A Comparison between the Kuroshio Extension and Pineapple Express Atmospheric Rivers Affecting the West Coast of North America

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ABSTRACT: Atmospheric rivers (ARs) originating near the Kuroshio Extension and the Hawaiian Islands and making landfall onto the west coast of North America in the North Pacific in the boreal winter season (October–March) are detected and tracked using ERA5 reanalysis (2000–19), and are classified as Kuroshio Extension (KE) and Pineapple Express (PE) ARs, respectively. Compared with KE ARs, PE ARs are longer and wider with higher intensity and shorter duration. Although the total occurrence of PE ARs is lower, the occurrence of extreme ARs is substantially higher than KE ARs. PE (KE) ARs are oriented more meridionally (zonally) with more equatorward (poleward) landfalling positions and associated precipitation. The genesis, development, and decay of KE and PE ARs and their relationships with extratropical cyclones (ECs) are investigated. Along- and cross-section analyses show that PE ARs are associated with stronger, deeper low pressure systems with closer tropical connections. Compared with KE ARs, PE ARs originate from well-developed ECs with stronger southward intrusion of cold fronts, forming closer to the ECs’ centers along the sharp temperature/pressure gradient zone. They are accompanied by enhanced and deeper vertical motion and stronger low-level wind. The intensity difference between KE and PE ARs is largely determined by the orientation and the strengths of temperature/pressure gradients of associated ECs rather than the intensity of associated ECs themselves. Furthermore, the evolution of ARs and ECs is not always synchronized, suggesting complicated AR and EC interactions that require further investigations.

KEYWORDS: North Pacific Ocean; Atmospheric river; Extratropical cyclones

1. Introduction

Atmospheric rivers (ARs) are defined as long narrow synoptic water vapor transport corridors, usually thousands of kilometers in length and hundreds of kilometers in width. Characterized by high water vapor content and strong low-level wind, ARs contribute over 90% of poleward water vapor transport in the midlatitudes (Zhu and Newell 1998; Gimeno et al. 2014; Ralph et al. 2019). When forced upward or making landfall especially in mountainous region, ARs can produce heavy precipitation and can be both beneficial for providing water resources and disastrous for causing severe floods (Dettinger et al. 2011; Payne et al. 2020). Moreover, the occurrence of ARs is typically associated with extratropical cyclones (ECs). It was documented that 82% of ARs are paired with ECs (Z. Zhang et al. 2019). Thus understanding of AR dynamics is also potentially important for the understanding of weather and climate system in the midlatitudes (Cordeira et al. 2013; Hu et al. 2017; Liu et al. 2021).

One of the most AR-impacted regions is the west coast of North America (WCNA). Not only have most of the severe historical floods in California been related to ARs in the North Pacific, but the interannual variability of extreme precipitation also closely follows the variation of AR occurrences (Dettinger 2011; Dettinger et al. 2011, 2015; Rutz et al. 2014; Konrad and Dettinger 2017). The water vapor transported by ARs has both tropical and extratropical origins (Eiras-Barca et al. 2017). A particular form of ARs that is widely discussed in the North Pacific is the “Pineapple Express” ARs (PE ARs), which exhibit strong tropical connection and transports water vapor from the vicinity of Hawaiian Islands to the WCNA (Lackmann and Gyakum 1999; Fig. 1). Another important AR genesis region in the North Pacific is the Kuroshio Extension (KE) region east of Japan. ARs generated in this region show considerable seasonal variability and strong connection with low-frequency climate modes like ENSO and the East Asian subtropical jet (Mundhenk et al. 2016; W. Zhang et al. 2019). Researchers have found that the genesis of summer ARs in the western North Pacific is extended farther into southeastern China and there is higher probability for summer ARs to make landfall along the east coast of Asian and affect Japan and southeastern China (Kamae et al. 2017; Guan and Waliser 2019). In this study, we pay attention to winter season ARs that generated in the Kuroshio.
Extension region and can make landfall along the WCNA. These ARs that transport water vapor from the extratropical moisture reservoir along the western boundary current are less connected to tropical moisture source and are referred to as KE ARs hereafter in this study. Both PE and KE ARs carry warm and moist air eastward and poleward, being forced upward when encountering the steep and high mountain near the coast, and are primarily responsible for enhanced vertical motions. On one hand, water vapor convergence and ascending motion along the warm sector of EC is favorable for AR genesis (Dacre et al. 2019). On the other hand, latent heat release associated with ascending motion inside the AR provides additional potential vorticity and in turn strengthens the growth of cyclones (Hoskins et al. 1985). Mechanisms and processes associated with the formation, development, and decay of PE and KE ARs and their relationship with ECs may also differ, which is another intriguing question to be investigated by this study.

We intend to provide a three-dimensional comparison between PE and KE ARs that can affect the WCNA as well as their relationships with ECs in this study. The remainder of the paper is organized as follows: data and methods used to detect PE and KE ARs and ECs are described in section 2. Comparisons of two-dimensional features between PE and KE ARs are presented in section 3, including their occurrence frequencies, distributions, and intensities, landfalling locations, and the associated precipitation responses. The vertical structures are shown in section 4 to complete three-dimensional views of PE and KE ARs. Respective relationships of PE and KE ARs with ECs are demonstrated in section 5. Processes following different evolutionary phases of KE and PE ARs are investigated in section 6. Conclusions and discussion are provided in section 7.

2. Data and methods
   a. Data
      The synoptic scale and long narrow feature of ARs require high-resolution datasets both temporally and spatially. The dataset used in this study is the recently released 6-hourly, 0.25°, three-dimensional ERA5 reanalysis (the fifth-generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis dataset, 2000–19; Hersbach et al. 2020). ARs are detected using vertically integrated (1000–300 hPa) water vapor transport: $(1/g) \sqrt{\frac{
u q}{\nu \theta}}$ [Other variables analyzed include specific humidity, horizontal and meridional wind components, vertical velocity, potential temperature, geopotential, sea level pressure, and precipitation. The analyses are performed in the North Pacific (10.5°–65.5°N, 20°–45°N, 130°–160°W). The solid red box (20°–45°N, 130°–160°E) outlines the region used to define KE ARs, and the dotted red box (10°–45°N, 165°–145°W) outlines the region used to define PE ARs.

   ![Fig. 1. Genesis frequency of all ARs landfalling along the WCNA in the North Pacific. The genesis of an AR is defined as the first snapshot detected along an AR life track. The genesis frequency is calculated as the number of genesis AR snapshots divided by the total number of 6-hourly records in boreal winter season (ONDJFM) during 2000–19 (4 × 182 × 20). The solid red box (20°–45°N, 130°–160°E) outlines the region used to define KE ARs, and the dotted red box (10°–45°N, 165°–145°W) outlines the region used to define PE ARs.](image-url)
99.5°E–100.5°W) region during boreal winter season [October–March (ONDJFM)] when ARs are mostly active (Gimeno et al. 2014; Guan and Waliser 2015).

b. AR detection and tracking

Detection of ARs mainly relies on IWV or IVT using either a fixed or flexible threshold. A comprehensive collection of AR detection algorithms can be found at the Atmospheric River Tracking Method Intercomparison Project (ARTMIP) (Rutz et al. 2019; Shields et al. 2018). Two widely used thresholds to define ARs are the 250 kg m⁻¹ s⁻¹ fixed IVT (IVT250) and the 85th percentile flexible IVT (IVT85%; Rutz et al. 2014, 2015; Nayak et al. 2014; Guan and Waliser 2015). In this study, we choose a newly developed image-processing based detection and tracking method (IPART) from ARTMIP (Xu et al. 2020a; https://www.cgd.ucar.edu/projects/artmip/algorithms.html). This new method exploits the spatial and temporal transient nature of ARs and achieves the AR detection without specifying any threshold on IVT. Compared with conventionally used IVT250 or 85th percentile thresholding approaches, this method has a higher tolerance to a broader range of IVT intensities, and therefore is capable of detecting weaker ARs during the genesis and decaying stages and covering the entire AR life cycle (Xu et al. 2020a,b).

Geometrical considerations during the detection of ARs also follows those of Xu et al. (2020a): the length restriction of AR axis is [800, 11 000] km; the area restriction is [50, 1800] × 10⁴ km²; a minimal length/width ratio (2.0) and isoperimetric quotient ratio (0.7) are used to distinguish the “long narrow” shape. To capture both PE and KE ARs, the geometrical centroid of an AR is required to be located within a latitudinal band from 10° to 55°N. A minimum 24-h duration restriction is applied to the AR tracking to exclude short-lived moisture filaments. Landfalling ARs are defined as if the outer edge of an AR intersects the western coastline of North America. PE ARs are defined as if an AR originates around the Hawaiian Islands (10°–45°N, 165°–145°W; the dotted red box in Fig. 1) and meanwhile at least one grid point of the AR locates in the tropical area (10°–25°N, 165°–145°W). A relatively large area extended to the south of the Hawaiian Islands is chosen to ensure that PE ARs have a tropical origin. KE ARs are defined as if an AR generates from the Kuroshio Extension region (20°–45°N, 130°–160°E) (the solid box in Fig. 1) and does not propagate into the tropical region of 10°–25°N, 165°–145°W. These restrictions ensure no overlaps between PE and KE ARs and a clean comparison of the two groups. To evaluate potential uncertainties induced by different AR detection methods, a comparison between IPART, IVT250, and IVT85% is provided in the appendix and the results suggest that although the number of detected KE/PE ARs changes, the primary conclusions of this study do not alter. More detailed discussion can be found in the appendix.

Detection of ECs relies on sea level pressure anomalies (SLPa) following previous studies (Hodges 1994, 1995; Z. Zhang et al. 2019). SLPa are derived by applying a temporal (15-day high pass) and a spatial (1° × 1° low pass) filtering to remove low-frequency and small-scale features not associated with ECs. The center of an EC is defined as SLPa minimum with a closed contour, with an additional requirement of a minimum of 2 hPa increase away from the center within 4° radius (Liu et al. 2021). EC tracks are formed by stitching the nearest EC centers within a 1000-km searching distance during consecutive time steps. A minimum of 24-h duration and 1000-km distance restriction are applied to construct EC tracks (Colle et al. 2013).

c. AR and EC composites

To facilitate creation of AR composites, an axis is first sought in each AR. The AR axis is defined in a topological approach as the path that runs through the AR interior with the largest integral of along-path IVT. This method provides a satisfactory fitting of both the shape and the moisture flux orientation of the AR (Xu et al. 2020b). Vertical along-section analysis is performed along the AR axis and the composite is constructed by normalizing the AR length. Vertical cross-section analysis is taken in the middle of and perpendicular to the AR axis. To include the full structure of AR-related processes, the vertical cross section of each AR is extended to 4000 km wide and normalized to a width from −0.5 to 0.5, centered at the AR axis. When studying the relationship between ARs and ECs, a paired AR (EC) is defined as if the IVT maxima of the AR (SLP minima of ECs) coexist within a 25° × 25° box around the EC (AR) center. The related fields are then used to create the AR/EC composites following previous studies (Zhang and Colle 2017; Liu et al. 2021).

3. Two-dimensional characteristics of KE and PE ARs

a. Occurrence, distribution, and precipitation

A total of 28 972 AR snapshots (6-hourly) from 1937 AR tracks are detected during the 20 winter seasons in the North Pacific from ERA5. Among these tracks, 977 AR tracks make landfall along the WCNA. Taking the first snapshot from the landfalling AR track as genesis, Fig. 1 shows the spatial distribution of genesis frequency of all landfalling ARs. It can be seen that the KE and PE domains correspond to the two most active AR genesis regions in the North Pacific and are used to define KE and PE ARs as described in section 2. According to the definition, a total of 12 021 (3065) AR snapshots from 734 (236) KE (PE) AR tracks are selected. Among them, 260 (142) KE (PE) AR tracks make landfall along the WCNA, accounting for 35% and 60% of the total KE and PE AR tracks, respectively (Table 1). A large portion (65%) of KE ARs cannot reach the WCNA and dissipate in the central North Pacific. Compared with landfalling KE ARs, these non-landfalling KE ARs are weaker and shorter in length and duration. In the following of this paper, we focus on those landfalling KE and PE ARs that can affect the WCNA and trace their life cycles to study the evolution features. Hereafter, PE and KE ARs refer to landfalling KE and PE ARs only.

Figure 2a shows the overall distribution of all AR snapshots during the whole life tracks of landfalling KE ARs. It extends
northeastward from the Kuroshio Extension region to the eastern North Pacific (140°E, 120°W), collocating with midlatitude jet stream and storm tracks (Fig. 2a). In contrast, PE ARs originate north of the Hawaiian Islands and mainly occur in the eastern Pacific (170°W, 120°W) and thus a shorter travel distance is expected (Fig. 2c). Also, KE and PE ARs show significant difference in orientations, with PE ARs exhibiting a stronger southwest–northeast tilt. Detailed duration and orientation differences are demonstrated later in the probability density function (PDF) analyses. Clearly, KE ARs have much higher occurrence frequency than PE ARs. The overall occurrence frequency of KE ARs is about 2–3 times that of PE ARs (Figs. 2a,c, Table 1). The spatial distribution of averaged IVT associated with KE and PE ARs resembles that of their respective occurrence frequencies. KE ARs demonstrate longer and narrower extension across the whole basin with weaker intensity (Figs. 2b,d). The averaged IVT associated with KE ARs is ~25% lower than that of PE ARs.

Table 1. Detected AR tracks and snapshots in boreal winter in the North Pacific in ERA5 during 2000–19. AR tracks are the number of total AR life tracks detected in the North Pacific and AR snapshots are the corresponding number of all AR snapshots during total AR life tracks. Landfalling AR tracks and snapshots are the number of life tracks and all associated snapshots during whole life cycles of ARs that make landfall along the WCNA.

<table>
<thead>
<tr>
<th></th>
<th>AR tracks</th>
<th>AR snapshots</th>
<th>Landfalling AR tracks</th>
<th>Landfalling AR snapshots</th>
</tr>
</thead>
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<tr>
<td>ALL</td>
<td>1937</td>
<td>28,972</td>
<td>977</td>
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</tr>
<tr>
<td>KE ARs</td>
<td>734</td>
<td>12,021</td>
<td>260</td>
<td>5835</td>
</tr>
<tr>
<td>PE ARs</td>
<td>236</td>
<td>3065</td>
<td>142</td>
<td>2091</td>
</tr>
</tbody>
</table>

The IVT, IWV, and precipitation associated with the genesis and landfalling snapshots of KE and PE ARs are shown in Figs. 3 and 4. KE ARs originate from the Kuroshio Extension in the western Pacific with weaker IVT (~120 kg m⁻¹ s⁻¹) and IWV (8 mm) (Figs. 3a,b). They make landfall and dissipate with an average IVT of ~180 kg m⁻¹ s⁻¹ in the mountainous region along the WCNA, leading to intensive precipitation (Figs. 4a,b). Compared with the initial stage (Fig. 3a), the increase of landfalling IVT (Fig. 4a) suggests that water vapor replenishment must exceed depletion during propagation of KE ARs. PE ARs initiate in the subtropical region of eastern Pacific and are loaded with heavy water vapor from the beginning (IVT ~240 kg m⁻¹ s⁻¹) (Figs. 3c,d). Like KE ARs, they also produce stronger IVT and precipitation when making landfall along the WCNA (Figs. 4c,d). Unlike KE ARs, the averaged IVT associated with landfalling PE ARs (Fig. 4c) is lower compared with its initial value (Fig. 3c), indicating an overall depletion of water vapor during development. Although the large moisture dissipation of both

![Fig. 2](image-url)
KE and PE ARs occur along the WCNA, there is a loca-
tional shift between these two types of landfalling ARs as
revealed by the differences of associated IVT and precipita-
tion (Figs. 4e,f). In specific, landfalling of KE ARs tends to
occur farther northward compared with PE ARs.

As shown in Fig. 4, much of the heavy precipitation associ-
ated with landfalling ARs along the WCNA occurs in the
high mountainous terrain. PDFs of the precipitation over the
high precipitation region show that although landfalling ARs
only occur in ∼10% of the wintertime, their contribution to
extreme precipitation (>100 mm day⁻¹) can reach as high as
60%–80% (Figs. 5a,b). Further examination of KE and PE
landfalling AR-induced precipitation shows that the contribu-
tion of KE/PE ARs to extreme precipitation is ∼20% with
slightly higher value for KE ARs (Fig. 5b). The median value of AR
length is 3690 (3790) km for KE (PE). The median area is
1.64 (2.02) \times 10^6 km^2 for KE (PE) ARs (Table 2). Corre-
spondingly, the median value of AR width is 457 (538) km for
KE (PE). The averaged cross-section water vapor transport is
about 2.44 (2.77) \times 10^8 kg s⁻¹ for KE (PE) ARs (Table 2).

Substantial differences also exist between KE and PE ARs’
duration, orientation, and landfalling position. The duration
of KE ARs ranges from 24 to 270 h with a median value of
126 h (5.25 days). On the contrary, the duration of PE ARs is
much shorter with a median value of 72 h, about half
that of KE ARs, consistent with their shorter travel distances.

Analyses of orientation PDFs show that ∼90% of KE and PE
ARs’ orientation angle falls in the northeastern quadrant
(Fig. 6e), in agreement with the southwest–northeast tilt of
ARs (Fig. 2). A comparison between KE and PE orientation
PDFs shows an obvious rightward shift with increased occur-
rence of PE ARs as the angle increases (Fig. 6e), supporting
by the increased median angle from 36.1° (KE) to 50.5° (PE)
(Table 2). Typical landfalling positions of KE and PE ARs
vary between 32° and 60°N (Fig. 6f). Over 50% of KE ARs
make landfall north of 52°N. On average, the landfalling posi-
tion of KE ARs is about 5.7° northward of that of PE ARs
(Table 2). The above results indicate that compared with KE
ARs, PE ARs are generally longer and wider with higher IVT
intensity and shorter duration, having a more signifi-
cant meridional tilt and southward landfalling position. Aside from
discernible differences in mean AR features, the standard
deviations of KE and PE AR features are also computed

b. Geometrical characteristics of KE and PE ARs

By tracing back KE and PE landfalling ARs and including
all AR snapshots during their life tracks, characteristic PDFs
of these two types of ARs including duration, length, area,
orientation, total IVT, and landfalling locations are investi-
gated and shown in Fig. 6. Overall, the shapes of length, area,
total IVT, duration, and orientation angle distributions are
logarithmic, in agreement with previous studies (Guan
et al. 2018). In specific, the length and area of KE and PE
ARs show similar distributions with higher median values
for PE ARs (Figs. 6a,b; Table 2). The median value of AR
length is 3690 (3790) km for KE (PE). The median area is
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meridional tilt and southward landfalling position. Aside from
discernible differences in mean AR features, the standard
deviations of KE and PE AR features are also computed

FIG. 3. Averaged IVT and IWV during genesis of KE and PE ARs affecting the WCNA. Averaged IVT (kg m⁻¹ s⁻¹)
associated with genesis snapshots of landfalling (a) KE and (c) PE ARs. (b),(d) As in (a) and (c), but for integrated water
vapor (IWV; mm). The averaged IVT (IWV) is calculated as the sum of IVT (IWV) associated with the first snapshot of
landfalling KE/PE ARs divided by the number of first AR snapshots.
The variabilities of typical AR characteristics are largely comparable between PE and KE ARs except that KE ARs tend to have higher variability in length and duration (Table 2), possibly due to their larger spatial distribution and longer travel distance. Figure 7 further highlights the KE–PE differences with respect to their area, total IVT, duration, and orientation angle, especially when considering extreme ARs. The occurrence of PE ARs is ~100% higher than KE ARs when counting extreme ARs (area $>6.0 \times 10^5$ km$^2$, cross-section water vapor transport $>6 \times 10^8$ kg s$^{-1}$). The result suggests though the total occurrence of PE ARs is much lower than KE ARs (Fig. 2), there is a higher chance of extreme ARs to occur in the PE group, transport more moisture poleward, and make a crucial contribution to extreme precipitation events along the U.S. West Coast. Compared with previous studies (Ralph et al. 2017; Guan et al. 2018), the averaged width and water vapor transport analyzed here are slightly narrower and weaker, likely because the IPART detection method gives a slightly more accurate delineation of the AR shape as shown in the appendix and also the work by Xu et al. (2020b).

4. Vertical structure of KE and PE ARs

The above analyses based on IVT are basically two-dimensional and do not reveal the vertical structure of the ARs. To provide a complete three-dimensional view, the vertical structure of the KE and PE ARs affecting the WCNA is investigated in this section. Vertical profiles of related variables averaged inside ARs show that both KE and PE ARs are characterized by warm moist air, high wind speed, and upward vertical motion (Figs. 8a,b). Although the absolute moisture maximum is located near ocean surface (not shown), the maximum specific humidity anomalies (anomalies are defined as 6-hourly deviations from 20-yr climatological monthly mean) occur above the planetary boundary layer (PBL) at around 800 hPa (blue lines in Fig. 8a). The water vapor anomalies above PBL contribute over 60% to the whole column water vapor increase. As revealed by a recent study (Liu et al. 2021), it is the water vapor transported above PBL that seems to couple with ECs and is crucial for AR genesis. Two positive potential temperature anomaly maxima appear at around 900 and 400 hPa, respectively (red lines in Fig. 8a).
The lower-level temperature maximum is likely associated with the warm advection from the south and the upper-level maximum is related to latent heat release associated with ascending motion. The wind profiles show stronger wind speed anomalies at high level and are associated with the upper-level jet stream (green lines in Fig. 8a). The low-level jet signal here is weak when averaging all grid points inside ARs, but can be seen more clearly from the along- and cross-section structures introduced later (Fig. 9). The averaged vertical motion is positive throughout the whole troposphere, corresponding to a deep ascending inside ARs. The ascending motion peaks around middle troposphere and penetrates deep into the upper troposphere (orange lines in Fig. 8b). The averaged geopotential profiles show low/high

FIG. 5. (a) Contribution of landfalling AR-induced precipitation to total precipitation along the WCNA. PDFs of total accumulated precipitation (mm day\(^{-1}\); histograms), total landfalling AR-induced precipitation (blue line), KE landfalling AR-induced precipitation (red line), and PE landfalling AR-induced precipitation (yellow line) based on 6-hourly precipitation averaged in the red box in Figs. 4b and 4d. (b) PDFs of fraction contribution (%) of the total landfalling AR-induced precipitation (histograms), KE landfalling AR-induced precipitation (red line), and PE landfalling AR-induced precipitation (yellow line) to total precipitation. (c) PDFs of fraction contribution (%) of the KE landfalling AR-induced precipitation (red lines) and PE landfalling AR-induced precipitation (yellow lines) to total precipitation averaged along the west coast of Canada (the northern box in Fig. 4f, solid lines) and along the U.S. West Coast (the southern box in Fig. 4f, dotted lines). The blue shading highlights the extreme precipitation that exceeds 100 mm day\(^{-1}\).

FIG. 6. (a) Characteristic PDFs of KE and PE ARs affecting the WCNA. PDF of length (10\(^3\) km) of KE (gray) and PE (red) ARs. The remaining panels are as in (a), but for (b) AR area (10\(^5\) km\(^2\)), (c) total cross-sectional IVT (10\(^7\) kg s\(^{-1}\)), (d) duration (10 h), (e) orientation angle (10\(^8\)), and (f) landfalling latitude (°N). The PDFs are computed based on all AR snapshots during entire life tracks of landfalling KE and PE ARs. The total cross-sectional IVT is calculated as water vapor transport across a vertical AR section (Guan et al. 2018). Median values of respective distributions are annotated by vertical lines and nearby numbers.
geopotential anomalies in the lower/upper troposphere (purple lines in Fig. 8b) and are largely defined by the southward intrusion of the cold front associated with an EC as discussed later.

Compared with KE ARs, PE ARs are accompanied with higher specific humidity and wind speed anomalies throughout the whole air column (Fig. 8a), consistent with higher IVT of PE ARs (Figs. 2, 6, Table 2). The largest water vapor difference between KE and PE ARs also occurs around 800 hPa above PBL (Fig. 8a). The largest wind difference between KE and PE ARs occurs in the upper troposphere in line with upper-level jet stream (Fig. 8a). The potential temperature anomaly induced by PE ARs is generally lower than that of KE ARs in both the lower and upper troposphere due to the enhanced southward intrusion of the cold front associated with PE ARs. The ascending motion inside PE ARs is about 1.5 times that of KE ARs (Fig. 8b). Analysis of the variances of KE and PE AR variables (Figs. 8c,d) shows higher variability of specific humidity, wind speed, and potential temperature anomalies associated with KE ARs than PE ARs, perhaps because KE ARs are distributed more dispersively and collocate with midlatitude storm tracks (Fig. 2a). The results above suggest that, on average, PE ARs are stronger and have lower variability than KE ARs.

The vertical structure differences between KE and PE ARs can be seen more clearly from the along- and cross-section profiles (Figs. 9 and 10). These vertical sections are oriented such that the along section goes from the west (left) to the

**Table 2.** Medians and standard deviations (STDs) of AR characteristic PDFs. Total IVT is calculated as the cross-section water vapor transport (Guan et al. 2018). Angle indicates the orientation of AR axis.

<table>
<thead>
<tr>
<th></th>
<th>Length (km)</th>
<th>Area (km²)</th>
<th>Total IVT (kg s⁻¹)</th>
<th>Duration (h)</th>
<th>Angle (°)</th>
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**Fig. 7** (a) PDFs of relative area difference (%) between PE and KE ARs affecting the WCNA in reference to KE ARs derived from Fig. 6. (b)–(d) As in (a), but for total cross-sectional IVT (10⁷ kg s⁻¹), duration (10 h), and orientation angle (10°), respectively.
east (right) and the cross-section profile is viewed from the north to the south on the plot (Fig. 9c). Considering the overall southwest–northeast orientation of ARs and the dominating westerlies in the midlatitude, the left (right) side in both the along- and cross-section plots correspond to the upwind (downwind) side. Although the cross-section profiles show a narrow band (~400 km) of high water vapor that centers slightly downwind of the AR’s center for both KE and PE (color shading in Figs. 9b,d), water vapor across PE ARs has a longer and stronger tail in the south. Moreover, the along-section profiles show that water vapor maximum occurs at the southwest region of PE ARs while water vapor is highest near the central region of KE ARs (color shading in Figs. 9a,c). Both the along sections and cross sections of specific humidity anomalies confirm the closer connection to tropical moisture of PE ARs.
The maximum core of wind speed anomalies ($>10 \text{ m s}^{-1}$) corresponding to the low-level jet is clearly shown in the vertical along-section wind profile (black contours in Figs. 9a,c). The low-level jets associated with PE ARs and KE ARs center below 850 hPa. Compared with KE ARs, the distribution of wind speed anomalies below 500 hPa inside PE ARs is more homogenous due to stronger vertical mixing. The cross-section wind speed anomalies of PE ARs show a deeper and narrower downward intrusion of high winds from the upper troposphere to the surface (black contours in Fig. 9d), again possibly owing to stronger turbulent mixing inside PE ARs, which is further verified in Fig. 10.

The cross-section geopotential of PE ARs shows a deep frontal structure with low (high) pressure on the upwind (downwind) side, corresponding to a cold front coming from the north (color shading in Figs. 10b,d). Along the cold front, frontogenesis induces a secondary ageostrophic circulation and enhances the vertical motion (Cordeira et al. 2013). The amplitude of the vertical motion is proportional to the temperature gradient across the front and the largest ascending motion occurs downstream of the cold front and extends deep into the troposphere (black contours in Figs. 10b,d). The northward tilt of the cold front is also consistent with the frontogenesis discussed by previous studies (Cordeira et al. 2013). The temperature front and pressure gradients associated with PE/KE ARs, the low (high) pressure anomalies are accompanied by cold (warm) air in the upwind (downwind) side, corresponding to a cold front coming from the north and downstream of the cold front (Fig. 9d). The tilting of ARs also induces ageostrophic circulation developed along the cold front as discussed below in Fig. 10. The along-section geopotential profiles show that compared with KE ARs, deeper low pressure anomalies lie under high pressure anomalies for PE ARs (red contours in Figs. 9a,c), suggesting a stronger southward intrusion of the low pressure system associated with PE ARs.

Across PE/KE ARs, the low (high) pressure anomalies are accompanied by cold (warm) air in the upwind (downwind) side, corresponding to a cold front coming from the north (color shading in Figs. 10b,d). Along the cold front, frontogenesis induces a secondary ageostrophic circulation and enhances the vertical motion (Cordeira et al. 2013). The amplitude of the vertical motion is proportional to the temperature gradient across the front and the largest ascending motion occurs downstream of the cold front and extends deep into the troposphere (black contours in Figs. 10b,d). The northward tilt of the cold front is also consistent with the frontogenesis discussed by previous studies (Cordeira et al. 2013). The temperature front and pressure gradients associated with PE/KE ARs, the low (high) pressure anomalies are accompanied by cold (warm) air in the upwind (downwind) side, corresponding to a cold front coming from the north (color shading in Figs. 10b,d). Along the cold front, frontogenesis induces a secondary ageostrophic circulation and enhances the vertical motion (Cordeira et al. 2013). The amplitude of the vertical motion is proportional to the temperature gradient across the front and the largest ascending motion occurs downstream of the cold front and extends deep into the troposphere (black contours in Figs. 10b,d). The northward tilt of the cold front is also consistent with the frontogenesis discussed by previous studies (Cordeira et al. 2013). The temperature front and pressure gradients associated
with KE ARs are weaker than PE ARs (Figs. 10b,d), consistent with the weaker low pressure system. Correspondingly, the ascending motion of KE ARs is considerably weaker and shallower (black contours in Fig. 10b). Along PE ARs, extensive warming and ascending occur along the entire air column (Fig. 10c). The maximum warming and ascending occur toward the northeast region where ARs are connected with the warm conveyor belt of ECs (Dacre et al. 2019). In contrast, ascent inside KE ARs also occurs along the warm conveyor belt but is significantly weaker due to the weaker thermal front and pressure gradients associated with KE ARs as mentioned above (Fig. 10a).

The above along- and cross-section analyses based on an abundant collection of ARs provide a complete three-dimensional view of processes associated with KE and PE ARs. The formation of an AR typically occurs ahead of the cold front of an EC (Cordeira et al. 2013; Ralph et al. 2018). When the cold front associated with dry air and low pressure from the north encounters warm and moist air associated with high pressure in the south, the cold air intrudes under the warm air, and sharp temperature and pressure gradients form along the cold front. With the presence of a strong thermal front, deep vertical motion develops downstream of the front induced by the ageostrophic circulation and leads to strong downward momentum mixing. The sharp pressure gradient along with downward momentum mixing sustains strong low-level jet, leading to enhanced IVT convergence along and ahead of the cold front, creating favorable conditions for AR formation and development. Compared with PE ARs, KE ARs develop with weaker thermal front and the vertical ascending motion is shallower and weaker, leading to decreased IWV and IVT.

5. Relationship with extratropical cyclones

Although ARs are closely related with ECs, the relationship between ARs and ECs is complicated. According to previous study, while ~80% of ARs are paired with ECs, only 45% of ECs are paired with ARs (Z. Zhang et al. 2019). Similar EC–AR pairing analyses were performed here using the ERA5 dataset. For all ARs detected in the North Pacific, 69% of ARs are associated with ECs, while 42% of ECs are paired with ARs, consistent with the previous results. Considering those KE and PE ARs that eventually make landfall along the WCNA, we found that during their life cycles 74% (68%) of KE (PE) ARs are paired with ECs. This indicates a higher concurrence rate of KE ARs and ECs. This may be understood from the fact that the KE ARs occur primarily in the extratropical region and collocates with midlatitude storm tracks (Fig. 2a). On the contrary, PE ARs occur farther south (Fig. 2c) and can entrain sufficient water vapor from the tropics and subtropics, thus having a higher chance of forming without an EC.

Focusing on the landfalling ARs along the WCNA, we carefully examined their relationship with ECs. During landfall, the fraction of ARs associated with ECs is reduced to

![Fig. 10. As in Fig. 9, but for potential temperature anomaly (color shading: °C) and vertical velocity (black contours; −ω, Pa s⁻¹).](image-url)
~60% for both KE and PE ARs. Figure 11 shows the composite of ECs paired with landfalling KE and PE ARs, referred to as EC-KE and EC-PE, respectively. The low pressure anomalies associated with EC-KE are oriented more zonally with a northward expansion, along with strong eastward and poleward surface winds located southeast of the EC center (Fig. 11a). The strong wind leads to enhanced water vapor transport along the warm sector and is clarified as “feeder airstream” (Dacre et al. 2019). One branch of water vapor is converged toward the center of the EC, along the storm’s conveyor belt within warm sector, forming maximum precipitation in front of the EC’s center and depleting the total water vapor (Fig. 11c). The remaining IVT from the feeder airstream contributes to the formation of ARs and the maximum IVT largely occurs southeast of the EC (Fig. 11b). In contrast, the low pressure anomalies associated with EC-PE are oriented more meridionally with a southward expansion (Fig. 11d), leading to increased northerly wind component and decreased easterly wind component (Fig. 11g), in agreement with the stronger southward intrusion of the cold front associated with PE ARs. Correspondingly, the associated IVT and precipitation are stretched and rotated farther northward, leaving a longer southern tail (Figs. 11e,f). The orientation difference between EC composites is consistent with the orientation analysis between KE and PE ARs discussed in section 3. Besides, IVT around the center of EC-PE is about 50 kg m$^{-1}$ s$^{-1}$ stronger than that associated with EC-KE (Fig. 11h). However, the central SLP anomalies of EC-KE and EC-PE are comparable, suggesting a disproportional relationship between EC and AR intensity, which is also noted by a previous study (Z. Zhang et al. 2019).
Figure 12 shows the composite of landfalling ARs paired with ECs. Consistent with the EC composite, both KE and PE ARs form southeast of ECs associated with deep low (high) pressure anomalies to the northwest (southeast) (Figs. 12a,d). The distance between the KE AR and EC center is ∼1500 km while the distance for PE AR is ∼700 km, indicating that PE ARs are closer to the EC’s center, with sharper pressure gradients. The low pressure system associated with PE ARs is oriented more meridionally and has stronger southerly wind, also in line with EC composite. The orientation difference between KE and PE ARs is also evident from the IVT composite (Figs. 12b,e), leading to a quadripartite structure in the difference map (Fig. 12h). Maximum precipitation generally follows IVT with slightly forward movement along the warm sector of the EC (Figs. 12c,f,i).

The above results reveal a higher percentage of ARs coinciding with ECs along their whole life tracks and the percentage drops when ARs make landfall, indicating the probability for ECs and ARs to decouple during the decaying stage for both KE and PE ARs. Composite analyses of paired ECs and ARs further verify that ARs form southeast of EC along the strong pressure gradient zone. Compared with KE ARs, PE ARs are located closer to the EC center with stronger pressure gradient and the sharper thermal front, therefore being more favorable for enhanced vertical motion and higher IVT. Furthermore, ECs associated with PE ARs have a more southward intrusion and meridional tilting, increasing their connection to tropical moisture source, also contributing to higher IVT. However, the intensities of ECs associated with KE and PE ARs are comparable. Thus, it is inferred that the orientation of ECs and the relative location of ARs and ECs

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**Figure 12.** Composites of ARs paired with ECs. Composites of sea level pressure anomalies (SLPa; contours; hPa) and 10-m wind (vectors; m s$^{-1}$) of landfalling (a) KE and (d) PE AR snapshots paired with ECs, and (g) the corresponding difference between KE and PE ARs. (b),(e),(h) As in (a), (d), and (g), but for composite of IVT (kg m$^{-1}$ s$^{-1}$) associated with ARs. (c),(f),(i) As in (a), (d), and (g), but for composite of precipitation (mm day$^{-1}$) associated with ARs. All composites are centered at the AR center, which is determined by the IVT maximum. The difference above 95% confidence level based on a two-sided Student’s test is shaded by gray dots.
are crucial in determining the intensity difference between KE and PE ARs while the intensity of ECs themselves plays a less important role.

6. Evolution of KE and PE ARs

To gain further understandings of processes associated with the genesis, development, and decay of ARs, we analyzed the composites of related variables during different evolutionary phases of ARs. The whole life track of AR is separated into four phases: origin (beginning of cycle), prophase (1/3 of cycle), metaphase (2/3 of cycle), and anaphase (ending of cycle), respectively. Examples of the four phases during a typical KE/PE AR’s evolution are shown in Fig. 13.

At the origin phase of KE ARs (green line in Fig. 14a), the accumulated water vapor (water vapor summed up over all
grid points inside ARs) is relatively low (≈5 × 10³ g kg⁻¹ at the surface). Water vapor gradually builds up through evaporation and IVT convergence and sustains the growth of ARs during the prophase and metaphase (red and blue lines in Fig. 14a). The water vapor reaches the highest (>1.0 × 10⁴ g kg⁻¹) level at the prophase (red line in Fig. 14a). At anaphase, a large amount of water vapor is released through precipitation, leading to the decay of KE ARs. The water vapor amount returns to the lowest level at this stage (<5 × 10³ g kg⁻¹) (orange line in Fig. 14a). For PE ARs, the evolution of moisture is analogous to KE ARs, but the accumulated water vapor at the origin phase (green line in Fig. 14b) is already relatively high (≈7.5 × 10³ g kg⁻¹), ~1.5 times that of KE ARs. The above results suggest an overall replenishment (depletion) of water vapor during the developing (decaying) phase for both KE and PE ARs. However, we should point out that the analyses are based on accumulated water vapor over a certain period. In reality, evaporation, precipitation, and horizontal and vertical transport of water vapor occur from time to time during the evolution of ARs, leading to constant water vapor replenishment and depletion throughout the whole life cycle of ARs.

An increase of wind speed occurs from origin to prophase and the wind remains relatively stable for the following phases for KE ARs (Fig. 14c). For PE ARs, wind anomalies remain almost unchanged through the entire life track and are generally higher than KE ARs (Fig. 14d). This can be explained by the deep and well-developed pressure systems associated PE ARs as shown in Figs. 15 and 16. No obvious change of wind occurs during the decaying phase for both KE and PE ARs, suggesting the decay of ARs is mainly attributed to the depletion of water vapor upon landfalling. The averaged ascending motion inside PE ARs is consistently stronger than that of KE ARs and there is an abrupt increase of ascending at anaphase for both PE and KE ARs, due to topography lifting upon landfalling (Figs. 14g,h). The persistent ascending motion inside ARs causes latent heat release, and thus the temperature gradually increases following the development of ARs and is the highest at the anaphase for PE ARs (Figs. 14e,f). The maximum warming transits from lower to upper levels following AR evolution and the increase of the maximum warming level is more evident for KE ARs.

The SLPa composites during different phases of ARs show PE ARs originate from well-developed ECs with deep low pressure anomalies and strong meridional wind (Fig. 15a). The intensity of ECs reaches its maximum at prophase and decays at metaphase and anaphase (Figs. 15f–h). Correspondingly, the strong cold fronts ahead of the ECs appear from the origin and reach maximum amplitude and the deepest vertical structure at prophase and metaphase (Figs. 16 and 17e–g). The sharp pressure and temperature gradients lead to strongest vertical motion at prophase (Fig. 17f), supporting the high moisture transport and the full development of PE ARs at prophase (Fig. 14b). At the anaphase, the pressure and temperature gradient decreases, along with weakened vertical motion and decreased water vapor transport (Figs. 16 and 17h), corresponding to the decaying of the ARs (Fig. 14b). Both the highest water vapor and the lowest pressure associated with PE ARs occur at prophase, indicating an largely in-phase evolutions of ECs and PE ARs. As suggested by previous studies (Wernli and Davies 1997; Sodemann and Stohl 2013; Cordeira et al. 2013), the rising motion and related latent heat release may be crucial for the positive feedback between cyclone and AR development.
Compared with PE ARs, KE ARs originate from weaker ECs with a more zonal wind component; the low pressure system gradually strengthens and deepens, grows into maximum at metaphase, and decays at anaphase (Figs. 15a–d). The corresponding cold fronts of the ECs are also weaker and shallower from the origin (Figs. 16 and 17a). Due to the inhibited southward intrusion of the cold front (Figs. 16 and 17a–d), the low pressure system is much weaker and the high pressure system gradually dominates. The reduced cold front and low pressure system associated with KE ARs lead to notably weaker vertical motion than that of PE ARs throughout the life cycle (Fig. 17). Unlike PE ARs, the evolution of KE ARs and ECs is less synchronized, with the maximum KE AR IWV occurring at prophase (Fig. 14a), with minimal EC SLPa occurring at metaphase (Fig. 15c). The out-of-phase change between KE ARs and ECs suggests complicated processes involved with the evolution of ARs and ECs, which requires further investigation.

7. Conclusions and discussion

Based on 20-yr high-resolution ERA5 reanalysis, ARs affecting the WCNA in the boreal winter season (ONDJFM) in the North Pacific are detected and tracked. Two maximum genesis regions are found: one near the Kuroshio Extension (KE ARs) and another just north of the Hawaiian Islands (PE ARs). By tracing back landfalling KE and PE ARs, a comprehensive comparison between the two groups is made. Compared with KE ARs, the overall occurrence of PE ARs is lower than KE ARs, but the occurrence of extreme PE ARs is substantially higher. Also, PE ARs are longer and wider with higher intensity and shorter duration. The most striking
The difference between PE and KE ARs is their orientation: KE ARs are oriented more zonally while PE ARs are oriented more meridionally. Correspondingly, the position of landfalling ARs and precipitation associated with PE (KE) ARs is more equatorward (poleward). The averaged landfalling position of KE ARs is about 5.7° north of that of PE ARs.

A three-dimensional composite shows that PE ARs have a stronger, deeper low pressure structure with a closer tropical connection. Also, PE ARs originate from well-developed ECs with strong southward intrusion of the cold fronts, developing closer to the centers of ECs (700 km). They are associated with sharp temperature/pressure gradient, enhanced vertical motion, and stronger low-level wind, all contributing to their higher IVT. In contrast, KE ARs originate from weaker and shallower ECs, develop further away from ECs center (1500 km) with weaker temperature/pressure gradients and reduced vertical motion, as well as weaker low-level wind and reduced IVT. The strengths of temperature/pressure gradients associated with the cold front of an EC is crucial for vertical motion and AR development along the front. We found that the intensity difference between KE and PE ARs is primarily related with the orientation and the strengths of temperature/pressure gradients of associated ECs rather than the intensity of associated ECs themselves.

Evolution of ARs and ECs are not exactly synchronized and the interaction between ARs and ECs is complicated. There is a possibility for ECs and ARs to decouple during landfall. The composite analyses of water vapor and SLP associated with ARs at different phases appear to imply that the evolution of PE ARs and ECs is largely in phase, but the evolution of KE ARs and ECs is not, although validation of this requires further in-depth investigations. The results suggest high complexity of dynamics associated with the evolution of ARs and ECs and lots of details are still unknown. Although they are both closely related to ECs, the locational differences of KE and PE ARs suggest different propagation pathways, which may be related to different types of Rossby wave breaking (Payne and Magnusdottir 2014; Hu et al. 2017). Moreover, the related mechanism in the formation of ARs, especially PE ARs that involves with water vapor entrainment from the tropics, is also not clear. Further studies are needed to investigate the dynamics associated with AR genesis and interactions between ARs and ECs.

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Data availability statement. All datasets used to perform the analyses in this study were derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis (https://www.ecmwf.int/en/forecasts/datasets).
**APPENDIX**

**Result Sensitivity to AR Detection Approaches**

To evaluate the uncertainties induced by AR detection methods, a comparison between IPART (Xu et al. 2020a) and other two widely used AR detection methods—the “absolute” 250 kg m\(^{-1}\) s\(^{-1}\) IVT threshold method (IVT250) and the “relative” 85th percentile IVT threshold method (IVT85%)—is performed.

Two typical AR cases detected by the three methods are shown in Figs. A1a,b. Compared with IPART (green contours in Figs. A1a,b), weaker ARs (the one near the west coast of North America in Fig. A1a) tend to be missed by IVT250 (black contours in Figs. A1a,b), and individual ARs tend to have larger area and cover more regions with low IVT intensity by IVT85% (purple contours in Figs. A1a,b). It can be seen that the IPART method delineates primarily the highest IVT area inside an AR (green contours in Figs. A1a,b). On average, statistical distributions of all ARs in the North Pacific detected by the three methods indicate that IVT85% ARs have the highest occurrences, the largest area, and the greatest width but the weakest IVT intensity as shown in the boxplots (Figs. A1c–f). In contrast, IVT250 have the lowest occurrences but the highest IVT intensity.

**FIG. A2.** Occurrence frequency and IVT intensity during whole life tracks of KE and PE ARs detected by IVT250. As for Fig. 2, but for the IVT250 AR detection method.

**FIG. A3.** Occurrence frequency and IVT intensity during whole life tracks of KE and PE ARs detected by IVT85%. As for Fig. 2, but for the IVT85% AR detection method.
The number, area, width, and intensity of IPART ARs lie between the two methods (Figs. A1c–f), consistent with previous studies (Xu et al. 2020b). The boxplots of AR distributions also suggest that weaker ARs tend to be omitted by IVT250 while IVT85% tends to capture too many weaker ARs. This is because the relative IVT85% threshold is derived from long-term climatology and in regions where background IVT is low, weaker IVT plumes tend to be included as ARs as well. Therefore, the IPART method is chosen in our study to cover the entire AR life cycle and at the same time to avoid including too many weaker ARs in low background IVT regions.

KE and PE ARs detected by IVT250 and IVT85% are further analyzed and compared with those detected by IPART. Compared with IPART (Fig. 2 in the main text),

**Fig. A4.** Characteristic PDFs of KE and PE ARs detected by IVT250. As for Fig. 6, but for the IVT250 AR detection method.

**Fig. A5.** Characteristic PDFs of KE and PE ARs detected by IVT85%. As for Fig. 6, but for the IVT85% AR detection method.
the overall occurrence frequency and IVT intensity of KE and PE ARs detected by IVT250 show similar spatial distribution but the occurrence frequency is lower, only about half of that from the IPART (Fig. A2), again due to the omission of weaker ARs, or the omission of the weaker boundaries of some strong ARs. In contrast, the occurrence of KE and PE ARs detected by IVT85% expands in larger area and leads to the weakest IVT intensity among the three methods (Fig. A3). Characteristic PDFs of IVT250 and IVT85% KE and PE ARs including their length, covering area, IVT, duration, angle, and landfalling positions are shown in Figs. A4 and A5. Consistent with IPART, comparison between PE and KE ARs detected by IVT250 and IVT85% also indicates that PE ARs are longer and stronger, cover larger area, have shorter duration, and are oriented more meridionally with more equatorward landfalling positions. Generally, the results based on IVT250 are closer to IPART while the distinction between KE and PE ARs based on IVT85% becomes smaller.

REFERENCES


