River, Peabody River-Androscoggin River, and Ellis River
        - No stream gauges located w/in Ellis River watershed
        - Headwaters Saco River included in its stead



Kimball
Howland
Russell
Pine Knob
US 3
NH 115
Cherry-Owlshead
Hardwood
Cherry
Martha-South Peak
Appleby
Cherry Stones
Mitten
Bowman
First Howk
Second Howk
Fourth Howk
Madison
Mount Adams
Adams 5
NH 16
Imp Face
Imp
Middle Moriah
Moriah
Howe East
Hastings
Gammon
Caribou
Haystack
Ammonoosuc River at Bethlehem Stream Gauge
Beech
302
Carrolls Twin
Dartmouth
Deception
Jefferson
Washburn
Mount Clay
North Carter
Middle Carter
South Carter
Sunday River-Androscoggin River
East Royce
West Royce
Bobcat
Durgin
Speckled
Little Deception
Nelson Crag
TMP
Washington
Lilly Ledge
Lions Head
Hight
Carter
Blue Brook
Ragged Jacket
Meader
Sugarloaf
Stoneham
Blueberry
Cleveland
CCC Camp
North Sugarloaf
Oscar
Rosebrook
Stickney
Echo
Mount Monroe
Franklin
Boott Spur
Wildcat
Wildcat B
Wildcat D
Bicknell
Middle Baldface
South Baldface
Palmer
Adams
Stiles
Gammon
Abbot
Priest
Nubble
Hale
Eisenhower
Slide
Montalban-North Peak
Deer
Harndon
Joe McKeen
Pierce
Pierce-South Peak
Rocky Branch-North Peak
Black
Isolation
Sable
Eastman
Pine
Colton
Peaked
Tom
Avalon
Jackson
Davis
Engine
Chandler
Scarface
Flat Top
North Twin
Big Bickford
Hale South Peak
Field
Webster
Middle Davis
Garfield East
Garfield
South Twin
Zealcliff
Field-West Peak
Willey
South Davis
Spruce
Round
Kezar Pond-Saco River
Wiley
Kezar Lake
South Twin-Lower Knob
The Knoll
Lafayette-North Peak
Guyot
Maple
Popple
North Doublehead
South Doublehead
Creeper
Lafayette
Truman
Mount Lincoln
The Foot Stool
Eagle
Carroll
Hatch
Stow
Bond
Shoal Pond
Grafton
Frankenstein Cliff
Stairs
Resolution
Tin
Fairview
Little Haystack
Bondcliffs
Middle
Walter
Shaw
Major
Crawford
Iron
Christ
Twintop
Thorn
Shave
Pemigewasset Wilderness
Bemis
Nancy
Parker
The Twins North
The Twins South
Lovell
Thorn
Liberty
Peaked
Flume
East Branch Pemigewasset River
Anderson
Rickers Knoll
Mack
Oak
Langdon
Kearsarge North
Duck Pond
Hope
The Gripples
Vose Spur
Hardwood
Saunders
Hopeless
Saco River at Bartlett Stream Gauge
Pickering
Pine
Carrigain
Whaleback
Hart Ledge
Surprise
Hancock
Big Coolidge
Hancock-East Peak
Birch
Kezar Pond
Potash Knob
Hitchcock
South Hancock
Sawyer
Hurricane
Carrigain Brook
South Hancock-South
Little Attitash
Conway Lake-Saco River
Black Cap
Tremont-Northwest Peak
Tremont
Huntington
Black
Big Attitash-West Peak
North Moat
Huntington-West Peak
Owls Cliff
Peaked
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# Stream Gauges

## Saco Hydrologic Unit

Saco River at Bartlett Gauge:

- -Drainage area of 91sq mi
- -Southern aspect drainage along the Dry River

Saco River at Conway Gauge:

- -Outside of adjacent subbasins, but drained directly from the higher summits
- -Drainage area of 385sq mi
- -Included for length of daily discharge record (1903-present)

## Upper Connecticut Hydrologic Unit

Ammonoosuc River at Bethlehem Gauge:

- -Drainage area of 87.6sq mi
- -Western aspect along Ammonoosuc River

## Lower Androscoggin Hydrologic Unit

Peabody-Androscoggin River at Gorham Gauge

- -Omitted due to headwater storage and flood mitigation impacts

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# Mount Washington Surficial Geology (Fowler 2010)

- **Summit Cone:**
  - Upper Slope Diamicts
    - Angular, cobble-boulder sized clasts over bedrock

- **Ravines:**
  - Colluvial debris on or below slopes, overlying bedrock

- **Middle Elevations (non-ravine):**
  - Lower Slope Diamicts overlying bedrock
    - Highest elevation area w/ significant silt and clay

- **Lower Elevations:**
  - Till: variable clasts, silt, sand, and clay
  - Generally, deposits of 20ft or less, but can reach up to 100ft deep in specific areas

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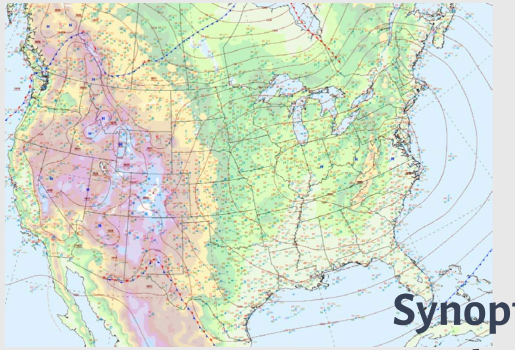
# Methods:

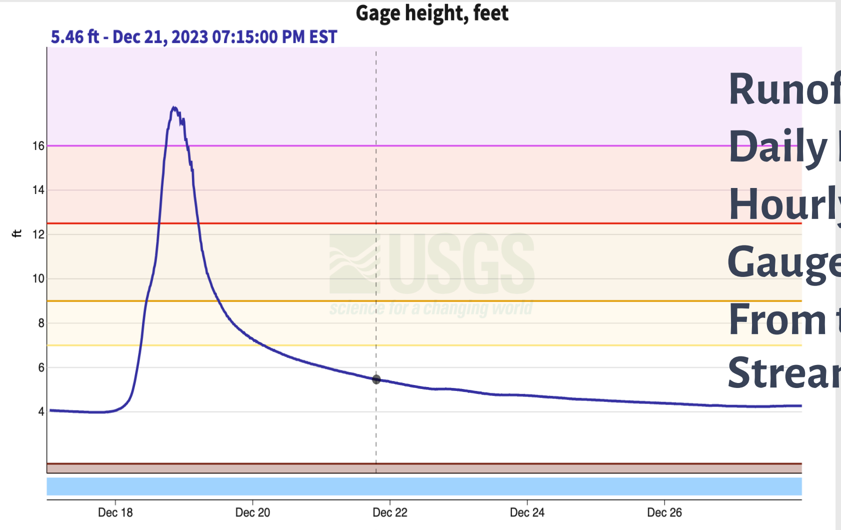


Synoptic Evolution Analyzed Using Historic Surface Analysis Charts

Localized Development Analyzed Using MWOBS Hourly Data

Snowpack Development Analyzed Using Hermit Lake Snow Plot Observations and Community Snow Observations, confirmed against Summit Observations

Runoff Analyzed using Daily Discharge, Hourly Discharge, and Gauge Height Data From the Selected Stream Gauges

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# Results

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# Weather Conditions:

## Preceding Event:

-Generally Clear
-No Precipitation Dec 14-17

## During Event:

-31 hours of continuous precipitation

-wintery mix, becoming rain, becoming brief snow

-Elongated low, increased wind field over Atlantic

-4.1 inches total liquid precipitation at summit

-3.71 inches liquid precipitation at NCON3 station

-Peaking in intensity afternoon of December $18^{th}$

-Repeated warm fronts

-New daily record high temp for December $18^{th}$ (41°)

## After Event:

-Temperatures decrease back below freezing
-Generally clear, only trace precipitation recorded in week following

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# Snow Depth

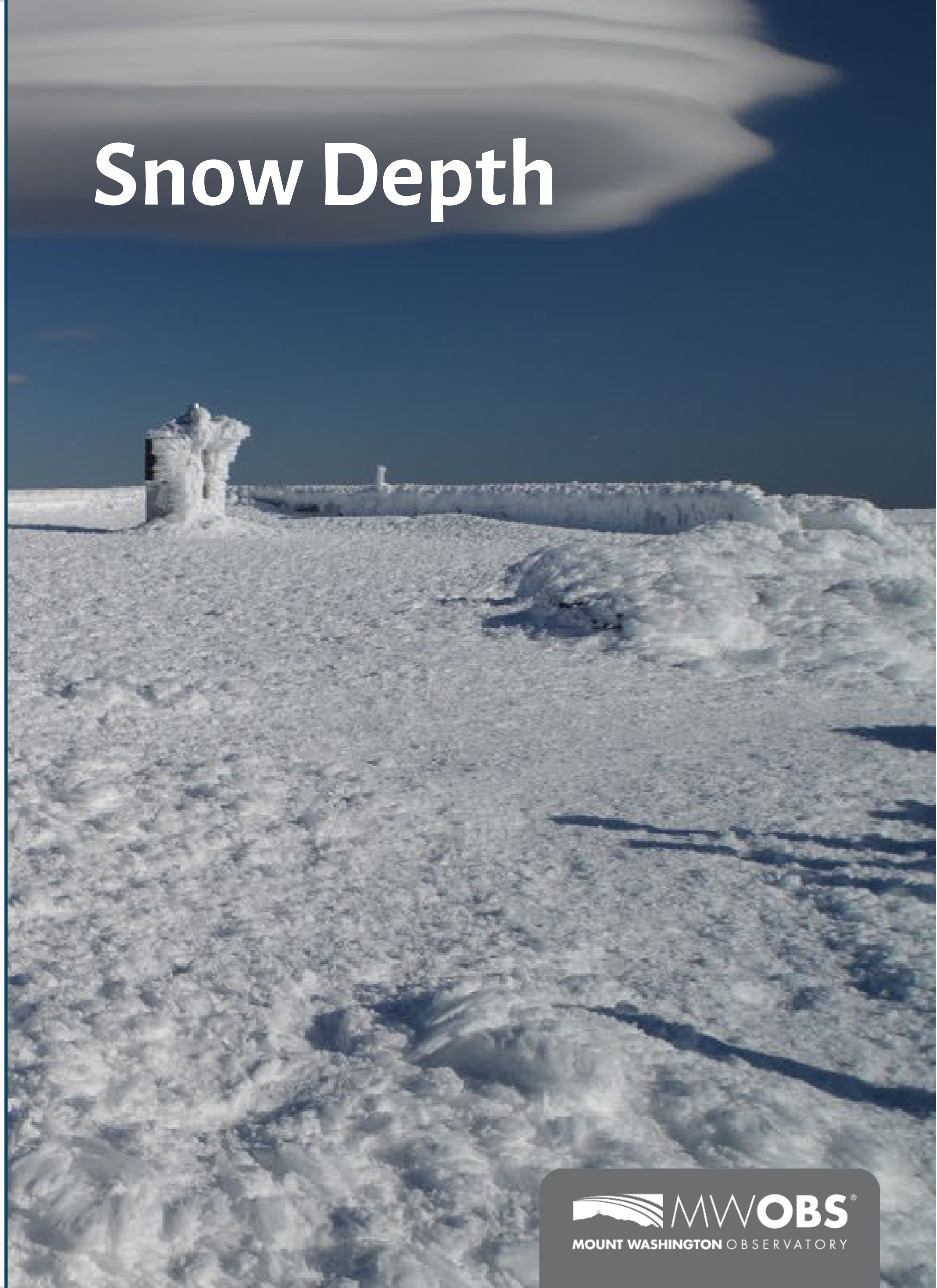
**December 17th:**

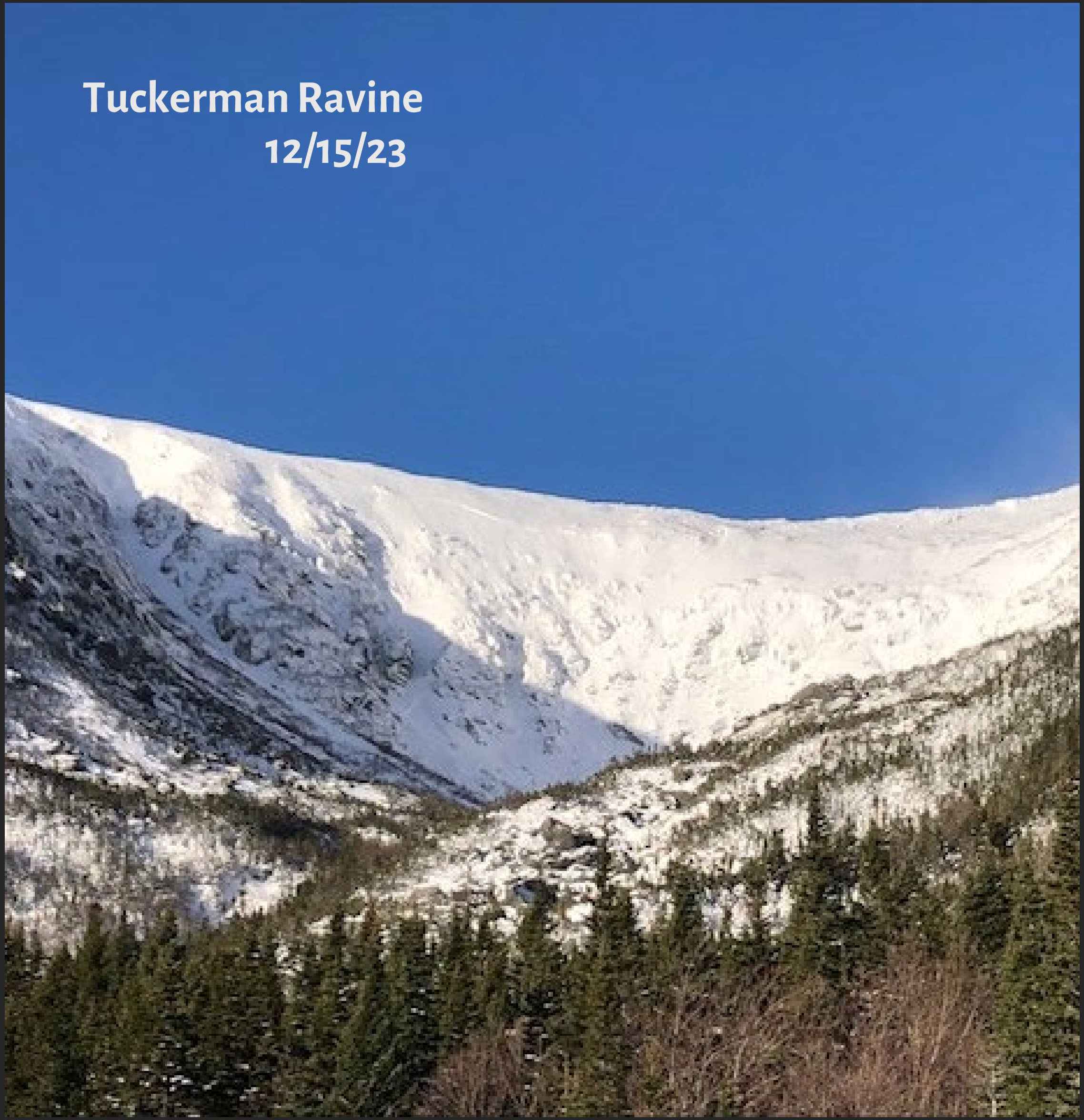
- -Lower Elevations (Carroll NH): 4.5 inches of snow
- -Hermit Lake: 18 inches of snow
  - -Below average for this date
- -Mount Washington Summit: 5 inches of snow and ice

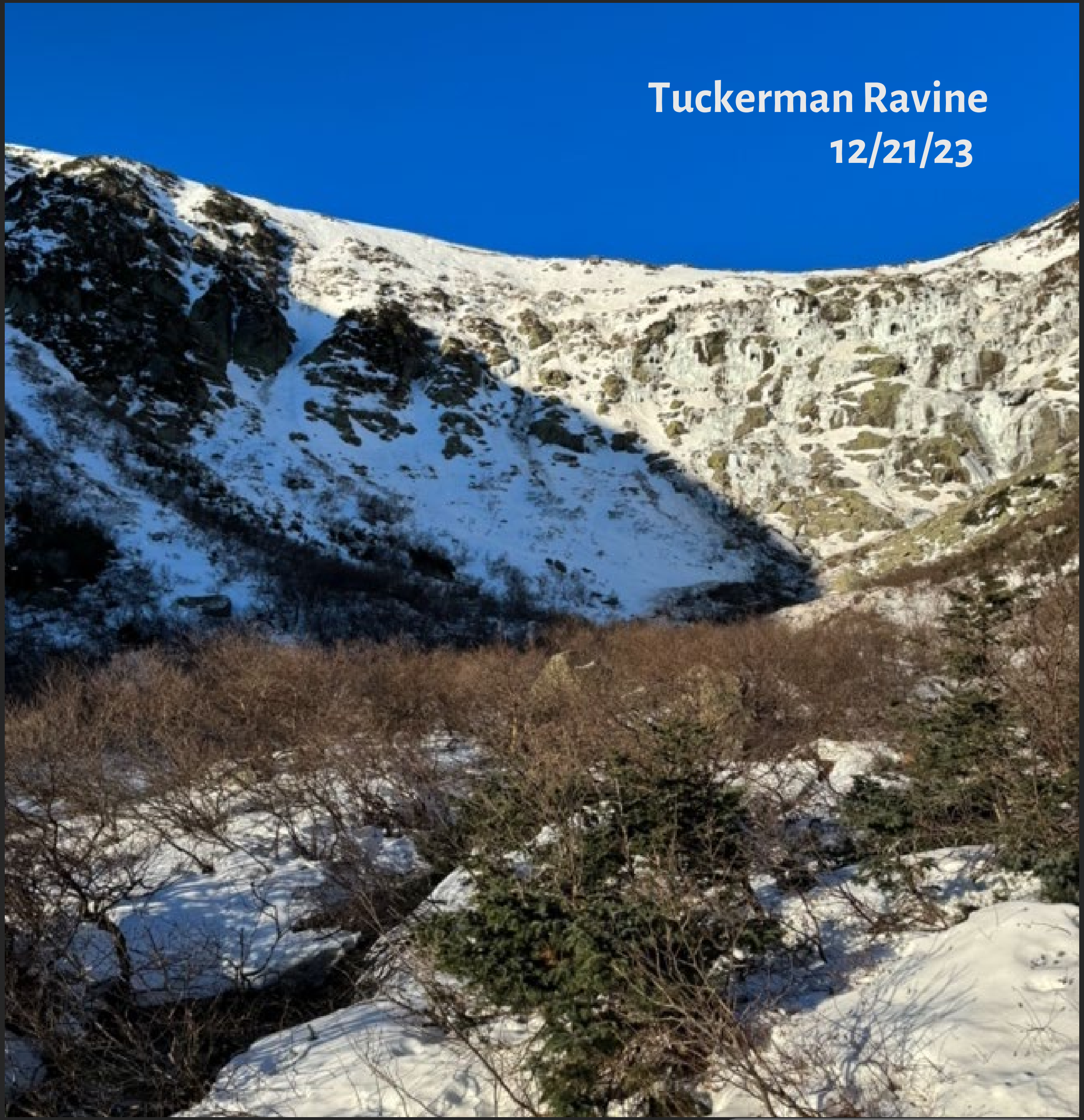
**December 19th:**

- -Lower Elevations (Carroll NH): 0 inches of snow
- -Hermit Lake: 0 inches of snow
- -Mount Washington Summit: 1 inch of snow and ice

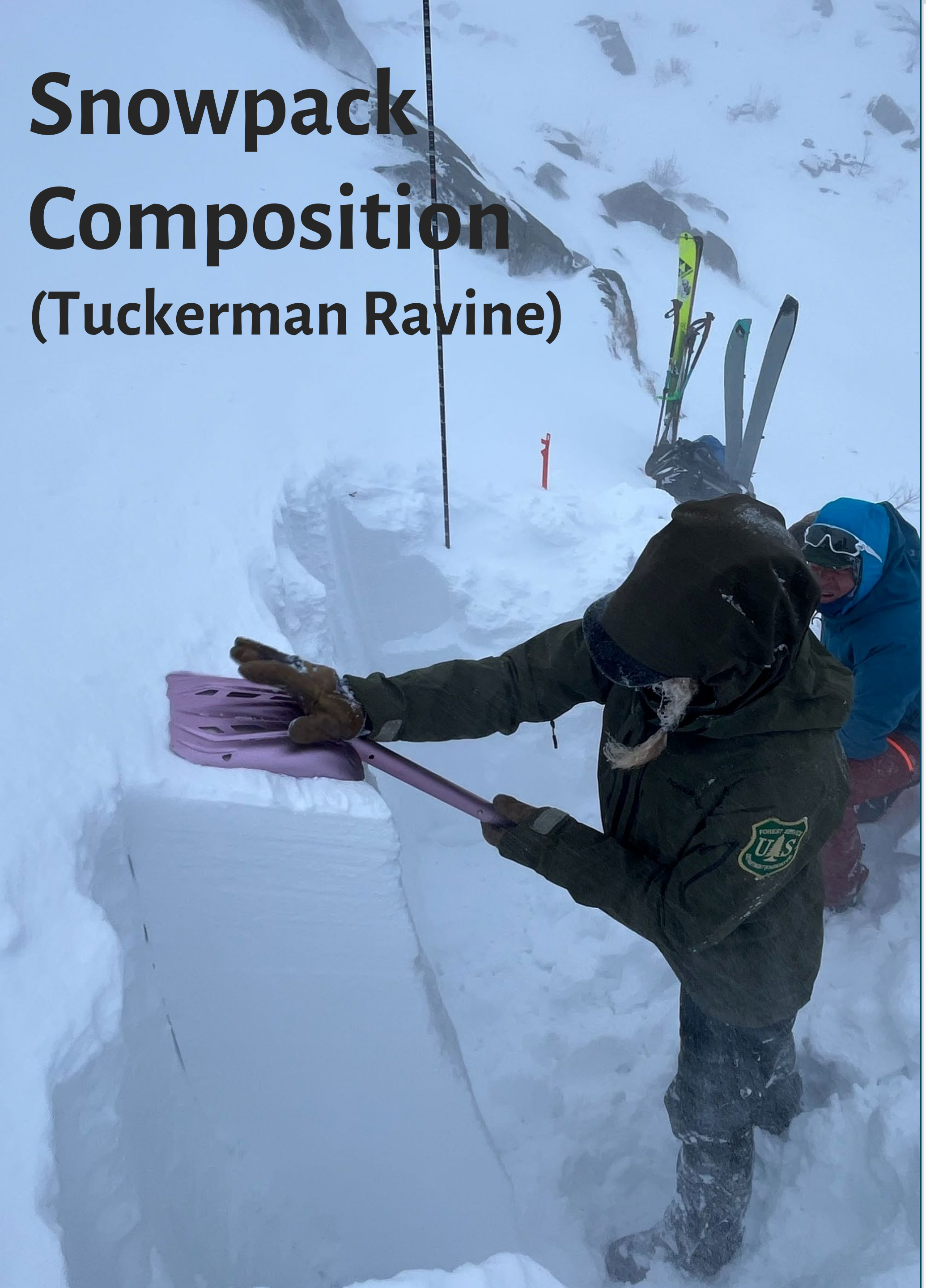
Complete eradication of lower elevation snowpack; near complete eradication of summit snowpack




Tuckerman Ravine
12/15/23


Tuckerman Ravine
12/21/23

# Snowpack Composition
## (Tuckerman Ravine)



## From December 15th USFS MWAC Forecaster Observation:

-Variable snow depths, up to 83 inches, particularly deep on eastern aspects

-Snow Stratigraphy:
- -Substantial layer of wind blown snow
- -Multiple thin crusts
- -Damp granular snow at base

-Damp granular base suggesting general absence of basal ice
- -Potential for infiltration and/or runoff

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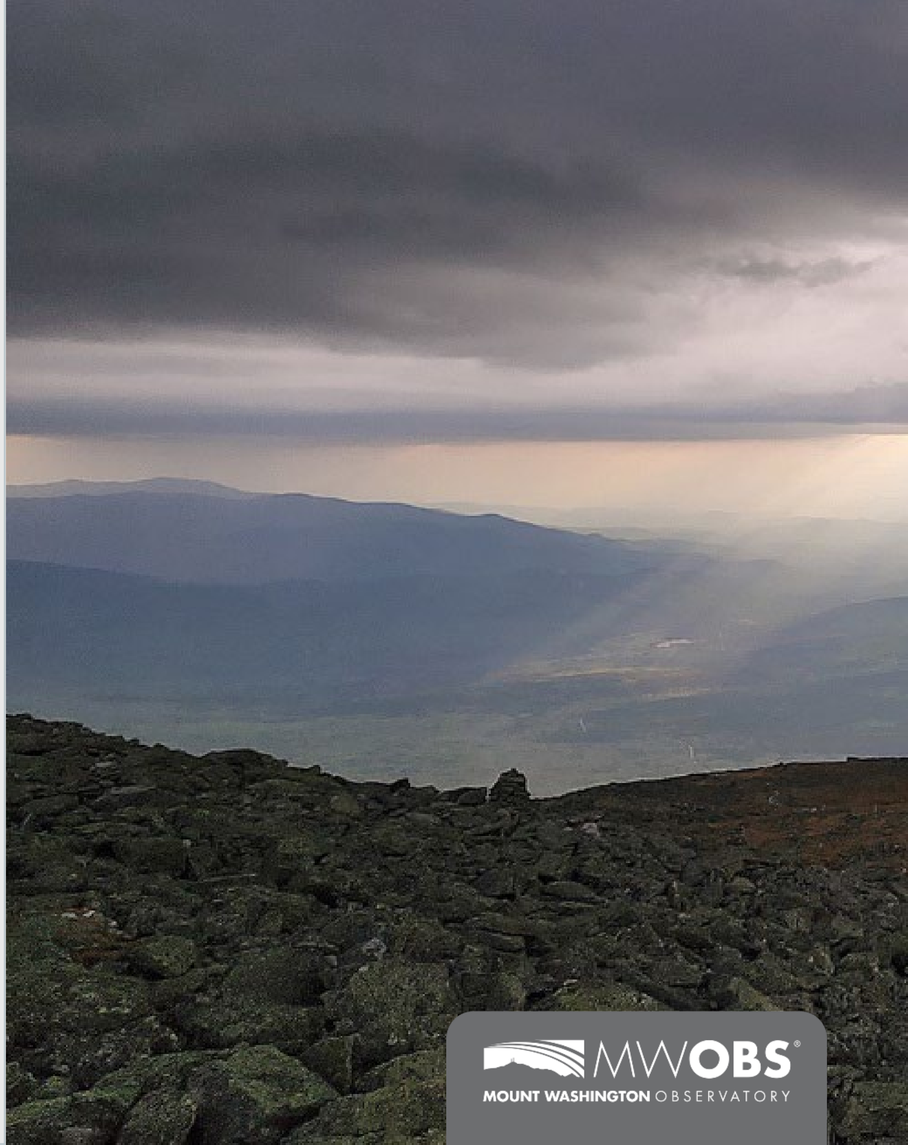
# Ground Conditioning and Almanac Data



## From the NCON3 Station:

- 2023 Year = 4th wettest on record
    - 61.7 inches liquid equivalent

- December = 2.8 inches wetter than average at 7.35 inches liquid equivalent

HOWEVER:

- Fall Season (September – November) = 3.16 inches DRIER than average
    - November = 1.84 inches drier than average

IF ground was not frozen, potential for infiltration with somewhat drier than average conditions throughout the fall

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# Stream Conditions

## Gauge Heights:

-Major flooding at both Saco gauges

-Moderate flooding at Ammonoosuc

## Daily Streamflow:

-Highest value ever recorded by Bartlett gauge

(9810 ft^3/s)

-$4^{th}$ largest at Bethlehem gauge

(4760ft^3/s)

-$6^{th}$ largest at Conway gauge

(24300ft^3/s)

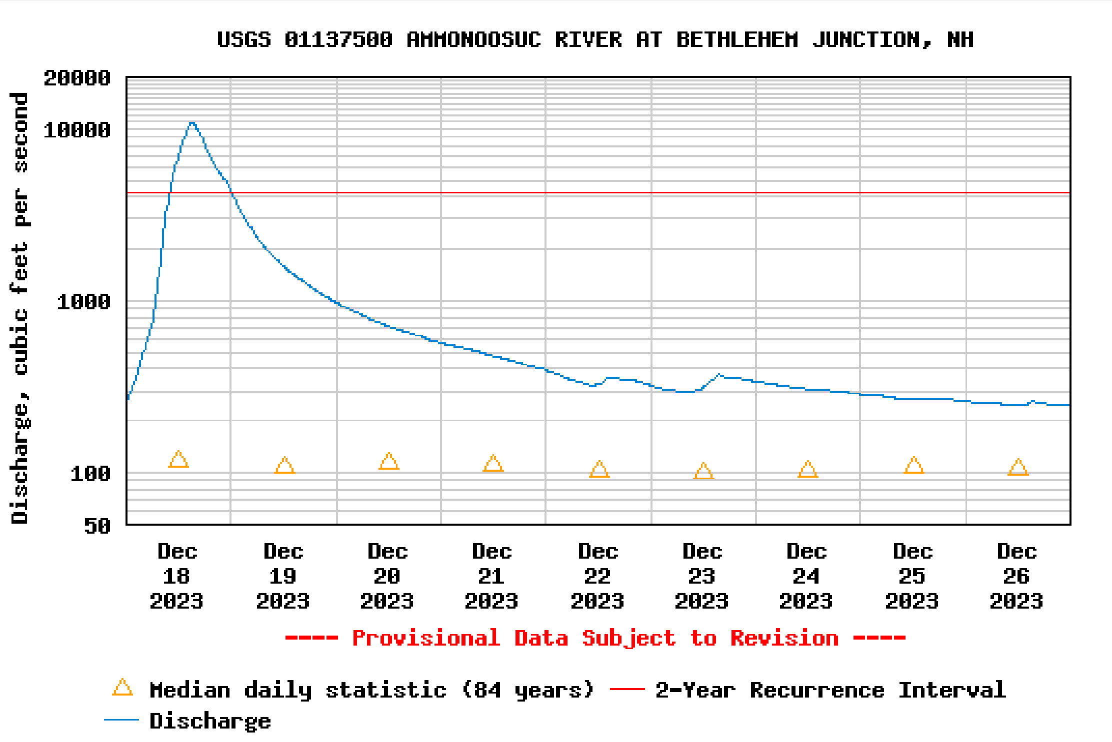
-Larger values than any Hurricane or out-of-season ROS event on record at these gauges

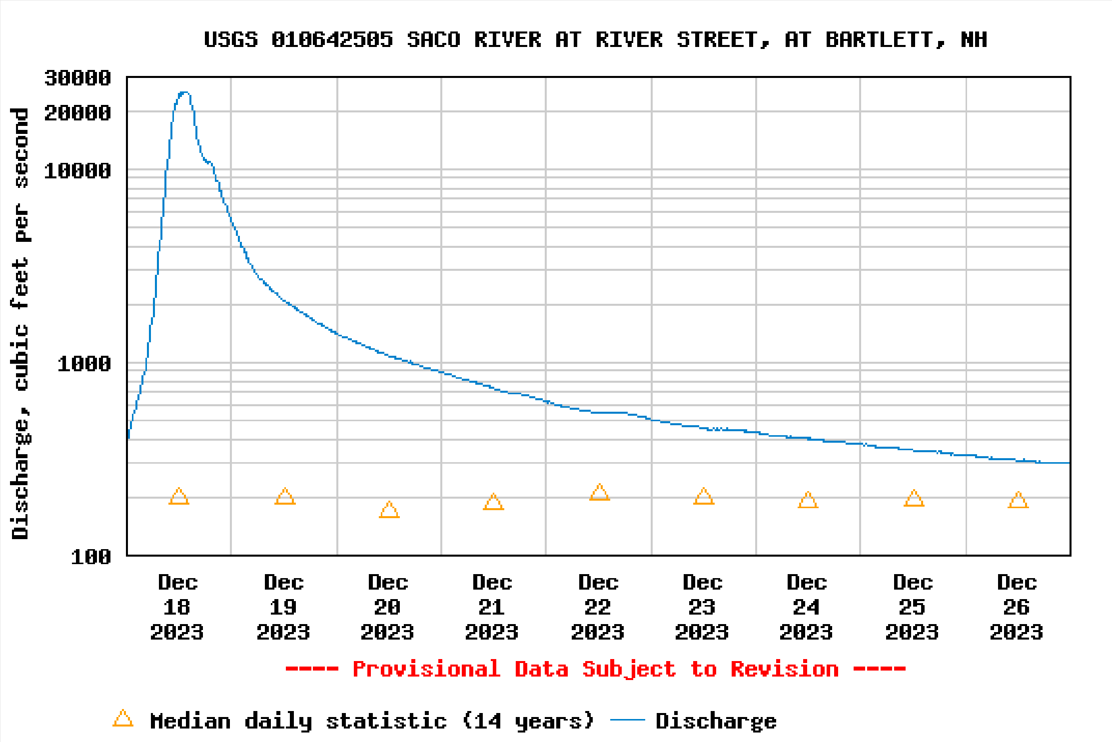
## Recurrence Intervals:

Ammonoosuc: 800 years for Dec 18, 125 years for Dec 19

Saco (Conway): 795 years for Dec 18, 485 years for Dec 19

# Discharge (Instantaneous):

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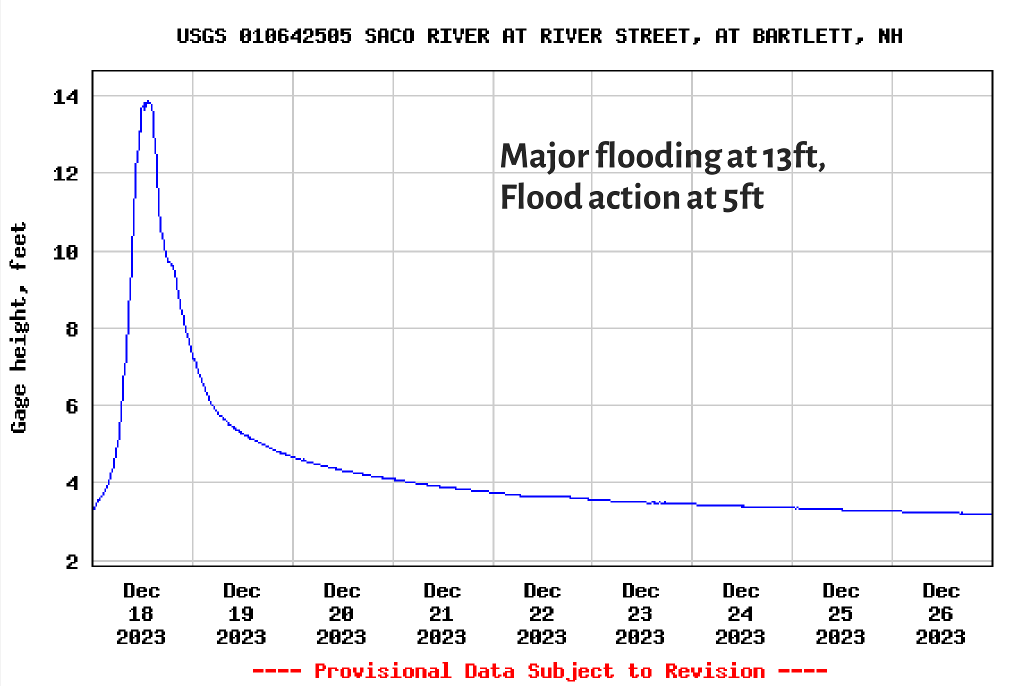


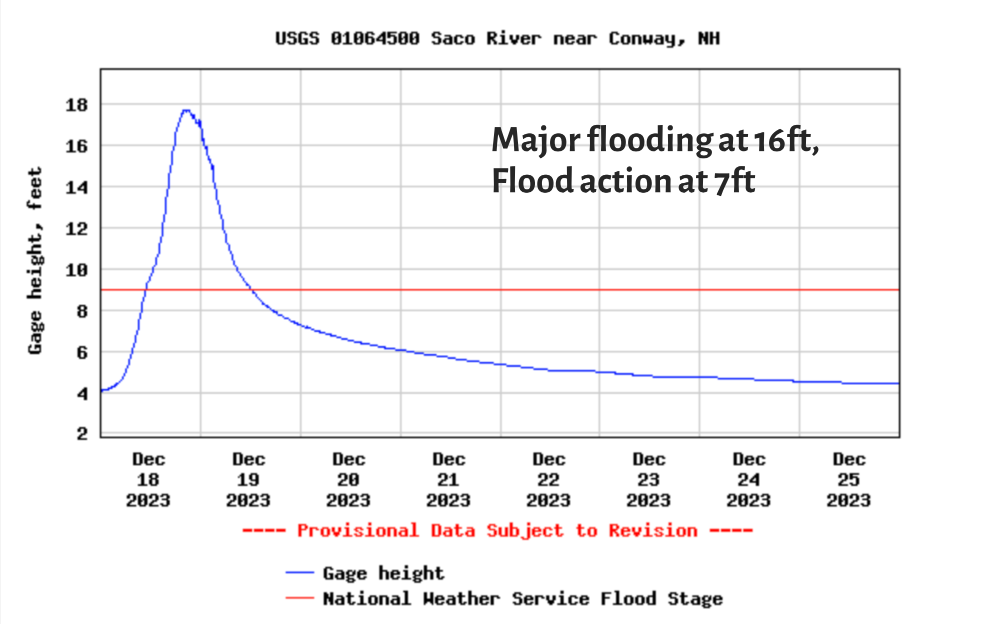


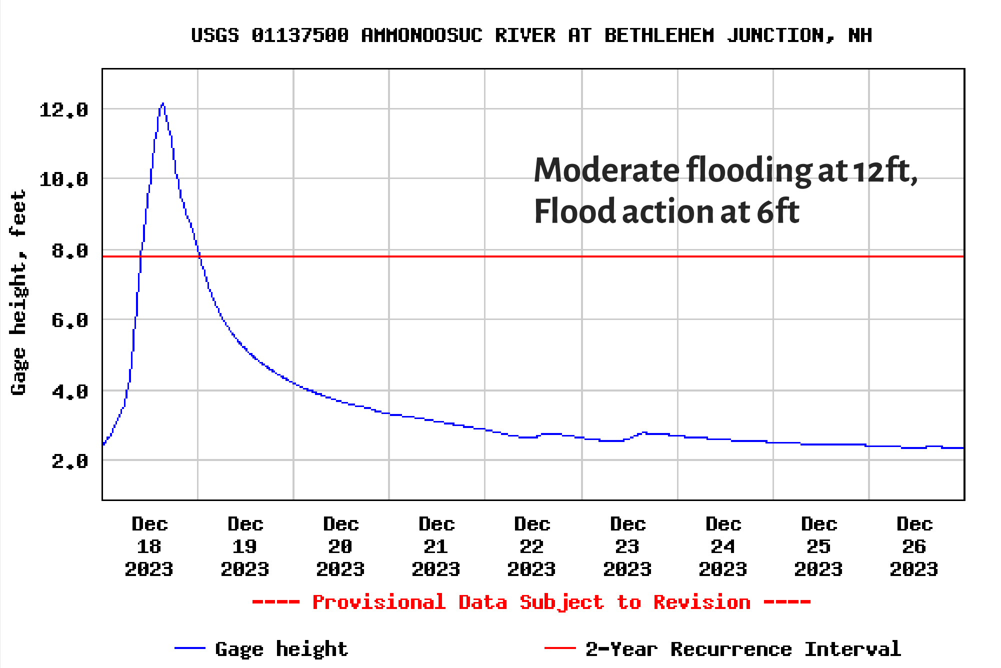


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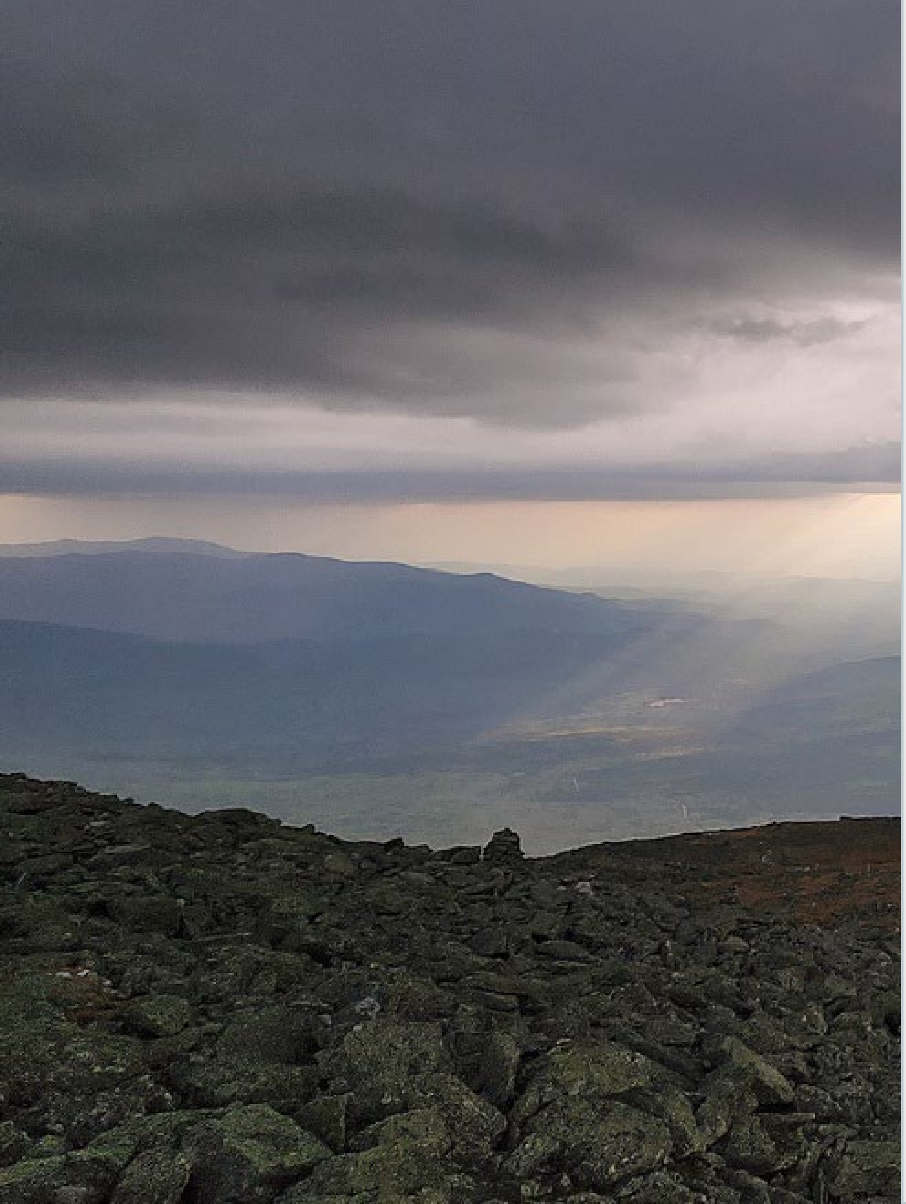
# Discussion:



- Event duration fits within average for this study (1.7 days or ~40 hours)
- Shortest duration event to trigger runoff >21000ft^3/s at the Conway Gauge (record back to 1903)
- Much less precipitation than events creating larger runoff response w/o influence of snowmelt (6.37 and 11.35 inches liquid equivalent)
- Rainfall fell on a below average early season snowpack of only ~18 inches
- Nonetheless, the event resulted in a historic runoff response

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# Future Work:

## What allowed such a thin snowpack and non-extreme rainfall to create a historic runoff response?

## What is the runoff generating potential of thin snowpack?

**Further Examination of Major Factors:**

- SWE of snowpack at all elevations
- Extent of snow cover before and after event, depth values would also be extremely useful
- Freeze/thaw elevations throughout the event
- Ground saturation and infiltration

# Takeaways:

Upland basins, like Mount Washington are most heavily influenced by ROS events. It is important to understand the development of these events as their frequency increases, especially with a global trend of increasing water cycle intensity. Given the extent of damages caused by this event, increasing frequency of this magnitude of ROS flooding could have significant implications for the communities and ecosystems on and around Mount Washington.


# Thank You!

## Works Cited:


Brown, P. J., R. S. Bradley, and F. T. Keimig, 2010: Changes in extreme climate indices for the Northeastern United States, 1870-2005. *J Clim*, **23**, 6555–6572, https://doi.org/10.1175/2010JCLI3363.1.

Fowler, B., 2010: Interim Surficial Geologic Map Mt. Washington 7.5 Minute Quadrangle. *USGS Statemap.*

Kattelmann, R., 1996: *Flooding from rain-on-snow events in the Sierra Nevada.* IAHS Publ.

Kroczynski, S., 2004: *A COMPARISON OF TWO RAIN-ON-SNOW EVENTS AND THE SUBSEQUENT HYDROLOGIC RESPONSES IN THREE SMALL RIVER BASINS IN CENTRAL PENNSYLVANIA.*

Murray, G. L. D., and Coauthors, *Northeastern Naturalist Climate Trends on the Highest Peak of the Northeast: Mount Washington, NH*. 11 pp.

Pomeroy, J. W., R. E. Stewart, and P. H. Whitfield, 2016: The 2013 flood event in the South Saskatchewan and Elk River basins: Causes, assessment and damages. *Canadian Water Resources Journal*, **41**, 105–117, https://doi.org/10.1080/07011784.2015.1089190.

Pörtner 2023: Summary for Policymakers. *Climate Change 2022 – Impacts, Adaptation and Vulnerability*, Cambridge University Press, 3–34

Rössler, O., P. Froidevaux, U. Börst, R. Rickli, O. Martius, and R. Weingartner, 2013: A non-forecasted rain-on-snow flood in the Alps Retrospective analysis of a non-forecasted rain-on-snow flood in the Alps-a matter of model-limitations or unpredictable nature? A non-forecasted rain-on-snow flood in the Alps A non-forecasted rain-on-snow flood in the Alps. *Hydrol. Earth Syst. Sci. Discuss*, **10**, 12861–12904, https://doi.org/10.5194/hessd-10-12861-2013.

Vahedifard, F., A. Aghakouchak, E. Ragno, S. Shahrokhabadi, I. Mallakpour, 2017: Lessons from the Oroville Dam. *Science*, **355**, 1139-1140, DOI: 10.1126/science.aan0171.

Young, S. S., and J. S. Young, 2021: Overall warming with reduced seasonality: Temperature change in New England