The formation and the lifespan of the PCAPs depends on the wind speed above the basin especially the synoptic mesoscale flows that can erode the PCAP. Some of the studies have found out that when wind speeds above the valley exceeds a specific limit, the nocturnal inversion layer in the valley can be interrupted. This ultimately results in weakening of the inversion layer’s intensity. The intensity of the wind required to affect the inversion will differ depending on the regional topography such as the valley shape and depth. For example (Yasuda, Kondo, and Sato 1986) found out that with the downslope wind speed of 4 m/s at the ridge surrounding the valley, the cold air pool in a V-shaped basin collapsed quickly. In another study in Colorado (Orgill et al. 1992) concluded that the cold air pool erosion processes were activated when the wind speed above the valleys exceeded 5 m/s in western Colorado. It will be interesting to investigate that threshold windspeed aloft that leads to the erosion of the PCAP.

Atmospheric processes such as high pollution episodes and effective dispersion of the pollutants can be understood with the help of air mass trajectory analysis. A comprehensive experimental determination of the air trajectories is only possible during a complex and significant campaign such as PCAPS. To obtain flow patterns, models such as Air Resources Laboratory (ARL’s) Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) with atmospheric transport, dispersion and deposition simulations (Draxler et al. n.d.); the FLEXTRA model developed by the European Center for Medium-Range Weather Forecasts (ECMWF) which permits boundary layer trajectories and calculations with vertical wind component equal to zero (Stohl 1998); and Meteorological data Explorer (METEX) which is flexible in terms of accepting meteorological data in variety of formats (Zeng, Matsunaga, and Mukai 2010) can be used. It is significant to trace the transportation of the precursors and secondary pollutants formed as result of photochemistry. The air trajectory analysis from these models during the PCAPs can help in better understanding of the photochemistry involved. The back trajectories can provide useful information on the origin of the airmass and can be used to understand better the origins of PM2.5 concentrations in SLV. The cluster analysis can, nevertheless, provide a good indication of the geographic locations most strongly associated with elevated concentrations of PM2.5. It will be interesting to study how injections of the precursors during the transport can change the air mass feature and its impact at the downslope sites where pollution episodes occur.

The scales of basins have a large impact on the relative importance of inter (between) and intra (within) basin exchange. transport processes. Workshop participants agreed that many previous field studies have not had the spatial data collected of both meteorological and chemical measurements to answer the above questions. Different regions within basins will have different emissions and chemistry, as well as variations in meteorology. Better understanding of spatial variations in thermodynamic/dynamic and chemical emissions and processes are all needed in order to tackle these important questions. Care as to how to sample the canyon and slope regions is needed in order to design experiments of exchange processes along the valley slopes (Oldroyd et al. 2016). Comparison of vertical profiles away from basin walls (e.g. from towers or via remote sensing) to pseudo profiles taken with sensors vertically deployed up a sidewall can probe the role of canyon wall exchange.

Role of sloped sidewall flows:

The degree to which side wall flows, return flows, secondary circulations, and entrainment by buoyantly-driven downslope (katabatic) flows impact mixing, ventilation or entrainment/injection of relatively cleaner air or oxidants into the CAP is largely unknown and require a multiscale observational approach. Stably-stratified, quiescent periods associated with CAP formation can also lead to buoyantly-driven downslope (katabatic) flows over valleys/basin side walls or down a sloped valley itself (Prandtl 1942; Defant 1949; Whiteman 2000; Serafin et al. 2018). Through cold air advection down the slopes, katabatic flows may enhance the development of CAPs, especially in the early formation stages (Gryning et al. 1985; De Wekker and Whiteman 2006; Mahrt et al. 2010; Choukulkar et al. 2012; Burns and Chemel 2014b; Arduini et al. 2016); however, the growth of the CAP can overtake the slope-layer inversion and cause the katabatic winds to weaken, cease, or ‘peel off’ the sidewall (intrude) and flow horizontally toward the basin center for elevations within the CAP (Clements et al. 2003; Mahrt et al. 2010; Whiteman et al. 2010; Haiden et al. 2010; Soler et al. 2014). These CAP and katabatic flow interactions can generate waves (Burns and Chemel 2014a, 2015), or perturbations that lead to CAP ‘sloshing’ and enhanced mixing (Lehner et al. 2015; Lareau and Horel 2015; Jeglum et al. 2017) that are not fully understood quantitatively and difficult to parameterize in models. When approaching CAPs, a katabatic jump (analogous to a hydraulic jump) may also develop, again generating turbulence and strong vertical motions (Gallée and Schayes 1992; Yu et al. 2005; Yu and Cai 2006). Through principles of mass and/or heat conservation, katabatic slope flows can generate cross-valley circulations, vertical scalar transport, especially in closed basins where convergence can generate uplifting motions, and mesoscale heat transport (Hennemuth 1986; Kuwagata and Kimura 1997; Noppel and Fiedler 2002; Weigel et al. 2007; Choukulkar et al. 2012; Arduini et al. 2016).

Furthermore in valleys, turbulent surface fluxes have been shown to scale better with the slope-scale variables from the regions above than with the local variables (Rotach et al. 2008), and turbulence characteristics for katabatic flows, such as the turbulent flux divergence observed near the surface in katabatic flows (e.g., Oldroyd et al. 2014; Grachev et al. 2016; Stiperski et al. 2019), can extend over the horizontal terrain below, forming a layer akin to an advected internal boundary layer (Mahrt et al. 2018). These studies confirm that idealized, constant-flux surface layer, horizontal-terrain theories and parameterizations are insufficient for modeling flows in basins and valleys in the presence of side wall drainage flows and motivate the need for advanced turbulence models for CAPs. In sum, side wall katabatic flows and CAP interactions can generate a wide range of multi-scale phenomena that lead to varying degrees of mixing (Soler et al. 2002; Trachte et al. 2010; Martínez et al. 2010; Choukulkar et al. 2012; Serafin et al. 2016; Jeglum et al. 2017). Predicting when, where and how these interactions will occur, and especially, understanding how to parameterize the associated mixing during these interactions are difficult tasks requiring a suite of spatially distributed turbulence measurements to drive new parameterization development and model capabilities.

To fully understand how flows over sloped side walls impact CAP development and growth, dynamics, mixing and transport in basins and valleys, it is critical to understand key characteristics about the slope-scale winds and katabatic flows, such as their spatiotemporal development and decay, the depth of the surface exchange layer, and the physical processes driving turbulence generation and maintenance or suppression. In essence, we need to be able to predict their presence and structure; however, these flows exhibit a number of characteristics that pose significant modeling challenges.

1. Drainage flows over side-walls typically exhibit a shallow jet-shaped velocity profile with an elevated peak near the surface, of order 10 m deep with peaks located as low as 1-5 m (Oldroyd et al. 2014; Grachev et al. 2016). The turbulent surface exchanges, driving heat and mass transport, occur over this shallow layer and hence, the grid resolution of most basin-scale models will be insufficient to resolve the dynamics below the jet peak and some may miss the katabatic layer entirely. Even relatively high-resolution models will need some methodology to parameterize the mean advective and turbulent transport occurring in this the shallow layer.
2. The specific roles that dry versus wet soil moisture conditions play in energy flux partitioning and therefore, the onset, depth and strength of drainage flows are inconsistent between studies (Banta and Gannon 1995; Chow et al. 2006; Schmidli et al. 2009; Sastre et al. 2015; Jensen et al. 2017). Additionally, Foster at al. (2017) showed that modeled katabatic flows are sensitive to the treatment of snow in the land surface model, but little experiment work has been done, specifically addressing this question. These indicate a need to better understand the sensitivity to and impact of surface boundary conditions on katabatic flows and for systematic studies across a variety of climatic zones.
3. Given the static stability and shallow flow layer, anisotropy in katabatic flows may skew turbulence scaling relations, posing additional modeling challenges (Stiperski and Calaf 2017; Sfyri et al. 2018)
4. The extent to which other SBL phenomena like intermittency (Pardyjak et al. 2002) and submeso motions (see Mahrt 2009) complicate katabatic modeling have not been systematically studied, but likely play some role. In particular, submeso motions can drive horizontal diffusion and contaminant dispersion (Mahrt and Mills 2009; Mahrt et al. 2010) but are very difficult to parameterize (Vercauteren et al. 2016).
5. In addition, surface turbulence decoupling near the katabatic jet peak may occur due to the sign change in the velocity gradient, momentum fluxes and slope-parallel buoyancy fluxes (Horst and Doran 1988; Denby 1999; Grachev et al. 2016). However, significant turbulence transport, which is often negligible over horizontal terrain, tends to transfer TKE toward the jet peak from below and above, and serves as an important turbulence coupling mechanism to maintain non-zero TKE at the peak (Arritt and Pielke 1986; Horst and Doran 1988; Denby 1999; Smeets et al. 2000; Söderberg and Parmhed 2006).
6. Nearly all numerical weather prediction models rely on turbulence parameterizations that were empirically derived over horizontal, homogeneous terrain exhibiting a constant-flux surface layer (e.g., those base on Monin-Obukhov similarity theory, or MOST). Not only does sloping terrain violate the horizontal terrain assumption, katabatic flows exhibit strong turbulent flux divergence, or a strong variation with distance from the ground, making these widely used turbulence parameterizations inadequate for katabatic flows (Oldroyd et al. 2014; Grachev et al. 2016).
7. Mechanisms of turbulence kinetic energy (TKE) generation occur differently over slopes than for horizontal terrain. As in most stable boundary layer flows, kelvin-Helmholtz shear instabilities and shear-driven mixing are important in katabatic flows, and perhaps more so due to high velocity gradients observed throughout the jet profiles (Strang and Fernando 2001a, b; Monti et al. 2002); however, the role that buoyant suppression/production of TKE plays in slope flows differs from that over horizontal terrain due to the contributions of the slope-parallel buoyancy fluxes in the net vertical buoyancy flux (Horst and Doran 1988; Denby 1999; Oldroyd et al. 2016). For the a statically stable stratification, this contribution can reduce buoyant TKE suppression (Horst and Doran 1988; Denby 1999) and even lead to buoyant TKE production for, especially for relatively steep slopes (Oldroyd et al. 2016). This phenomenon opens new questions regarding how to characterize stability over slopes and how to parameterize the effects of the slope-parallel buoyancy flux (Oldroyd et al. 2016).
8. Many studies aimed to evaluate turbulence closure models and scaling relations or develop new scaling relations to replace traditional, horizontal-terrain MOST-based relations for katabatic flows in WNP simulations. These range from bulk transfer models (e.g., Manins and Sawford 1979; Fitzjarrald 1984; Lalaurette and André 1985; Kondo and Sato 1988), eddy-diffusivity models stemming from Prandlt’s (1942) slope-flow model (e.g., Defant 1949; Lee and Kau 1984; Ye et al. 1990; Burkholder et al. 2011; Shapiro et al. 2012; Shapiro and Fedorovich 2014), variable eddy-diffusivity models to account for a more complicated turbulence structure (e.g., Rao and Snodgrass 1981; Grisogono and Oerlemans 2001, 2002; Grisogono 2003; Parmhed et al. 2004; Kavčič and Grisogono 2007; Giometto et al. 2017), Richardson number models (e.g., Pardyjak et al. 2002), flux-gradient parameterizations based on MOST (e.g., Lee and Kau 1984; Ye et al. 1990; Gallée and Schayes 1992), local MOST-based flux-gradient closure schemes (e.g., Horst and Doran 1988; Forrer and Rotach 1997; Oldroyd et al. 2014; Grachev et al. 2016; Stiperski et al. 2019), TKE closures (e.g., Arritt and Pielke 1986; Nappo and Rao 1987), and higher-order turbulence closure models (e.g., Horst and Doran 1988; Oerlemans 1998; Denby 1999; Goger et al. 2018). So far, no closure scheme has been shown to be comprehensively appropriate for all slope angles or locations in the katabatic layer. This is partially due to a limited number studies with a sufficient resolution of turbulence measurements until relatively recently (e.g., Oldroyd et al. 2014; Grachev et al. 2016; Fernando et al. 2018; Stiperski et al. 2019) and partially related to the dearth of systematic, long-term measurements outside of Alpine environments (Stiperski and Rotach 2016). While these more recent studies with high spatial resolution turbulence observation have started to chip away holes in our understand of turbulence in katabatic flows (as discussed above), there is an insufficient sampling of katabatic flows over a range of slope angles (see Oldroyd et al. 2016) and climate zones to robustly assess turbulence closure models or to propose new ones that hold for multiple slope angles and a range of surface boundary conditions and canopy covers.

An extensive inter-comparison between experimental PBLH using instruments (using the remote sensing instruments) and that obtained from various models such as WRF (using popular PBL schemes) and HYSPLIT (using meteorological data such as NAM 12 km). This will be a good opportunity to test the reliability of the computed model results with that obtained from the experiments. Along with the wind trajectories, HYSPLIT model also compute PBLH assuming that the depth of the PBLH is equal to the height at which the potential temperature changes by 2 K as compared to the ground level. The most common meteorological archive information used in the HYSPLIT model for calculating PBLH was EDAS (Eta Data Assimilation System) 40 km resolution. However, the EDAS dataset is no longer updated since January 2019. So, it will be interesting to use NAM 12km or HRR 3km dataset to calculate PBLH. The values can be verified with PBLH obtained from ceilometer and soundings. Intercomparing them will help us a great deal in understanding which amongst the current available datasets predicts the PBLH more precisely especially during the PCAPs. (Perrone and Romano 2018) established a relationship between the PBLH (using LIDARS and numerical prediction models) and particle scattering coefficient at the surface using nephelometers. It will be worth validating the claims made by the authors during the study of PCAPs.

Organic aerosols account for highest percentage of PM2.5 followed by ammonium sulfate, ammonium nitrate, black and brown carbon. (Baasandorj et al. 2017) observed ammonium nitrate is the principal component of PM2.5 in the Utah Valleys during the high pollution days and ammonium sulphate is a minor contributor. Organic and inorganic PM precursors via combined atmospheric photochemical and aqueous processes can result in secondary pollutants such as sulfate. It is a well-established fact that sulfate (SO4-2) is omnipresent in the atmosphere and is one key component of the fine PM family. Atmospheric sulfur chemistry is still a unsolved problem. Sulfate levels are frequently underpredicted by the atmospheric chemistry models (Wang et al. 2016).

The cessation of the PM2.5 growth in some Utah valleys due to dense foggy conditions, to a certain extent, can be associated with the surface and condensed phase chemistry. In terms of meteorology, we know that turbulent mixing of air plays an important role in determining the development of the PCAPs. It can also enhance the efficiency of fog droplets collecting fine particles by the collision-coalescence process.

The relationship between the fog and aerosols, especially the particulate matter (PM), is complex in nature. in their study. In a comprehensive study conducted by (JACOB et al. 1984) in the San Joaquin Valley, California, authors observed that the valley fog appeared to limit the accumulation of the PM concentration in the stagnant stratifies air mass. The fact that PCAP is also a stagnant air mass with limited mixing both vertically and horizontally can help us correlate and understand the interaction of the fog and PM.

For example, fog in some Utah Valleys is associated with the cessation of PM2.5 growth. Why? Is this The onset of low clouds, for example, changes the mixing structure within PCAPS from bottom-up to top-down turbulence, but with unknown impacts on the chemistry. related to a change in chemistry, cloud scavenging, or meteorology?

and ultimately howPCAPsPCAPs can be long-lived, lasting one to two weeks, during which a complex and varied array of coupled meteorological and chemical processes occur. The evolution of PCAPsPCAPs can be characterized by an onset or development phase, mature or steady state phase, and a breakup or decay phase. The meteorological and chemical characteristics of each of these phases vary, thus it is expected that meteorological and chemical process coupling varies similarly through the lifecycle of PCAPsPCAPs. AQUARIUS observational design will target the entire evolution of PCAPs so that the importance of various processes throughout the lifecycle of PCAPsPCAPs can be quantified. The development/onset phase of PCAPsPCAPs is often characterized in colder regions by fresh a snow cover and a resulting high surface albedo, cold temperatures, clear skies, and ample but low-angle solar radiation. As PCAPsPCAPs mature, frequently a transition from a clear or dry PCAP to a fog-filled, moist, or stratus-capped PCAP is observed. The initial clear phase sees the accumulation or ramp-up of the concentrations of NOx, particulate pollution, and pollution precursors. Observations from the Salt Lake Basin in Utah show that phase is often accompanied by the lowering of a strong subsidence capping inversion and strong near-surface diurnal temperature variations, adding a nocturnal near-surface inversion and daytime convective surface layer to the complex thermal structure of the PCAP. During this phase, photochemical processes are favored (???), thermally-driven exchange processes at the edges of the PCAP play an important role in coupling and mixing processes, and nocturnal de-coupling and daytime re-coupling of the near-surface with the rest of the PCAP influence chemical processes (N2O5 chemistry ???). Further, moisture is typically accumulating in the basin, ultimately leading to saturation, fog development, and a stratus deck below the capping inversion. This transition fundamentally changes the thermal structure of the PCAP. Top-down convection throughout the entire diurnal cycle, reduced solar and higher thermal downward fluxes dramatically reduce the near-surface diurnal temperature variation and eliminates diurnal de- and re-coupling of the surface layer where the majority of emissions occur, potentially changing the chemical processes by keeping the entire PCAP coupled and mixed. This transition leads to a reduction or shut-off of deeply-penetrating thermally-driven sidewall and canyon flows, reducing background ozone injections, and reduction in UV radiation for photochemical processes, and thus to fundamental changes in the chemical processes.

PCAPsPCAPs

During the breakup or decay phase, the depth of the PCAP typically continues to decrease while concentrations of criteria pollutants may increase.

No previous field campaign has provided the breadth and depth of contemporaneous observations at the surface and aloft that could address For example, while the PCAPS project established many of the meteorological controls on PCAPS intensity and duration, it lacked the detailed chemical the complex coupled meteorological and turbulence observations to resolve the chemistry processes impacting PCAP air quality and internal variability, which strongly affects the societal impact of a given cold-air pool.of importance. As we will elaborate in future sections, observing the complexity of coupled chemistry and meteorological processes in mountain basins requires nimble multi-. The willsensor networks and innovative deployment strategies (e.g., plane, in situ and surface-based remote, mobile, drones, IOTs) to link the chemistry and meteorology. Specifically, the science plan factors in the strength and weaknesses of diverse sensor types for the complex and evolving boundary layer and air quality conditions observed during PCAPs. One goal of the AQUARIUS field campaign is the collection of the highly complex dataset that is required to evaluate – and identify the key weaknesses of – current forecast model capabilities during the study, to develop and test new parameterizations of key processes, and to ulimately improve research and operational simulations of PCAPs from both the meteorological and air quality point of views. Considerable work is underway or has been conducted in recent years improving model simulations of PCAPs (e.g., Lareau and Horel 2015b, Ahmadov et al. 2015, Foster et al. 2017, Tran et al. 2018, Sun and Holmes 2019; Kelly et al. ; Sun et al. 20202018).

Additional discussion of the state-of-scientific understanding related to key meteorological-chemical coupling during PCAPs and potential new scientific understanding that would result from coupled meteorological and chemical measurements during the AQUARIUS field campaign for four major topic areas are described below:

The AQUARIUS workshop identified several key areas where targeted meteorological-chemical coupling observations should be conducted: Large-scale forcing, terrain-forced and thermally-driven flows, radiative processes and feedback (clouds, albedo, solar angle), vertical and horizontal transport and mixing processes, boundary-layer structure and layering, and clouds (wet vs dry PCAPsPCAPs) (Table 1 and Figure 2).

Numerical model forecasts of the PCAPS are difficult due to complex, coupled land and atmosphere processes, such as the interactions amongst the surface state (e.g., snow cover), surface fluxes of heat and moisture, boundary layer budgets (e.g., turbulence, temperature, moisture, etc), cloud formation, thermally driven terrain flows, and synoptic-scale processes (e.g., advection, large scale pressure gradient force) (Holtslag,et al. 2011, Wei et al. 2013, Lu and Zhong 2014Lareau et al. 2013, Smith, 2019, Sun et al. 2020).

PCAPs are weakened or destroyed by weather systems accompanied by strong winds, cold air advection, or precipitation (Lareau et al. 2013; more refs).