1. Introduction

Atmospheric rivers (AR; Zhu and Newell 1998) are recurring high impact year-round weather events associated with significant water vapor transport from the tropics to mid-latitudes around the globe (Guan and Waliser 2015). Studies on ARs have shown that other large-scale weather and climate patterns modulate the extratropical circulation and hence influence AR evolution. From the tropics, these large-scale weather and climate patterns are the Madden–Julian oscillation (MJO; Guan et al. 2012), quasi-biennial oscillation, and El Niño–Southern Oscillation (ENSO; Mundhenk et al. 2016, 2018). From the mid- and high latitudes, they include Rossby wave breaking (Strong and Magnusdottir 2008; Payne and Magnusdottir 2014), mesoscale frontal waves (Ralph et al. 2011; Neiman et al. 2016), and cutoff lows (Hirot a et al. 2016). AR interactions with midlatitude cutoff lows have caused extreme precipitation events over the central Pacific Ocean, Iberian Peninsula, West Africa, East Asia, and South Africa (Tsui and Takayabu 2019).

Over the U.S. West Coast, more ARs also occur during the negative phase of Pacific–North American pattern (PNA). Comparisons with in situ observations from dropsondes over the eastern Pacific indicate that model reanalysis products have larger biases than dropsondes in depicting the AR’s sharp integrated vapor transport (IVT) gradients, intensity, and landfall location (Neiman et al. 2014).

Cool-season (October–March) eastern Pacific landfalling ARs along the U.S. West Coast make up a significant percentage of the annual precipitation in this region (Cayan and Roads 1984; Lamjiri et al. 2017; Gershunov et al. 2017). The climatology daily precipitation maxima of inland penetration of ARs on the U.S. West Coast occur over and west of the Sierra range (Rutz et al. 2014). Most of the poleward and eastward water vapor flux associated with ARs occurs in the lower troposphere, below an altitude of 2.5 km (Ralph et al. 2005, 2014). While these AR events bring precipitation/snowfall and provide needed seasonal freshwater for the U.S. West Coast, they can also generate extreme precipitation and associated hazards such as floods and landslides (Leung and Qian 2009; White et al. 2013; Ralph et al. 2020 and references therein). Monitoring extreme landfall AR precipitation in the U.S. West Coast using extensive observation networks is very important for both water resource management and emergency response in the region and for hydrometeorological model verification (White et al. 2013; Hatchett et al. 2020).

A moisture-laden AR that stretches from Hawaii to the U.S. West Coast, often resulting in heavy West Coast precipitation, is colloquially referred to as a “Pineapple Express.” This phenomenon in satellite imagery appears as a narrow ribbon of enhanced water vapor that extends northward and eastward from locations near Hawaii toward the U.S. West Coast. Aircraft observations near Hawaii in the cool season suggest that ARs in this region draw from abundant moisture.
pools in the tropics and transport that moisture northward to the midlatitudes (Ralph et al. 2011). Neiman et al. (2014) did a backward trajectory analysis and confirmed that an AR near Hawaii has a moisture source originating from the equatorial region and has higher integrated moisture and lower wind speeds than subtropical and midlatitude ARs located in other regions of the world.

Another important subtropical synoptic feature in the central and eastern Pacific—the so-called kona low first described by Daingerfield (1921) as a kona storm—often resides in this region during the cool season. The kona low is a cold-core subtropical cyclone. Simpson (1952) analyzed 76 kona storms over a 20-yr period from November to March (see his Table 1). He found 48 of these kona storms first originated as surface occluded cyclones associated with the intrusion of extratropical upper-level troughs into the subtropics. The remaining 8 cases were cyclogenetic events in the trade wind easterlies with no apparent preexisting cold fronts. Additionally, the highest number of kona storms occurred in the month of January. He also found from 10 years of synoptic chart analysis that the Atlantic tropical region also had 16 kona-like cyclones, which tended to form southwest of the Azores under similar synoptic scenarios. These Atlantic kona-like cyclones often developed into tropical cyclones in November (see Table 2 of Simpson 1952). A detailed case study by Morrison and Businger (2001) further suggested that rapid intensification of kona lows result from strong lower tropospheric vorticity advection near the surface low pressure center. Subsequently, Otkin and Martin (2004) used a 10-yr period, 1986–96, European Centre for Medium-Range Weather Forecasts (ECMWF) Tropical Ocean Global Atmosphere (TOGA) dataset to further classify the cold-frontal type kona storm cyclogenesis into eastward- and westward-propagating subtypes. They identified 115 kona storms and found that a maximum number occurred in the October–November period with a secondary maximum in February. They also found the kona storms had no correlation with ENSO.

A recent study by Hatchett et al. (2020, see their Fig. 4c) suggests the moisture in the southern plume of southern 2019 Valentine’s Day AR was transported poleward from the tropics by a northeastward-moving kona low. They identified this AR event as a category-5 AR based on the duration and integrated water vapor transport criteria by Ralph et al. (2019). Other large-scale conditions for this case described by Hatchett et al. (2020) include the planetary-scale shortwave trough, anticyclonic Rossby wave breaking (RWB), a ridge of subtropical high pressure, the jet stream, and a surface cyclone northwest of the California coast. Because of the close proximity of the kona low and the 2019 Valentine’s Day AR, it is meaningful to further quantify whether the kona low circulation affects the 2019 Valentine’s Day AR’s poleward and eastward transport of moisture. The goal of this case study, therefore, is to investigate the role of a wintertime kona low associated with the 2019 Valentine’s Day AR event using a state-of-the-art coupled air–ocean cloud-resolving model. Key scientific questions of interest include the following: (i) does the kona low circulation aid the AR integrated water vapor transport (IVT) over the ocean, and (ii) does the strength of the kona low, positioned 2000–3000 mi (1 mi = 1.6 km) west of the U.S. West Coast, affect the coastal AR landfall, and if so, how and why? In section 2 we provide a large-scale overview of the tropical environment of the 2019 Valentine’s Day AR environment to complement the analysis of Hatchett et al. (2020). Section 3 gives the descriptions of the coupled model and model setup used for this study. Section 4 presents the control simulation results, followed by the kona low sensitivity experiments in section 5. Section 6 discusses the AR evolution conceptual model, and section 7 summarizes the key findings.

2. The large-scale environment of the 2019 Valentine’s Day atmospheric river

2a. GOES-17 IR

On 14 February 2019, a land-falling eastern Pacific AR produced more than 200 mm of rainfall over a 3-day period, causing widespread flooding and landslides that wreaked havoc in California (Hatchett et al. 2020). This event is well captured by a sequence of GOES-17 ABI infrared images (Schmit et al. 2017) that show an elongated region of cloud top brightness temperature (<−30°C) and associated cloud band that extends from the tropical region southwest of Hawaii to the U.S. West Coast (Fig. 1a). Clouds associated with the kona low located to the north of Hawaii become evident on 11 February, with the coldest cloud top temperatures occurring northeast of the islands (Fig. 1b). For the following two days, clouds associated with the kona low surged northeastward and contributed to a narrow band of cold cloud top temperatures (<−60°C) extending from Southern California to Colorado (Figs. 1c–e). By 16 February, the Valentine’s Day AR event began to become less coherent in the satellite imagery as a linear feature and by 17 February, only a large cloud cluster remained evident to the northeast of Hawaii.

2b. Tropical anomalies

Equatorial forcing mechanisms that may have promoted the growth of the 2019 Valentine’s Day AR include the MJO and equatorial Rossby waves. Analyses of the seasonal and subseasonal modes of variability show that the equatorial region was indeed favorable for the development and landfall of ARs in California in February 2019. According to the oceanic Niño index (ONI), El Niño conditions developed in October 2018 and persisted until June 2019; in February 2019 the ONI was 0.8°C. At the time of this AR, sea surface temperature (SST) anomalies were higher in the central Pacific Niño 4 region (0.96 K) than in the eastern Pacific Niño 1 + 2 region (0.31 K). AR landfalls are most common during El Niño events and tend to affect the southwestern United States most during central Pacific–dominated El Niño conditions such as in this case (Kim et al. 2019). In the first half of February, the real-time multivariate MJO (RMM) index (Wheeler and Hendon 2004) moved from phase 6 to phase 8 maintaining an amplitude of 1–2 σ. Mundhenk et al. (2016) showed that ARs are most likely to impact California in MJO phases 7 and 8.
FIG. 1. GOES-17 water vapor images showing the progression of the kona low and atmospheric river from 0000 UTC 10 Feb to 0000 UTC 17 Feb 2019: (a) 10 Feb, (b) 11 Feb, (c) 12 Feb, (d) 13 Feb, (e) 14 Feb, (f) 15 Feb, (g) 16 Feb, and (h) 17 Feb 2019.
To clarify the relationship between seasonal-to-subseasonal modes of variability and the AR, Fig. 2 shows weekly averaged OLR anomalies in the central and eastern Pacific filtered for low-frequency (LF; >100 days), MJO, and Equatorial Rossby (ER) wave signals [wavenumber-frequency bands follow Janiga et al. (2018)]. The LF OLR anomalies show a persistent signature of OLR near 180° at the equator as well as between 120°–150°W and 15°–30°N indicating that the connection between the West Coast of North America and the deep tropics was unusually strong throughout the 2018 autumn–2019 winter season. The MJO OLR anomalies show an MJO convective envelope moving southeastward from the “Maritime Continent” into the South Pacific Convergence Zone. Focusing near the equator, the ER anomalies show a disturbance moving westward from the central Pacific toward the Maritime Continent. The week prior to the Valentine’s AR, the LF, MJO, and ER all contributed to enhanced convection downstream of the AR near 180° at the equator.

c. The kona low

In addition to the tropical contribution to the 2019 Valentine’s AR, a second contribution is the midlatitude cyclonic circulation about the kona low. This low is evident in the Navy Global Environmental Model (NAVGEM; Hogan et al. 2014) analysis on 10–11 February (Figs. 3a,b). Bosart and Leicht (personal communication) noted the kona low is located on the southwestern end of a deep, positively tilted trough. Dropsondes deployed within and near the kona low as part of the multiyear AR Reconnaissance field campaign on 11 February 2019 (Ralph et al. 2014, 2020) show the dropsonde IVT values for this date ranging from 349 to 241 kg m⁻¹ s⁻¹ to the north and east side of the kona low (AR Reconnaissance website: https://cw3e.ucsd.edu/arrecon_data/). Dropsondes taken on 13 February showed drier conditions near the north and east of the kona low. The special dropsondes deployed by the AR Reconnaissance field campaign conducted in the winter of 2019 (Ralph et al. 2020) were assimilated into the global atmospheric system through the four-dimensional hybrid variational-ensemble data assimilation system (NAVDAS-AR; Rosmond and Xu 2006). For this case, a total 72 dropsondes from three AR Reconnaissance flights on 11 and 13 February were assimilated into NAVGEM. The dropsondes in this case were not directly assimilated into the Coupled Ocean–Atmosphere Mesoscale Prediction System (COAMPS). The NAVGEM provides the lateral boundary conditions to COAMPS on 11 and 13 February. They are also used to evaluate model-simulated IVT and IWV described in the next section.

As the AR gained strength and moved northeastward, on 12–13 February, the kona low transitioned from a circular closed-low to a more elongated shape (Figs. 3c,d). The northeastward and southward surge in NAVGEM analysis of low-
level moisture appears to merge with the kona low–associated moisture on 14–15 February (Figs. 3e,f).

3. Model description and experimental design

The model used for this study is COAMPS at 5-km horizontal grid spacing for both the atmosphere and ocean components. The domain covers the area of 7.2°S–44.8°N and 162.7°–105.2°W. The initial and lateral boundary conditions for the atmosphere is taken from NAVGEM analyses. The ocean boundary conditions are derived from the Navy Global Ocean Forecasting System (GOFS; Metzger et al. 2010).

The COAMPS atmospheric model component of the coupled system uses a terrain following \( \sigma \) vertical coordinate system described in Chen et al. (2003) that allows for a variable user-defined stretched vertical grid spacing. In this simulation, the vertical grid spacing was varied from 10 m near the surface to a value of 2500 m near the model top of 50 km. The vertical grid spacing in our study gradually increases from 10 to 200 m over the lowest 3 km of the atmosphere. Above 3 km, the vertical grid spacing increases by 50 m for each subsequent model layer up to a maximum of 700 m, which is reached near an elevation of 5 km.

The configuration of the COAMPS atmospheric model physics follows the MJO configuration described in Chen et al. (2015). The physics suite includes the Schmidt microphysics (Gaudet and Schmidt 2005, 2007), Mellor–Yamada turbulent kinetic energy mixing, and Coupled Ocean–Atmosphere Response Experiment (COARE) 3.0 surface fluxes over the ocean. Over the land, soil temperature and moisture initialization are derived from a 1/4° global Land Information System (LIS; Kumar et al. 2006).

The ocean component used in the study is the Navy Coastal Ocean Model (NCOM: Martin 2000). Its vertical coordinate is bathymetry following at the bottom, transitioning to constant height levels (sigma-Z) in the upper ocean. The top NCOM layer is at 1-m depth. NCOM’s initial and lateral boundary conditions are taken from GOFS. The lateral boundary update frequencies for both the atmosphere and ocean are every 3 h.

The COAMPS experiments are setup to investigate the sensitivity of the Valentine’s Day AR evolution and the AR’s subsequent landfall on the U.S. West Coast to the kona low strength. In addition to the COAMPS control simulation, four coupled sensitivity experiments are designed that vary the circulation strength of the initial kona low. This is achieved by reducing the kona low circulation magnitude through the depth of the troposphere in the NAVGEM analysis fields used as the initial condition on 10 February as well as the subsequent lateral boundary conditions extending out in time to 17 February. The technique utilized is the same technique used in previous studies to remove a hurricane vortex from the ambient conditions within a user-specified radius of influence from the vortex center (Davis et al. 2008; Galarneau and Davis 2013; Torn et al. 2015). As applied here, the method first removes the nondivergent and irrotational components of NAVGEM analysis winds from the surface up to the model top within the radius of a 6° circle centered on the kona low circulation. This is done in such a manner to minimize
discontinuities between the modified flow field and that of the ambient conditions well removed from the core (Davis et al. 2008). This value for the radius of influence was found through experimentation to adequately reduce or completely remove the circulation of this observed kona low feature from the NAVGEM analyses while retaining features of interest in the broader environment. The solution method is a combination of two techniques to remove the kona low wind and temperature perturbations over the specified radius of influence. In the first step, vorticity inversion is applied at each vertical level using the technique described by Davis et al. (2008) and Galarneau and Davis (2013). For the no kona low experiment, this technique zeros out the computed vorticity and divergence field within the radius of the kona low. The irrotational wind and nondivergent wind components are then computed within the region of the removed kona low using spherical harmonics using the National Center for Atmospheric Research (NCAR) Command Language (NCL; https://www.ncl.ucar.edu/Document) spherical harmonics “dv2uvgr” and “vr2uvgr” functions. Next, the new irrotational and nondivergent wind components are recombined to get the new total wind field in the absence of the kona low. For the NAVGEM temperature field within the radius of the kona low circle, a simple Poisson grid fill, the NCL Poisson_grid_fill function, is used to recompute the temperature fields initially zeroed out within the radius of the kona low circle. This NCL function “poisson_grid_fill” interpolates the temperatures within the radius by all the adjacent points around the kona low circle. Finally, a variational hydrostatic adjustment scheme (Barker 1980) is used to balance the NAVGEM mass and momentum fields after the kona low strength is reduced or removed. In this study, four sensitivity runs are performed by reducing the magnitude of the initial winds at each model level by 75%, 50%, 25% and 100% within the radius of influence. The same sequence of aforementioned steps is used to alter the 75%, 50%, and 25% kona low NAVGEM fields. Instead of completely zeroing out the irrotational and nondivergent wind components, they are retained by 75%, 50%, and 25% of their original values, respectively. More complex balanced fields can be accomplished using a piecewise potential vorticity inversion (Davis 1992; Davis and Emanuel 1991, see their appendix A) and a Helmholtz partitioning method (Riemer and Jones 2014).

Because of the nature of this solution technique, the flow field beyond the specified 6° radius of influence will also be altered. This is evident in Fig. 4, which shows 320-K potential temperature, 850-hPa vorticity, and IVT for the control NAVGEM analysis valid on 0000 UTC 10 February, both before and after the kona low was removed from the NAVGEM analysis. One can see, for example, that the process effectively not only removes the kona low, but also impacts the surrounding areas such as reducing the IVT to east of Hawaii at the COAMPS initial time. One also sees perturbations extending outward to the lateral boundaries, although to a lesser extent. The solutions discussed are thus best cast in light of the removed circulation as well as impacts that will come through the lateral boundary conditions.

4. COAMPS control simulation results

a. Model-simulated IWV, IVT, and precipitation

The realism of the COAMPS control simulation from 10 to 17 February is evaluated using multisensor microwave satellite integrated water vapor (IWV) and dropsonde IVT. Comparisons of the COAMPS domain mean (encompassing the area of 7.2°S–44.8°N and 162.7°–105.2°W) IWV (mm) with the 0.5°-resolution multisensor microwave satellite IWV product from the University of Wisconsin–Madison Space Science and Engineering Center and CIMSS (Wimmers and Velden 2011) show that the model has a mean moist bias of less than 2.5 mm at the initial time (Fig. 5a). These differences are well below previous studies of global model 7-day forecast IWV biases of −5 and 2 mm (Wick et al. 2013, see their Fig. 2). At the COAMPS model initial time on 10 February, the domain mean IWV from NAVGEM is 32.5 mm as compared with the satellite observation of 30.0 mm (Fig. 5b).

To further evaluate the COAMPS-simulated AR IWV as compared with satellite observations, the satellite IWV is interpolated to the COAMPS model grid points to compute additional statistic measures including threat score (TS), probability of detection (POD), and false alarm ratio (FAR, Wilks 2011). TS is defined as the number of grid points at which COAMPS has the same IWV threshold as the satellite observations and is computed using 2- (Wick et al. 2013), 3-, and 4-cm thresholds about the IWV medians from dropsondes deployed on 10 and 13 February, respectively. A TS value of 1 indicates the model has the same IWV thresholds as the observations on every model grid point. Conversely, POD and FAR respectively represent fractions of grid points at which the model has accurate and missed forecasts of the observed IWV thresholds. For the 2-cm IWV threshold, COAMPS has a mean of 0.93 TS, 0.9 POD, and 0.11 FAR for all lead times (Figs. 5c–e). When compared with the global models’ AR forecasts evaluated by Wick et al. (2013, see their Fig. 3), COAMPS TS is better than the global models, and the POD and FAR are comparable to the scores for global model 7-day forecasts. For the 3- and 4-cm IWV thresholds that are closer to the AR core, COAMPS mean TS decreases to 0.65 and 0.36, respectively. For these two IWV thresholds, the mean POD/FAR are 0.79/0.14 and 0.53/0.19, respectively. Overall, the COAMPS control 7-day simulation of IWV compares reasonably well to the satellite observations, with mean correlations above 0.9 throughout the 7-day simulation period. While not perfect, we anticipate that such high correlations will help to mitigate the growth in forecast errors that may arise from errors in the water vapor field over open-ocean basins as noted in the adjoint studies of Doyle et al. (2019) and Reynolds et al. (2019).

For the COAMPS-simulated IVT evolution from 10 to 17 February (Fig. 6), the maximum IVT values, exceeding
2100 kg m$^{-1}$ s$^{-1}$, occurred on day 3 of the simulation (13 February) east of the kona low. There is also a second, smaller IVT band to the north of the maximum IVT with IVT values of about 1200 kg m$^{-1}$ s$^{-1}$ at this time and, together, they form a continuous broad and high IVT feature moving toward the U.S. West Coast. It appears that both the northern and southern IVT bands are connected to the kona low circulation. Hatchett et al. (2020) suggests the moisture in the AR’s southern plume was transported poleward from the tropic from a northeastward moving kona low based on a 0.25° Global Forecast System (GFS) final analysis (see their Fig. 5a). After landfall at day 6, 15 February, COAMPS-simulated AR IVT values continue to decrease. At the end of the 7-day simulation, only a broad
The region of moist air remains to the east of Hawaii consistent with the satellite observation shown in Fig. 1h. The mean COAMPS IWV and IVT at the 72 AR Reconnaissance dropsonde locations deployed on 11 and 13 February are consistent with the mean dropsonde values (Fig. 7).

However, dropsonde data from 13 February that sampled the main AR axis (Fig. 6d, magenta color circles) shows that the median of IWV and IVT values are about 26% less than COAMPS (Fig. 7c). This COAMPS IVT positive bias is consistent with the IWV wet bias. COAMPS forecast AR

FIG. 5. Comparisons of COAMPS vertically integrated water vapor (IWV; mm) with multisensor microwave satellite-based estimates for the 7-day simulation initialized at 0000 UTC 10 Feb 2019. Shown are COAMPS and satellite domain mean (a) correlation and (b) IWV (mm), (c) threat score, (d) probability of detection, and (e) probability of false alarm ratio. The COAMPS domain covers the area of 7.2°S–44.8°N and 162.7°–105.2°W.

FIG. 6. COAMPS control simulation integrated water vapor transport (IVT; kg m⁻² s⁻¹; shaded) from 10 to 17 Feb 2019. The black arrows are the IVT vectors. The blue circles in (b) and (d) depict the dropsonde locations from three research flights taken on 11 and 13 Feb 2019, respectively.
daily precipitation maxima coincided with the IVT maxima (Fig. 8). Over the ocean, the heaviest daily precipitation of 327.8 mm occurred on 11 February. The precipitation pattern on this day has enhanced rainbands to the northwest of Kona low and to the south of the emerging AR core (Figs. 7a,b). On 12 February, the AR leading precipitation band reaches the U.S. West Coast but the heaviest rains still occur over the ocean between 20°–30°N and 132°–144°W (Fig. 8c). COAMPS daily precipitation has many streak-like bands that resemble the precipitation bands observed on the south side of extratropical cyclone fronts (Glinton et al. 2017), and these features will be addressed further in section 6. The COAMPS precipitation forecast correctly placed the AR maximum landfall precipitation location over the U.S. West Coast, on Valentine’s Day 14 February (Fig. 8c). COAMPS predicted widespread heavy rains on the California coastal zone and Sierra Nevada similar to the observations. The coastal and Sierra Nevada precipitation predicted by COAMPS lasts less than 24 h because of the continuous southward movement and weakening of the AR IVT with time until the end of model simulation (Figs. 8f,g).

b. Model-simulated kona low

At the initial model time on 10 February, the kona low from the NAVGEM analysis already has a well-defined sea surface pressure center (Fig. 3a), a warm core above 300 hPa (not shown) and a cold core in the lower levels. The kona low vortex is vertically aligned with little vertical tilt evident in either the circulation or thermodynamic variables at this time (Fig. 9a). In the center of the kona low, the air is relatively dry with higher moisture values evident in the peripheral regions of the circulation (Fig. 9b). There is a strong lateral moisture gradient extending to the southeast, along the southern boundary of the surface high pressure center located farther to the northeast. There is also a low pressure center farther to the east of the surface high between 40° and 60°N. Both the surface high and the upper-level trough are outside the COAMPS northern boundary at the model initial time but are evident in the NAVGEM analysis (Fig. 3a).

On 11 February, the eastern flank of the kona low connects with the westward and poleward tropical moisture surge south
Fig. 8. COAMPS accumulated daily precipitation (mm; shading) for the 24-h time intervals ending at (a) 0000 UTC 11 Feb, (b) 0000 UTC 12 Feb, (c) 0000 UTC 13 Feb, (d) 0000 UTC 14 Feb, (e) 0000 UTC 15 Feb, (f) 0000 UTC 16 Feb, and (f) 0000 UTC 17 Feb 2019. The black vectors are the 10-m wind speed (m s$^{-1}$). The blue circles in (a) and (c) depict the dropsonde locations from three research flights taken on 11 and 13 Feb 2019, respectively.
FIG. 9. COAMPS control simulation of specific humidity (kg kg$^{-1}$; shaded) geopotential height (m; white contours), and winds (m s$^{-1}$; black arrows) for (left), (right center) 300 and (left center), (right) 850 hPa for (a), (b) model initial time; (c), (d) 24-h forecast, valid on 11 Feb; (e), (f) 48-h forecast, valid on 12 Feb; and (g), (h) 72-h forecast, valid on 13 Feb. The blue circles in (c) and (d) and in (g) and (h) depict the dropsonde locations from three research flights taken on 11 and 13 Feb 2019, respectively.
of 10°N latitude (Figs. 9c,d). On 12 February, the lower portion of the kona low circulation is stretched farther toward the southeast as the AR continues to intensify and surge toward the U.S. West Coast (Figs. 9e,f).

5. COAMPS sensitivity experiments—Valentine’s AR and kona low interaction

For this AR case, there are complex mesoscale (kona low) and synoptic (subtropical high, shortwave trough, and low-level low) environmental phenomena in which the AR is embedded. There is compelling evidence from the analysis of the COAMPS control run described in section 4 that illuminates a plausible interaction between the kona low and the AR, especially during 11–13 February period when the AR strengthens and begins its surge toward the U.S. West Coast. The set of COAMPS model sensitivity runs described here are designed to investigate the influence of the kona low on the AR by reducing the magnitude of kona low circulation to 75%, 50%, and 25% of its original value.

We choose to use the 300 and 450 kg m⁻¹ s⁻¹ Hovmöller IVT contours to highlight differences between the control and kona low sensitivity experiments. The control run with the original kona low from NAVGEM shows the eastern extent of the 300 kg m⁻¹ s⁻¹ IVT contour reaching 133°W by February 14 with the maximum mean value exceeding 450 kg m⁻¹ s⁻¹ between 12 and 13 February (thick black lines in Fig. 10a). In the 75% kona low experiment, the 300 kg m⁻¹ s⁻¹ IVT values still reached the coast but the area contained within the 450 kg m⁻¹ s⁻¹ IVT contour are reduced (Fig. 10b). The eastward extent of 300 kg m⁻¹ s⁻¹ IVT contour remains west of 138°W for the 50% kona low experiment and the area of 450 kg m⁻¹ s⁻¹ contour between 153° and 143°W is diminished considerably (Fig. 10c). This indicates a significant reduction of the AR strength and eastward propagation when the kona low circulation is reduced to one-half of its original value. In the 25% kona low experiment, the westward displacement pattern continues and the eastward extent of the 300 kg m⁻¹ s⁻¹ IVT contour retreats back to 141°W (Fig. 10d). The maximum 450 kg m⁻¹ s⁻¹ IVT contours between 12 and 13 February completely vanish. For the last sensitivity experiment run without a kona low, there is no eastward or northward growth of the AR IVT (not shown).

Similarly, the mean time–latitude plots of the IVT averaged between 105° and 162°W show a diminishing IVT northward surge when the kona low strength is reduced (Fig. 11). The control run has 300 kg m⁻¹ s⁻¹ IVT values as far south as 2°N on 12 February (Fig. 11a). In the 75% kona low experiment, IVT values of 300 kg m⁻¹ s⁻¹ start at 5°N and a day later than the control run (Fig. 11b). The mean 450 kg m⁻¹ s⁻¹ IVT contoured area is also smaller than in the control. In the 50% kona low experiment, the northward AR is further weakened.
and delayed, with 300 kg m\(^{-1}\) s\(^{-1}\) IVT values starting on 13 February at 7°N (Fig. 11c). The 450 kg m\(^{-1}\) s\(^{-1}\) IVT contours nearly disappear as compared with the control run. As for the 25% kona low experiment, the northward surge time, southern extent, and mean AR strength are further diminished and delayed (Fig. 11d). As the magnitude of the kona low circulation is reduced in the kona low sensitivity experiments, IVT values of 300 kg m\(^{-1}\) s\(^{-1}\) occur later in the forecast and start at more northerly latitudes, and the 450 kg m\(^{-1}\) s\(^{-1}\) IVT values diminish. Relative to the control averaged latitude and longitude of IVT progression with time, the AR is shrinking in the sensitivity experiments. In general, they show a ≈2° westward displacement, a 2°–3° northward displacement, and a 1-day delay of northward surge for each 25% reduction in the kona low magnitude. This tendency continues until the AR surge is completely eliminated in the experiment with no kona low.

Relative to the control simulation’s 7-day accumulated precipitation ending by 0000 UTC 17 February (Fig. 12a), the 75% kona low experiment has reduced snowfall in regions of Sierra Nevada range and the mountains of the Great Basin in Nevada. It also shows a reduced accumulated coastal precipitation from Oregon down to Southern California (Fig. 12b). For the 50% kona low experiment, the accumulated landfall precipitation on the coast and mountain regions continue to diminish in magnitude (Fig. 12c). The accumulated precipitation on the southern portion of the Coastal Range north of Los Angeles has completely disappeared in the 25% kona low experiment (Fig. 12d).

6. Discussion and conceptual model

From the analysis of COAMPS control and kona low sensitivity experiments described in section 5, there is compelling evidence that the existence and strength of the kona low strongly influenced the subsequent northeastward surge of IVT associated with the Valentine’s Day AR. The coexistence of the kona low and mesoscale anticyclone off the coast on 10 February 2019 also plays a role in the genesis of the Valentine’s Day AR and its northeastward propagation. The origin of this mesoscale high (Fig. 6b) is unclear. **Strong and Magnusdottir (2008; see their Figs. 1a and 3c)** showed that the kinematic response to the anticyclonic RWB was an anticyclonic high pressure anomaly on the south side of their composite anticyclonic RWB centroid. This increased an easterly flow anomaly in the tropics and a westerly flow anomaly in the subtropics that help promote moisture transport from the tropics to the west of the high pressure anomaly. Two thirds of landfalling AR events on the U.S. West Coast are associated with RWB, and AR IVT transport occurring under anticyclonic RWB condition impinging on the coast is in a more westerly direction (Hu et al. 2017).
than for other AR cases. The mesoscale high may also be a kinematic response to the formation of the upper troposphere short wave ridge.

The corridor between the kona low and the AR, an area covering 17°–22°N and 160°–135°W, exhibits a substantial growth of convection at the critical time during which the AR begins to strengthen and surge on 11–12 February (Fig. 6b). The 850–200-hPa vertical wind shear vector is westerly with a magnitude of less than 2 m s\(^{-1}\) in this region (not shown). Model sounding profiles in the kona low and AR corridor show that the conditional available potential energy (CAPE) is small or close to zero in this region (not shown). CAPE is the positive area on the tephigram and indicates the maximum amount of potential energy that is available for air parcels to undergo upward convection when the air parcels are more buoyant than the environment. However, there is a possibility that conditional symmetric instability (CSI) in the corridor can support slantwise-elongated convection growth along the thermal wind direction (Shutts 1990). The air parcels adjust to the unstable buoyancy gradients from latent heat release and grow along a new equilibrium absolute angular moment surfaces (Emanuel 1983). Shutts (1990) described two-step process to compute the model slantwise conditional available potential energy (SCAPE). The first step is to find air parcel ascent paths along a slantwise trajectory in which the intersecting absolute momentum \(M\) and \(N\) surfaces have the same values as the initial starting point of the modeled sea level \(M\) and \(N\) fields:

\[
M = fx + v \quad \text{and} \quad N = fy - u, \tag{1}
\]

where \(M\) and \(N\) are the absolute momentum in zonal and meridional directions and \(u\) and \(v\) are the zonal and meridional winds, which are used because the geostrophic winds have been found to be too noisy in high-resolution modeling systems (Shutts 1990). The second step is to compute

![Figure 12](image-url)
CAPE using the pressure, temperature, and humidity values along these trajectories obtained from Eq. (1). Because CAPE is computed along a sloped ascent, it is equivalent to SCAPE:

$$\text{SCAPE} = \int_{L_{\text{nb}}}^{L_{\text{fc}}} R_d (T_{v,\text{parcel}} - T_{v,\text{env}}),$$

(2)

where $L_{\text{nb}}$ is the pressure at the level of neutral buoyancy, $L_{\text{fc}}$ is the pressure at the level of free convection, $R_d$ is the gas constant of dry air, $T_{v,\text{parcel}}$ is the virtual temperature of air parcel, and $T_{v,\text{env}}$ is the virtual temperature of environment along the sloped trajectory. Figure 13 shows that in the corridor the SCAPE (black contours) values are less than 10 J kg$^{-1}$ at the 54-h simulation time when the COAMPS-simulated IVT begins to surge northeastward (Fig. 13a). The areal coverage encapsulating the 10 J kg$^{-1}$ SCAPE contour increases in the next 4 h (Figs. 13b,c). By the 60-h simulation time, both the SCAPE and IVT surge decrease within the corridor (Fig. 13d). A necessary condition for the release of positive CSI is the coexistence of negative or very small or close-to-zero moist potential vorticity (Schultz and Schumacher 1999). Here we used the equivalent potential temperature $\theta_e$ to compute the three-dimensional form of isentropic moist potential vorticity (MPV) in saturated environment over the AR surge corridor [McCann 1995, his Eq. (2)]:

$$\text{MPV} = -g \left[ \frac{\delta w}{\delta y} \frac{\delta u}{\delta p} \frac{\delta \theta_e}{\delta x} + \left( \frac{\delta u}{\delta p} - \frac{\delta w}{\delta x} \right) \frac{\delta \theta_e}{\delta y} + \left( \xi_{\theta_e} + f \right) \frac{\delta \theta_e}{\delta p} \right],$$

(3)

where, on the isentropic surface, the $u$, $v$, and $w$ are the three components of wind in the zonal, meridional, and vertical directions, respectively; $p$ is pressure; $f$ is the Coriolis force; $g$ is gravity; and $\xi_{\theta_e}$ is the relative vorticity [Eq. (4)]. The first
and second terms in Eq. (3) represent the MPV generation from tilting of the horizontal gradient of equivalent potential temperature by the vertical vorticity. The third term is the stretching of MPV by the horizontal absolute vorticity and the vertical stability. A generalized potential temperature $u^*$ with limitation on low relative humidity or no condensation conditions can be used to compute MPV to account for different degrees of saturation in the atmosphere (Gao et al. 2004). Another generalized form of MPV is to replace the potential temperature with the conservative moist-air entropy potential temperature that is valid for dry air or mixing with water vapor and condensate (Marquet 2014).

The low SCAPE values are much smaller than those shown by Glinton et al. (2017) to occur along the warm conveyor belt of extratropical cyclones in United Kingdom. However, Fig. 13 shows SCAPE is accompanied by negative MPV (green contours) so that convection can occur through the release of SCAPE. In addition, there is mechanical lifting of air parcels by strong low-level convergence in the corridor, with a magnitude from approximately $1.0 \times 10^{-3}$ to $1.0 \times 10^{-2}$ s$^{-1}$ ahead of the rainbands (white contours in Fig. 13). The release of small SCAPE works in tandem with strong low-level convergence to sustain the growth of convection during the AR surge phase. As for the COAMPS kona low experiments, decreasing the cyclonic flow of the kona low reduces the horizontal convergence of moisture from the tropics. This negative effect leads to the reduction of AR intensity and delays the northeastward IVT surge.

From the aforementioned analyses, a conceptual model of the 2019 Valentine’s Day AR emerges and consists of following four stages: genesis, growth, northeastward surge, and decay. In stage 1, the genesis of the AR is composed of a moisture source tap initiated by the passage of an equatorial Rossby wave and a coexisting cyclonic kona low to the
northeast of AR on 10 February (Fig. 14a). In Stage 2, the growth of convection in the AR is aided by small SCAPE values and increasing low-level convergence between the kona low and a mesoscale-high pressure that leads to the northward AR surge (Fig. 14b). The eastward surge appears to be associated with the southward push of a midlatitude trough that nudged the AR eastward during 11–13 February. In Stage 3, the AR reaches the U.S. West Coast and caused widespread floods in the Sierra Nevada Mountains and Southern California on 14 February (Fig. 14c). Stage 4 marks the decay of the AR after rainout at landfall and the cutoff of the tropical moisture tap on 16 February (Fig. 14d).

7. Summary and conclusions

The study uses large-scale analyses and limited-area coupled model experiments to explore the relationship between the kona low and the 2019 Valentine’s Day AR. The large-scale analyses show an equatorial Rossby wave, mesoscale high pressure, midlatitude shortwave trough, PV streamer, and kona low work in tandem and lead to the formation and surge of a Pineapple express AR that makes landfall along the U.S. West Coast. This AR event caused widespread flooding in the Sierra Nevada Mountains and Southern California. Using the limited area high-resolution air–sea coupled model COAMPS, we found the COAMPS control simulation is capable of capturing many large-scale and mesoscale features of the Valentine’s Day AR event that lasted from 10 to 17 February 2019. The analysis of the COAMPS control run shows that the model-simulated AR IVT and IWV compare reasonably well to the satellite and dropsonde observations in both the spatial patterns and the overall magnitude.

The COAMPS-simulated kona low has a dry and cold core with a region of convection concentrated along its eastern flank. The CAPE in this region is near zero or negative, eliminating the possibility of upright growth of the convection. Pronounced continued convective growth occurs in the corridor between the kona low and a westward approaching anticyclonic circulation. Analyses of the COAMPS control run indicates that in this corridor, the air parcels have a small amount of slantwise conditional instability and negative moist potential vorticity, which means convection can occur along a slantwise path. However, increased low-level convergence within the corridor is in conjunction with the release of SCAPE for the AR northward surge. The forced ascent associated with the low-level frontal convergence has been noted in other AR case studied by Neiman et al. (2008). While this is occurring, a southeastward approaching midlatitude trough forces the eastward movement of the AR.

The COAMPS kona low sensitivity experiments show that reducing the magnitude of kona low circulation causes a delay of the simulated AR landfall, landfall precipitation values, and a decrease in the IVT and IWV values, for this particular event. The simulated AR has up to a 2° westward displacement per 25% of kona low reduction, and a 1 day delay in the northward surge of IVT per 25% of kona low reduction. These kona low sensitivity experiments also show reduced AR landfall precipitation on the U.S. West Coast. Southern California precipitation nearly vanishes in the 25% kona low experiment. The impact of reducing the magnitude of the kona low circulation in these COAMPS experiments reveals that the kona low has a connection to the AR landfall precipitation over the U.S. West Coast 2–3 thousand kilometers to the east.

The study reveals a complex multiscale interaction between the large and mesoscale environments and the 2019 Valentine’s AR. It also shows the AR northeastward surge is sensitive to the magnitude of kona low circulation. This implies that if numerical forecasting models are deficient in forecasting the kona low circulation, this will lead to errors in the forecasting of the AR strength, landfall, and subsequent flooding. However, the AR forecast skill is also influenced by its interaction with other phenomena such as the extratropical cyclone, Rossby wave breaking, transient mesoscale frontal waves, the PV streamer (elongated high PV filament), and midlatitude troughs, which have not been examined here. Plausible interplay of these synoptic and mesoscale features with the 2019 Valentine Day AR may be inferred from other studies:

- A recent study using a 30-yr reanalysis shows that more than 75% of U.S. West Coast ARs are associated with an extratropical cyclone (EC), and the percentage increases to 94% for extreme AR events (Zhang et al. 2019). However, ~20%–30% of no-EC AR cases occur at latitudes less than 35°N because of the extratropical/subtropical moisture tap. The 2019 Valentine’s Day AR falls into this no-EC AR category.

- The mesoscale frontal waves have been observed to occur during AR landfall in Southern California where the lower portion of the main cold front was blocked by the coastal terrain (Neiman et al. 2004). The remnant of the cold and stable lower portion of the cold front excited a pair of mesoscale frontal waves on the scale of ~125 km that reoriented the precipitation bands over the coastal ocean and over the terrain. Mesoscale frontal waves can also occur along the synoptic cold front associated with an AR event examined by Ralph et al. (2011).

- The upper-level PV streamer in the 2019 Valentine Day AR propagates equatorward and westward with time. It is located to the north of intense AR IVT. Upper-level PV streamers associated with ARs are also found in four Switzerland flood events where the intense AR IVTs are located on the northeastern, eastern, or southeastern edge of PV streamers (Froidevaux and Martius 2016). Funatsu and Waugh (2008) show that the PV streamer will enhance the upward motion, destabilize the lower troposphere, and increase the moisture transport downstream ahead of the PV anomaly. The PV streamers intrusion into the subtropical region can promote tropical-extratropical interactions and can serve as a precursor for flood prediction (De Vries et al. 2018).

- The penetration of the U.S. West Coast ARs into the U.S. Northwest or Southwest interiors have been linked to the location of the synoptic ridge/trough over the North Pacific (Rutz et al. 2014). They show higher frequency of AR penetration into the northwest interior occurs when the coastal region is occupied by a synoptic 500-hPa ridge at landfall.
when the 500-hPa trough is west of the ridge over the North Pacific Ocean. ARs that penetrate into the southwest interior have the 500-hPa trough off the U.S. West Coast 24 h prior to the AR landfall. The 2019 Valentine AR case is consistent with their first scenario where the upper-level trough was off the North Pacific Ocean before the AR California landfall.

Additional case and process studies, such as those to investigate the frequency of kona lows occurring with nearby ARs, are warranted in the future to deepen our understanding of these processes, understand how frequently these interactions occur, and improve the model's ability to accurately predict ARs on synoptic and seasonal to subseasonal time scales.

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Data availability statement. The numerical model data created by this study are openly available from the HPCMP archive server.

REFERENCES


This content is incomplete or contains errors. The text is not formatted correctly and appears to be a mixture of citations and incomplete sentences. It seems to be from a scientific paper discussing atmospheric rivers and their interactions, but it is not fully transcribed or formatted properly. The file appears to be corrupted or incomplete. If you need specific information from this page, please provide the sections or topics you're interested in, and I'll do my best to assist you with the available data.


