Radar Feasibility Study

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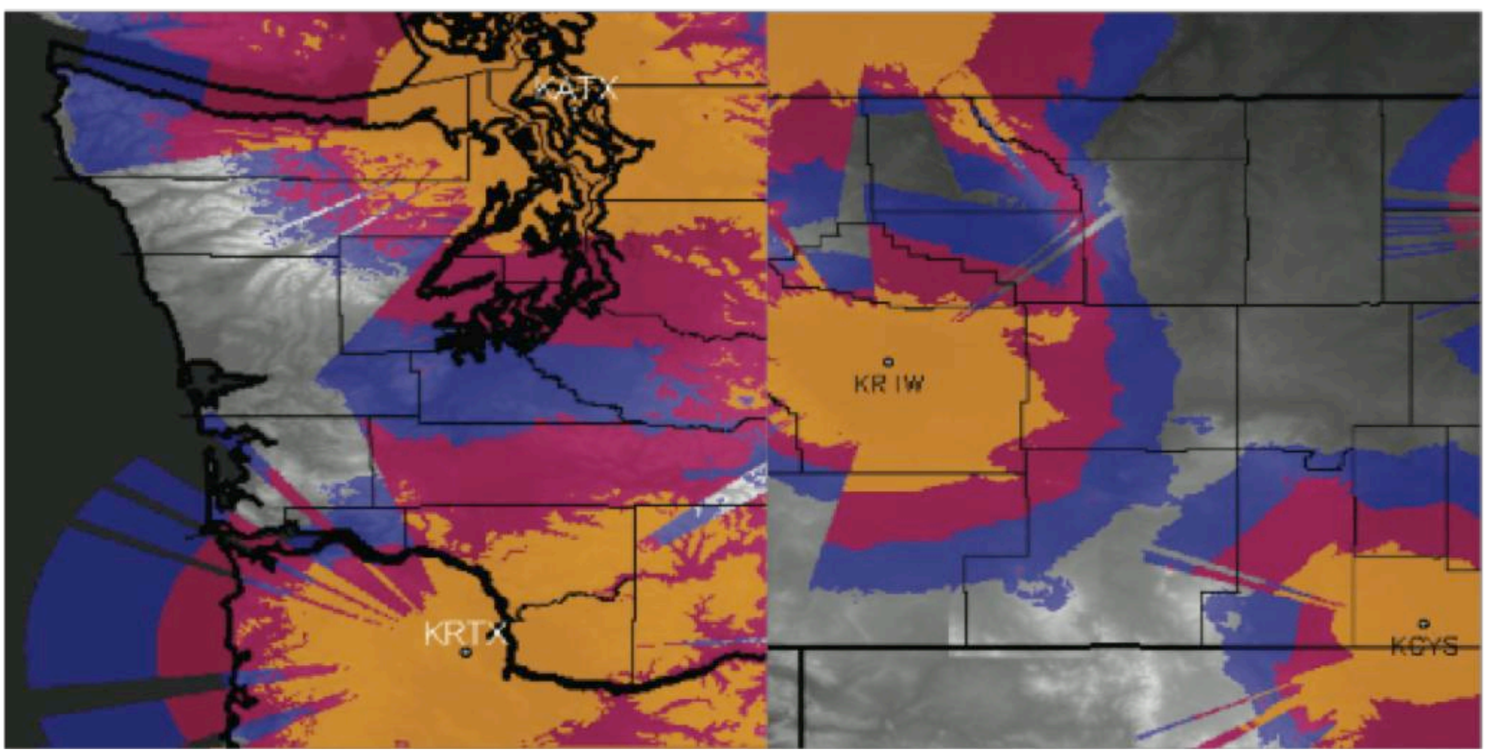

Preface

Tornado and coastal storm-induced injuries, fatalities and economic losses in the states of Wyoming and Washington were the motivation for this report on the feasibility of new technologies to fill coverage gaps in today's national weather radar network. This report contains an assessment of current radar coverage in these regions from a meteorological, social, and economic point of view as well as an analysis of the improvements in coverage that would be achieved by installing additional radars in Wyoming and Washington.

This report was funded by a congressional appropriation "to determine the applicability to northeastern Wyoming and other regions the feasibility of integrating a number of small-scale Doppler radar technologies into future National Weather Service observing systems." The small-scale Doppler radar technologies cited in this language are the R&D focus of the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) one of the nation's 15 Engineering Research Centers chartered by the National Science Foundation. Under rigorous and continuous peer review from the science and engineering community, CASA is investigating a concept in which networks of small, low-cost radars could be deployed on rooftops, communication towers, and other infrastructure elements to address coverage gaps in today's radar infrastructure. The CASA Engineering Research Center is a partnership among nearly 20 institutions, configured into academic, government, and industrial arms. This configuration enables the participants of the center to: develop the concepts behind small radar networks; translate these concepts into new technologies; and commercialize and implement the best concepts in practice. As of this writing, CASA is in its 6th year as a national Engineering Research Center; many of the center's key concepts have been demonstrated in research trials, and development and commercialization of various technologies is underway.

This report was funded by a contract from NOAA to CASA through the University of Oklahoma with Dr. Jerry Brotzge as Principal Investigator. The University of Oklahoma, in turn, subcontracted part of the work to the College of Engineering at the University of Massachusetts - the organization that leads CASA. Researchers from both institutions contributed to this report. In addition to the meteorological, social, economic and radar coverage assessments in this report, the authors analyze the additional radar coverage that would be achieved by installing small "CASA-type" radars as well as additional larger conventional weather radars in gap regions.

Previous experience with weather radars, including gap-filling weather radars, shows that additional components of the overall "system solution" can be just as important as the radars themselves. These additional components include the operating software, the mechanisms for transporting data to users and integrating the new observations into the existing observational infrastructure, and the provision for ongoing operations and maintenance of the various components of the new radar system throughout its intended lifecycle. This report includes some benchmark cost information but stops short of predicting what it would actually cost for a manufactured solution to the radar gap problem. Such costing information is more appropriately obtained through Requests for Information and Requests for Proposals from radar technology developers and manufacturers who are set up for delivering solutions to problems such as those considered in this report.

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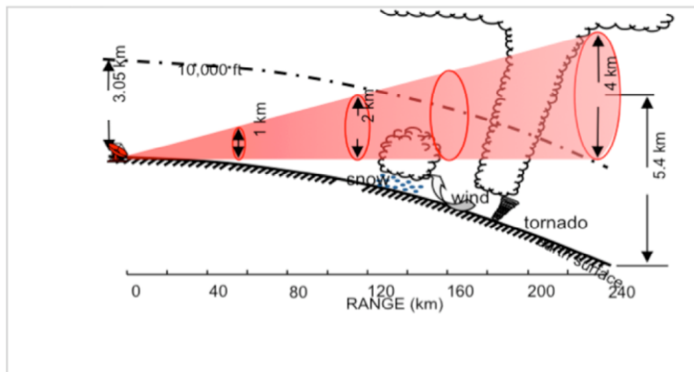
Executive Summary

I. Introduction

Is it feasible to deploy additional weather radar in Wyoming and western Washington? This study assesses the meteorological need for and the feasibility of deploying additional radars to augment the current radar observing system in northeastern and southwestern Wyoming and coastal Washington. The current NEXRAD WSR-88D radar network is operated by the National Oceanic and Atmospheric Association (NOAA) through the National Weather Service (NWS).

The catalysts for this study[1] were two severe weather events, an F-2 tornado in northeastern Wyoming and a three-day coastal storm system in Washington that raised awareness of the radar coverage gaps that exist in the current observing system. These coverage gaps have several causes: the distance between radars (345 km in the western United States); radar beam blockage due to mountains and other terrain; and the "horizon problem" which prevents long range radars from observing the lowest parts of the atmosphere [< 3 km above ground level (AGL)] at distances greater than 175 kilometers. Radar beams travel generally in a straight path, while the earth curves away from the beam. Therefore, at greater distances, radar can only observe the mid- and upper atmosphere as shown in the figure above (NRC 2005). Furthermore, weather climatology research demonstrates that many hazardous weather phenomena occur in the lowest 3 kilometers (~10,000 feet) of the atmosphere (NRC 1995).



The authors' approach to this radar feasibility assessment incorporates NOAA's vision which is "to understand and predict changes in the earth's environment …to meet our nation's economic, social, and environmental needs." In addition, we also take a holistic approach to evaluating the radars as part of an end-to-end warning system where socioeconomic, meteorological, geographic and technical factors all contribute to the performance of the system. We focus on specific regions – northeastern and southwestern Wyoming and coastal Washington – with the expectation that these results may also be applicable to other "radar gap" regions across the country.

[1] This study is funded through a Congressional appropriation sponsored by Senators Mike Enzi of Wyoming and Maria Cantwell of Washington and managed by in the National Oceanic and Atmospheric Administration (NOAA) through the National Severe Storms Laboratory. The National Severe Storms Laboratory, in turn, contracted this study to CASA, the Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere, a National Science Foundation research center focusing on the development of low-cost, short-range Doppler radar networks.

Part I of this study evaluates current system performance in the radar gap regions to determine if service deficiencies exist. This section looks at socioeconomic risk factors, climatology, historical impacts of hazardous weather, current radar coverage, NWS performance metrics, and feedback from stakeholders, such as emergency managers. Based on these findings, Part II evaluates which radar attributes, network solutions, and supporting infrastructure are needed. Both short-range and long-range radar solutions are considered.

II. Key Conclusions

The summary information compiled for this report points to three key conclusions:

- **Service deficiencies exist across the radar gap regions identified in Wyoming and western Washington.** Case studies, stakeholder interviews, and NWS warning statistics all indicate that severe storm warning lead times are below-average for those regions with limited radar coverage at low levels (< 3 km AGL). Detections of precipitation and wind shear at low levels are limited in radar gap regions.

- **Additional radar coverage below 3 km (10,000 ft) likely could improve public safety and reduce negative economic consequences from hazardous weather through improved real-time analysis and prediction.** In Wyoming, some towns (e.g., Gillette) and critical infrastructure (interstate highways, coal mines) have limited low-level radar coverage. Additional low-level radar data are needed in these areas for improving winter weather quantitative precipitation estimation (QPE) and quantitative precipitation forecasts (QPF) as well as monitoring low-level storm features. Dual-polarization would also aid quantifying winter precipitation and summertime convection, and higher spatial and temporal collection would improve monitoring of severe storms. For coastal Washington, high socially vulnerable areas and weather sensitive industries (e.g., fishing industry) have limited low-level radar coverage. Greater radar coverage in this region, particularly over the ocean, could improve the analysis and prediction of synoptic systems. Furthermore, dual-Doppler estimated winds could aid in identifying areas of strong winds, and higher temporal and spatial sampling could improve QPE and QPF.

- **Deploying additional weather radars in Wyoming and western Washington will require a system engineering approach to achieve an effective solution to the gap problem.** Hardware costs, siting, tower infrastructure, communication and electric power requirements, installation, communications interfacing, software integration and long-term maintenance and operations all will need to be carefully considered. For the deployment of short-range radars, consideration must be given to the availability of multiple sites, small power radars and communication availability, and long-term maintenance. For the deployment of long-range radars, consideration must be given to the "social footprint" (e.g., visual impact, land use) and specialized power and other infrastructure needs that accompany the installation of a large high-power radar systems.

More specific discussion of the meteorological assessment and feasibility of additional weather radar in Wyoming and western Washington are discussed below.

Wyoming

- **Significant radar coverage gaps exist in northeastern and southwestern Wyoming.** The gap regions in Wyoming lack radar coverage because of the distance between radars and mountain blockage. In Campbell County, no radar coverage is available below 3 km AGL, and only 24% of Johnson County and 39% of Sweetwater County have coverage below 3 km AGL.

- **Radar gap areas are regionally active areas for severe weather.** Based on historical data, Campbell County is three times more likely to report a tornado and twice as likely to experience flooding than other counties in Wyoming. Regional weather hazards during the warm season include tornadoes, hail, and straight-line winds. During the winter, storms often have snow, ice, and winds as their primary hazards.

- **A range of low to moderate societal vulnerability exists within the radar coverage gap regions.** Overall, Wyoming has a low population density with many isolated communities. The complex terrain contributes to highly variable weather risks across the state. However, Wyoming ranks 8th in the country in the percentage of homes that are mobile home units, thereby increasing resident vulnerability to tornadoes and high winds. Wyoming ranks 5th in the country in the percentage of the population born out-of-state. Non-native residents may be more susceptible than long-term residents to flooding and winter weather hazards common to Wyoming.

- **The principal socioeconomic risks in these counties are to the mining industry and transportation.** Wyoming provides 40% of the nation's coal, and 70% of this coal is mined in Campbell County. The coal industry uses forecasts and nowcasts of convective activity, snow, and winds to conduct its operations and protect its workforce. In Sweetwater County, Interstate 80 is a major east-west transit freight transportation route which closes from 3 to 45 days annually due to wind and snow, with an estimated negative impact to the national economy of approximately $84,000 to $333,000 per hour.

- **Interviews with National Weather Service forecasters having jurisdictional responsibility over radar gap regions indicate that the lack of observations in gap areas impact their ability to provide expert knowledge and warnings to stakeholders.** Findings from the interviews are confirmed by emergency managers and reinforced by the NWS warning statistics. For the counties sampled in the radar gap areas, lead times for severe storms, tornadoes, and flash floods are all below parent WFO averages. Most verification statistics for these three counties are below or much-below national averages. For example, in Sweetwater County only 14% of thunderstorm warnings are issued in advance.

- **Additional low-level coverage is recommended for the gap areas in Wyoming.** Low-level radar data are needed for improving winter weather QPE and QPF as well as monitoring low-level storm features. Dual-polarization would also aid quantifying winter precipitation and summertime convection, and higher spatial and temporal collection would improve monitoring of severe storms.

- Forty-two small X-band radars (21 radars in NE Wyoming and 21 radars in SW Wyoming) or two large S-band radars (one in each region), could provide this coverage. The 42 short-range (X-band) radars, deployed strategically along critical infrastructure, would provide extensive multi-Doppler coverage of wind and rain at low-levels (below 2 km AGL), thereby enabling real-time monitoring and improved prediction of warm-season severe thunderstorms and low-level winter weather. Two long-range weather radars could provide equivalent coverage at and above 2 km AGL.

Western Washington

- Radar coverage gaps in coastal Washington are primarily caused by beam blockage. Much of the region is blocked by the Olympic Mountains to the west, and so there is virtually no coverage over the ocean where the majority of western Washington's weather hazards originate.

- Large synoptic storms are the primary weather events faced by these regions. Powerful, mid-latitude cyclones often come ashore in western Washington and are the primary weather hazard to the region. These storms bring large areas of high wind and precipitation which interact with the mountainous terrain and create highly localized and intense wind and rainfall, events which are difficult to predict in numerical forecast models.

- Population along the west coast of Washington exhibits high social vulnerability based on a national index. This index measures a population's ability to prepare for and recover from natural disasters. Counties along the Washington coast share a high societal vulnerability and yet experience the greatest impacts from Pacific storms.

- Western Washington has significant industries and transportation routes that contribute to the national and international economy and that are sensitive to hazardous weather. For example, the lack of weather radar coverage over the ocean poses a safety hazard to the fishing industry. Interstate 5 is one of the busiest routes in the nation and intersects a radar gap area.

- NWS forecasters lack observations over the ocean and reliable data over land. Because of the lack of radar data over the oceans, analysis, tracking and prediction of these large synoptic storms is difficult. Only satellite data and a few buoy observations are available for assimilation into NWP models. Furthermore, because of the highly complex terrain, radar blockage, and a low melting layer (~ 2 km AGL), radar reflectivity over land also poses problems. Radar is often considered "a secondary tool", since the estimates may not reflect ground truth.

- Additional low-level coverage is recommended for the gap areas in Washington. A single, long-range radar deployed along the coast would expand coverage to include an additional 28,400 km^2 over the ocean, and up to 165 km offshore, enabling improved real-time analysis and long-term prediction of synoptic-scale systems. In addition, such radar data upstream of western Washington would provide impetus for the assimilation of radar data into numerical forecast models, an activity not currently undertaken. A network of 27 short-range radars, deployed along the coast, would provide multi-Doppler coverage as low as 1 km AGL along the coast and up to a distance of 40 km from shore. Over terrain, high resolution radar observations would help quantify locally intense terrain-forced precipitation improving QPE and identifying low-level wind hazards.

Three additional recommendations for determining if, when, and what type of radars to deploy to radar gap regions:

- Conduct an exhaustive cost-benefit analysis with detailed examination of siting requirements, infrastructure needs including communications and power, and a consideration of long-term operations and maintenance.

- Partner with local and state governments and other federal agencies (e.g., transportation) and the private sector (e.g., energy and railroad industries) for increasing local observational capabilities.

- Deploy a limited test radar network for a more complete evaluation. The full benefits, advantages or disadvantages of new technology, such as the short-range radars, may not be fully understood.

In summary, additional weather radar, strategically placed along and near critical weather-sensitive industries and infrastructure in radar gap regions, may improve public safety and reduce weather-imposed economic loss. Beyond simply filling gaps in existing coverage, additional radar capabilities such as rapid scanning, higher spatial resolution and multi-Doppler coverage and enhanced radar products such as provided by dual-polarization have the potential to significantly improve current observing and predicting capabilities. While financial resources may ultimately determine the type and number of radars deployed, the potential and far-reaching benefits posed by new observational systems should be thoroughly considered.

Introduction

Chapter 1

This study examines the risks, needs, and integration requirements for adding additional weather radar systems to fill gaps in the current weather radar coverage across northeast and southwestern Wyoming and western Washington. Approximately 70% percent of Wyoming and 37% of western Washington lack radar coverage at low levels (≤ 2 km above ground level (AGL)) because of the distance between existing radars, earth curvature, and mountain blockage. Weather climatology demonstrates that many hazardous weather phenomena form in the lowest few kilometers of the atmosphere.

Wright Tornado, Wyoming

On 12 August 2005 at 4:40 pm MDT, an F2 tornado with wind speeds estimated between 113-152 mph hit a mobile home park in the town of Wright, Wyoming. The tornado track was approximately 450 yards wide and 2 miles long, killing 2 people, injuring 13, and causing over $5 million in property damage, including damage to over 120 mobile homes. A NWS severe thunderstorm warning was in effect for the county prior to tornado formation, but a tornado warning was not issued by the NWS until 4 minutes after tornado touchdown. Wright, Wyoming, is located in northeast Wyoming, approximately 215 km (134 miles) from the nearest WSR-88D radar in New Underwood (Rapid City), South Dakota.

Two severe weather events, an F2 tornado in Wyoming and a three day coastal storm system in Washington, were the catalysts for this study. These events raised public awareness of deficiencies in the low-level weather radar coverage provided by the current National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) operational weather radar network of Weather Surveillance Radar – 1988 Doppler (WSR-88D) units, also known as Next Generation Weather Radar (NEXRAD). As a result, Senators Mike Enzi of Wyoming and Maria Cantwell of Washington sponsored this study as a 2008 U.S. Congressional appropriation "to determine the applicability to northeastern Wyoming and other regions the feasibility of integrating a number of small-scale Doppler radar technologies into future National Weather Service observing systems."

This report evaluates the *applicability* of installing short-range radars in northeastern and southwestern Wyoming and coastal Washington. This study provides a *meteorological assessment* of the need for additional weather radar, and if so determined, investigates the type of radar and radar attributes required for each region. This assessment is based upon the hazardous weather climatology, societal vulnerability, and current data limitations. This report does not address all the practical and technical engineering challenges of installing additional weather radars, as that requires a detailed cost-benefit analysis that is beyond the scope of this study. However, some experimental radar costs, siting challenges, and integration discussion are included in this report as guidance for more detailed, follow-up analyses.

Two radar solutions are considered by this study - short-range radars, such as those prototyped by CASA (National Science Foundation Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere), and for comparison, long-range radars, such as the WSR-88D. Networks of short-range (X-band) radars are now being designed and built in the research community. The advantages and disadvantages of short- and long-range radar solutions are examined and specific solution configurations are presented for each region of study.

This report examines the capabilities of short range X-band technology based on the expertise and experience of the authors with CASA radars. The CASA radars currently deployed in the CASA Oklahoma testbed are magnetron-based, mechanically scanning radars and are the prototype referenced herein. An electronic-scanning panel (Sanchez and Jackson 2008) is now being designed by CASA as a research tool. A commercial version is being developed by Raytheon (Sarcione et, al, 2008)

It is important to note that the X-band technology discussed in this report, namely the CASA radars, were designed specifically for research experiments conducted by CASA's academic participants. CASA is set up with an industrial arm of radar technology and manufacturing companies. These companies have rights to commercialize the technology being developed within CASA and technology transfer efforts are underway. Commercial sales of these radars have not occurred as of this writing.

December 1 – 3 Coastal Storm, Washington

Between 1 and 3 December 2007, a series of three consecutive storm systems hit the western Washington and Oregon coasts, bringing severe winds, flooding rains and heavy snow. During 2 and 3 December, strong to severe winds were recorded for nearly 36 hours, with coastal winds reaching up to 220 km/hr (137 mph) at Holy Cross, Washington and 208 km/hr (129 mph) at Bay City, Oregon. Heavy rains were also recorded during 2 December, with over 270 mm (10 inches) of rain recorded within 24 hours at Bremerton, Washington. Fourteen people were killed and over $1 billion in property damage were reported in western Washington. National Weather Service high wind warnings and river flood warnings were issued well in advance, but flood warnings for stream headwaters for at least one county, Lewis County, were issued several hours after flood rescue operations had commenced. Areas of flooding were over 120 km (75 miles) from the nearest WSR-88D located in Portland, Oregon.

This report applies the criteria used for evaluating radar network performance as set forth by the National Research Council (NRC) 1995 report titled "Toward a new National Weather Service: Assessment of NEXRAD coverage and associated weather services" including analysis of weather phenomena in the area of concern, radar coverage, and performance of the composite system. In addition, user needs for weather information are evaluated. These topics are addressed through the following questions that form the outline of this study:

Evaluating System Performance

- **What are the severe weather threats, risks, and vulnerabilities?** This question is answered in Chapter 2 which reviews the weather risks and impacts across Wyoming and western Washington and how well these phenomena are detected by the current weather observing system. The economic sensitivity and social vulnerability of each region is examined in detail.

- **What data limitations exist with current weather radar coverage?** Chapter 3 quantifies the low-level radar coverage (< 3 km AGL) and identifies those areas with limited radar coverage across Wyoming and coastal Washington.

- **Do current data limitations impact service performance?** The NWS warning performance and the associated warning infrastructure are considered in Chapter 4.

Feasibility of Additional Radar

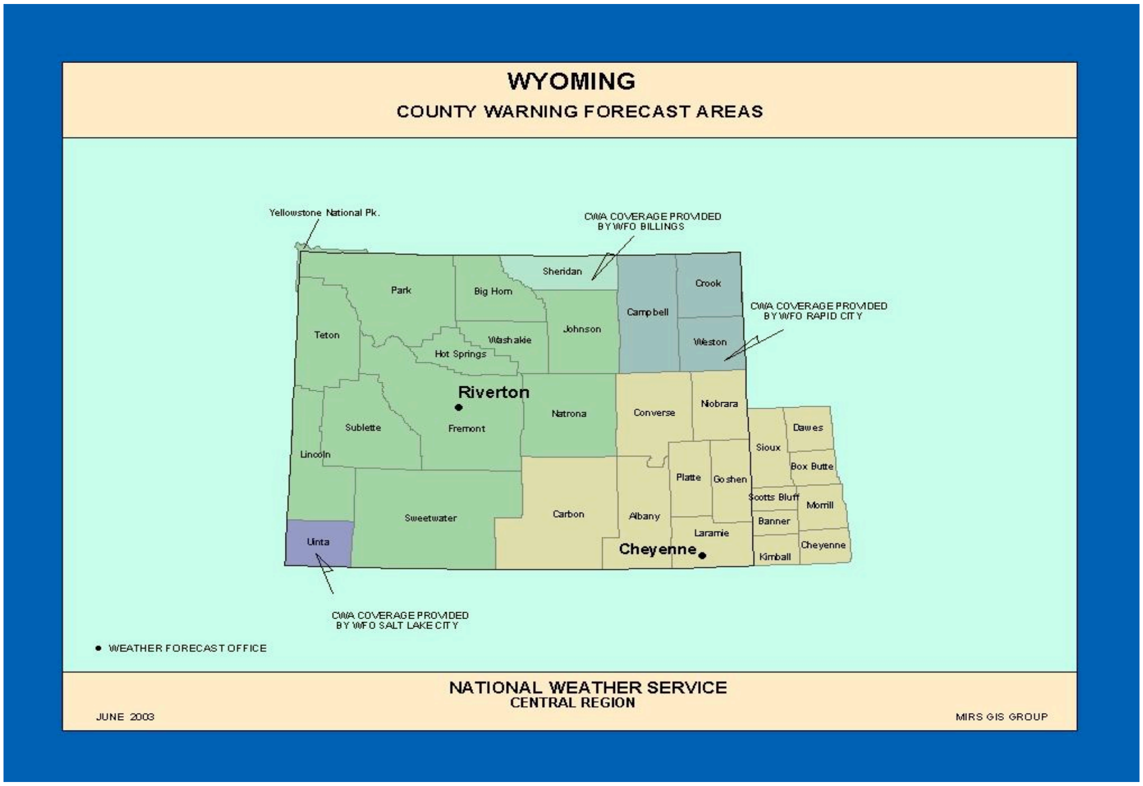
- **What specific radar attributes are required to address these needs?** An examination of the radar attributes required to address the needs and data coverage gaps across northeastern and southwestern Wyoming and western Washington are summarized in Chapter 5. The specific radar attributes needed at each location will vary with the weather phenomena and societal vulnerability.

- **What potential radar solutions could address these needs and data limitations?** In Chapter 6, radar network solutions are considered. The specifications of long-range and short-range radars are compared against the observing needs of each region of interest.

- **What supporting infrastructure and integration requirements are needed to support additional radars?** Costs, logistics, and integration issues potential radar solution are listed in Chapter 7. Hardware costs, siting, infrastructure requirements, and long-term maintenance and integration are considered for each potential solution within each area of interest.

The areas of focus for this study are limited to the radar gap regions (i.e., those areas without radar coverage at or below 3 km AGL) of Wyoming and western Washington. In Wyoming, the study will be limited to portions of the NWS Weather Forecast Office (WFO) County Warning Area (CWA) of Riverton, WY, Rapid City, SD, and Billings, MT (Figure 1.1), with particular focus on three specific counties within the radar gap regions – Sweetwater, Johnson, and Campbell Counties. In western Washington, the study will be limited to the WFO CWA of Seattle, WA, and Portland, OR (Figure 1.2), with a particular focus on Grays Harbor, Pacific, and Lewis Counties. Although the analysis is for these specific areas, we expect that many of the results from this study can be applied to other locations nationwide.

The scope of this study was limited to investigation of radar deployment only, and as a result, there is little discussion of non-radar systems. A complete listing of radar and *in situ* networks for Wyoming and western Washington are provided in Appendix A.



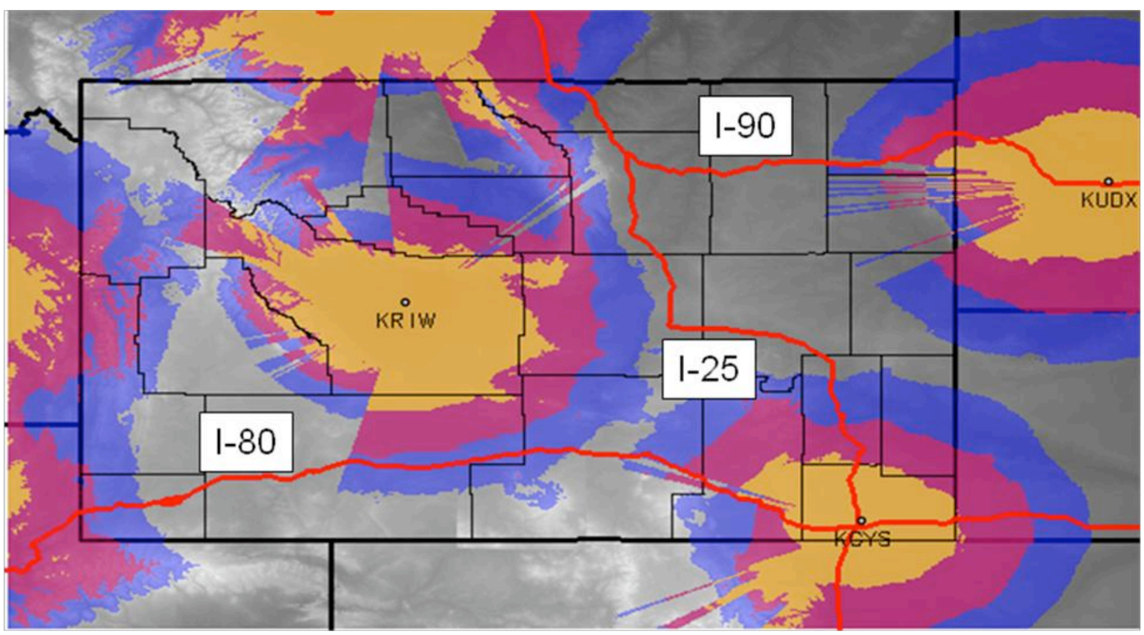


Figure 1.1: (Top) The County Warning Forecast Areas of Wyoming. Figures courtesy of the NWS (http://www.weather.gov/mirs/public/prods/maps/state_list_cwfa.htm). (Bottom) The existing radar coverage at heights 1 km (yellow), 2 km (red) and 3 km (blue) AGL. Interstate highways are marked in red and county outlines are marked in black.

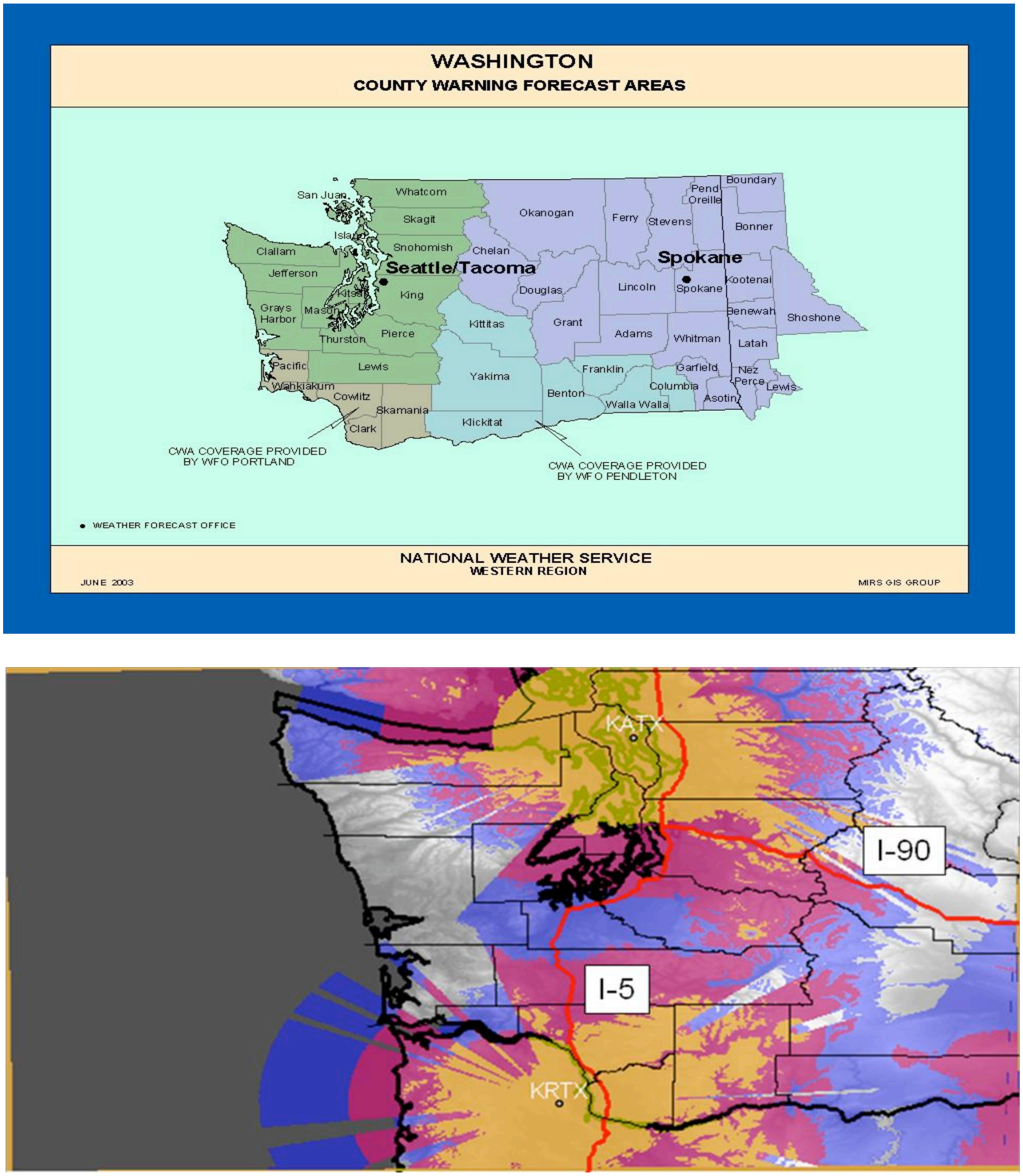


Figure 1.2: (Top) The County Warning Forecast Areas of western Washington. Figure courtesy of the NWS: (http://www.weather.gov/mirs/public/prods/maps/state_list_cwfa.htm). (Bottom) The existing radar coverage at heights 1 km (yellow), 2 km (red) and 3 km (blue) AGL. Interstate highways are marked in red and county outlines are marked in black.

System Performance

Chapter 2: Socioeconomic and Climatological Risks

What are the severe weather threats, risks, and vulnerabilities?

2.0 Introduction

This chapter assesses the weather information needs and deficiencies, as well as risks and impacts from hazardous and severe weather[2] in areas with limited radar coverage below 3 km AGL (i.e., "radar gap areas") in northeastern Wyoming, southwestern Wyoming, and coastal Washington. We examine these needs in the context of the NOAA and NWS mission — protecting life and property, supporting the economy, and managing natural resources (NOAA 2008) — and the role of radar data supporting this mission.

As described in Chapter 6, NEXRAD was originally deployed to improve detection and forecasting of severe thunderstorms, tornadoes and wind events. The weather Service Modernization act of 1992 established the radar coverage criterion that the system provides complete coverage over the conus at the height of 3.05 km (10,000 ft) above ground level. Population density and the relative location of airports, military weather service facilities were the principal socioeconomic factors used to determine priority areas for lower altitude radar coverage (Leone et al. 1989). In this chapter, we update these criteria to include current knowledge and experience. To address NOAA's mission of protecting life, we reviewed population patterns as before, but we also introduce new criteria — expanding on CASA's experience (e.g. Philips 2007, Donner 2007, Baumgart 2009) in evaluating user needs for weather radar — such as *i)* feedback from local emergency managers on the adequacy of weather information, *ii*) indicators of social vulnerability, a measure of a population's ability to prepare for and recover from natural disasters (Cutter et al. 2003), and *iii)* NOAA data on deaths, injuries, and property damage caused by hazardous weather events. We address NOAA's mission of promoting the economy by examining industries and infrastructure that are sensitive to hazardous weather and that are important to the state and national economy. And lastly, we review a broad range of weather phenomena, such as snow events and flooding, as observed with NEXRAD to identify any limitations inherent to the current system.

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[2] *Severe weather is generally understood as referring primarily to convective events such as tornadoes, large hail, strong winds and flash flooding and is officially defined by the NWS. For example, the official NWS definition of a severe thunderstorm is one that produces tornadoes, hail ≥ 0.75 inches in diameter, or winds ≥ 50 knots (58 mph). However, hazardous weather is understood more broadly as any weather phenomena that has the potential to cause damage to property or threaten public safety and may also includes lightning, extreme temperatures or heavy snowfall. The NWS also issues warnings to the public for non-convective events, such as high wind warnings for winds ≥ 58 mph (or ≥ 40 mph sustained for at least one hour) and wind chill warnings for wind chill temperatures below -30° F. For this study, we will refer in broad terms to hazardous weather, but for verification purposes will use the strict NWS definitions when classifying event severity.*

In the first section, the socioeconomic risk factors are reviewed. These include industries, populations, and infrastructure that have social or economic significance and that could benefit from more informative nowcasts (weather information and forecasts of 0-1 hours) and forecasts (weather forecasts beyond 1 hour). "Significance" at this stage is broadly defined, through comparison to nationwide or statewide rankings from the following data sources: US Census, Bureau of Economic Analysis, the National Climatic Data Center, the Hazards and Vulnerability Center at the University of South Carolina, and federal and state transportation departments. These data and statistics are used in conjunction with interviews of industry representatives, weather service forecasters, and emergency management personnel conducted by the authors. This section will identify areas where additional radar data, and by extension radar deployments, are likely to have positive socioeconomic impact. Further analysis, through the deployment of prototype test beds or additional research could quantify more precise benefits and serve as a basis for policy decisions.

Second, hazardous weather climatology is reviewed for each region. The climatology is defined by the *frequency*, *severity*, *spatial extent*, and *duration* of the hazardous weather event. To provide this historical context, a summary is presented of previous Presidential Federal Disaster Declarations and storm event archives from the NOAA National Climatic Data Center (NCDC) which highlights the hazardous risk type and frequency for each region. State climatology data details specific risk areas.

And lastly, a series of case studies are presented for each of the severe weather hazards found within each state. These case studies provide examples of the challenges faced by forecasters when attempting to detect and forecast such events, particularly in areas where data are limited. Because radar data are key to the detection and warning of many hazardous weather events, case studies focus on those areas where low-level radar data are sparse due to distance and/or terrain blockage.

These sections together paint a picture of the risk factors faced by the counties in the radar gap areas and set the stage for evaluating additional radar coverage.

2.1 Wyoming

Wyoming is among the most vast and sparsely populated states in the country. The estimated state population in 2006 was 515,000, ranking Wyoming as the least populated of all 50 states (U. S. Census Bureau 2006). In land area, Wyoming ranks 10th (U. S. Census Bureau 2000), yielding a population density of 2.0 persons per square kilometer. This compares with a national average population density of 32.6 persons per square kilometer. Many communities throughout Wyoming are small (< 100 people) and isolated, posing challenges for hazardous weather warning and response operations.

Wyoming had a Gross Domestic Product (GDP), a measure of economic activity, of $31 billion in 2007, ranking the state 48th in the nation; however, the per capita GDP is among the top five in the nation (Bureau of Economic Analysis 2006). The state economy depends on the mining industry which accounts for 30% of the GDP and allows Wyoming to have among the lowest taxes in the nation. Wyoming provides 40% of the coal for power generation in the U.S. (Energy Information Administration 2008).

The greatest weather hazards in Wyoming are winter storms, tornadoes, and severe thunderstorms, which include severe wind, hail, and floods. Despite these many hazards, however, the threat to public safety and infrastructure remains low (relative to other areas of the country) due in part to the sparse population. Nevertheless, certain population centers, infrastructure, and weather-sensitive industries are at risk, and as will be shown in Chapter 3, these same regions have limited low-level radar coverage. Wyoming's complex, mountainous topography complicates weather nowcasting and forecasting operations throughout the state. Microclimates vary within each mountain pass and valley, resulting in significant differences in temperature, precipitation, and wind across very short distances. As shown in Chapter 3, mountains block radar coverage at low levels.

The chart in Table 2.1 summarizes several key socioeconomic risk factors for select counties in the state of Wyoming. These are explained in more detail in subsequent sections.

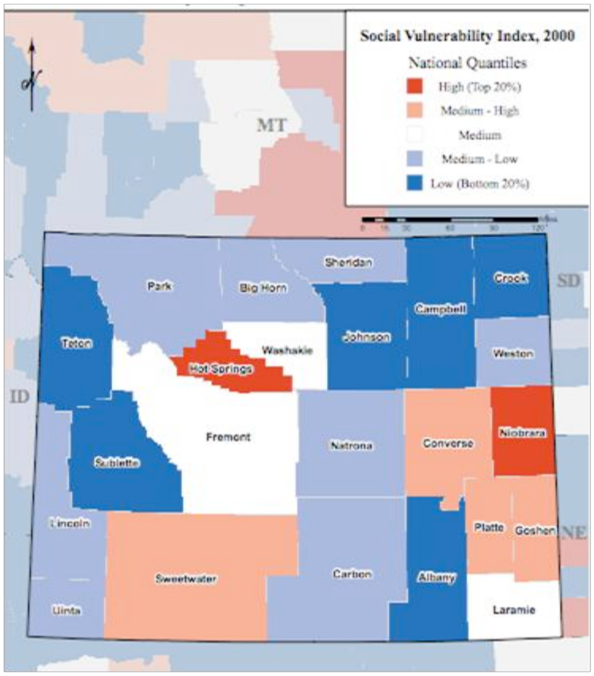
Table 2.1: Summary of the socioeconomic risk factors in select counties in the gap coverage regions of Wyoming.

Risk Criteria	Campbell County	Johnson County	Sweetwater County
Emergency Manager Concerns[3]	Sufficient lead time for tornadoes, severe winds. Forecasts of snow and ice.	Sufficient lead time for floods	Lead time for winter weather, high winds, floods.
Overall Social Vulnerability (Year 2000)[4], quintiles for US counties	Low (5th quintile)	Low (5^{th} quintile)	Med (3^{rd} quintile)
Population[5], quintiles for US counties	Low (5^{th} quintile) Total Population: 38,934	Low (5^{th} quintile) Total Population: 8,014	Low (5^{th} quintile) Total Population: 38,073
Population Density[5] US: 32.2 people per sq. mile	Low 7 per sq. mile	Low 1.7 per sq. mile	Low 3.6 per sq. mile
Population Growth US Avg: 2000-2006 6.4%	15.5%	13.3%	3.6%
Property Damage, Injuries, Deaths [6]1960- 2005 Statewide Comparison	High	Med/Low	Low
Economic Activities Sensitive to Hazardous Weather[7]	Mining Transportation (rail)	Transportation	Mining Transportation Airport

[3] *Based on interviews with emergency mangers having jurisdictional responsibility in the three counties*
[4] *Based on data from the Hazard and Vulnerability Research Center*
[5] *US Census data*
[6] *NCDC data and FEMA data compiled by the Hazards and Vulnerability Research Center by county*
[7] *Defined as organization that i) uses nowcasts and forecasts to protect workers or schedule/modify operations, ii) operates in the gap coverage areas and ii) and is ranked among the top three sectors by gross domestic product for a state (Bureau of Economic Statistics), or contributes to the national economy.*

2.1.1 Socioeconomic risks

a. Vulnerable populations.



According to a national social vulnerability index (SVI), which measures the ability for populations to prepare for and recover from environmental disasters based on socioeconomic status, many areas of Wyoming have a low level of vulnerability (Figure 2.1). This index includes several factors such as the concentration of elderly and children, development density, rural agriculture, race, gender, ethnicity, infrastructure employment, and county debt/revenue (Cutter 2008). The low population, relatively high per capita income, and young age of the population in Johnson and Campbell counties indicates that these areas are less socially vulnerable to hazardous weather. On the other hand, Sweetwater County, located in a second radar gap area, has a medium to high SVI[8].

Figure 2.1: Social vulnerability index calculated per county for Wyoming in 2000 (Hazards and Vulnerability Research Institute; Cutter 2008).

However, despite the small population and high per capita income, social vulnerability in these counties is increasing. Figure 2.2 shows the percentage population growth by county from 2000 – 2006. Two counties experiencing rapid growth, Johnson County (+ 15.1%, population of 8,000) and Campbell County (+20.0%, population of 33,698), are located in a climatologically active area for severe storms. These areas historically have had relatively low lead time for severe weather events (see Tables 4.2-4.4). In addition, Wyoming ranks 8th in the country in the percentage of housing units that are mobile homes, with approximately 14.2% +/- 1.1% of all housing units identified as mobile homes (U. S. Census Bureau 2006). Residents of mobile homes are much more likely to be injured or killed by a tornado (Ashley 2007). The two deaths from the tornado in Wright, Wyoming, in 2005 occurred when the tornado struck a mobile home park. Moreover, Wyoming has a large ratio of residents from out-of-state; less than half (43.8% +/- 1.1%) of current residents were born in Wyoming (U. S. Census Bureau 2006). Wyoming is ranked 5th in the country in the percentage of current residents born out-of-state. Newcomers to an area are less familiar with local severe weather hazards, the behavior of local rivers and streams, political boundaries, escape routes and shelters, and local emergency information, and are thus more vulnerable to local weather hazards (personal communication, NWS forecasters).

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8 *A more detailed analysis of each county may reveal sub-regions of social vulnerability.*

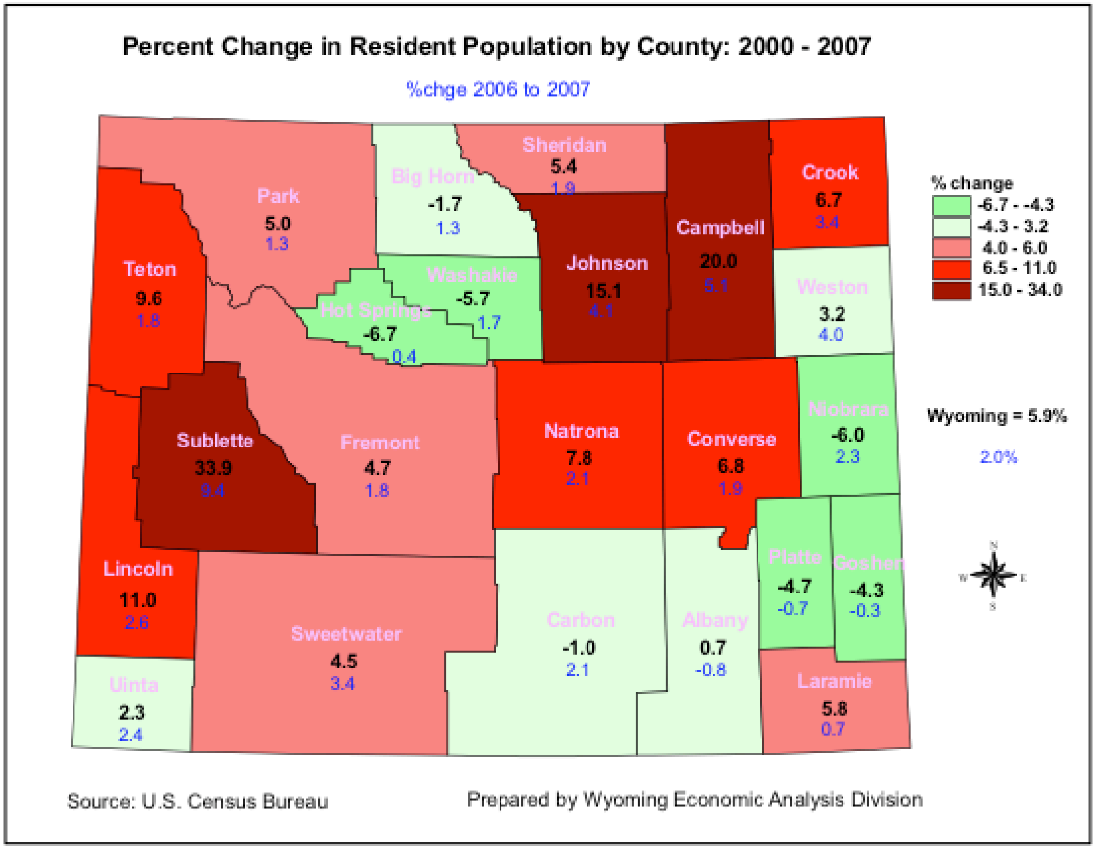

Figure 2.2: Percentage growth in population from 2000 – 2007 by county (Liu 2008a).

b. Importance of the mining industry to the state and national economy.

Wyoming's economy is dominated by mineral production including coal, natural gas, crude oil and non-metallic mining. Mining accounts for 30% of Wyoming's Gross Domestic Product, which was $31 billion in 2007 and contributes a full two thirds of the state's local total revenue, making the household tax burden in Wyoming among the lowest in the nation (Liu 2008b). Wyoming's coal production is also important to the national economy as Wyoming typically provides 40% of the coal consumed by the rest of the United States (Detweiler and Yu 1998). According to a 1998 report, 66.8 percent of total statewide coal mining occurs in Campbell County, and 72% percent of the total non-metallic (trona, bentonite, soda and potash) quarrying was in Sweetwater County. Both counties are located in radar coverage gap areas (i.e., bottom of lowest radar beam is ≥ 3 km AGL across 100% of Campbell County and 61% of Sweetwater County; see Table 3.2). Oil and gas production is concentrated in Sublette, Sweetwater, Johnson, Fremont, and Campbell Counties.

The top ten coal producing mines in the country are located in the Powder River Basin in Campbell County (Wyoming Coal Information Committee 2007) and this coal is carried from the mines to power plants across the country by Burlington Northern Santa Fe, and Union Pacific Railroads. NWS products are regularly used to facilitate the production, air pollution mitigation, and transportation of coal. Some companies maintain on-site weather stations to measure temperature and wind direction and all routinely consult with NWS offices for forecasts. Mining companies use weather information in three ways:

1. *To protect employees from snowstorms, cold, severe weather and winds.* Mining companies consult three hour to one day forecasts to determine whether traveling and working conditions are safe for the miners. Inaccurate forecasts can translate to lost revenues for the day.

2. *For blasting operations.* Wyoming coal is extracted through blast mining which occurs at the surface and involves large machinery. In order to start blasting operations, mining companies consult one to two day forecasts looking for periods of time with no convective activity and wind speeds below 20 mph.

3. *To protect equipment and monitor the flow of dust particulate matter.* If wind speeds increase beyond 20 mph, coal mining companies take steps to protect the very large equipment used and may cease operations to reduce the flow of dust into areas outside of the mining region. In addition, mining companies are required to file reports to environmental agencies when wind levels exceed the 20 mph threshold.

The railroads that carry the coal from the mines to the Midwest are critical to utility power generation in that region. In fact, disruptions and delays in the transportation of coal can have impacts on utility prices. In an extreme case, in August 2005, the tracks in the Powder River Basin washed out due to rain and accumulation of coal dust, causing a major disruption in service. One report estimated that utility prices increased by 15% in parts of the Midwest due to the disruption (Stainsby 2005). Daily railroad operations are weather sensitive. Winds, snow and ice are tracked to determine safe speeds of travel, and temperature and wind are monitored to determine if and when chemicals should to be applied to freight cars to minimize the dispersion of coal dust. BNSF contracts with Weather Data, a third-party weather forecast provider, who has indicated that the lack of low-level radar data in Campbell County presents challenges for providing weather forecasts.

c. Freight transportation (railroad and highway)

Freight transportation, which includes rail, highway, and pipeline networks, contributes to the state and national economies. At the state level, the transportation system links the geographically sparse towns and cities and carries state-produced goods out of Wyoming. Mining products, primarily coal and soda ash, were valued at $21 billion and accounted for 316 million tons of freight (Office of Freight Management and Operations 2002). Railroads carry most of the coal from the Powder River basin in Campbell County, while trucks transport other commodities such as cement and soda ash. Pipelines are an important source of transport for the oil and gas industries (Young et al. 2005).

The busiest rail and highway routes extend though the radar gap coverage areas in Campbell, Johnson and Sweetwater counties. Federal interstate I-80, a 402 mile east-west route across the southern part of WY, has the highest daily average commercial traffic count in the state. The second busiest highway, I-25, extends north-south for 315 miles, partly through Johnson county and connecting to I-90. The two principal railroad routes are oriented north to south through Campbell County, bringing coal from the Powder River area and from areas close to I-80.

Although economically important to Wyoming, freight transport to, from and within the state explains only 8% of overall transportation activity. Commercial freight traveling through Wyoming to other states accounts for the vast majority of activity, almost 92% of the tonnage transported. Interstate 80 is the principal interstate highway commerce route, and traffic on I-80 is projected to double by the year 2020. I-80 serves as an important route for moving goods from the Midwest to the Intermountain Region and beyond to the West Coast. Thus, disruptions in traffic impact not only the state economy, but also have national economic repercussions. The increasingly widespread use of Just-in-Time inventory techniques makes road weather closures even more disruptive to the national economy (Young et al. 2005).

Wyoming highways are affected by snow, ice, high wind and blowing snow conditions (i.e., > 40 mph) that cause transportation officials to close roads or restrict traffic on the roads. For example, between March 2005 and March 2008, I-80 was closed in Sweetwater County for 101 hours due to poor weather conditions, according to the WYDOT Research Center. An important issue is the cost of these road closures, a question that has been addressed by several white papers (Schneider et al. 2005, Mallet 2004, and Maze et al. 2005).

One Wyoming Department of Transportation (WYDOT) study on alternative transportation strategies (Schneider et al. 2005) estimated the cost of road closures for I-80 based on research from Maze et al. (2005), where commercial freight costs were estimated between $100 – $140 per hour per truck for expected delays and about $370 per hour per truck for unexpected weather delays. These estimates include the downstream cost of impacts such as delays in manufacturing, or missed opportunities for sales due to low inventory levels. The study also assumes that with projected road traffic of 300 trucks per hour, closed interstates cost between $84,000 and $333,000 per hour. At these rates, the I-80 closures during January and February 2008 in Sweetwater County cost the national economy an estimated $22 - $90 million dollars. Although there is a wide range in these costs, they show the magnitude of the impacts of road closures, and the potential of reducing economic costs by decreasing road closings even by a small percentage.

WYDOT's first priority is to understand weather conditions, rain, snow, ice, and high winds on the roads. Wyoming has recently installed Road Weather Information Systems (RWIS) along I-80 that provide point information (see Appendix A). However, the provision of volumetric, lower-troposphere, geographically specific radar data could provide more comprehensive weather and road condition nowcast information. One WYDOT study (Schneider et al. 2005), which correlated accidents with high winds, concluded "if more information were available about what type of weather conditions and corresponding traffic speeds cause crashes, officials could make better operational decisions about when to close the road and when to post warnings and speed reduction recommendations. If the effects of weather were better understood, officials could maintain freight movement for longer periods while still maintaining a high level of safety."

2.1.2 Weather hazard climatology

Based upon historical records of fatalities, injuries, and damage estimates, the predominant weather hazards for Wyoming include snow and ice storms, hail, tornadoes, flooding, and severe straight-line winds. Severe thunderstorms are common across the eastern one-third of Wyoming during the spring and summer months, with snow and ice storms common across much of the state during the winter season. Archives of Presidential Federal Disaster Declarations and NCDC Storm Event records present a historical overview of the weather hazard climatology of Wyoming.

Presidential Federal Disaster Declarations

Since 1953, Wyoming has had seven Presidential Federal Disaster Declarations (Appendix Table B.1). During the last ten years, there have been three events, including two severe winter storms and one tornado.

Wyoming is tied at 54th out of 59 U.S. states and territories in the number of Presidential Federal Disaster Declarations between 1953 and 2008 (FEMA 2008). The relatively few Declarations requested for Wyoming appears more a function of the sparse population and impact rather than the relative hazard risk (as shown by Table 2.1). Since 1953, there have been 1,774 federally declared disasters nationwide, with a national average of 32 per year (FEMA 2008). The average number can vary significantly with presidential administration and is not necessarily an indication of storm severity; federal declarations are made when local and state agencies request federal assistance (FEMA 2008).

NCDC Storm Event Archives

An examination of the U.S. Storms Event Database from the NCDC shows a much more complete record of severe weather hazards for Wyoming. Comprehensive storm records began on 1 January 1993 and select storm events recorded in Wyoming since that time are tabulated in Table 2.2. For all storm data collected between 1 January 1993 and 30 June 2008 3,674 storm events are listed for Wyoming, ranking it 36th among 55 U.S. states and territories. NCDC data on economic impacts reflect reported damage to property caused by the event. It does not include, for example, the economic cost of road closures and opportunity costs for businesses.

Table 2.2: Storm events for Wyoming as recorded in the NCDC Storm Events database between 1 January 1993 and 30 June 2008.

Event	Total	Fatalities	Injuries	Damage ($)
Tornadoes	161	2	17	$ 6.1M
Thunderstorm, High Wind	1,032	1	68	$ 4.7M
Hail	1,404	0	7	$62.6M
Lightning	42	6	45	$ 0.8M
Floods	176	2	0	$ 5.0M
Snow/Ice	634	21	130	$ 9.3M
Extreme Temperatures	10	1	0	$ 0.2M
Forest Fires	65	1	11	$ 4.3M
Total	3,524*	34	278	$93.0M

*Additional storm events not shown include reports of heavy precipitation, fog, drought, dust storms, funnel clouds, and ocean and lake surf.

According to the NCDC storm event statistics, snow and ice storms are the single greatest cause of weather-related fatalities and injuries, while hail has the greatest economic impact. Many of the snow/ice related fatalities are associated with avalanches.

Storm event statistics also are presented for three Wyoming counties (Campbell, Johnson, and Sweetwater Counties) in Appendix Tables C.1 – C.3. As shown in Chapter 3, these counties are in areas located either far from an existing WSR-88D or in an area of significant radar blockage (Figure 3.3, Table 3.2). Storm Event records show a total of 358 events for Campbell County, 111 events for Johnson County, and 87 events for Sweetwater County recorded since 1 January 1993. A tornado, flood and extreme cold event led to the four weather-related fatalities in Campbell County, with most injuries due to tornadoes and severe thunderstorms. Hail and tornadoes also caused the greatest economic impact. For Johnson and Sweetwater Counties, flooding caused the greatest economic impact, with severe thunderstorms, lightning, and winter weather the cause of the injuries and one fatality.

A comparison of the total number of storm events from select counties from within the gap areas with an average from all counties in Wyoming are shown below in Figure 2.3. These figures show that Campbell County is a climatologically active area for severe convection, floods and snow events.

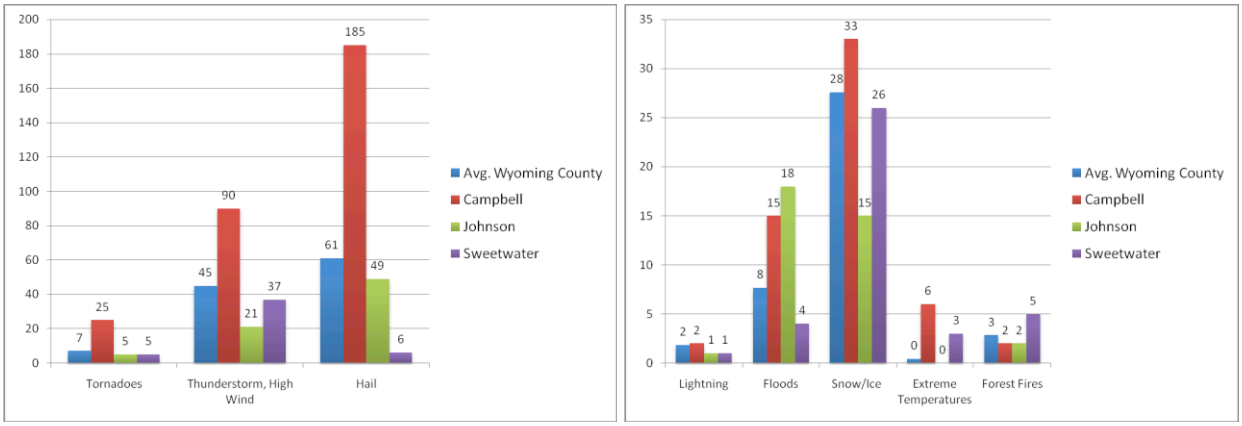

Figure 2.3: Total number of storm events for the period 1 January 1993 to 30 June 2008 for select counties from within the radar gap regions and averaged per county from across Wyoming.

2.1.3 Selected Case Events

As shown, Wyoming experiences the full range of weather-related threats including winter weather, severe thunderstorms (wind, hail, and tornadoes), flash floods, severe winds, and fire weather. Examples from specific weather events highlight the challenges facing stakeholders in observing these phenomena.

a. Winter Weather

Winter weather includes blizzards, heavy and drifting snow, ice, avalanches, and extreme cold, and as shown in Table 2.2, is the greatest threat to public safety across Wyoming. Winter weather accounts for over 62% of all weather-related fatalities and 47% of all injuries. Many of these fatalities are avalanche deaths; Wyoming is 6th in the country in annual avalanche deaths with an average 1.7 per year and 41 fatalities since 1985 (Moore 2008). As discussed, winter weather has major economic impacts on transportation, shutting down major transportation routes (e.g., I-25, I-80) sometimes for days at a time. High winds that occur during and after snow events blow snow on the highway, greatly decrease visibility and which can lead to road closures. Wyoming has installed snow fences along long stretches of highway to help mitigate this problem. Snowmelt has a tremendous impact on the state's water supply and can contribute to flood levels in the spring and early summer months.

In discussions with county emergency managers, many cited winter weather as their greatest weather hazard. Stakeholders require both real-time observations of snowfall and winds as well as forecasts of temperature, moisture, and potential snowfall amounts and locations. Schools, highway transportation, and aviation all are dependent upon both real-time weather information as well as short- and long-term forecasts. However, decision-makers cite three factors limiting their ability to nowcast and forecast such events: i) the microclimates associated with complex terrain; ii) the typically low-topped elevation of most snowstorms (< 25,000 ft (~ 7.62 km)); and iii) limited radar coverage at low levels.

Most winter precipitation falls from shallow, stratiform systems, and as shown by Heggli and Rauber (1988), much of the supercooled liquid water that contributes to heavy snowfall is found within the lowest 1 km near the surface. In complex terrain, much of this lowest layer is not observed by weather radar and surface in-situ observations often are scarce. Furthermore, the wind and temperature variability within terrain-induced microclimates further complicate nowcast and forecast capabilities.

A winter storm event in Gillette, Wyoming, on 27 March 2008 illustrates the challenge of observing snowfall in real-time from the current suite of weather radars. Surface stations in Gillette reported thundersnow at 2300 UTC and moderate snow at 0000 UTC. However, data collected by the nearest WSR-88D, KUDX, in Rapid City, SD, showed no radar reflectivity and thus no snowfall during that time (Figure 2.4). The height of the lowest beam from KUDX is ~ 4.5 km AGL over Gillette.

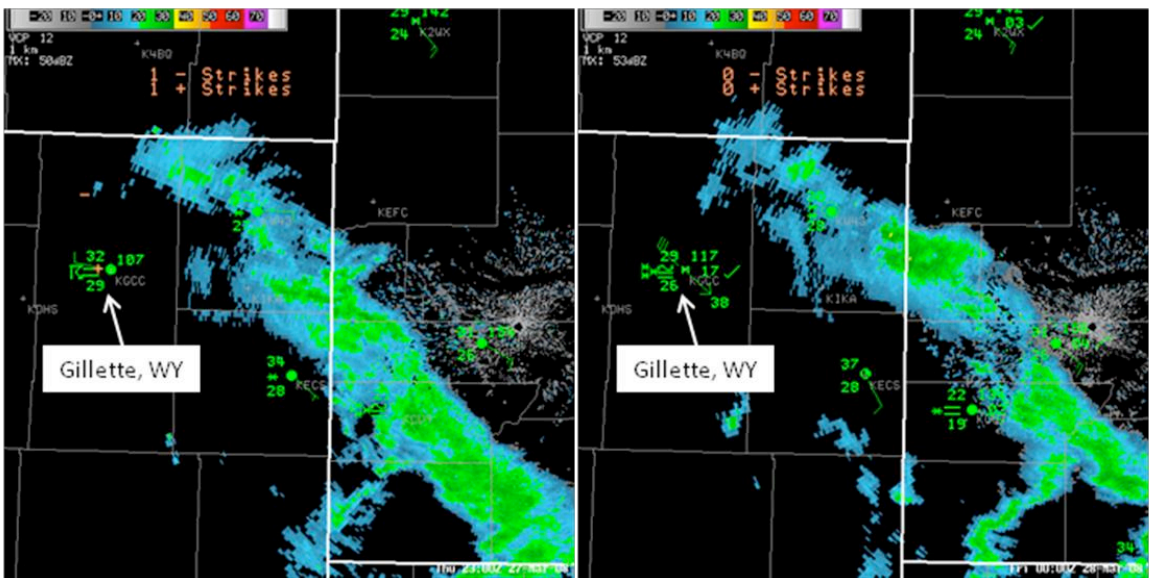

Figure 2.4: Reflectivity from KUDX on 27 March, 2008. Data collected at a) 2300 UTC, and b) 0000 UTC. Surface observations at Gillette indicate thundersnow, but radar imagery shows little reflectivity across Campbell County. Case study and figures provided by Matthew Bunkers, Rapid City WFO.

b. Severe Thunderstorms

Severe thunderstorms (tornadoes, hail, and severe winds) and lightning together cause over 26.5% of fatalities, 49.3% of injuries, and over 74.2% of all economic damage from weather-related causes in Wyoming (NCDC Storm Events Data). An annual climatology of thunderstorm days shows that the greatest thunderstorm activity is confined to the eastern one-third of the state (Figure 2.5; Curtis and Grimes 2004); much of the severe thunderstorm activity (and subsequent damage) is also confined to this region.

Tornadoes pose a significant threat to some areas of Wyoming (Figure 2.6). Data collected from the Storm Prediction Center (SPC) show that between 1950 and 1994, Wyoming recorded 434 tornadoes, ranking them 25th (out of 56 states and territories). During that same period, Wyoming had 2 tornado fatalities, ranking the state 33rd nationwide in tornado fatalities. In data collected between 1950 and 1999, annual tornado damage amounted to over \$1.7 million per year, ranking Wyoming 40th of all 50 states.

Tornado vortex signatures (TVSs) cannot be observed by weather radar beyond ~ 100 km from radar, so mesocyclones and rear flank downdrafts (RFDs) are used by forecasters as indicators of a possible tornado threat. Nevertheless, in regions of severe blockage and distances far from existing radar, such as Campbell County, even these indicators may not be observed. Further complicating warning operations, landspout tornadoes are also more common in the western U.S.; landspouts are tornadoes that form from vertical stretching of low-level vorticity, rather than as a result of strong rotation in mid-level mesocyclones. Landspouts can produce damaging tornadoes and many such tornadoes are observed in the Denver area and also near Cheyenne (Szoke et al. 2006; David King, personal communication). In both of those areas, southeasterly winds, often bearing moisture from the Plains, interact with the local terrain (Palmer Divide and Cheyenne Ridge for Denver and Cheyenne, respectively) to produce low-level cyclones that can provide the source of low-level vorticity for landspout tornadoes.

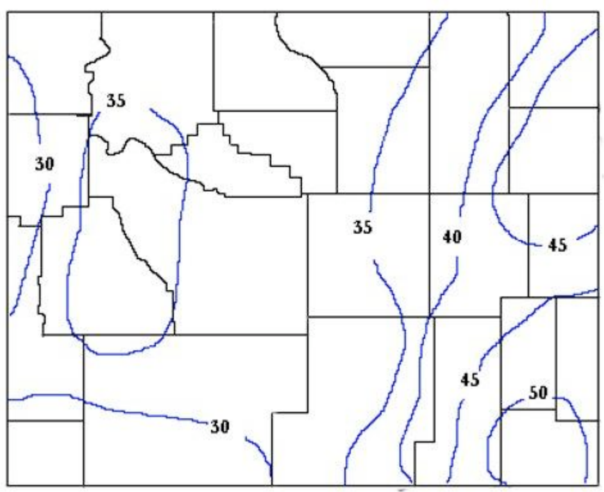

Figure 2.5: Climatology compiled from data collected 1901-1995 of average number of thunderstorm days in Wyoming (Curtis and Grimes 2004).

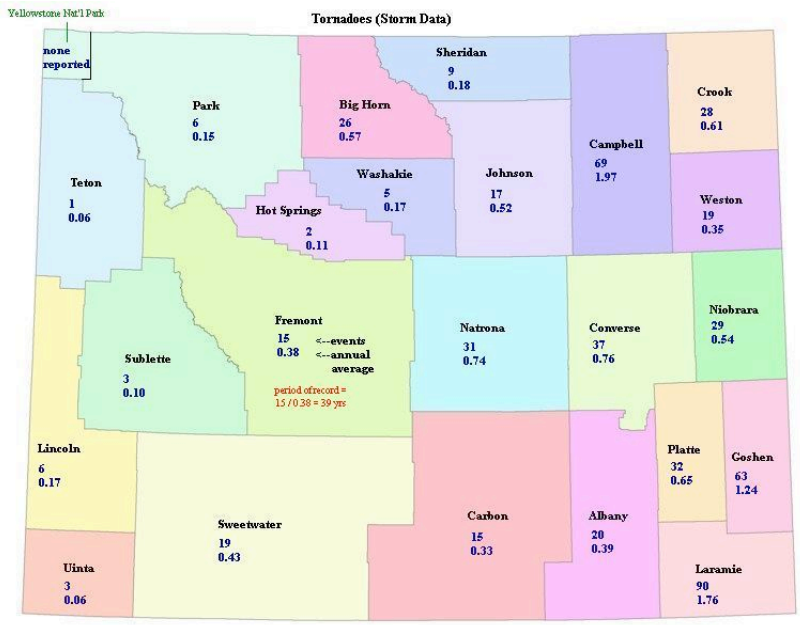

Figure 2.6: Climatology of the average annual number of tornadoes in Wyoming by county. Data record length varies by county and is shown (Curtis and Grimes 2004).

One recent tornado near Gillette, Wyoming, on 20 June 2008 demonstrates the challenge in providing advanced tornado warning to some areas. The storm occurred outside of the velocity coverage range of radars at Billings (KBLX) and Rapid City (KUDX), and radar reflectivity data from KUDX did not show any signs of possible tornadic development (Figure 2.7). Thunderstorm warnings were in effect for the storm (as shown by the warning polygon overlays in Figure 2.7), but the environment was perceived to be less than favorable for tornadoes (Matthew Bunkers, personal communication). The tornado occurred at approximately 5pm MDT without advanced NWS warning.

Several county emergency managers from southwestern Wyoming cite severe winds as their greatest hazard, and NWS forecasters state that their worst verification statistics are for severe, straight-line wind events. Winds from dry microbursts, caused by strong downdrafts from thunderstorm rain evaporating in dry boundary layer air, can reach speeds of up to 75 mph and are common in some counties with limited radar coverage such as Sweetwater and Washakie Counties. Severe winds can damage property and livestock and endanger public safety. An annual climatology of severe thunderstorm winds is shown in Figure 2.8 (Curtis and Grimes 2004).

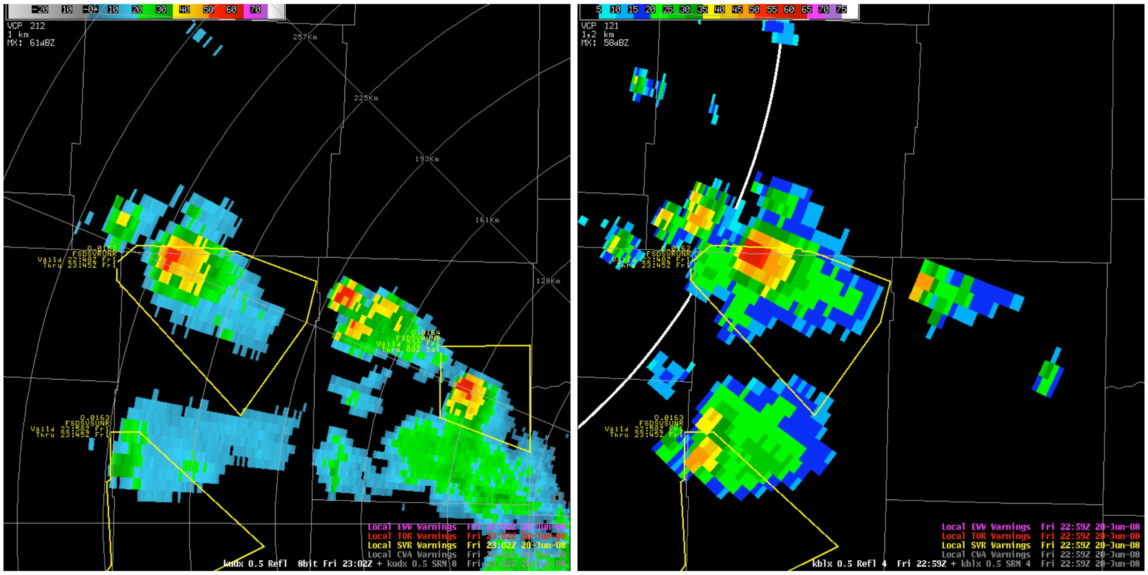

Figure 2.7: Reflectivity from KUDX at 2302 UTC 20 June, 2008. Figures provided courtesy of Matthew Bunkers, Rapid City WFO.

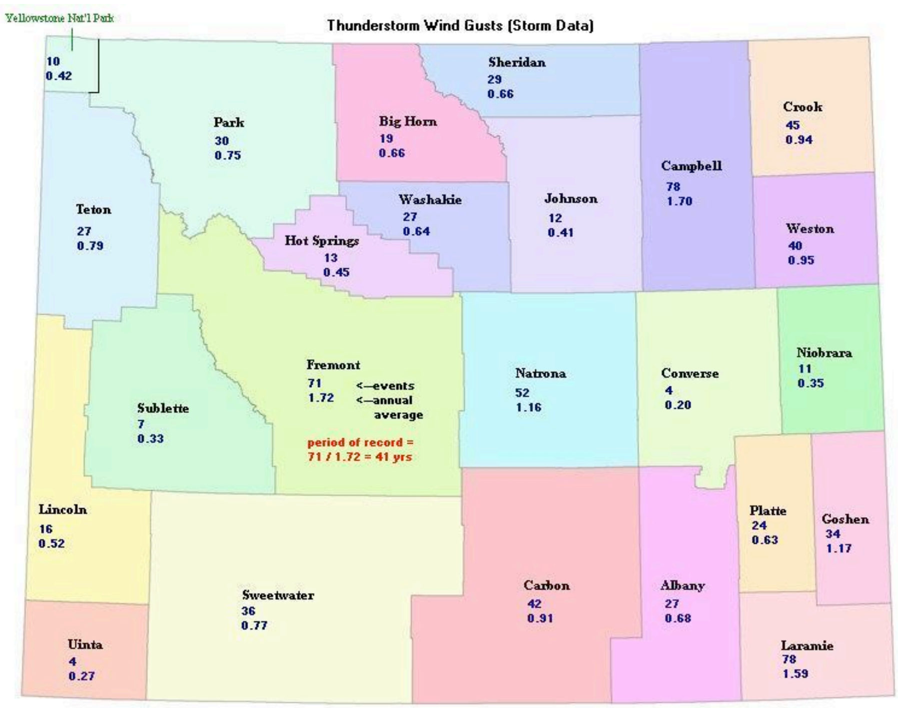

Figure 2.8: Climatology of the average annual number of thunderstorm wind gusts (> 49 mph) by county (Curtis and Grimes 2004). Data record length varies by county; the number of years included in each county data record is shown above the county average.

c. Flash Floods

Using data collected between 1955 and 1999, Wyoming ranks 49th in the country in the amount of flood damage per year, and yet still incurs \$3.8 million in damage annually (Extreme Weather Sourcebook 2001). Because of the complex mountain topography, microclimates, and radar blockage and overshooting, forecasters state that localized quantitative precipitation estimation (QPE) remains a significant challenge. Much of the mountainous terrain flooding in the headwaters of streams and rivers occurs quickly ("flashy"), often with no more than 15 – 20 minutes lead time possible. In addition, new residents to Wyoming are now building near flood-prone waterways and are vulnerable to flash flooding events. Typically, QPE is underestimated in complex terrain due to full or partial radar beam blockage, yet can be overestimated when the low-levels are sufficiently dry such that much of the rain falling from high altitudes (where it can be seen by radar) evaporates before reaching the ground. Furthermore, sparse rain gauge networks make calibration of radar-derived QPE difficult.

Three examples are listed below that demonstrate the significant underestimation in radar-derived QPE due to distance from the radar (i.e., overshooting) and beam blockage from the Black Hills (Melissa Smith, Service Hydrologist, UNR WFO).

On 28 May 2001 a surface trough across central Wyoming with weak southeasterly flow led to a series of storms tracking over the same area (training storms) near Gillette in the Donkey Creek basin. Forecasted atmospheric soundings from numerical weather prediction models indicated 100 – 200 CAPE (convective available potential energy), near average precipitable water and weak upper-level winds. Storm total precipitation ranged from 0.18 inches at the Gillette Airport to 7.5 inches 4 miles southwest of Gillette. The maximum radar-estimated QPE was less than 4 inches for storm total (total storm duration about 8 hours; Figure 2.9). Damage included \$50,000 to a golf course and business losses totaling \$400,000.

On 5 May 2007 periods of intense rain totaling 2 to 4 inches fell over Campbell and Crook counties in northeastern Wyoming within a 24-hour period. Minor street flooding occurred in Gillette, and water flowed over several county roads north and east of Gillette washing out culverts. The Little Powder and Powder rivers both overflowed their banks. Damage was estimated at \$58,025. Radar QPE showed little precipitation in or near Gillette (Figure 2.10).

Heavy rainfall during 23-24 May 2008 caused minor flooding across portions of Johnson, Campbell, and Weston Counties with 24 hour rainfall amounts of ~ 2 inches of rain and two-day rainfall amounts up to 4 inches, with much of the rain falling within several hours. Several secondary roads were flooded, culverts were washed out and a few homes were flooded. Radar QPE showed a maximum of one inch of rain in most locations (Figure 2.11).

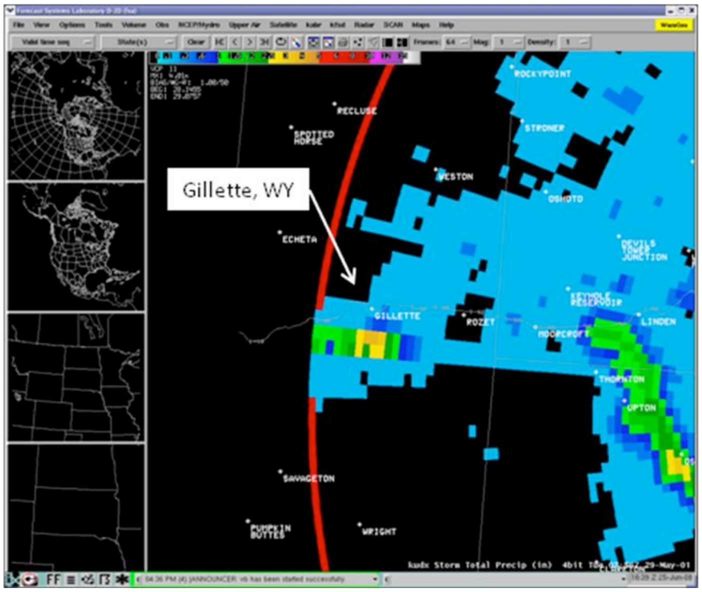

Figure 2.9: Storm total precipitation (inches) as derived from KUDX reflectivity on 29 May, 2001. Figure provided by Melissa Smith, service hydrologist at Rapid City WFO.

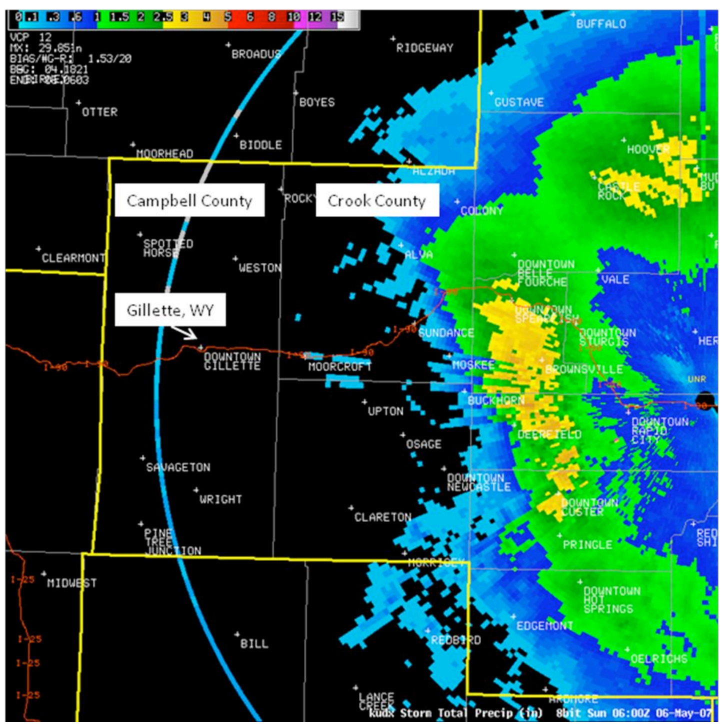

Figure 2.10: Storm total precipitation (inches) as derived from KUDX reflectivity on 0600 UTC on 6 May, 2007. Figure provided by Melissa Smith, service hydrologist at Rapid City WFO.

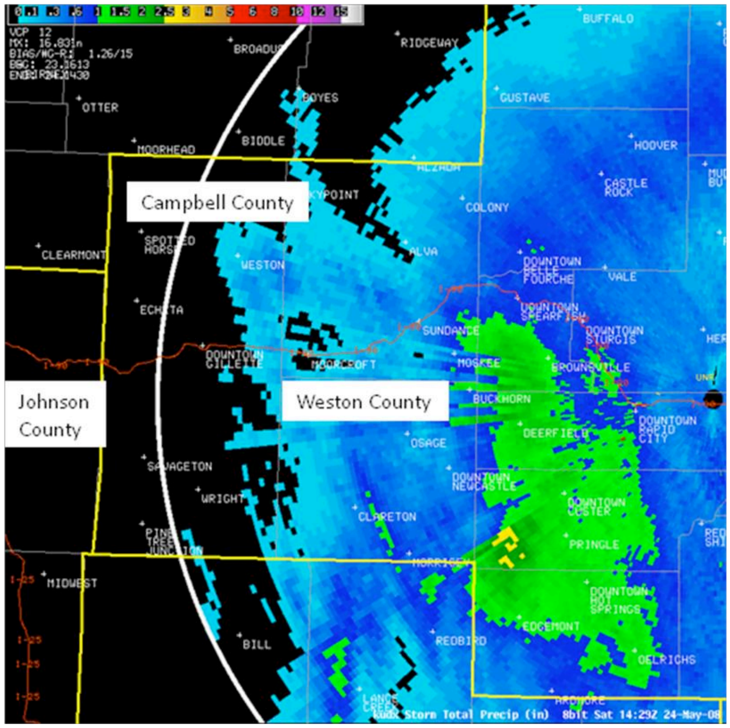

Figure 2.11: Storm total precipitation (inches) as derived from KUDX reflectivity on 1429 UTC on 24 May, 2008. Figure provided by Melissa Smith, service hydrologist at Rapid City WFO.

d. Lightning and Fire Weather

Wyoming is ranked 1st in the country in the annual number of lightning casualties (fatalities and injuries) per capita with 7.21 casualties per million people and 2nd in the country in annual per capita lightning deaths with 1.47 fatalities per one million people (Curran et al. 2000). A statewide climatology of lightning shows that the most frequent lightning occurs in the eastern one-third of the state (Figure 2.12), though since 1993 all lightning fatalities and a majority of injuries from lightning have occurred in the western mountainous regions of the state.

Lightning is also the leading cause of wildfires across much of the state (Curtis and Grimes 2004). The source points of wildfires caused by lightning are shown in Figure 2.13. The NWS provides real-time fire weather support, and weather radar is a key tool used by forecasters. The monitoring of low-level winds is essential, and tracking thunderstorm outflow boundaries is particularly critical. The ability to monitor low-level winds is hampered in radar gap regions.

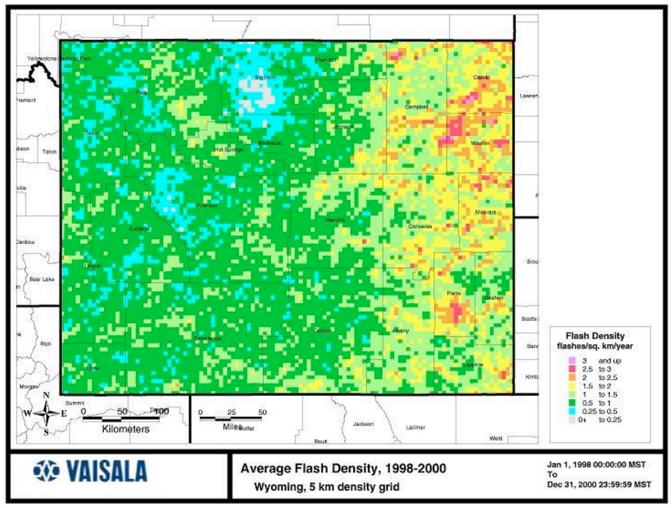

Figure 2.12: Annual lightning flash density between 1998 and 2000 (Curtis and Grimes 2004). Each pixel represents a 5 km^2 area.

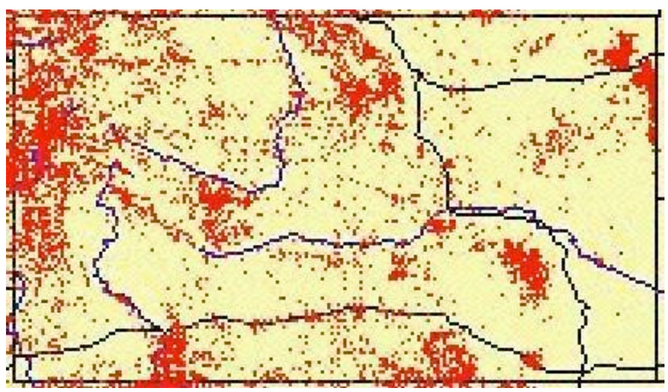

Figure 2.13: Lightning-induced wildfires between 1970 and 2000 (Curtis and Grimes 2004).

2.2 Washington

Western Washington is a diverse region with a mix of rural and urban communities. The estimated state population in 2006 was 6,375,000, ranking Washington as the 14th most populated state (U. S. Census Bureau 2006). In land area, Washington ranks 18th (U. S. Census Bureau 2006), yielding a population density of 37.1 persons per square kilometer. This compares against the national average population density of 32.6 persons per square kilometer.

Flooding and severe (non-thunderstorm) winds are the primary weather threats to western Washington state. While the number of severe weather events is relatively low, these events are typically large in scale, duration, and severity. Several recent storms have demonstrated the disruption such storms can have on transportation, tourism, and trade and the significant impacts of such events on the local, state and national economies.

Key risk criteria for select counties in western Washington are listed below in Table 2.3.

Table 2.3: Summary of the socioeconomic risk factors in select counties in the gap coverage regions of western Washington.

Risk Criteria	Grays Harbor County	Pacific County	Lewis County
Emergency Manager Concerns[9]	Lead time for winter weather, high winds, floods	Sufficient lead time for floods	Lead time for winter weather, high winds, floods.
Overall Social Vulnerability (Year 2000)[10], quintiles for US counties	Med/High (4th quintile)	High (1st quintile)	Med (3rd quintile)
Population[11], quintiles for US counties	Low (5th quintile) Total Population: 71,587	Low (5th quintile) Total Population: 21,735	Low (5th quintile) Total Population: 73,585
Population Density[11] US: 32.2 people per sq. mile	35.1 per sq. mile	22.5 per sq. mile	28.5 per sq. mile
Population Growth US Average 2000-2006 6.4%	6.5%	3.6%	3.6%
Property Damage, Injuries, Deaths[12] 1960- 2005 Statewide Comparison	High	High	High
Economic Activities Sensitive to Hazardous Weather[13]	Fishing	Transportation (Columbia River)	Transportation (Highway)

[9] Based on interviews with emergency mangers with jurisdictional responsibility in the three counties.
[10] Based on data from the Hazard and Vulnerability Research Center
[11] US Census data
[12] NCDC data and FEMA data compiled by the Hazards and Vulnerability Research Center by county.
[13] Defined as organization that i) uses nowcasts and forecasts to protect workers or schedule/modify operations, ii) operates in the gap coverage areas and ii) and is ranked among the top three sectors by gross domestic product for a state (Bureau of Economic Statistics), or contributes to the national economy.

2.2.1 Socioeconomic Risks

a. Social Vulnerability

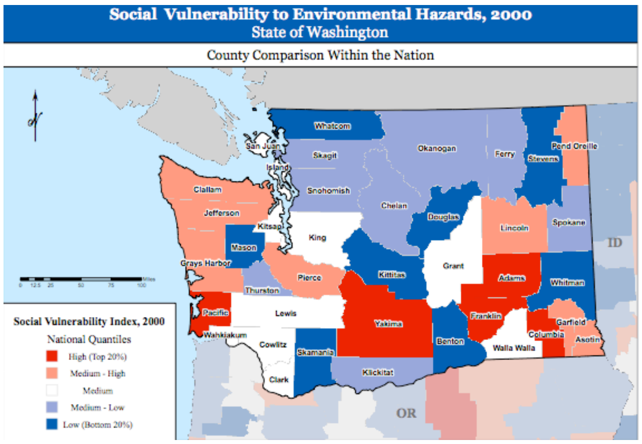

Figure 2.14: Social vulnerability index calculated per county for Washington in 2000 (Source: Hazards and Vulnerability Research Institute).

According to a national social vulnerability index, which provides measures of the ability of populations to prepare for and recover from environmental disasters based on socioeconomic status, development density, age and other factors (Cutter 2008), the gap areas of coastal Washington have medium to high social vulnerability compared to the rest of the nation (Figure 2.14). The high vulnerability rating for Pacific County is due to the percentage of population over 65 which is nearly twice the national average. Other factors such as a higher-than-average population with income below the poverty level also contribute to the higher index.

Between 1980 and 2000, the greatest population growth across Washington was in the Seattle to Olympia corridor (Figure 2.15), areas vulnerable to flooding and which experience some radar coverage gaps because of the mountainous terrain. Population is expected to grow minimally in those coastal counties (Jefferson, Grays Harbor, Pacific) that lack low-level (< 3 km AGL) radar coverage. Similar to Wyoming, Washington has a large ratio of residents from out-of-state; only 53.9% +/- 0.4% of current residents were born in Washington (U. S. Census Bureau 2006). Washington is ranked 11th in the country in the number of current residents born out of state.

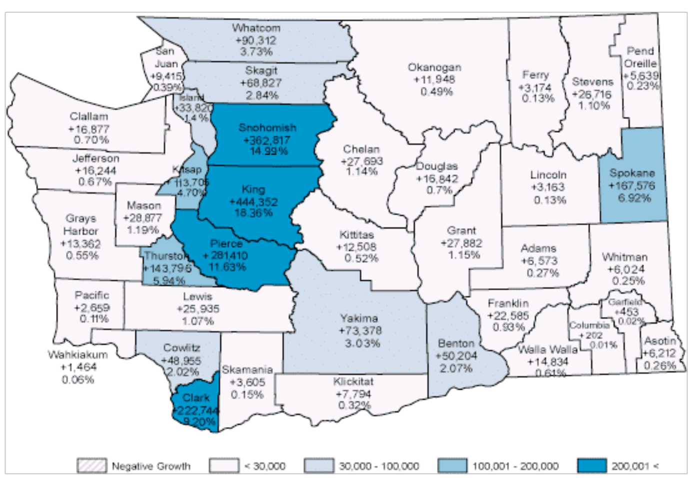

Figure 2.15: Population growth by county from 1980 to 2000. Source: Washington State office of Financial Management.

b. Economic impact.

Washington has a diverse economy, with a GDP of $311 billion, and is in the top quintile for growth rates from 2006 to 2007 (U.S. Bureau of Economic Analysis 2006). Agriculture and services comprise the largest portion of the GDP. In the coastal areas, lumber, agriculture and fishing are the largest industries. Washington State plays an active role in international trade to Asia.

c. Freight Transportation.

Freight transportation in Washington plays a critical role in state, national, and international trade. Washington is the principal entry point for goods shipped from Asia to the U.S. Products from Alaska and Canada also travel through Washington State on their way to other parts of the country. For Washington State, about two-thirds of its agricultural products are shipped out of state or exported abroad, and the vast majority of lumber harvested is sold out of state. Commodities shipped from, to or within Washington state totaled 466 billion in tonnage and $353 billion in value in 1998 (Ivanov and Stratton 2005).

The interstate highways, I-5 and I-90, and freight traffic along the coast and on the Lower Columbia River are the transportation routes most affected by the lack of low-level radar coverage in western Washington. The Columbia River is the 4th longest river in the nation and empties into the Pacific Ocean in a region that lacks radar coverage below 3 km. The mouth of the Columbia river is part of the "graveyard of the Pacific", named for its extreme weather, high surf and dangerous sand bars, and which extends north to Grays Harbor (Cooper 2007). The river is used to transport grain and lumber on barges for export to Asian markets. In 2005, 15 billion metric tons of goods were transported on the Columbia River. Currently weather data are gathered through point observations through buoys and sensors along the river (Cooper 2007; see Appendix A).

Interstate I-5 is the principal north-south transportation corridor and I-90 is the principal east-west corridor for commerce. From 1998 to 2020, freight volumes in Washington are expected to increase by 80 percent (Ivanov and Stratton 2005), making these routes among the busiest and most congested in the United States. These routes are routinely impacted by winter weather and floods. For example, flooding caused the closure of a 20 mile section of I-5 near Chehalis, Washington, for a three day period from 3 – 6 December 2007. Washington State Department of Transportation (WSDOT) estimated that this road closure costs the state economy $47 million. In addition, later that winter record snowfall and warm temperatures created avalanche conditions in the mountain passes, closing I-90 at Snoqualmie Pass from 29 January - 2 February, 2008. The total time of closure for I-90 during the 5-day period was 89 hours. Almost $28 million in economic losses were attributed to the I-90 closures. In addition to the cost of road closures, costs are incurred when crews are deployed to distribute de-icing chemicals.

d. Fishing Industry

Washington has an active fishing industry along the Pacific coastline that contributed $312 million to the state's economy in 2004 (Pacific States Marine Fisheries Commission, 2006). The fishing industry depends on weather information to protect the safety of the fishermen and vessels and to determine the optimal time to harvest different species. Grays Harbor in Grays Harbor County and the Lower Columbia River Basin in Pacific County are important ports for the fishing industry but have poor radar coverage at low-levels because of mountain beam blockage and beam overshoot. The NWS provides a Coastal Waters Forecast (CWF) out to a range of 111 km (60 nmi) from shore to meet the needs of the fishing and shipping industries.

The fishing industry has a need for: i) long-term, synoptic forecasts for predicting large weather systems coming onshore; ii) intermediate, 6 to 12 hour forecasts of ocean and near-shore conditions; and iii) nowcast and surface information on wind and wave heights. Limited radar coverage limits the forecasting ability to determine the severity and duration of large systems coming onshore from the Pacific Ocean. Weather buoys provide some information on wave height and wind; however, these buoys are widely spaced and can be out of service for months at a time during the critical winter season (see Appendix A for more information on the buoy network). Satellite data are used extensively by forecasters to determine the timing, location and severity of large-scale systems moving onshore.

Commercial fishing is among the most dangerous occupations in the country with some of the highest per capita mortality rates. Furthermore, a recent study by the Centers for Disease Control reported that Washington, Oregon and California have twice the number of fishing related fatalities than the national average. The study found that of the deaths from 2000 to 2006 attributed to either falling overboard or the loss of a vessel, weather conditions were a factor in 79% of the deaths and large waves were a factor in 40% (a death could have multiple causes). Having additional weather information may help in reducing the number of deaths, although the report also states that unsafe practices among commercial fishing in Washington, Oregon and California, such as malfunctioning life boats and aggressive schedules, were also key contributors to the fatalities (Centers for Disease Control 2008).

2.2.2 Weather hazard climatology

The majority of severe weather in western Washington is dominated by mid-latitude, extratropical cyclones moving east to northeast from the Pacific. The amplitude and track of the low pressure center plays a determining role in the location and severity of associated wind and precipitation (McDonnal and Colman 2003), and one major problem is the difficulty in assessing the exact location of a low pressure center as it approaches Washington. With the absence of radar, forecasters often utilize numerical models, satellite data and buoys to track the low pressure centers.

Presidential Federal Disaster Declarations

Washington state had 41 Federal Declared Disasters during the period of record from 1953 to 2008 (see Appendix Table B.2). During the last ten years, there have been six events, including five severe storms and one earthquake.

Of all Federal Disaster Declarations from 1953 to 2008, Washington is tied for 15th out of 59 states and territories in the number of Presidential Federal Disaster Declarations during that time. Nationally, there were 1,774 Federal Disaster Declarations during that time, with an average of 32 per year. Note that the exact number declared per year varied largely by presidential administration.

NCDC Storm Event Archives

In the NCDC Storm Events data base, there are 2,155 storm events recorded for the state of Washington for the period 1 January, 1993, to 30 June, 2008. This ranks Washington 46th among 55 U.S. states and territories in the number of storm events recorded by NCDC. All storm events recorded for western Washington since 1 January 1993 are tabulated in Table 2.4. The counties included in this table for western Washington are: Clallam, Clark, Cowlitz, Grays Harbor, Island, Jefferson, King, Kitsap, Lewis, Mason, Pacific, Pierce, San Juan, Skagit, Skamania, Snohomish, Thurston, Wahkiakium, and Whatcom.

While Washington has relatively few storms listed in the NCDC Storm Events archive, the significant number of Presidential Federal Disaster Declarations testifies to the size and severity of the severe storms that did occur. In general, relatively few severe storms impact western Washington, but those that do are large in size and significant in severity.

Table 2.4: Storm events for western Washington as recorded in the NCDC Storm Events database between 1 January 1993 and 30 June 2008.

Event	Total	Fatalities	Injuries	Damage ($)
Tornadoes	22	0	0	$ 1.0M
Thunderstorm, High Wind	91	21	20	$ 76.1M
Hail	19	0	6	$ 0.1M
Lightning	46	2	18	$ 1.3M
Floods	58	6	0	$129.6M
Heavy Precipitation	115	0	36	$184.4M
Ocean & Lake Surf	8	0	1	$ 2.6M
Snow/Ice	34	4	33	$ 1.6M
Extreme Temperatures	0	0	0	$ 0.0M
Forest Fires	1	0	0	$ 0.0M
Total	394*	33	114	$396.7M

*Additional storm events not shown include reports of fog, drought, funnel clouds and dust storms.

According to the NCDC Storm Event statistics for western Washington, high winds are the greatest causes of weather-related fatalities accounting for 63.6% of all fatalities and 17.5% of injuries, followed by floods and heavy rain, together accounting for 18.2% of fatalities and 31.6.% of injuries. Heavy rainfall, flooding and high winds are responsible for 98% of the region's total property damage. Wind events also have a direct impact on associated marine hazards such as high, rough seas and visibility.

Tornadoes are rare in western Washington. The only deadly tornado in Washington since SPC records began in 1950 occurred in Vancouver in Clark County, Washington (just across the Columbia River from Portland, Oregon) on 5 April 1972 at 1250 Local Time, hitting a grocery store, bowling alley and grade school. The tornado caused 6 fatalities, 300 injuries, and $25M in damage. The damage path was 9 miles long, 440 yards wide and based on the damage intensity, the tornado was rated an F3, indicating winds between 250 and 330 km/hr (158-206 mph).

NCDC Storm Events data for three Washington counties (Grays Harbor, Pacific and Lewis Counties) with limited low-level radar coverage are shown below in Figure 2.16 and are listed in Appendix Tables C.4 – C.6. Grays Harbor and Pacific Counties are coastal counties located southwest of the Olympic Mountains. Lewis County is inland east of Pacific County in the Chehalis River valley. Heavy precipitation and flooding and wind are the greatest threats to public safety and economic damage for all three counties. Nevertheless, a review of county statistics as listed in the NCDC Storm Events database compared against known storm events appears to indicate a significant underreporting of events (e.g., high wind cases) from coastal Washington.

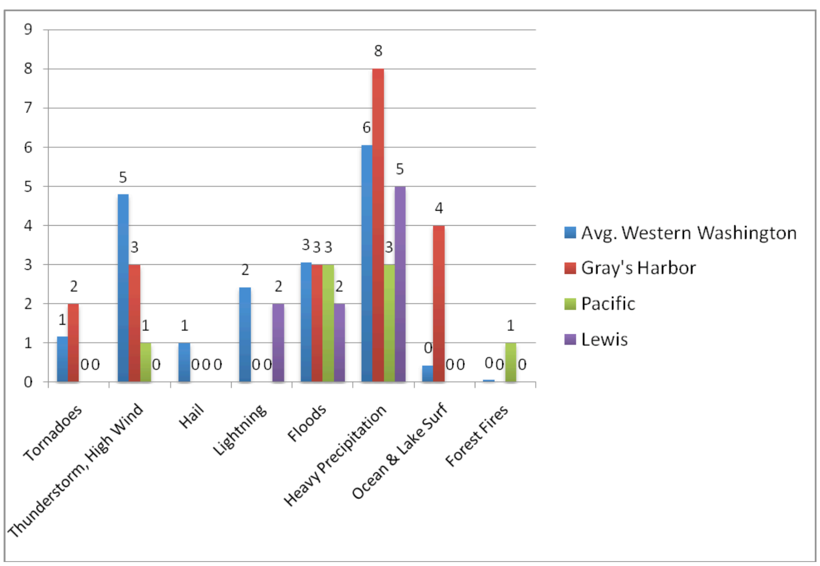

Figure 2.16: Total number of storm events for the period 1 January 1993 to 30 June 2008 for select counties from within the radar gap regions and averaged per county from across western Washington.

2.2.3 Selected Case Events

As described, western Washington's primary hazardous weather-related threats are flooding and severe (non-convective) wind storms. Severe thunderstorms (hail, wind and tornadoes), though rare, also occur. The challenges to observing these events by stakeholders are discussed.

a. Flooding

Flooding played a role in at least 30 of the 41 Presidential Federal Disaster Declarations declared for Washington since 1953. According to NCDC Storm Events records, since 1993 heavy precipitation and flooding have caused 6 fatalities, 36 injuries and $314.0M in damage across western Washington. In data collected between 1955 and 2006, Washington is ranked 33rd nationwide in the amount of property damage from flooding with total damage of $1.6 billion (2006 dollars; Extreme Weather Sourcebook 2001). The majority of flooding in Washington occurs west of the Cascade Mountains.

Flooding in western Washington is driven at the synoptic scale. At midlatitudes, 90% of the total meridional water vapor flux is transported via narrow zones of high water vapor, known as "atmospheric rivers" (Zhu and Newell 1998; Ralph et al. 2004; Neiman et al. 2008). Also referred to as the "Pineapple Express" phenomenon, atmospheric rivers (ARs) are described as pre-frontal, low-level jets within midlatitude cyclones, typically found parallel to the polar cold front. They are typically about 500 km wide and less than 4 km deep and are common features among oceanic extratropical cyclones impacting the U.S. West Coast (Ralph et al. 2004). Nieman et al. (2008) found that the presence of an atmospheric river doubled the average precipitation rates along the West Coast when compared against more typical (non-AR) storms. Flooding is amplified as west-southwesterly ARs interact with north-south oriented mountain ranges.

Flooding occurs at multiple scales. Microclimate variability in wind flow around specific topographical features leads to preferred locations for rapid and frequent flooding. In some locations the direction of wind flow plays a decisive role in the formation and amount of terrain-driven precipitation. Mesoscale flow around the Olympic Mountains contributes to what is called the Puget Sound Convergence Zone (Whitney et al. 1993), which dramatically enhances localized precipitation in the lee of the mountains.

Flash flooding is limited to mountain, headwater streams but these streams have few stream gages. Some basins can "quasi-flash flood" if they are fed by many ungaged streams (Larry Scheck, U.S. Army Corps of Engineers, personal communication). Snowmelt also enhances flooding, although contribution by snowmelt is limited generally to less than 25% of the flood total (Brent Bower, NWS, personal communication). During heavy rain events, the NWS may issue Small Stream Flood Advisories or Areal Flood Warnings; however, advanced warning is difficult without adequate low-level radar or rain gauge/stream gage coverage.

To date, weather radar has been of limited value to forecasters in Washington for monitoring flood events. High precipitation variability, radar blockage and overshooting, bright band contamination, and the relatively low-topped (i.e., melting layer at 2 km AGL) storms typical of western Washington make radar QPE difficult and highly inaccurate. Because of these limitations, neither the NWS River Forecast Center (RFC) in Portland, OR, nor the WFO in Seattle assimilate radar data into their rainfall modeling efforts, but instead use radar qualitatively to confirm other data and information. Radar data are used to increase confidence in products prior to their release to stakeholders.

An example of radar underestimating storm total precipitation (STP) is shown in Figure 2.17 from the December 2007 storm event. Most areas received 3 to 8 inches of rainfall, similar to radar STP estimates; however, the Willapa Hills and southern Olympic mountains along the coast received 10 to 20 inches of rainfall. These are regions completely blocked by the Olympic Mountains.

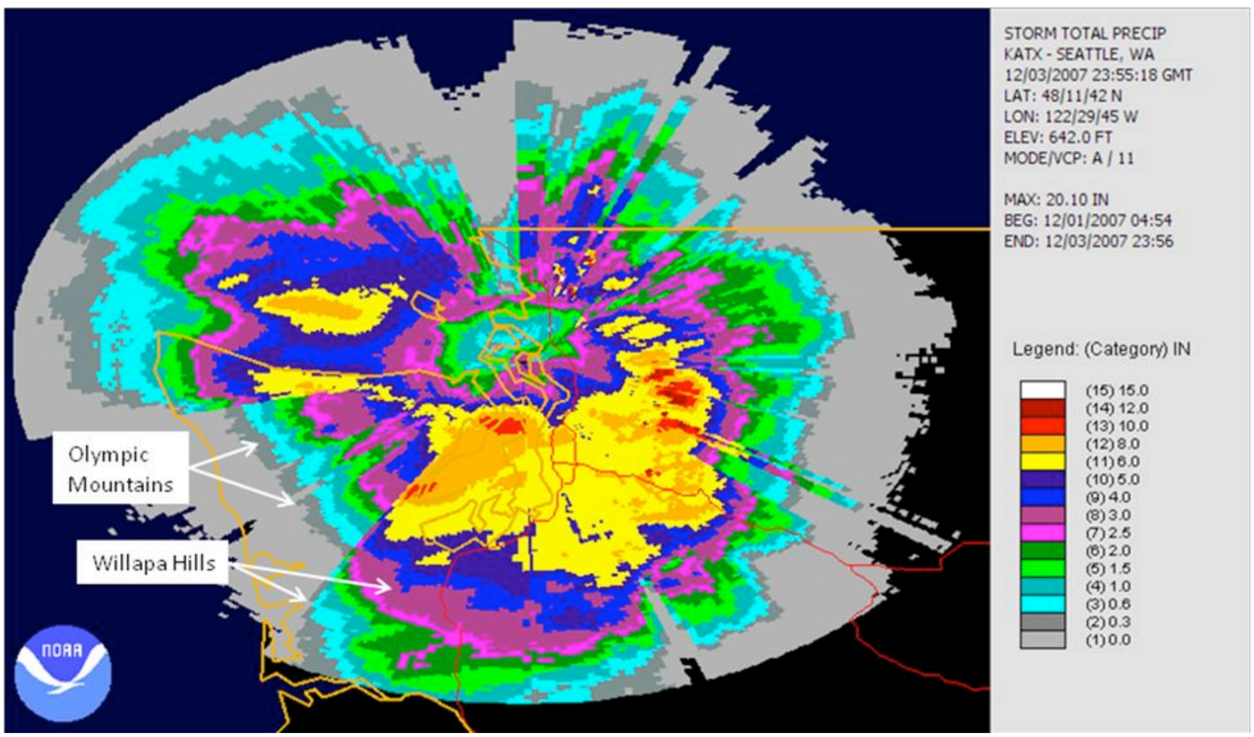

Figure 2.17: Storm total precipitation summed from KATX reflectivity observations between 0500 UTC 1 December and 0000 UTC 4 December. Note radar blockage to the north and southwest of the radar.

b. Non-convective severe winds

Like flooding, wind events in western Washington are driven at the synoptic scale. Severe wind storms are associated with significant low pressure extratropical cyclones, and their interaction with local mountainous topography can act to enhance low-level winds (e.g., Steenburgh and Mass 1996). While generally rare, severe wind events along the northwest coast can impact hundreds of square kilometers and continue for days. As noted, such events can lead to rough, high seas and low visibility, thereby significantly impacting marine-related industries.

Washington is second only to California in the number of non-convective wind-related deaths (Ashley and Black 2008).

Observing and forecasting meso- to microscale impacts from such wind events are difficult. Local topography (e.g., Puget Sound) can impose considerable shear and variability; surface wind velocities can differ significantly from winds at 1 km (3,000 feet). In fact, much of the stronger winds aloft remain decoupled from the winds near the surface; forecasters look for areas of convection that can bring these stronger winds aloft down to the surface.

Weather radar is not the primary tool used by stakeholders to monitor or forecast wind events. Numerical model and pressure gradient forecasts, satellite, Quikscat winds, surface reports and buoy observations are used routinely to identify and forecast severe wind events. Radar blockage and overshooting of the radar beams preclude routine usage of weather radar for wind monitoring.

c. Winter weather

Since 1993 snow and ice storms across western Washington have led to 4 fatalities, 33 injuries and about $1.6 million in damage. Snow and ice causes problems for transportation and other weather-sensitive industries. Weather radar is used to track snow bands, but QPE remains a challenge. Similar to Wyoming, the microclimates associated with complex terrain, bright band contamination, the typically low-topped elevation (< 7.5 km) of most snowstorms, and limited radar coverage at low levels are cited by decision-makers as limiting their ability to nowcast and forecast such events.

d. Severe thunderstorms

Severe thunderstorms are rare in western Washington but as described can occur occasionally and even produce tornadoes. Data collected from the SPC show that between 1950 and 1994, Washington recorded 55 tornadoes, ranking them 43rd (out of 56 states and territories). During that same period, Washington had 6 tornado fatalities (all from the one tornado in Clark County in 1972), ranking it 29th nationwide in tornado fatalities; Washington recorded 303 injuries from tornadoes (300 injuries from the Clark County tornado), ranking it 27th in tornado related injuries. Washington also recorded tornado damage (Consumer Price Index adjusted dollars) totaling $2,107,114, ranking it 46th in tornado damage.

Chapter 3: Current Weather Radar Coverage

What data limitations exist in current weather radar coverage?

3.0 Introduction

As described in Chapter 1, the NRC 1995 panel identified three criteria for evaluating service performance: i) weather phenomena; ii) radar coverage; and iii) composite system performance. Chapter 2 provided a detailed climatology of weather phenomena for Wyoming and western Washington and challenges inherent in their observation. This chapter evaluates current weather radar coverage. It begins in Section 3.1 with a discussion of the levels used for assessing radar coverage, in this case, 1, 2, and 3 km. Next in Section 3.2, coverage of the operational NEXRAD network at these levels is displayed and quantified for each region on a county-by-county basis. A summary of current coverage and a description of ongoing enhancements to the network using Terminal Doppler Weather Radars (TDWR) and FAA radars (ASR-9, ASR-11, and ARSR-4) follows in Section 3.3.

3.1 Importance of Low-level Radar Coverage

In Chapter 2, the importance of weather observations were discussed in the context of weather risks and vulnerabilities in Wyoming and western Washington. The composite risks summarized in Tables 2.1 and 2.3 illustrate that both regions suffer from weather hazards and could potentially benefit from more complete low-level weather radar coverage. In this section, the emphasis is on the importance of lower level radar observations, specifically at 1, 2, and 3 km AGL.

The general need for low-level observations is illustrated in Figure 3.1 which has been adapted from NRC (1995). The figure shows estimated tops of hazardous weather phenomena; the central point represents the median and the error bars show the typical range. If the height of the top is less than the radar observation height, the phenomenon will be overshot by radar and not be detected. In particular, the data suggest that the wind signatures of many atmospheric hazards are observable only below 2 km AGL. For example, 50% of hook echoes from supercell storms are observable only below 2 km AGL, while those of mini-supercell storms generally occur below 1 km. Similarly, damaging winds from storm downdrafts (i.e. micro- and macrobursts) typically occur below 1 km. Hence, 1, 2, and 3 km AGL are used to illustrate “low-level” coverage in this study.

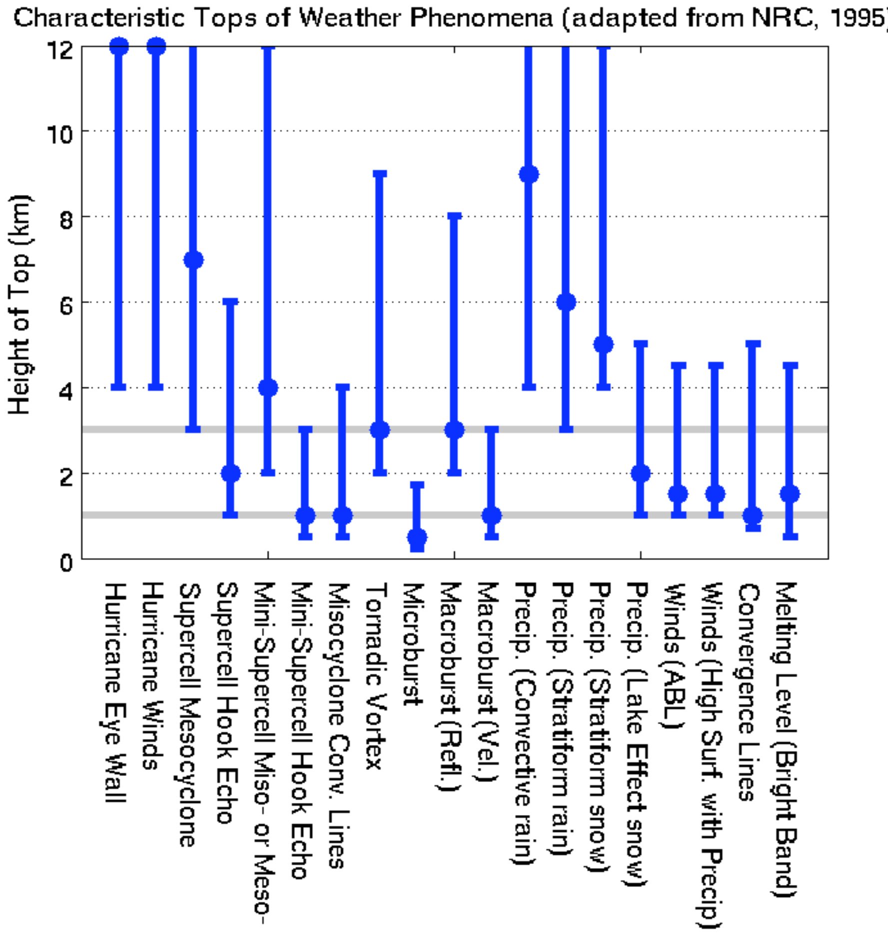

Figure 3.1: Graphic showing the mean and range of characteristic heights (km) of mesoscale phenomena (adapted from NRC 1995).

3.2 Low-level NEXRAD WSR-88D Coverage

During the late 1980s, a tri-agency team of the Department of Commerce/National Weather Service (DoC/NWS), Department of Defense (DoD), and Department of Transportation/Federal Aviation Administration (DoT/FAA) formed the NEXRAD program to provide contiguous radar coverage at 10,000 feet (3.05 km) across the entire country. As a result, a network of 159 WSR-88D radars were installed, 141 in the conterminous United States (Figure 3.2). It is clear from the figure that the density of radars is greater east of the Rockies than to the west, with characteristic spacing of 230 km and 345 km, respectively (NRC 1995).

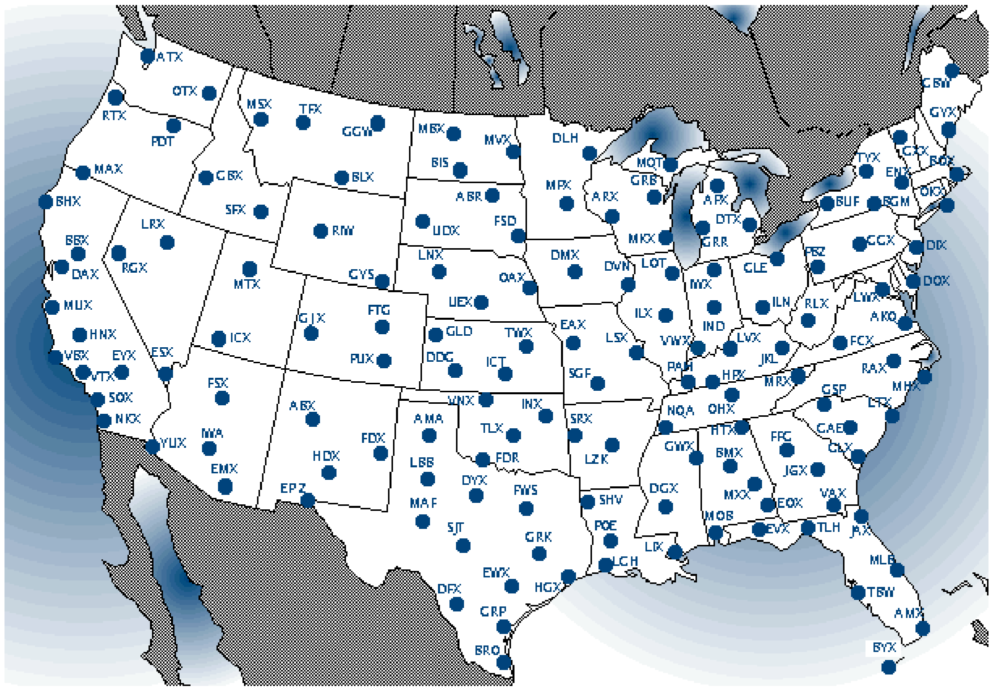

Figure 3.2: Map showing the locations and names of all WSR-88D radars. Figure copied from http://www.weatherwatch.info/radar/.

The WSR-88D was recently upgraded to support increased spatial resolution, clutter rejection, and range/velocity ambiguity mitigation (Saffle et al. 2007). Within the next five years, all radars will be upgraded to include collection of dual-polarization variables, including differential reflectivity, correlation coefficient, differential phase, and specific differential phase. The dual polarization variables can help distinguish between heavy rain, snow, bright bands, and hail and is expected to improve QPE estimates. Information regarding radar performance specifications is listed in Appendix A.

Although the NEXRAD upgrades will provide more accurate measurements of precipitation and wind within the radar's footprint, they will not overcome the fundamental limitations of beam blockage and overshooting. Westrick et al. (1999) first focused attention on the relatively sparse low-level radar coverage across the U.S. West Coast. In the study, the authors considered central and northern California, western Oregon and western Washington which included the coverage area of seven WSR-88Ds. Using the center of the lowest elevation beam, the authors found that over 71% of the domain area had no radar coverage at 2 km AGL, and only 22% of the domain had unobstructed coverage.

Following the work of Westrick et al. (1999), Maddox et al. (2002) recreated continental U.S. maps of radar coverage at 1-, 2-, and 3-km AGL and 3- and 5-km above mean sea level (MSL). The authors show that while areas of the east and central U.S. have limited radar coverage at 2 km AGL, large portions of the western U.S. have radar no coverage at or below 2 km AGL. In the following two sections, NEXRAD radar coverage at 1, 2, and 3 km is quantified for both Wyoming and western Washington.

3.2.1 Wyoming

Six WSR-88D radars cover Wyoming. These radars are located at Riverton (KRIW) and Cheyenne (KCYS), WY; New Underwood (Rapid City), SD (KUDX); Billings, MT (KBLX); Springfield (Pocatello), ID (KSFX); and Salt Lake City, UT (KMTX). Figure 3.3 shows radar coverage for these radars at 1, 2, and 3 km as orange, red, and blue, respectively. It is evident from the figure that both the significant distance between radars and mountain blockage limit the low-level coverage available across much of the state.

As demonstrated by the cases studies presented in Chapter 2, low-level radar coverage is needed for routine detection of snow, flooding rains, and low-topped thunderstorms. As shown in Table 3.1, 16 of Wyoming's 23 counties have less than 5% of their county area with WSR-88D coverage at 1 km AGL; 20 of 23 counties have less than 15% of their county area with radar coverage at 1 km AGL. Nine counties have less than 50% coverage at 3 km AGL (Campbell, Converse, Niobrara, Johnson, Sweetwater, Carbon, Park, Weston, and Sheridan Counties). Converse and Campbell Counties have less than 5% coverage below 3 km AGL.

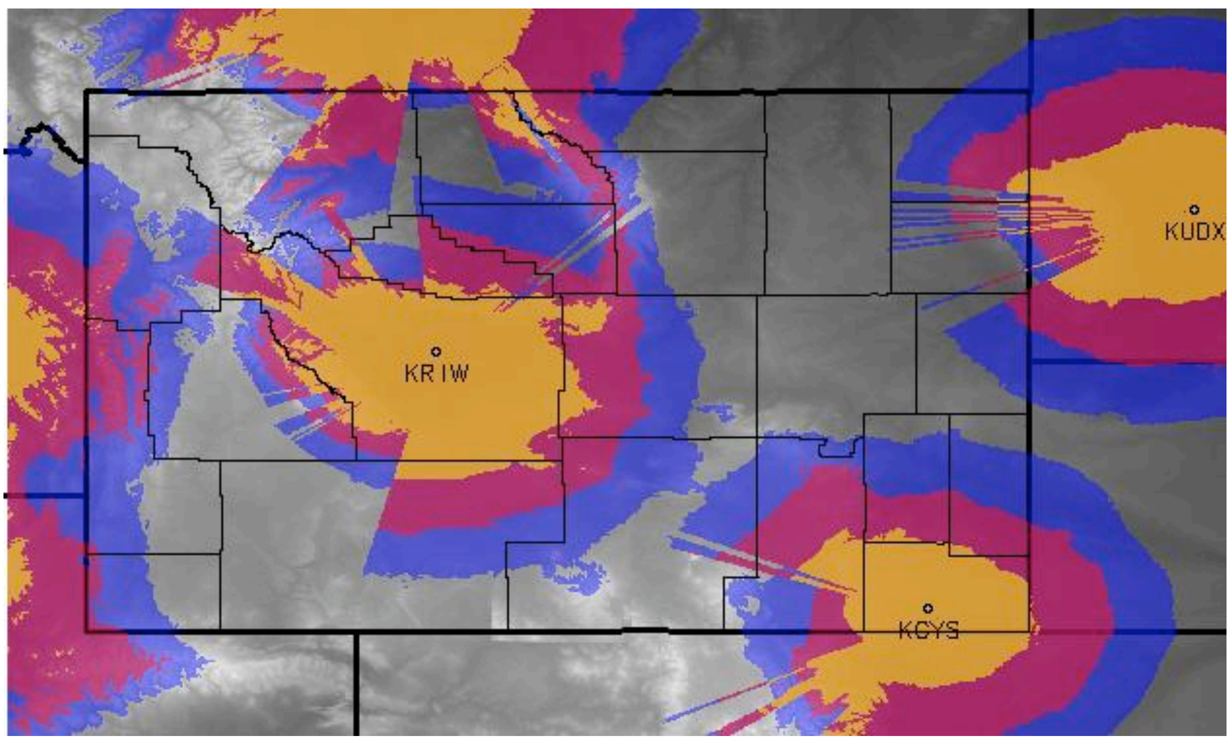

Figure 3.3: Shades of color represent the areas where weather radar coverage is available at or below 1 km, 2 km and 3 km AGL (orange, red and blue, respectively). Areas with no color shading represent areas with no weather radar coverage below 3-km AGL.

Table 3.1: Population and percent area of radar coverage of each county in Wyoming.

County	Population 2000 Census	WSR-88D Area Coverage (%) 1 km	2km	3 km
Campbell	33,698	0%	0%	0%
Converse	12,052	0%	0%	4%
Niobrara	2,407	0%	4%	38%
Johnson	7,075	0%	7%	24%
Carbon	15,639	0%	8%	47%
Uinta	19,742	0%	10%	52%
Teton	18,251	0%	17%	64%
Lincoln	14,573	0%	24%	65%
Washakie	8,289	0%	31%	93%
Park	25,786	2%	23%	48%
Goshen	12,538	2%	34%	78%
Crook	5,887	3%	30%	76%
Platte	8,807	3%	37%	81%
Weston	6,644	4%	11%	29%
Sublette	5,920	4%	17%	51%
Sweetwater	37,613	4%	21%	39%
Sheridan	26,560	6%	22%	42%
Big Horn	11,461	8%	27%	64%
Natrona	66,533	9%	40%	69%
Hot Springs	4,882	13%	67%	88%
Albany	32,014	16%	57%	95%
Fremont	35,804	79%	95%	99%
Laramie	81,607	94%	100%	100%

3.2.2 Washington

Two NEXRAD WSR-88D radars cover western Washington. These radars are located in Camano Island, Washington (KATX) and near Portland, Oregon (KRTX). Significant radar blockage from the Olympic Mountains and Cascade Range limits the low-level coverage available across a large fraction of western Washington (Figure 3.4). While the population centers are well covered by radar even at low levels, little radar coverage is available below 3 km AGL for areas west of the Olympic Mountains, giving the socially-vulnerable coastal communities less time for preparation and providing little to no radar data over the ocean. Data over the ocean can be critically important for accurate warning and forecasting.

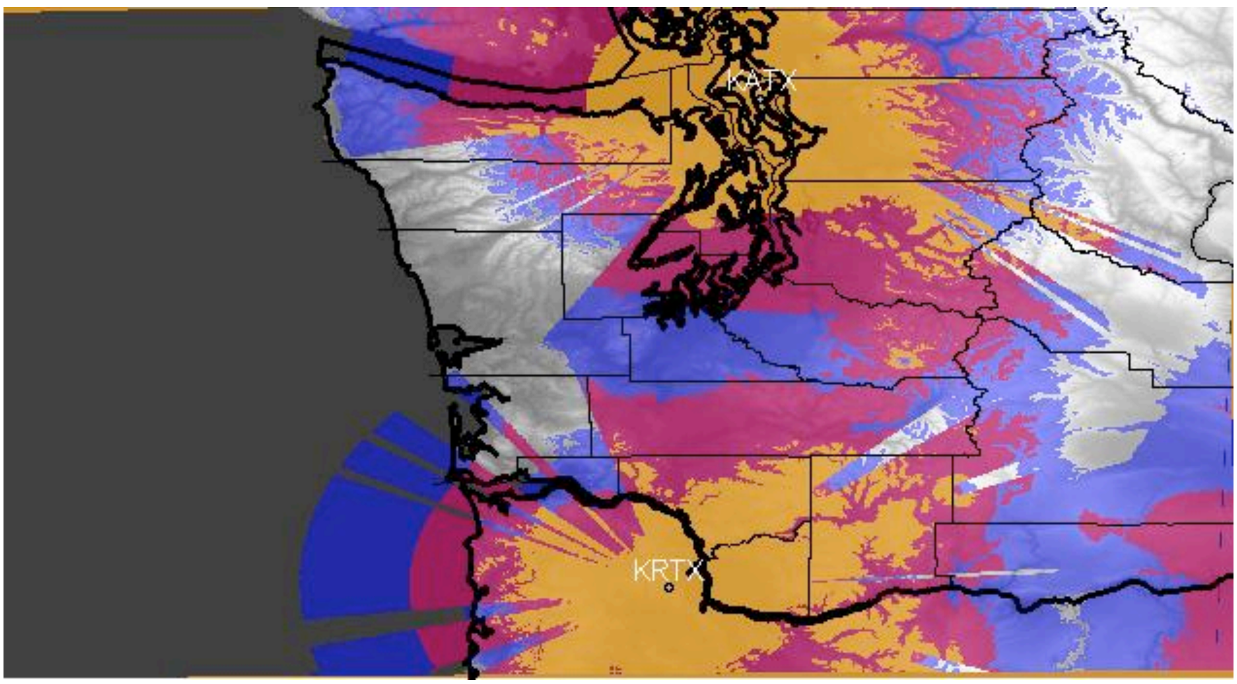

Figure 3.4: Shades of color represent areas where weather radar coverage is available at or below 1 km, 2 km and 3 km AGL (orange, red, and blue, respectively). Areas with no color shading represent areas with no weather radar coverage below 3 km AGL.

A review of Table 3.2 shows that 7 of western Washington's 19 counties have less than 5% area radar coverage at 1 km AGL. Even King County, with a population in 2000 of 1.7 million, has radar coverage over only 1/3 of the county area at 1 km AGL. Three counties – Grays Harbor, Thurston, and Pacific – have less than 10% of their county area with radar coverage at 2 km AGL. Nevertheless, 12 of 19 counties have over 90% radar coverage at 3 km AGL. The greatest limiting factor is the inability of existing weather radars to observe incoming weather systems over the ocean.

As found in Westrick et al. (1999), adequate coverage at about 1.5 km (MSL) in the Seattle area is critical for observing the lower edge of the melting layer and enabling reliable QPE. This melting layer is routinely observed in radar reflectivity data as a "bright band", as the water coated snow enhances the return scatter of radar energy. The bright band significantly reduces the accuracy of radar-based QPE. To achieve more reliable estimates of radar-based precipitation, radar measurements should ideally be collected below the melting level (Fulton et al. 1998). Medina et al. (2007) observed the melting layer from roughly 1 km to 2 km MSL during the passage of three winter storms. See Chapter 4 for more discussion of the impact of the bright band layer on QPE.

Table 3.2: Population and percent area of radar coverage of each county in western Washington.

County	Population	WSR-88D Area Coverage (%)		
	2000 Census	1 km	2km	3 km
Grays Harbor	67,194	0%	0%	15%
Thurston	207,355	0%	2%	100%
Mason	49,405	0%	48%	81%
Pacific	20,984	0%	7%	26%
Wahkiakum	3,824	1%	18%	85%
Lewis	68,600	2%	74%	95%
Pierce	700,820	3%	68%	100%
Clallam	64,525	26%	53%	84%
Jefferson	25,953	29%	46%	57%
Whatcom	166,814	29%	61%	88%
King	1,737,034	32%	91%	99%
Skagit	102,979	43%	75%	97%
Skamania	9,872	54%	93%	98%
Snohomish	606,024	57%	85%	100%
Kitsap	231,969	59%	100%	100%
Cowlitz	92,948	66%	99%	100%
San Juan	14,077	89%	100%	100%
Clark	345,238	95%	100%	100%
Island	71,558	100%	100%	100%

3.3 Ongoing Enhancements

There are two primary efforts to enhance the national weather radar system. As mentioned previously, the first enhancement consists of improvements to the NEXRAD WSR-88D, including greater spatial resolution, clutter rejection, velocity/ambiguity mitigation, and dual-polarization capability. These improvements will enable much more accurate characterization of precipitation type and location for QPE.

The second enhancement consists of making both Terminal Doppler Weather Radars (TDWR) and FAA Surveillance Radars (ARSR-4, ASR-9, and ASR-11) data available to the NWS for warning and forecasting operations. The NWS has recently completed the capability to ingest data from all 45 TDWR units; generate numerous base reflectivity, base velocity and derived products in WSR-88D format for AWIPS (Advanced Weather Interactive Processing System) compatibility; and provide the products to forecasters via AWIPS. This capability has been tested in Watford City, North Dakota. The NWS is also developing the capability to access reflectivity data from other FAA radars, e.g., the ARSR-4, ARS-9, and ARS-11. See Appendix A for the hardware specifications and locations of the FAA radars.

System Performance

Chapter 4: Warning Service Performance

Do current data limitations impact service performance?

4.0 Introduction

Chapter 3 highlighted areas of northeastern and southwestern Wyoming and coastal Washington that have limited low-level radar coverage. How does this lack of low-level coverage impact NWS warning performance?

According to Leik et al. (1981), an integrated warning system consists of four parts: i) forecast; ii) detection; iii) dissemination; and iv) public response. Historically, the NWS has focused on forecasting and detection and shared responsibility with local communities and media outlets for dissemination and public education to elicit proper public response when a warning is issued. For this evaluation of service performance, we review the overall structure of the warning system for each state, including feedback from emergency managers with jurisdiction in the gap coverage regions, and impact of insufficient low-level radar coverage. The extent and health of the working relationship between the NWS WFOs and local communities can influence the preparedness and safe response of the public to hazardous events.

Next, a comprehensive evaluation of NWS warning performance is examined at the regional, WFO, and county levels. NWS warning statistics from the WFO CWA of interest are compared against regional and national averages. In the Intermountain West, data are examined from the Riverton, Wyoming (RIW), and Rapid City, South Dakota (UNR) offices. In the Pacific Northwest, data are examined from the WFOs in Seattle, Washington (SEW) and Portland, Oregon (PQR). This comparison forms a baseline for quantifying the current level of service, as defined by NWS metrics.

4.1 Wyoming

4.1.1 Warning System

County and municipality level emergency managers are responsible for notifying the public of hazardous weather. The principal communication challenge for the weather warning system in Wyoming concerns disseminating information to a sparse population. Local television stations in Wyoming are limited and, unlike many states, are not the primary source of severe weather information for the public (e.g., Hammer and Schmidlin 2002). Because of the sparseness of the population in Wyoming, tornado sirens are used only in the most densely populated areas. In less populated areas, NOAA Weather Radio, local radio stations, automated calling technology, and even old fashioned telephone trees are used to disseminate information to the public.

The NWS Forecast offices rely more heavily on an extensive network of storm spotters, emergency managers, public safety officials and the public to provide ground truth information on convective events, precipitation rates, and snow accumulation in the radar gap areas. A strong environment of mutual respect and collaboration permeates the warning community across Wyoming.

4.1.2 Sample Emergency Manager Feedback

Emergency managers from counties located in radar gap regions provide additional insight into the impacts of limited low-level radar coverage on system performance and warning operations.

Campbell County – David King has worked as the emergency manager for Campbell County, focusing on the cities of Gillette and Wright, for the past 20 years. He is concerned that the lack of radar coverage contributes to shorter lead times for severe weather warnings and at times he "feels blind." He stated, "We don't count on radar for weather" because the weather in his area "hugs the ground" and is significantly impacted by terrain effects that extend from north to south in Campbell County. Mr. King states that his emergency management work is further complicated by the fact that Campbell County lies near the intersection of three different NWS forecast office areas. Moreover, weather information provided by the media is not helpful because the television stations use commercial providers (e.g., Accuweather) which smooth the radar data, so that frequently no echoes appear in the TV images when precipitation is occurring in the region. King relies on an extensive spotter program, WYDOT reports, and the Rapid City forecast office which collects data from mesonet stations in the Powder River Basin mining sites. There have been several instances, reported by Lewis, where tornadic activity has been reported first by the local spotter network and then followed by a tornado warning issued by the NWS forecast office. NWS warning statistics confirm this observation where 50% of tornado warnings offer no lead time (see Table 4.2). For warnings, King activates tornado sirens in the city of Gillette and Wright and also relies on local radio stations and NOAA weather radio to reach individuals in the more sparsely populated regions. Many of the ranches in rural regions have satellite dishes.

Johnson County - Johnson County is a sparsely populated county that is experiencing high growth due to the natural gas industry. Two interstates, I-25 and I-90, intersect in Johnson County in the city of Buffalo. According to Marilyn Johnson, the county emergency manager, the county rarely experiences significant severe weather; however she could benefit from more lead time for precipitation and winter weather, preferably on the order of several hours, to dispatch spotters, to make decisions about school closings, and to anticipate traffic delays and road closures. Real-time information of precipitation amount, snow melt and wind direction and wind speed would help her determine if, when, and if so, which portion(s) of the Powder River might flood. When flooding occurs on the Middle Fork of the Powder river, the small town of Kaycee is impacted, a town without access to real-time weather information. The town of Kaycee has one Citizen Weather Observer Program (CWOP) participant which provides some limited weather information.

Sweetwater – Sweetwater County is the largest county in Wyoming and is an area known for the mining of potash and natural gas. For Sweetwater, the emergency managers interviewed are most concerned about wind gusts, including microbursts, flooding and winter weather. The population center, Rock Springs, is located along two creeks - the Bitter Creek and Killpecker Creek - and is prone to flash floods. Local Emergency Planning Committee member, Angelo

Kallas, indicated that the city is located “in a basin” and therefore does not receive adequate radar coverage. Judy Valentine, the Sweetwater County emergency manager, states that radar information would help with mitigation and warning activities. In addition, Interstate 80, the major east-west commerce route extending though the gap coverage area, was closed for a total of 45 days during the winter of 2007-2008 due to winter weather and blowing snow. Emergency managers coordinate re-routing of traffic, determine adequate lodging, and ensure the safety of those waiting on the highways and interstates to reopen. Her ideal storm prediction would be 72 hours advance notice of potential highway closings so that lodging and alternate routes can be worked out in advance.

4.1.3 NWS Warning Service Performance

Warning verification statistics provide one historical measure of the quality of service provided by the National Weather Service to any given county or warning area. Records are compiled of all severe storm events (e.g., severe thunderstorms, flash floods, tornadoes) and all NWS warnings from all WFOs and counties in order to track changes in warning statistics with time. Several standard statistics are applied to the raw numbers to summarize the results; these statistics include the Probability of Detection (POD), the False Alarm Rate (FAR), and the Critical Success Index (CSI; also known as Threat Score). For the purposes of this study, POD is the ratio of successfully warned events to the total number of hazardous weather events; FAR is the ratio of warnings that did not verify to the total number of warnings; and CSI is the ratio of successfully warned events to the total number of severe events plus unverified forecasts for severe events. An additional statistic shown is the percentage of warnings issued with positive lead time. These statistics are calculated as described in Schaefer (1990) and Brooks (2004) as follows:

POD = *events with warning* / *total events* = $X / (X+Y)$

CSI = *events with warning* / [*total events* + *warnings without event*] = $X / (X + Y + Z)$

FAR = *warnings without event* / *total warnings* = $Z / (X + Z)$

where X is the number of events that occurred with an NWS warning, Y is the number of events that occurred without a warning, and Z is the number of warnings issued without an event (Table 4.1). All indices vary between 0.0 and 1.0. A perfect verification score is 1.0 for POD and CSI and 0.0 for FAR.

Table 4.1: Contingency table.

		NWS Warning?	
		Yes	No
Hazardous Weather Event?	Yes	X	Y
	No	Z	

Verification statistics were calculated based on over seven years of data collected between 1 January 2000 and 30 September 2007 as provided by the NWS. Statistics were calculated nationally, for each of the four NWS regions (Figure 4.1), and for each WFO and county.

Figure 4.1: The NWS WFOs are organized into four regions – Eastern (red), Southern (blue), Central (Yellow) and Western (light green).

One caveat to note when reviewing these NWS verification statistics is that the warning statistics may not necessarily reflect a relationship to the adequacy of the radar coverage. In other words, each statistic may or may not have been impacted by the availability of radar coverage when the warning was issued. Many other factors, such as the availability and number of storm spotters, climatology, environmental conditions, and numerical weather prediction model forecasts, can play a critical role in if and when a warning is issued. For example, one difficulty with issuing warnings in Wyoming is the sparseness of the population, which complicates warning verification.

4.1.4 Wyoming NWS warning statistics

Warning verification statistics for Wyoming are calculated for severe thunderstorms, tornadoes and flash floods (Tables 4.2 - 4.4). National and Central Region verification statistics are listed with WFO statistics from the Riverton (RIW) and Rapid City (UNR) offices. Also shown are verification statistics for three specific counties; Campbell County, WY, is within the UNR CWA and Johnson and Sweetwater Counties are within the RIW CWA. All three counties have limited low-level radar coverage.

Verification statistics for severe thunderstorms show few trends (Table 4.2). UNR has above-average regional POD, CSI and below-average FAR; Campbell County statistics reflect these averages, but in general are slightly below-average compared with other counties within the UNR CWA. RIW has below-average regional POD and CSI and above-average FAR; Johnson

County figures are comparable to RIW averages while Sweetwater County has much-below-average POD and CSI and lower FAR and average lead time.

Table 4.2: National, regional, CWA and county WFO verification statistics for *severe storms* in Wyoming.

Severe Thunderstorms	Number of Events	Number of Warnings Issued	Probability of Detection (POD)	Critical Success Index (CSI)	False Alarm Rate (FAR)	Average Lead Time (Min)	Percentage of events with > 0 min lead time
National	173,392	221,845	0.801	0.473	0.465	16.3	77.6%
Central Region	78,623	89,623	0.787	0.490	0.435	16.1	76.4%
RIW WFO	264	471	0.663	0.282	0.671	12.8	62.1%
Sweetwater County	21	27	0.238	0.116	0.815	3.9	14.3%
Johnson County	37	72	0.784	0.317	0.653	12.7	70.3%
UNR WFO	2,466	2,420	0.876	0.633	0.305	20.8	85.2%
Campbell County	156	148	0.821	0.619	0.284	19.4	76.3%

Tornadoes are relatively rare across Wyoming, and both RIW and UNR have below-average POD, CSI, and lead time compared to national figures (Table 4.3). FAR is also higher than the national average for both RIW and UNR. However, Campbell County has much higher POD and CSI (and much lower FAR) than the national averages, despite the lack of low-level radar coverage. Nevertheless, the average warning lead time for Campbell County is half of the national average and less than the UNR average lead time.

Flash floods are also relatively rare across the RIW and UNR CWAs (Table 4.4), with below-average POD, CSI, average lead time, and higher FAR compared against regional and national averages. Only Johnson County averaged seven or more events during the seven year record, and these statistics also reflected below-average POD, CSI and lead-time compared against national estimates.

In summary, the Central Region compares on par with national statistics for severe thunderstorms, tornadoes and flash flood warning. Compared against Central Region estimates, both RIW and UNR have below-average POD and CSI and above-average FAR for tornadoes and flash flood warning; for severe thunderstorms, UNR has above-average POD, CSI, and lead time while RIW has below-average figures. Average lead times for RIW and UNR were particularly poor for flash floods and tornadoes when compared against the national averages. While the sample size is small, these data show that Campbell County had above-average POD and CSI (and below-average FAR) for severe thunderstorms and tornadoes compared to the national averages, but Campbell, Johnson and Sweetwater Counties had below-average lead time compared to their parent WFO averages.

Table 4.3: National, regional, CWA and county WFO verification statistics for *tornadoes* in Wyoming.

Tornadoes	Number of Events	Number of Warnings Issued	Probability of Detection (POD)	Critical Success Index (CSI)	False Alarm Rate (FAR)	Average Lead Time (Min)	Percentage of events with > 0 min lead time
National	10,745	28,879	0.744	0.224	0.757	12.2	66.2%
Central Reg.	5,023	11,949	0.780	0.252	0.728	13.1	68.4%
RIW WFO	15	34	0.333	0.130	0.824	0.5	13.3%
Sweetwater County	3	2	0.0	0.0	1.0	0.0	0.0%
Johnson County	0	5	**	**	1.0	**	**
UNR WFO	58	144	0.586	0.187	0.785	8.9	37.9%
Campbell County	14	18	0.929	0.584	0.389	6.3	50.0%

Table 4.4: National, regional, CWA and county WFO verification statistics for *flash floods* in Wyoming.

Flash Floods	Number of Events	Number of Warnings Issued	Probability of Detection (POD)	Critical Success Index (CSI)	False Alarm Rate (FAR)	Average Lead Time (Min)	Percentage of events with > 0 min lead time
National	24,910	47,041	0.886	0.543	0.416	49.4	74.6%
Central Reg.	7,230	13,105	0.894	0.533	0.431	55.4	72.5%
RIW WFO	56	84	0.571	0.317	0.583	27.0	41.1%
Sweetwater County	2	2	0.500	0.333	0.500	0.0	0.0%
Johnson County	11	18	0.636	0.389	0.500	16.6	36.4%
UNR WFO	30	51	0.767	0.441	0.490	26.0	40.0%
Campbell County	2	3	1.0	0.667	0.333	0.5	50.0%

4.2 Washington

4.2.1 Warning System

In Washington, the principal weather concerns are flooding and severe wind storms. In western Washington, lead time is generally not a major concern because the weather systems that impact Washington tend to be large and long-lived. The key issues are the analysis and prediction of local maxima of precipitation and wind. The lack of data over the ocean and microclimate variability over land complicate nowcasting and prediction efforts. For example, in the Olympic Mountains slight variations in the wind speed and direction affect local precipitation rates, and small variations in the location of precipitation maxima affect which rivers will flood and the intensity of the flooding to downstream towns and cities.

Emergency managers in western Washington have responsibility for notifying the public, determining when mitigation efforts, such as placing sand bags along a river, should occur, and initiating evacuation. Emergency managers have only basic knowledge of weather forecasting and radar and rely largely on the local forecast office for guidance. The Seattle forecast office, for example, holds teleconferences to notify emergency managers of predicted severe events and their potential impacts. The forecast offices also advise local industry and public utilities. The Seattle forecast office and the emergency management community is refining this communication strategy to include multiple points of communication within a single county. During winter 2007, emergency management in Grays Harbor missed a critical communication meeting with the NWS forecast office that hampered the emergency manager's ability to prepare for a major severe wind event. Since that event, the forecast office and county emergency managers have put into place a more redundant communication system.

The WFO and RFC offices use radar data only as a secondary source of information because of the coverage gaps in the network. River gages and rain gauges are used to measure and predict the rate of water flow.

4.2.2 Sample Emergency Manager Feedback

Lewis County - Ross McDowell is the county emergency manger for Lewis County. Wind and rain from winter storms are the greatest hazard for his county. Advance notification is important so he can take mitigation steps such as placing sandbags along key areas of the river in his county. For flooding, he uses two radio stations as the primary means of communication. Mr. McDowell states that he needs better information upstream of his jurisdiction to predict floods where low-coverage radar data and rain gauge data are not available. The river gauges downstream from his area do not provide McDowell with additional lead-time for his district. During the winter storm of 2007, his county experienced a flash flood without any advanced flood warning. McDowell issued a flash flood warning for his jurisdiction, in advance of the NWS. Currently, he has several residents who maintain high water markers on their property, and he contacts them to get ground truth information about precipitation rates and flooding.

Grays Harbor County – This county is blocked from radar coverage by the Olympic Mountains. For Anne Sullivan, the emergency manager for Grays Harbor, the key issues are the severity and duration of the event and the expected conditions along the near-shore. Grays Harbor has a telephonic warning system, similar to a reverse 911 system. Weather information is particularly critical to the crab fishing industry, a major staple to the economy of the region.

4.2.3 Western Washington NWS Warning Statistics

Verification warning statistics for Washington are calculated for severe thunderstorms, tornadoes and flash floods (Tables 4.5 – 4.7). National and Western Region verification statistics are listed with WFO statistics from the Seattle (SEW) and Portland (PQR) offices. Severe thunderstorms, tornadoes, and flash floods are rare across both WFO CWAs; statistics are shown in part to indicate the rarity of such events. The warning performance statistics for Washington are not as relevant for the issues faced by these forecast offices as it is the intensity and duration of the weather event that is often the greater concern.

Table 4.5: National, regional, CWA and county WFO verification statistics for *severe storms* in Washington state.

Severe Thunderstorms	Number of Events	Number of Warnings Issued	Probability of Detection (POD)	Critical Success Index (CSI)	False Alarm Rate (FAR)	Average Lead Time (Minutes)	Percentage of events with > 0 min lead time
National	173,392	221,845	0.801	0.473	0.465	16.3	77.6%
Western Reg.	6,203	11,437	0.735	0.309	0.652	17.0	68.8%
SEW WFO	4	16	0.500	0.111	0.875	0.3	25.0%
PQR WFO	32	93	0.531	0.203	0.753	5.5	25.0%

Table 4.6: National, regional, CWA and county WFO verification statistics for *tornadoes* in Washington state.

Tornadoes	Number of Events	Number of Warnings Issued	Probability of Detection (POD)	Critical Success Index (CSI)	False Alarm Rate (FAR)	Average Lead Time (Minutes)	Percentage of events with > 0 min lead time
National	10,745	28,879	0.744	0.224	0.757	12.2	66.2%
Western Reg.	293	472	0.358	0.161	0.773	4.5	26.3%
SEW WFO	9	0	0	0	**	0.0	0.0%
PQR WFO	12	0	0	0	**	0.0	0.0%

The quality of the warning service provided by SEW and PQR is difficult to evaluate due to the relatively few severe thunderstorms, tornadoes, and flash floods that occur within the CWAs. For those events that did occur, the POD, CSI and average lead time were much below-average for severe thunderstorms and tornadoes compared to national and Western Region means; too few flash floods occurred within the SEW and PQR CWAs to determine statistical averages.

It is noteworthy that of the 21 confirmed tornadoes to have occurred within the SEW and PQR CWAs during the seven year period, *none* of the 21 events had advanced warning provided. However, almost all tornadoes that form in the western U.S. are what are termed 'gustnadoes' or 'landspouts' (e.g., Wakimoto and Wilson 1989). As discussed in Chapter 2, these form when pre-existing vorticity is stretched due to the buoyancy associated with an updraft. Gustnadoes are generally very brief and weak, causing little if any damage and posing little threat to public safety. None of the 21 tornadoes noted in the record since 1993 caused any fatalities.

Table 4.7: National, regional, CWA and county WFO verification statistics for *flash floods* in Washington state.

Flash Floods	Number of Events	Number of Warnings Issued	Probability of Detection (POD)	Critical Success Index (CSI)	False Alarm Rate (FAR)	Average Lead Time (Minutes)	Percentage of events with > 0 min lead time
National	24,910	47,041	0.886	0.543	0.416	49.4	74.6%
Western Reg.	1,610	3,531	0.730	0.342	0.609	35.9	56.0%
SEW WFO	2	0	0.0	0.0	**	0.0	0.0%
PQR WFO	1	11	1.0	0.091	0.909	0.0	0.0%

Feasibility of Additional Weather Radar

Chapter 5: Requisite Radar Attributes

What specific radar attributes are required to address the service needs and data limitations?

5.0 Introduction

As discussed in prior chapters, detection and prediction are primary components of an integrated weather warning system and, for the most part, they are components managed by the NWS. In this chapter, radar attributes are discussed in the context of the contribution they can make to detection and warning. First, the limitations of the current NEXRAD radars are discussed in order to highlight the impact of additional data on weather analysis and hazard detection. Following this is a discussion of the value of radar data for assimilation into numerical weather forecast models. Finally, a summary of the requisite radar attributes (i.e. spatial and temporal resolution, altitude coverage, and dual-polarization) are outlined for the gap regions in Wyoming and western Washington.

5.1 Analysis and Detection

Weather radar is one of the primary tools used by meteorologists for detecting and monitoring severe and hazardous weather features. Observing dangerous phenomena is key to mitigating their effect by providing adequate advanced warning. The value of NEXRAD to this end is highlighted in Simmons and Sutter (2005) which shows that the NEXRAD radar network has significantly decreased the number of tornado fatalities and injuries and has increased the warning lead time of these events. Estimates of the physical characteristics and timescales of various weather phenomena are listed in Table 5.1, and the vertical extent of the phenomena are represented graphically in Figure 3.1. The physical characteristics are from NRC (1995) and the timescales are estimated from the authors.

At the current mean spacing of NEXRAD radars, approximately 250 km, or 156 miles (Vasiloff et al. 2007), tornadic vortex signatures (TVSs), minisupercells, misocyclones, and microbursts cannot be observed across much of the nation. Similarly, boundary layer winds and convergent lines are unable to be observed beyond 80 km (50 miles), and the bright band signatures typically limit the accuracy of stratiform precipitation measurements beyond 45 km (28 miles) of the radar. In addition to observation of these weather hazards, adequate high-resolution, low-level radar coverage is essential to improving QPE (Vasiloff et al. 2007).

As discussed in Zrnic et al. (2007), the timescales of many mesoscale phenomena may be much shorter than can be observed with the NEXRAD network which completes a low-level scan every 4.5 to 10 minutes (4.5 to 6 minutes when storms are occurring). Tornadic vortex signatures, misocyclones, and microbursts may all occur within this time frame, and it is expected that faster update times will result in greater warning lead times.

In some locations where there is virtually no radar coverage, such as over the ocean off the coast of Washington, any radar data at mid-, low-, and high elevations would likely improve the NWS' current ability to monitor weather conditions and thereby improve warning performance.

Table 5.1: The physical characteristics of various weather phenomena as presented in NRC 1995. The median character value is listed for each feature, with a range of values listed in brackets.

Phenomena	Top (km)	Horizontal Dimension (km)	Reflectivity (dBZ)	Time scales*	Maximum WSR-88D range for detection (km)
Supercell					
Mesocyclone	7 [4-10]	8 [4-12]	45 [25-60]	10-90 min	180 [150-230]
Hook echo	2 [1-4]	8 [4-12]	45 [25-60]	10-90 min	100 [40-160]
Mini-supercell					
Miso-, mesocyclone	4 [2-8]	4 [1-8]	35 [20-60]	1-10 min	100 [70-150]
Hook echo	1 [0.5-2]	4 [2-8]	35 [20-60]	1-10 min	70 [30-110]
Misocyclone (convergent lines)	1 [0.5-3]	2 [0.5-4]	20 [5-50]	1-10 min	35 [10-70]
Tornadic Vortex Signature	3 [1-6]	0.2 [.02-2]	40 [25-55]	1-90 min	45 [10-130]
Microburst	0.5 [0.3-1.2]	3 [2-4]	45 [5-65]	1-10 min	35 [20-50]
Macroburst					
Reflectivity signature	3 [1-5]	50 [15-100]	40 [30-50]	Minutes-Hours	150 [100-250]
Velocity signature	1 [0.5-2]	15 [4-30]	50 [40-65]	Minutes-Hours	70 [50-100]
Precipitation					
Convective rain	9 [5-17]	**	40 [25-65]	Minutes-Hours	350 [200-460]
Stratiform rain	6 [3-8]	**	30 [15-45]	Hours	250 [150-350]
Stratiform snow	5 [1-7]	**	20 [10-30]	Hours	180 [120-240]
Lake-effect snow	2 [1-3]	**	20 [10-30]	Hours	120 [80-160]
Winds					
Boundary layer	1.5 [0.5-3]	**	10 [-5-20]	Minutes-Hours	80 [20-120]
High sfc winds w/precip	1.5 [0.5-3]	**	30 [15-45]	Minutes-Hours	70 [20-120]
Convergent lines	1 [0.3-4]	**	10 [-5-45]	Minutes-Hours	80 [40-120]
Melting level (bright band)	1.5 [1-3]	0.3 [0.2-0.5]	35 [20-45]	Minutes-Hours	45 [25-70]

* Time scales estimated by report authors.
** Not applicable.

5.2 Numerical Weather Prediction

When NEXRAD was first deployed, much attention was given to using radar data for real-time analysis and monitoring. However, assimilation of radar data into numerical weather prediction (NWP) models has also become a valuable weather forecasting tool. Radar data and products are now routinely assimilated into operational NWP models such as those run by the Korean Meteorological Administration (Xiao et al. 2008) and the European Centre for Medium-range Weather Forecasts (ECMWF; Lopez and Bauer 2007), and real-time experimental NWP models (e.g., Brewster et al. 2008).

An ever-growing list of research shows the improvement in NWP with the addition of weather radar data and products. Xiao et al. (2005) show improved skill in predicting heavy rainfall by assimilating radial velocity data, and Zhao et al. (2006) observed improved skill in forecasting three-dimensional wind fields when assimilating radial velocity data. Xiao and Sun (2007) demonstrate with one squall line case that the more radar sites and data included in the assimilation, the greater the improvement in the quantitative precipitation forecast (QPF) prediction. They also found that the model forecasts are most improved by assimilating both radial velocity and reflectivity data. Zhao and Jin (2008) show improved prediction in hurricane intensity and structure by assimilating radial velocity and reflectivity from five WSR-88Ds. Hu et al. (2006) demonstrated improved supercell structure and tornado prediction with the assimilation of radial velocity and reflectivity data. Assimilating radar data via four-dimensional variational analysis (4DVAR) is shown to speed up the spin-up time significantly and thereby improve short-term forecasts (Sun and Zhang 2008).

Dual-polarization and dual-Doppler provide additional information for storm analysis and prediction. Using a simulation, Jung et al. (2008) demonstrated improvement in storm analysis when directly assimilating polarimetric data including differential reflectivity, reflectivity difference, and specific differential phase. Dual-Doppler data allow the three-dimensional wind structure to be observed (e.g., Frame et al. 2008; Marquis et al. 2008), and thermodynamic variables can be indirectly extracted (Gal-Chen 1978; Hane et al. 1981).

The use of data from short-range, low-scanning radars for NWP also has been investigated. Xue et al. (2006) demonstrated that the addition of short-range radars, when combined with existing WSR-88D data, can improve storm analysis, particularly at low levels. Brewster et al. (2008) and Schenkman et al. (2008) show improvement in prediction of low-level vorticity with the assimilation of CASA radial velocity and reflectivity data.

The extent to which specific forecasts are improved with the addition of weather radar data and products varies substantially as a function of weather uncertainty, model physics, resolution, assimilation technique, quality control, and the availability of non-radar weather information. Nevertheless, years of research have shown that the inclusion of radar data has a positive and significant impact on weather prediction, and additional weather radar coverage will contribute towards improvements in local weather analysis and forecasting.

5.3 Summary of Radar Needs

This section summarizes our findings thus far and answers the question: What are the needs for additional weather radar systems to fill gaps in the current weather radar coverage across northeast and southwestern Wyoming and western Washington? Below is a prioritized list of observing needs that have been developed for Wyoming and western Washington.

5.3.1 Northeast and southwest Wyoming

A summary of weather risks for Wyoming and associated radar requirements for real-time detection, monitoring and NWP are shown in Table 5.2. The greatest needs across Wyoming, as identified by area stakeholders, for real-time detection and monitoring are improving cold and warm season QPE and improving our ability to monitor severe thunderstorms and gust fronts.

As shown in Chapter 4, NWS warning lead times for severe storms, tornadoes, and flash floods for the three counties examined in radar gap areas are below WFO regional averages. One problem is that Wyoming is often a region of thunderstorm genesis and increasing lead times may require the use of NWP prediction. Additional weather radar data could improve model initialization in these areas and offer real-time observations for forecasters. Improved radar coverage at low levels also could improve hydrological prediction of heavy rain events by identification of low-level boundaries and high moisture pools via refractivity.

It is anticipated that the dangers posed by many hazardous weather events could be reduced by more complete low-level radar coverage. Other, specific radar attributes needed include dual-polarization, a greater sampling rate at low-levels, and dual-Doppler capability. The spatial resolution and sensitivity of any new radar should be comparable to the WSR-88D.

5.3.2 Western Washington

A summary of weather risks for western Washington and associated radar requirements for real-time detection and monitoring are shown in Table 5.3. The greatest need across western Washington, as identified by area stakeholders, is short-range (0-12 hour) analysis and prediction; in particular, they request additional radar data over the ocean to improve the analysis and forecasting of surface low pressure systems. The precise track and intensity of these low pressure systems is often difficult to analyze and predict with current radar coverage (e.g., McMurdie and Mass 2004). Additional weather information over the ocean would contribute directly toward mitigating much of the dangers posed to weather-sensitive industries such as shipping and tuna fishermen who operate in areas up to 111 km (60 nmi) off-shore, now in areas not covered by weather radar. Furthermore, an extensive regional prediction system is already in place and could readily assimilate any new observations from weather observing systems installed in the area (Mass et al. 2003).

Other needs cited by stakeholders include the need to improve cold and warm season QPE, and a more reliable ability to monitor low-level winds. As in Wyoming, more complete low-level radar coverage would enhance monitoring and prediction capabilities. Other, specific radar attributes needed include dual-polarization and dual-Doppler capability. Again, the spatial resolution and sensitivity of any new radar should be comparable to the WSR-88D.

Table 5.2: Summary of weather needs for northeast and south-central Wyoming and associated radar attributes required for real-time detection, monitoring and numerical weather prediction. Low-level (1-km) radar coverage is needed region wide to address all weather risks.

Need		Problem	Radar Requirements
Real-time detection, monitoring			
	1. Winter weather, low-level winds	Winter QPE – snowfall detection	Dual-polarization High sensitivity
	2. Severe thunderstorms, tornadoes	Detection of mesocyclones, RFDs, TVSs, landspouts, microbursts	High spatial resolution Rapid scan, update time Dual-polarization Dual-Doppler
	3. QPE	Highly variable QPE due to microclimates, terrain	High spatial resolution Dual-polarization
	4. Low-level wind shifts, boundaries	Detection of gust fronts (fire weather)	High sensitivity High spatial resolution Dual-Doppler
Numerical Weather Prediction			
	1. Storm prediction (mesoscale)	Improving severe storm, tornado warning lead time; Improving forecasting of storm genesis.	High spatial resolution Dual-polarization
	2. QPF	Winter weather; flood prediction; Assimilation for hydrological models.	High spatial resolution High sensitivity Dual-polarization

Table 5.3: Summary of weather needs for western Washington and associated radar attributes required for real-time detection, monitoring and numerical weather prediction. Low-level (1-km) radar coverage is needed region wide to address all weather risks.

	Weather Risk	Problem	Radar Requirements
Real-time detection, monitoring			
	1. Storm analysis (synoptic to mesoscale)	Locating/tracking center of surface low pressure systems; Monitoring off-shore weather	Additional radar data over the ocean at low-, mid-, and high- elevations.
	2. QPE	Bright-band contamination; Highly variable QPE due to microclimates, orographic influence	High spatial resolution Dual-polarization
	3. Low-level winds	Highly variable due to microclimates, orographic influence; Highly sheared environment	High spatial resolution High sensitivity Dual-Doppler
Numerical Weather Prediction			
	1. Storm prediction (synoptic to mesoscale)	Assimilation for meteorological synoptic and mesoscale models.	Dual-polarization
	2. QPF	Assimilation for hydrological models	Dual-polarization

Chapter 6: Potential Radar Solutions

What are some potential radar solutions that might address the service needs and data limitations?[14]

6. Introduction

This chapter analyzes the coverage that would be obtained in the radar gap areas of Wyoming and western Washington by installing large radars and networks of small radars. Section 6.1 summarizes the radar performance of physically large, high-power S-band and physically small, low-power X band radar technologies. C-band radars, which tend to be intermediate in size between X and S band systems, are a third alternative used by some countries but are not discussed in this report. We discuss S-band radars owing to the substantial U.S. experience with installing and operating these radars as part of the NEXRAD program. We discuss X-band radars owing to the potential for improved low-level coverage provided by these radars as reflected in the ongoing research in the NSF Engineering Research Center for CASA.

In Section 6.2.1, idealized S- and X-band radar networks are presented to gauge both the number of radars required to cover the domains of interest (i.e. northeast and southwest Wyoming, and western Washington) and to quantify the coverage achievable at given altitudes. This initial section is idealized – meaning that it does not consider the blockage effects of terrain; this is done as a way to illustrate the different types of coverage that would be achieved using large vs. small radars. Section 6.2.2 removes the idealization and quantifies the performance associated with different radar network configurations in the presence of irregular and blocking terrain. This is achieved through the use of high-resolution elevation maps, radar occultation calculations, and geographic information system (GIS) software to quantify the coverage of each type for each domain.

6.1 Long range vs. short range radar deployments

6.1.1 Long-range weather radar (e.g., WSR-88D)

Long-range weather radars operate at a wavelength of ~ 10 cm in the S-band frequency range. Radars designed to operate over long ranges (e.g., >230 km) need large antennas (8.5 m diameter antenna for the WSR-88D/NEXRAD system) and high power transmitters (peak power of 750 kW for the WSR-88D) and they require dedicated land and substantial physical support infrastructure. A photograph of such a radar is shown in Figure 6.1. This is the class of radars

[14] *This section of the report was prepared by: Dr. R. Contreras, CASA PhD candidates Jorge Salazar and Anthony Hopf, CASA Principal Engineer/Budget Director, Eric Knapp, and report authors. Dr. Contreras was funded in part by this study's NOAA contract and in part by the CASA general funds. The work of Messrs. Salazar, Hopf, and Knapp was supported by the CASA general funds including the NSF Engineering Research Center grant 0313747. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.*

used in today's national network of S-band weather radars; while they provide effective coverage at heights above 2 - 3 km, the spacing between these radars limits observations from low-levels.

Figure 6.1: The 10 m diameter radome of a long-range S-band WSR-88D/NEXRAD radar is shown at left. A small CASA radar is shown at right atop an 8 m tower.

6.1.2 Short-range weather radar (e.g., CASA)

The NSF Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) is pursuing a concept in which networks of small, short-range radars overcome the earth curvature and terrain blockage problems faced by long-range radars. Such radars would have the potential to be deployed nationwide – as a supplement or replacement to the large radars in use today – or in a "gap fill" mode, addressing gaps such as those in Wyoming and Washington State. The short-range (~ 40 km) radars being considered by the CASA project operate at X-band (McLaughlin et al. 2005; Figure 6.1) and require substantially smaller antenna (~1 m diameter) and lower radiated power (average power ~ 10s of Watts) than the long-range S-band radars in the national network. The CASA project has deployed 4 of these radars in a research test bed in Oklahoma, an average 25 km apart (Brotzge et al. 2007).

The short-wavelength of the CASA-type radars requires that careful attention be paid in the design to the effects of attenuation due to rainfall. Dual-polarization and overlapping beam coverage provide two methods for real-time correction of attenuation (Gorgucci and Chandrasekar 2005; Lim et al. 2007). As discussed in Chapter 5, overlapping beam coverage also provides the additional benefit of having dual-Doppler coverage available across much of the network domain, which allows for the derivation of three-dimensional wind information. CASA radars also provide adaptive scanning capabilities through Distributed Collaborative Adaptive Sensing, or DCAS (Brotzge et al. 2008). Automated data mining algorithms operate on reflectivity and velocity data in real-time, creating new scanning commands for the radars every scanning cycle heartbeat, in this case, once per minute. Once a storm of interest is identified, the radars immediately begin sector scanning that particular area, completing a full volume scan of the storm within one minute. Additional capabilities provided by CASA radars include automated range-height indicator scans (RHIs) and possibly differential refractivity, a promising technique for quantifying low-level moisture (Cheong et al. 2007). The "Observing the Weather…" report from the National Academy recommends that the adaptive scanning associated with this type of radar be employed by future radars when appropriate (page 12).

Table 6.1: Technical specifications listed for CASA and WSR-88D radars.

	CASA	WSR-88D
Operating frequency	9.41 GHz	2.7 – 3.0 GHz
Wavelength	3 cm	10.0 cm
Antenna diameter	1.20 m	8.53 m
Antenna gain	38 dB	45.5 dB
Antenna beamwidth	1.8º	1.0º
Oversampling	1.0º	Planned for future build.
Range gate spacing	100 m	250 m
Maximum rotation rate	35 deg s^{-1}	36 deg s^{-1}
Acceleration rate	50 deg s^{-2}	15 deg s^{-2}
Average transmitter power	9 W/polarization	1.56 kW
Peak transmitter power	7.5 kW/polarization	750 kW
Minimum Detectable reflectivity (10 km)	-2 dBZ	-23 dBZ
Pulse repetition frequency	1.6 kHz, 2.4 kHz	318-452 pulses/sec 318-1304 pulses/sec
Pulse width	660 nsec	1.6, 4.5-5.0 μ sec
Dual-polarization?	Yes	Scheduled for 2010-2012.
Radome, diameter	2.4 m	11.9 m

6.2 Potential radar solutions

This section explores example network configurations of short-range and long-range radars in the domains of Wyoming (Domains A and B in Figure 6.2) and western Washington (Domain C in Figure 6.3). These domains were selected to address the needs outlined in Section 2. Idealized calculations are presented in Section 6.2.1 to give an idea of the number of radars required to cover a given area and to highlight differences between long-range radars and networks of short-range radars as a function of height. These calculations are "ideal" in that they assume a regular grid (equilateral triangular with 35 km spacing) and do not simulate radar blockage by terrain; they are "smooth-earth" calculations and only consider curvature. Following this is Section 6.2.2, "smooth-earth" coverage is calculated using realistic radar placements to determine the importance of siting to the overall coverage statistics. In Section 6.2.3, simulations of radar coverage with the realistic locations and actual terrain are presented and compared to the "smooth-earth" cases.

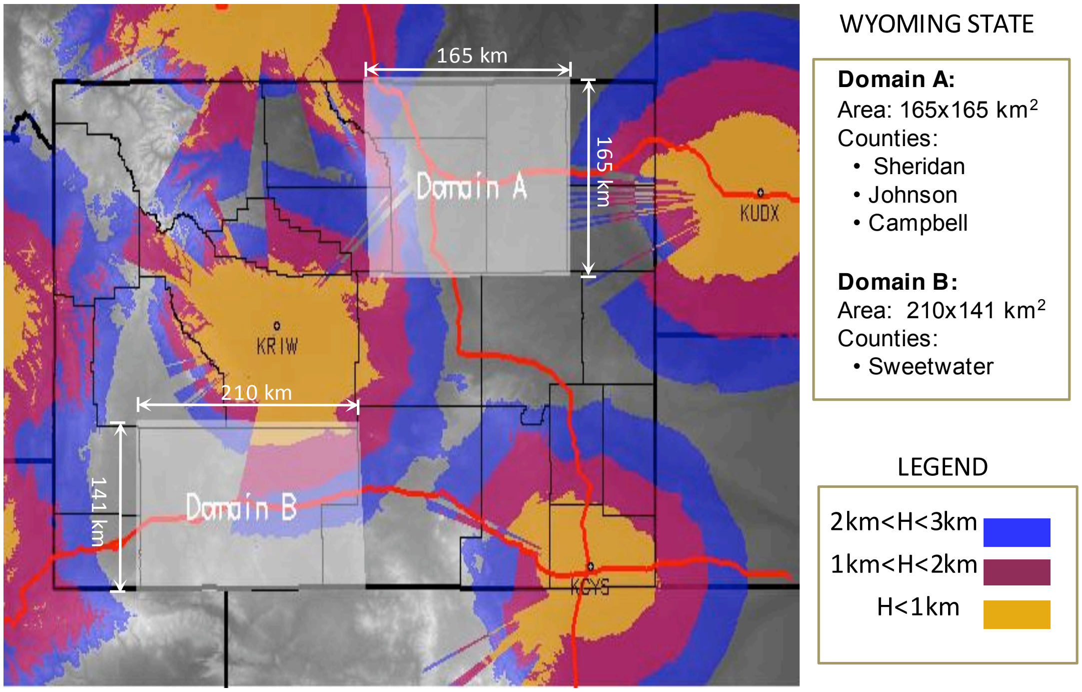

Figure 6.2: Wyoming radar gap-coverage analysis Domains A and B.

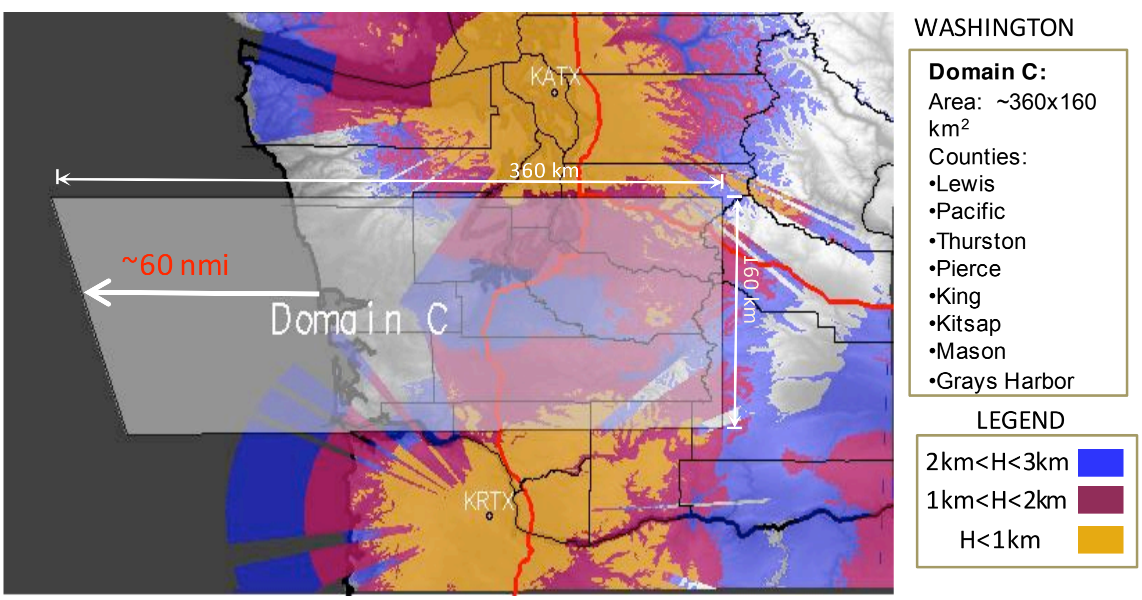

Figure 6.3: Western Washington radar gap-coverage analysis domain C.

6.2.1 Idealized radar calculations (smooth-earth, equilateral grid)

The "idealized" calculations, which assume no terrain blockage and a regular triangular grid, provide theoretical understanding of the value of long-range vs. short range radar systems. The calculations also provide estimates of the numbers of both types of radars needed to provide coverage across a specified domain. Figure 6.4a shows the number of short-range radars (blue) and long-range radars (red) that would be required to provide coverage across a given-size domain. Figure 6.4b shows the percentage coverage of the atmosphere as a function of altitude, independent of domain, for long-range radars (red) and short-range radars (blue) systems. Figure 6.4b shows networks of short-range radars provide similar coverage at 2 km, superior coverage below about 1.5 km. At 1 km, long-range radars give only about 40% of the 100% coverage the networks of small radar provide. Of course, these estimates are valid only over land areas and do not apply to areas over open water, such as in Domain C of Figure 6.3.

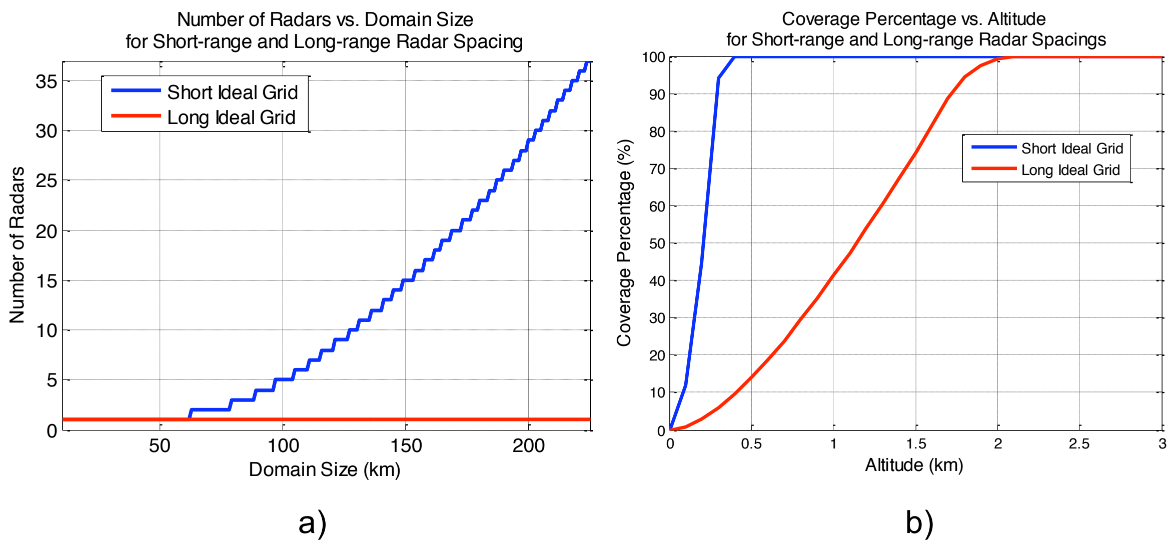

Figure 6.4: a) Number of radars needed to populate a given domain size for short-range (35 km) and long-range (225 km) radar spacing. The domain considered is square with the side of the square defined by the "domain size" in kilometers. The radars are arranged within the domain in an ideal equilateral triangular grid with overlap to the center of the closest neighbor. b) Percent coverage evaluated at a given altitude for short-range (35 km) and long-range (225 km) radar spacing. The radars are arranged in an ideal equilateral triangular grid with overlap to 5 km past the center of the closest neighbor. Percent coverage is evaluated at the center of the radar beam, 0.9 deg and 0.5 deg for the short-range and long-range radars, respectively, and takes into consideration the curvature of the earth.

6.2.2 Coverage for example radar networks

The calculations above place no geographic restrictions on the radar locations within the domain of interest. To investigate the role of radar placement to overall radar coverage and separate the effects of irregular radar placement from those of terrain blockage, the calculations done in Section 6.2.1 are carried out for an example radar network as shown in Figure 6.5. The short-range radars (crosses) were sited to be accessible by road and not to be obscured by local topography. The layout is nominally a triangular grid with roughly 35 km spacing. Long-range radar placements are shown as circles placed in nominally ideal locations that coincided with roughly the centers of the domains. Both short-range and long-range radars were sited with the goal of covering the domains of interest. Coastal settings where the domains of interest extend substantially over the ocean prohibit complete coverage by short-range radars.

Radar coverage for the additional radar(s) as a function of altitude (AGL) is shown in Figure 6.6. For the Wyoming domains (Figure 6.6a and b), coverage is complete at about 1.8 km for long-range radars. For short-range radars there is 100% coverage down to ~0.7 km for domain A and 98% coverage at ~0.7km in domain B. Generally, in domains A and B the short-range radars have superior coverage from the surface to about 1.5 km. Figure 6.6c shows the coverage for the coastal domain of western Washington. Similar to the figures for Wyoming, short-range radars give superior coverage at low levels over land. The coverage for the short-range radars plateaus with ~70% coverage, which results from the inability of the small radars to make observations over the ocean at ranges greater than 40 km.

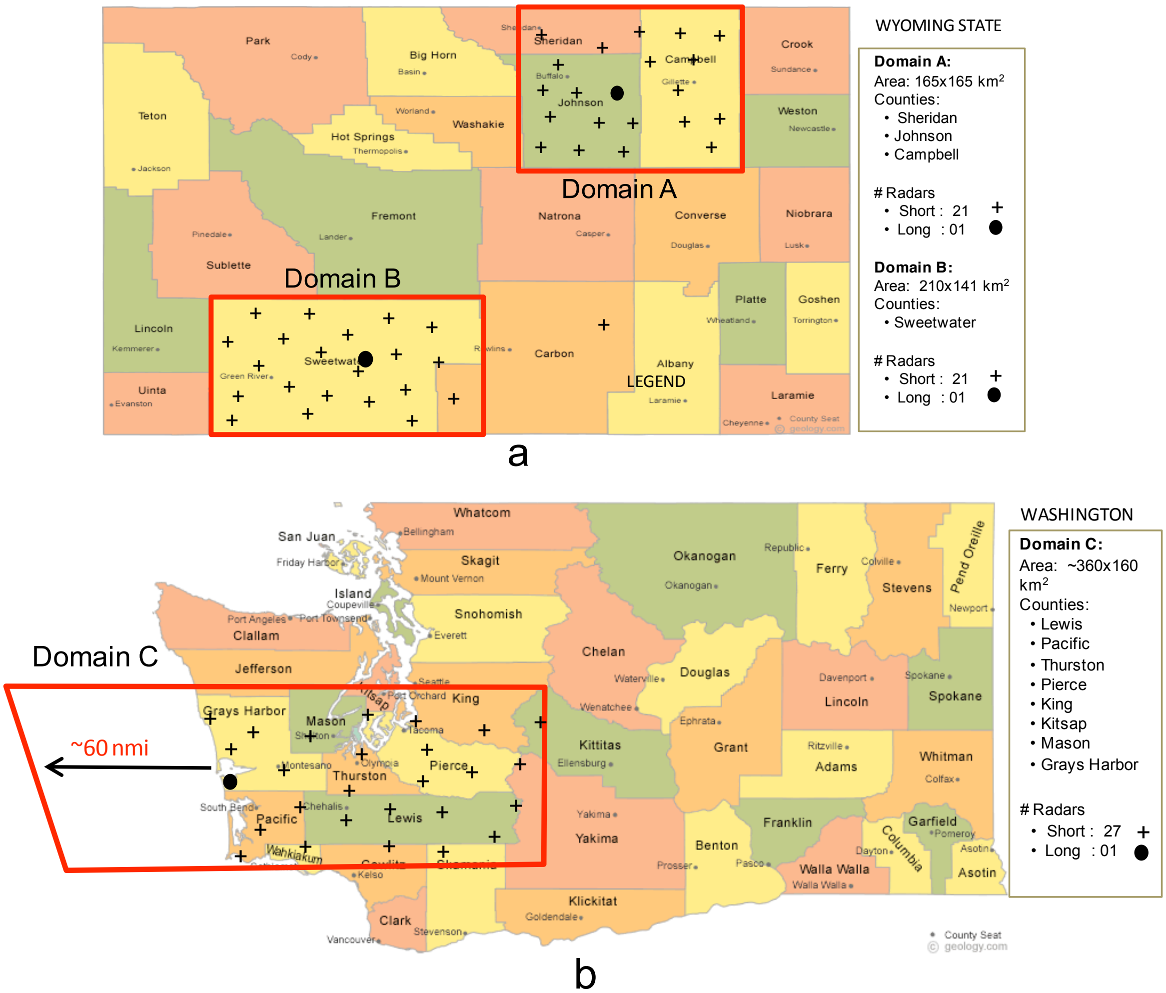

Figure 6.5: Potential long-range (large circle) and short-range radar locations (crosses) for a) Wyoming Domains A and B and western Washington Domain C.

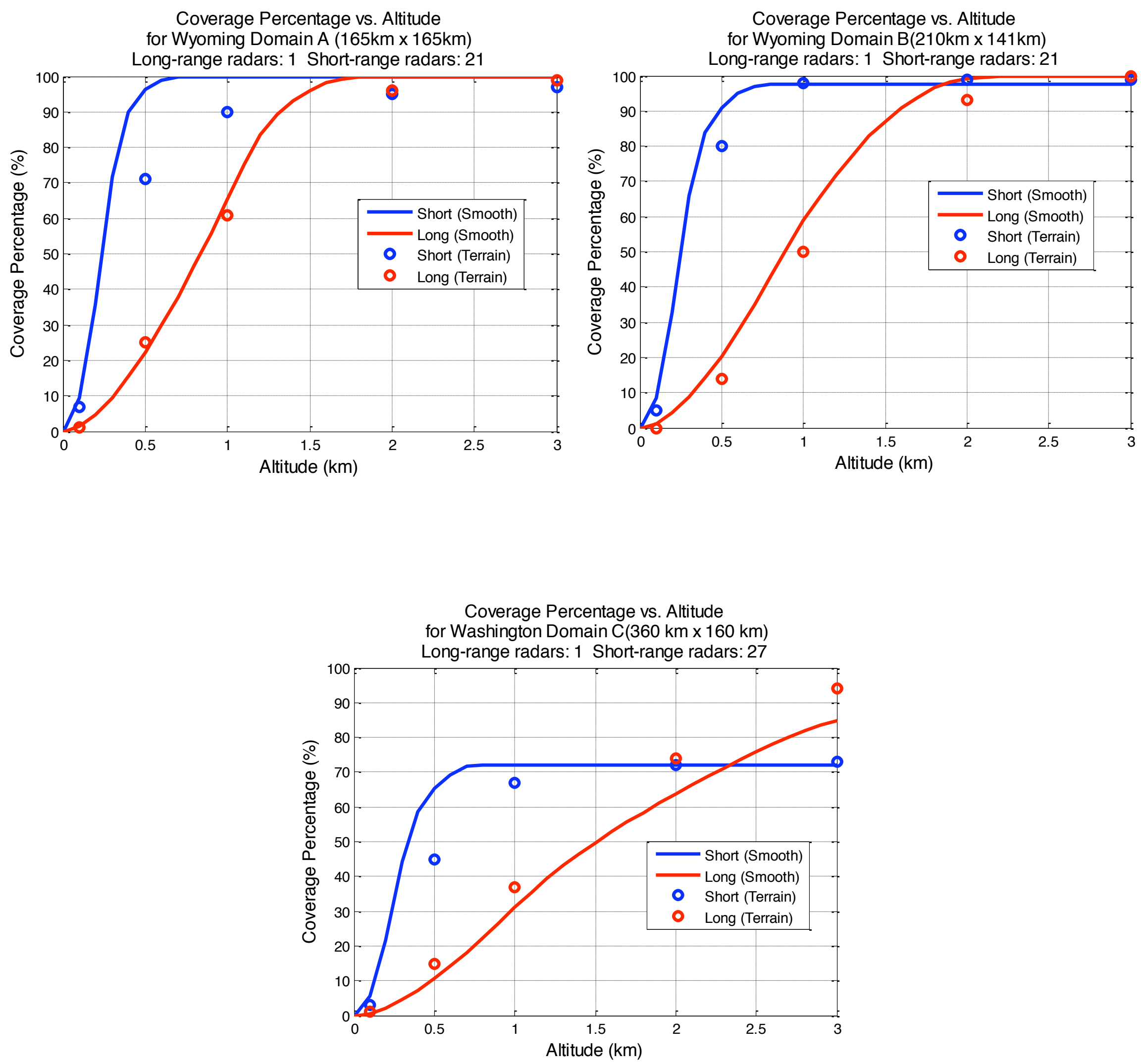

Figure 6.6: Percentage coverage of long-range (red) and short-range (blue) radar systems at given altitudes for a) northeastern Wyoming (Domain A), b) southwestern WY (Domain B), and c) western Washington (Domain C). The solid lines represent the calculations with the example network of Figure 6.5 without terrain and circles represent the coverage simulated with terrain, as explained in Section 6.2.3. Both example networks, as represented in each of the above plots, assume irregular station spacing.

6.2.3 Radar coverage simulations

To determine radar coverage of short-range vs. long-range radars in terrain, simulations of radar occultation are calculated for the given radar locations using software that uses high resolution digital elevation maps to calculate beam blockage. The radar beam is considered blocked when the path integrated occultation is greater than 50%. The blockage calculations are described in detail in Appendix D. Geographic Resources Analysis Support System (GRASS) Geographic Information System (GIS) was used for both analysis and visualization of the blockage simulations.

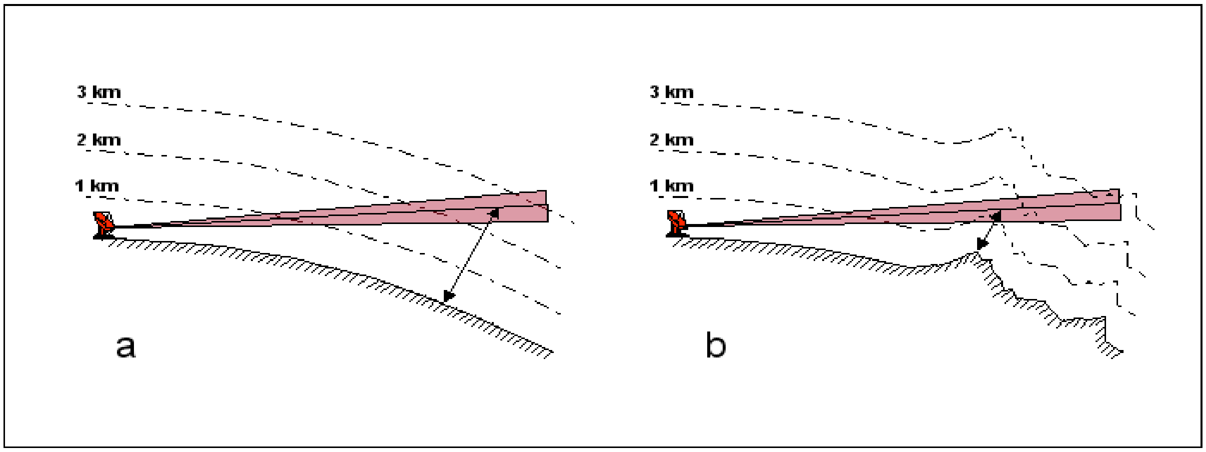

Figure 6.7: Illustration of height of the radar beam (AGL) for a) "smooth-earth" coverage calculations and b) those over terrain. Note that when height is given as AGL the height is relative to the terrain. This can result in greater low-level coverage than the “smooth-earth” case.

When considering radar coverage in actual terrain, it is necessary to adopt an altitude convention for which coverage is calculated. Figure 6.7a and b illustrates the convention used here: above ground level (AGL). Defining the coverage altitude as AGL can have the effect of increasing the area of low-level coverage when compared to “smooth-earth” calculations.

Wyoming

In northeast Wyoming, the radar coverage possible using one long-range radar and a network of twenty-one short-range radars are shown in Figure 6.8a and 6.8b, respectively. As expected, both radar systems dramatically increase the coverage. The long-range radar covers progressively higher altitudes with range, whereas, the short-range radars have virtually complete coverage at these altitudes out to their maximum range. This difference in coverage at low-levels results from the high density of short-range radars. Table 6.2 shows the percentage coverage of Domain A by the additional radars at 100, 500, 1000, 2000, and 3000 m AGL for both radar systems. To show consistency with the idealized calculations, these values are also shown in Figure 6.6a.

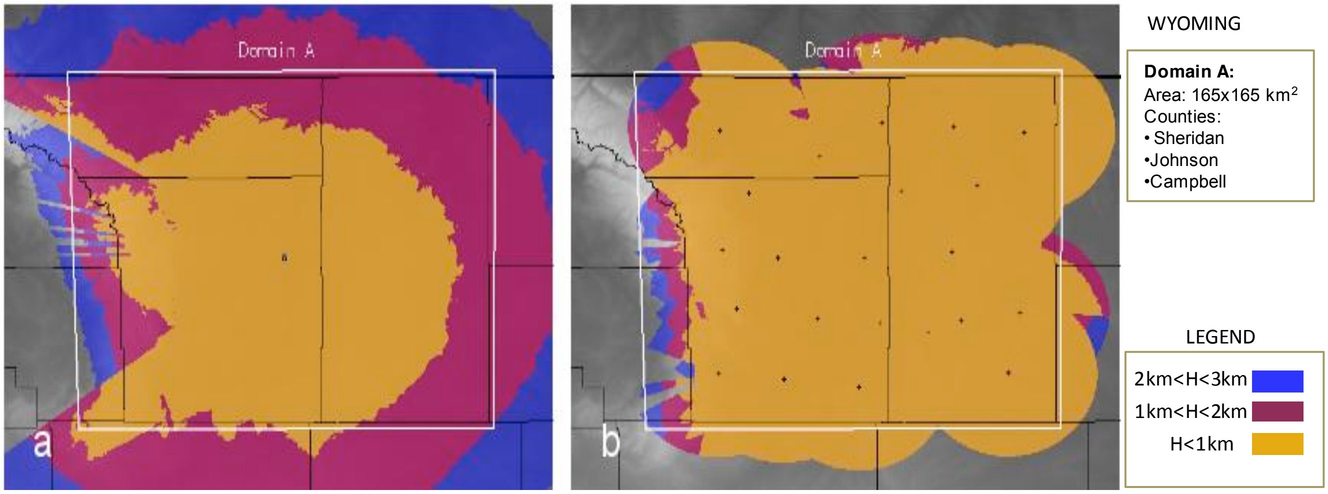

Figure 6.8: Radar coverage maps of Domain A in northeast Wyoming at 1, 2, and 3 km AGL for a) one long-range radar and b) twenty one short-range radars.

Table 6.2: Coverage simulations in northeast Wyoming (Domain A).

Altitude (m)	Coverage (%) Long (1 radar)	Coverage (%) Short (21 radars)
100	1%	7%
500	25%	71%
1000	61%	90%
2000	96%	95%
3000	99%	97%

Figure 6.9a and 6.9b show similar coverage results for southwest Wyoming with the coverage of the domain almost complete between 2-3 km altitudes. Table 6.3 shows the coverage statistics which are also consistent with the "smooth-earth" calculations.

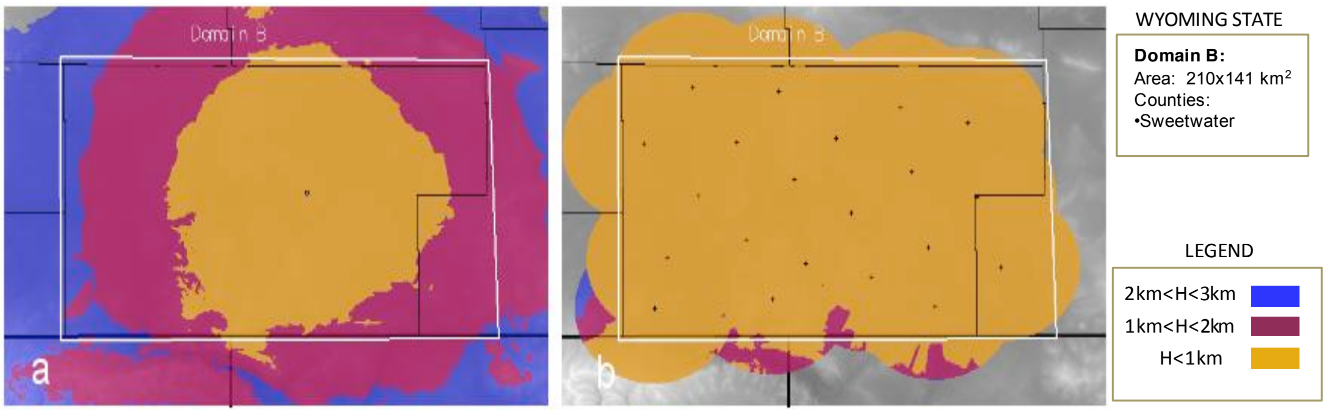

Figure 6.9: Radar coverage maps of Domain B in southwest Wyoming at 1, 2, and 3 km AGL for a) one long-range radar and b) twenty-one short-range radars.

Table 6.3: Coverage simulations in southwest Wyoming (Domain B).

Altitude (m)	Coverage (%) Long (1 radar)	Coverage (%) Short (21 radars)
100	0%	5%
500	14%	80%
1000	49%	98%
2000	93%	99%
3000	100%	99%

Western Washington

The mountainous coastal regions of western Washington State exemplify the strengths and weaknesses of both radar systems. Figure 6.10a is the simulated coverage of one long-range radar placed in Westport, WA, and Figure 6.10b is the coverage of twenty-seven short-range radars placed throughout Domain C. As shown in Figure 6.10a and statistics in Table 6.4, long-range radar placed on the coast gives substantial long range coverage over the ocean, while the network short-range radars (Figure 6.10b) are more effective at observing low-levels over the rugged terrain of the Cascades. What is not shown is the additional radar coverage over the ocean above 3 km, as provided by the long-range radar.

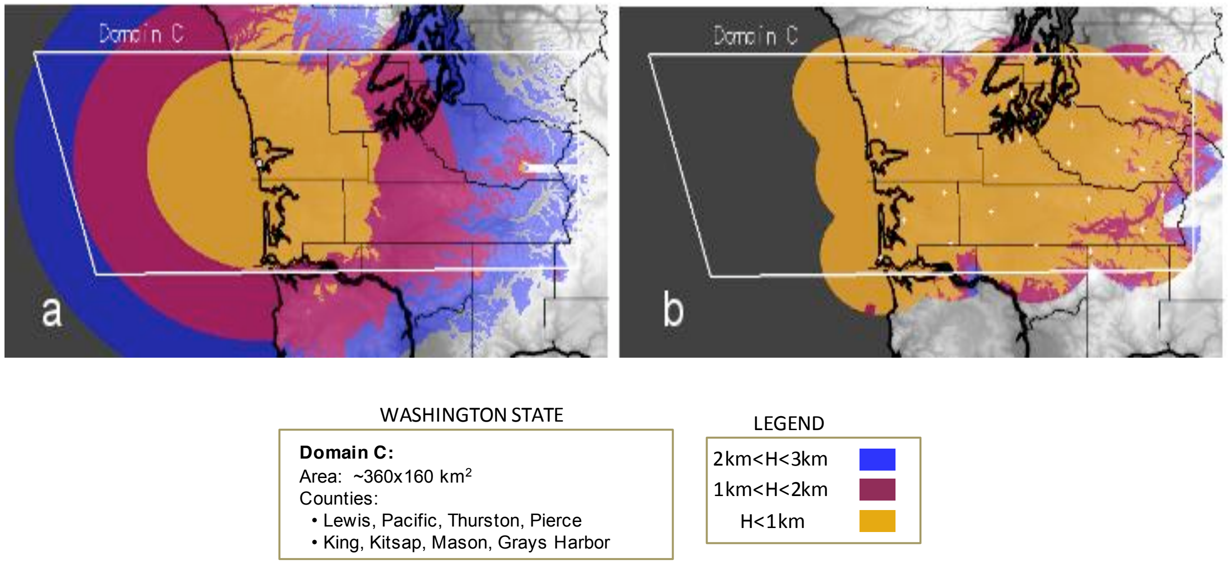

Figure 6.10: Radar coverage maps of Domain C in western Washington State at 1, 2, and 3 km AGL for a) one long-range radar and b) twenty seven short-range radars.

Table 6.4: Coverage simulations in western Washington (Domain C).

Altitude (m)	Coverage (%) Long (1 radar)	Coverage (%) Short (27 radars)
100	1%	3%
500	15%	45%
1000	37%	67%
2000	74%	72%
3000	94%	73%

Feasibility of Additional Weather Radar

Chapter 7: Infrastructure and Integration

What supporting infrastructure and integration requirements are needed to support additional radars?

7.0 Introduction

In addition to assessing the technical performance and coverage of new radars, issues such as radar siting and installation, data calibration, quality control and the integration of new observational data into weather service operations need to be assessed and planned. In addition, plans need to be made to address operations, maintenance, and perhaps upgrades throughout the life-cycle of the system. Emplacing new radars into weather service operations is a systems engineering problem, and the specific requirements, costs, and timetables associated with getting the job done will need to be detailed in a contract (or contracts) between buyers and vendors. This section of the report touches briefly on some of these issues. Rather than attempting to speculate on the details and specifics of such contract issues in this report, we broadly frame some of them below.

7.1 Radar Integration

Performing data quality control and integrating data into weather service operations are important components of a gap-fill radar solution. The current approach to gathering observational data from multiple radars, assembling it, and disseminating data to operational weather forecasters, is through the AWIPS data system. Based upon interviews conducted during this study, there exists a preference among the stakeholder community to treat each new radar/radar network *as a separate and independent data stream* when considering how to integrate new observations into the overall observing system. An example of a separate and independent data stream is the observational data from the Terminal Doppler Weather Radar (TDWR) network. The National Weather Service uses a separate workstation (separate from the NEXRAD network) for the TDWR. This Supplemental Product Generator (SPG) ingests the TDWR data, converts it to WSR-88D format, and then generates products in WSR-88D formats for compatibility with AWIPS and other users of WSR-88D data. AWIPS mosaic capability then visually combines the TDWR data with the WSR-88D data for operational forecasters to use. The SGP allows TDWR data to be displayed within AWIPS for data manipulation, visualization, and digital overlay with other NWS products. Training material has been developed to highlight the data characteristic differences (e.g., attenuation, spatial resolution, volume coverage patterns, and temporal resolution) between different types of radars. This approach might be used for the gap-fill solution as well.

The NWS has set up the Operations and Services Improvement Process (OSIP) for incorporating new products and capabilities into forecaster operations through AWIPS. OSIP provides a framework for managing the process of new data project development, acquisition of parts, establishing and managing requirements and finances, and deploying new capabilities. This process may be helpful in creating an effective gap fill radar solution.

In addition to addressing data integration, provision will be needed for the operations and maintenance of any new radar. Different radar designs are likely to have different operation and maintenance issues and schedules compared with the WSR-88Ds. There will not necessarily be identical repair, upgrade, and enhancement programs and procedures among heterogeneous radars in a composite system. The NWS has some recent experience with the installation of a large S-band radar for gap-filling in Evansville, Indiana (Leslie 2001; Stagliano et al. 2003). The radar was similar to the NEXRAD system but not identical, and different operations and maintenance procedures were needed for that radar compared to the NEXRAD system. This difference in procedures led to that gap-filling radar being decommissioned. This case illustrates an important challenge with addressing the gap-fill problem: the upfront/acquisition and installation phases of a new radar are only part of the overall program: planning for and budgeting for recurring operations and maintenance is also critical for a successful program, and this needs to be thought through at the outset.

7.2 Cost Issues[15]

This report has been prepared by a team of researchers from the Universities of Oklahoma and Massachusetts, and provision has not been made in this volume to bring the industrial/radar manufacturing/technology development sector into the creation of this report. Since the authors and their Universities are not manufacturers/sellers of radars, this report does not address radar system cost in detail.[16]

7.2.1 Long-range radar

Installing new observing systems is a multistep process including site selection and preparation and the construction of supporting infrastructure. Critical support infrastructure includes tower support, communications, site access, and electrical power. The general criteria used to establish installation sites for WSR-88D/NEXRAD radars are described by Leone et al. 1989. The siting of weather radar includes site selection, evaluation of infrastructure, safety, and environmental assessment. A broad area for siting was chosen based upon population centers and severe weather climatology. A more precise site location within the broad area was then chosen based upon site ownership and availability, local topography, flood zoning, soil type, and land usage. The site must also have adequate supporting infrastructure such as easy access, water supply, sewage disposal, fuel storage capability, electric power and communications. Finally, an environmental assessment and frequency allocation analysis are required, and local zoning laws and building permits must be followed.

In the case of NEXRAD, site selection required from one to three years to complete, per site. One challenge was the lack of high terrain locations available in many areas with many preferred locations already in use. Acquiring land for government use was also complicated in some areas.

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[15] *This section of the report uses text from a paper prepared by the CASA project for publication in the Bulletin of the American Meteorological Society. That paper is currently under review.*

[16] *The CASA project is set up with an industrial arm that is comprised of radar vendors and technology developers. One approach to obtaining more accurate, specific, and realistic cost information than is provided here would be to solicit the CASA industrial participants (and potentially other industrial entities as well) through a Request For Information.*

Further, identifying a site with adequate roads, utilities, and communications was necessary, and in urban areas there was the potential for siting to become a political issue.

An estimate for the up-front cost for a long-range S-band radar (including the costs to buy and install the radar as well as the land and supporting infrastructure) is $10M. This figure was cited in 2008 in a National Research Council report (NRC 2008) based on a Lincoln Laboratory estimate. This estimate is derived based on the fact that the 156 radar WSR-88D/NEXRAD radar network cost $1.56 billion to deploy between 1990 and 1997, or ~ $10M per radar. Unisys was the supplier of these radars. More recently, the National Weather Service issued a contract for $8.6M (NOAA 2001-R279, 2001) to Enterprise Electronics Corporation for an S-band radar similar to the WSR-88D system. It is not possible to be more precise about these estimates, nor is it possible to do a detailed comparison between the NEXRAD network costs and Evansville cost, given that the contract terms for these acquisitions include items such as spare parts, development, training, tools, test equipment, support systems, in addition to the radar itself. The yearly operation and maintenance costs of the WSR-88D network are currently approximately $78 million (OFCM 2006). Dividing this cost by 156 radars results in an estimate of a recurring cost of ~$500k per radar.

7.2.2 Short-range radar

The concept being pursued by the CASA project is to place short-range radars close together (e.g., 10's of km apart) to accomplish two things: (1) defeat the earth curvature and terrain blockage problem that limits the performance of large radars and (2) enable the use of small, lightweight, low-cost radars that can be installed on simple dedicated towers or on buildings and existing towers as illustrated in chapter 6. The CASA project has set an aim-point of $200k[17] as the up-front cost of each radar in a dense radar network and per-site recurring cost of $20k per radar per year. This is a "cost bogie" set by the academic leadership of the CASA project; the CASA team has deployed research versions of these radars, but commercial sales of weather radars with this price point have not yet occurred. Below, we summarize CASA's costing experience with research radars and we discuss current thinking about what it would cost to manufacture similar radars commercially.

7.2.2.1 CASA's costing experience with research radars

CASA's costs to build, install, and operate the radars of its Oklahoma test bed is described in (McLaughlin et al. 2009). Four prototype radars were designed and fabricated by CASA participants[18] during 2004 - 2005 using a combination of off-the-shelf and custom-made

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[17] *CASA has also used the figure of $100k to reflect the target parts-cost of these radars. Assuming a 2x multiplier between parts cost and sell-cost, we arrive at the $200k figure indicated above.*

[18] *This was a joint effort among several universities: the radars were designed and fabricated by the Microwave Remote Sensing Laboratory (MIRSL) of the Electrical and Computer Engineering Depart at UMass – Amherst. Meteorological Command and Control software was done by UMass Computer Scientists. Waveform design was done by the Colorado State University ECE Department. University of Oklahoma meteorologists established the radar siting. The CASA project is led out of the College of Engineering at UMass Amherst. CASA's industrial partners provided advice, assistance, and in some cases, components for the radars.*

components and subsequently deployed in southwest Oklahoma. Custom components include the transceiver and two-channel reconfigurable data acquisition unit. The total parts-cost of the transceiver, antenna, computers, and data acquisition system is $78k. The total parts cost for each of the radars, including all needed towers and other infrastructure, was $229,500 Assuming that the cost to purchase one of these radars is twice the cost of the parts, the price tag for one of these radars would be $459,000. CASA's recurring costs for each radar is $29k. Two caveats are noted: 1) the CASA radars were developed by an academic team for use as an experimental research facility, and cost-containment was not a strong design driver in realizing this system; 2) these represent low volume costs, given that the CASA project produced only four radars for this test bed.

7.2.2.2 Road mapping exercise to estimate feasibility price of CASA-type radars

The CASA project has set a "cost bogie" of $200k as the price tag for these radars when they are manufactured in larger quantities than the CASA Oklahoma deployment. When compared to the performance of CASA's fielded research radars and the $200k cost bogie, lower cost & performance and higher cost & performance radars do exist in the market for various applications; this provides a bracketing context for envisioning the low-cost weather radars envisioned here. As is the case with other electronic components, cost is driven by both required performance and sales volume. Current market offerings for radars include $200 solid-state radars manufactured in high volumes for automobile collision avoidance, marine radars with rotating antennas in the $2k-$20k range, mechanically-scanned weather radars in the sub-$1M to $10M range, up to very high-performance multi-function phased array radar systems developed for defense applications costing hundreds of millions to billions of dollars. The short-range radars considered here transmit only 10's of Watts of average microwave power; from the point of view of transmitted power, such radars are in the same performance category as marine radars (indeed, CASA's radars in Oklahoma were built around a marine radar transmitter and modulator).

Figure 7.1 shows two artistic concept drawings illustrating how such radars and existing infrastructure elements might be installed (e.g., communication towers and buildings). While such an installation has not yet been prototyped, it is worth mentioning that this research is proceeding apace. In 2008, the National Research Council of the National Academies noted that the CASA project is creating a "Deployment scenario of low-cost microwave radar sensors in an urban environment where the radar antenna panels are attached to the edges of the taller buildings. The electronic-scanning sensors merge seamlessly with the background and have no moving parts" (NRC, 2008, page 119).

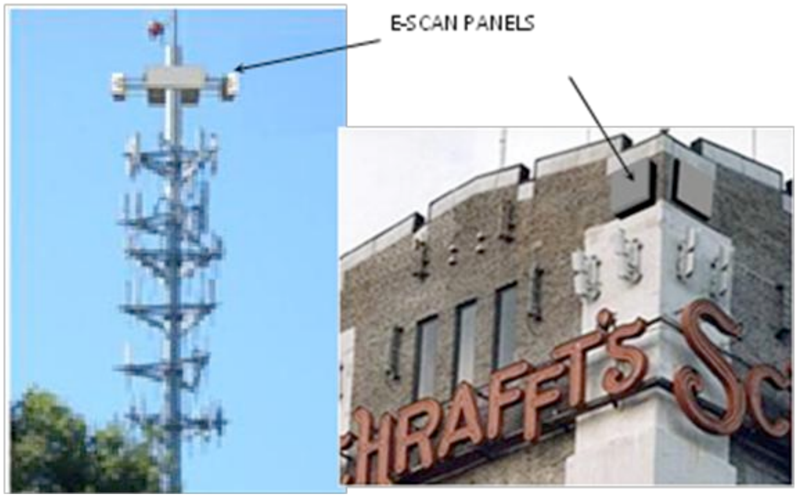

Figure 7.1. Artistic concept of CASA radar panels attached to a cellular telephone tower and the sides of a building.

7.2.3 Systems Engineering and Costing

Solving the radar coverage gap problems addressed in this report will require the acquisition and installation of new radars and supporting infrastructure as well as provisions for integrating new radar into weather service operations for maintenance of the system components throughout the intended lifecycle. The integrative life-cycle complexity of the problem means that it can not be solved simply by purchasing commercial off-the-shelf (COTS) technology; rather, this problem requires a systems engineering approach that begins with a requirements analysis, proceeds through conceptual and detailed design, to production and installation, and then extends to yearly operations and maintenance, ending with to the ultimate disposition of the technology at the end of its intended service life. The cost to accomplish a systems engineering project such as this will depend on the required performance, reliability, and other terms that would be specified in a contract between a buyer and technology provider.

Report Summary

Chapter 8: Summary and Recommendations

In summary, the information compiled for this report points to three key conclusions:

- **Service deficiencies exist across the radar gap regions identified in Wyoming and western Washington.** Case studies, stakeholder interviews, and NWS warning statistics all indicate that severe storm warning lead times are below-average for those regions with limited radar coverage at low levels (< 3 km AGL). Detections of precipitation and wind shear at low levels are limited in radar gap regions. Furthermore, portions of the gap regions are shown to have above-average societal vulnerability to severe weather hazards.

- **Additional radar coverage below 3 km (10,000 ft) likely could improve public safety and reduce negative economic consequences from hazardous weather through improved real-time analysis and prediction.** In Wyoming, some population centers (e.g., Gillette) and critical infrastructure (interstate highways, coal mines) have limited low-level radar coverage. Additional low-level radar data are needed in these areas for improving winter weather QPE and QPF as well as monitoring low-level storm features. Dual-polarization would also aid in quantifying winter precipitation and summertime convection, and higher spatial and temporal collection would improve monitoring of severe storms. For coastal Washington, high social vulnerable areas and weather sensitive industries (e.g., fishing industry) have limited low-level radar coverage. Greater radar coverage in this region, particularly over the ocean, could significantly improve analysis and prediction of synoptic systems. Furthermore, dual-Doppler could aid in identifying areas of strong winds, and higher temporal and spatial sampling could improve QPE and QPF.

- **Deploying additional weather radars in Wyoming and western Washington will require a system engineering approach.** Hardware costs, siting, tower infrastructure, communication and electric power requirements, installation, communications interfacing, software integration and long-term maintenance and operations all will need to be carefully considered. For the deployment of short-range radars, consideration must be given to the availability of multiple sites, small power radars and communication availability, and long-term maintenance. For the deployment of long-range radars, consideration must be given to the "social footprint" (e.g., visual impact, land use) and specialized power and others infrastructure needs.

More specific discussion of the meteorological assessment and feasibility of additional weather radar in Wyoming and western Washington are discussed below.

8.1 Wyoming

- **Significant radar coverage gaps exist in northeastern and southwestern Wyoming.** The gap regions in Wyoming lack radar coverage because of the distance between radars and mountain blockage. Sixteen of 23 counties in Wyoming have less than 5% area coverage below 1 km AGL, and 9 of 23 counties have less than 50% coverage below 3 km AGL. In Campbell County, radars cannot see below 3 km AGL anywhere within the county, and only 24% of Johnson County and 39% of Sweetwater County have coverage below 3 km AGL.

- **Radar gap areas are climatologically active areas for severe weather.** Based on historical data, Campbell County is three times more likely to report a tornado and twice as likely to experience flooding than other counties in Wyoming. Regional weather hazards during the warm season include tornadoes, hail, and straight-line winds. During the winter, snow, ice, and winds are the primary hazards.

- **A range of low to moderate societal vulnerability exists within the radar coverage gap regions.** Overall, Wyoming has a low population density with many isolated communities. The complex terrain contributes to highly variable weather risks across the state. However, Wyoming ranks 8^{th} in the country in the percentage of homes that are mobile home units, thereby increasing resident vulnerability to tornadoes and high winds. Wyoming ranks 5^{th} in the country in the percentage of the population born out-of-state. Non-native residents may be more susceptible than long-term residents to flooding and winter weather hazards common to Wyoming.

- **The principal socioeconomic risks in the coverage gap regions are to the mining industry and transportation.** Wyoming provides 40% of the nation's coal, and 70% of this coal is mined in Campbell County. The coal industry uses forecasts and nowcasts of convective activity, snow, and winds to conduct its operations and protect its workforce. In Sweetwater County, Interstate 80 is a major east-west transit freight transportation route which closes from 3 to 45 days annually due to wind and snow, with a negative impact to the national economy on the order of $84,000 to $333,000 per hour.

- **Interviews with National Weather Service forecasters with jurisdictional responsibility over coverage gap regions indicate that the lack of observations in gap areas impact their ability to provide expert knowledge and warnings to stakeholders.** Findings from NWS interviews are confirmed by emergency managers and reinforced by the NWS warning statistics. For the counties sampled in the radar gap areas, lead times for severe storms, tornadoes, and flash floods are all below parent WFO averages. Most verification statistics for the three select counties studied for this report are below or much-below national averages. For example, in Sweetwater County only 14% of thunderstorm warnings are issued in advance, compared with 75% nationally.

- **Additional low-level coverage is recommended for the gap areas in Wyoming.** Low-level radar data are needed for improving winter weather QPE and QPF as well as monitoring low-level storm features. Dual-polarization would also aid in quantifying winter precipitation and summertime convection, and higher spatial and temporal collection would improve monitoring of severe storms.

- Forty-two short-range X-band radars or two long range radar could provide this coverage. Across Wyoming, a network of 42 short-range (X-band) radars, deployed strategically, would provide extensive multi-Doppler coverage of wind and rain at low-levels (below 2 km AGL), thereby enabling real-time monitoring and improved prediction of warm-season severe thunderstorms and low-level winter weather. Two long-range weather radars could provide equivalent coverage at and above 2 km AGL.

Table 8.1: Summary of the severe weather vulnerability, climatology, radar coverage, service performance, radar needs, and potential deployment solutions established for Wyoming.

Wyoming	
Weather Vulnerabilities	• Isolated communities, low population density • High SVI in southwest, low SVI in northeast • High mobile home rate • High non-native population • Complex terrain, highly variable • Weather-sensitive industries (mining) and infrastructure (highways, track)
Weather Risks	1. Winter weather 2. Severe thunderstorms (tornadoes, hail, wind, downbursts)
Radar Coverage	• 16 of 23 counties ≤ 5% coverage at 1 km AGL • 19 of 23 counties ≤ 50% coverage at 2 km AGL • 9 of 23 counties ≤ 50% coverage at 3 km AGL
Service Performance	• Lead time for severe storms, tornadoes, and flash floods for 3 sample counties in radar gap areas are all below parent WFO averages. Most verification statistics for these 3 counties are below or much-below national averages.
Radar Needs	1. Winter weather: - Low-level radar data (QPE, QPF) - Dual-polarization 2. Severe thunderstorms: - Low-level radar data - High spatial/temporal data collection
Potential Solution	• Two networks of 21 short-range radars would provide nearly complete coverage (> 1 km AGL) across the gap coverage regions. • Two long-range radars would provide coverage at and above 2 km AGL across the gap coverage regions.

8.2 Western Washington

- **Radar coverage gaps in coastal Washington are primarily caused by beam blockage.** Much of the radar coverage to the west of the KATX and KRTX WSR-88D radars are blocked by the Olympic Mountains, and so virtually no radar coverage is available over the ocean where the majority of western Washington's weather hazards originate. With the addition of one long-range radar along the coast, the area of low-level coverage below 3 kilometers would expand to include an additional 28,400 km^2 over the ocean, and up to 165 km offshore.

- **Large synoptic storms are the primary weather events faced by these regions.** Powerful, mid-latitude cyclones are the primary weather hazard to the region and which often make landfall on the Washington coast. These storms bring large areas of high wind and precipitation which interact with the mountainous terrain and create highly localized and intense events, which are difficult to analyze and predict.

- **Population along the west coast of Washington exhibits high social vulnerability based on a national index.** This index measures a population's ability to prepare for and recover from natural disasters. Like Wyoming, the complex terrain of Washington highly variable weather risks across the region. Furthermore, Washington also has a high percentage of residents born out of state, making them more vulnerable than long-term residents to the severe weather hazards common to Washington.

- **Western Washington has significant industries and transportation routes that contribute to the national and international economy and that are sensitive to hazardous weather.** For example, the lack of weather radar coverage over the ocean poses a safety hazard to the fishing and shipping industries. Interstate 5 is one of the business routes in the nation and intersects a radar gap area.

- **NWS forecasters lack observations over the ocean and reliable radar data over land.** Because of the lack of radar data over the oceans, analysis, tracking and prediction of these large synoptic storms is difficult. Only satellite data and a few buoy observations are available for assimilation into NWP models. Furthermore, because of the highly complex terrain, radar blockage, and a low melting layer (~ 2 km AGL), radar reflectivity over land also poses problems. Radar is often considered "a secondary tool", since the observations may not reflect ground truth.

- **Additional low-level coverage is recommended for the gap areas in Washington.** A single, long-range radar deployed along the coast would expand coverage to include an additional 28,400 km^2 over the ocean and up to 165 km offshore, enabling improved real-time analysis and long-term prediction of synoptic-scale systems. In addition, such radar data upstream of western Washington would provide impetus for the assimilation of radar data into numerical forecast models, an activity not currently undertaken. A network of 27 short-range radars, deployed along the coast, would provide multi-Doppler coverage as low as 1 km AGL along the coast and up to a distance of 40 km from shore. Over terrain, high resolution radar observations would help quantify locally intense terrain-forced precipitation, improving quantitative precipitation estimation (QPE) and identifying low-level wind hazards.

Table 8.2: Summary of the severe weather vulnerability, climatology, radar coverage, service performance, radar needs, and potential deployment solutions established for western Washington.

Western Washington	
Weather Vulnerabilities	• Moderate to high population density • High SVI along coast • High non-native population • Complex terrain, highly variable • Weather-sensitive industries (fishing) and infrastructure (ports, highways)
Weather Risks	1. Severe (non-convective) wind storms 2. Flooding
Radar Coverage	• 7 of 19 counties ≤ 5% coverage at 1 km AGL • 6 of 19 counties ≤ 50% coverage at 2 km AGL • 2 of 19 counties ≤ 50% coverage at 3 km AGL (2 coastal counties)
Service Performance	• Verification statistics for severe storms, tornadoes, and flash floods for WFOs are much below national averages. However, these events are rare and are not a major concern; those that do occur are different in type and generally weaker in intensity than those found east of the Rocky Mountains.
Radar Needs	1. Severe (non-convective) wind storms - More radar coverage over the ocean - Dual-Doppler 2. Flooding (QPE/QPF): - Low-level radar data - High spatial/temporal data collection
Potential Solution	• A network of 27 short-range radars would provide nearly complete coverage (> 1 km AGL) over land and partial low-level coverage up to a distance of 40 km from shore. • One long-range radar would expand coverage at and above 2 km AGL across the gap coverage regions over land and up to 165 km offshore at 3 km AGL.

8.3 Final Recommendations

Three additional recommendations for determining if, when, and what type of radars to deploy to radar gap regions are as follows:

- **Conduct an exhaustive cost-benefit analysis with detailed examination of siting requirements, infrastructure needs including communications and power, and a consideration of long-term operations and maintenance.** A detailed cost benefit analysis will need to be completed to determine if additional weather radar would be warranted for deployment across portions of Wyoming and western Washington. Furthermore as demonstrated by this report, the type of radar and radar attributes required will vary significantly with location. The costs and benefits would largely determine the type of radar, radar attributes, and number of radars deployed within each region. Estimated costs must include generous estimates for long-term maintenance and operations; a major concern expressed by many stakeholders was an underestimate in the amount of money set aside for overall radar long-term maintenance and operational costs.

  The total costs associated with any observational tool should be carefully weighed against the totality of its benefits, with the caveat that many of the benefits provided will be indirect and difficult to quantify. This report is meant as a guide for issues to consider when starting the process of new radar deployment.

- **Partner with local and state governments and other federal agencies (e.g., Federal Highway Administration) and the private sector (e.g., energy and railroad industries) for increasing local observational capabilities.** Some community representatives interviewed for this study are already working to purchase and install their own local weather radar. While some agencies now have the resources to purchase radar hardware, they lack the expertise to operate and maintain such equipment and are unclear how to provide such data to the NWS to improve local warning capabilities.

- **Deploy a limited test radar network for a more complete evaluation. The full benefits, advantages or disadvantages of new technology, such as the short-range radars, may not be fully understood.** The suite of benefits provided by new technologies, such as rapid scanning, multi-Doppler, refractivity, and dual-polarization, may not be fully realized. Furthermore, an initial testbed may help uncover any unforeseen yet significant problems with the technology unique to the deployment area.

National Weather Service operations already compensate in many ways for the lack of weather radar data in gap areas by making greater use of satellite, surface, and ground truth information and model output. In most cases the addition of weather radar to these areas will not be a ‘magic bullet’ for improving NWS operations, but is expected to improve the confidence of NWS forecasters in development of products for dissemination to stakeholders. In some cases, immediate improvement to nowcasting and forecasting capabilities may be seen; less immediate yet significant improvements to short- to long-range forecasts are likely.

In summary, additional weather radar, strategically placed along and near critical weather-sensitive industries and infrastructure in radar gap regions, will improve public safety and reduce weather-imposed economic loss. Beyond simply filling gaps in existing coverage, additional radar capabilities such as rapid scanning, higher spatial resolution and multi-Doppler coverage and enhanced radar products such as provided by dual-polarization have the potential to dramatically improve current observing and predicting capabilities. While financial resources may ultimately determine the type and number of radars deployed, the potential and far-reaching benefits posed by new observational systems should be thoroughly considered.

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Abbreviations

AGL	Above ground level
APRS	Automatic Position Reporting System
AR	Atmospheric river
ASR	Airport Surveillance Radars
ARSR	Air Route Surveillance Radars
ASOS	Automated Service Observing System
AWIPS	Advanced Weather Interactive Processing System
AWOS	Automated Weather Observing System
CASA	Center for Collaborative Adaptive Sensing of the Atmosphere
C-MAN	Coastal Marine Automated Network
CoCoRaHS	Community Collaborative Rain, Hail, & Snow Network
COOP	Cooperative Observer Program
CSI	Critical Success Index
CWA	County Warning Area
CWOP	Citizen Weather Observing Program
ECMWF	European Centre for Medium-range Weather Forecasts
EM	Emergency Manager
FAA	Federal Aviation Administration
FAR	False Alarm Rate
FEMA	Federal Emergency Management Agency
FTE	Full-time equivalent
GDP	Gross Domestic Product
IP1	Integrated Project One
MDSS	Maintenance Decision Support System
MIC	Meteorologist-in-charge
MSL	Mean sea level
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NEXRAD	NEXt Generation Weather RADar
NLDN	National Lightning Detection Network
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSSL	National Severe Storms Laboratory
NWP	Numerical Weather Prediction
NWS	National Weather Service
OSIP	Operations and Services Improvement Process
POD	Probability of Detection
QPE	Quantitative Precipitation Estimate
QPF	Quantitative Precipitation Forecast
RAWS	Remote Automated Weather Stations
RFC	River Forecast Center (NWS)
RFD	Rear flank downdraft
RWIS	Road Weather Information Systems
SNOTEL	Snowpack Telemetry

SOO	Science and Operations Officer
SPC	Storm Prediction Center
STP	Storm Total Precipitation
SVI	Social vulnerability index
TDWR	Terminal Doppler Weather Radar
TVS	Tornado Vortex Signature
USGS	U. S. Geological Survey
VCP	Volume Coverage Pattern
WCM	Warning Coordination Meteorologist
WDSS-II	Warning Decisions Support System – Integrated Information
WSDOT	Washington State Department of Transportation
WCM	Warning Coordination Meteorologist
WSR-88D	Weather Surveillance Radars – 1988 Doppler
WFO	Weather Forecast Office
WYDOT	Wyoming Department of Transportation
4DVAR	Four-dimensional variational analysis

Appendix A: Radar Network and Surface Observing Systems

Federal and state government agencies and non-profit volunteer organizations support a wide range of surface observing networks, making data available in real-time for use by forecasters, hydrologists, firefighters, climatologists, researchers and the private sector community among others.

When making critical decisions, forecasters often use both radar data and ground truth from surface sensors. Despite dense networks of surface sites, the resolution of the most dense surface mesonets remain sparse compared to the high spatial and temporal resolution provided by weather radar. Surface data remains necessary as ground truth for calibration and verification of weather radar.

This appendix lists the major radar networks and surface observing systems used by the NWS and other stakeholders.

a. Weather Surveillance Radar - 1988 Doppler (WSR-88D)

Each WSR-88D operates using an S-band (10.0-11.1 cm wavelength) klystron transmitter with a nominal peak power of 750 kW and a pulse width of 1.57 µs (Crum and Alberty 1993). Each radar has an antenna approximately 8.5 m (28 ft) in diameter with an antenna half-power beamwidth of 0.95º. Reflectivity, mean radial velocity, and spectral width are collected within each sample volume. Reflectivity is sampled at a spatial resolution of ¼ km by 1º and data descretization of 0.5 dBZ. Mean radial velocity and spectrum width are sampled at a spatial resolution of ¼ km by 1º and a velocity resolution of 0.25 ms^{-1}. For the elevation angles below 1.5°, data are collected at an angular resolution of 0.5°. Reflectivity data are collected out to a range of 460 km (286 miles), and velocity and spectrum width are collected out to a range of 300 km (186 miles). However, for both data types, data collection stops when the data reach a height of 70,000 ft. The lowest tilt is nominally at a 0.5 degree elevation angle. Radars scan 360º stepping through several elevation angles using one of several predetermined volume coverage patterns (VCPs), requiring 4.5 - 10 minutes to complete each volume scan. The raw radar data and a number of derived products are produced in real-time and made available for display.

b. Terminal Doppler Weather Radar (TDWR)

During the late 1980s and early 1990s, the FAA developed the Terminal Doppler Weather Radar (TDWR) designed for the purpose of providing air traffic controllers with more detailed information on nearby precipitation and hazardous wind shear. Forty-five operational TDWRs were deployed at airports nationwide (Figure A.1). TDWRs have a very narrow beamwidth (0.55º) and a rapid update time (1 minute updates at the lowest elevation) for detecting severe winds and precipitation near the ground.

Each TDWR operates using a C-band (5.5-5.65 GHz wavelength) transmitter with a nominal peak power of 250 kW and a pulse width of 1.1 µs (Weber 2000). Reflectivity data are collected to a range of 460 km (286 miles), and radial velocity are collected to a range of 89 km (55 miles).

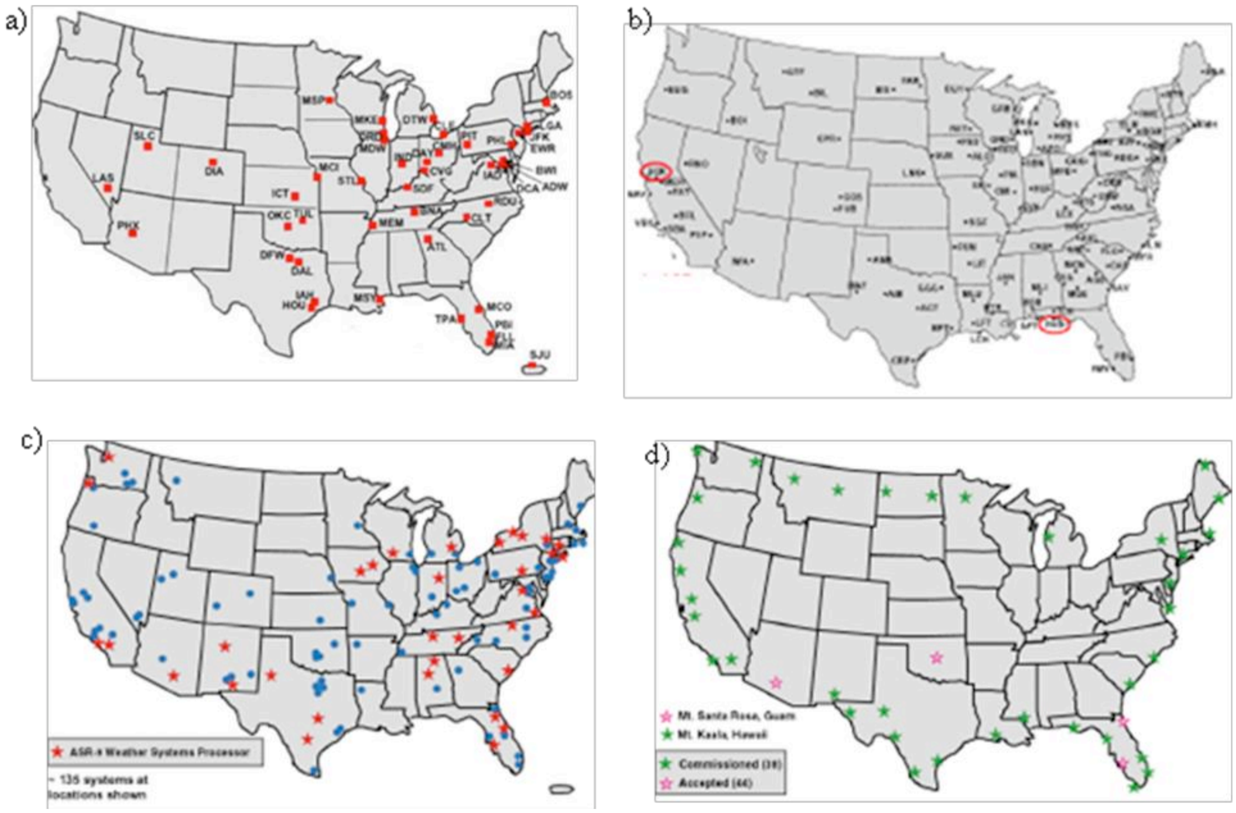

Figure A.1: Map showing the locations of the operational a) TDWR radars, b) ASR-11s, c) ASR-9s, and d) ARSR-4s (Weber 2000).

c. FAA Surveillance Radars (ASR-9, ASR-11, and ARSR-4)

In addition to the TDWR, the FAA also operates Airport Surveillance Radars (ASRs; Weber 2000). These radars are deployed at airports nationwide and are designed for moving target and weather detection. The ASR-9 was the first such radar to display both aircraft and weather simultaneously. The ASR-11, also known as the Digital Airport Surveillance Radar (DASR), is very similar to the ASR-9 but with slightly reduced sensitivity (Weber 2000). The ASR-9 and ASR-11 each have a primary surveillance range of 97 km (60 miles) with secondary surveillance range of 193 km (104 miles). Together, there are 233 ASR radars deployed at airports nationwide. The Air Route Surveillance Radar - Model 4 (ARSR-4) is designed as a long-range radar system operating in L-band. Forty-five ARSR-4s are deployed around the perimeter of the continental U.S. to provide long range surveillance for the FAA and U.S. Air Force. The ARSR-4 has a range of about 370 km (230 miles). Radar statistics for the TDWR, ASR-9, ASR-11, and ARSR-4 are shown in Table A.1.

Table A.1: Radar specifications for TDWR, ASR-9, ASR-11, and ARSR-4 (Weber 2000).

	TDWR	ASR-9	ASR-11	ARSR-4
Transmitter:				
Frequency	5.5 – 5.65 GHz	2.7-2.9 GHz	2.7-2.9 GHz	1.2-1.4 GHz
Polarization	Linear	Linear or circular	Linear or circular	Linear or circular
Peak power	250 KW	1.1 MW	20 kw	60 kw
Pulse width	1.1 μs	1.0 μs	1.0 s, 80 μs	150 μs
PRF	2000 (max)	~ 1000 Hz avg	~ 1000 Hz avg	~ 288 Hz avg
Receiver:				
Sensitivity	0 dBz @ 190 km 1 m^2 @ 460 km	0 dBz @ 20 km 1 m^2 @ 111 km	0 dBz @ 20 km 1 m^2 @ 111 km	0 dBz @ 10 km 1 m^2 @ 370 km
Antenna:				
Elevation beamwidth	0.55 deg	5.0 deg	5.0 deg	2.0 deg
Azimuth beamwidth	0.55 deg	1.4 deg	1.4 deg	1.4 deg
Power gain	50 dB	34 dB	34 dB	35 dB (transmit) 40 dB (receive)
Rotation rate	5 RPM	12.5 RPM	12.5 RPM	5.0 RPM

d. Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS)

The Automated Surface Observing System (ASOS) network is a shared system, jointly operated by the National Weather Service, Federal Aviation Administration, and the Department of Defense. ASOS sites provide data hourly; approximately 880 sites comprise the nationwide network. ASOS sites also provide special observations when pre-specified, severe thresholds are exceeded.

Each site provides the following information:

- Temperature and dewpoint
- Wind speed, direction, and character (gustiness, squalls, wind shifts, and peak wind)
- Precipitation accumulation, type (rain, snow, freezing rain), intensity, and beginning/end times
- Altimeter and sea level pressure and pressure changes (rapid pressure changes, pressure tendency)
- Visibility (up to 10 miles)
- Obstructions to vision, including fog, haze, and dust
- Sky conditions up to 12,000 ft (cloud height and amount)
- Lightning (using the National Lightning Detection Network; NLDN)

The Automated Weather Observing System (AWOS) sites are nearly identical to the ASOS sites but are operated exclusively by the FAA.

Wyoming has 16 ASOS sites and 13 AWOS sites, while Washington has 27 ASOS sites and 7 AWOS sites.

For more information, go to: http://www.weather.gov/asos/ and http://www.nws.noaa.gov/asos/

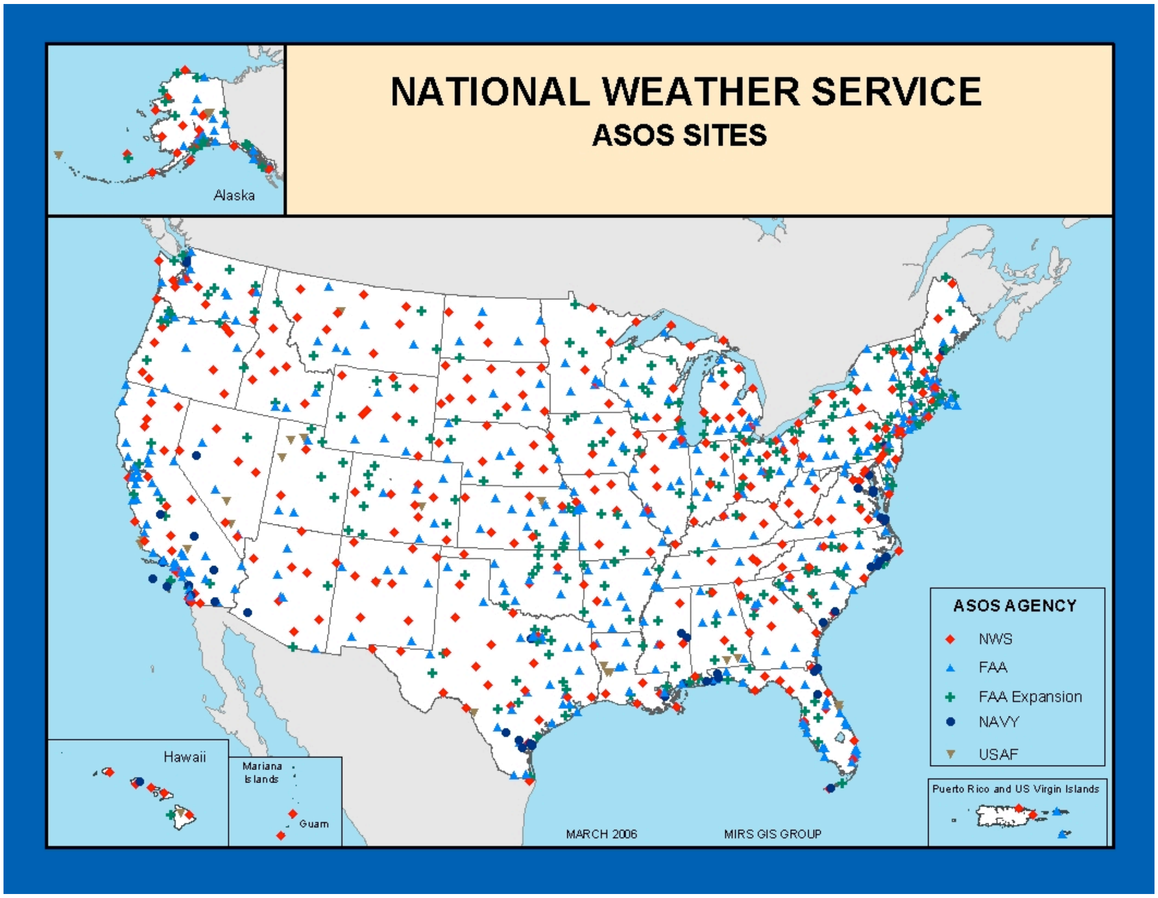

Figure A.2: Map of approximately 880 ASOS sites deployed nationwide. Figure courtesy of the National Weather Service. http://www.weather.gov/mirs/public/prods/maps/natl_asos.htm

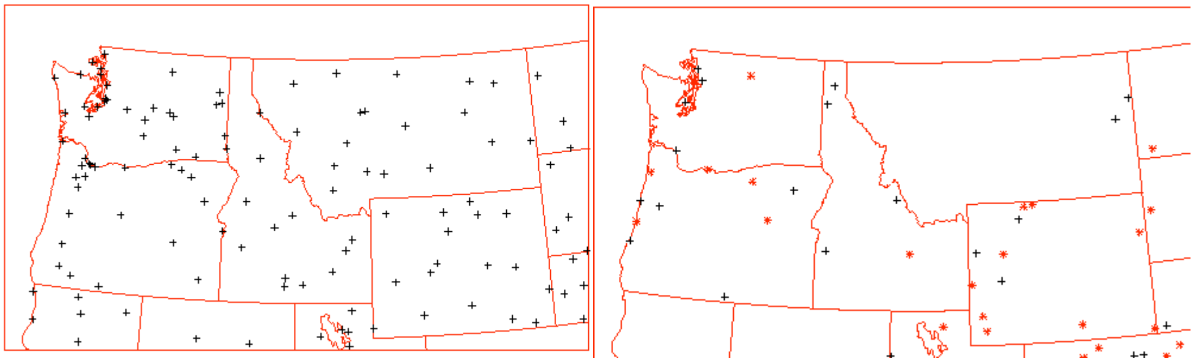

Figure A.3: Map of all NOAA/NWS a) ASOS, and b) AWOS sites across the Pacific Northwest. Figures courtesy of http://www.eol.ucar.edu/projects/hydrometnet/.

e. NOAA/NWS Cooperative Observer Program (COOP)

The Cooperative Observer Program is operated by the National Weather Service whereby historically volunteers collect and provide daily weather observations. The COOP collects data from over 11,000 volunteers. A recent COOP Modernization program began in 2003 with the upgrade of equipment to provide data in real-time. Approximately 8,000 sites will be equipped with modern, automated equipment. The following data will be made available:

- Hourly temperature and precipitation data, available in real-time.
- Daily 24-hour snowfall and snow depth totals
- Soil temperature, soil moisture, relative humidity and evaporation at select sites.

Approximately 229 COOP observers report across Wyoming, and about 271 COOP volunteers are available across WA.

For more information, see: http://www.nws.noaa.gov/om/coop/index.htm and http://www.nws.noaa.gov/om/coop/coopmod.htm.

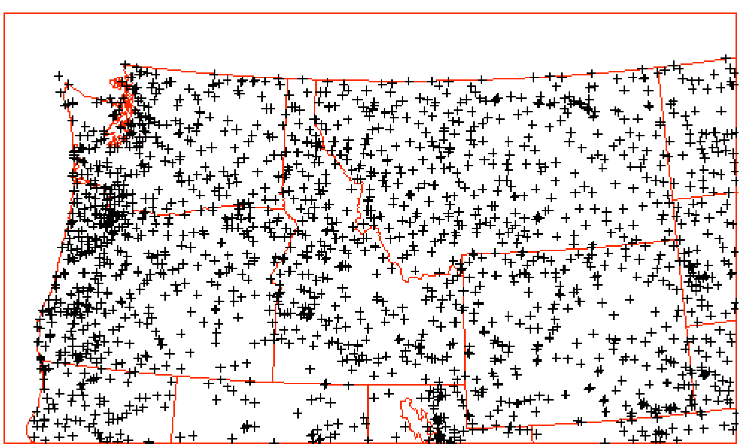

Figure A.4: Map of all NOAA/NWS Cooperative Observer Program participants across the Pacific Northwest. Figure courtesy of http://www.eol.ucar.edu/projects/hydrometnet/.

f. Remote Automated Weather Stations (RAWS)

Remote Automated Weather Stations are operated by a collection of land management agencies. Nearly 2,200 RAWS are deployed throughout the Western U.S. generally in remote areas to aid federal agencies in monitoring air quality, firefighting efforts and research.

RAWS provides hourly data of air temperature, precipitation and 10-minute averages of relative humidity, wind direction and wind speed; some sites also provide atmospheric pressure, soil moisture and fuel moisture and temperature. Data are transmitted to a receiving station via GOES technology.

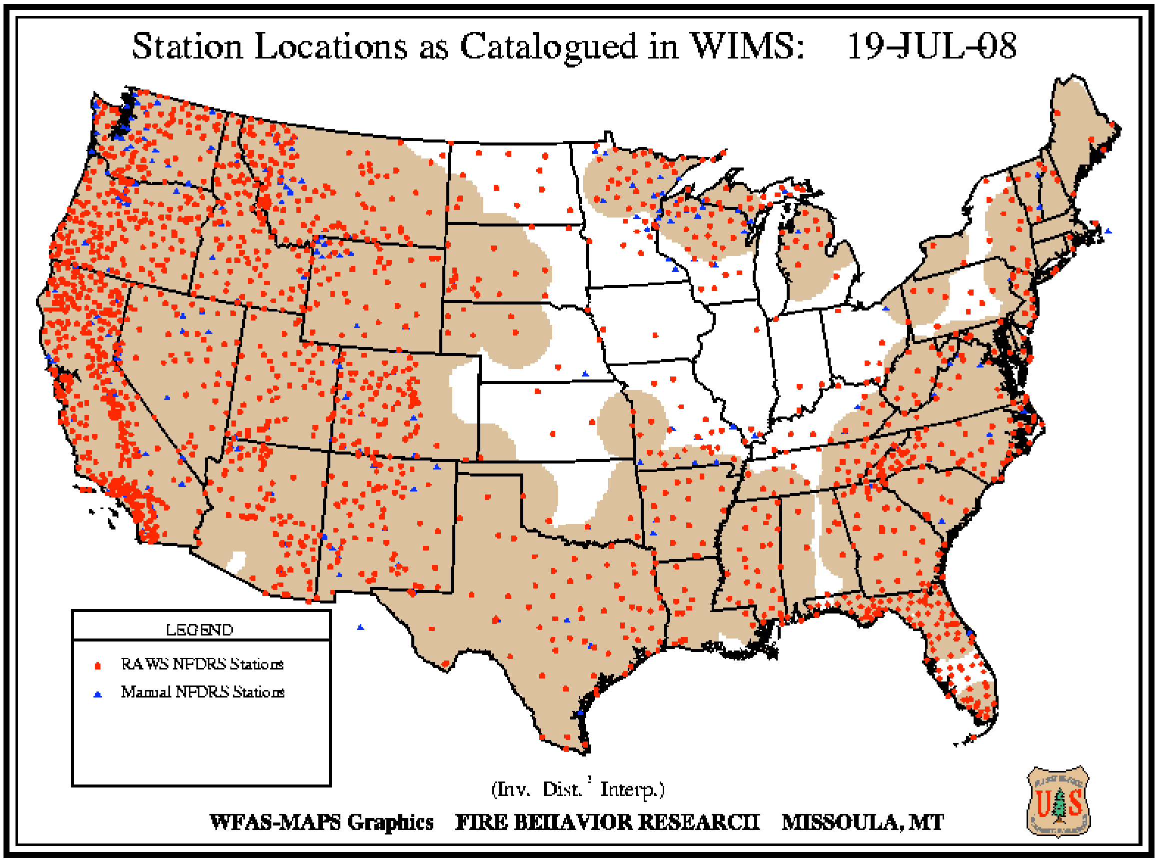

Figure A.5: Map showing all RAWS sites nationwide. Figure courtesy of the U.S. Forest Service, http://www.fs.fed.us/land/wfas/stn_loc.gif.

Approximately 41 RAWS sites are available across Wyoming, and another 81 sites are available across Washington state.

For more information, see: http://www.fs.fed.us/raws/ and http://www.wrcc.dri.edu/wraws/.

g. State Departments of Transportation (WYDOT, WSDOT)

Many Department of Transportation (DOT) state agencies operate Road Weather Information Systems (RWIS). RWIS are used to improve monitoring and forecasting of hazardous weather along state and federal highways and are generally made up of three elements (Aurora 2008):

i) Environmental Sensing Stations (ESS)
ii) Forecast models and algorithms
iii) Dissemination platforms for displaying data to end-users

ESS provide a suite of surface and near-surface weather and road information, including:

- Air temperature, dew point, and relative humidity
- Wind speed and direction
- Precipitation type and amount
- Visibility
- Road pavement and subsurface temperatures
- Surface conditions (wet, dry)
- Amount of deicing chemical on roadway
- Freezing point of roadway

These data are available in real-time every 5 to 15 minutes.

The Wyoming DOT (WYDOT) has deployed 31 sensor networks throughout the state along major highway systems. In addition, they've installed 40 web cams, 27 along federal interstates and another 13 along state highways. Together, these two systems are used extensively by stakeholders and the general public, primarily during winter weather.

The Washington state DOT (WSDOT) has deployed 83 weather stations across the state. In addition, the WSDOT web site links to over 400 weather sensors across multiple networks.

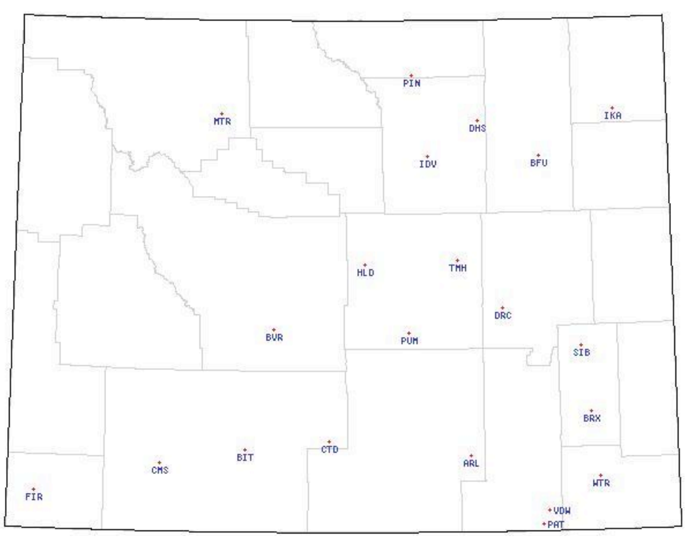

Figure A.6: Roadside weather stations deployed by the Wyoming Department of Transportation.

For more information, see:

- http://www.aurora-program.org/what_is_rwis.cfm
- http://www.ofcm.gov/fp-fy00/pdf/sec3c_dot.pdf
- http://www.tfhrc.gov/its/pubs/04101/index.htm
- http://www.wyoroad.info/
- http://dot.state.wy.us/ReadMore.jsp?sCode=infhe&sCID=2294
- http://www.geoxmf.com/geoxmf_public/wyoming%20dot%20case%20study.pdf
- http://www.wsdot.wa.gov/traffic/weather/default.aspx?station=2786&id=aw

h. Snowpack Telemetry (SNOTEL)

Snowpack Telemetry (SNOTEL) sites are operated by the Natural Resources Conservation Service (NRCS) of the U.S. Department of Agriculture. Approximately 730 SNOTEL sites are deployed in remote locations across 13 western states including Alaska. The primary goal of SNOTEL sites is to provide routine measurements of snowpack for the purpose of forecasting water supply.

Standard SNOTEL sites provide routine measurements of air temperature, precipitation and snow water content and depth. Enhanced sites also provide barometric pressure, relative humidity, soil moisture and temperature, solar radiation, and wind speed and direction. Data are recorded every 15 minutes, and the data are downloaded to receiving stations once per day.

Approximately 82 SNOTEL sites are located across Wyoming, and 64 SNOTEL sites are located across the state of Washington.

For more information, see http://www.wcc.nrcs.usda.gov/factpub/sntlfct1.html

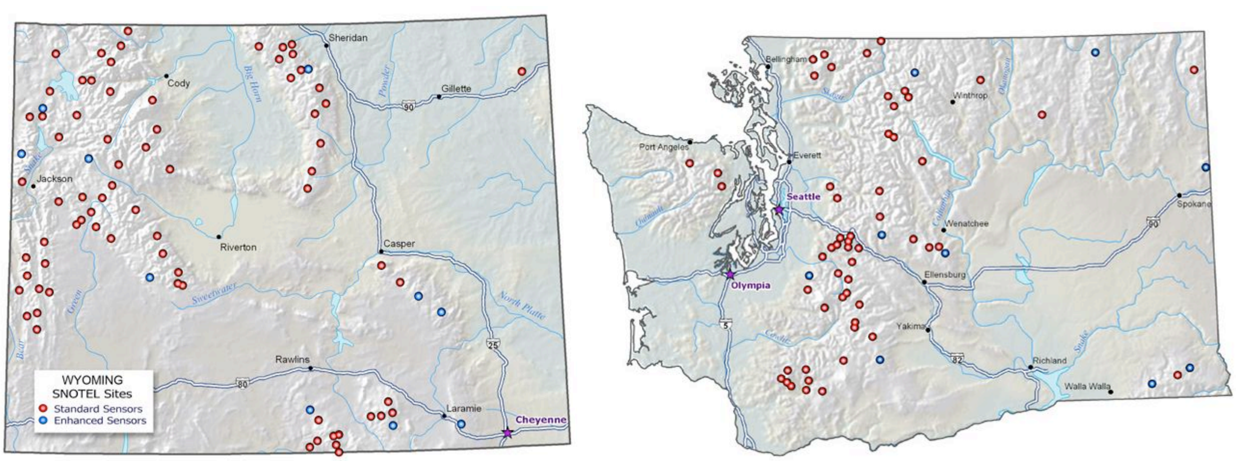

Figure A.7: Map of SNOTEL sites located across a) Wyoming and b) Washington.
Figures copied from: http://www.wcc.nrcs.usda.gov/snotel/Wyoming/wyoming.html and http://www.wcc.nrcs.usda.gov/snotel/Washington/washington.html.

i. United States Geological Survey (USGS) stream gauges

Over 7,200 stream gauge sites are deployed nationwide by the United States Geological Survey (Wahl et al. 1995) and are funded by a consortium of federal, state and local government agencies. These gauges are used for multiple reasons including:

- Monitor hydrological systems of individual basins
- Regional hydrology
- Water management operation
- Hydrologic forecasting
- Water quality monitoring
- Planning and design of future water management projects
- Legal operations and treaties
- Research

Real-time data from approximately 6,600 of these sites are available for use by the NWS and other agencies for flood monitoring with update times of 4 hours or less (Erwin and Hamilton 2005). Two key measurements are provided from stream gauges (Mason and Weiger 1995):

i) Water depth of stream or river, above some arbitrary reference (historical) point
ii) Discharge rate – volume of water flow within a given period of time

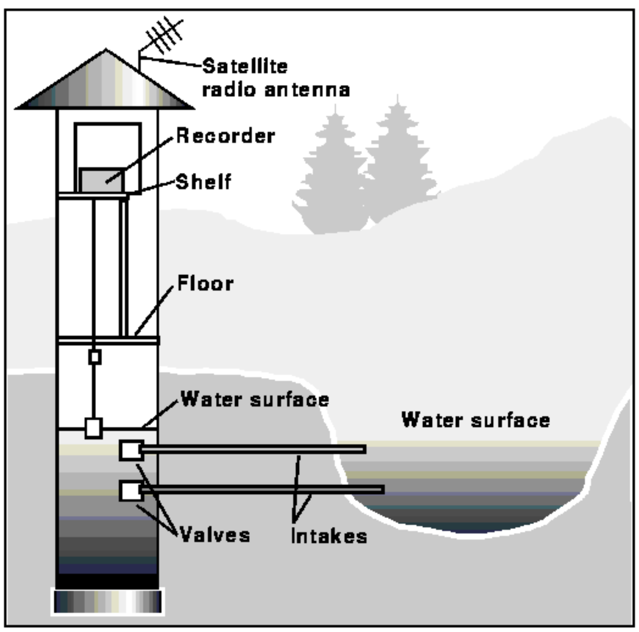

Figure A.8: Schematic of a stream-gauge station (Mason and Weiger 1995).

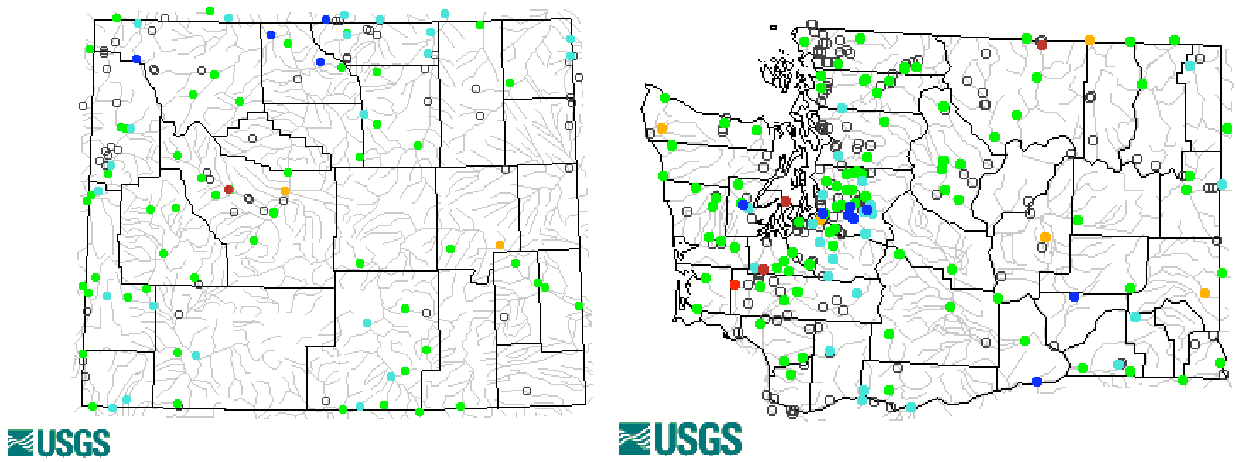

Figure A.9: Map of USGS stream-gage sites located across a) Wyoming and b) Washington. Figures copied from http://waterdata.usgs.gov/wy/nwis/rt and http://waterdata.usgs.gov/wa/nwis/rt.

Wyoming has approximately 142 stream-gage sites reporting in real-time, and Washington has approximately 262 stream-gages reporting in real-time.

For more information, see: http://water.usgs.gov/ and http://waterdata.usgs.gov/nwis/rt.

j. Community Collaborative Rain, Hail, & Snow Network (CoCoRaHS)

The Community Collaborative Rain, Hail & Snow Network (CocoRaHS) is a non-profit, volunteer program started in 1998 at the Colorado Climate Center at Colorado State University. Approximately 9,000+ volunteers nationwide now participate. Each participant records precipitation amount, snow depth and water equivalent, and the presence and size of hail; all data are recorded daily and immediately made available to the National Weather Service and others.

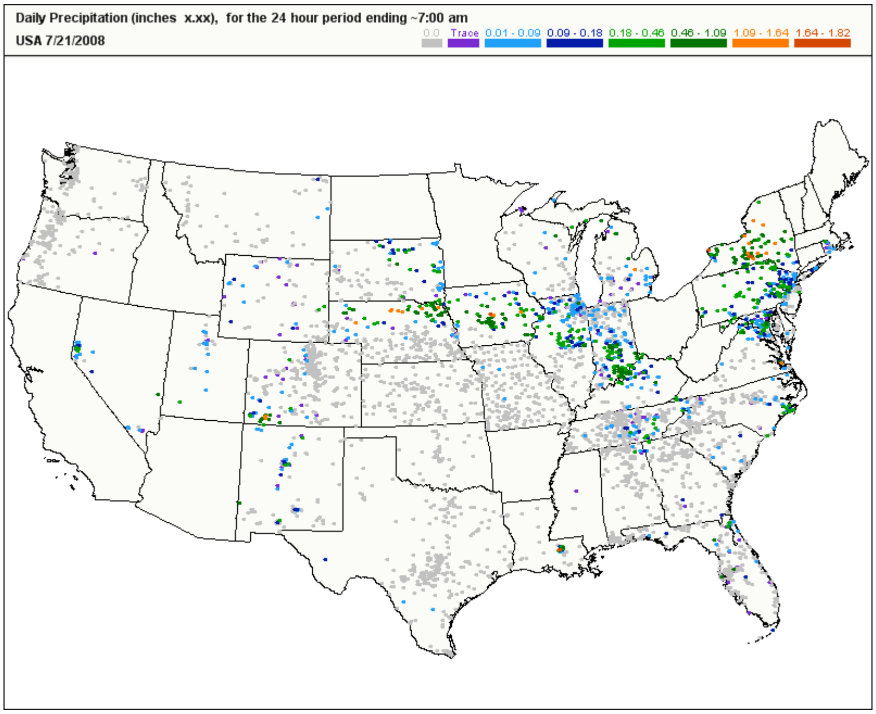

Figure A.10: The CoCoRaHS network of over 9,000 volunteers nationwide. Participants record local rain, snow and hail information daily.

Wyoming joined CoCoRaHS in 2003 and now has over 416 volunteer observers. Washington recently joined CoCoRaHS in June 2008 and is in the process of recruiting new volunteers.

For more information, see: http://www.cocorahs.org/

k. Automatic Position Reporting System/Citizen Weather Observing Program (APRS/CWOP)

The Automatic Position Reporting System-Citizen Weather Observing Program is an amateur radio based volunteer organization. Volunteers provide daily observations of temperature, dew point, wind speed and direction, atmospheric pressure, and rainfall. Wyoming has approximately 41 APRS/CWOP volunteers, and Washington state has about 250 observers.

For more information, see: http://wxqa.com/resources.html

I. Buoy and Coastal Marine Automated Network (C-MAN) stations

The National Data Buoy Center operates a network of 90 buoys and 60 Coastal Marine Automated Network (C-MAN) sites nationwide. Each station provides hourly observations of:

- Wind speed, direction, and gust information
- Atmospheric pressure
- Air temperature

All buoy and some C-MAN sites also provide:

- Sea surface temperature
- Wave height and period

Some select stations also provide water current and conductivity information.

Washington state has 3 moored buoys and 4 C-MAN sites along and just off shore from the western coast.

Particularly severe weather may render buoys inoperable, and repair is difficult during the winter months. During the winter of 1997-1998, only one buoy remained in operation by the end of the winter season. Repair of buoys requires having a readily deployable replacement buoy ready, an available ship and crew, and relatively calm seas. Buoys are also expensive, ranging up to $250,000 each.

For more information, see: http://www.ndbc.noaa.gov/about_ndbc.shtml

Figure A.11: a) Photo of moored buoy station 46041 located 45 miles northwest of Aberdeen WA. b) Photo of C-MAN Station DESW1 located on Destruction Island, WA. Photos courtesy of NDBC: http://www.ndbc.noaa.gov/maps/NW_Straits_Sound.shtml.

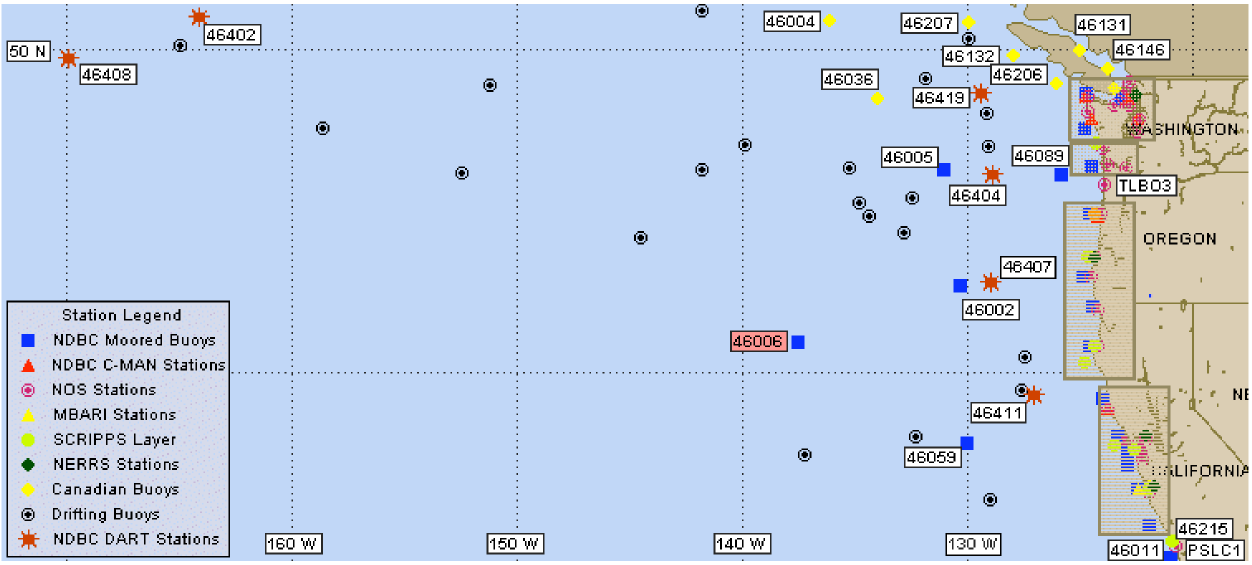

Figure A.12: Map showing the location of all NDBC buoy and C-MAN sites as well as other buoy stations across the eastern Pacific. Figure courtesy of NDBC: http://www.ndbc.noaa.gov/maps/Northwest.shtml.

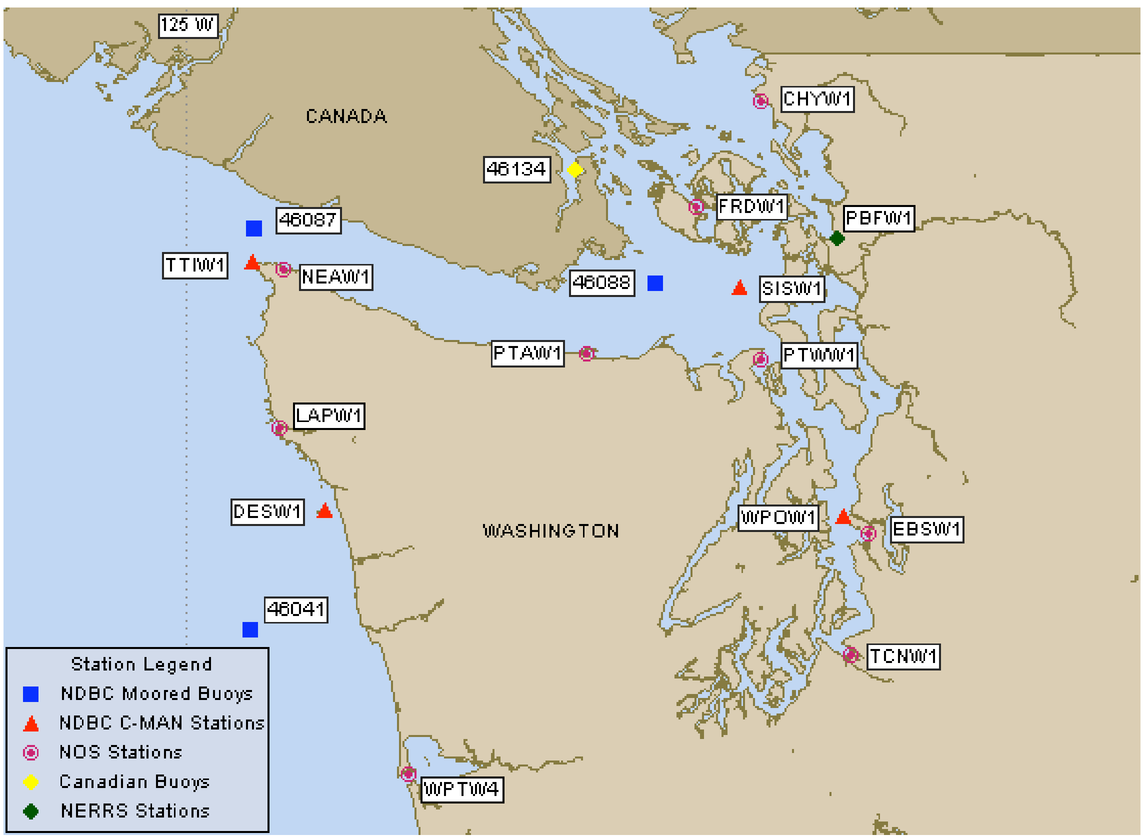

Figure A.13: Map showing the location of all NDBC buoy and C-MAN sites as well as some NOS, Canadian buoys and NERRS stations within the Seattle WFO County Warning Area. Figure courtesy of NDBC: http://www.ndbc.noaa.gov/maps/NW_Straits_Sound.shtml.

Table A.2: Surface observational systems deployed across Wyoming.

Network	Number of Sites	Data Collection Rate	Variables
ASOS AWOS	16 13	Hourly, Special obs	T, Td, wind speed and dir., precip amount and type, pressure and pressure tendency, visibility, sky conditions, obstructions, lightning data.
COOP	229	Hourly Daily	Max and min T, precipitation Snowfall amount and snow depth
RAWS	41	Hourly	T, precipitation 10-min avgs: RH, wind speed and dir *Enhanced sites:* Pressure, soil moisture, fuel moisture and temperature.
WYDOT	31	Every 5 - 15 minutes	T, Td, RH, wind speed and dir., precipitation amount and type.
SNOTEL	82	Available daily	T, precipitation, snow water content and depth *Enhanced sites:* Pressure, soil moisture and temp., solar radiation, wind speed and dir.
USGS	136	Updates every 1-4 hours	Water depth and discharge rate.
CoCoRaHS	416	Available daily	Precipitation amount and type, snow depth and water equivalent, hail size.

Table A.3: Surface observational systems deployed across Washington state.

Network	Number of Sites	Data Collection Rate	Variables
ASOS AWOS	27 7	Hourly, Special obs	T, Td, wind speed and dir., precip amount and type, pressure and pressure tendency, visibility, sky conditions, obstructions, lightning data.
COOP	271	Hourly Daily	Max and min T, precipitation Snowfall amount and snow depth
RAWS	81	Hourly	T, precipitation 10-min avgs: RH, wind speed and dir *Enhanced sites:* Pressure, soil moisture, fuel moisture and temperature.
WSDOT	83	Every 5 - 15 minutes	T, Td, RH, wind speed and dir., precipitation amount and type.
SNOTEL	64	Available daily	T, precipitation, snow water content and depth *Enhanced sites:* Pressure, soil moisture and temp., solar radiation, wind speed and dir.
USGS	262	Updates every 1-4 hours	Water depth and discharge rate.
CoCoRaHS	**	Available daily	Precipitation amount and type, snow depth and water equivalent, hail size.
Buoys	3	Hourly	T, Td, Pressure, wind speed and dir., sea surface temperature, and sig. wave height.
C-MAN	4	Hourly	T, Td, Pressure, wind speed and dir., sea surface temperature, and sig. wave height.

** Washington state joined CoCoRaHS 1 June, 2008.

Appendix B: Presidential Federal Disaster Declarations

Table B.1: List of all Presidential Federal Disaster Declarations declared for Wyoming between 1953 and 2008 (FEMA 2008).

Year	Date	Disaster Type
2005	08/22	Tornado
2000	12/13	Winter Storm
1999	02/17	Severe Winter Storm
1985	08/07	Severe Storms, Hail, Flooding
1979	07/19	Severe Storms, Tornadoes
1978	05/29	Severe Storms, Flooding, Mudslides
1963	07/04	Heavy Rains, Flooding

Table B.2: List of all Presidential Federal Disaster Declarations declared for Washington between 1953 and 2008 (FEMA 2008).

Year	Date	Disaster Types
2007	12/08	Severe Storms, Flooding, Landslides, and Mudslides
2007	02/14	Severe Winter Storm, Landslides, and Mudslides
2006	12/12	Severe Storms, Flooding, Landslides, and Mudslides
2006	05/17	Severe Storms, Flooding, Tidal Surge, Landslides, and Mudslides
2003	11/07	Severe Storms and Flooding
2001	03/01	Earthquake
1998	10/16	Landslide In The City Of Kelso
1998	10/05	Flooding
1997	07/21	Snowmelt/Flooding
1997	04/02	Severe Storms/Flooding/Landslides/Mudslides
1997	01/17	Severe Winter Storms/Flooding
1997	01/07	Ice and Snow Storms
1996	02/09	Severe Storms/Flooding
1996	01/03	Storms/High Winds/Floods
1994	08/02	El Nino Effects (The Salmon Industry)
1993	03/04	Severe Storm, High Winds
1991	11/13	Fires
1991	03/08	High Tides, Severe Storm
1990	11/26	Flooding, Severe Storm
1990	01/18	Flooding, Severe Storm
1989	04/14	Heavy Rains, Flooding, Mudslides

1986	12/15	Severe Storms, Flooding
1986	07/26	Severe Storms, Flooding
1986	03/19	Heavy Rains, Flooding, Landslides
1986	02/15	Severe Storms, Flooding
1983	01/27	Severe Storms, High Tides, Flooding
1980	05/21	Volcanic Eruption, Mt. St. Helens
1979	12/31	Storms, High Tides, Mudslides, Flooding
1977	12/10	Severe Storms, Mudslides, Flooding
1975	12/13	Severe Storms, Flooding
1974	01/25	Severe Storms, Snowmelt, Flooding
1972	06/10	Severe Storms, Flooding
1972	03/24	Heavy Rains, Flooding
1972	02/01	Severe Storms, Flooding
1971	02/09	Heavy Rains, Melting Snow, Flooding
1965	05/11	Earthquake
1964	12/29	Heavy Rains & Flooding
1963	03/02	Flooding
1962	10/20	Severe Storms
1957	03/06	Flooding
1956	02/25	Flooding

Appendix C: NCDC Storm Event Archives

Table C.1: Storm events for Campbell County, WY, as recorded in the NCDC Storm Events database between 1 January 1993 and 30 June 2008.

Event – Campbell County	Total	Fatalities	Injuries	Damage ($)
Tornadoes	25	2	13	$ 5.5M
Thunderstorm, High Wind	90	0	7	$ 0.6M
Hail	185	0	2	$17.1M
Lightning	2	0	0	$ 0.0M
Floods	15	1	0	$ 0.5M
Snow/Ice	33	0	0	$ 0.7M
Extreme Temperatures	6	1	0	$ 0.1M
Forest Fires	2	0	0	$ 0.0M
Total	358	4	22	$ 24.5M

Table C.2: Storm events for Johnson County, WY, as recorded in the NCDC Storm Events database between 1 January 1993 and 30 June 2008.

Event – Johnson County	Total	Fatalities	Injuries	Damage ($)
Tornadoes	5	0	0	$ 0.0M
Thunderstorm, High Wind	21	0	0	$ 0.0M
Hail	49	0	0	$ 0.0M
Lightning	1	0	1	$ 0.0M
Floods	18	0	0	$ 0.6M
Snow/Ice	15	0	2	$ 0.0M
Extreme Temperatures	0	0	0	$ 0.0M
Forest Fires	2	0	0	$ 0.0M
Total	111	0	3	$0.6M

Table C.3: Storm events for Sweetwater County, WY, as recorded in the NCDC Storm Events database between 1 January 1993 and 30 June 2008.

Event – Sweetwater County	Total	Fatalities	Injuries	Damage ($)
Tornadoes	5	0	0	$ 0.0M
Thunderstorm, High Wind	37	0	11	$ 0.0M
Hail	6	0	0	$ 0.0M
Lightning	1	0	0	$ 0.0M
Floods	4	0	0	$ 0.3M
Snow/Ice	26	0	3	$ 0.1M
Extreme Temperatures	3	1	0	$ 0.1M
Forest Fires	5	0	0	$ 0.3M
Total	87	1	14	$ 0.8M

Table C.4: Storm events for Grays Harbor County, WA, as recorded in the NCDC Storm Events database between 1 January 1993 and 30 June 2008.

Event – Grays Harbor	Total	Fatalities	Injuries	Damage ($)
Tornadoes	2	0	0	$ 0.0M
Thunderstorm, High Wind*	3	2	1	$ 0.0M
Hail	0	0	0	$ 0.0M
Lightning	0	0	0	$ 0.0M
Floods	3	1	0	$ 0.8M
Heavy Precipitation	8	0	0	$ 4.5M
Ocean & Lake Surf	4	0	0	$ 1.1M
Forest Fires	0	0	0	$ 0.0M
Total	18	3	1	$ 6.4M

*Note: The database for Grays Harbor appears underreported; only 3 'Thunderstorm, High Wind' reports are listed, with no high wind events listed after 1994.

Table C.5: Storm events for Pacific County, WA, as recorded in the NCDC Storm Events database between 1 January 1993 and 30 June 2008.

Event – Pacific County	Total	Fatalities	Injuries	Damage ($)
Tornadoes	0	0	0	$ 0.0M
Thunderstorm, High Wind	1	0	0	$ 0.0M
Hail	0	0	0	$ 0.0M
Lightning	0	0	0	$ 0.0M
Floods	3	0	0	$10.0M
Heavy Precipitation	3	0	0	$ 0.0M
Ocean & Lake Surf	0	0	0	$ 0.0M
Forest Fires	1	0	0	$ 0.0M
Total	8	0	0	$ 10.0M

Table C.6: Storm events for Lewis County, WA, as recorded in the NCDC Storm Events database between 1 January 1993 and 30 June 2008.

Event – Lewis County	Total	Fatalities	Injuries	Damage ($)
Tornadoes	0	0	0	$ 0.0M
Thunderstorm, High Wind	0	0	0	$ 0.0M
Hail	0	0	0	$ 0.0M
Lightning	2	0	1	$ 0.0M
Floods	2	3	0	$58.8M
Heavy Precipitation	5	0	0	$ 0.1M
Ocean & Lake Surf	0	0	0	$ 0.0M
Forest Fires	0	0	0	$ 0.0M
Total	9	3	1	$ 58.9M

Table C.7: Summary of county population, area, and storm statistics.

County	Population 2000 Census	Area (km^2)	Storm Events 1993 - 2008	Damage ($ M) 1993 - 2008	Area with radar coverage at 3km AGL
Campbell County	33,698	12,436	358	$24.5 M	0%
Johnson County	7,075	10,812	111	$ 0.6 M	24%
Sweetwater County	37,613	27,172	87	$ 0.8 M	39%
Grays Harbor Cty	71,587	5,761	18	$ 6.4 M	15%
Lewis County	73,585	6,310	8	$10.0 M	95%
Pacific County	20,984	3,169	9	$58.9 M	26%

Appendix D:
Methodology for Determining Unblocked Radar Beam Height

To determine the beam height above ground for a radar or a network of radars, it is necessary to know the terrain at high-resolution and to estimate the beam height above the radar for elevation angles in scanning strategy to be used.

For this work the terrain is analyzed to a 1-km Cartesian grid on a Lambert Conformal grid. Digital Elevation Model (DEM) data from the United States Geologic Survey (USGS), having resolution of 3 arc seconds in latitude and longitude (approximately 90 m and 70 m, respectively, at 40° N), are linearly interpolated from nearby DEM points to the Cartesian map points. This defines the high resolution terrain map using the ARPSTRN (Advanced Regional Prediction System (ARPS) Terrain) program of the ARPS numerical weather prediction system (Xue et al. 1995).

Under the assumption that temperature and humidity are horizontally homogeneous so that the refractivity is a function only of height above ground, it is possible to derive formulations which express the ray path in terms of a path following a curve of a sphere of radius $k_e a$ (e.g., Doviak and Zrnic 1992), where a is the earth's radius and k_e is a multiplier which is dependent on the vertical gradient of refractivity. For the United States Standard Atmosphere the refractivity index has a gradient of about –1/4a in the first kilometer of the atmosphere. Thus it can be shown that the so-called four-thirds earth model (k_e equal to 4/3) can be used for calculating the expected height of the radar beam, when the beam height above the radar, h, is restricted to the first 10-20 km. The following two equations relate h and the surface range (distance along the earth's surface), s, to radar-measurable parameters, the slant path, r and elevation θ_e:

$$s = k_e a \sin^{-1}\left(\frac{r\cos\theta_e}{k_e a + h}\right). \qquad (1)$$

$$h = \left[r^2 + (k_e a)^2 + 2 r k_e a \sin\theta_e\right]^{1/2} - k_e a \qquad (2)$$

Then, expressed in terms of surface range, the height is

$$h = k_e a\left(\cos\theta_e \Big/ \cos\left(\theta_e + \frac{s}{k_e a}\right) - 1\right) \qquad (3)$$

The height above ground of the center of the beam at a grid point, with index i,j, is then

$$\Delta h_{i,j} = (h + z_r) - z_{i,j}$$

where z_r is the height of the radar feedhorn above sea level and $z_{i,j}$ is the height of the terrain at the grid point.

Spherical geometry using the latitude and longitude of each Cartesian grid point and the latitude and longitude of each proposed radar site is used to find the surface range of each point from the radar. High resolution topographic maps from the USGS (e.g., via topozone.com) are used to estimate the height of the ground at each proposed radar site and the radar is situated on a tower giving the radar feedhorn a height of 20 m above the site elevation. For the NEXRAD radars, a table of latitude, longitude, and radar elevation, including tower height provided by the Radar Operations Center is used. The data for the NEXRAD radars relevant for this study are shown in Table D.1

To determine beam blockage, if the center of the beam is at or below the height of the interpolated high-resolution terrain, the beam is considered blocked. This is equivalent to half the radar energy being blocked by the beam. Any points in the radial beyond this occurrence are then considered blocked as well. A table of beam blockage is first calculated at a resolution of 1˚ in azimuth, going out in range in 100 m steps. Then for the determination of blockage at a given Cartesian point, the beam blockage data from the table rounded to the nearest whole degree is used. For the NEXRAD radars, the elevation angles considered were the first three operational elevation angles used for common precipitation scanning VCPs, namely, 0.5˚, 1.5˚ and 2.5˚.

For a network of radars the beam height for each of the radars and for each elevation angle is determined at each Cartesian point. Then the minimum unblocked beam height among those heights is displayed as the network beam height for that point.

Table D.1 NEXRAD Radar Site Information

Radar Site	Site ID	Latitude	Longitude	Radar Height (m)
Billings, MT	KBLX	45.8539	-108.6067	1112
Riverton, WY	KRIW	43.0661	-108.4772	1712
Cheyenne, WY	KCYS	41.1519	-104.8061	1883
Rapid City, SD	KUDX	44.1250	-102.8297	949
Everett, WA	KATX	48.1944	-122.4958	181
Portland, OR	KRTX	45.7147	-122.9653	492