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North American Monsoon Impacts Southern California's Coastal Low Clouds

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Key Points:

- An increase in free-tropospheric moisture over coastal southern California in summer is attributed to the North American Monsoon (NAM)
- NAM moisture intrusions can diminish southern California coastal low cloudiness by decreasing longwave cloud-top cooling
- These results link two iconic regional climate phenomena of the U.S. Southwest

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Abstract Low-level stratiform clouds modulate California's coastal climate during the warm season. Previous work describing the seasonal and daily variability of coastal low cloudiness (CLC) suggests that in July, August, and September southern California's CLC is under the influence of an additional driver, which has less impact in northern California. In this work, we introduce the link in which free-tropospheric moisture dictated by North American Monsoon (NAM) processes can impact southern California CLC. We use in situ and remote sensing observations, as well as reanalysis and single column model simulations to identify and investigate this previously missing component. We find that monsoonal moisture advected by southeasterly flow from the core NAM region into southern California reduces CLC by diminishing cloud-top longwave cooling. To add to an already complex brew of known factors influencing coastal cloudiness, another one is hereby introduced and should be accounted for in future work.

Plain Language Summary Low-altitude marine layer clouds shade and cool coastal California in spring and summer. When these clouds are low enough that the base of the cloud intercepts terrain (which is known as fog), they additionally add moisture to the landscape during a typically dry time of year in California. Future trends in coastal low cloudiness (CLC) are uncertain. Although CLC impact the whole coast of California and beyond, previous studies have exposed differences in seasonal and daily CLC behavior in southern and northern California. The North American Monsoon (NAM), which becomes active in the US Southwest in summer, brings rain and thunderstorms to the desert southwest. Coastal southern California is on the northwest edge of the NAM influence and typically does not receive much rain from NAM. In this study, we show how low altitude coastal cloud cover in southern California and northern Baja California can be diminished by higher altitude moisture from the NAM. Dry and stable air above the top of low clouds helps to maintain the cloud layer, and higher altitude moisture interrupts this process. To better understand how CLC varies and may change, an accounting of all key drivers of CLC behavior, including the NAM, is needed.

1. Introduction

The Southwest United States has a diverse palette of topography, climate and ecosystems grading from the open Pacific coast to arid interior landscapes. The region straddles the mid and subtropical latitudes and is greatly influenced by proximity to the Pacific Ocean and Gulfs of California and Mexico (Steenburgh et al., 2013). In summertime, while low-elevation southeastern California and southwestern Arizona are the hottest regions of the contiguous U.S. (Steenburgh et al., 2013), relatively cool upwelled water of the Pacific Ocean modulates coastal California climate through sea breeze circulations and shading by low-level stratiform clouds (Iacobellis & Cayan, 2013). Much of California experiences a Mediterranean-like climate and receives most its precipitation from Pacific storms during the cool season (Polade et al., 2017). In contrast, the onset, typically in July, of the North American Monsoon (NAM), provides some temperature relief and up to 50% of annual precipitation to the hot interior Southwest (Douglas et al., 1993; Higgins et al., 2006).

The NAM, like other regional monsoons throughout the globe, is characterized by a large-scale seasonal shift in atmospheric circulation and air masses (Adams & Comrie, 1997; Wang et al., 2021). In the summertime an upper-level monsoon anticyclone sets up above a thermal low, which typically reaches its northernmost position over the Four Corners region (Cavazos et al., 2002). Surface winds shift accordingly from northwesterly to southeasterly at the entrance of the Gulf of California (Bordoni et al., 2004). Importantly the monsoon flow taps into moisture with a varying degree from the Gulf of California, eastern subtropical and/or tropical Pacific and to a

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lesser extent from the Gulf of Mexico (Adams & Comrie, 1997; Turrent & Cavazos, 2009; Wright et al., 2001). Thus, this flow reversal also represents a critical change from a dry to moist airmass. Together with strong surface heating, this moisture can lead to instability and severe thunderstorms. The center and strength of the monsoon ridge is variable and its location impacts patterns of rainfall and severe thunderstorms (e.g., Cavazos et al., 2002; Maddox et al., 1995). The wettest monsoon year in the last 40 years, 1984, was linked to warm sea surface temperatures along southern California and Baja California, a weak North Pacific High, and moisture advection from the tropical Pacific to the core monsoon region and then to southern California (Cavazos et al., 2002).

Observations, reanalysis, regional and climate models agree on an ongoing northwestward expansion of the NAM monsoon high, but since an anomalous ridge does not necessarily drive precipitation extremes, the future effects on the mean behavior of NAM remains uncertain (Pascale et al., 2019; Torres-Alavez et al., 2014; Wang et al., 2021). However, a robust projection of the NAM is a late onset and a late demise of the monsoon rains due to increased sensible heating and tropospheric warming, respectively, especially under the RCP8.5 scenario at the end of the 21st century (Ashfaq et al., 2021). Moreover, significant warming (0.34°C/decade) in the monsoon region has been already observed in the last few decades (Cavazos et al., 2020). In California, the strengthened monsoon ridge may have lately led to more southerly flow aloft (Lahmers et al., 2016).

Coastal low clouds (CLC), which are horizontally extensive stratiform clouds (stratus, stratocumulus and fog), form under a low-level atmospheric temperature inversion which acts to inhibit mixing at cloud-top. Longwave (LW) cooling at cloud-top is essential to the maintenance of these boundary layer clouds (e.g., Lilly, 1968; Wood, 2012). Through cooling at cloud-top, the inversion is maintained and even strengthened. Cloud-top cooling also drives turbulence and mixing within the boundary layer, which, over the ocean, supplies moisture to the cloud layer. In addition to cooling summertime daytime temperatures (Iacobellis & Cayan, 2013), CLC, when present as fog (cloud base height intercepting the landscape), provides critical water and nutrient input, particularly to semiarid and arid ecosystems (Torregrosa et al., 2014; Weathers et al., 2020). In fact, CLC impact a wide array of human and natural systems including air traffic control (e.g., Hilliker & Fritsch, 1999), maritime navigation (e.g., Filonczuk et al., 1995), solar resources management (e.g., Mathiesen et al., 2012), coastal agriculture efficiency (e.g., Baguskas et al., 2018), natural land management including native plant restorations (Torregrosa et al., 2016), among others.

Recent studies show declines in California's coastal low cloud and fog. We (Schwartz et al., 2014) observed a slight but statistically significant decrease in summertime low cloudiness at airports along the West Coast from 1950 to 2012. We also described the connection between a natural climate mode of variability in the North Pacific—Pacific Decadal Oscillation (PDO, Mantua et al. (1997))—and low cloud variability. Johnstone and Dawson (2010) infer a 33% reduction in fog for northern CA over the last century, but this was not necessarily driven by anthropogenic climate change and may be attributed to natural atmospheric variability (Johnstone & Mantua, 2014). Williams et al. (2015) find a trend of increased cloud base height and a corresponding loss of fog in southern CA that is attributed to urbanization. Climate change projection of northern CA fog from a regional climate model "hints at a slight decline in the future" but the results are highly uncertain (O'Brien, 2011; Torregrosa et al., 2014). For stratocumulus clouds over the open ocean, including offshore and south of coastal California, Qu et al. (2014) find "medium overall confidence (that) low cloud cover will decrease" according to climate model simulations. Myers and Norris (2016) also find evidence for a small positive feedback—warming leading to less low clouds and more warming—but these studies do not focus on the coast specifically.

Here, we explore monsoonal mid-tropospheric moisture intrusion as a mechanism for modulating southern California coastal low-level cloudiness. This current work is directly motivated by our previous research on daily drivers of California coastal low cloud behavior and by a broader aim to understand all key mechanisms influencing CA CLC variability to better inform research on trends and observed, as well as projected, changes. In Clemesha et al. (2017) we found that day-to-day changes in northern California CLC were significantly linked to upwind lower tropospheric stability (LTS) during May through September. We found that this association only held for southern California CLC in May and June which suggested that, later in summer, southern California's CLC is under the influence of another key driver which has less impact in northern California. In fact, southern California CLC usually declines in July, but tends to thrive through August in northern California (Clemesha et al., 2016). In this work, through analysis of observations, reanalysis and the use of a single column model, we uncover that free-tropospheric moisture input, from the North American Monsoon, reduces the occurrence of coastal low clouds in southern California through interrupting a cloud maintaining radiative process.

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2. Data and Methods

We use the NASA/NOAA Geostationary Operational Environmental Satellite (GOES) derived coastal low cloud record described by Clemesha et al. (2016). The record starts in 1996 and ends in 2020; it is half hourly and at 4 km spatial resolution for the region 25°–50°N and eastward of 130° to the terrestrial coast. The low cloud detection algorithm uses common tests (e.g., Baum et al., 1997; Ellrod, 1995; Lee et al., 1997) and utilizes the GOES visible channel and two infrared channels to identity low cloud during day and night. As in Clemesha et al. (2016), coastal low cloudiness (CLC) is quantified daily as the percent of time low cloud was present relative to the number of corresponding valid observations in a 24-hr day.

We also use airport-derived ground-based records of cloudiness to ensure the detection of low clouds is not blocked by the possible presence of high clouds. Hourly cloud cover and base height observations were obtained from the National Center for Environmental Information (NCEI) Integrated Surface Data (ISD) for airports at San Diego, CA (KSAN). Airport-derived low cloudiness is defined as a temporal fraction of low cloud (1,000 m base or below) over a 24-hr period. Cloud observations are nominally hourly, and the daily cloudiness value is set to missing if more than 50% of the hourly observations are missing. As in Schwartz et al. (2014), an hourly low cloud observation is defined as having fractional sky cloud cover of at least 0.75.

Daily winds at 700 hPa ($winds_{700}$), geopotential height at 700 hPa (Z_{700}), specific humidity at 700 hPa (q_{700}), temperatures at 700 hPa (converted to potential temperature, θ_{700}), and temperatures at 2 m (T_{2m}) are obtained from NCEP/NCAR Reanalysis (Kalnay et al., 1996). We define LTS as the difference between θ_{700} and $T_{2m.}$

Sounding data are provided by the NOAA/ESRL Radiosonde Database. We use 12Z radiosonde data for southern (Miramar in San Diego; KNKX) and northern (Oakland; KOAK) California. For a measure of free-tropospheric moisture, we calculate the precipitable water from 850 to 300 hPa (denoted in the text as PW* to clarify the metric is not calculated over the full column).

The single column model radiative scheme of Iacobellis and Somerville (2006) is used to test the radiative impact of PW* for typical regional conditions.

3. Results and Discussion

To investigate the differences between southern and northern California daily CLC behavior (Clemesha et al., 2017), we examined the 25-year (1996–2020) monthly seasonality of PW* at two coastal radiosonde sites. We found that from June to July, moisture in the free-troposphere increases substantially over southern California, but not over northern California (Figure 1). In southern California monthly mean PW* more than doubles from June (6.65 mm) to July (14.25 mm), and typically stays near July levels in August (14.06 mm) and, remains elevated, although less so, through September (10.67 mm). In northern California, PW* in June (mean = 7.59 mm) is similar to that in southern California, but in strong contrast, there is no significant increase in moisture over Oakland in July (7.61 mm), August (7.41 mm) or September (7.46 mm). This suggests that during July, August and September the free-tropospheric moisture conditions of southern and northern California operate under different regimes.

3.1. Moisture Source Diagnoses

To understand the wider spatial pattern associated with this summertime increase in moisture above the boundary layer observed in southern California, we investigated seasonal changes in specific humidity (q_{700}), over Western North American using reanalysis data (Figures 1b and 1c). In north-western Mexico there is a marked increase in q_{700} from May to June, which gives rise to the onset of the monsoon in early June in the core monsoon region. By July, q_{700} is even greater and the moist pulse has moved farther north (Figure 1c). In July, southern California registers this seasonal influx of moisture aloft. While the major increase in q_{700} is greatest over north-western Mexico in the core of the NAM region, this mid-summer moisture ramp-up also covers southern California, albeit not to the same degree. This seasonal spatio-temporal pattern reflects the seasonally-expanding activity of the North American Monsoon (e.g., Turrent & Cavazos, 2009) and, together with the San Diego PW* observations (Figure 1a), indicates that NAM ramps up the free-tropospheric moisture over southern California in late summer (JAS).

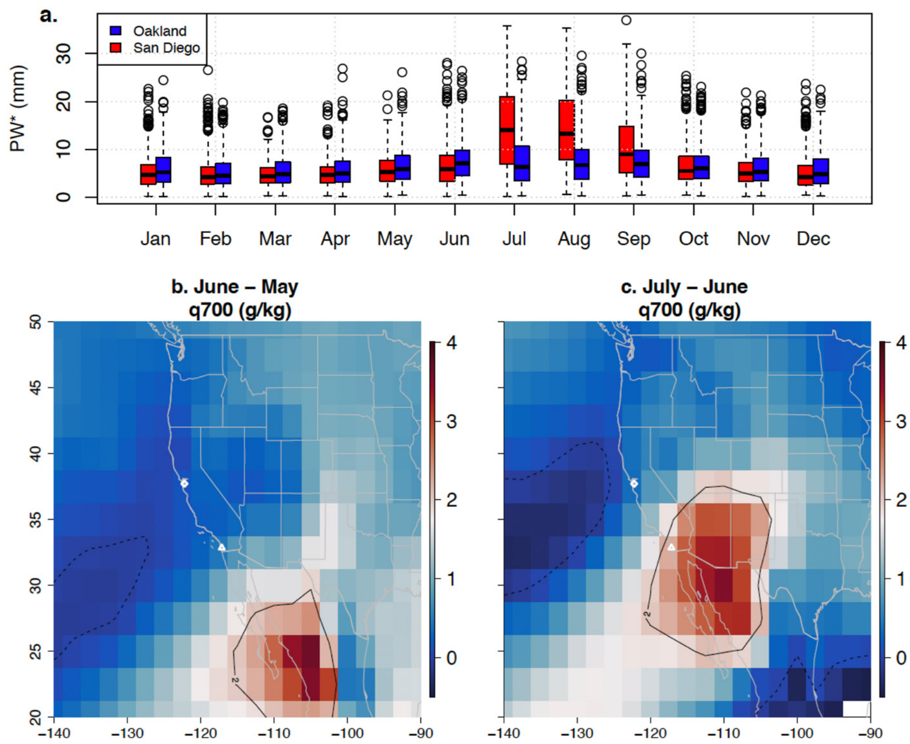

Figure 1. (a) Box and whiskers plots by month for PW* over southern California (San Diego—red) and northern California (Oakland—blue) for the 1996–2020 period. Solid black lines denote the monthly median, boxes extend to the 25th and 75th percentiles, whiskers extend to two times the interquartile range. The difference between June and May (b) and July and June (c) mean q_{700} in g/kg. The dashed, solid black contours denote 0 and 2 g/kg, respectively.

Adding texture to this seasonal picture, daily time scales elucidate the circulation structure driving injections of free-tropospheric moisture over southern California. Examining daily composites of specific humidity (q_{700}), geopotential heights (Z_{700}), and vector winds ($winds_{700}$) at 700 hPa composited by low and high occurrences of PW* (Figure 2) over San Diego, we find that southern California's position on the northwest flank of the core monsoon region is conducive to mid-late-summer fluctuations between dry mid-level southwesterly flow and monsoonal moisture intrusions from the southeast. In cases of low PW* (<25th percentile), there is a trough located along the California coast. The southwesterly flow around this trough into southern California is from a dry region of subtropical subsidence extending offshore of coastal California where eastern Pacific waters are

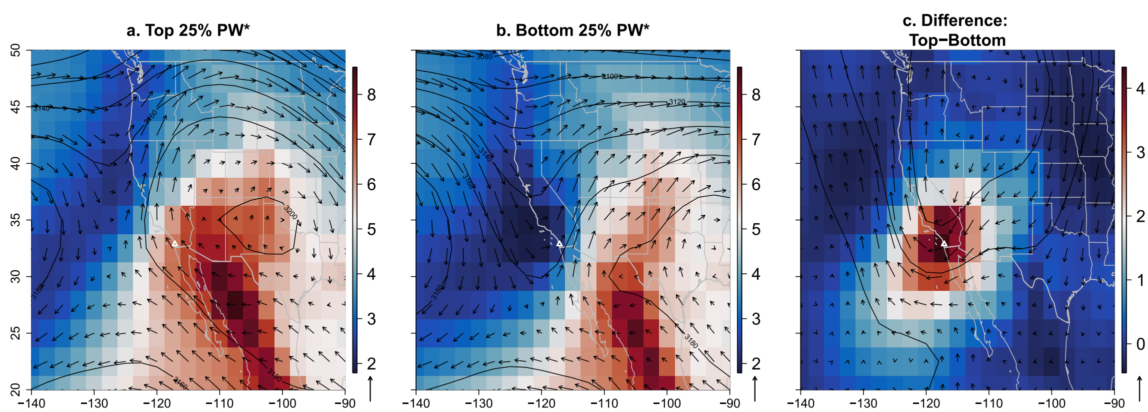

Figure 2. Composites of mean daily variables at 700 hPa for (a) top quartile and (b) bottom quartile of July, August, and September PW* at San Diego (location denoted by white triangle). (c) Difference of (a–b). Geopotential heights (Z_{700}) are shown as black contours in m, specific humidity (q_{700}) are shown as colors in g/kg, and wind vectors are overlaid in m/s (the arrow length below the color scale denotes 5 m/s).

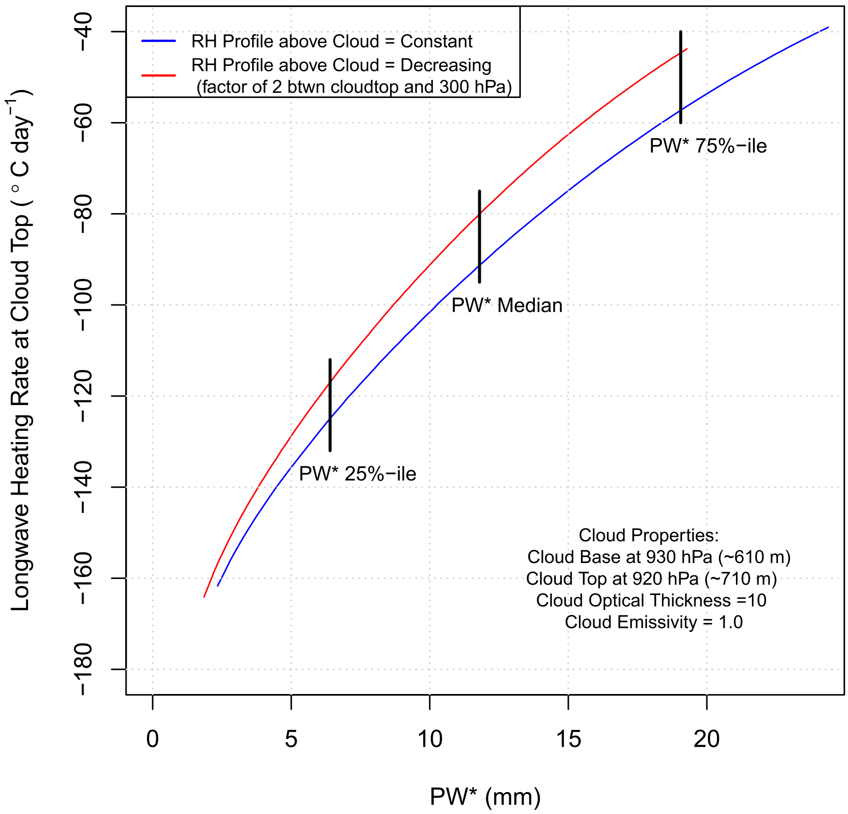

Figure 3. Longwave heating rate at cloud-top for varying PW*. The 25th, 50th, and 75th percentile of July, August, September southern California PW* content are marked by vertical black lines. The blue and red curves denote two methods for representing moisture above the cloud top as noted in the legend.

relatively cool. Conversely, during periods of elevated PW* (>75th percentile), higher mid-tropospheric pressure (Z_{700} > 20 m) over the continent, a strong "monsoon ridge"—a thermal high pressure aloft—is associated with anomalous easterly $winds_{700}$ (Figure 2c) and more moisture (q_{700}) invading southern California from the southeast (Figure 2a). These winds are part of the NAM circulation; when present, this configuration advects monsoonal mid-tropospheric moisture over southern California.

3.2. Radiative Modeling

Previous work has shown that increase in free-tropospheric moisture greatly inhibits effective cloud-top longwave cooling. According to Siems et al. (1993) in their examination of air overlying stratocumulus, "we can view the warm, moist overlying air as a thermal blanket that can largely negate LW cloud-top cooling." The Large-Eddy Simulations (LES) of Sandu and Stevens (2011) show that moistening of the free troposphere amplifies cloud breakup. Bretherton et al. (2013) and Bretherton and Blossey (2014) also find the radiative impact of increased water vapor in the free troposphere to thin stratocumulus through reducing turbulence.

Since longwave cooling at cloud-top is a critical component for the maintenance of low-level cloud decks, this evidence strongly suggests that NAM moisture intrusions alter radiative cooling and thus thins/reduces CLC in southern California. We test this hypothesis by utilizing a single column model (Iacobellis & Somerville, 2006) tailored to cloud and atmospheric conditions typical of southern California (as shown in Figure 3). For a given range of PW* that occurs in southern California, our hypothesis is supported by an examination of the longwave heating rate at cloud top. An increase in PW* from the 25th to 75th percentile of July, August, September PW* in southern California, decreases longwave cloud-top cooling by approximately 50%. More specifically, under these observational constraints, cloud top cooling drops from approximately −125° to −60°C/day when modeling a constant relative humidity profile above cloud top. We also calculate cloud top cooling under a relative humidity profile that decreases by a factor of two (up to 300 hPa) and find a reduction from approximately

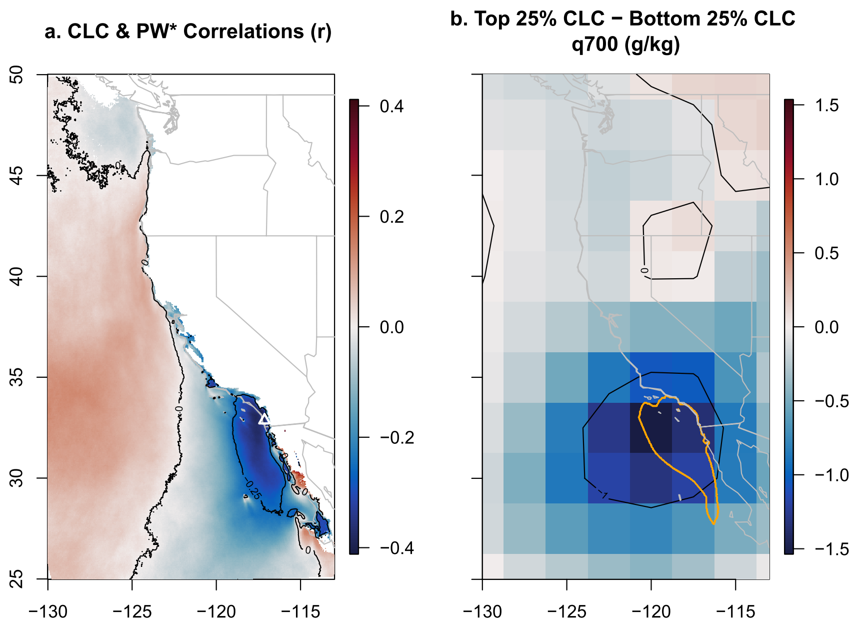

Figure 4. Maps relating satellite-derived coastal low cloudiness and measures of free-tropospheric moisture during July, August, September. (a) Correlations of daily CLC anomalies to PW* at San Diego (location denoted by white triangle), black contours denote $r = 0$ and -0.25. (b) q_{700} (g/kg) for the top quartile of CLC (more low cloudiness) minus the bottom quartile of CLC (less low cloudiness) in the southern California CLC domain (location denoted by orange contour). The black contours denote $q_{700} = 0$ and -1 g/kg.

−115° to −45°C/day. Our model results indicate that an influx of moisture above the cloud-top is on the order of what is observed by monsoonal intrusions. This moisture substantially reduces cloud-top cooling by several degrees/day—a crucial process in allowing radiational cooling and sustaining CLC.

3.3. Empirical Validation

Having demonstrated that simulated fluctuations within the observed range of PW* have a significant impact on longwave cloud-top cooling, we lastly investigate if observational evidence supports the model results. To do so, we compute temporal correlations of CLC and PW* as well as q_{700} composites using satellite and airport derived CLC observations. In mid to late summer in southern California and northern Baja California, we observe a significant ($r \sim -0.4$) correlation between PW* at Miramar and nearby CLC (Figure 4a). Correlation using the San Diego airport low cloud record ($r = -0.36$) is in agreement with that using the satellite record suggesting that the presence of high clouds is not biasing the satellite results. To put these correlation values in context, the maximum strength of Lower Tropospheric Stability (LTS)—CLC correlations reported in Clemesha et al. (2017) were about $r = 0.55$. Thus, from these correlation analyses alone PW* appears less linked to daily CLC variance than LTS, explaining up to 20% of daily variability. However, LTS near San Diego and PW* are themselves correlated ($r = -0.58$), so the radiative effects of PW* and subsequent change in turbulence may alter inversion characteristics such as LTS and inversion base height (Betts & Ridgway, 1989; Wood, 2012).

In contrast to southern California, Oakland PW* is not significantly correlated to daily CLC anomalies in northern California (not shown). Iacobellis and Cayan (2013) found that CLC vary coherently over hundreds of kilometers along the California coastline, but that Point Conception divides two distinct zones of coherent cloud variability. The strong anticorrelation between PW* and CLC found only south of Point Conception (Figure 4a) may, in part, explain these distinct north-south patterns of variability.

The negative relationship between free-tropospheric moisture and daily southern California CLC in mid to late summer also emerges in composite difference q_{700} maps formed from upper versus lower quartile CLC days (Figure 4b). The cloudier days are associated with lower q_{700} directly over the southern California CLC region. Thus, in mid to late summer in southern California our observational reports suggest that moisture in the free troposphere comes into play as a significant driver of daily CLC fluctuations.

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4. Conclusions

We find that increased mid to late summer (July, August, September) free-tropospheric moisture in southern California is associated with the North American Monsoon (NAM) and can diminish coastal low cloudiness (CLC) by reducing longwave (LW) cloud-top cooling. In late summer, southern California sits between the North Pacific semi-permanent subtropical high and the North American monsoon ridge with small fluctuations in the relative positions of these two opposing influences causing marked sub-seasonal variation in mid-tropospheric moisture. Using a single column model prescribed with typical atmospheric moisture conditions over southern California, the radiative effect of monsoonal moisture intrusions on the efficiency of CLC cloud-top cooling is substantial. This result, validated by observations, links these two iconic regional climate phenomena across the Southwest U.S.

While known to operational meteorologists of the region (Small, 2006), to our knowledge, this NAM—coastal cloud connection has not been previously elucidated in peer-reviewed scientific literature. The cloud radiative processes at play, however, have been previously described. Our findings are in agreement with a radiative mechanism in which free-tropospheric moisture reduces cloud-top longwave cooling and thins and/or diminishes cloudiness (Bretherton & Blossey, 2014; Bretherton et al., 2013; Sandu & Stevens, 2011). Myers and Norris (2015) also found a negative relationship between satellite-derived observations of maritime low-level cloudiness and specific humidity at 700 hPa (q_{700}).

Here, we address just one impact of the monsoon on CLC; the radiative effect of moisture above the cloud layer. The negative relationship between coastal low clouds and free-tropospheric moisture has been reported by forecast meteorologists in the southern California region (Small, 2006). According to Small (2006), other impacts of NAM on coastal clouds include a reduction in the onshore pressure gradients due to reduced heating in the deserts, which may influence penetration of coastal cloudiness inland, and the dissipation of thin coastal clouds by westward traveling thunderstorm outflow boundaries. The inland extent of low cloudiness is also controlled by inversion base height (Iacobellis & Cayan, 2013) which, due to a shared synoptic pattern, can vary inversely with PW* (Schwartz, 2015). Future work should quantify the impact of this radiative effect relative to other known controls on CLC variability.

To add to an already complex brew of factors influencing California coastal cloudiness, an additional influence is hereby introduced to the concoction. Accounting for free-tropospheric monsoonal moisture intrusions can inform coastal weather forecasting and subseasonal to seasonal research efforts. Such efforts could be further bolstered by improved understanding of the link between CLC variability and interannual NAM variability, which is known to be sensitive to land processes such as soil moisture and snow cover (e.g., Notaro & Zarrin, 2011; Small, 2001). Beyond weather prediction considerations, climate change opens a panoply of additional questions. If changes occur in the seasonality, intensity, or spatial footprint of the North American monsoon southern California coastal low cloudiness would be impacted. These model results and observations provide a rich context for further exploration including: How may a late demise of the monsoon (Ashfaq et al., 2021) change the moisture advection to southern California? Will future surface and tropospheric warming weaken the North Pacific subtropical high and therefore allow for more influx of monsoon moisture to California and Baja California? Will the expected expansion of the Monsoon High (Pascale et al., 2019) reduce southern California's CLC? This work provides an additional specific mechanism operating across the Southwest to consider in envisioning the increasingly convoluted future of southern California's iconic coastal low clouds.

Data Availability Statement

The data used in this study are available via the UCSD library repository (Clemesha et al., 2023). NCEP-NCAR Reanalysis 1 daily files at 700 hPa for specific humidity, V-wind and U-wind, geopotential height, and temperature are openly available and provided by the NOAA PSL, Boulder, Colorado, USA, from their website: https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html.

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