NOAA'S RAPID RESPONSE TO THE HOWARD A. HANSON DAM FLOOD RISK MANAGEMENT CRISIS

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NOAA operations and research personnel joined forces to better predict a possible flood and help calm public fears regarding reduced flood protection from a western Washington dam.

After nearly 50 years of service providing flood risk management for areas near Seattle, the U.S. Army Corps of Engineers (USACE) discovered signs of a potential dam failure at Howard A. Hanson Dam (HHD) after a potent winter storm in early January 2009. This dam safety issue increased the risk of catastrophic flooding in the now highly developed Green River Valley (GRV) downstream. As part of a broad set of actions by local, state, and federal agencies, the National Oceanic and Atmospheric Administration (NOAA) implemented a rapid response effort, coordinated between the National Weather Service (NWS) and the Office of Oceanic and Atmospheric Research (OAR), to enhance services to the communities at risk. These enhancements drew from ideas developed at NWS offices with inputs from regional stakeholders and took advantage of innovations in science and technology from NOAA's Hydrometeorology Testbed (HMT; Ralph et al. 2005a), which has focused on extreme precipitation events over the last several years (http://hmt.noaa.gov). This paper briefly describes the HHD and what happened to it,

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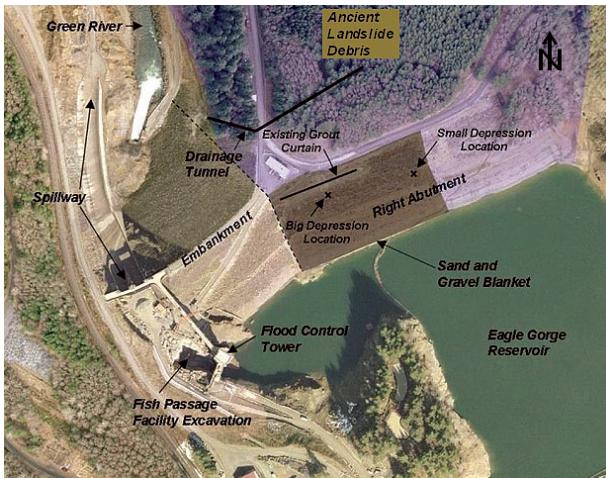E-mail: allen.b.white@noaa.gov

FIG. 1. Aerial photograph of Howard Hanson Dam with notations of features described in the text (from the USACE).

summarizes key elements of NOAA's rapid response and their impacts, and recommends next steps to address the ongoing risk. Major rapid response elements consisted of 1) gathering the unique requirements for information and forecasts needed by the community; 2) implementing new data and tools; 3) synthesizing these specialized inputs into the forecast process and into new products at the NWS Seattle Weather Forecast Office (WFO), the NWS Northwest River Forecast Center (NWRFC), and the USACE to meet the emerging user requirements; and 4) collecting forecaster and stakeholder feedback and evaluations of new tools, data, and products.

Overall, the NOAA effort provided much improved flood watch and warnings, improved and strengthened the ties between NOAA and key stakeholders and recognition for NOAA's capabilities, demonstrated a rapid and coordinated response to provide enhanced services, and worked with the USACE to help reduce the high level of concern in the local communities. An expansion of HMT resources and lessons learned, combined with a new scanning weather radar that will be placed along Washington's western coast, will provide the region with enhanced monitoring and forecast capabilities of extreme precipitation events to better manage flood risk and protect life and property.

Background. The HHD (Fig. 1) is a USACE-operated dam located near the headwaters of the Green River in King County, Washington, 103 km (along the river) upstream from the river's mouth into Elliott Bay and the Puget Sound (Fig. 2). The HHD serves multiple purposes by providing flood risk reduction, water storage for river flow regulation, municipal water supply, and summer low flow augmentation for maintaining a healthy fish habitat. Construction of the dam, including 21 km of railroad relocation, began in February 1959. Although completion was not scheduled until April 1962, the dam went into operation on Christmas Day 1961. The capacity of the Eagle Gorge Reservoir behind the HHD is 130,753,000 m^3 (106,000 acre-ft).

Before the HHD was constructed, floodwaters of the Green River periodically spread generally unimpeded across the GRV. Prior to the commissioning of the dam, the valley had flooded more than 30 times in 70 yr. Flood control provided by the HHD opened the way for increased development in the GRV. The valley is currently the home to the nation's fifth largest industrial park (second largest along the U.S. West Coast) and approximately 400,000 residents. The economic impact based on a flood scenario of 708 m^3 s^{-1} (25,000 cfs) measured at the Green River stream gauge at Auburn, Washington (with no levee failures), is estimated to be $107 million per day, including 100,000 jobs with a $16 million daily payroll (Harris and Goodwin 2010).
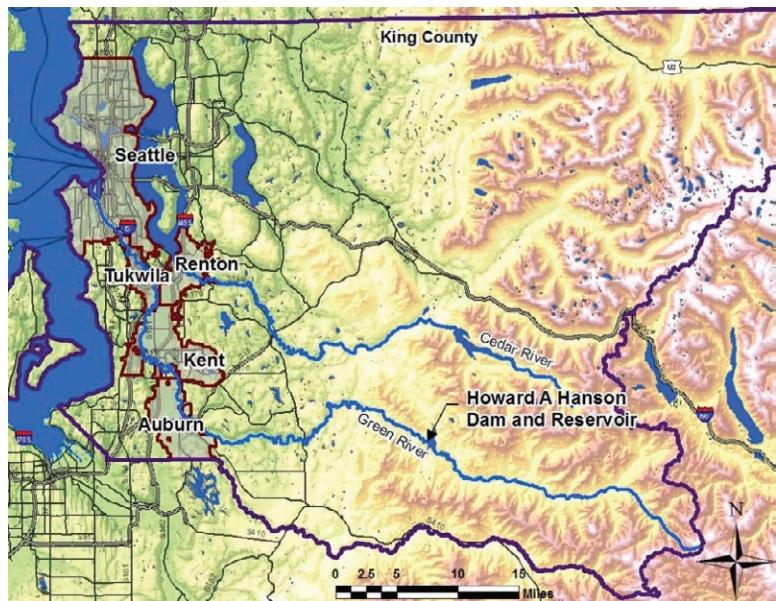

FIG. 2. Map indicating the locations of the Green River, the HHD, and downstream communities. Terrain elevations are depicted schematically (from the USACE).

Meteorologists and hydrologists have long been aware of the atmospheric conditions in winter storms that most likely lead to flooding on western Washington watersheds (e.g., Colle and Mass 1996, 2000; Garvert et al. 2007). More recently, microwave satellite technology, such as the Defense Meteorology Satellite Program's Special Sensor Microwave Imager (SSM/I), has allowed scientists to look more in depth into the global extent of these plumes of enhanced water vapor transport, now known more generally as "atmospheric rivers" (ARs; Zhu and Newell 1998). Atmospheric rivers are narrow regions of enhanced water vapor transport that are responsible for flood-producing rains along the U.S. West Coast (Ralph et al. 2003, 2004, 2005b, 2006, 2012; Neiman et al. 2008a,b, 2012; www.esrl.noaa.gov/psd/atmrivers/), Western Europe (Stohl et al. 2008), and elsewhere around the world. The main reason that strong ARs can lead to flooding is that they are characterized by moist neutral static stability, relatively warm conditions with high snow levels, and strong horizontal water vapor transport, creating ideal conditions for heavy orographic rain (Ralph et al. 2005b; Neiman et al. 2009).

The storm that impacted Washington on 6–8 January 2009 was a classic, strong AR event (Fig. 3), and it produced heavy rainfall exceeding 10–15 in. over a wide geographic area of western Washington (www.climate.washington.edu /events/2009floods/). As a result, many floods occurred across western Washington on 8 January, and, despite the successful efforts by the USACE to provide flood risk management for the Green River and other basins during this event, King County still reported damages totaling $28 million.

ARs are accompanied by anomalously high snow levels (Neiman et al. 2008b, 2009, 2011; White et al. 2010), which further exacerbates the flood threat by exposing more of the altitude ranges in a basin to rain (e.g., White et al. 2002; Lundquist et al. 2008). In addition, the warm moist conditions in ARs can accelerate snowmelt, which contributed to the widespread flooding and numerous landslides that occurred as a result of the January 2009 storm (Grizzel et al. 2009; Mastin et al. 2010).

During the storm of 6–8 January 2009, water was stored behind the HHD to an elevation of 362 m to prevent flooding downstream. This height represents a record flood storage for the dam. The total economic impact of preventing flooding downstream of the HHD during this event was estimated to be $4 billion (www.nws.usace.army.mil/PublicMenu/documents /HHD/D4-HHDFactSheetMarch2011.pdf). After the
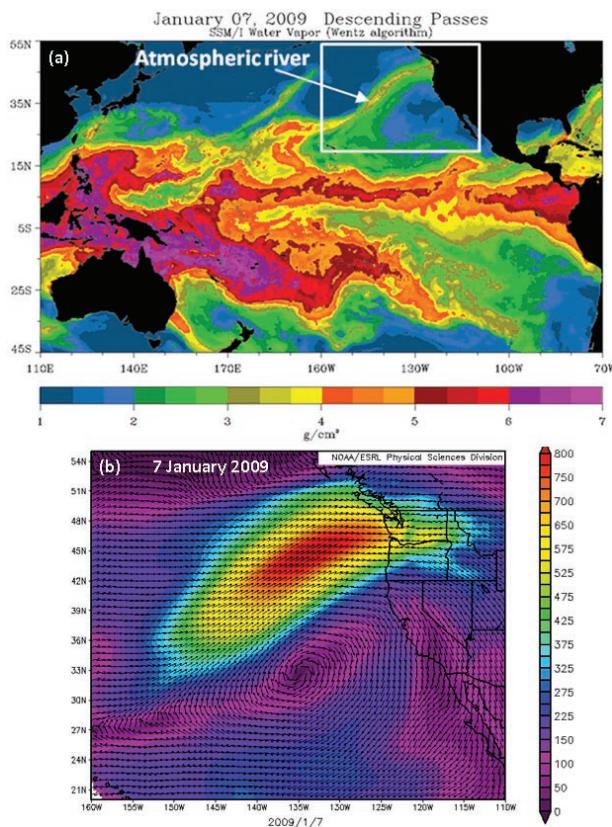

FIG. 3. (a) Composite satellite image of IWV (g cm²) produced from the SSM/I constellation on 7 Jan 2009 (from 1200 to 2359 UTC). A flood-producing atmospheric river is shown impacting the Washington coast. (b) NCEP–National Center for Atmospheric Research (NCAR) daily reanalysis of integrated vapor transport (kg s⁻¹ m⁻²) over the domain of the inset box in (a).

storm, USACE staff discovered that two depressions had formed on the upstream face of the right abutment of the dam (Fig. 1). Sediment-laden water was observed from one of the drains in the right abutment drainage tunnel. These occurrences created concern that a flow path through the right abutment could potentially be developing that could ultimately lead to dam failure. After several tests were conducted by USACE during the spring of 2009, an interim repair of the right abutment was constructed during the summer to decrease seepage and make improvements to the drainage tunnel. This work included constructing a grout curtain along 475 ft of the right abutment (Fig. 1).

Prior to this repair work, the USACE had estimated the risk for significant flooding along the GRV immediately after the January 2009 storm to be 1:3. This risk created great concern for GRV residents, businesses, emergency managers, and political leaders because the fully operational dam

flood risk is 1:140. After improvements to the abutment and subsequent testing, the USACE revised the flood risk estimate in the fall of 2009 to be 1:25. By August 2010, the USACE had become more confident that the HHD could provide some flood risk management for the upcoming winter, so they reduced their estimate of flood risk in the GRV to 1:60. Subsequently, the USACE office in Seattle was given an emergency appropriation for $44 million in the 2011 fiscal year (FY11) federal budget to perform additional improvements on the HHD (see "Longer-term implications" section).

DEVELOPING AN OVERALL PLAN TO ADDRESS THE HHD CRISIS. The Washington U.S. Congressional delegation was the primary authority requesting NOAA to address the potential flood risk associated with the damaged HHD. The mitigation efforts to address potential flooding lay within the purview of the NWS, which took advantage of recent advances from the HMT in forming a coordinated response for political leaders and the USACE.

Once the flood threat was identified after the January 2009 storm, there were just nine months until the beginning of the next wet season to plan and implement actions to mitigate the flood threat. The first step was to elicit cooperation and collaboration between and with all involved partners including the Federal Emergency Management Agency (FEMA), USACE, the Washington State Emergency Management Division, King County Emergency Management, the King County Flood Warning Center, affected cities (Auburn, Kent, Renton, and Tukwila), the National Weather Service [including the Seattle WFO, NWRFC, National Centers for Environmental Prediction (NCEP), and Office of Hydrologic Development (OHD)], and elected officials. Although each of the affected groups throughout this process developed its own action plans, it became clear that the triggering thresholds for these plans must be developed and coordinated such that they could accommodate the needs of each group (including lead time) and

yet remain soundly grounded in the current state of the science.

Among these interested parties, separate groups were organized to address three major aspects of the problem: warning and notification; elected officials, policy planning; and public outreach, education, and awareness. Of these, only the warning and notification group is discussed here. The Seattle WFO senior service hydrologist and warning coordinator meteorologist were members of this group, which met several dozen times during 2009, finishing with accepted plans by September. A week-long functional exercise with each of the jurisdiction's operational staff was held in late September to test the warning and notification plans. Seattle WFO staff participated by issuing a sequence of flood warning messages during the week and conducting daily online weather briefings.

A requisite step in developing the necessary forecasts and warnings was to define what amount of rainfall would lead to runoff exceeding the capacity of the compromised flood risk management system on the Green River. This was accomplished by the NWRFC, working with USACE, running a series of tests using the NWS' operational streamflow prediction model for differing amounts of precipitation and varying antecedent soil moisture and snowpack conditions. These tests generated time series of hypothetical inflow into HHD, which could then be compared with the thresholds for inflow identified by USACE as low level of risk, elevated level of risk, or high level of risk (Fig. 4).
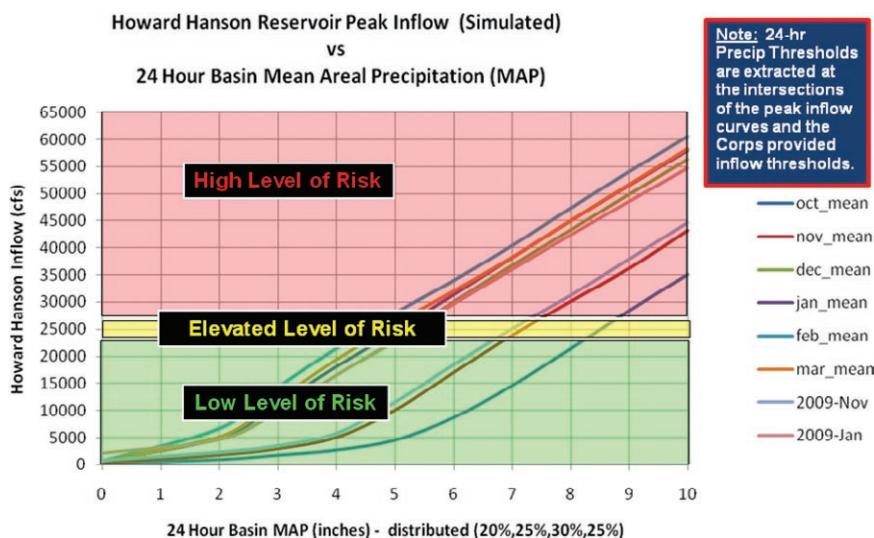

Fɪɢ. 4. **Results of sensitivity tests translating hypothetical heavy rainfall on the Green River over 24 h into HHD inflow. The runs were conducted by the NWRFC and used varying antecedent conditions (soil moisture and snow pack). The levels of risk were assigned based on inflow thresholds defined by the USACE.**

NEW DATA AND TOOLS. Local and regional forecast offices worked together with the NOAA/NCEP to provide new methods that could be applied to this crisis. Additionally, since the winter of 2003/04 HMT has been researching conditions that lead to extreme precipitation on the U.S. West Coast and has been developing and testing new methods and tools to better monitor and predict such conditions, not necessarily based on today's operational tools. These innovations at forecast offices, at NCEP, and in HMT were aligned to quickly respond to the emerging flood risk. Several recent advances were the foundation of the
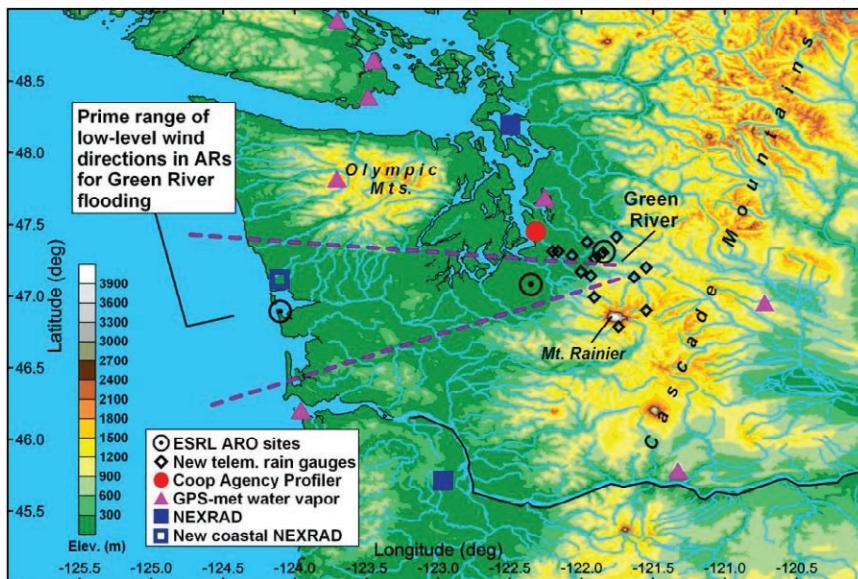

FIG. 5. Base map indicating the locations of the newly telemetered rain gauges provided by the NWS (open black diamonds), the atmospheric river observatory equipment deployed by PSD (three bull's-eyes), and a few additional observing system assets in the region (see key). The wedge depicting the prime range of low-level wind directions in ARs for Green River flooding is based on a recent study by Neiman et al. (2011).

rapid response: that is, the emergence of probabilistic QPF methods; the importance of atmospheric river conditions in creating extreme rainfall; the ability to monitor the snow level; networking of rain gauges with real-time communication, rapid-refresh high-resolution numerical modeling techniques tailored to the West Coast; and experience gained by forecasters in working with new tools, including in HMT. To help evaluate the impacts of these new methods and data, a feedback and evaluation process was established, and it is described and reported on in the "End user feedback from the 2009/10 winter season" section.

New observations. An integral part of the rapid response was deployment of new observations that allowed for improved monitoring of winter storm impacts ranging geographically from within the watershed to the coast 150 km west ("upwind") of the Green River (Fig. 5; Table 1).

ENHANCED RAIN GAUGE NETWORK. Staff from the NWS Western Region Headquarters enhanced the existing weather and precipitation reporting network critical to Green River forecasts by 1) installing new rain gauges to fill existing gaps, or at locations where an observation site had been lost; 2) adding satellite transmission to existing gauges not reporting in real time to allow reports to be used during an event; and

3) adjusting and/or improving data ingest and communications of existing telemetry data to improve access and reliability. In two cases NWS partnered with another agency to leverage assets: the U.S. Geological Survey installed a NWS-purchased rain gauge at a river gauge telemetry location, and the NWS gained access to a King County rain gauge along Big Soos Creek using NWS telemetry. The locations of the newly available rain gauges are listed in Table 1 and plotted on a map in Fig. 5. The data provided by this enhanced network were used to refine NWS river forecast models and to determine a more accurate estimate of precipitation that accumulated across the basin during storms.

SNOW-LEVEL MEASUREMENTS. It is well known that the snow level is a primary determinant of flood risk in the mountainous terrain of the western U.S., where most flooding is a cool-season phenomenon. For example, in a study using the NWS's operational hydrologic model, White et al. (2002) demonstrated that a 600-m uncertainty in snow level could translate to a factor of 3 difference in runoff. White et al. (2002) also developed an automated algorithm to measure the snow level (defined here as the altitude in the atmosphere where snow changes to rain) in real time using wind profilers or vertically pointing precipitation radars (S-PROF; White et al. 2000). The resulting

Instrument or obs system	Location: lat, lon	Site ID	Site operator	Measurements	Distance to HHD (km)
	TABLE 1. Observing system enhancements deployed in response to the HHD flood risk management crisis.				
Rain gauge	Ranier Carbon 46.994°N, 121.911°W	RCRW1	NWS	Hourly rainfall	32.8
Rain gauge	Cedar Lake 47.413°N, 121.756°W	CEDW1	NWS	Hourly rainfall	15.3
Rain gauge	Palmer 3ESE 47.306°N, 121.851°W	PALW1	NWS	Hourly rainfall	5.8
Rain gauge	Landsberg 47.377°, 121.961°W	LNBW1	NWS	Hourly rainfall	17.2
Rain gauge	Mud Mountain Dam 47.141°N, 121.936°W	ENUW1	NWS	Hourly rainfall	18.9
Rain gauge	Buckley 47.169°N, 122.004°W	BUCW1	NWS	Hourly rainfall	20.3
Rain gauge	Enumclaw 47.133°N, 121.633°W	GENW1	NWS	Hourly rainfall	19.8
Rain gauge	White River 46.900°N, 121.500°W	WHTW1	NWS	Hourly rainfall	47.2
Rain gauge	Green near Lester 47.200°N, 121.550°W	LESW1	NWS	Hourly rainfall	19.8
Rain gauge	Newaukum near BIK 47.283°N, 122.067°W	BKDW1	NWS	Hourly rainfall	21.1
Rain gauge	Paradis ranger station 46.786°N, 121.742°W	ASFW1	NWS	Hourly rainfall	54.7
Rain gauge	Auburn 47.313°N, 122.203°W	AUBW1	NWS	Hourly rainfall	31.6
Rain gauge	Big Soos Creek 47.313°N, 122.164°W	BSKW1	NWS	Hourly rainfall	28.7
Rain gauge	Lake Walker 47.264°N, 121.909°W	N/A	NWS	Hourly rainfall	9.3
Mobile ARO	Westport 46.910°N, 124.110°W	WPT	ESRL/PSD	Hourly updated surface meteorology* (2-min avg), GPS IWV (30-min avg), wind profiles (60-min avg.), 15-min updated S-PROF radar reflectivity and Doppler vertical velocity profiles (30-s avg), and snow level (15-min avg.)	180.5
ARO wind profiler	Spanaway 47.080°N, 122.360°W	SPW	ESRL/PSD	Hourly updated surface meteorology* (2-min avg), GPS IWV (30-min avg), and wind profiles and snow level (60-min avg)	48.5
ARO S-PROF	Ravensdale 47.310°N, 121.850°W	RVD	ESRL/PSD	Hourly updated surface meteorology* (2-min avg), 15-min updated S-PROF radar reflectivity and Doppler vertical velocity profiles (30-s avg), and snow level (15-min avg)	6.0

*Pressure, temperature, relative humidity, wind speed, wind direction, peak gust, and rainfall.

snow-level product has been used extensively by the forecast community for nearly a decade and has "changed the way [the California Nevada River Forecast Center (CNRFC)] does business with respect to snow level forecasting" (A. F. Henkel 2010, personal communication) and has also allowed for unique verification of snow-level forecasts in the region (White et al. 2010). These results led to the development of a low-power, low-cost radar design tailored to this application that is being deployed permanently at 10 key watershed sites in California.

NOAA's Physical Sciences Division (PSD) deployed vertically pointing Doppler radars (Table 1) at three separate sites to measure the snow level in real time. These included a coastal site, Westport (WPT), which PSD had already committed to deploying as part of a coastal atmospheric river observatory (ARO; White et al. 2009) for AR-focused research (see next section), as well as a site near HHD at Ravensdale (RVD) and one in between at Spanaway (SPW; Fig. 5; Table 1). Local forecasters indicated that snow levels along the upper Green River basin would likely often be lower than at the coast due to the influence of "spillover" of cold continental air from east of the Cascades, a hypothesis validated uniquely by this array. An additional application of the S-PROFs deployed at WPT and RVD is to detect cloud and precipitation echoes when the closest two NWS operational Weather Surveillance Radar-1988 Doppler (WSR-88D) radars [Next Generation Weather Radar (NEXRAD)] at Portland and Seattle (Fig. 5) are incapable of properly representing conditions at the surface: for example, in virga, during shallow rain, or through brightband contamination (White et al. 2003; Neiman et al. 2005; Kingsmill et al. 2006; Yuter et al. 2006; Williams et al. 2007; Martner et al. 2008; Jankov et al. 2009). These sampling limitations are key causes of the NEXRAD-based QPE errors documented by Westrick et al. (1999). Figure 6 illustrates the S-PROF's ability to monitor snow level in real time during precipitation and the challenge of monitoring shallow nonbrightband rain (White et al. 2003) using scanning radar data from the Portland NEXRAD. Note that, in this case, even after the high-altitude radar echo disappeared and the low-altitude echo and fall velocities decreased significantly by 2000 UTC, the surface rain rate remained nearly steady, a result of the preponderance of small drops that existed in the feeder cloud after the seeder cloud aloft had moved away (Martner et al. 2008).

During the winter of 2010/11, the NWS Western Region Office was conducting a snow-level forecast evaluation project. The snow-level product available from the Earth System Research Laboratory (ESRL)/PSD's vertically pointing radars provided the primary source of verification data for NWS snow-level forecasts.

ATMOSPHERIC RIVER OBSERVATORIES AND A REAL-TIME WATER VAPOR FLUX TOOL. Before becoming aware of the HHD crisis, PSD had already planned to extend its AR research effort to the Washington coast for the
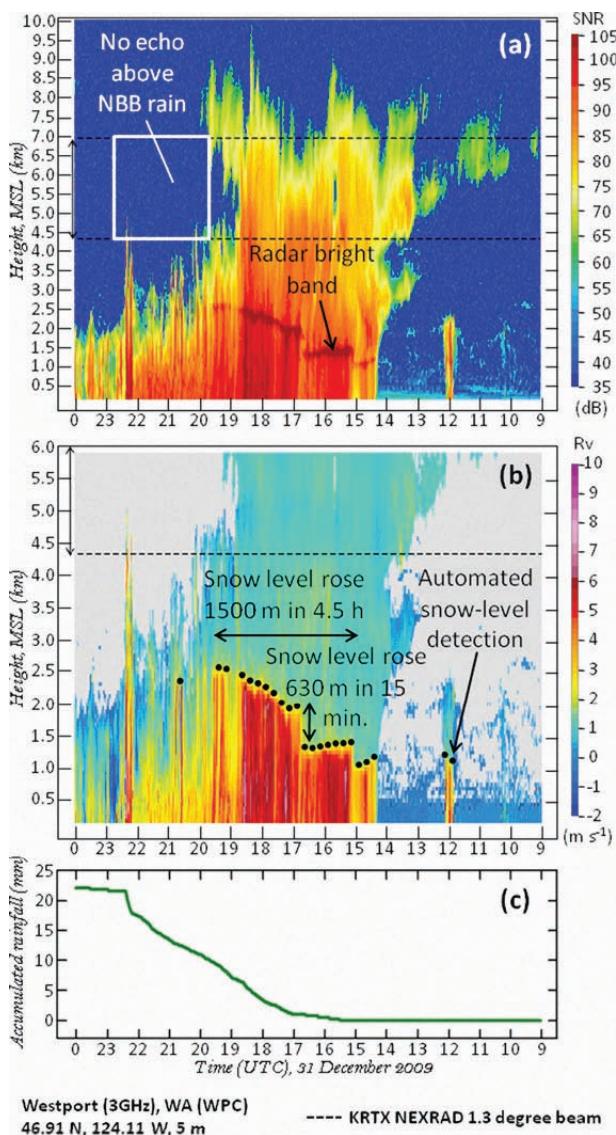

FIG. 6. Example data displays of (a) S-PROF uncalibrated radar reflectivity (dB), (b) S-PROF Doppler vertical velocity (m s⁻¹; positive downward) with the derived snow level indicated by the black dots, and (c) surface rainfall accumulation (mm) measured with a tipping bucket rain gauge collocated with the S-PROF. The S-PROF displays include the position (horizontal dashed lines) of the lowest useable beam tilt from the Portland, Oregon, WSR-88D (NEXRAD).
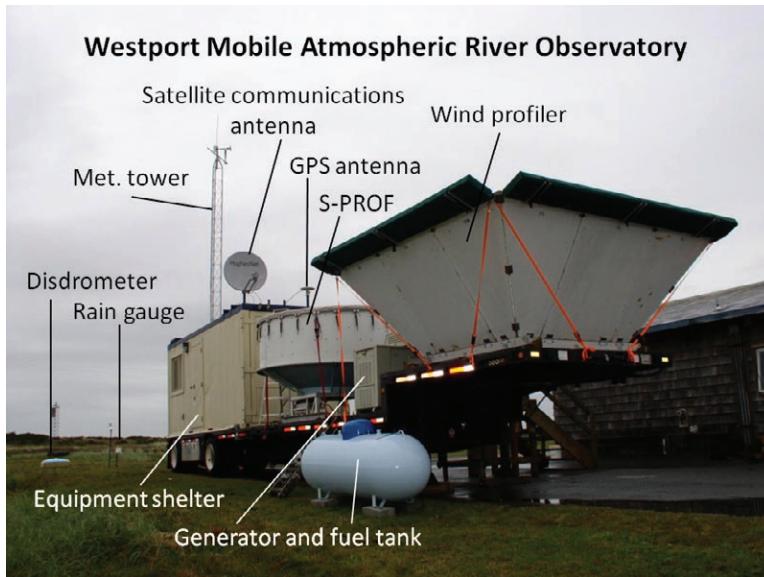
Fig. 7. The mobile atmospheric river observatory operated by PSD at Westport, Washington, during the winter of 2009/10.

winter of 2009/10. When the HHD crisis emerged, it was thus possible to rapidly deploy a new mobile ARO (Fig. 7; White et al. 2009) to the coast at WPT and then another ARO couplet to SPW, closer to the Green River (Fig. 5; Table 1). Also, the existing wind profiler at Seattle (SEA) was supplemented with a GPS receiver, which provided measurements of integrated water vapor (IWV; Bevis et al. 1992; Duan et al. 1996), to create a partial ARO at SEA. The domain of the deterministic mesoscale numerical forecast model generated for HMT in California (described in "HMT's high-resolution rapid-refresh model" section) was extended to include Washington.

The actual "up/down" time for the ARO instruments during the 2009/10 field deployment is listed in Table 2. Given that the instruments operated in an unattended mode, the up time for most of the instruments was good. There was a roughly 16-day outage associated with instrument failure of the wind profiler in the Westport ARO. All other real-time outages were caused by data communication failures. In these cases, the data were backfilled on the ESRL/PSD data server once communications were reestablished.

One of the real-time displays from an ARO is referred to as the water vapor flux tool and is available to the public (www.esrl.noaa.gov/psd/data/obs/). It uses thresholds for IWV, upslope wind, and bulk IWV flux that identify AR conditions (Neiman et al. 2002, 2009; Ralph et al. 2004, 2006). Neiman et al. (2009) showed that, in order to produce orographic rain rates > 10 mm h^{-1} in California's coastal mountains, an IWV flux exceeding 25 cm m s^{-1} is required. An example from the WPT ARO recorded on 11–12 January 2010, when a well-defined AR impacted Washington, is provided in Fig. 8. The 48-h total observed rainfall, starting at 0000 UTC 11 January, was 85 mm at WPT and 136 mm at Humptulips in the Olympic Mountains. The HMT forecast model predicted the AR forcing (upslope flow, water vapor, and snow level) particularly well, although the rainfall was poorly represented for this particular case.

TABLE 2. Operating performance of the instruments in the two ESRL/PSD ARO deployments and the display of the Seattle cooperative agency wind profiler on the ESRL/PSD Internet site.

Site	Instrument	Start date	End date	Operating days	Operating hours	Down hours	Up time (%)
Westport	Wind profiler	1 Nov 2009	1 Apr 2010	152	3,648	410*	88.8
Westport	S-PROF	1 Nov 2009	1 Apr 2010	152	3,648	6.25	99.8
Spanaway	Wind profiler	21 Nov 2009	1 Apr 2010	132	3,168	24	99.2
Ravensdale	S-PROF	10 Dec 2009	1 Apr 2010	113	2,712	338**	87.5
Seattle	Wind profiler	12 Nov 2009	21 Mar 2010	129	3,096	252	91.9

*Note that 16 out of 17 down days for Westport wind profiler were due to instrument failure. All other reported ARO data outages were caused by data communications failures. In these cases, the ARO data were later backfilled once communications were reestablished.

**Two extended outages in Dec 2009 and Jan 2010 were caused by satellite communications failures that required on-site service from the commercial satellite communications provider. Once satellite communications were reestablished, the data were backfilled on ESRL/PSD's data server.

A primary determinant of whether a storm will produce heavy rain in the GRV is the wind direction. This has been illustrated by a flooding event in California where wind profilers documented a dividing streamline that defined the boundary of rain shadowing downwind of coastal mountains (Ralph et al. 2003). The regional geography of western Washington suggests that ARs within only a narrow range of wind directions are able to penetrate to the GRV without encountering mountains upwind of the GRV. Figure 5 shows this wedge of low-altitude wind directions (255°–275°) for which strong AR conditions would place GRV at the highest risk of heavy rainfall. Thus, the coastal ARO at WPT was well positioned to observe key AR conditions that could later impact HHD (IWV, low-altitude wind speed and direction, and snow level). For example, the case in Fig. 8 contains south-southwesterly winds in the controlling layer, and thus the event was not a high risk for the GRV.

New QPF products and numerical modeling. Although the new observations enabled better monitoring of conditions over the watershed and upwind at the coast, which helped with evaluation of how well short-term forecasts were performing, several stakeholders required forecasts with much greater lead time than the observations could provide

directly. Thus, new quantitative precipitation forecast (QPF) products and methods were created, and regional mesoscale model runs were enhanced.
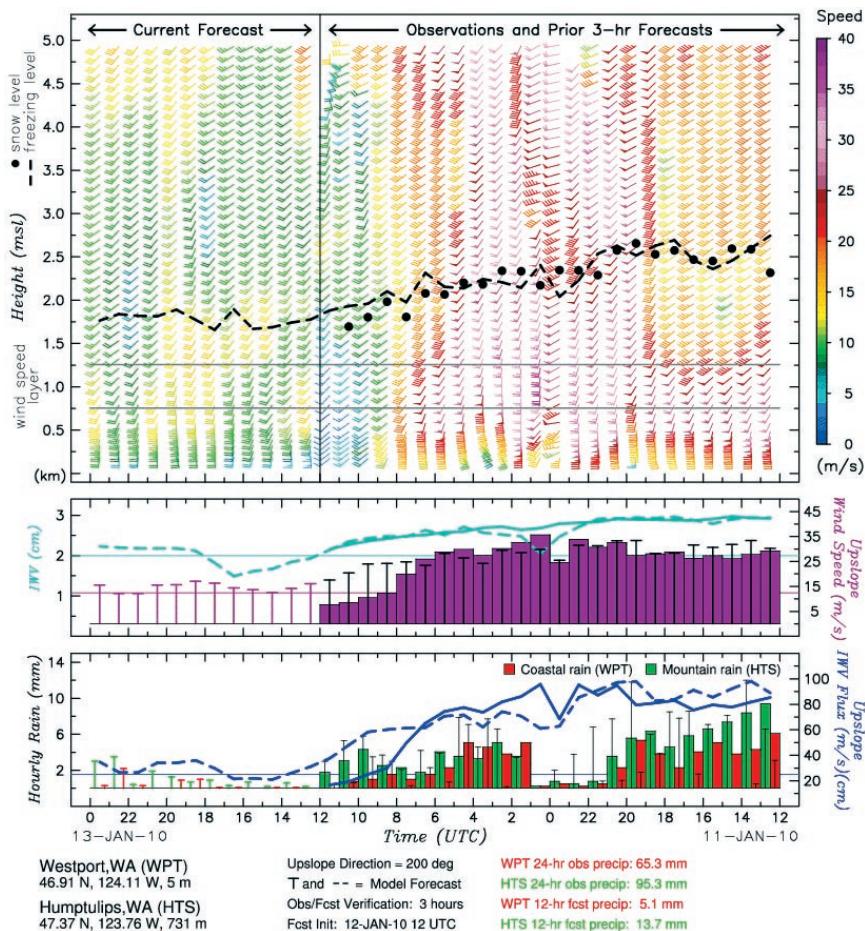

FIG. 8. Example from 11–12 January 2010 of the atmospheric river water vapor flux tool displayed on the Internet (www.esrl.noaa.gov/psd/data/obs/). Time moves from right to left along the horizontal axis. The current time is indicated by the vertical line in the top panel. Data plotted to the left of this line in each panel display the current HMT rapid-refresh mesoscale model forecast only (i.e., no observations), whereas data plotted to the right of the line in each panel are a combination of observations and model output (described next). (top) Wind profiler hourly averaged observations of the snow level (bold dots) and retrospective hourly HMT model forecasts of the freezing level (dashed line) at 3-hr verification time along with time–height section of hourly averaged wind profiles (flags = 25 m s^{-1}; barbs = 5 m s^{-1}; half-barbs = 2.5 m s^{-1} – wind speed color coded) observed by the ARO at Westport. (middle) Time series of hourly averaged upslope flow (m s^{-1}; from 200°) observed (histogram) and predicted (T posts) in the layer between 750 and 1,250 m MSL (bounded by the dashed lines in the top panel), and IWV (cm) observed (solid line) and predicted (dashed line) by the HMT forecast model. (bottom) Time series of hourly averaged IWV flux (m s^{-1} cm) observed (solid line) and predicted (dashed line) by the HMT forecast model, and hourly rainfall histogram from Westport (mm; red) and Humptulips (mm; green), in the Olympic Mountains. Minimum thresholds of upslope flow, IWV, and IWV flux for the potential occurrence of heavy rain (>10 mm h^{-1}) in atmospheric river conditions defined by Neiman et al. (2009) are indicated by the thin horizontal lines in the middle and bottom panels.

EXTENDED RANGE (7-DAY) QPF. Prior to the HHD initiative, the NWS Hydrometeorological Prediction Center (HPC) provided QPF at 6-h intervals through 72 h and a subsequent 48-h QPF, allowing a 5-day total QPF over the continental United States (CONUS). This suite of products is issued in final form bearing initial time stamps of 0000 and 1200 UTC, respectively, for the evening and morning (eastern standard time) deliveries, each completed before those initial times. Because some facilities in the GRV require as much as a 7-day-lead-time warning to optimize preparations for possible flooding, HPC was asked to provide a 7-day total QPF. This was accomplished by adding another 48-h QPF to the product suite, but only for a small area over the Pacific Northwest rather than the entire CONUS. With this addition, HPC extended its QPF coverage to 7 days for the HHD area without additional staffing.

The HPC 7-day forecast is a collaborative effort among three forecasters working at three separate desks focusing on the day-1 QPF, the days-2–3 QPF, and the days-4–7 QPF. In terms of guidance considered by these forecasters, the approach is homogeneous including both NCEP and non-NCEP model output. For the early part of the forecast period, the mesoscale and global model suite is augmented by high-resolution guidance from experimental model runs and a reforecasting technique similar to that described by Hamill et al. (2006). For the West Coast in particular, the standardized anomaly technique (Junker et al. 2009) developed in the HMT is a useful tool for assessing the likely severity of heavy precipitation relative to climatology based on model data. Beyond 3 days, forecasters rely on the NCEP, Environment Canada [Global Environmental Multiscale (GEM) model], and European Center for Medium-Range Weather Forecasts (ECMWF) global ensemble forecasts and their respective higher-resolution control runs. In evaluating this guidance, forecasters examine the Junker et al. (2009) anomalies and may also consider the influences of hemispheric or global signals (e.g., the Madden–Julian oscillation; Bond and Vecchi 2003) that often indicate possibilities for enhanced regional precipitation accumulations.

PROBABILISTIC QPF. Over the past two decades, the Global Ensemble Forecast System (GEFS) has been developed and implemented at NCEP to simulate the effects of initial conditions and model uncertainties on forecast errors (Toth and Kalnay 1993; Tracton and Kalnay 1993). The probabilistic applications and evaluations and the differences between deterministic and ensemble forecasts from the GEFS are presented

by Zhu et al. (2002). The GEFS-based probabilistic quantitative precipitation forecast (PQPF) for different thresholds, out to 16 days, has been generated since 2004 (Zhu 2004, 2005). In response to the HHD project, NCEP's Environmental Modeling Center (EMC) provided real-time daily PQPF for extreme precipitation exceedances of 25.4, 50.8, 101.6, and 152.4 mm, out to 16 days, and updated four times per day (0000, 0600, 1200, and 1800 UTC). This differs from the operational NCEP global ensemble-based PQPF product (www.emc.ncep.noaa.gov/gmb /yzhu/html/PQPF_6h.html), which uses a 6-h forecast period rather than a daily one with smaller precipitation exceedance values.

More recently, HPC has initiated a project to develop experimental PQPFs over the entire CONUS to be issued at 6-h intervals out to 72 h. These PQPFs would be based on a combination of the HPC QPF and ensemble forecasts without additional human input beyond the deterministic QPF itself. To accommodate the HHD project, HPC accelerated development and delivery of the PQPF product suite, ultimately expanding it to include forecast days 4–7 and 24-h accumulation intervals. The requested PQPF products were probabilities of precipitation accumulation exceeding 0.25-, 2.54-, 6.35-, 12.7-, 19.1-, 25.4-, 38.1, 50.8, 63.5-, and 76.2-mm thresholds for the 6-h PQPFs and probabilities of exceeding 101.6- and 152.4-mm thresholds for the 24-h PQPFs.

To provide the 6-h PQPFs beyond day 3, the 48-h HPC QPF amounts are automatically disaggregated into 6-h amounts in proportion to the fractional contribution of each 6-h interval total to the 48-h total found in the GEFS mean QPF, available at 6-h intervals. The 24-h amounts are easily obtained by adding the 6-h amounts, yielding 24-h totals at 6-h intervals through the 7-day forecast period over the HHD region. Once the 6- and 24-h deterministic QPFs are in hand, the parameters of a fitting probability density function (PDF) are computed using information from an ensemble. The PDF is used to compute the probabilities of exceeding thresholds at each point on a grid covering the HHD area. An example of HPC's PQPF product is provided in Fig. 9 for an exceedance threshold of 152.4 mm of rain in 24 h that was determined could generate inflows into HHD that would represent a high level of risk.

HMT'S HIGH-RESOLUTION RAPID-REFRESH MODEL. The weather forecast model used in the real-time water vapor flux tool described above is a rapid-refresh version (3.0) of the Weather Research and Forecasting model (WRF; Skamarock and Klemp 2008). The
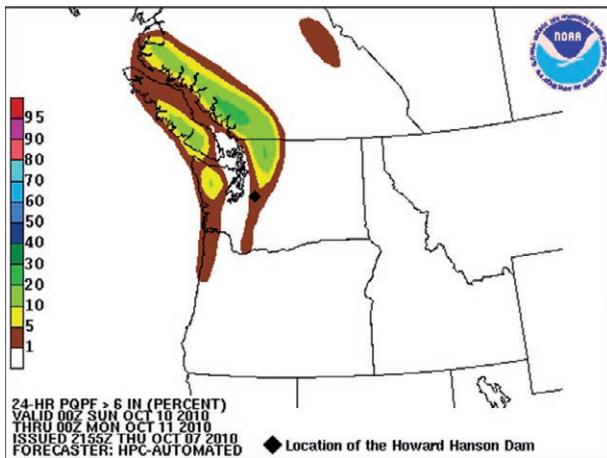
FIG. 9. Example of a new product issued by NCEP (via HPC and EMC) showing the chances of 24-h precipitation exceeding 152.4 mm (6 in.), based on an ensemble of numerical model forecasts. The HHD region is seen to have a 1%–5% chance of rainfall exceeding this threshold.

version employed for HMT by the Global Systems Division (GSD) uses the Advance Research WRF (ARW-WRF) core. The 10-km resolution model integration domain is shown in Fig. 10. The model has 40 vertical levels. Lateral boundary conditions are updated every 3 h using the 12-km North American Mesoscale (NAM) model forecasts generated by NCEP. The selectable physics packages used in the HMT model include the Thompson microphysics scheme (Thompson et al. 2004) and the nonlocal mixing Yonsei University (YSU) planetary boundary layer scheme (Noh et al. 2003). These schemes were chosen based on 5 yr of experience gained in running the ARW-WRF over the western United States for HMT (Jankov et al. 2007, 2009, 2011; Yuan et al. 2008, 2009). This experience allowed for rapid extension of the HMT model to cover the Pacific Northwest and for the water vapor flux tool to be tested in a new environment.

In order to provide hourly model forecasts for the water vapor flux tool, a separate HMT model run is initialized every hour using the Local Analysis and Prediction System (LAPS). LAPS analysis is produced over the same domain and with the same horizontal and vertical grid spacing as the model. By reproducing the analysis every hour, the latest observations, both operational and experimental, are included for the next forecast cycle (Jian et al. 2003). The analysis production starts 20 min after the hour in order to allow the latest data collected during the previous hour to arrive. The updated analysis grid is available 25–26 min after the hour. This new LAPS

analysis is used to initialize the HMT model run and its 12-h forecast. The forecast, along with hourly output, is available approximately 45 min after the hour. Gridpoint data extraction necessary for the water vapor flux tool is done almost instantaneously.

Forecaster and stakeholder training. In November 2009, two scientists from PSD and the meteorologist in charge (MIC) from the San Francisco Bay Area WFO visited the Seattle WFO to learn more about the HHD crisis, provide training on the ARO data and products, and request Seattle WFO staff to provide feedback on their use of the AROs in their daily forecast operations. The meeting was well received by all who attended and was a key step leading to the successful collaboration between NOAA research and operations on this project. For example, because the San Francisco Bay Area MIC had vast experience developing and using HMT data products in daily forecast operations for more than a decade, he was able to explain to Seattle WFO staff the operational value of the Washington ARO deployments, including how the AROs provide situational awareness about atmospheric river forcings and orographic precipitation enhancement, information that is otherwise unavailable in the NWS forecaster toolbox. He also explained that, because these observational tools were being provided by a research agency in an unattended fashion, which made the deployments financially
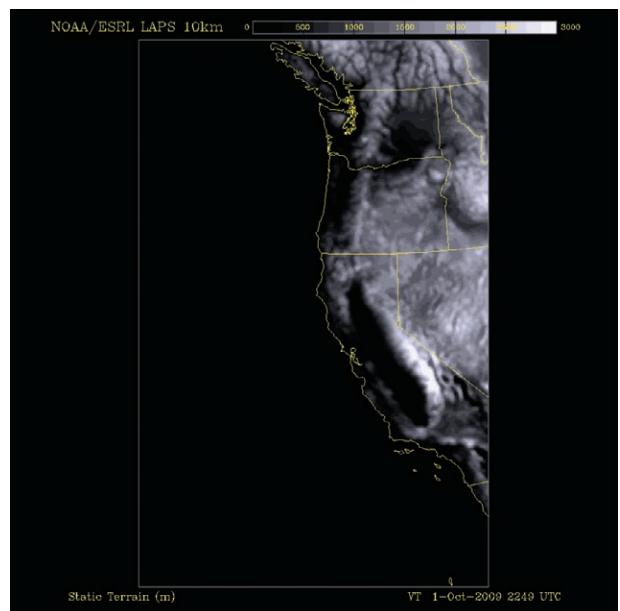

FIG. 10. 10-km domain for the HMT rapid-refresh WRF-based model run used for the water vapor flux tool. Terrain elevation, as represented in the model, is indicted by the grey shading.

feasible, NWS staff should not expect 24/7 operation and maintenance of the ARO instruments.

In addition to internal forecaster training, steps were taken within the larger outreach effort to provide training to stakeholders on the new resources and tools that were being brought to bear for HHD support. This included presentations at trade shows, meetings with local decision makers, and local and regional workshops. Three examples include the 2010 Pacific Northwest Weather Workshop and two 2010 Annual Media and Emergency Management workshops, the latter two being focused specifically on educating local, state, and national emergency managers and decision makers on critical local issues. There were many opportunities through local and national media interviews during actual weather events to highlight and explain the benefits of the new resources. Seattle WFO was also involved in the joint public outreach effort. Some of the key events included two community open houses at the city of Kent's ShoWare Center with a total attendance of 3,500 and the Green River Disaster Preparedness Fair with an attendance of about 1,000.

During most of the field deployment period, the OAR project manager provided weekly (or more often as needed) status reports via email to project personnel on the operation and maintenance of the ARO equipment. On occasion, these reports would include demonstrations of ARO data products, along with a brief discussion of how they might have been used retrospectively, during scientifically interesting storm events.

SYNTHESIS OF SPECIALIZED INPUTS (DATA, MODELS, AND CONCEPTS) INTO FORECASTS AND NEW PRODUCTS. *New forecast products from the NWSRFC and Seattle WF.* In direct response to federal, state, and local partners' requests for maximum lead time on any potential flood event on the Green River (beyond the general target of 72 h for a standard flood potential outlook), the Seattle WFO issued twice-daily macro-level alert forecasts targeting the 3–5-day period. To make these extended outlooks more useful for decision makers, the NWRFC partnered with the USACE to run multiple "what if"

scenarios to determine two precipitation thresholds that correlate with critical inflows into the HHD reservoir (described in "Developing an overall plan to address the HHD crisis" section). The detailed analysis and established thresholds provide the basis for all federal, state, and local partners to begin collaborated discussions regarding an increase in flood threat beyond 3 days. These macro-level alert forecasts were disseminated via email to partners; additionally, a secure website was developed to offer alternative access. Figure 11 illustrates the differing time horizons for forecasts and warnings that emerged from this rapid response effort.

Seattle WFO also added a new discussion section to the area forecast discussion (AFD) dedicated to hydrology and potential flood situations. This section of the AFD was updated four times per day, in contrast to the twice-daily updates traditionally provided by WFOs across the United States, and included an overview of any potential heavy rain threat through 10 days. A specific statement pertaining to the flood potential for the Green River was always included.

Web portal created to provide easy access to key information and new products. Seattle WFO staff created a dedicated tab on their web page that offers a "one stop" portal to all NWS information and forecasts related to the HHD (www.wrh.noaa.gov/sew/hhd .php). This dedicated web page gives users direct
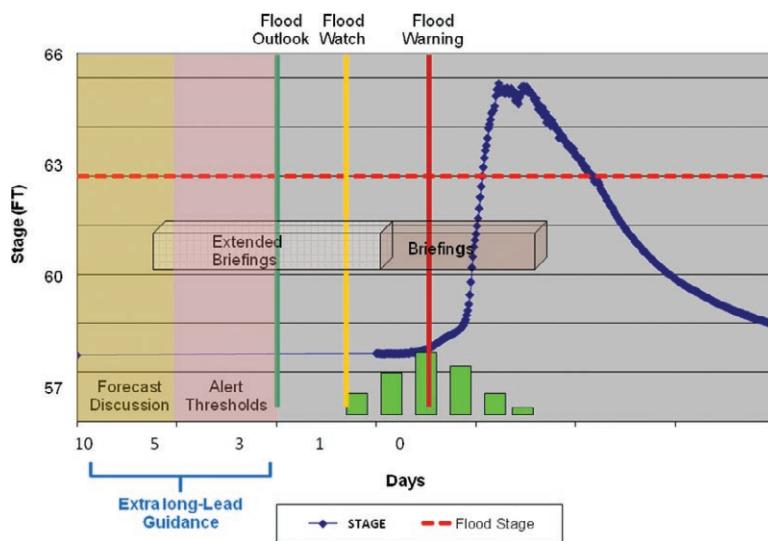

Fig. 11. Schematic overview of the timeline of a hypothetical extreme event, ranging from extra-long-lead guidance (out to 3–10 days), to flood outlook, watch, and warning times and the time frame for special briefings. Hypothetical precipitation (green bars every 6 h), hydrograph (blue curve), and flood stage (dashed red line) are indicated to illustrate the forecast lead times provided by the HHD rapid response efforts.

access to the latest flood-related watches, warnings, and statements; the latest hydrology discussion section from the AFD described above; a hydrograph for the Green River stream gauge at Auburn; and links to observing assets described in the "New observations" section, specialized HPC products described in "New QPF products and numerical modeling" section, NWRFC publicly available forecasts, the blended total precipitable water product displays produced at NCEP and by the Cooperative Institute for Research in the Atmosphere (CIRA), and other pertinent information related to HHD. The NWRFC also created a nonpublic website to share with all key partners their HHD-specific critical observations, modeling, and forecast guidance products.

END USER FEEDBACK FROM THE 2009/10 WINTER SEASON. *Feedback on NWS operational forecasts and services.* The operational forecasts and services provided by the Seattle WFO and NWRFC for the HHD flood risk management crisis were well received by the emergency management community. For example, Jim Mullen, the Washington State Director of Emergency Management, praised the NWS and OAR for providing "maximum service that they could to local and state government response personnel and decision makers." Dr. Dennis Hunsinger, acting regional administrator of FEMA, summed up the overall effort: "This work represents the very best of what can happen when we all work together collaboratively with our partners."

Impact of ARO data products on forecast operations. ESRL/PSD staff used two methods to track if, when, and how data products from the ARO deployments were being used in the Seattle WFO's daily forecast operations. First, the number of times one of the ARO data product displays was accessed by the WFO via the Internet was automatically logged. Unfortunately, this information was not stored for the complete deployment period. This analysis covers the following periods: 24 November–23 December 2009
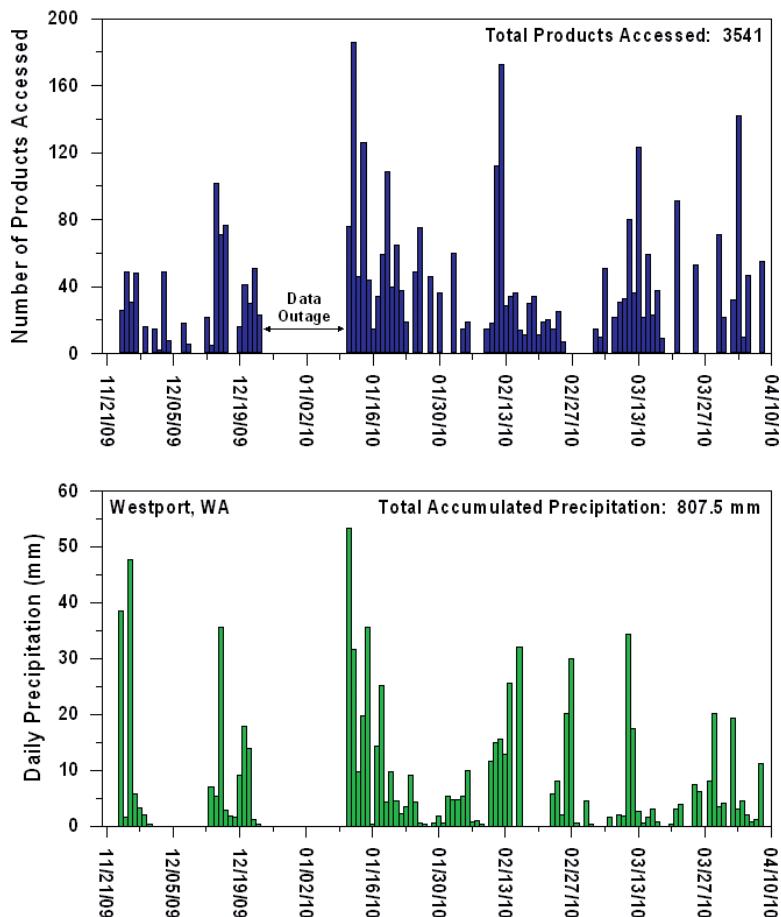

FIG. 12. (a) Histogram of how many times a product from one of the ARO deployments was accessed on the Internet by a staff member from the Seattle WFO each day. (b) Histogram of daily precipitation (mm) measured at Westport.

and 1 January–8 April 2010. During these periods, one of the ARO data products was accessed on 3,541 separate occasions. Figure 12 shows when the products were accessed in relation to storm events. From this analysis, it is clear that the ARO data products were used most often just prior to and during active weather periods.

The second method used by ESRL/PSD staff to evaluate the impact of ARO data products on daily forecast operations relied on the participation of forecasters in the Seattle WFO. During the meeting held at the Seattle WFO in November 2009, ESRL/PSD staff requested that if an ARO observation (including snow level) was used in making a forecast decision, to have the forecaster include that information in the AFD. Although forecasters often rely on several different observing systems and output from multiple numerical forecast models to make their forecast

TABLE 3. Sample excerpts from the 59 individual AFDs written by staff at the Seattle WFO that document forecaster use of one or more of the data products available on the Internet from the ESRL/PSD ARO deployments. PST is Pacific standard time and PDT is Pacific daylight time.

Time and date	Discussion
0300 PST 23 Dec 2009	The layer is not very thick with the tops on the ARO profiler at Westport around 2,000 feet above the bases with the cloud deck thinning the closer one gets to the cascades.
1600 PST 1 Jan 2010	ARO profiler observed from Westport and Spanaway are showing low-level flow southwest around 40 kt, which fits well with the models.
0912 PST 3 Jan 2010	Handy ARO upward profiling radar at Ravensdale shows a nice virga signature coming down to about 11,000 ft., which fits the Sea-Tac observations.
1540 PST 8 Jan 2010	The air mass in general remains warm with ARO data showing the snow level still up around 7,500 ft. this afternoon.
0340 PDT 29 Mar 2010	The ARO observations at Westport support the potential flood problem for the Skokomish River. Profiler is showing winds near 65 kt in the sweet spot between 2,500 and 4,000 ft.

decisions, this was one way to gauge whether the new observational products provided by AROs were useful. During the ARO operating periods, ESRL/PSD staff logged each AFD. After the experiment, the AFDs were analyzed using text recognition tools. Forecasters specifically mentioned one of the ARO data products in 59 separate AFDs. Excerpts from five of these are shown in Table 3 to illustrate the variety of forecast applications for which the ARO data products were used. Figure 13 gives the relative frequency of the meteorological applications for which the ARO products were quoted in the 59 AFDs.

Independent feedback on ARO impacts came from Larry Schick, meteorologist with the USACE in Seattle. With regard to a mid-January 2010 storm event, Mr. Schick said, "We were right on the edge of taking over Wynoochee Dam today for flood risk management, but we had high confidence we did not need to with the ARO info that the rain would taper off quickly—and it did."

After the field deployment ended, the meteorologist in charge from the Seattle WFO and the OAR project manager were asked to provide feedback to NWS headquarters from the point of view of their respective organizations on the value of specific components of the overall HHD project for not only the field season that had recently ended but also looking forward to the 2010/11 field season. The responses that NWS headquarters received from this exercise are summarized in Table 4. In general, the feedback was positive about the new observations, models, and guidance products provided by NOAA/NWS and NOAA/OAR to assist with hydrometeorological

forecasts concerning the GRV. Naturally, some of these were thought to be more useful than others. This feedback also helped prioritize activities to be carried out for the 2010/11 winter season (see "Future work" section).

DISCUSSION AND SUMMARY. Staff across NWS and OAR collaborated successfully to quickly organize, develop, and implement wide ranging and comprehensive mitigation efforts in order to support the federal, state, and local groups involved with mitigating the HHD flood risk management crisis. This involved six NWS offices or centers (Seattle WFO, NWRFC, NCEP/HPC, NCEP/EMC, OHD, and Western Region Headquarters), two OAR divisions (PSD and GSD), and two standing cross-organizational efforts (HMT and the "NOAA-West collaboration team"). The immediate impacts of this work were 1) to allow the NWS to provide much improved flood watch and warnings for the GRV; 2) to improve and strengthen the ties between NOAA and key stakeholders and recognition for NOAA's capabilities; 3) to demonstrate the responsiveness of NOAA to the
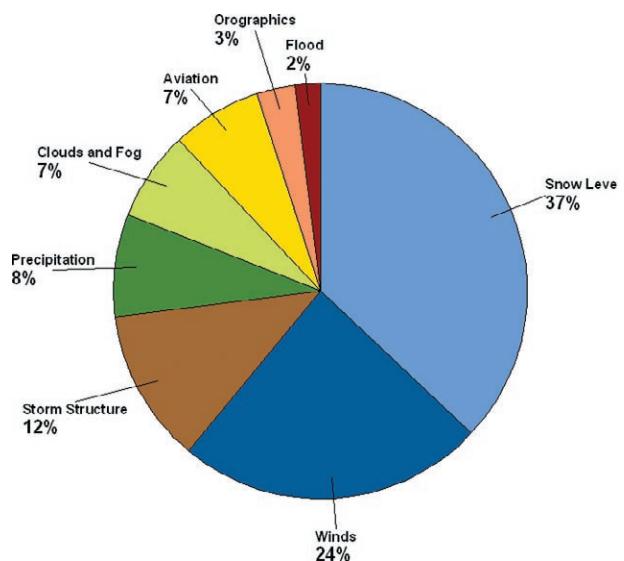
FIG. 13. Weather forecast applications for which ARO data products were quoted in 59 individual AFDs issued by the Seattle WFO.

TABLE 4. Responses from SEA WFO and ESRL/PSD staff on the value of specific components of the overall HHD project. Evaluation scores are as follows: 3 = very valuable, 2 = valuable, 1 = useful but not critical, and 0 = not useful.

New tools, equipment, methods	WFO forecasting value from 2009/10 winter	WFO forecasting value for next winter	ESRL/PSD research value for 2009/10 winter	ESRL/PSD research value for next winter	WFO Notes
High-resolution rapid-refresh modeling (10-km grid size)	1	2	2	2	We probably did not give this a good chance. We only had web access and that always compromises model data for a NWS forecaster on the Advanced Weather Interactive Processing System (AWIPS), especially because we have several different 12-km simulations. For next year, assuming we can get it into AWIPS, I would envision it being more valuable.
NCEP model ensembles	3	3	—	2	The ensemble guidance was particularly important because the derived guidance was customized to our critical precipitation thresholds. We used the data extensively in creating our trigger threshold forecast product twice daily.
New rain gauges	3	3	1	2	The winter was rather benign, so the data were not used to the extent they would be if there were an event. Nonetheless they were used for general day-to-day situational awareness. Also, I believe the NWRFC would place their value very high given several are old calibration locations.
Ravensdale S-PROF and surface meteorology	3	3	3	3	This radar was used frequently throughout the winter to pin down the free atmosphere snow level for general forecast purposes.
Spanaway wind profiler and surface meteorology	2	2	3	2	Used frequently for general forecast purposes. We ranked it slightly below the S-PROF simply because of proximity considerations. The other important point is that, because we never had a heavy precipitation event, we never got to see their potential value in that kind of a situation. Therefore, it is somewhat untested.
Westport ARO	2	2	3	3	Used frequently for general forecast purposes. Regarding HHD, it is simply due to proximity considerations.
IWV flux tool at Westport	2	2	3	3	Interesting, but again, given the lack of events, its full potential is probably not recognized.
IWV flux tool at Spanaway	2	2	3	2	Interesting, but again, given the lack of events, its full potential is probably not recognized.
Seattle wind profiler display on HMT web page	1	1	2	1	Used frequently for general forecast purposes; display format greatly improved data value. It is not so important for HHD given location.
Training at WFO on new tools, methods	3	3	3	1	Very important given the new and unique datasets.
NCEP tools	3	3	2	2	Critical to our ability to extend our forecast confidence to greater lead times and to get quantitative guidance for specific thresholds.
ALPS workstation	0	3	1	2	Did not get set up for real-time use. High potential from what we know.
Other (additional AWIPS workstation from western region)	3	3	—	—	Rather simple, but this additional workstation is (will be) important for any major flood event, especially to maintain the extra staffing for HHD.

Washington Congressional delegation by showing a rapid and coordinated response to provide enhanced services for their constituents; and 4) to reduce the high level of concern in the local communities in the GRV. Although the seasonal rainfall was near normal for the Seattle area, the synoptic pattern was for the most part progressive, which prevented any storms from stalling over western Washington and the GRV. In addition, the orientation of the storms generally produced southerly component flow while ARs were present rather than more zonally directed flow, which prevented a sustained and unimpeded orographic fetch into the GRV.

The effort surrounding the HHD flood risk management crisis also resulted in a major advancement in NOAA customer service. Many customers were involved, including 1) USACE, 2) Washington state officials involved in public safety, 3) Washington county officials involved in the emergency management community, 4) the Washington media including TV, radio, and newsprint, 5) businesses, commerce, and general public in the GRV, and 6) the Washington state Congressional delegation. These customer groups were served by being much better prepared and knowing that an emergency action plan was put into place for early warning.

Insufficient time has passed since the winter of 2009/10 to allow research findings from the OAR observation and modeling activities to come to full fruition. A couple of early results are worth noting. First, as HMT has demonstrated in California, it is clear that atmospheric rivers play a key role in generating heavy wintertime precipitation and flooding in western Washington. In fact, a recent study by Neiman et al. (2011) reviewed the flooding history of four western Washington watersheds over the past 12 yr and found that 46 out of 48 flood events were associated with atmospheric rivers. Second, HMT research has shown that a shallow, warm rain process accounts, on average over 10 winter seasons, for about one-third of the total seasonal rainfall observed in the coastal mountains north of San Francisco. This shallow rain is significant because often it is undetected by NEXRAD. PSD staff recently completed a similar analysis for the two S-PROF sites operating during the 2009/10 winter season in western Washington. Both the coastal site at Westport and the inland site at RVD exhibited a significantly smaller contribution from this shallow, warm rain process than farther south in coastal California. The reason for this behavior is as of yet unclear, but it may be related to large-scale upward motion being more common and widespread in western Washington, resulting in an abundance of

deeper precipitating clouds involving both ice and liquid water processes. One surprising observation was the high frequency of multiple brightband events (Martner et al. 2007) near the GRV using the S-PROF at RVD. This behavior implies that forecasting the difference between snow and rain in the GRV (and hence runoff) is highly sensitive to errors of even 1°C in temperature forecasts for the lower atmosphere above that basin.

FUTURE WORK. *USACE plans for further improvements to the HHD.* The USACE has determined that additional improvements are required to restore the HHD to a safe condition and to provide full flood storage capacity for the GRV. This work will include the installation of additional filtered drains in the right abutment and improvements to and extension of the existing drainage tunnel. Along with these improvements, the USACE is pursuing additional projects to increase confidence that the dam can safely operate during extreme flood events. These measures include the following:

- installation of additional log booms to prevent debris from blocking the spillway;
- improvements to the spillway to allow improved flow passage;
- further stabilizing the spillway by improving how it is anchored to bedrock; and
- placing rock in key places along the upstream face of the dam to protect it against erosion from fast-moving water in the event the spillway is used.

The repair work could begin during the winter of 2010/11 if federal funding arrives. The USACE also stresses that the return to full operational capacity of HHD, in addition to a functioning levee system downstream, does not eliminate all risks of flooding.

Winter 2010/11 ARO deployments. Based on the positive feedback provided by the Seattle WFO staff, as documented by the archive of their daily area forecast discussions, as well as the overall favorable impressions of the value of the observing equipment (see Tables 3, 4), the ARO at WPT was reinstalled for the 2010/11 winter season in mid-October 2010. Concurrently, the S-PROF radar and surface meteorology tower were reinstalled at RVD, closer to the HHD.

All of the new tools, products, and services employed by the NWS to inform the public about the potential for flooding in the GRV have been in place

and tested during the winter of 2009/10 and were extremely useful again during the winter of 2010/11. Furthermore, because the USACE has been forthcoming with information about HHD improvements and how the dam will be operated over the next several years, the public should be adequately informed and prepared, avoiding the widespread anxiety felt by residents, business owners, and local officials that occurred after the crisis emerged in early 2009.

Longer-term implications. The snow level is a major determinant of streamflow in the mountains of the region, second only to precipitation amount. Although the NWS tracks QPF forecast performance using 25.4-mm rainfall in 24 h with one-day lead time as the measure, clearly such events are not the ones of most importance in addressing the HHD crisis. Alternative verification approaches have been developed that instead focus on extreme precipitation and were developed based on HMT experience in West Coast storms (Ralph et al. 2010). In terms of snow level, there is currently no formal forecast performance measure, but, as noted earlier, the snow-level measurements now available from AROs and S-PROF radars are providing a feasible method for verification (Lundquist et al. 2008), and initial evaluations of forecast performance have been demonstrated by White et al. (2010). These new strategies for evaluating forecasts of snow level and extreme precipitation are being considered for formal implementation.

Finally, Washington State will soon have a powerful new scanning weather radar in place near the state's western coast, in the form of a NEXRAD radar being deployed by NWS (Fig. 5). This will enable detection of upper-level radar echoes well offshore of the radar, lower-altitude echoes near the radar, and a broad area-averaged wind profile when precipitation is present. It will also enhance real-time precipitation estimates near the radar, albeit with limitations due to sampling altitudes evident with existing NEXRAD radars. A major strength of the new scanning radar will be its use of polarimetric methods to enhance rainfall estimates and likely implementation of better precipitation estimation algorithms tailored for the region based partly on research findings from HMT. More widespread implementation of the type of rapid response efforts provided for HHD combined with the NEXRAD system will result in greatly improved monitoring and forecast capabilities for winter storms and their impacts and will advance WFO and RFC efforts to provide the public with flood risk information and warnings for protecting lives and property.

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