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Role of persistent low-level clouds in mitigating air quality impacts of wintertime cold pool conditions

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HIGHLIGHTS

- Pollutants were characterized during an extended stagnation event.
- Onset of low-level cloud coincided with sharp decline primary pollutants.
- Secondary pollutants exhibited different behavior.

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ABSTRACT

The Yakima Air Wintertime Nitrate Study (YAWNS) was conducted in January 2013 to investigate the drivers of elevated levels of fine particulate matter ($PM_{2.5}$) frequently present in the region during winter stagnation periods. An extended stagnation period occurred during the study. For the first four days of the event, skies were clear and the strong diel variation in air pollution patterns were consistent with the expected effects of strong low-level nighttime temperature inversions with moderate mixing during daylight hours. Later in the event a low-level cloud layer formed that persisted over the Yakima Valley for the next seven days while regional conditions remained stagnant. Coincident with the onset of cloud, the levels of all measured primary pollutants, including CO_2, CO, NO_x, particle number concentration, and black carbon, dropped dramatically and remained low with negligible diel variation for as long as the cloud layer was present. The observed patterns for these air pollutants are consistent with decreased stability and enhanced mixing associated with the cloud-topped boundary layer. Interestingly, levels of secondary pollutants, most notably particulate ammonium nitrate, did not exhibit the same decline. This difference may be due to shifts in the chemical production of secondary pollutants during cloudy conditions, or may merely reflect a further influence of mixing. The results imply that the best strategies for managing wintertime air quality during episodes of persistent cloud are likely different from those needed during clear-sky stagnation events.

1. Introduction

Severe wintertime particulate pollution episodes are a major environmental concern in cooler climates, especially in populated areas with valley topography. Such episodes are typically driven by a combination of increased emissions of particulate material (PM) from burning wood for home heating, increased vehicle emissions from engine cold starts, and reduced ventilation due to unfavorable meteorological conditions (Malek et al., 2006; Silcox et al., 2012; Lareau et al., 2013; Whiteman et al., 2014; Largeron and Staquet, 2016). Managing wintertime air pollution episodes requires different strategies than are employed during summertime photochemical pollution episodes. While the latter have been

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studied more extensively, the relative lack of understanding of the factors impacting wintertime air quality could potentially lead to ineffective air quality management decisions.

The typical severe wintertime PM episode is associated with stagnant atmospheric conditions that result from a combination of meteorological and topographic factors. The stagnation occurs under a large-scale high-pressure system that leads to subsidence (downward atmospheric motion), and is normally associated with clear skies, cold nights, and low surface wind speeds (Wolyn and McKee, 1989; Whiteman et al., 1999, 2001). During winter when there is reduced solar heating of the surface, these conditions will also be associated with a shallow planetary boundary layer (PBL). At night under clear skies, a strong surface temperature inversion can occur, and this condition can extend through the daylight hours when snow cover is present. The combination of a shallow, stable PBL and minimal horizontal advection can lead to the buildup of high pollutant concentrations, especially when emissions also increase due to activities associated with cold temperatures, such as wood burning and vehicle cold-starts and idling.

The effects of stagnation are exacerbated by valley topography where cold-air pooling can occur (Whiteman et al., 2001, 2008; Lareau et al., 2013; Chachere and Pu, 2016). A cold-air pool forms when surface cooling leads to low-level atmospheric stability while the valley topography inhibits horizontal advection, enhancing the stagnant condition. The result is that persistent cold-air pools can lead to exceptionally high pollution levels. These events have been the focus of several studies. Green et al. (2015) compared trends in several cities in the western United State, and additional targeted studies there have been conducted in the Treasure Valley in Idaho (Kuhns et al., 2003; Stockwell et al., 2003), the Cache Valley in Utah (Malek et al., 2006; Silva et al., 2007), Salt Lake City, Utah (Silcox et al., 2012; Lareau et al., 2013; Whiteman et al., 2014; Holmes et al., 2015), and near Reno, Nevada (Chen et al., 2012). Outside of the U.S., the effects of cold-air pools on PM levels have been investigated in the Chamonix Valley (Chazette et al., 2005) and the Arve River Valley (Chemel et al., 2016; Largeron and Staquet, 2016) in France, and in Nelson, New Zealand (Grange et al., 2013). Current modeling capabilities have proven inadequate for predicting the severity of the pollution impacts of these events (Zhang et al., 2014; Holmes et al., 2015).

The generalized conceptualization of a stagnation event implies clear-sky conditions, and such conditions have been the primary focus of past studies. However, the existence of cold-air pools can also lead to a different meteorological condition, wherein a persistent low-level cloud layer forms. The presence of clouds inhibits surface daytime warming and nighttime cooling and thus disrupts the typical diel pattern in boundary layer mixing (Wolyn and McKee, 1989; Whiteman et al., 2001; Zhong et al., 2001). These dynamics have been described previously (Pataki et al., 2005), but they have proven difficult to capture in meteorological models and thus remain challenging to forecast (Reeves and Stensrud, 2009; Reeves et al., 2011; Hughes et al., 2015; Pu et al., 2016). The specific impacts of persistent clouds on air pollution within valley cold air pools have not been thoroughly examined.

In two recent studies, air quality has been measured during periods of persistent low-level cloud within cold air pools, revealing notably different characteristics than are observed during clear sky stagnation conditions (Wallace et al., 2012; Mwaniki et al., 2014). Unlike the elevated air pollution observed during nighttime surface inversions under cold clear sky conditions, during these cloudy events there was instead a significant decline in most air pollutants, and almost no diel variability. This phenomenon was first noted in the Treasure Valley in Idaho in the United States during the winter of 2008–09, when the area became persistently foggy during a week-long stagnation period.

Here we present a more thorough examination of the phenomenon using observations made in Washington State's upper Yakima Valley in January 2013, as part of the Yakima Air Wintertime Nitrate Study (YAWNS). Although Yakima is compliant with the United States federal 24-h fine particulate material ($PM_{2.5}$) standard, monitored wintertime $PM_{2.5}$ concentrations frequently approach the standard. Yakima is unusual within the region in that a significant fraction of the wintertime $PM_{2.5}$ is comprised of particulate nitrate; YAWNS was commissioned by the Washington State Department of Ecology to better understand conditions leading to elevated wintertime aerosol nitrate. An extended regional stagnation period occurred during the study, beginning on 12 January, leading to the formation of a cold pool within the valley. Clear skies characterized the first few days of the period, but then a cloud layer formed over the Yakima Valley that persisted for the next seven days. We present here a detailed analysis of the air quality characteristics for the clear and cloudy stagnation periods, relating the meteorological conditions to observed changes in the trace gas and particulate pollutants.

2. Study design

2.1. Site description

The YAWNS observations were made from 5 to 27 January 2013, in Yakima, Washington in the United States (Lat: 46.6° N, Lon: 120.5° W). Yakima is a small city (population 93,101, estimated 2012) located within the Upper Yakima Valley. The valley is bounded by the Cascade Mountains to the immediate west, and by east-west ridges to the north and south that eventually merge several kilometers to the east (Fig. S1). The topography forms an enclosed basin at the surface that restricts horizontal air flow within the valley. Yakima has a semi-arid climate due largely to it location in the rain shadow of the Cascade Mountains. January is its second wettest month (after December), with 29.0 mm of precipitation falling on average (1981–2010 mean). Mean daily high and low temperatures during January are 3.7 and −4.6 °C, respectively, making it the second coldest month of the year on average (again after December) (NOAA NOWData, 2013).

The Washington State University Mobile Atmospheric Chemistry Laboratory (MACL) was deployed for the study to the campus of Yakima Valley Community College (YVCC) (Lat: 46.58854°, Lon: 120.5283° W, Elev. 327 m), located in a medium-density mixed residential and commercial neighborhood approximately 1 km west of the urban center. There were major surface streets approximately 150 m west and 400 m south of the site. In the immediate vicinity, there was little vehicle traffic except for small amounts of student parking. Significant amounts of wood smoke were emitted in the neighborhoods near the sampling site due to use of wood fuels for wintertime home heating (VanderSchelden et al., 2017).

2.2. Measurements

The MACL trailer provided a temperature-controlled environment for operating the instrumentation during the study. A10-m crank-up tower mounted on the trailer elevated sensors and sampling inlets above the immediate surroundings. For YAWNS, the primary trace gas sampling line was mounted at 10 m, a heated aerosol sampling inlet was mounted at 9 m, and a dedicated NO_x/NO_y inlet line was located at 8 m above ground level. A full discussion of the MACL facility and the instrumentation used during the YAWNS study can be found in the project report (Washington Department of Ecology, 2014); those measurements used for the present analysis are briefly described here. Most instruments