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Asian Long-range Transport in Relation to Atmospheric Rivers in Northern California

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ASIAN LONG-RANGE TRANSPORT IN RELATION TO ATMOSPHERIC
RIVERS IN NORTHERN CALIFORNIA

A Thesis

Presented to

The Faculty of the Department of Meteorology & Climate Science

San José State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

by

Catherine N. Liu

August 2019

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The Designated Thesis Committee Approves the Thesis Titled

ASIAN LONG-RANGE TRANSPORT IN RELATION TO ATMOSPHERIC
RIVERS IN NORTHERN CALIFORNIA

by

Catherine N. Liu

APPROVED FOR THE DEPARTMENT OF METEOROLOGY & CLIMATE
SCIENCE

SAN JOSÉ STATE UNIVERSITY

August 2019

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ABSTRACT

ASIAN LONG-RANGE TRANSPORT IN RELATION TO ATMOSPHERIC RIVERS IN NORTHERN CALIFORNIA

by Catherine N. Liu

The study investigated the effect of aerosol long-range transport on precipitation over northern California during atmospheric river (AR) events in the 2017 cold season (January-April). ARs in 2017 were among the strongest to date and the intense precipitation associated with the ARs resulted in flooding, destruction of property, and contamination of water supplies. The aerosol optical depth (AOD) from Moderate Resolution Imaging Spectroradiometer (MODIS) data showed Asian dust traveling across the northern Pacific Ocean along with AR events. Aerosol measurements in California, provided by the Interagency Monitoring of Protected Visual Environments (IMPROVE), showed that more Asian dust tends to be observed over the coast while non-Asian/localized dust is observed inland. A mixture of Asian and localized dust was observed over the mountains, although higher amounts of both were observed in the spring (March-April). Back trajectory analysis confirmed that Asian aerosols were transported along with the air parcels, and each AR event had its own transport pattern in terms of horizontal advection and vertical lifting. The study resulted in low correlations between precipitation and aerosols, which suggests that aerosols contributed little to the increase of local precipitation during the 2017 AR events.

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CHAPTER 1: INTRODUCTION

In April 2017, California lifted its State of Emergency declared in January 2014 in response to a five-year drought (“Governor’s Drought Declaration”). The 2017 water year alone (October 2016-April 2017) saw significant amounts of rain, with the majority of station readings in California reading above 120% of normal levels. For example, Los Angeles International Airport reached 128% of its normal rain total compared to the previous year at 57% of its normal level (California Nevada River Forecast Center [2017]; [2016]). While the rain alleviated drought conditions within the state, the intense precipitation resulted in flooding of cities and freeways, mudslides and mountain trail erosions, destruction of property, and contamination of water supplies, all of which threaten public safety.

The motivation for the study is to improve precipitation forecasts and prepare for future extreme events by understanding the dynamics and characteristics of atmospheric phenomena that contribute to U.S. west coast precipitation amounts. To start, most of California’s rainfall arrives during the cool months (October-March) when low level jets draw heat and moisture from the tropics, near Hawaii, northeastward to the midlatitudes (Dettinger 515-518). This strip of heat and moisture to the North American West Coast is commonly known as the Pineapple Express, or an Atmospheric River (AR) (Eiserloh and Chiao 1-2). ARs are usually characterized by a length of around 2,000 km and a width up to 1,000 km. The air column typically has at least 2 cm of integrated water vapor (IVW), or

greater than $250 \text{ kg m}^{-1}\text{s}^{-1}$ of integrated water vapor transport (IVT), within the first 2.5 km from the surface and a center of strong winds at 2 km (Neiman et al. 23; Ralph et al. “Calwater” 1213-1214).

Recent studies have been using IVT measurements in place of IVW since IVT is highly correlated with winter precipitation over the U.S. West Coast (Rutz et al. 908), as well as being strongly correlated with precipitation over terrain (Dettinger 515-518; Rutz et al. 908; Y. Wang et al. 6894-6899). The 2017 heavy rainfall, attributed to consecutive AR events that occurred multiple times during January and February, gave rise to the question of what made the 2017 AR events occur more frequently and with more rainfall. One consideration is cloud-aerosol interactions, particularly due to long-range transport. Long-range transport is used to describe aerosol and gas transfer through the atmosphere between continents, which has the potential to increase greenhouse gas (GHG) concentrations, such as surface ozone, and particulate matter in other parts of the globe outside their place of origin (Y. Wang et al. 6894-6898). For example, Ding et al. used Lagrangian particle dispersion modeling (LPDM) with Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) and found that the increase in ozone and carbon monoxide had traveled to Hong Kong from Southeast China via long-range transport. Although the distance traveled is not as far as the northern Pacific, the study showed how aerosol transport affects areas outside of their original locations (9475-9487). More importantly, the aerosols affect the microphysics in clouds by acting as cloud condensation nuclei

(CCN) and ice nuclei (IN) (Creamean et al."Dust" 1572-1577). As a result, public health and local environmental conditions are also affected (Y. Wang et al. 6894-6898).

Previous studies indicate that Asia is the leading contributor of anthropogenic aerosols over the northern Pacific. North America, which is situated downwind, receives much of that pollution (Y. Wang et al. 6844-6898; Liang et al. 2-14). With an increase of particulate matter in the atmosphere, there is an interest in Asian aerosol effects on cloud dynamics such as deep convective clouds over the northern Pacific (K. Wang et al. 1-21; Zhang 5295-5298). Aerosol long-range transport from the Asian continent to the western coast of the United States consists of two pathways, referred to as the outflow (from the Asian continent) and import (to the North American continent) (Liang 2-14). First, as convection occurs, and is especially strong in the spring and summer, aerosols are injected upwards into the troposphere where they are transported across the northern Pacific via midlatitude cyclones. As aerosols reach the northeastern Pacific, those in the free troposphere are pulled westerly through advection, while those closer to the surface are transported directly along the boundary layer. The free troposphere transport then continues with either subsidence in the subtropical Pacific high, or through the dry air in the upper troposphere sinking behind cold fronts, or by subsidence induced by mountain waves as it crosses the North American western coast (2-14).

One of the uncertainties that contribute to the difficulty in understanding cloud dynamics is the effect of aerosols on cloud microphysics. As mentioned earlier, aerosols function as CCN and IN, the building blocks of cloud formation. Uncertainties result from aerosol properties, such as mineral versus anthropogenic, which have varied effects on cloud growth, precipitation, location, and intensity. In some cases, studies have shown different findings for the same aerosols (Creamean et al. "Dust" 1572-1577; "Changes" 7296-7306; Liang 2-14; K. Wang et al 1-21; Zhang 5295-5298; Fan 81-99; Ault et al. 1-14; Patil 1-7). Creamean et al. found that dust aerosols originating from a number of deserts, ranging from the Sahara in Africa to the Gobi and Taklimakan in Asia, were a key factor for the IN formation, invigorated convection, and enhanced precipitation, especially in mixed-phase clouds ("Changes" 7296-7306). Also, aerosols lifted to heights of at least 5,000 m were able to travel longer distances, as seen with the Taklimakan desert dust that was recorded to have circled the earth in thirteen days. Their study also discussed the seasonality of dust aerosol with Taklimakan dust detection maximums between April and May. The Gobi desert, despite being frozen during the winter, is still an important dust source because of the strong Siberian winter storms that blow through it. Lastly, the Sahara is a major mineral source since dust is lifted all year round and not limited seasonally like the Taklimakan or Gobi deserts (Creamean et al. "Dust" 1572-1577). Ault et al. also showed that dust leads to the formation of IN, increasing riming rates, the rate at which frost covers an ice particle, and increasing precipitation (1-14).

While Creamean et al. and Ault et al. showed IN formation due to dust, which contributes to increase in precipitation, Patil et al., on the other hand, found that an increase in Asian dust aerosols inhibited deep convective clouds and ice water path. This led to an increase in cloud top pressure, almost opposite of what was recorded by the other two studies (1-7).

Despite the discrepancies in dust aerosol effects in various studies, they all agree that aerosol transport is the strongest in the spring, when Asian dust and pollution emissions are the highest (Y. Wang et al. 6844-6898; Creamean et al. "Dust" 1572-1598; Ault et al.1-14; Patil et al.1-7; Heald et al.1-11). However, little to no literature has described the extent and effects of Asian aerosol transport on the U.S. West Coast during the cool months (October-March) in terms of atmospheric processes (precipitation, development, etc.). That being said, Ault et al. detected mineral dust from Asia in orographic precipitation over California during the CalWater Early Start campaign which examined two extratropical cyclone systems between February 22 and March 11, 2009. The enhancement of horizontal water vapor transports and integrated water vapor (I WV) concentrations that resulted from the two systems was attributed to AR conditions (1-14).

Still, the question of how the long-range transport of Asian aerosols affect precipitation amounts, system location, and AR frequency, particularly for the 2017 events, remains. The study will compare the properties of six 2017 AR events to a ten year (2006-2016) climatology in order to (1) understand the effect

of Asian long-range aerosol transport on different locations over northern California during ARs, (2) examine how long-range transport of aerosols affect precipitation intensity, location, and frequency of ARs over northern California, and (3) assess how aerosols are correlated with precipitation associated with AR events. It is hypothesized that there is a positive correlation between aerosols and precipitation in that aerosols will have contributed to the precipitation enhancement of the 2017 AR events.

CHAPTER 2: ATMOSPHERIC RIVER EVENTS AND SYNOPTIC CONDITIONS IN 2017

For the study, the months of January to April were taken into consideration, with a focus on the months of January and February as the rainfall was particularly heavy during this time. The highest amounts of observed rainfall occurred at the coasts and mountains, as seen in Figure 1a (National Weather Service), with amounts exceeding 20 inches (508 mm). Inland measurements were up to 6-10" (152-254 mm). Rainfall amounts were higher overall in northern California and decreased towards the south, as well as further inland on the other side of the Sierras. The trend is also observed during March and April. In comparison to climatological rainfall norms collected by the National Oceanic and Atmospheric Administration (NOAA) since 2005, the majority of California experienced a 110% to 600+% increase during January and February 2017 (Figure 1b), with the highest percentage changes in the mountains. For March and April, 2017 rainfall was at or slightly below normal amounts for central California, while southern California amounts were below 50%. Most of the damages as a result of flooding and erosion occurred during January and February. Overall, California experienced at least 150% of its normal rainfall amounts for 2017. For this reason, case studies were taken from these two months.

Figure 1. (a) Monthly observed precipitation, and (b) Monthly percent of normal precipitation (National Weather Service).

2.1. January 2017

The first series of AR events occurred from 01/07-01/11, bringing as much as 20" (508 mm) of rainfall to areas such as Strawberry Valley, located at the western base of the Sierras. On 01/08, the Uvas Creek in Santa Clara County flooded roads and properties with up to three feet (914.40 mm) of water due to the Uvas Reservoir overflowing and spilling into the creek. The reservoir typically receives a monthly average of 4.88" (124.95 mm) of rainfall during January, but experienced a 48 hour rainfall total of 7.05" (179.07 mm) in 2017. Other incidents that occurred during this event were road flooding in Morgan Hill and 48 hour rain gauge amounts of 8.74" (222 mm) at the Guadalupe Watershed, 9.49" (241.05 mm) at Uvas Canyon County Park, and 6.73" (170.94 mm) at the Lexington Reservoir. January rainfall amounts at these areas are generally 3.47", 3.63", and 3.97" (88.14 mm, 92.02 mm, 100.84 mm), respectively (*2017 Flood Report* 2-8).

The second series of AR events occurred between 01/17 and 01/19 when southern California received up to 1.5" (38 mm) of rainfall, central California received up to 4" (101 mm), and northern California received up to 6" (152 mm) ("Water Year 2017 Precipitation in California").

2.2. February 2017

The third series of AR events occurred between 02/06 and 02/10. Around 6.5" (165.1 mm) were recorded for areas at higher elevations, as well as reports of river flooding in parts of Sonoma County and the San Francisco Bay area, such

as the San Francisquito Creek flooding nearby businesses and the U.S. Highway 101 bridge. In addition, the Oroville Dam flooding incident that led to the evacuation of over 188,000 people mid-February was partly caused by the heavy rainfall the lake experienced on 02/07 (White et al. 55-67). The fourth series of AR events occurred between 02/15 and 02/21. From 02/15-02/17, two storm systems saturated the soil which led to runoff and reservoir overflow, as seen with the Anderson Reservoir spillage on 02/18. On 02/21, the combination of Coyote Creek and Anderson Reservoir overflow caused numerous flooding events in San Jose, inundating several neighborhoods, businesses, and roads (2017 Flood Report 9-30).

In term of post flood damages, Santa Clara Valley Water District's 2017 Flooding Report estimated that San Jose identified about \$50 million in private property damages and \$23 million in public property damages. Around 14,000 people were evacuated during these events, with no reports of injury or death during rescue operations (2017 Flood Report 31).

2.3. Synoptic Conditions and Observations

The synoptic conditions for the four different AR events are examined to see if a specific synoptic condition can provide favorable conditions for enhancing the long-range aerosol transport, and how the potential vorticity (PV) associated with the upper-level jet evolves with time during the AR events.

Figure 2 shows the map of ERA-Interim PV at 250 hPa, specific humidity (q) overlaid by the horizontal wind at 850 hPa, temperature at 850 hPa, and sea

level pressure for AR events during January-February 2017 (Domain: 5-80°N, 100-255°E). Strong upper-level troughs with large PV were located offshore near the coast of California at this time, which implied that stratospheric air through the tropopause (PVU=1.5 PVU is regarded as a dynamic tropopause) penetrated downward to the mid-troposphere (~ 500 hPa, not shown). PV intrusion mostly occurs anticyclonically (i.e., clockwise rotation) over the Pacific and the western U.S., extending toward the west coast of the U.S. On 01/19/17, unlike others, PV penetrated the western U.S. cyclonically, mimicking cyclonic wave breakings (Thorncroft et al. 17-53). The filamentary, northward directing water vapor bands over the Pacific reflected the lower-level water vapor field's response to the upper-level trough in the developing mid-latitude baroclinic system (Fig. 2b). For all AR events, the high and narrow water vapor band was elongated from southwest to northeast with strong southwesterlies extending toward the California coast. A low temperature feature developed offshore, which seemed to be associated with the narrow and deep penetration of elevated upstream PV (Figs. 2a, c). The region of maximum horizontal temperature gradient traveled farther south, and the temperature was slightly cooler inland over areas north of the San Francisco Bay Area, especially in February AR cases. Di-pole patterns of surface low and high pressures developed during all AR events (Fig. 2c). A strong contrast between surface low and surface high was shown both in the Pacific and on the western coast of the U.S., confirming that these are prominent features of AR events. Low sea level pressure also developed over the

northeastern Pacific, which was associated with the upper level trough for all AR events.

Figure 2. Longitude-latitude cross section of (a) potential vorticity (PV) at 250 hPa with $\text{PVU} = 1.5$ ($1 \text{ PVU} = 10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$); (b) water vapor mixing ratio (q, g kg⁻¹) overlaid by horizontal wind vector (m s⁻¹) at 850 hPa; (c) temperature (°C) at 850 hPa; (d) sea level pressure at 00Z 01/07/17 (1st row), 01/19/17 (2nd row), 02/09/17 (3rd row), and 02/21/17 (4th row) obtained from the ERA-Interim reanalysis data.

By two to three days after each AR event, the high water vapor moved inland with cooler temperatures as the low sea level pressure moved closer to the western U.S. The upper level trough was also weakened and decayed (not shown). Overall, as the AR approaches the western U.S., a strong upper-level trough with large PV rotating either anticyclonically or cyclonically is located offshore near the coast of California, leading to strong low-level southerlies and southwesterlies over the coast with relatively dry air mass. This also suggests that the large-scale upper-level trough extending toward northern California may provide a favorable condition for the long-range aerosol transport from Asia during AR events.

CHAPTER 3. DATA AND METHODOLOGY

3.1. Satellite Data

Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua was used to determine whether there was Asian long-range transport occurring during the 2017 cases chosen. Aerosol optical depth was measured daily at 500 nm with 1° resolution. MODIS data were visualized one week before the AR event, as it takes approximately five to seven days for Asian dust to travel across the northern Pacific. As shown in Figure 3, there is a visible transport of aerosol across the northern Pacific. Cloud cover contributes to most of the missing data, but in some cases MODIS-Aqua was able to pick up AOD signals along the edges of cloud cover. It is acknowledged that there are limitations to using satellite data because of cloud cover. While alternate methods include the use of Lidar to visualize from the surface up, this is not currently possible over the ocean. In the case of CALIPSO data, the swath rarely went over the areas of interest. Another alternative would be to use reanalysis or model data. However, the goal of the study was to first use observational data. MODIS was used as part of the motivation for the study to see whether aerosols were present during the chosen AR days.

Figure 3. 2017 Daily 1° Moderate Resolution Imaging Spectroradiometer-Aqua Aerosol Optical Depth (MODIS-AOD) (550 nm) for the period of (a) 01/03–01/11, and (b) 02/09–02/17. These are examples of atmospheric river (AR) events that occurred in January and February. Satellite imaging was examined 5+ days before the 01/11 and 02/16 AR events. Black lines represent aerosol particulates being transported across the northern Pacific during AR event weeks.

The Special Sensor Microwave Imager Sounder (SSMIS) data (Wentz et al.), provided by NOAA/NESDIS at 0.25° grid spacing and average twice daily (e.g., 00-12Z and 12-24Z), was employed to visualize AR event progression off the western coast of the U.S. in January and February (Figure 4). Some examples of four case studies (01/07-01/10, 01/17-01/19, 02/06-02/10, and 02/15-02/21) are shown in Figure 4. AR events can be identified when water vapor amounts are at least 2 cm of IWV.

Figure 4. SSMIS I WV 0.25° grid spacing and average twice daily from 00-12Z (am) and 12-24Z (pm) for four AR events, 01/07-01/11, 01/17-01/19, 02/06-02/10, and 02/15-02/21 of 2017. Examples of AR events that occurred during these time periods are shown. Water vapor amounts above at least 4 g/cm^2 ($> 2 \text{ cm}$) represents an AR.

3.2. Observation Site Data

The Interagency Monitoring of Protected Visual Environments (IMPROVE) data were used for aerosol measurements in California (Cremaean et al. “Dust” 1572-1577; Heald et al. 1-7; Interagency Monitoring Protected Visual Environment; Creamean et al. “Chemical” 13-25). Measurements were taken for twenty-four hours every three days. A combination of sites were used to represent differences between coastal (Redwood National Park, Point Reyes National Shores, Pinnacles National Park), inland (Trinity, Fresno), and mountainous (Lassen Volcanic National Park, Bliss State Park, Kaiser) areas (Figure 5). The Trinity site was omitted from the final analysis since measurements ended in 2015. Therefore, Fresno was the only site to represent inland conditions.

Figure 5. The seven observational sites used in the study were taken to represent data at coastal (Redwood NP, Point Reyes NS, and Pinnacles NM), inland (Fresno), and mountainous (Lassen Volcanic NP, Bliss SP, and Kaiser) regions. Elevation was recorded in units of meters above mean sea level.

Iron, calcium, and soil measurements were used to determine Asian dust amounts at the sites. Using a method employed in Creamean et al., the dust source was separated into Asian or localized dust using a ratio of iron (Fe) to calcium (Ca), which is generally accepted as the composition of Asian desert dust (“Chemical” 13-25; VanCuren et al. 1-19). Ratios less than one indicated Asian dust presence, hence long-range transport, while ratios greater than one indicated localized dust. Based on Fe/Ca ratios in Equation (1), soil measurements collected at each site, for each day, were categorized as either all Asian dust or all localized dust for simplicity.

$$if \begin{cases} \frac{Fe}{Ca} < 1: Asian \text{ dust} \\ \frac{Fe}{Ca} > 1: Localized \text{ dust} \end{cases} \quad (1)$$

Other aerosols analyzed from the sites were black carbon (BC) and sulfate (SO₄).

3.3. Integrated Water Vapor Transport and Precipitation Data

Integrated water vapor transport (IVT) measurements were taken from the Modern-Era Retrospective analysis for Research and Applications, version 2.1 (MERRA 2), with a horizontal resolution of 0.5° by 0.66°. Reanalysis data, measured every three hours, were provided by the AR catalog created by Rutz et al. Because this was a gridded dataset, IVT measurements were taken from the latitude and longitude pairs closest to the IMPROVE site locations. It is acknowledged that this may lead to minor differences in analysis results.

However, for the purposes of the study, IVT amounts closest to the observational sites are sufficient. To match with IMPROVE dataset dates, daily IVT averages were calculated every three hours from the MERRA dataset, and then plotted every three days. IVT measurements were used to note whether an AR event was present (if measurements were greater than $250 \text{ kg m}^{-1} \text{ s}^{-1}$), along with calculating AR frequency and strength, as later discussed in Section 4.2.

The Climate Prediction Center Unified Gauge-Based Analysis of Daily Precipitation over CONUS Real-time (NCEP CPC RT) was used for daily precipitation measurements. The dataset has a resolution of $0.25^\circ \times 0.25^\circ$ and was manipulated to match IMPROVE's every three-day temporal resolution. Precipitation data were available beginning in 2007, therefore climatological precipitation and aerosol correlations only included data from 2007-2016.

3.4. Back Trajectory Model Simulation

The NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used to analyze parcel back trajectories (Creamean et al. "Chemical" 13-25). The Global Data Assimilation System (GDAS) 0.5 degree archive ensembles at Redwood NP (coast), Fresno (inland), and Lassen Volcanic NP (mountain) were simulated at 3, 5, and 7 km for 10 days. These three heights were chosen to observe parcel lifting during the trajectory track. During model set-up, heights were chosen in meters, but are displayed in hPa for the trajectory plots. This was to provide an easier way of following parcel heights along the track as well as comparison with synoptic plots.

CHAPTER 4. RESULTS

4.1. Dust Measurements

The total dust amounts from 01/01 to 04/28 from the seven sites were investigated. As shown in Figure 6, there was an increase in instances of localized dust presence as the system moved southward among the coastal sites. In terms of the inland site, Fresno dust measurements were mainly attributed to localized dust, which is most likely the result of its surrounding city and/or agricultural land. At the mountainous sites, there were a mixture of Asian and localized dust. However, there is a similar pattern where there was more dust present at the northern sites and less at the southern sites. Elevation differences might be a reason for why the mountainous sites showed Lassen Volcanic (northernmost site) as localized dust dominant compared to Kaiser (southernmost site). The Lassen Volcanic site is recorded to be on the windward side of the mountain, as well as about 1,000 m lower in elevation than Bliss or Kaiser. Overall, these results are similar to findings in Rutz et al. (909-919).

Figure 6. 2017 Total dust amounts. The most northern and southern sites for the coastal and mountainous regions were selected to show aerosol patterns as the AR system moved along the U.S. West Coast. At each site, dust amounts were totaled from January to April then separated into Asian-influenced (blue) or non-Asian/localized dust influenced (red).

4.2. Integrated Water Vapor Transport Measurements

Likewise, the time evolution of dust and IVT amounts during 01/01-04/28 from the seven sites was also observed. Figure 7 shows Redwood NP, Fresno, and Lassen Volcanic NP to represent coasts, inland, and mountainous sites. IVT associated with AR events are distinguishable from non-AR events when IVT amounts exceed $250 \text{ kg m}^{-1}\text{s}^{-1}$.

Figure 7. 2017 time evolution of Asian, non-Asian dust and IVT of all three regions in Fig. 5. At each site, Asian dust (blue) influenced, non-Asian/localized dust (red) influenced, and IVT amounts (orange) are displayed every three days from January to April.

When comparing the coastal sites to each other, it is noted that IVT amounts drop (600 , 400 , and $350 \text{ kg m}^{-1}\text{s}^{-1}$, respectively) as events travelled down the coast from Redwood NP to Pinnacles NP. This aligned with observations in the previous studies mentioned in Chapter 1. In addition to lowering IVT

measurements, there was also an increase in instances of localized dust presence as moving southward among the coastal sites. In terms of the inland site, Fresno dust measurements were mainly attributed to localized dust. This suggests that the amount of localized dust present inland typically exceeds any possible Asian dust that is transported over the Pacific. Another possibility is that there was a lack in Asian dust present due to wet deposition, where rainfall would wash away the Asian dust. At the mountainous sites, the majority of dust measurements appeared around the beginning of March and onward. This is likely because East Asia experiences dust events during the spring season rather than the winter. Unlike the coastal sites, IVT measurements at the mountainous sites were slightly higher further south at Bliss SP and Kaiser than at Lassen Volcanic NP. Elevation differences might be a reason for why the mountainous sites did not follow the North-South decrease in IVT trend.

4.3. 2006-2016 Climatological Analysis in Comparison to 2017

The evolution of aerosol for January to April from 2006-2016 was constructed using Redwood NP, Fresno, and Lassen Volcanic NP to represent coasts, inland, and mountains, respectively (Figure 8). It is seen that the majority of dust amounts at coastal sites were attributed to Asia, with some amounts due to localized dust. Inland at Fresno, localized dust was the majority with hardly any trace of Asian influenced dust. Again, this is not surprising considering Fresno is located in the valley, where it is expected that localized dust is trapped compared to coastal or mountainous sites. Lastly, the majority of Asian and locally

influenced dust varied from year to year at the mountainous regions. This is more so in the case of Lassen Volcanic NP due to the fact that the observation site is located at a lower elevation on the windward side of the mountain.

Figure 8. 2006-2016 total dust amounts. Dust amounts per year were totaled then separated to examine how much of that dust was Asian and non-Asian influenced.

AR frequency and strength comparisons between the 2006-2016 climatology and year 2017 were conducted (Table 1). For example, Redwood NP usually receives around four AR events per year. This was calculated by visually counting the number of IVT peaks greater than $250 \text{ kg m}^{-1}\text{s}^{-1}$ (Figure 9). Five AR events were experienced in 2017, one moderate event and four weak events, according to the strength chart created by Ralph et al. This chart categorizes AR strength by IVT measurements where $250\text{-}500 \text{ kg m}^{-1}\text{s}^{-1}$ are weak events, $500\text{-}750 \text{ kg m}^{-1}\text{s}^{-1}$ are moderate events, $750\text{-}1000 \text{ kg m}^{-1}\text{s}^{-1}$ are strong events, $1000\text{-}1250 \text{ kg m}^{-1}\text{s}^{-1}$ are extreme events, and greater than $1250 \text{ kg m}^{-1}\text{s}^{-1}$ are exceptional events (“A Scale” 275). Apart from 2017, years 2010, 2012, 2014, and 2015 also experienced moderate AR events. The year 2012 experienced five weak and one moderate AR event, while 2010 and 2015 experienced two weak and one moderate AR event. Point Reyes NS, further south, typically receives an average of five weak AR events. However, 2017 experienced eleven weak events. Likewise at Pinnacles NP, 2017 experienced six weak events when the site typically receives one to two AR events. Inland at Fresno, similar to results found above, the site usually receives one to two events, while three occurred in 2017. Similarly at the mountainous sites, from north to south, Lassen Volcanic NP, Bliss SP, and Kaiser received six, five, and four weak events, respectively, in 2017. These sites usually received an average of three, one, and zero AR events. Table 1 summarizes 2006-2017 AR frequencies and strengths. For each site, AR frequency and strength were determined based on 1) the number of IVT

peaks above $250 \text{ kg m}^{-1}\text{s}^{-1}$ for a given year, which is the minimum IVT level for an AR event to be present, and 2) classifying strength based on the chart created by Ralph et al.: weak ($250\text{-}500 \text{ kg m}^{-1}\text{s}^{-1}$), moderate ($500\text{-}750 \text{ kg m}^{-1}\text{s}^{-1}$), strong ($750\text{-}1000 \text{ kg m}^{-1}\text{s}^{-1}$), extreme ($1000\text{-}1250 \text{ kg m}^{-1}\text{s}^{-1}$), and exceptional ($>1250 \text{ kg m}^{-1}\text{s}^{-1}$) (“A Scale” 275). Overall, 2017 has seen more frequent AR events compared to the last 10 years.

Table 1. January-April 2006-2017 AR Frequency and Strength

Year	Coasts				Inland				Mountains												
	rdwd	freq	strn	ptrey	freq	strn	pinn	freq	strn	fres	freq	strn	lavo	freq	strn	bliss	freq	strn	kaiser	freq	strn
6	6	5	w	6	6	w	6	1	w	6	1	w	6	3	w	6	0	---	6	0	---
7	7	1	w	7	3	w	7	2	w	7	0	---	7	0	---	7	0	---	7	0	---
8	8	1	w	8	2	w	8	1	w	8	1	---	8	0	---	8	1	w	8	0	---
9	9	4	w	9	3	w	9	3	w	9	0	---	9	3	w	9	1	w	9	0	---
10	10	3	w	10	5	w	10	1	w	10	1	w	10	3	w	10	1	w	10	0	---
11	11	4	w	11	8	w	11	3	w	11	2	w	11	3	w	11	1	w	11	0	---
12	12	5	w	12	7	w	12	1	w	12	2	w	12	3	w	12	0	---	12	0	---
13	13	1	w	13	0	w	13	1	w	13	0	---	13	0	---	13	0	---	13	0	---
14	14	1	w	14	6	w	14	2	w	14	3	w	14	3	w	14	0	---	14	0	---
15	15	3	w	15	2	w	15	2	w	15	0	---	15	2	w	15	0	---	15	0	---
16	16	4	w	16	8	w	16	2	w	16	1	w	16	2	w	16	0	---	16	0	---
17	17	4	w	17	11	w	17	6	w	17	3	w	17	6	w	17	5	w	17	4	w

Note: For each site, AR frequency (freq) and strength (strn) were determined based on 1) the number of IVT peaks above $250 \text{ kg m}^{-1} \text{ s}^{-1}$ for a given year as seen in Figure 8, which is the minimum IVT level for an AR event to be present, and 2) classifying strength based on the chart created by Ralph et al.: weak ($250\text{-}500 \text{ kg m}^{-1} \text{ s}^{-1}$), moderate ($500\text{-}750 \text{ kg m}^{-1} \text{ s}^{-1}$), strong ($750\text{-}1000 \text{ kg m}^{-1} \text{ s}^{-1}$), extreme ($1000\text{-}1250 \text{ kg m}^{-1} \text{ s}^{-1}$), and exceptional ($>1250 \text{ kg m}^{-1} \text{ s}^{-1}$) ("A Scale" 275).

Figure 9. 2006-2016 aerosols and IVT time series. Column (a) is the climatology for Redwood NP to represent the coasts, column (b) is the climatology for Fresno to represent inland, and column (c) is the climatology for Lassen Volcanic NP to represent mountains. Black lines represent the $250 \text{ kg m}^{-1}\text{s}^{-1}$ limit needed for AR occurrence while the dashed lines in column a represent the $500 \text{ kg m}^{-1}\text{s}^{-1}$ limit needed for a moderate AR event.

In addition to dust, black carbon (BC) and sulfate (SO_4) were also measured at each site. A correlation analysis was conducted between these three aerosol types and precipitation amounts. Figure 10 shows the correlation at coasts, inland, and mountainous sites from climatological data (2007-2016) compared to 2017. NCEP CPC RT data began in 2007, therefore climatological correlations were calculated from 2007-2016.

Figure 10. R-value correlations between dust (Asian: blue, nonAsian: red), BC, and SO₄ against precipitation. The sites shown are Redwood, Fresno, and Lassen Volcanic to represent coasts, inland, and mountains, respectively. Climatological data (2007-2016) is represented in the lighter colored circles while 2017 data is represented by the darker diamonds.

Tables 2 and 3 summarize the correlation coefficient (R-values) for all sites. Overall, R-values varied from being low climatologically to between 0.30-0.50 for 2017 data. Correlation values with low P-values ($\alpha = 0.10$) at 90% confidence are statistically significant and are highlighted. The majority of the correlations for

both time periods were negative, meaning that aerosols were found to have a suppressing effect on precipitation. This trend was also found when calculating correlations between aerosols and IVT (not shown). Starting with climatological data (Table 2), statistically significant correlation values appeared to be Asian dust and SO₄ for Redwood NP (-0.15 and -0.12). While these values in and of themselves were relatively small, these were the highest at this site that also had p-values less than α . BC contributed to the highest statistically significant negative correlation in five out of seven sites at the two most southerly coastal sites, and at each of the mountainous sites (-0.11, -0.18, -0.12, -0.11, and -0.14). SO₄ amounts were also slightly higher at the southerly mountainous sites and Pinnacles NM (-0.09, -0.12, and -0.08). In terms of 2017 data (Table 3), Asian dust and SO₄ were the most likely contributors to precipitation suppression at Redwood NP with values of -0.44 and -0.43, respectively. At Point Reyes NS, BC and SO₄ had the highest negative correlation (-0.30 and -0.27). Pinnacles NM, Fresno, Lassen Volcanic, and Bliss all had higher negative correlations of locally influenced dust, BC, and SO₄. This makes sense for the first three sites as they are more inland, or facing inland (Pinnacles, Fresno, Lassen Volcanic), and located near the southernmost half of northern California.

Table 2. 2007-2016 Correlations

	Dust (Asian)		Dust (nonAsian)		Black Carbon		Sulfate	
	R- value	P- value	R- value	P- value	R- value	P- value	R- value	P- value
RDWD	- 0.15	<0.05	0.04	0.48	- 0.23	5.21	-0.12	<0.05
PTREY	- 0.07	0.15	- 0.07	0.19	- 0.11	<0.05	- 0.02	0.76
PINN	- 0.07	0.14	-0.08	0.10	- 0.18	<0.05	- 0.08	0.09
FRES	- 0.03	0.61	- 0.01	0.91	0.02	0.76	- 0.03	0.54
LAVO	- 0.06	0.22	- 0.08	0.09	- 0.12	<0.05	- 0.08	0.10
BLISS	- 0.07	0.14	- 0.07	0.14	- 0.11	<0.05	- 0.09	0.06
KAIS	- 0.09	0.06	- 0.06	0.20	- 0.14	<0.05	- 0.12	<0.05

Table 3. 2017 Correlations

	Dust (Asian)		Dust (nonAsian)		Black Carbon		Sulfate	
	R- value	P- value	R- value	P- value	R- value	P- value	R- value	P- value
RDWD	- 0.44	<0.05	- 0.17	0.47	- 0.64	7.38	- 0.43	<0.05
PTREY	- 0.15	0.37	- 0.18	0.26	- 0.30	0.06	- 0.27	0.09
PINN	- 0.08	0.60	- 0.33	<0.05	- 0.44	<0.05	- 0.37	<0.05
FRES	0.25	0.12	- 0.46	<0.05	- 0.39	<0.05	- 0.39	<0.05
LAVO	- 0.23	0.15	- 0.36	<0.05	- 0.47	<0.05	- 0.39	<0.05
BLISS	- 0.18	0.26	- 0.31	<0.05	- 0.36	<0.05	- 0.28	0.08
KAIS	- 0.14	0.38	- 0.19	0.24	- 0.20	0.23	- 0.20	0.23

Note: Correlation Analysis between aerosols and precipitation at coastal (RDWD, PTREY, PINN), inland (FRES), and mountainous (LAVO, BLISS, KAIS) sites. Highlighted values are correlations (R-values) with P-values at 90% confidence ($\alpha=0.10$).

4.4. HYSPLIT Back Trajectory Analysis

Figure 11a shows the ten-day back trajectories for Redwood NP, Fresno, and Lassen Volcanic NP starting from 01/07/17 at 23Z. It appears that from each location, air parcels originated from East Asia in the deserts of China, which is most visibly shown from the Lassen Volcanic NP ensemble. Figure 11b shows parcel heights during the back trajectory. Parcels started near the surface, below 900 hPa, for the first few days before being vertically advected to around 450-300 hPa between 01/02-01/03. After two to three days, parcels lowered to around 700 hPa when they reached the sites.

Figure 11. HYSPLIT back trajectories from 01/07/17. (a) Redwood, Fresno, and Lassen Volcanic were shown to represent the coasts, inland, and mountains, respectively. (b) Air parcel height levels during the 10-day back trajectories.

The 10-day back trajectories and parcel height comparisons at Redwood NP, for the 2017 AR events on 01/07, 01/19, 02/09, and 02/21, are shown in Figure 12. The trajectories of the four AR events, as shown in Figure 12a, align with those in Figure 11a. Both figures suggest that the origin of the Asian dust for these events are somewhere between northern China and Japan. However, it is interesting to note the differences between tracks for each event. For instance, the ensemble trajectories for 01/07 generally showed patterns of shorter and steeper ridges and troughs as the parcel was advected over the north Pacific. 01/19 and 02/09, on the other hand, generally displayed longer and more zonal ridge and trough movement. In Figure 12b, all four events (01/07, 01/19, 02/09, and 02/21) showed ensemble trajectories where there were steep lifting from the surface to around 450 hPa, with 01/07 and 02/21 being most noticeable. Events with longer and zonal movement generally result in lifting from the surface to around 750 hPa, as seen on 01/19 and 02/09, with some air parcels being an exception. This difference could be a possible explanation for the differences in parcel vertical advection as seen in Figure 12b. To summarize, the majority of parcels were lifted from the surface to higher levels before settling back down to the surface. These track patterns follow and agree with the synoptic conditions described in Figure 2.

Figure 12. HYSPLIT back trajectories at Redwood NP for (a) back trajectories calculated at the first day of 2017 AR events, and (b) 10-day back trajectories (day 0 to day 9, from left to right) at different heights (hPa).

CHAPTER 5. DISCUSSION AND CONCLUSIONS

Comparing the properties of a 2006-2016 long-term analysis to selected 2017 AR events, the study aimed to understand three main processes: 1) the effects of long-range aerosol transport on different terrain regions over northern California, 2) how aerosols affect precipitation intensity, location, and frequency using IVT as a proxy, and 3) how aerosols are correlated with AR associated precipitation. It is shown that more Asian dust tends to be observed over the coast at higher latitudes, while locally influenced dust tends to be observed as the system travels south and inland. In terms of intensity and frequency, 2017 saw more frequent events throughout all sites, yet the strength of each event was about the same as those climatologically. Nonetheless, frequent weak AR events can be just as damaging as one strong AR event. The hypothesis was that aerosols would have enhanced the precipitation from the 2017 AR events (positive correlations). However, all 2017 aerosols had a correlation of less than -0.50. Asian dust and SO_4 appeared to have a slight suppression of precipitation, particularly in the northernmost coastal site, Redwood NP. On the other hand, local dust, BC, and SO_4 appeared to show suppression for all other sites (Table 2). It is interesting to note that BC and SO_4 had higher negative correlations in 2017 when local dust also had higher negative correlations (Table 3). This could indicate that the BC and SO_4 collected at these sites were also locally influenced rather than from long-range transport. In summary, correlation values were low, suggesting that the long-range transport of aerosols from East Asia had little effect on aerosol-

precipitation interactions for both AR events climatologically and 2017. Reasons for low correlation values could be wet deposition and scavenging as the aerosols travel across the northern Pacific. Determining lag time between aerosols and effect on precipitation was attempted, but was difficult to apply for each day and year due to daily variability.

In terms of future work, AR events occurring in March-April, when more dust is present, should be compared to AR events occurring in January- February. Since there were evidence that AR events occurred during the late winter to early spring months (March-April), it would be interesting to see whether there is a difference in aerosol-precipitation correlations seasonally. Another aspect to study would be aerosol amounts, particularly BC and SO₄, leaving East Asia and observing whether those amounts could be tracked across the northern Pacific. Tracking long-range transport of dust is slightly easier because varying mineral ratios can indicate the source of the dust. This is, to my knowledge, not true of BC and SO₄, making it harder to define its exact source.

In addition, future work should look into addressing the lag time between aerosol and precipitation measurements at each site, as this will take wet deposition into account. This will be a challenge since lag time will differ from day to day. Numerical simulations should also be utilized to compare model aerosol transport effects on local precipitation and cloud microphysics to the observation data collected in this study.

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