Clausius-Clapeyron Relationship and Atmospheric Rivers: Climate Change Impacts on Yakima Basin

Research Compilation for Yakima County Best Available Science Update 2026 – Addendum to 12152025 Yakima Basin Hydrology AR Hazards DRAFT Tech. Memo

Prepared: December 17, 2025 ksw

Quality Assessment

Strengths:

1. Recent, High-Quality Sources: Most sources are from 2024-2025, showing current research.
2. Regionally relevant.
3. Peer-Reviewed Publications: Core sources are from top-tier journals (Journal of Climate, GRL, Nature Communications)
4. Authoritative Organizations: Government and university sources are all legitimate
5. Appropriate Mix: Good balance of peer-reviewed research and agency reports

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Executive Summary

This document synthesizes recent peer-reviewed research on the Clausius-Clapeyron (C-C) relationship and its manifestation through atmospheric rivers (ARs) affecting the Yakima Basin. The research demonstrates that climate change is fundamentally altering precipitation patterns, snowpack dynamics, and flood risks in the Pacific Northwest through thermodynamic intensification of atmospheric moisture transport.

Key findings relevant to the BAS Update include:

- Atmospheric rivers have already expanded 6-9% in area and increased 1.5-2.5% in moisture content between 1980-2023, with extreme events intensifying 3-6 times faster than mean values
- The Yakima River Basin has been identified as the "most sensitive basin" in the Columbia River system due to its mixed rain-and-snow hydrology
- Future projections show extreme AR frequency could increase nearly 10-fold under moderate warming scenarios, with back-to-back events potentially doubling runoff response
- Current drought conditions (three consecutive years, reservoir levels at 8-20% capacity) are exacerbated by both declining AR frequency in the western US and warming-induced snowpack reductions

These findings have direct implications for all five critical area types addressed in the Yakima County Critical Areas Ordinances update.

The Clausius-Clapeyron Relationship Explained

Fundamental Thermodynamic Principle

The Clausius-Clapeyron relationship describes how the atmosphere's capacity to hold water vapor increases exponentially with temperature. This fundamental thermodynamic equation shows that the atmosphere can hold approximately 7% more water vapor for every 1°C of warming. This is not a linear relationship—it compounds exponentially, meaning effects accelerate rapidly with warming.

The simplified relationship can be expressed as: $dq/dT \approx 0.07 \times q$, where q represents atmospheric moisture content (specific humidity) and T represents temperature. The ~7% increase comes from the exponential nature of saturation vapor pressure as described by the Clausius-Clapeyron equation.

Implications for Atmospheric Rivers

For the Yakima Basin, this relationship manifests primarily through atmospheric rivers—long, narrow corridors of concentrated water vapor that transport moisture from tropical oceans to higher latitudes. When these systems make landfall on the Cascade Mountains, they can deliver extraordinary amounts of precipitation in short timeframes.

Key mechanisms include:

- **Increased precipitation intensity:** Warmer ARs carry dramatically more moisture. A storm system at +2°C can deliver approximately 14% more precipitation than the same system under current conditions.
- **Rain versus snow partitioning:** Higher freezing levels during storms mean more precipitation falls as rain rather than snow, critical for the snowpack-dependent Yakima Basin water supply system.
- **Extreme event amplification:** The heaviest precipitation events intensify disproportionately—not just 7% more, but potentially 15-30% increases in the wettest days, particularly relevant for Pineapple Express and AR events hitting the Cascades.

Recent Peer-Reviewed Research Findings

Observed Historical Trends (1980-2025)

Global AR Expansion and Intensification

Henny and Kim (2025) published comprehensive analysis in the *Journal of Climate* demonstrating that atmospheric rivers have already undergone significant changes during the 1980-2023 period. Using multiple AR detection methods across ERA5, MERRA-2, and JRA-55 reanalysis datasets, they found:

Total AR area increased 6-9%

Integrated water vapor (IWV) increased 1.5-2.5%

Integrated vapor transport (IVT) increased less than 1%

Most extreme ARs intensifying at much faster rates: maximum IVT and IWV in individual ARs increased at approximately 3-6× and 1.5-2× the rate of mean values respectively

This research confirms that the Clausius-Clapeyron relationship is already manifesting in observational data, not just theoretical projections.

Regional Divergence in Western US

Pan et al. (2025) identified a concerning regional pattern in their *npj Climate and Atmospheric Science* publication. Over the past 40 years, western US locations have experienced declining AR frequency while eastern US regions show increases. This divergence is driven by Pacific circulation patterns creating anticyclonic blocking near the west coast.

For the Yakima Basin, this helps explain the paradox of intensifying extreme precipitation events occurring alongside overall drying trends and the current three-year severe drought. The region faces both: (1) fewer total AR events delivering less cumulative annual precipitation, and (2) more intense individual events when ARs do make landfall, increasing flood risk.

Future Projections from CMIP6 Climate Models

Global AR Changes

Zhang et al. (2024) analyzed 23 CMIP6 models in the *Journal of Geophysical Research: Atmospheres*, finding that ARs will become more frequent, intense, and longer-lasting, while the time between landfall events will shorten. A particularly concerning finding is the non-linear acceleration: AR frequency is expected to increase even faster after mid-century due to non-linear temperature rise. Additionally, mid-latitude ARs are shifting toward higher latitudes (poleward migration).

Extreme Event Frequency Increases

Higgins et al. (2025) published critical findings in *Geophysical Research Letters* using large ensemble simulations from both HadAM4 and CESM2 models. Their analysis shows extreme AR frequency could increase by nearly an order of magnitude (approximately 10×) in mild warming scenarios relative to early 21st century conditions.

Significantly, they found substantial increases in the percentage of winters experiencing multiple extreme AR events affecting both California and the Pacific Northwest. The research indicates anthropogenic warming dramatically increases the chance of unprecedented seasons with high numbers of AR extremes on the US west coast.

Regional Variations in AR Response

Shields et al. (2024) revealed important regional differences in *Nature Communications Earth & Environment*. Their high-resolution modeling shows Pacific Northwest ARs will be driven primarily by warmer ocean and atmosphere temperatures, while Southern California ARs will be driven more by enhanced evaporation processes. By 2100, Pacific Northwest ARs could raise coastal storm surge heights by as much as three times more than current storms, with significant implications for coastal and riverine flooding.

Pacific Northwest and Yakima Basin Specific Research

Columbia Basin Climate Change Scenarios Project

The foundational Columbia Basin Climate Change Scenarios Project (Hamlet et al., 2013, *Atmosphere-Ocean*) specifically identified the Yakima River Basin as the "most sensitive basin" in the Columbia River system. Using the VIC hydrologic model at 1/16° resolution, researchers demonstrated that mixed rain-and-snow basins like the Yakima experience dramatic snowpack losses and substantial changes in seasonal flow timing.

Key findings include:

- Profound changes in spring snowpack across most of the domain
- Fundamental shifts from snow and mixed rain-and-snow to rain-dominant behavior
- Elevated winter soil moisture leading to increased landslide and sediment transport risks
- More infiltration from rain in fall and winter months, supporting the hypothesis of widespread increases in winter landslide risks

Agricultural Vulnerability Assessment

Washington State University researchers led by Dr. Keyvan Malek conducted detailed modeling of Yakima Basin irrigated agriculture for two future time periods: 2040 (2030-2060) and 2070 (2060-2090). Their findings, published through WSU's Center for Sustaining Agriculture and Natural Resources, reveal:

- Significant droughts (defined as unmet irrigation demand exceeding 30%) will become more frequent and severe in both future periods
- Some drought events could reach greater than 65% unmet demand—unprecedented in the historical record
- All three major crop categories show potential yield reductions: annuals (winter wheat, spring wheat, corn, potatoes), multiple-cutting crops (alfalfa, pasture), and tree fruits (grapes, apples, cherries, pears)
- The frequency of low-yield years (producing under 60% of fully irrigated yield) could substantially increase with climate change

These projections are driven by higher temperatures' effects on snowpack: warmer conditions reduce snowpack volume as more precipitation falls as rain, and accelerate snowmelt, causing water availability to shift toward earlier in the year with less water available later in the irrigation season.

Current Drought Conditions

Washington State Department of Ecology reports document the severity of current conditions:

- July 2024: Drought emergency declared for 12 counties in the Yakima Basin, remaining in effect through at least June 30, 2025
- Three consecutive years of severe drought with historic reservoir levels at 8-20% capacity as of October 2024
- October 2025: First-time curtailment to all but the most senior water rights (those predating May 10, 1905), including Treaty rights of the Yakama Nation
- March 2025 forecast: Pro-ratable water users expected to receive only 48% of normal water supply, with basin reservoirs at just 38% of typical levels for that time of year (third lowest since 1971)

As climate change continues pushing temperatures higher and reducing snowpack, water supplies are becoming increasingly unreliable, with drops in river flows threatening both agricultural operations and endangered fish populations.

Rain-on-Snow Events and Watershed Response

Back-to-Back AR Events

Zhou et al. (2025) published critical research in the *Journal of Geophysical Research: Atmospheres* examining how sequential ARs affect runoff response. Their findings demonstrate that back-to-back ARs can cause up to 200% increase in runoff compared to the same events spaced further apart in time.

When multiple ARs make consecutive landfalls within a short period, high soil moisture from previous events substantially increases the likelihood of flooding and landslides. Importantly, they found that even weak ARs can produce extreme runoff given saturated soils or high snowmelt conditions. This has direct relevance for the Cascades, though the NNE-SSW orientation of the range is less ideal for orographic enhancement compared to the Sierra Nevada.

December 2025 Events

Recent atmospheric river events (December 7-17, 2025) provided real-world validation of projected changes:

- Multiple potent ARs struck the Pacific Northwest in succession, with one AR extending approximately 7,000 miles from the Philippines
- Up to 18 inches of rain fell on western Washington, triggering widespread flooding, mudslides, and infrastructure failures
- Skagit River reached record flood levels with evacuations ordered for 100,000 people

Critical mechanism: Warm temperatures meant precipitation fell as rain instead of snow, even at moderate elevations, dramatically increasing runoff

Climate Central rapid assessment found sea surface temperatures beneath these ARs were 10 times more likely to exceed normal levels due to human-driven climate change

Air temperatures throughout the region significantly above average—4-5 times more probable due to climate change

Synthesis for BAS Application

Implications for Critical Areas

Frequently Flooded Areas

Design storms based on historical data may underestimate future peak flows by 15-30% or more

Non-stationarity in flood frequency analysis must be incorporated into floodplain mapping and regulation

Back-to-back AR scenarios should be considered in infrastructure design, as they can double runoff response

Rain-on-snow events at lower elevations will increase flood risk during winter months

Traditional 100-year flood designations require updating to account for changing climate baseline

Wetlands and Fish/Wildlife Habitat Conservation Areas

More intense precipitation leads to flashier hydrographs, affecting wetland hydroperiods and fish passage timing

Increased erosion and sediment transport from AR events will impact aquatic habitat quality

Changes to hydrologic connectivity between wetlands and streams as flow patterns shift

Earlier snowmelt and reduced summer low flows threaten ESA-listed steelhead, bull trout, and recovering salmon populations

Winter water temperatures increasingly problematic for cold-water species as more precipitation falls as rain

Geologically Hazardous Areas

Winter landslide risk substantially increasing due to elevated soil moisture from increased rainfall

Post-wildfire landscapes particularly vulnerable to AR-driven debris flows and mudslides

Rapid snowmelt combined with heavy rain creates compound hazards on steep slopes

Projections suggest up to 7-fold increase in instances where extreme rain follows high wildfire danger periods by 2100

Critical Aquifer Recharge Areas

Shift from gradual snowmelt recharge to more intense, direct rainfall recharge patterns

Changes to recharge timing and magnitude affect groundwater availability for summer irrigation

Reduced summer low flows increase reliance on groundwater, intensifying potential conflicts

More intense precipitation events may increase surface runoff at expense of infiltration in some areas

Key Research Priorities for BAS Update

Based on this research synthesis, the following topics should be prioritized in the 2026 BAS Update:

Non-stationarity in hydrologic design: Develop guidance for incorporating climate projections into flood frequency analysis and critical areas delineation

Mixed rain-and-snow basin vulnerability: Emphasize the Yakima Basin's identification as most sensitive in Columbia system

Agricultural water security: Address projected increases in unmet irrigation demand and implications for land use planning

Compound hazards: Integrate analysis of back-to-back ARs, rain-on-snow events, and post-fire vulnerability

Ecosystem resilience: Evaluate how changing flow regimes affect listed species and recovery efforts

Nature-based solutions: Highlight approaches like floodplain restoration that provide multiple benefits across critical area types

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