OLYMPEX
Implementation Plan

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1. OLYMPEX: A COMPREHENSIVE GROUND-VALIDATION CAMPAIGN – GOALS AND OVERVIEW

The primary objective of the Global Precipitation Mission (GPM) is to measure rain and snow globally especially in areas lacking surface observations or ground-based radar coverage. In order to achieve this goal, the GPM constellation of satellites must be able to detect solid and liquid precipitation over a wide range of intensities (from 0.2 mm/hr to 110 mm/hr), a wide range of locations (from ocean to complex terrain), and a wide range of regimes (light snowfall to intense convection). The core satellite of GPM is scheduled for launch in early 2014 and will be instrumented with a passive microwave radiometer, the GPM Microwave Imager (GMI) and the first space-borne Ku/Ka band Dual Frequency Precipitation Radar (DPR). To satisfy the GPM measurement requirements and to assess how remotely sensed measurements of precipitation can be applied to a range of data applications (e.g. determining storm structures, monitoring flooding events and droughts) ground validation (GV) field campaigns are vital. We describe herein a comprehensive ground validation Experiment (OLYMPEX) for GPM to be conducted in Washington State during the 2016 water year, (November 2015 - February 2016) and which will address a wide range of GV needs.

The Olympic Peninsula is an ideal location to conduct a GV campaign for GPM. It is situated within an active mid-latitude winter storm track in the northwest corner of Washington State. It reliably receives among the highest annual precipitation amounts in North America ranging from over 2500 mm on the coast to about 4000 mm in the mountainous interior. In one compact area, the Olympic peninsula ranges from ocean to coast to land to mountains, where the terrain height ranges from sea-level to elevations over 2000m in a distance of approximately 50 km. This unique venue is of an ideal size for a field campaign involving aircraft, radars, and other ground-based sensors. OLYMPEX will be able to monitor the storm characteristics and processes over the ocean, their modification over complex terrain, and the resulting hydrologic impacts. OLYMPEX is ideally suited to quantify the accuracy and sources of variability and uncertainty inherent to GPM measurements in such a varied region.

OLYMPEX simultaneously addresses several basic GPM goals:

- Physical validation of the precipitation (rain and snow) algorithms for both the GMI and DPR.
- How precipitation mechanisms in midlatitude frontal systems and their modification by terrain affect GPM rainfall estimation uncertainties.
- Quantifying the accuracy and uncertainty of the GPM precipitation data and its hydrologic applicability.
- Merging numerical modeling and satellite observations to optimize precipitation estimation in hybrid monitoring systems of the future.

Specific goals under these broad categories are listed in Table 1.

To address the broad focus of OLYMPEX, the ground validation program will need to include accurate measurements of all aspects of the hydrological cycle on a range of spatial and temporal scales. Specifically, OLYMPEX will need to monitor the following quantities:

- Seasonal accumulation of the snowpack (in terms of snow water equivalent, or SWE) over the higher terrain, and its variability in the rain/snow transition zone
- The storm-by-storm liquid and frozen precipitation at multiple sites over the coast, the lowlands, foothills, and mountains
- The upstream meteorological conditions over the Pacific Ocean.
- Brightband variability in height and over ocean, coastal, and mountain surfaces
- Microphysical properties within all sectors of midlatitude storms, before and after their passage over complex terrain
- Emissivity of a variety of surfaces including the ocean, coastal lowlands, forest and snow-covered mountains.
- River response and runoff.

These requirements can be met with a multi-faceted approach to the observational assets. OLYMPEX will include:

- Surface precipitation gauge networks and snowpack monitoring instrumentation
- Accurate surface measurements of falling liquid and solid precipitation using a combination of radar and gauge instruments
- Disdrometer networks to measure microphysical properties of falling hydrometeors
- A suite of scanning, dual-polarization, and vertically pointing surface-based radars
- Satellite-simulator and microphysical measurements from aircraft
- Streamflow monitoring
- Use of numerical modeling tuned with ground-based data to estimate microphysical properties of precipitation and SWE of accumulated snow on the ground for the more remote areas where it is difficult to obtain direct surface measurements.

Through this combination of surface-based instrumentation, snowpack monitoring strategies, multi-frequency radars, aircraft satellite simulators, aircraft and surface-based microphysical measurements, hydrologic measurements, and numerical model estimates of many of these quantities, OLYMPEX will provide an unprecedented comprehensive picture of the surface and in-cloud microphysical properties and their variability for a wide-range of meteorological and topographic conditions. The following sections will provide details of the physical venue of the Olympic Peninsula, the GV science goals, and the instruments available for the project.

Table 1: Lists of specific science goals for each of the 4 foci of the OLYMPEX project.

Physical Validation	Precipitation in Midlatitude Storms	Hydrology	Modeling
Melting level structure and spatial variability	Sample storms over the ocean with aircraft and radar	Flood applications – monitoring precipitation and runoff in fast response rivers and determining how the satellite can aid in such monitoring	Forecasts of oncoming storms for field operations
Microphysical properties of hydrometeors below/within/above the melting level – PSD, PID	Sample stratiform and convective regimes (pre-frontal and post-frontal) and determine how the precipitation detection and estimation varies from convective to stratiform conditions	Seasonal snow accumulation during cold season and melt-off during warm season (SWE) and whether the satellite can determine the snowfield evolution from space	Use combined atmospheric and land surface modeling with assimilated surface and radar measurements to estimate SWE
Surface emissivity and backscatter cross-section of ocean, coast and complex terrain with variable surfaces including snow and forest cover	Sample storms over land and complex terrain and determine how the precipitation detection and estimation changes from one to the other		Blending model estimates of precipitation with satellite estimates
Snow algorithm physics	Role of processes on different scales (frontogenesis, waves, cold/warm cloud microphysics, embedded convection) and how these processes impact the ability of the satellite to detect precipitation		Use satellite derived precipitation as a data source for data assimilation
Precipitation intensity variability	Vertical variability of microphysical properties and how these profiles affect the ability of the satellite to detect precipitation		Microphysics testbed to aid physical validation via comparison with radar and aircraft measurements
Radar back-scatter cross-section and radiometer brightness temperature variance over complex terrain			
Radar and radiometer retrieval uncertainty due to subpixel variability			

2. THE OLYMPIC PENINSULA

2.1. The Region

The Olympic Peninsula is situated in the northwest corner of Washington State and in the heart of the Pacific midlatitude storm track. A map of the Olympic Peninsula with terrain and several key locations mentioned later in the text is shown in Fig. 1. Much of the interior of the Peninsula is remote and access is limited to trails and unpaved roads that are closed in the winter. The Olympic National Park covers a large portion of the Peninsula, encompassing the high terrain and some sections of the Washington Coast. To the immediate south and east of the National Park, there are wilderness areas administered by the National Forest Service. The Olympic National Forest surrounds most of the National Park and the Quinault Indian Reservation is to the southwest. The ground-based portion of the OLYMPEX field campaign will be conducted within these areas. It will be necessary to obtain permissions and the cooperation of these different groups for the field campaign to be successful. Discussions with all of these groups have begun and are favorable. They will be participants in all upcoming planning activities for OLYMPEX.

The Olympic Peninsula has several major river systems. The hydrologic component of OLYMPEX will focus on two major river basins: the Quinault and the Chehalis. These basins are indicated on Fig. 1. The Chehalis has an upper reach which includes the Wynoochie and Satsop rivers and a lower reach which has its headwaters to the south and east of the Olympic Peninsula. More details concerning these rivers can be found in section 3.2.

2.2. Climatology

From November through May, frequent midlatitude cyclones and their frontal systems make landfall on the Olympic Peninsula. The mean November – February low-level flow is southwesterly (Fig. 2), and it provides ample moisture from the Pacific Ocean. This moisture-laden flow is then lifted over the higher terrain of the Olympic Peninsula, which results in very high annual precipitation amounts owing to the reinforcing combination of frontal and orographic processes. These amounts range from 2500 mm on the coast to well over 4000 mm over the higher terrain (Fig. 3).

The precipitation is not evenly distributed over the year. Monthly average precipitation is highest during the months of November, December and January at all stations on the Peninsula. The monthly average precipitation and variance for the co-op observing station, Clearwater (on the coast, see Fig. 1) is shown in Fig. 4. On average, November, December and January are the rainiest months at this site with monthly average precipitation over 16.5” (420 mm). However, there is a lot of variability in the monthly precipitation in the winter months. For example, the monthly precipitation in November has been as little as 3.65” (92.5 mm in 1936) or as much as 30”(726 mm in 2006 and 2009). The probability of measurable rain on the coast at Clearwater (i.e. daily precipitation > 0.01 “ or 0.4 mm) on any given day during November, December or January is 73% and the probability of receiving moderate rainfall (>0.5”) on any given day during this same period

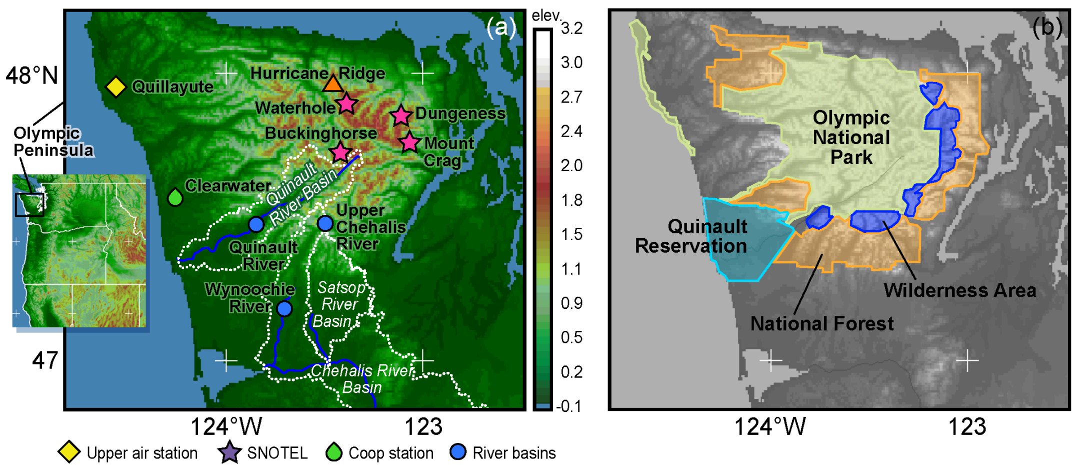

Figure 1: The Olympic Peninsula with terrain. (a) The Quinault, Satsop, and Upper Chehalis river basins are indicated along with the upper air station at Quillayute (yellow diamond), SNOTEL sites (pink stars), and the coop surface station at Clearwater (green teardrop). (b) The boundaries of the Olympic National Park, the Quinault Reservation and the National Forest Service Wilderness Areas and Olympic National Forest.

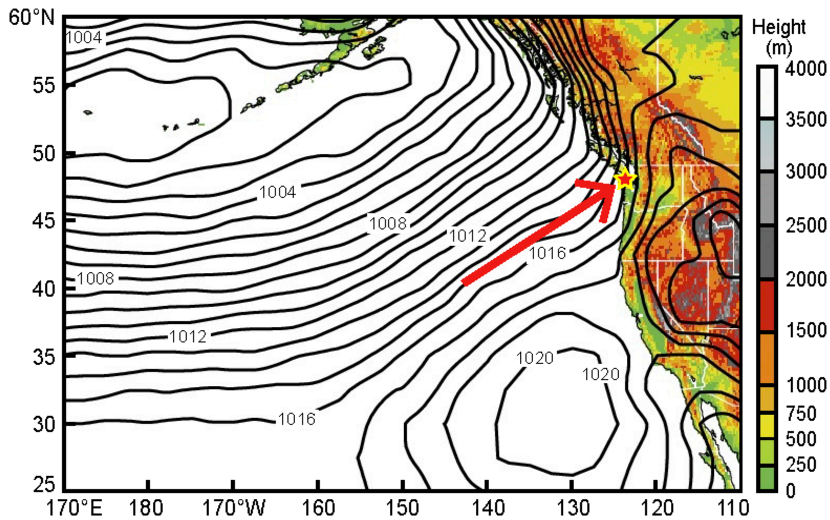

Figure 2: Long-term mean sea level pressure for the period November – February from reanalysis data (1979 – 2012). Star indicates location of Olympic Peninsula and arrow highlights the direction of low-level flow.

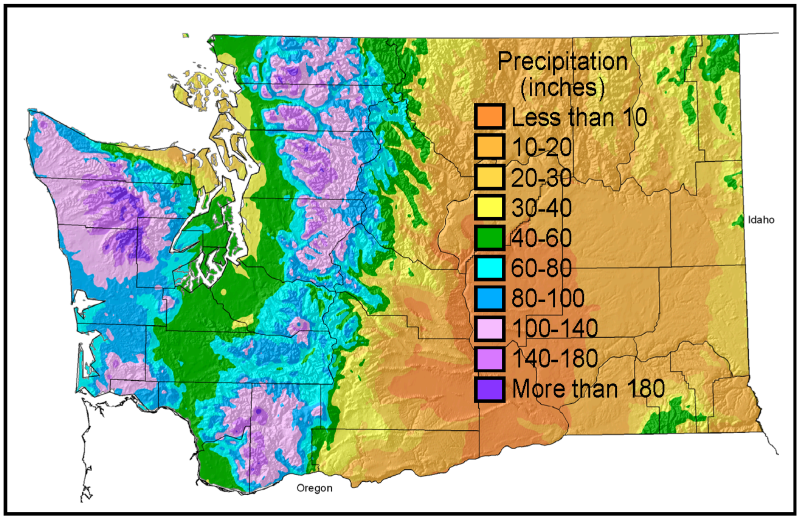

Figure 3: Annual average precipitation in inches from the Parameter-elevation Regressions on Independent Slopes Model(PRISM). The Olympic Peninsula has 100" or more of precipitation annually.

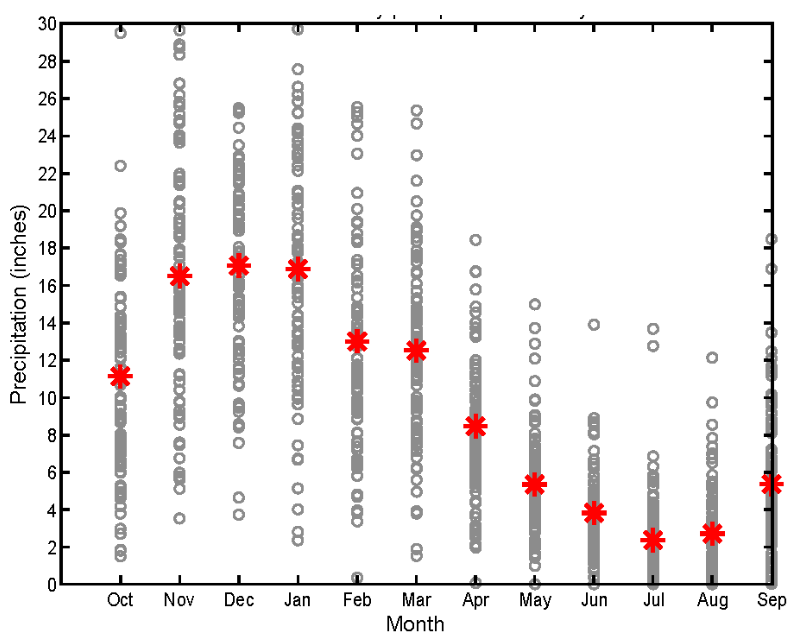

Figure 4: Average monthly precipitation and variance at Clearwater (on coast, see Fig. 1). Black circles indicate the monthly precipitation for a particular year and red stars indicate the mean monthly precipitation for that particular month. The number of years of record is 98.

is 36%. Large rainfall amounts (>1") have a 20% chance of occurring on any given day and very high daily rainfall totals (>2") have a 6% chance of occurring on any given day within this same period. Other stations along the coast and along the perimeter of the west and southern sides of the Olympic Mountains experience similar rain-rate probabilities, whereas stations on the northern and eastern flanks of the Olympics have lower annual precipitation and lower rainrate probabilities. Using the daily rainfall data at Clearwater, the longest dry spell, where less than 0.01" of rain fell during the months of November through February, was 18 days during December 1985. However, dry spells of 2 weeks during those four months are extremely rare, where the probability of a 2-week period with less than 0.05" of rain of occurring is less than 1%. Wet spells, on the other hand, are more common during these months. The probability of receiving over 14" of rain within a 2-week period during November – February is over 6%.

Over the higher terrain of the Olympics, precipitation falls frequently as snow. Throughout the winter season, the snow accumulates and is at its peak depth and snow water equivalent (SWE) in early spring. Despite the occasional warm rain event (where the melting level is high) and periods where the temperatures rise above 0°C in the higher terrain, a significant snow pack develops above elevations of 1 km (3000'+). For example, a timeseries of SWE for the water year 2010 obtained at two of the SNOTEL sites shown in Fig. 1 (Waterhole and Buckinghorse, both above 1500m elevation) is given in Fig. 5. At both locations, the peak SWE was over 1300 mm (>50 inches) by mid-April. Both stations experienced rapid snowpack accumulation during the month of November during that particular water year.

Intermediate elevations (e.g., ~300-900 m elevation) fall within the so-called rain-snow transition zone, where the form of precipitation alternates between rain and snow many times during the winter season. Near the upper limit of this zone, snow usually accumulates as SWE, and rain-on-snow events typically result in increases, rather than decreases in SWE, as liquid moisture is stored in the snowpack, and subsequently refrozen when temperatures decrease. Near the lower limit of the rain-snow transition zone, the snowpack often is completely ablated by rainfall events, and re-established during subsequent colder precipitation events. At these elevations, the surface transitions from bare to snow covered many times during the winter season.

Currently, accurate measurements of SWE, snow depth and daily precipitation in the Olympics are only available at 4 SNOTEL sites and 1 Northwest Avalanche site. Monthly estimates of snow depth and SWE are made at a few snow course sites. All of these stations are at fairly high elevation, and there are no measurements in the rain-snow transition zone and even at elevations up to about 1000 m. An important measurement challenge for OLYMPEX will be to document snowfall and snow accumulations at lower elevations and at a variety of locations throughout the peninsula.

Another important aspect of the climatology of the region is the variability of the 0°C isotherm during the winter season. A histogram of the elevation (in km) of the 0°C isotherm at Quillayute (KUIL, on coast, see Fig. 1) for flow that is moist and onshore is shown in Fig. 6. The mean elevation for 0°C isotherm during the winter months is 1.5 km, but it can vary from 0 to 4 km MSL. It varies strongly, both spatially and temporally, within

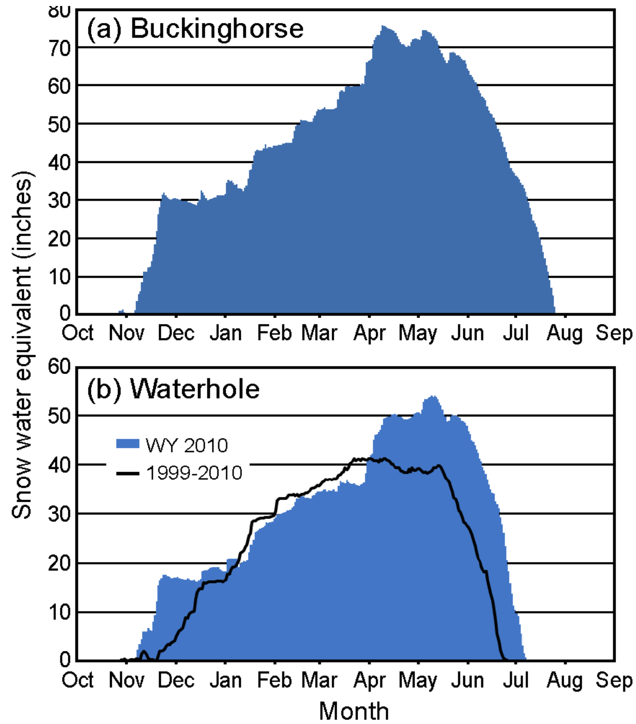

Figure 5: Snow water equivalent (SWE) at (a) Buckinghorse and (b) Waterhole SNOTEL sites for water year 2010. The climatology of SWE for Waterhole is also shown with the heavy black line in (b).

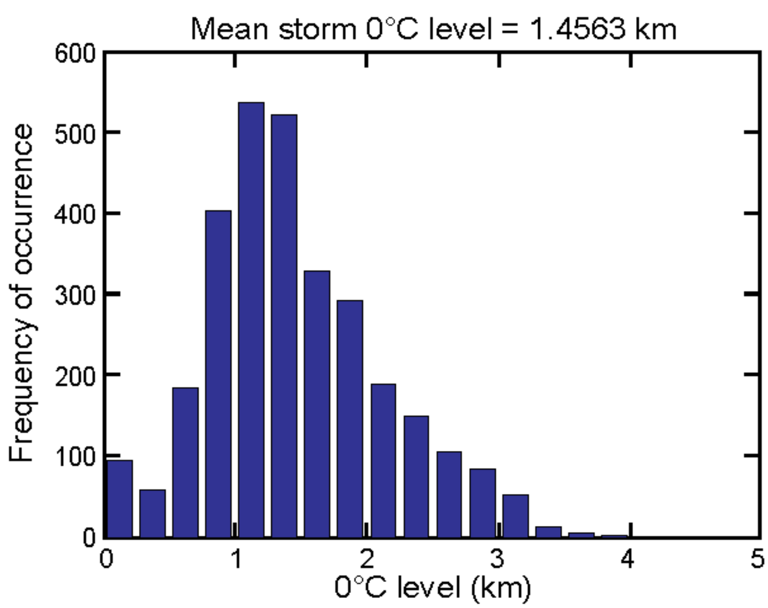

Figure 6: Melting level variability at UIL for flow that is moist and onshore. Mean melting level is 1.5 km.

each storm system impacting the Olympic Mountains. Large variation of the 0°C isotherm height is typical of midlatitude precipitation systems and is a major concern and challenge for GPM algorithms. In addition, significant precipitation may occur without an obvious bright band (Neiman et al. 2005). This fact is one of the major differences between TRMM and GPM algorithms; in TRMM the 0°C isotherm could be taken as constant. For GPM algorithms, the variation in the 0°C isotherm must be taken into account. In midlatitude cyclones, the 0°C isotherm is at higher levels in the pre-frontal, warm advection environment and much lower levels in the post-frontal, cold advection environment. Orographic processes introduce further variability. For example, the melting layer bends downward near sloping terrain (e.g. Medina and Houze 2005; Minder et al. 2011). This variability will be pronounced and therefore useful for testing algorithms in OLYMPEX. It is therefore a high priority for the OLYMPEX observations to determine the spatial and temporal variation of the melting layer (see section 3.1.3).

3. OLYMPEX SCIENCE OBJECTIVES

In this section, we outline how the different observational and modeling assets of the OLYMPEX field study will be used to address the specific scientific components of the GPM GV program. As discussed in section 1.1, these components include: physical validation of algorithms, hydrological applications, orographic precipitation processes and merging of models with satellite estimates of precipitation. An overview of the specific instrumentation, both committed and proposed, and how each instrument will address each science goal listed below is given in Table 2.

3.1 Physical validation component

Accurate algorithms that relate the brightness temperatures measured by GMI and radar reflectivities measured by the DPR to the physical state of the underlying atmosphere and surface need to be developed refined and tested. The primary focus of OLYMPEX is to provide ground-based and airborne observations that can be directly employed to validate specific parameters and assumptions that are crucial components of the microwave and radar algorithms for liquid and frozen precipitation. Details of the different algorithm components are provided below.

3.1.1 Rain algorithm verification and warm microphysics

As stated earlier, the constellation of GPM satellites must accurately retrieve rainfall over a large range of rain rate intensities in convective and stratiform regimes. It is common over the Olympics to experience rain rates that range widely from light drizzle to heavy rain during the fall and winter months. Also, within the midlatitude storm systems that impinge on the Olympics, the nature of the precipitation transitions from predominately stratiform where the 0°C isotherm is relatively high in the prefrontal environment to predominately convective where the 0°C isotherm is relatively low in the postfrontal environment. The middle sector of the storms is a mixture of convective and

Table 2a: Traceability of various ground validation requirements and the committed instruments that will address them.

Available Ground Validation Resources	Physical Validation of Rain and Snow Algorithms				Orographic Enhancement of Precipitation			Hydrology	
Committed Resources	Melting Level Variability	Rain Retrieval	Snow Retrieval	Satellite simulator	Upstream Conds.	Precip Var. with Elevation	Modification of Frontal Processes	Snowpack	Floods
Rain Gauges	X	X				X	X		X
Disdrometer	X	X				X	X		X
Pluvio/Hot Plate	X	X	X			X	X	X	X
Disdrometers	X	X	X			X	X	X	X
SNOTEL			X			X	X	X	X
Time-Lapse Photography	X		X			X	X	X	
Rawinsondes	X	X	X		X				
WSR 88D(S)	X	X	X		X	X	X		X
N-Pol Radar (S)	X	X	X			X	X	X	X
D3R (Ka/Ku)	X	X	X			X	X		
MRR (K)	X	X	X			X			
Atmos River Obs (ARO)	X	X	X		X	X	X		X
NASA DC-8 APR2	X	X	X	X	X	X	X		
NASA DC-8 PMW	X	X	X	X	X	X	X		
UND Citation	X	X	X		X	X	X		X
Model Virtual Snow and Rain	X	X	X		X	X	X	X	X

Table 2b: Traceability of various ground validation requirements and the proposed instruments that will address them.

Available Ground Validation Resources	Physical Validation of Rain and Snow Algorithms				Orographic Enhancement of Precipitation			Hydrology	
Proposed Resources	Melting Level Variabilty	Rain Algorithm	Snow Algorithm	Satellite Simulator	Upstream Conditions dropsonde	Precip Var. with Elev.	Modification of Frontal Processes	Snowpack	Flooding
Rain Gauges – Chehalis		X				X	X		X
Snow Courses			X			X		X	
SNOLITE			X			X	X	X	X
C-band – Rutledge	X	X	X		X	X	X		X
X-band DOW – Yuter, Colle	X	X	X		X	X	X		X
X and W band, McGill	X	X	X		X	X	X	X	
Ka Band – PNNL	X	X	X		X	X	X		
NASA ER-2		X	X	X	X		X		
Global Hawk				X	X				
Wyoming King Air	X	X	X		X	X	X	X	X
PNNL G-1	X	X			X	X			
Canadian NRC Convair	X	X	X		X	X			

stratiform components (Medina et al. 2007). Consequently, OLYMPEX will sample a wide range of precipitation intensities and regimes.

In order to verify the satellite-retrieved precipitation from the GMI and DPR instruments and to improve the algorithms, accurate depiction of the rainfall distribution and several microphysical quantities need to be measured. As listed in Table 2a and 2b, the ground validation of the rainfall distribution will be documented with the standard rain gauge network within the Olympic Peninsula and with the enhanced rain gauge networks in the Quinault and Chehalis river basins. The deployed Pluvio weighing gauges (hereafter referred to as "Pluvios") and hot plates will provide more accurate estimates of precipitation amounts and will supplement the other ground instrumentation. In addition, rain rate estimates can be obtained from the preexisting, committed and proposed scanning and vertically pointed radars.

Under relatively warm conditions, microphysical properties of the falling raindrops will be documented with ground-based and airborne particle sampling and multi-parameter radars. Important properties to measure include drop size distribution and growth of precipitation below the bright band. These observational assets will provide a temporally continuous vertical profile of precipitation processes and rain growth below the bright band and how it varies as storm systems progress through the region.

3.1.2 Ice microphysics

Several recent studies (Skofronick-Jackson et al. 2004, Johnson et al. 2012) have highlighted the need to obtain careful observations of the large-scale environment and detailed in situ measurements of microphysical properties in order to build algorithms to provide frozen precipitation measurements from space. As listed in Table 2, several committed and proposed instruments will be able to directly address this need and provide physical validation of snow algorithms.

The environmental quantities that are crucial for physical validation of snowfall algorithms include profiles of temperature and humidity, ice-water-path (IWP) and liquid-water-path (LWP). Temperature and humidity can be obtained in OLYMPEX by surface-based rawinsondes (both at KUIL and additional ones during the field campaign), and by dropsondes and other in situ aircraft measurements.

Surface measurements of snowfall rates and accumulation throughout the complex terrain of the Olympic Peninsula are critical for algorithm validation, and these measurements will be made with the current SNOTEL sites plus additional estimates of SWE of falling snow and snow depth at several locations and elevations. Direct measurements of falling and accumulated snow will be made by a combination of Pluvio, hot plate instruments (Rasmussen et al. 2011), SNOLITE stations, snow courses, and time-lapse photography and are highlighted in Tables 2a and 2b.

Microphysical measurements are necessary for physical validation of the algorithms. Crucial parameters include: particle size distribution (PSD), particle phase, shape, fall speeds, mass and density, and effective diameter of ice particles. Of the committed instruments highlighted in Table 2, these parameters can be obtained from ground-based video disdrometer, airborne ice particle sampling, and the NPOL, WSR 88D and Atmospheric River Observatory Radars. In addition to these measurements, ancillary instrumentation proposed by various investigators inside and outside of NASA might be deployed in OLYMPEX. Specifically, the state-of-the-art microphysical instruments on the Canadian NRC Convair would provide additional microphysical measurements with the improved particle sampling probes on that particular aircraft. Additional radar coverage of the lowest levels of the precipitating systems by the mobile Doppler On Wheels (DOW) will provide a more complete picture of the hydrometeor distribution, the transition from frozen to liquid precipitation, and if two DOWs are deployed, dual-Doppler measurements of air motions in the precipitating clouds. Both the committed and the proposed observation systems will provide microphysical properties that are crucial for physical validation of the ice microphysics algorithms.

Total precipitation rates, ratios of frozen/liquid precipitation, the types of crystals residing in the cloud systems, and the vertical distribution of temperature and humidity will vary from storm to storm and within each individual storm (i.e. warm pre-frontal sector vs. cold post-frontal sector). The dataset will thus span measurement across the different types of storms and the differing types of sectors within each storm. This variety of measurements will greatly enhance the effectiveness of the dataset for providing excellent physical validation of the snowfall algorithms.

3.1.3 Bright band variability

As described earlier in section 2.2, the vertical location of the bright band, i.e. where falling snow melts into rain near the height of the 0°C isotherm, and its variability are critical for both the GMI and DPR algorithms and will be documented several ways during OLYMPEX. The suite of radar assets will be the primary method of monitoring the bright band variability. The vertically pointing radar of the Atmospheric River Observatory on the coast will sample the bright band upstream of the terrain, and the coastal WSR 88D in surveillance mode and the NPOL radar in RHI mode will document the melting layer's transition over land and complex terrain. The WSR 88D and NPOL radars may have difficulty accurately sampling the brightband when it is relatively low (~1 km or less) over the land due to blockage by the terrain. The D3R and/or additional proposed radars such as DOW and the McGill X and W-band could contribute additional sampling below the blocked regions. In addition, the APR2 on the DC-8 aircraft may provide spatial variations of the bright band. The spatial variability of the bright band from the coast to the mountain slope (where the latter matters for hydrology) can also be monitored with self-recording temperature sensors following methodology similar to Lundquist et al. (2008).

3.1.4 Surface emissivity

It is necessary to have detailed mapping of the surface emissivity for accurate precipitation retrievals. The OLYMPEX venue includes ocean, coast, field, forest and snow covered mountainous terrain. The emissivity is different for all these land surfaces and will be sampled by the DC-8 aircraft during non-precipitating periods. In addition, emissivity can vary with viewing angle and slope of the terrain. These variations will also be documented during OLYMPEX from the aircraft.

3.2 Hydrologic observational component

One of the five primary science objectives of GPM is *Improving hydrological modeling and prediction*, including *evaluating the quality of satellite products in hydrological applications***.** Along the Pacific Coast of North America, all of the flood events on NOAA's list of billion dollar natural disasters were attributable to extreme cold season precipitation. Furthermore, the three costliest natural disasters in the Pacific Northwest were all floods. The December 2007 floods in southwestern Washington shut down Interstate Highway 5, the main traffic artery along the Pacific Coast, for almost a week due to flooding of the Chehalis River, one of the target river basins for OLYMPEX observations. These facts illustrate that OLYMPEX is in an ideal location for studying the impact of GPM on hydrologic observations and forecasting.

Observations to be collected by OLYMPEX will contribute directly to the GPM objective of facilitating better hydrologic forecasting by providing the most complete documentation possible of the precipitation events during the heavy precipitation season in the Northwest. These detailed observations of precipitation and of the storm structures producing them will provide a testbed for determining the ability of GPM to better assess and forecast hydrologic processes and events. Proxy observations by aircraft will mimic GPM observations, and the OLYMPEX observations will be combined with and assimilated into forecast models for calculation of hydrologic quantities.

The Quinault and Chehalis River basins in the OLYMPEX area will provide the basis for hydrological model evaluation and diagnosis under contrasting hydrologic conditions during the late fall and early winter period when most floods occur in the region. The Quinault is strongly affected both by intermediate and high elevations that are snow dominated, as well as a lower transient rain/snow zone. The Chehalis is a much larger basin that is characterized by transient rain/snow and lower elevation, rain dominated portions. The Chehalis in particular is well observed by USGS stream gauges, with 11 active gauges in the basin, all of which are telemetered and provide data in near-real time (see Fig. 7).

3.2.1 Understanding the utility of GPM precipitation products for cold season flood forecasting

As noted above, one of the primary objectives of OLYMPEX is to use the hydrologic observations (combined with atmospheric and hydrologic modeling) to determine the ability of GPM to provide hydrologic inputs that will improve modeling and prediction of runoff and floods, especially in regions with sparse in situ and ground-based radar networks. The OLYMPEX site is located within a hydroclimatic region that is dominated by cold season precipitation. Recent work has shown that almost all major floods in the broader Pacific Coast region of which the Quinault and Chehalis River basins are typical arise from so-called Atmospheric River events (Ralph and Dettinger, 2012). In both river basins, the processes that affect flood generation include: 1) precipitation intensity and duration; 2) antecedent soil moisture and snowpack (the latter mostly at higher elevations, although low elevation snowpack at the onset of the January 2009 Chehalis River flood was a significant contributor); and 3) precipitation patterns relative to the basin's channel geometry, and relative precipitation amounts at high and low elevation.

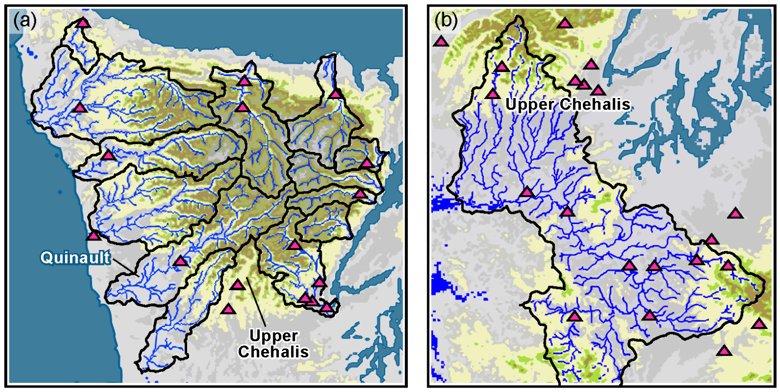

Figure 7: Map of river basins of the Olympic Peninsula and locations of USGS river gauges (red triangles). (a) All the basins of the Olympics, and (b) the full Chehalis (upper and lower portions) river basin.

One of the most important GPM products will be the IMERG precipitation estimates, which will combine DPR radar observations with passive microwave observations from the GMI and microwave instruments on other platforms. IMERG is effectively an outgrowth of the TRMM TMPA products, but will merge other satellite-based products as well. A key consideration is that the IMERG spatial resolution will be about 10 km, so the Chehalis River basin will contain about 70 IMERG grid cells, and major tributaries will mostly contain at least 10 grid cells. Hence, the basin is of a scale at which GPM should be expected to provide useful information for hydrological applications such as flood prediction.

To facilitate evaluation of GPM precipitation products, OLYMPEX will monitor precipitation falling on both the Chehalis and Quinault river basins using a combination of recording and accumulating in situ gauges, the Langley Hill NWS radar, and research radars (see Section 4.1.2). These instruments will further provide insight into the atmospheric processes producing the precipitation, in particular how those process are affected by the passage of frontal systems and their related clouds over a steep mountain range. The ground-based radars deployed in OLYMPEX will be especially valuable in determining the atmospheric processes involved in producing precipitation over the Quinault and Chehalis basins. The hydrologic observations in OLYMPEX will make extensive use of the USGS stream gauge network (see Fig. 7) and the DHSVM hydrological model as well as rain gauges in the region. Dual platform gauges operated and deployed by NASA Wallops will enhance the rain gauge network. The DHSVM model will be used to diagnose the effects of errors in GPM precipitation products over a range of spatial scales.

3.2.2 Snow observations and prediction

While OLYMPEX activities within the Chehalis basin should test the ability of GPM observations to improve hydrologic forecasting over a broad basin with moderate topography, observations within the Quinault basin will serve a somewhat different purpose. The Quinault is much smaller than the Chehalis basin, but more affected—especially in its upper reaches—by accumulated snowpack at higher elevations than those characterizing the Chehalis region. Hydrologic observations in the Quinault basin will be designed to assess how well GPM precipitation products can characterize the form of precipitation, and the prediction of accumulated snowpack in a basin affected strongly by both snowmelt and rain. OLYMPEX observations can serve as a surrogate for other locations with similar climatologies where accumulated winter snowpack is critical for municipal and/or agricultural water supply.

In addition to focusing on the Quinault and Chehalis basins, the hydrology component of OLYMPEX will also address the seasonal accumulation of the snowpack over the entire Olympic Range. One of the most important potential uses of GPM will be to monitor the snowpack accumulation over the world's great mountain ranges. The Olympics are a three-dimensional range rising well above the snow level and accreting a vast snowfield over the course of the winter. While covering a substantial area, the snowfield is not too big for OLYMPEX to thoroughly monitor in a way that can be used to determine if GPM is providing an accurate climatological assessment of snowpack. OLYMPEX will monitor the growth and decay of this snowfield over the cold season through a combination of existing infrastructure, supplemental ground-based measurements, and hydrologic modeling. Routine surface estimates of the snowpack in the area are made by four SNOTEL sites, the Northwest Avalanche Center site at Hurricane Ridge and a few monthly snow course surveys. These observations will be supplemented with other instrumentation or methods of estimating snow pack in OLYMPEX (see section 4.1.3).

It is not feasible to sample the snowpack exhaustively over the entire OLYMPEX domain using surface instruments. Therefore, we will be using a method that combines WRF operational surface products with both the NWS operational snow model and a complex land surface model (NOAH-MP) to estimate the geographical distribution of snow over a winter season. These model-produced estimates will then be compared to measurements at existing SNOTEL sites. The hydrologic data assimilation will exploit small-scale variability as represented by the high resolution WRF output to estimate snowpack where no ground observations are available. Once we have evaluated the snowpack estimates produced using this combination of model and surface observations, we will use the regional fields to compare with SWE estimates produced using the hydrological model forced with GPM-based (e.g., IMERG) precipitation. We will also make use of low-cost, non-invasive methods (namely, digital camera photos of depth markers) that directly monitor seasonal snow accumulation in remote areas. Snow surveys will also be used to provide SWE data over limited areas at specific observing times. These measurements can provide a basis for evaluation of the combined models in locations where no SNOTEL sites exist.

3.3 Orographic enhancement of midlatitude cyclone precipitation component

A variety of changes to storm structure occur when frontal systems encounter mountain ranges (see review of Houze 2012). OLYMPEX offers a unique opportunity to document how these changes to midlatitude cyclone structure impact the ability of GPM to determine the precipitation from the storms. This ability is critical to GPM since much of the Earth's midlatitude precipitation occurs in the vicinity of mountain ranges. OLYMPEX will document changes in storm structure as the systems make landfall and are modified by complex terrain. Monitoring these transitions will test the satellite's ability to measure precipitation in regions where the basic storm structure is modified by passage over the mountainous terrain. The changes in storm structure that occur as frontal systems pass over mountains occur on a wide range of scales, and processes on multiple scales will therefore be monitored to document the structure of each storm system and to test how well the satellite algorithms perform under each circumstance. A list of some of these processes is given in Table 1. They include stratiform vs. convective precipitation regimes, frontogenesis, vertical variability of the brightband, frontal waves, blocking, lifting over terrain, ridge/valley effects, and turbulence. The structures and processes on this range of scales will be monitored by combining the ground-based precipitation and snow gauges, the scanning and vertically pointing radars along the coast and inland, and the aircraft flights over the water and over the terrain. By sampling both offshore with radars and aircraft and over land and higher terrain with ground-based instruments, radar and aircraft, the structure of incoming storms and their modification will be documented.

3.4 Modeling component

High-resolution modeling and data assimilation will play a central role in OLYMPEX. For example, mesoscale numerical weather prediction will be crucial for planning and operations during the field phase of the campaign. Only modeling can provide a detailed description of the seasonal snowpack over the mountain barrier, since many locations are inaccessible. Atmospheric modeling will play an essential role in driving hydrological models for river level and flooding forecasts. Model description of the precipitation and microphysical fields represents the current state-of-the-art of scientific understanding of relevant processes and dynamics, and discrepancies between model estimates and observations reveal where more research is required. Finally, the assimilation of GPM satellite assets into the regional modeling will reveal the ability of GPM satellite information to foster a realistic description of the precipitation and microphysical conditions..

As described in more detail later, OLYMPEX modeling will be mainly done using the community Weather Research and Forecasting (WRF) modeling system. The University of Washington has deep experience with WRF, applying it in both real-time and case study applications. For the former, WRF has been run at high resolution (down to 4 km grid spacing) over Northwest U.S. for 15 years and has been optimized for this region. The UW also runs a high-resolution ensemble Kalman filter (EnKF) data assimilation system using WRF and the DART assimilation infrastructure for use in assimilating regional mesoscale data and making short-term forecasts. These modeling systems will be used during the OLYMPEX project as both prediction and analysis tools. During the OLYMPEX field experiment both current and field program observations will be assimilated.

4. THE OLYMPEX NETWORK—EXISTING RESOURCES AND NEEDED ENHANCEMENTS

4.1 Observational infrastructure

In this section, we will outline the existing and proposed observational assets that will be available or deployed for the OLYMPEX campaign. Fig. 8 presents an overview of the current and proposed locations of the instrumentation for OLYMPEX.

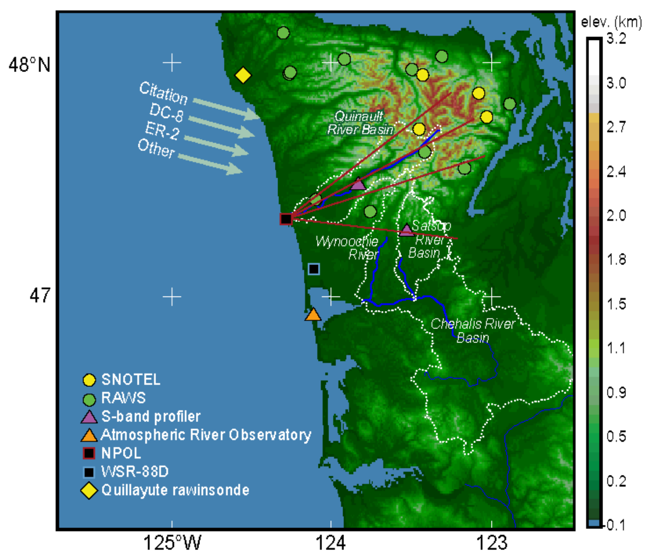

Figure 8: Proposed data network map for OLYMPEX

4.1.1 Rain

4.1.1.1 Rain gauge networks

Existing standard rain gauge network: A Map of the existing surface meteorological observing network is shown in Fig. 9. These include Automated Surface Observing Systems (ASOS) stations (i.e. KUIL, KHQM), RAWS (Remote Automated Weather Station??), C-Man, coastal buoys, Coop sites and the Climate Reference Network (CRN) station at Lake Quinault. The ASOS, CRN and RAWS stations measure most meteorological parameters including temperature, dew point temperature, surface pressure, winds, precipitation, current weather, ceiling, and cloud cover. The CRN station also measures solar radiation. The data are taken hourly, and ASOS stations will also report "specials" between hours when the weather situation warrants. These data are available in real time. There are a few Community Collaborative Rain, Hail and Snow Network (CoCoRahs) stations on the Olympic Peninsula, but these are mostly along the northeast portion of the Peninsula and near KUIL. CoCoRahs stations only report daily precipitation, snowfall or snow depth.

Supplemental rain gauges: Most of the stations shown in Fig. 9 reside around the periphery of the Olympics, except the SNOTEL sites, so there are very little direct measurements of precipitation at higher terrain. To address this shortcoming, the UW has installed a network of accumulating gauges that transect the ridge between the Quinault and Queets Rivers and includes two gauges along the coast (see Fig. 10). These are tipping-bucket type gauge, where the precipitation falls into an antifreeze solution, which then goes to a tipping-bucket gauge. This network has been deployed since ~2005 (Minder et al. 2008) and will be deployed up to and including the OLYMPEX time frame. These data are recorded in data loggers and are retrieved at the end of the winter season, so are not available in real time. The data from some of the lower elevation gauges can be downloaded midseason, but the higher elevation gauges are usually inaccessible during the winter due to snow on the roads.

For OLYMPEX purposes, another region that would benefit from additional surface rain gauges is the Chehalis river basin. As seen in Fig. 9, there are only a few RAWS sites and one Climate Reference Network site within the Chehalis basin and none of these sites reside in the northern, higher elevation region of the Chehalis watershed on the southern side of the Olympic Mountains. Therefore we will add additional rain gauges throughout the Chehalis river basin. If rain gauges were added to the southern side of the Olympic Mountains and several in the lower hills to the west of the town of Centralia, they would help document the precipitation in the Chehalis Basin and how the river responds to the input of precipitation. Gauges will need to be procured, and a site survey will need to be conducted to determine where they can be installed. NASA has 20 autonomous dual Met-One 12-inch funnel rain gauge platforms with telemetry capacity that we will deploy to the most critical sites to supplement the Quinault and Chehalis regions.

4.1.1.2 Microphysical properties of rain

In addition to documenting rainfall intensity and distribution, microphysical properties of the rainfall must also be directly measured. Either Joss-Waldvogel or video disdrometers will be used to obtain drop-size distributions at the surface. In the past, a disdrometer was in operation at Amanda Park situated on the southwest shore of Lake Quinault (Minder, personal communication). It should be possible to deploy a disdrometer at this site during OLYMPEX. Other potential sites, if OLYMPEX planners decide they are needed, could include coastal sites with access to power. If it is desired to have a disdrometer within the National Park or other remote areas, then power and permission issues will need to be arranged with the NPS.

4.1.1.3 Summary

The available and proposed observational assets for direct measurements of rain for the OLYMPEX project are summarized in **Table 3.**

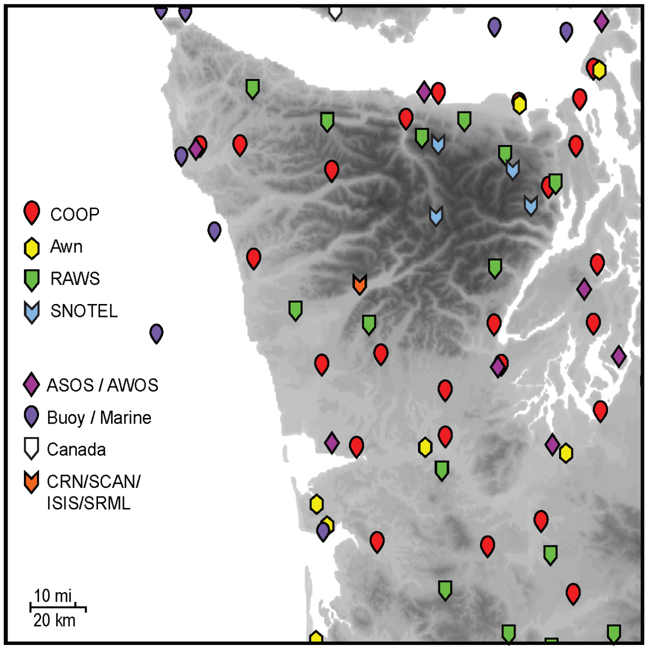

Figure 9: Map of current surface observation network where precipitation is measured either daily or hourly and reported real time at most stations. See legend for the different type of stations.

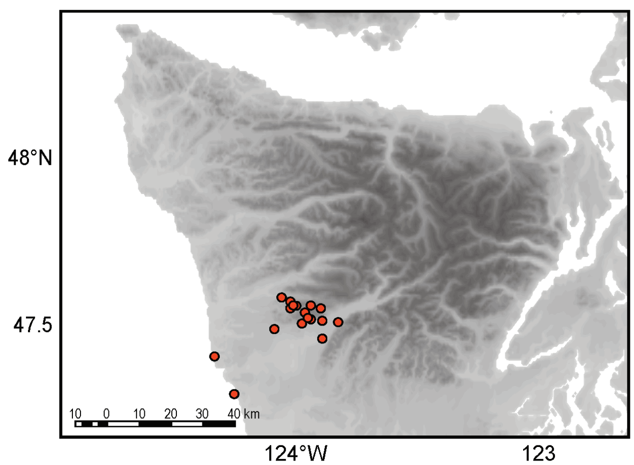

Figure 10: Map of the supplemental raingauge network. Gauges are installed at the beginning of the rainy season (~October) and retrieved in the spring. The gauges are small and large tipping bucket gauges.

Table 3: Summary of all ground-based precipitation measurement assets, existing and proposed.

Rain Measurements	Location and Number of Instruments	Quantities Measured	Observation Frequency	Length of Record	Data availability in real time	Issues to Overcome	Importance to OLYMPEX
Standard Rain Gauges	Lower elevations surrounding the Olympic Peninsula. See Fig. 8. ~20 or so	Standard observations of T, Td, V, cloud cover and precip.	Hourly or more	Stations deployed for multiple years	Yes	None	Essential
Supplemental Rain Gauges: Quinault	2 Gauges on coast, the rest (~16) on a transect across the ridge between the Quinault and Queets Rivers	Tipping bucket style gauges measuring precipitation at either 1 mm or .4 mm resolution	Whenever the bucket tips. Hourly rainrates can be calculated	Network on site for winter period only. Has been deployed for past several winters	No, retrieved at end of winter	Gauges need calibration, cannot be deployed in areas that primarily snow	Essential
Supplemental Rain Gauges: Chehalis	None are deployed yet. approx. 20 platforms	Dual-Tipping bucket style gauges (Met-One;12-inch)	Whenever the bucket tips. Hourly rainrates can be calculated		Data telemetered via cell network every 15 minutes.	Same as gauges in Quinault. May need to obtain permits to install gauges.	Essential
Disdrometer	Not yet determined. 10-20 disdrometers? Locations TBD	Falling hydrometeor shape and size	Will be deployed for OLYMPEX and perhaps the winter prior	Will be deployed for OLYMPEX only	Collected/telemetered during field campaign and archived	Needs to be deployed where power is available. May need to obtain permits	Essential

4.1.2 Ground-based and airborne radars

Ground-based radars that might be deployed in OLYMPEX are listed in Table 4. Both essential radars and possible added value radars are included in the table.

Table 4. Ground-based radars in OLYMPEX

Scanning Radars	Operating Agency/PI	Location	Guaranteed for OLYMPEX	Time frame on site	Operation time frame	Importance to OLYMPEX
WSR 88D	NOAA	On coast at Langley, WA	Yes	Operational radar, always on site	Continuous	Essential
N-Pol	NASA	TBD, but suggest near Taholah at mouth of Quinault	Yes	1-2 weeks prior to and after OLYMPEX	Continuous	Essential
D3R	NASA	TBD (often collocated with NPOL)	Yes	Same as NPOL	Same	Essential
C-band	Prof. Steve Rutledge, CSU	TBD	TBD	TBD	TBD	Useful
X-Band - DOW	Profs. Yuter, Colle, Kollias	Mobile scanning Doppler radar	TBD	TBD	(for particular events only?)	Useful
Vertically Pointing Radars	NASA MRR (4 platforms)	K-Band Doppler Spectra and Z	YES	IOP	IOP	Essential
Atmospheric River Observatory (ARO)	NOAA	On coast at Westport	TBD	Operational radar, always on site	Continuous	Essential
X and W bands	McGill University	TBD	TBD	TBD	TBD	Useful
Ka Band Radar	PNNL	TBD	TBD	TBD	TBD	Useful

4.1.2.1 Scanning S-band radars

The coastal NOAA NWS WSR-88D radar at Langley, WA, has been operational since fall 2011(see Fig. 8 for location). This S-band Doppler dual-polarization radar is positioned to sample precipitation over the offshore waters and the lowlands and southwestern slopes of the Olympic Mountains. Since it is an operational radar, the Langley 88D will conduct only PPI scans at pre-determined elevation angles to a maximum elevation angle of 19°. To obtain detailed information on the microphysical structure of storms, OLYMPEX will deploy the NASA NPOL, also an S-Band dual-polarization Doppler radar on the coast to the north of the WSR-88D, probably near the town of Taholah. To obtain fine resolution data in the vertical over the windward slopes of the Olympic Mountains, it will be operated in RHI sector scanning mode. The NASA Dual-Frequency (Ka/Ku Bands) Dual-Polarimetric Doppler Radar (D3R) will also be collocated with the NPOL radar, or possibly located up valley if a suitable site can be identified. The D3R will also perform coordinated RHI scanning with NPOL. NPOL and the D3R will be able to scan up the Quinault River valley up to the summit of the Olympics. These multi-frequency/polarimetric RHI sector scans will be crucial to optimize the vertical resolution of microphysical particle identification (PID) algorithms (such as that of Vivekanandan et al. 1999). The PID fields obtained in this manner combined with the Doppler radial velocity data will give insight into how the microphysical and kinematic properties of the storm are altered by the terrain. The combination of the PPI scanning of the Langley 88D and the NASA NPOL/D3R platforms will provide the most comprehensive three-dimensional high-resolution scanning possible to determine the microphysical, kinematic, and precipitation structure over the windward slopes. The combination of RHI scanning by an S-band dual-polarimetric radar with a PPI scanning radar has been used successfully to determine the microphysical and kinematic structure of frontal precipitation passing over the Alps in MAP and the Cascades in IMPROVE-II (Medina and Houze 2003, 2005; Rotunno and Houze 2007) and will be a backbone of OLYMPEX observations.

4.1.2.2 Essential vertically pointing radars

The currently operational NOAA Atmospheric River Observatory located at Westport, WA, (Fig. 8) includes a 915MHz Wind Profiling Radar, a S-band precipitation profiling radar, a Global Positioning System to measure column integrated water vapor, and a meteorological tower to measure near-surface conditions including falling precipitation. This facility has been operating since 2008, but it is scheduled to be removed for maintenance and due to lack of long-term funding. Renewing the site lease should be relatively straight forward, but funding needs to be secured. Its operation during OLYMPEX will be discussed at the upcoming planning meeting. This instrumentation is critical for OLYMPEX as it provides continuous time series of radar reflectivity and Doppler velocity that will show the upstream vertical structure of the precipitating column at the coast, including the vertical and temporal variation of the brightband upstream of the mountains. For OLYMPEX, vertically pointing radar coverage is also needed in valley locations to provide vertical profiles of radar reflectivity and velocity in zones blocked from view of the larger radars, most critically the Quinault Valley. This additional vertically pointing radar needs to be identified, but one excellent possibility would be the McGill University Group (Kollias, Kirshbaum, Fabry), who could deploy the VERTIX X-band vertically pointing radar for precipitation profiling and a W-band vertically pointing radar for cloud profiling. NASA GPM GV Micro Rain Radars (MRRs) will also be deployed to facilitate this vertical profiling. Details of possible supplemental radars are listed in Table 4.

4.1.2.3 C- and X-band ground-based precipitation radars

In addition to the ground-based radars described above, several other possible supplemental radars could add value to OLYMPEX if brought in by external investigators. For example, if the NASA TOGA C-band radar could be deployed, or the recently CSUacquired R/V Ronald Brown C-band radar (in collaboration with S. Rutledge of Colorado State University), the coverage over the Chehalis region could be greatly enhanced. Either of these C-band radars is well calibrated for rain measurement. There is a possibility that the former R/V Brown radar could be upgraded to make dual-polarization measurements. Smaller X-band radars operated by NCAR (R. Rasmussen) could also be used for this purpose. This C- or X-band overage will be very important in achieving hydrologic success in the Chehalis basin.

Another suggestion is that two or three Doppler-on-Wheels (DOW) radars could be employed by NSF investigators to obtain detailed Doppler velocity data in the frontal clouds (S. Yuter, B. Colle). This network would provide vertical air motions, not obtained by the other scanning radars.

4.1.2.4 Cloud radars

Pacific frontal systems have large upper cloud decks that precede and follow the precipitating core of the systems. These upper cloud decks contain ice particles that may fall as virga or light precipitation. Documenting how these cloud decks relate to the central precipitating part of the cloud band will be important to understanding the overall behavior of the frontal systems. Shorter wavelength cloud radars (K- or W-band), such as the NASA D3R Ka-/Ku-band scanning radar, will be used for the purpose. It can be supplemented by the DOE/ARM KAZR system, which has been proposed for use on the Olympic Peninsula during OLYMPEX by R. Leung of PNNL. The NASA Achieve vertically pointing W-band radar could also be used.

4.1.2.5 Airborne radars

Since relatively few overpasses of GPM can be expected during a 2-3 month field experiment, it is essential to have an aircraft proxy of the GPM radar. The APR 2 on the NASA DC8 will provide this critical component of OLYMPEX. In addition to the DC8, aircraft operated by external investigators could add value to OLYMPEX. For example, NASA ER-2 flights as part of ACE and/or NASA Global Hawk flights under an Earth Venture project would add further airborne proxy radar measurements. Flights of the Wyoming King Air by an NSF investigator (B. Geerts) would provide additional radar profiling that would complement the ground-based radars. See more on the OLYMPEX aircraft component in Section 4.1.5.

4.1.3 Surface snow measurement

Surface measurements of snow fall into two main categories for OLYMPEX:

1) Snowfall accumulation of snowfall in terms of either snow depth or SWE or both on long term (week, month, season) time scales
2) Microphysical properties of falling snow such as particle habit, particle shape, particle size, and total snow mass flux.

The first is essential for hydrologic application of GPM measurements. The second is critical for physical validation of algorithm assumptions. Therefore, both types of measurements will be made. Preliminary site surveys suggest that these measurements are possible but will be challenging in terms of power and accessibility of sites. Establishing these sites will be a high priority in the planning of OLYMPEX.

4.1.3.1 Existing SNOTEL sites

A SNOTEL (SNOpack TELemetry) site consists of a 4'x4'x16' electronics shelter, a 26' tall rocket style precipitation gage, a 10' diameter fluid based snow pillow, a sonar snow depth sensor and ambient air temperature sensor mounted to a 20-30' tall meteorological tower, and a three-element meteor burst communications antenna mounted on a 20-30' tall tower. SNOTEL sites are typically installed for long-term (20+ years) monitoring. The quantities that are measured and archived consist of air temperature, snow depth, SWE, and cumulative precipitation. There are currently four SNOTEL sites installed in the Olympic Mountains between 4000 – 5000' elevation, and their locations are shown in Figs. 8 and 9. Most have been on site since ~1980 or so, but the Buckinghorse SNOTEL (of the 4 sites, it is in the SW corner) was recently installed in 2008.

In addition, the Northwest Avalanche Center operates a station at Hurricane Ridge at 5250' elevation on the North side of the Olympic Peninsula near the Waterhole SNOTEL site. Hurricane Ridge is within the National Park where they operate a small ski area during the winter that is open on the weekends only. The road and several small buildings are open during the winter (weekends only), and power is available (i.e. at the Visitors Center). The following parameters are measured in real time at Hurricane Ridge: air temperature, wind speed and direction, precipitation, relative humidity and snow depth. It should be noted, however, that Hurricane Ridge is somewhat on the leeside of the Olympics. It will be important to take measurements at that site for comparison to windward side data, but this site does not remove the importance of obtaining measurements on the windward side.

4.1.3.2 Proposed additional SNOTEL or SNOLITE station(s)

The existing SNOTEL network is essential to the success of OLYMPEX. However, the network is not completely satisfactory for the goals of OLYMPEX because it does not adequately sample the windward west to southwest sides of the Olympic Mountains. We are therefore seeking to supplement the existing network with one or more additional sites to measure snowfall accumulation. One option would be to install another additional SNOTEL site somewhere on the southern or SW side of the Olympic Mountains. We have discussed several sites with agency representatives of the NPS and NRCS (Natural Resources Conservation Service). Since a SNOTEL site is designed to be a long-term monitoring site, the downside of a new installation would be not only the cost of installing the site, but also the complex permitting process (since almost all potential sites reside within the National Park, there is a detailed process to obtain permission to install instrumentation that have a large footprint), the maintenance costs (which are approximately 3K$ a year), and the fact that it would only add one additional data point.

An alternative, less costly possibility more amenable to the temporary siting needs of OLYMPEX would be to install SNOLITE stations. A SNOLITE installation consists of a snow depth sensor and an air temperature sensor. The data are transmitted in real time via satellite. They are typically installed on existing snow courses (see below). They have a much smaller footprint than a SNOTEL site, and since they are installed at existing snow course locations, the permitting process is much less challenging. For the same cost as one SNOTEL site, about 4 SNOLITE stations could be installed. The maintenance costs are half of a SNOTEL site, and SNOLITE stations are not considered permanent like a SNOTEL site. Since they only measure snow depth, there will not be information about falling precipitation and SWE of the snowpack. However, SWE can be inferred from snow depth, if there is some knowledge of the snowpack density, which could be gained via snow courses (see below). Sturm et al. (2010) point out that density is much less spatially variable than depth, so if density is known at a few locations, depth measurements at several other locations can be used to infer SWE.

4.1.3.3 Snow Courses

A snow course is a permanent site where manual measurements of snow depth and snow water equivalent are taken by trained observers. The courses are usually about 300 m long and are situated in small meadows protected from the wind. Measurements are usually taken every month during the winter and spring. Typically, personal are helicoptered to historical snow course sites, and they spend about ½ - 1 hour at each location. On the Olympic Peninsula, NRCS currently has three active snow courses, mostly to the North in the Elwha river drainage area. There are several other additional, but discontinued, snow courses in the Olympic peninsula that could be surveyed during the OLYMPEX project. In addition, the snow courses could be visited more frequently during OLYMPEX. The additional snow course measurements would require securing and funding additional helicopter time and coordination with NPS and NRCS. Preliminary discussions with the NPS indicate that this work is highly feasible and that they would enthusiastically carry it out.

4.1.3.4 Remote cameras and snow depth measurements

A low-cost supplement to the more permanent SNOLITE and SNOTEL type installations to measure snow depth would be to install time-lapse cameras with battery packs in trees and long snow depth markers in clearings to monitor the snow pack accumulation during the winter. Cameras and PVC measurement poles together cost roughly $200 -$300 each with the additional cost of personnel to install them. Several of these installed in traditionally poorly sampled areas would be a viable way to obtain reliable information on snow accumulation. These cameras and the depth measuring poles would remain on site for the entire winter season, and batteries would need to be able to last a long time. They would be collected and analyzed in the spring after the wet winter months. We are testing a limited number of these measurements during the 2013-2014 Water Year.

4.1.3.5 Hot Plates and other precipitation gauges

There are several types of precipitation gauges that can also measure liquid equivalent of falling frozen precipitation. At elevations where precipitation could fall as either rain or snow, these types of gauges would yield much more accurate estimates of precipitation rates than the tipping bucket type gauges. Hot Plate gauges have been shown to perform well in liquid-equivalent precipitation rates between 0.25 to 35 mm hr^{-1}. The hotplates do not require a windshield and are reliable and low-maintenance (Rasmussen et al. 2011). They consist of two independently heated plates, one facing upward and then other downward. The power required to melt and evaporate any precipitation falling on the upward facing plate gives an estimate of the precipitation rate. Since part of OLYMPEX is to examine precipitation variability in complex terrain, it may be important to deploy accurate precipitation rate gauges such as hot plates at various elevations. The main obstacle to overcome is the power to operate the gauges. As detailed earlier, large areas of the Olympic peninsula reside within wilderness areas without power, especially the higher terrain. Appropriate sites will need to be identified where the gauges could be installed in clearings and where they could be accessed in order to change batteries, if necessary. Solar power is not an option because of the low sun angle and persistent cloud cover during winter on the Olympic Peninsula.

4.1.3.6 Video Disdrometer

Physical algorithm assessment for both the GMI and DPR on GPM will require some on-the-ground microphysical measurements. Video disdrometers are a way to document the hydrometeor shape, size and mass concentration. They would need to be installed at higher elevation where it is likely to snow at least part of the time and, like the hot plate precipitation gauge, they also require power. It will be essential for the physical algorithm assessment to have video disdrometer measurements during OLYMPEX. A viable location for leeside measurements will be Hurricane Ridge, on the north side of the Olympic Mountains. It is at roughly 5000' elevation and is accessible by road during the winter on weekends and power is available there throughout the winter months. A site on the windward side remains to be determined, and finding such a site is a high priority in OLYMPEX planning. As noted above, preliminary site surveys have located sites that are suitable meteorologically but will require battery power and regular maintenance during the field project.

4.1.3.7 Summary of available and proposed snow measurement resources

The various methods for obtaining accurate measurements of snowfall accumulation, rates, and microphysical parameters discussed above are summarized in **Table 5**. Both permanent resources and installations to be added specially for OLYMPEX are included in the table.

4.1.4 Rawinsondes

There is one operational upper air station at Quillayute (KUIL) that releases rawinsondes at 00 and 12 UTC every day (see Fig. 1). During OLYMPEX, it will be important to supplement these operational soundings with additional ones in order to document the 3-dimensional structure of the precipitating environment. Several options can be considered. There can be additional soundings at KUIL at off-synoptic times (every 3 or 6 hours instead of only every 12 hours), and additional sounding locations. These potential

Table 5: Existing and proposed Snow measuring instrumentation for OLYMPEX

Long Term Snow accumulation Measurements	Location and Number of Instruments	Quantities Measured	Cost of installation	Observation frequency	Data availability timeframe	Issues to overcome	Importance to OLYMPEX
Existing SNOTEL	4 Sites above 4000', 2 on east slopes, 1 on North slopes, 1 near headwaters of Quinault, mostly sampling leeside or summit conditions	Air temperature, snow depth, SWE and precipitation	Already installed and maintained by other agencies (NRCS)	Hourly	Realtime	None	Essential
Proposed SNOTEL	1 additional site proposed at or near headwaters of the Skokomish river on South and southeast side of Olympic Mountains	Air temperature, snow depth, SWE and precipitation.	$37k, $3k annual maintenance in perpetuity	Hourly	Real Time	High cost of installation, long permit process, careful siting	Not vital if SNOLITE is used
Proposed SNOLITE stations	Several sites are possible, such as to the south and east of the Quinault near Wynoochee Lake and to the immediate west of Mt. Olympus	Snow depth, air temperature, inferred SWE	$8K, $1.5K annual maintenance during OLYMPEX years	Every 6 hours	Real time	Permitting process involved, careful siting necessary, doesn't measure SWE	Important -- choose between this and SNOTEL
Snow courses	Three active and several discontinued snow courses in the Olympics Additional snow courses are also possible.	Snow depth and SWE of snow pack	Must pay for helicopter time and possible some observer expenses; No estimate available	TBD, but likely once a month or more during OLYMPEX	TBD, but likely once a month	Identify snow courses, cost, obtain personal, schedule helicopter	Essential
Time Lapse Photography	As many as 10 cameras could be installed. Regions of interest include the west, south and southwest sides of the Olympics	Snow Depth	~ $200 for each camera etc., personal cost	Cameras can be set to take hourly pictures during daylight hours	Cameras retrieved at end of winter season	Battery life, doesn't measure precip or SWE	Essential

Table 5 continued

Snow Microphysical Measurements - Proposed	**Potential Locations**	**Quantities measured**	**Power Requirements**	**Operable on batteries?**	**Issues to overcome**	**Importance to OLYMPEX**
Pluvio 2	Along Quinault River?	Liquid equivalent precipitation, hourly?	**?**	Probably	Power and Accessibility for maintenance	Important
Hotplates	Near Wynoochee Lake, Hurricane Ridge, up Quinault?	Liquid equivalent precipitation, every minute?	?	Probably	Power and Accessibility for maintenance	Important
2D Video Disdrometers	TBD Supporting pol radar PSD estimates	Hydrometeor habit, size and volume	**?**	**N0**	Power and Accessibility for maintenance	Essential

locations would most likely be along the coast south of KUIL, such as where the NPOL radar will be deployed (Taholah).

4.1.5 Aircraft

4.1.5.1 OLYMPEX aircraft

NASA DC-8. The principal aircraft for OLYMPEX will be the NASA DC-8, which will function as the GPM proxy. A proxy aircraft is essential for a GV program since the satellite overpasses will be too infrequent to gain a statistically significant dataset to compare with the ground-based measurements. Therefore the DC-8 will be equipped with the APR-2 radar, the CoSMIR and possibly the AMPR radiometers , which together approximately mimic the radar and passive microwave measurements made aboard GPM. The DC-8 could potentially provide critical dropsondes upstream of the Olympic Peninsula to establish the moisture content of the incoming flow.

North Dakota Citation. This instrumented jet aircraft will be the primary microphysics platform and will obtain particle samples at a wide range of temperatures by flying at a range of altitudes. The microphysical profiling will be limited over the mountains in order to retain the 2500 foot clearance between the ground and flight level. This restriction adds importance to the collection of high-resolution dual-polarimetric radar data with NPOL (see above, Section 4.1.2) and vertically pointing ground based radar data at one or more valley locations.

4.1.5.2 Aircraft from other projects potentially operating concurrently with OLYMPEX

Several other aircraft facilities have expressed interest in operating in the context of OLYMPEX on a non-interference basis. These aircraft would all add value to the OLYMPEX dataset as follows.

NASA ER-2. The NASA ACE program has expressed interest in flying ER-2 missions during OLYMPEX. The data collected would add value to OLYMPEX by increasing the number of satellite proxy flights since the ER-2's payload could include both radar (EDOP) and passive microwave instruments. This group is primarily interested in over water flights which would be a significant benefit to the goals of OLYMPEX.

NASA Global Hawk: Two Earth Venture proposals include making Global Hawk flights upstream of the Olympic Mountains during OLYMPEX. If one of these proposals is funded, then OLYMPEX will gain additional dropsondes for upstream moisture conditions and additional satellite proxy measurements from its onboard radar (HIWRAP).

Wyoming King Air: NSF investigators led by B. Geerts might bring this aircraft to OLYMPEX to use its airborne W-band radar. This radar would add value to OLYMPEX by documenting the cloud structure not seen by the longer-wavelength precipitation radars, and it would provide internal cloud vertical motions at high resolution. It would also provide additional in situ microphysical measurements.

PNNL G-1: Under R. Leung, PNNL scientists are proposing under other funding sources to fly missions with the PNNL G-1 aircraft during OLYMPEX. Their goal is to obtain aerosol and cloud physics measurements that will help understand the role of aerosol in frontal cloud systems. This aspect is not central to GPM but will add a component of the context of the cloud systems investigated in OLYMPEX that will be of wide, general interest. This aircraft would be based in Richland, WA, and its operation would not interfere with OLYMPEX missions.

Canadian NRC Convair 580: Although it is not clear how this aircraft might be funded for OLYMPEX, it would be extremely valuable because its microphysical probes are state-of-the-art. They have the new pointed tips that avoid false indications of high ice particle concentrations due to particle splintering on the probes (Korolev et al. 2011). Canadian scientists are interested in OLYMPEX and the involvement of this aircraft in OLYMPEX would be a great asset.

4.1.5.3 Summary

These aircraft are all summarized in Table 6.

Table 6: Summary of committed and proposed aircraft for OLYMPEX

Aircraft	Instrumentation	Proposed Flight Paths	Committed to OLYMPEX	Primary Contact
NASA DC-8	GPM Proxy: APR-2, CoSMIR AMPR;	Over Olympic peninsula, upstream	Yes	NASA – Walt Petersen
North Dakota Citation	Microphysics	Over Olympic Peninsula	Yes	NASA – Walt Petersen
NASA ER-2	Satellite Proxy: EDOP	Upstream over Pacific	possible	NASA – Roger Marchand
NASA Global Hawk	Satellite Proxy and dropsondes	Upstream over Pacific	possible	NASA-JPL, NASA-Goddard
Wyoming King Air	Airborne w-band radar, microphysics	Over Olympics	possible	B. Geerts U of Wyoming
PNNL G-1	Aerosol and cloud physics measurements	Over Olympics and upstream over Pacific	possible	R. Leung of PNNL
Canadian NRC Convair 580	State-of-the-art microphysical probes	Over Olympics	possible	Walter Strapp or Mengistu Wolde (NRC)

4.1.6 River monitoring

United States Geological Survey operates river gauges that typically measure both river stage and river discharge for most of the significant rivers on the Olympic Peninsula. The data from these gauges are available in real time and the National Weather Service Advanced Hydrological Prediction Service provides hydrological forecasts at many of these sites. Most rivers are monitored at lower elevations near the mouth of the river where the river is most likely to adversely affect life and property in times of flood. There are no river gauges in the upper reaches of any of the rivers in the interior of the Olympic Peninsula. A map of all the river basins in the Olympic Peninsula and the USGS river gauges are given in Fig. 7a. A separate map of the entire Chehalis basin and its river gauges are shown in Fig. 7b.

4.2 Modeling Infrastructure

4.2.1 Operational forecast support

4.2.1.1 UW WRF

The atmospheric modeling and data assimilation capabilities of OLYMPEX will be extensive, comprehensive, and state-of-the-science. It is will include:

1. Twice-daily Weather Research and Forecasting (WRF) simulations, initialized with the National Weather Service GFS model grids, that will be run at 36, 12,4, and 1.3 km grid spacing. These forecasts have run for over a decade in the region and include physics and grid geometries selected to optimize prediction skill over the region.

2. An Ensemble Kalman Filter (EnKF) ensemble-based data assimilation and prediction system that makes use of the WRF model and the NCAR DART EnKF system. This data assimilation system is now run every three hours at 4-km grid spacing over the region using 64 members. The UW EnKF currently assimilates surface observations, radiosondes, ACARS aircraft data, and cloud/water vapor track winds. During the next year, we plan n assimilating local NWS radars and short-haul aircraft data (TAMDAR).

3. In support of the field program the EnKF will run operationally on a three-hour assimilation cycle, with 24 hr forecasts every 6 hours for the member closest to the ensemble-analysis mean. A parallel EnKF cycle will be run in a delayed model with assimilation of the GPM satellite assets and field experiment assets to produce the best possible analysis.

4. A separate ensemble system encompassing the WRF model (36-12 km grid spacing) and driven by analyses and forecasts of major international modeling systems has been run during the past decade and will be available during the OLYMPEX experiment. This will provide further guidance on the uncertainties of the synoptic/mesoscale evolution during field periods.

4.2.1.2 NASA NU WRF

4.2.2 Model estimated snowpack tuned to SNOTEL

An important goal of GPM is to provide global measurements of snowpack accumulation using satellite assets, and that requires the capability to determine snowpack even where surface observations are not available. With the help of numerical modeling, OLYMPEX will use the Olympic Mountains as a testbed to evaluate the viability of satellite-based snowpack estimation over terrain.

As noted earlier, there are only a few sites in the Olympics that report snow depth and SWE. Since the terrain causes substantial variation in snow depth, the distribution of snowfall needs to be estimated over different parts of the mountain range. High-resolution model simulations can reproduce a complex pattern of orographic modulation of precipitation and snowpack accumulation over a season (e.g., Anders et al. 2007, Minder et al. 2008).

As noted earlier, the WRF model will be run at 1.3 km grid spacing during the entire field phase of OLYMPEX, with all fields being archived. The modeling system will be run with a sophisticated land surface model (LSM) during that period, probably the NOAA-MP LSM. Model snowpack will be determined in two ways: (1) using the direct output of the selected LSM and (2) using the snow model developed by Professor Lundquist that will be driven by raw WRF fields. As a first step, we will compare the fidelity of the accumulated snowpack using these approaches with the amount measured at the limited number of snowpack observing sites (mainly SNOTEL). A second approach will make use of model calibration, in which a subset of the snowpack sites will used to determine the accumulated model snowpack errors, with these errors being used as corrections that are spread throughout the domain. We will use the observation-based correction of the model snowpack fields for both snowpack approaches (LSM and Lundquist).

4.2.3 UW Hydrologic Modeling

4.2.3.1 DHSVM

The Distributed Hydrology Soil Vegetation Model (DHSVM) has been widely used in forested catchments within the Pacific Northwest. It is a physically based, spatially distributed hydrological model that describes the effects of soil, vegetation, and topography on the movement of water at and near the land surface (Wigmosta et al., 1994), including the effects of forest vegetation on snowpack evolution and ablation. It uses a rectangular grid cell formulation, and is implemented at spatial scales appropriate to the representation of topographic, soil, and is most appropriate for catchments with drainage areas from 10s to up to thousands of km^2, a range that includes both the Quinault and Chehalis River basin. The grid cell dimensions typically are in the range from 10 to 150 m (we most likely will use a spatial resolution of either 30 or 90 m in OLYMPEX, resolutions at which both topographic and vegetation data are available). The model is forced with time-series (typically at 1- or 3-hourly temporal resolution) of meteorological variables including precipitation, temperature, downward solar and longwave radiation, relative humidity, and wind. These variables can be taken either from WRF output (as is the case in the implementation of the model over the Puget Sound basin) or from observations, in which case quantities that are not directly observed such as downward solar and longwave, radiation and humidity can be indexed to observed variables following methods assessed in Bohn et al, (2013). DHSVM includes a physically based snow accumulation and ablation model (Andreadis et al., 2009) that represents the effects of canopy interception and other effects of vegetation on hydrological processes, which are critical over the OLYMPEX domain.

4.2.3.2 Snow-17 model for snowpack

While DHSVM models snow accumulation and melt using a full energy balance approach, in data-sparse regions, a temperature-index approaches, which use calibrated relationships to sidestep the need to represent snowpack energetics, can work as well or better (e.g., Franz et al. 2008). For this reason, the National Weather Service River Forecasting offices use Snow-17 (Anderson 1976) for their operational flood forecasts. Snow-17 uses temperature and precipitation as input and estimates snow water equivalent and outflow (snowmelt plus rain) at each time step. We will calibrate the SNOW-17 model parameters using the existing SNOTEL stations on the Olympic peninsula and will test model performance using both in situ measurements and output from the WRF model system. We will also check model performance against snow depth measurements, using snow density measured at the SNOTEL stations to convert snow depth at other locations to snow water equivalent.

5. DATA ARCHIVE AND WEB SUPPORT FOR PROJECT OPERATIONS AND RESEARCH

A comprehensive data archiving and distribution plan have not yet been worked out in detail. The basic plan is to have a web-based catalog system (similar to those used in other large field programs). The web-based catalog will serve multiple purposes as the "one-stop shop" for OLYMPEX data. Lists of all the data obtained will be included in the catalog, with links to images of key data products for quick perusal and links to the digital data sets, which researchers can use to locate and access data. The catalog will also maintain imagery of near real time model and satellite products that can be used to support forecasting during the campaign, for flights and other OLYMPEX operations. The site will also host science summaries written by participants in the field. An important goal is to have the OLYMPEX datasets available to researchers as soon as possible after data are collected so that assessment of the GPM satellite and related research can proceed in a timely manner.

6. SUMMARY

The list of OLYMPEX objectives and the probability of successfully meeting those objectives are summarized in Table 7.

Table 7: Summary of the OLYMPEX Implementation Plan Objectives and probability of success.

OLYMPEX Objective	Key Observations	Concerns/deterrents	Probability of Success
Sample upstream precipitation events over ocean and coastal areas	Radars, aircraft, surface gauge network	Lack of events	95 – 100%
Sample melting level variability intra- and inter-storm	Scanning and vertically pointing radars, sondes	Blockage by terrain of key areas of interest	95 – 100%
Sample range of precipitation intensities from light to heavy in midlatitude storms	All observational assets	Lack of heavy precipitation events	95 – 100%
Sample winter-time stratiform and convective precipitation regimes	All observational assets	None except lack of events	95 – 100 %
Sample microphysical characteristics of mixed phase precipitation	Microphysical measurements on aircraft, dual-polarization radars, disdrometers	Difficult to get on-the-ground measurements of microphysical characteristics at high elevation due to remoteness	90%
Measure seasonal build-up of snowpack over the Olympic Peninsula	SNOTEL, snow surveys, remote cameras, modeling	Not enough samples in complex terrain, model errors	85 – 90 %
Sample high precipitation events and the river-runoff response	Surface observations of precipitation, radars, aircraft	May not get a flooding event	75 – 90%
Measure emissivity of a variety of surfaces including ocean, coast and snow-covered mountains	DC-8 aircraft	May not get a completely clear day	75 – 90%

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