An examination of North Pacific jet regimes conducive to landfalling atmospheric rivers along the West Coast of North America

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AN EXAMINATION OF NORTH PACIFIC JET REGIMES CONDUCIVE TO
LANDFALLING ATMOSPHERIC RIVERS ALONG THE WEST COAST OF NORTH
AMERICA

by

Eli J. Turasky

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ABSTRACT

Every year, the west coast of North America experiences significant economic damage and societal disruption due to the extreme precipitation associated with landfalling atmospheric rivers (ARs). ARs not only may produce significant economic and societal impacts, but also may contribute disproportionately to precipitation anomaly statistics along the west coast of the North America. The purpose of this study is to investigate: 1) the average state and evolution of the NPJ prior to AR landfall for selected categories of landfalling ARs; and 2) the dynamical processes applicable to the aforementioned categories of landfalling ARs that are linked to NPJ variability in (1).

This study employs an archive of landfalling ARs along the west coast of North America constructed by the Center for Western Weather and Water Extremes to examine the large-scale upper-tropospheric flow patterns associated with landfalling ARs during September–May 1979–2017. In this study, the large-scale upper-tropospheric flow patterns prior to landfalling ARs are examined in the context of the two-leading empirical orthogonal functions (EOFs) of 250-hPa zonal wind over the North Pacific Ocean. The first EOF corresponds to a zonal extension or retraction of the climatological exit region of the North Pacific Jet (NPJ), while the second EOF corresponds to a poleward or equatorward shift of the climatological exit region of the NPJ. The projection of 250-hPa zonal wind anomalies at one or multiple times prior to AR landfall onto these two leading EOFs provides an objective characterization of the instantaneous state or evolution of the upper-tropospheric flow pattern over the North Pacific prior to AR landfall, which is represented on a two-dimensional NPJ Phase Diagram. The analysis leverages the NPJ Phase
Diagram to examine the degree to which AR landfall latitude and AR intensity vary as a function of the structure and evolution of the NPJ prior to AR landfall along the west coast of North America. Additionally, composite analyses and illustrative cases for the Pacific–North American (PNA) and top 10% of integrated vapor transport (IVT) categories were constructed.

More specifically, the examination of landfalling ARs during the positive and negative phases of the PNA pattern yielded results that are statistically different. The NPJ evolves towards an extension and poleward shift regime during the positive phase of the PNA and evolves toward a retraction and equatorward shift regime during the negative phase of the PNA. ARs that make landfall in the top 10% of IVT most commonly evolve toward a poleward shift.
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1. Introduction

1.1 Motivation

Atmospheric rivers (ARs) are long, narrow, transient corridors of strong horizontal water vapor transport that are typically associated with a low-level jet (LLJ) stream ahead of a cold front linked to an extratropical cyclone (e.g., Ralph et al. 2018). When accompanied by vertical motion, such as orographic lifting or ascent in a warm conveyor belt, ARs may lead to heavy precipitation (e.g., Neiman et al. 2002; Ralph et al. 2006). This heavy precipitation may cause significant economic damage and societal disruption, including flooding, mudslides, and heavy snow. According to the National Centers for Environmental Information database of $1 billion disasters, at least two heavy precipitation events directly related to ARs have occurred in California since 1980. One example occurred during the winter of 2017, when several ARs made landfall in California over several weeks. During this period, nearly 690 mm of precipitation fell in the Feather River basin in the northern Sierra Nevada Mountains of California, which directly feeds into Lake Oroville (White et al. 2019). As a result, the Oroville Dam spillway was under extreme pressure and suffered immense damage. Emergency officials ordered a multiday evacuation downstream of the Feather River, concerned about potential flooding impacts due to the damaged spillway.

ARs not only may produce substantial economic and societal impacts, but also may contribute disproportionately to positive precipitation anomalies along the west coast of North America (e.g., Neiman et al. 2002; Ralph et al. 2004; Ralph et al. 2006). Roughly 30–50% of average annual rainfall along the west coast of the U.S. is directly associated with landfalling ARs.
(Fig. 1.1). Although ARs can occur year-round, Fig. 1.1 demonstrates that the maximum amount of precipitation from ARs typically falls during the fall and winter.

In view of the hazards and meteorological importance accompanying ARs, it is imperative to diagnose the dynamical processes and antecedent environments that govern landfalling ARs over the west coast of North America to improve understanding of ARs. Although previous studies have examined ARs in detail, many of these studies do not consider the relationships between North Pacific Jet (NPJ) regimes and landfalling ARs. Thus, the goal of this research is to improve understanding of how various NPJ regimes can modulate AR landfall.

1.2 Literature Review

1.2.1 Characteristics and Dynamics of ARs

ARs may be associated with heavy significant precipitation along the west coast of North America. In order to understand how ARs contribute to heavy precipitation, it is important to understand the dynamics of ARs. Zhu and Newell (1998) were the first to describe ARs in terms of moisture transport. They stated that ARs typically account for roughly 90% of total moisture transport in the midlatitudes, while only covering less than 10% of the Northern Hemisphere landmass outside the deep tropics. Ralph et al. (2004) studied ARs during CALJET (California Land-falling Jets Experiment) and discovered that on average ARs contain an integrated water vapor (IWV) plume with an aspect ratio (length to width) of 2:1. This IWV plume typically extends nearly 4 km vertically and accounts for roughly 20% of the total moisture flux near 35°N.

Ralph et al. (2004) were among the first studies to propose a conceptual model for landfalling ARs along the west coast of North America. This conceptual model features a strongly
occluded low-level cyclone near the Gulf of Alaska, a cold front impinging on the west coast of North America, and a moisture plume on the warm side of the cold front emanating from the tropical western Pacific. Ahead of the primary cold front, an LLJ exists and has been determined to play a major role in modulating characteristics of the cold front and the associated AR (e.g., Ralph et al. 2011). As a warm, humid air mass associated with an AR moves onshore, rising motion associated with the warm conveyor belt of the low-level cyclone or orographic lifting may lead to significant moisture flux convergence and heavy precipitation, which can be extreme.

On a broader scale, Neiman et al. (2008) focused on the synoptic-scale meteorological characteristics associated with eight years of landfalling ARs along the west coast of North America. In Fig. 1.2a, a composite integrated vapor transport (IVT) plume in the northern domain is observed impinging along the Pacific Northwest (PNW) of the U.S. The associated anomaly (Fig. 1.2e) reaches a maximum near 380 kg m$^{-1}$ s$^{-1}$. Figures 1.2b,f are similar to Figs. 1.2a,e, but for a southern domain and tend to be weaker in magnitude. For those ARs making landfall in the northern domain, Figs. 1.3a,e indicate an upper-level ridge centered along the west coast of the U.S., as well as an upper-level trough centered between the Bering Strait and the Gulf of Alaska. In the southern domain Figs. 1.3b,f exhibit an upper-level ridge centered over the northern central U.S., and a strong upper-level trough positioned just offshore of the PNW.

In summary, ARs feature a long, narrow corridor of high IVT along the warm side of a cold front (Fig. 1.4a). The cold front extends from an occluded front associated with an occluded cyclone. Figure 1.4b, a cross-section view of an AR, depicts the cold front from Fig. 1.4a and demonstrates that the front slopes northwestward with height. Ahead of the cold front, near the surface, a localized area of moisture and horizontal moisture flux is shown. Along with the localized area of moisture, an LLJ of around 25 m s$^{-1}$ is present.
1.2.2 Forecasting of ARs

Although the dynamics of ARs are relatively well understood, forecasts of AR landfall position in numerical weather prediction (NWP) models and subsequent human forecasts remain problematic. Wick et al. (2013) evaluated forecasts of water vapor signatures for ARs using five major operational forecast models, which comprised those from the European Centre for Medium-Range Weather Forecasts (ECMWF), National Centers for Environmental Prediction, United Kingdom Met Office, Canadian Meteorological Center, and Japan Meteorological Agency. Figure 5 illustrates large errors in AR forecast position that grow with increasing forecast lead time. By forecast lead day 10 all five models have a root-mean-square (RMS) error greater than 700 km (Fig. 1.5a). Additionally, all five models have a southward bias of landfall position, with the worst models having a bias of nearly −3° latitude (Fig. 1.5b). DeFlorio et al. (2018) demonstrated similar findings. They validate that the hit rate of ARs for the ECMWF ensembles [number of hits/(number of hits + number of misses)] within their subjectively defined U. S. West Coast domain decreases rapidly with increasing forecast lead time. This result signals an AR forecast position error that grows with time, similar to the result found in Wick et al. (2013). However, DeFlorio et al. (2018) find that forecasts of AR position at 10 day lead time are more useful [more hits and fewer false alarms, relative operating characteristic (ROC) curve score of 0.76] during a positive El Niño Southern Oscillation (ENSO) and Pacific North America (PNA) pattern, and less useful during a negative ENSO and PNA pattern (ROC curve score of 0.65). Overall, Wick et al. (2013) and DeFlorio et al. (2018) make evident that forecasts of AR position can and should be improved.
ARs and Their Relationship to NPJ Variability

AR position and strength can be affected by the large-scale flow. Large-scale flow variability can originate from decadal to seasonal phenomena such as the Pacific Decadal Oscillation (PDO) and ENSO; but also, from subseasonal and synoptic-scale variability such as the Madden–Julian Oscillation (MJO) and teleconnections. Gershunov et al. (2017) investigated the effects of the PDO on landfalling ARs over the west coast of North America. They demonstrated that a positive (negative) PDO correlates with higher (lower) IVT values and generally more (less) precipitation (Fig. 1.6a,d). During a positive PDO, a strong SST gradient (Fig. 1.6b) forms over the central Pacific, allowing for the formation of a strong and extended NPJ as implied by the thermal wind. Evidence for an extended NPJ can be seen in a strong zonal IVT pattern (Fig. 1.6c), indicative of moisture transport from the tropical western Pacific to the west coast of North America.

On seasonal time scales, Mundhenk et al. (2016) examined AR frequency differences based on ENSO. AR frequency differences across the Pacific basin during positive and negative ENSO are displayed in Fig. 1.7. During positive ENSO (Fig. 1.7a), enhanced AR activity is found near California and likely on the west coast of Mexico, along with suppressed AR activity on much of the west coast of the U.S. The enhanced/suppressed AR activity during positive ENSO is likely due to an enhanced and zonally extended NPJ. However, during negative ENSO (Fig. 1.7b), enhanced AR activity is found in the PNW and British Columbia (BC), with suppressed activity southward. The enhanced/suppressed AR frequency pattern during negative ENSO is likely due to a poleward shift of the NPJ. This poleward shift focuses the storm track farther north and consequently transports the moisture farther north into the PNW and BC. Additionally, Mundhenk
et al. (2016) suggests a deeper investigation AR variability as a function of synoptic teleconnection patterns.

From a subseasonal variability perspective, Higgins et al. (2000) discussed ways that tropical convection can affect the position of the NPJ and consequently ARs. They showed that extreme precipitation events (precipitation above the 90th percentile) in the PNW are preceded by enhanced convection over the tropical western Pacific and Indonesia (centered near 120°E), with suppressed convection over the Indian Ocean and the central tropical Pacific. For extreme rainfall events in California, enhanced tropical convection shifts eastward such that extreme events in southern California are preceded by enhanced tropical convection near 170°E. Higgins et al. (2000) concluded that as the tropical heating moves eastward, anomalous divergent outflow acts as an anomalous Rossby wave vorticity source in the subtropics, consistent with an eastward extension of the NPJ. The eastward extension of the NPJ facilitates the transport of moisture from the subtropical western Pacific towards the west coast of North America.

While Higgins et al. (2000) did not focus specifically on the MJO, Guan et al. (2012) were interested in how the MJO affected snowpack growth in the Sierra Nevada Mountains resulting from ARs. They demonstrated that enhanced convection in the equatorial western Pacific (typical of MJO phase 6) is associated with ARs and extreme snow events in California (Fig. 1.8a), as well as some less impactful snow events (Fig. 1.8b). Additionally, they confirmed that MJO phase 3 (8) tends to be the best (worst) for snowpack growth in the Sierra Nevada Mountains. During MJO phase 3 (8), low-level winds tend to be onshore (offshore), likely associated with a negative PNA and retracted NPJ (positive PNA and extended NPJ). Higgins et al. (2000) and Guan et al. (2012) agree well on how tropical convection patterns affect extreme precipitation events over the west coast of North America.
Finally, on the synoptic and subsynoptic scale, DeFlorio et al. (2018) investigated the effects of phase locking between ENSO and PNA on AR landfall location. They established that ARs that make landfall during a positive ENSO and PNA do so more often in the PNW, likely owing to an extended and/or poleward-shifted phase of the NPJ. ARs that make landfall during a negative ENSO and PNA do so more often in California and western Mexico, likely owing to a retracted and/or equatorward-shifted phase of the NPJ. These results are validated by Winters et al. (2019), whereby during a positive (negative) PNA, jet extensions and poleward shifts (jet retractions and equatorward shifts) are most likely.

Similarly, Guan et al. (2015) demonstrated that ARs making landfall during a positive (negative) PNA most often make landfall in British Columbia (southern California). The ARs making landfall in British Columbia (southern California) can likely be attributed to jet extensions and poleward shifts (jet retractions and equatorward shifts). Additionally, Guan et al. (2013) established that phase locking between a negative AO and negative PNA produced the most AR frequency days along the west coast of North America. During a phase lock between a negative AO and negative PNA, a surface cyclone is positioned northwest of California, likely resulting from a jet extension or poleward shift.

On the subsynoptic scale, anticyclonic Rossby wave breaking (RWB) in the eastern Pacific and subsequent NPJ perturbations typically occur before strong AR landfall (Payne et al. 2014). They illustrated that the location of the AR and RWB in the 11 strongest (Fig. 1.9a) and weakest ARs (Fig. 1.9b) (strength based on the lifetime average of the areal maximum IVT for each AR recorded at each analysis time). Their analysis found that the strongest ARs are associated with anticyclonic RWB in the eastern Pacific, a strong and highly perturbed upper-level jet, a low-level cyclone to the north or northwest of the AR and a low-level anticyclone to the south or southeast
of the AR. On the other hand, the weakest ARs have the same characteristics, but every feature is weaker in magnitude.

1.2.4 The NPJ Phase Diagram and NPJ Regimes

Previous studies (e.g., Athanasiadis et al. 2010; Jaffe et al. 2011; and Griffin and Martin 2017) investigated the large-scale jet stream variability over the North Pacific. They concluded, via an empirical orthogonal function (EOF) analysis, that there are two primary modes of variability over the North Pacific commonly referred to as EOF 1 and EOF 2. A positive (negative) EOF 1 describes a jet extension (retraction) of the climatological jet exit region (e.g., Winters et al 2019). A positive (negative) EOF 2 describes a poleward (equatorward) shift of the climatological jet exit region (e.g., Winters et al 2019). This EOF analysis results in four distinct NPJ regimes. Griffin and Martin (2017) investigated each NPJ regime and discovered unique weather patterns over North America associated with each regime. A jet extension (retraction) is typified by an upper-level trough over ridge (upper-level ridge over trough) dipole over the central Pacific and an upper-level ridge (upper-level trough) centered over western North America. A poleward (equatorward) shift is typified by a broad upper-level trough over ridge (upper-level ridge over trough) dipole covering nearly the entire Pacific basin and an upper-level ridge (trough) centered over the northern U.S. and southern Canada.

Based on results from Griffin and Martin (2017), Winters et al. (2019a,b) showed that the weather patterns associated with four NPJ regimes may be related to increased/decreased NWP forecast skill. Winters et al. (2019a,b) further demonstrated that forecasts verifying during jet relocations and equatorward shifts exhibit reduced forecast skill in the context of the NPJ phase
diagram compared to jet extensions and poleward shifts. Given that the NPJ phase diagram can be used to anticipate periods of lower/higher forecast skill, it seems plausible that a better understanding of ARs in terms of their variability within the NPJ phase diagram and associated NPJ regimes may lead to improved forecasts of ARs.
1.3 Research Goals and Thesis Structure

ARs play an important hydrological and societal role in cool season rainfall along the west coast of North America. This research is focused on the NPJ phase diagram and NPJ regimes prior to AR landfall. Most of the previous literature contains relatively little emphasis on NPJ regimes and their relationship with ARs. Examining ARs through an NPJ regime/NPJ phase diagram lens may provide new insights into the dynamics and variability of ARs, which may lead to improved forecasts of these features and the extreme precipitation associated with them. Thus, the goals of this thesis are to improve the understanding of: 1) the average state and evolution of the NPJ prior to AR landfall for selected categories of landfalling ARs; and 2) the dynamical processes applicable to the aforementioned categories of landfalling ARs that are linked to NPJ variability in (1).

The organization of the remainder of this thesis is as follows. Data, methodology, and the NPJ phase diagram are described in chapter 2. The average state and evolution of the NPJ prior to landfalling ARs are described in chapter 3. Composite dynamical evolutions and illustrative cases for a PNA subset and 90th percentile of IVT subset are described in chapter 4. Discussion and conclusions, along with suggestions for future work, are provided in chapter 5.
Fig. 1.1 Contribution (%) of AR-related precipitation to (a) total annual and (b)–(e) seasonal precipitation. The gridded precipitation product is in-situ observed daily precipitation interpolated onto a 6 × 6 km grid (Livneh et al. 2013) and spanning 1950–2013. Figure and caption are from Geshunov et al. (2017; their Fig. 2)
Fig. 1.2. Composite vertically integrated horizontal water vapor flux (IVT; kg m$^{-1}$ s$^{-1}$) derived from the NCEP–NCAR daily reanalysis dataset for SSM/I IWV plumes intersecting the north–coast and south–coast domains on a daily basis (0000–0000 UTC) in winter and summer: means for (a) north–winter, (b) south–winter and anomalies for (e) north–winter, (f) south–winter. The vectors show the direction of IVT. The bold light-blue dots along the coast denote the boundaries of the north–coast and south–coast domains. Standard frontal notation in (a)–(b) and (e)–(f) is used to mark the composite near-surface frontal positions. In each panel, the blue (red) square in the north– (south–) coast domain marks the position of NCEP–NCAR reanalysis thermodynamic and wind profiles. Figure and caption are adapted from Neiman et al. (2008; their Fig. 5).
Fig. 1.3. Same as in Fig. 2, but for 500-hPa geopotential height (m). Figure and caption are adapted from Neiman et al. (2008; their Fig. 6)
Fig. 1.4. Schematic summary of the structure and strength of an AR based on dropsonde measurements deployed from research aircraft across many ARs and on corresponding reanalyses that provide the plan-view context. Figure and caption are adapted from Ralph et al. (2018; their Fig. 1).
Fig. 1.5. Estimates of error in forecast AR landfall location as a function of lead time. (top) The total RMS error (km) in the detected landfall location along the west coast of North America. (bottom) The bias in the latitude of the detected landfall relative to satellite observations. The error bars represent ±1 standard deviation of the mean to reflect uncertainty in the mean value. Figure and caption are from Wick et al. (2013; their Fig. 11).

Fig. 1.6. (a) Leading canonical correlation as a function of the PDO and their associated spatial patterns expressed as correlations between the time series and their respective fields of variables: (b) SST during the Jan.–Mar. season and (c) seasonally summed AR-associated IVT. Maximum possible arrow length is the square root of 2, shown to the right of the color scale, corresponding to the u and v components of the IVT field. (d) Correlations between the IVT time series [panel (a), blue bars] and AR-associated precipitation. Figure and caption are adapted from Gershunov et al. (2017; their Fig. 3).
Fig. 1.7. Comparison of AR frequencies composited based on Oceanic Niño Index values for (a) El Niño and (b) La Niña conditions with the annual mean AR frequencies removed. Stippled regions denote significance at the 90% confidence level based on 1000 bootstrap samples. Figure and caption are adapted from Mundhenk et al. (2016; their Fig. 7).
Fig. 1.8. Anomalies of 200-hPa geopotential height (m; contours) and 20–100-day filtered OLR (W m\(^{-2}\); shading) over (a) high- and (b) low-impact AR events during water years 1998–2010. Anomalies are relative to the daily climatology for each variable. The contour interval is 20 m for geopotential height, and the zero contour is omitted. Hatching indicates areas where the difference in the OLR anomaly between (a) and (b) is statistically significant at the 80% level based on the Wilcoxon–Mann–Whitney test. Figure and caption are adapted from Guan et al. (2012; their Fig. 3).
Fig. 1.9. Relationship between the location of the AR (filled black dot) and anticyclonic RWB for the (a)–(d) 11 strongest and (e)–(h) 11 weakest ARs. The four regions correspond to 175°–160°W, 160°–145°W, 145°–130°W, and 130°–115°W. The region the AR occupies is outlined in black and all RWB occurring within and leading that region is plotted, where shading (PVU) indicates the position of RWB and size indicates its zonal extent. Figure and caption are adapted from Payne et al. (2014; their Fig. 11).
2. Data and Methodology

2.1 Data

The National Centers for Environmental Prediction (NCEP) 0.5° × 0.5° Climate Forecast System Reanalysis (CFSR; available every 6 h; Saha et al. 2010, 2014) is utilized for this study. CFSR data during Sept.–May 1979–2016 are chosen to align with the methodology used to construct the NPJ phase diagram in Winters et al. (2019a,b). This study also employs an archive of landfalling ARs (N = 1765) along the west coast of North America, constructed by the Center for Western Weather and Water Extremes (Gershunov et al. 2017) during Sept.–May 1979–2016. ARs from the Gershunov et al. (2017) dataset were automatically detected from IVT and IWV signatures in the NCEP–National Center for Atmospheric Research reanalysis over the west coast of North America. To ensure accuracy, Gershunov et al. (2017) validated the AR signatures against other datasets, which include: a different AR dataset (Neiman et al. 2008), a precipitation dataset resolved daily over the western U.S. (Livneh et al. 2013), and a comparison of pre-satellite and satellite AR climatologies to the NOAA 20th Century Reanalysis (Compo et al. 2013).

The AR dataset is categorized subsequently in section 2.3, with two of the categories being the phase of the PNA and AO. This study utilized teleconnection indices during Sept.–May 1979–2016 from the Climate Prediction Center, which include the PNA (https://www.cpc.ncep.noaa.gov/data/teledoc/pna.shtml) and AO (https://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml). In addition to aiding in the construction of the NPJ phase diagram, CFSR data are utilized to create composite dynamical analyses, which are detailed in section 2.3.
2.2 NPJ Phase Diagram

The variability of the NPJ over the North Pacific can be characterized using a traditional EOF analysis that is conducted on 250-hPa zonal wind anomaly data over the North Pacific basin during Sept.–May 1979–2014. EOF analysis can objectively determine which modes of NPJ variability are most dominant. Furthermore, previous work suggests that the dominant modes of NPJ variability are linked to physically meaningful large-scale flow patterns and evolutions over the North Pacific and North America (e.g., Griffin and Martin 2017; Winters et al. 2019a,b). Griffin and Martin (2017) and Winters et al. (2019a,b) demonstrate that the structure and evolution of the NPJ is well described by the two leading EOFs of 250-hPa zonal wind anomalies during the cool season. A positive (negative) EOF 1 pattern corresponds to an extension (retraction) of the climatological jet-exit region. A positive (negative) EOF 2 pattern corresponds to a poleward (equatorward) shift of the climatological jet-exit region. Figure 2.1a depicts the structure of the regression of 250-hPa zonal wind anomaly data onto the first standardized principal component (PC 1) pattern, and Fig. 2.1b depicts the structure of the regression of 250-hPa zonal wind anomaly data onto PC 2. In a typical geoscience EOF analysis, PC 1 and PC 2 are instantaneous PCs. However, Griffin and Martin (2017) note that instantaneous PCs are noisy because of small-scale variability of the NPJ that occurs on daily time scales. Accordingly, weighted PCs which are described in detail in section 2.3, are utilized to attempt to describe the evolution of the NPJ with greater temporal resolution, while preserving some of the small-scale variability on daily time scales.

A two-dimensional phase diagram, hereafter referred to as the NPJ phase diagram, can be constructed to diagnose the state of the NPJ in the context of the two leading modes of NPJ
variability identified from the aforementioned EOF analysis. The 250-hPa zonal wind anomalies at any time can be projected onto the two leading EOF patterns, resulting in a single point on an NPJ phase diagram. Figure 2.2 delineates the four primary NPJ regimes in the context of the NPJ phase diagram. The distance along the x-axis represents the strength of the projection of 250-hPa zonal wind anomalies onto EOF 1. Similarly, the distance along the y-axis represents the strength of the projection of zonal wind anomalies onto EOF 2. Periods during which the NPJ is less than the Euclidian distance of at least one standard deviation from the origin are not classified into one of the four characteristic NPJ regimes, but rather as “origin” or “neutral.” An example NPJ phase diagram trajectory is provided (Fig. 2.3), along with the corresponding total 250-hPa wind speed evolution (Fig. 2.4). Beginning at 0000 UTC 15 Feb. 2017, the NPJ is zonally elongated, spanning the majority of the Pacific basin (Fig. 2.4a). Forty-eight hours later, at 0000 UTC 17 Feb. 2017, the NPJ remains zonally elongated, but has become more meridional (Fig. 2.4b). At 0000 UTC 19 Feb. 2017, the NPJ begins to buckle with two distinct regions of highly amplified flow, one centered at 140°E and the other at 140°W (Fig. 2.4c). By the last analysis time, 0000 UTC 21 Feb. 2017, the flow within the NPJ is substantially amplified, exhibiting a distinct split upper-level flow pattern (Fig. 2.4d). In this example, the NPJ begins in an extended regime. At the last analysis time, the projection is inside the unit circle and is interpreted as an NPJ that does not project strongly onto the two leading modes of NPJ variability (i.e., EOF 1 and EOF 2).

Each NPJ regime was found to be associated with distinct large-scale flow patterns (Winters et al. 2019a). A jet extension is characterized by a strong, elongated NPJ and an upper-level ridge over the west coast of North America (Fig. 2.5a). South of the Bering Sea, an anomalous surface low-level cyclone directs anomalous southerly flow towards the west coast of North America, resulting in warm low-level temperature anomalies (Fig. 2.5b). A jet retraction is
characterized by a split NPJ and a broad upper-level trough over the west coast of North America (Fig. 2.5c). An anomalous surface anticyclone is in place just east of the Dateline and acts to advect colder air from higher latitudes southward along the west coast of North America (Fig. 2.5d). The most notable feature for a poleward shift is a strong upper-level trough-over-ridge pattern in the central North Pacific (Fig. 2.5e). The upper-level flow pattern associated with a poleward shift yields a low-level cyclone in the Gulf of Alaska, which results in anomalous southerly flow over much of North America and warm low-level temperature anomalies (Fig. 2.5f). An equatorward shift features an upper-level ridge-over-trough dipole over the central Pacific (Fig. 2.5g), reminiscent of an upper-level blocking pattern, with a strong low-level anticyclone anchored near Alaska (Fig 2.5h). The position of the anomalous surface anticyclone leads to anomalous northerly flow over Canada and yields cold low-level temperature anomalies (Fig. 2.5h). While the preceding analyses focus on circulation and temperature anomalies, these circulation and temperature anomalies may reveal locations that might be more likely to experience a landfalling AR during a particular NPJ regime. A goal of this study is to examine the relationship between these NPJ regimes and AR activity along the west coast of North America. This goal is accomplished with the utilization of the NPJ phase diagram.

2.3 AR Classification Scheme

Landfalling ARs are classified into five categories, which include season, landfall latitude, phase of the PNA and AO, and the top 10% of cases with respect to their associated IVT. Understanding how NPJ variability plays a role in modulating AR landfall may result in increased forecast skill during a specific season or at a specific latitude. Following a suggestion by
Mundhenk et al. (2016), the PNA and AO are selected for further investigation in this study because of their influence on ARs on synoptic time scales. Documenting the variability of the NPJ preceding AR landfall during different atmospheric teleconnection patterns has not been done previously to my knowledge. Hu et al. (2017) suggest that IVT and precipitation intensity are positively correlated. Based on this suggestion, ARs with higher IVT are more likely to produce more noteworthy societal and meteorological impacts. Thus, the final category consists only of ARs in the top 10% of cases regarding their IVT. All of the aforementioned categories are investigated in terms of their antecedent large-scale flow patterns.

As discussed in section 2.1, ARs are identified during Sept.–May 1979–2016 to coincide with the availability of CFSR data used to construct the NPJ phase diagram. ARs are only selected from the cool-season nonsummer months because the NPJ phase diagram is not applicable during the warm-season summer months. Consequently, the seasons comprise: autumn (Sept.–Nov., N=731), winter (Dec.–Feb., N=615), and spring (March–May, N=419). In addition to seasons, three distinct latitude bands are subjectively selected to define a southern domain (22.5°N–32.5°N, N=273), a central domain (32.5°N–45°N, N=588), and a northern domain for landfalling ARs (45°N–57.5°N, N=904). These bands roughly coincide with the west coast of Mexico, the west coast of the United States, and the west coast of Canada, respectively.

Another method for classifying landfalling ARs consists of investigating ARs based on the prevailing atmospheric teleconnection pattern. The teleconnection data are selected to identify AR landfall days that most strongly project onto various teleconnection patterns. This selection is accomplished by examining landfalling AR days that rank in the top 10% or bottom 10% with respect to their associated teleconnection indices at the time of landfall. Specifically, the 90th (10th) percentile of PNA values is roughly 1 (N=266) and above (−1 and below, N=171). The 90th
(10th) percentile of AO values is roughly 2 (N=168) and above (−2 and below, N=186). Additionally, IVT data are selected to retain only the top 10% of all landfalling ARs to focus on the most impactful ARs (N=176).

In order to examine the five categories of landfalling ARs, the NPJ phase diagram (Winters et al. 2019a) is utilized. The classification scheme determines whether the position of the NPJ within the NPJ phase diagram is more than one standard deviation from the origin and whether the absolute value of PC 1 or PC 2 is greater. In addition to single-event NPJ phase diagram trajectories, the NPJ phase diagram can be used to create composite NPJ phase diagram trajectories. The upper-level flow pattern is projected onto the NPJ phase diagram during a preselected period prior to each individual AR event, with the last analysis time coinciding with AR landfall. To produce a composite trajectory, the weighted PCs are calculated at 6-h intervals from the instantaneous PCs within ±24 h of each analysis time \( t_0 \) (Winters et al. 2019a). The weight, \( w \), given to the instantaneous PCs at each time \( t \) within ±24 h is defined as \( w = 5 - |t - t_0|/6 \) for \( |t - t_0| \leq 24 \) h. (Winters et al. 2019a). The weighted PCs are then positioned so that the first analysis time during the preselected period starts at the origin of the NPJ phase diagram. The construction of a composite NPJ phase diagram trajectory permits a direct comparison between each category of ARs defined in this subsection by determining the various NPJ evolutions that typically precede AR landfall.

Similarities and differences between the AR categories in terms of NPJ variability prior to AR landfall are investigated by analyzing the average state of the NPJ during the 5-day period prior to AR landfall and the evolution of the NPJ during the 10-day period prior to AR landfall. The average state of the NPJ is calculated by averaging the position of the NPJ in the NPJ phase diagram over the 5-day period prior to AR landfall. The evolution of the NPJ during the 10-day
period prior to AR landfall is constructed using a composite NPJ phase diagram trajectory, discussed previously in this subsection. The geographical landfall location during the four NPJ regimes also is determined in order to examine the degree to which the landfall location varies as a function of the prevailing NPJ regime.

Lastly, CFSR data are used to construct composite upper- and lower-level analyses. In addition to composite analyses, representative cases are chosen for the PNA and top 10% of IVT categories. While the AO category is examined in terms of the state and evolution of the NPJ prior to AR landfall, the positive and negative phases of the AO are determined to have less NPJ variability prior to AR landfall than the positive and negative phases of the PNA, and thus the AO is omitted from the further analysis. The upper-level composite analyses include 250-hPa wind speed, 250-hPa geopotential height, and 250-hPa geopotential height anomalies. The lower-level composite analyses include IVT and vectors, mean sea level pressure, and 850-hPa temperature. The upper- and lower-level composite analyses, along with the representative cases, offer a dynamical view of the variability of the NPJ prior to AR landfall.
Fig. 2.1. (a) Sept.–May 250-hPa mean zonal wind is contoured in black every 10 m s$^{-1}$ above 30 m s$^{-1}$, and the regression of 250-hPa zonal wind anomaly data onto standardized PC 1 (i.e., EOF 1) is shaded (m s$^{-1}$). The variance of 250-hPa zonal wind during the cool season that is explained by EOF 1 is listed in the top right of the panel. (b) As in (a), but for the regression of 250-hPa zonal wind anomaly data onto standardized PC 2 (i.e., EOF 2). Figure and caption are adapted from Winters et al. (2019a; their Fig. 1).
Fig. 2.2. Schematic illustrating the classification scheme for landfalling ARs with respect to the NPJ phase diagram. Figure and caption are adapted from Winters et al. (2019; their Fig. 4).

Fig. 2.3. NPJ phase diagram trajectory valid 0000 UTC 15 Feb.–0000 UTC 21 Feb. 2017. The jet position starts at the green diamond and ends at the red diamond. Each blue diamond represents 0000 UTC and each successive blue dot after a diamond represents 0600 UTC, 1200 UTC, and 1800 UTC, respectively.
Fig. 2.4. 250-hPa total wind speed (m s$^{-1}$) shaded in the fill pattern. (a) 0000 UTC 15 Feb. 2017, (b) 0000 UTC 17 Feb. 2017, (c) 0000 UTC 19 Feb. 2017, and (d) 0000 UTC 21 Feb. 2017.
Fig. 2.5. Composite mean 250-hPa wind speed (m s$^{-1}$) is shaded in the fill pattern, 250-hPa geopotential height is contoured in black every 120 m, and 250-hPa geopotential height anomalies are contoured in solid red and dashed blue every 30 m for positive and negative values, respectively, 4 days following the initiation of (a) a jet extension, (c) a jet retraction, (e) a poleward shift, and (g) an equatorward shift regime. Composite anomalies of mean sea level pressure are contoured in solid and dashed black every 2 hPa for positive and negative values, respectively, and 850-hPa temperature anomalies are shaded in the fill pattern every 1 K, 4 days following the initiation of (b) a jet extension, (d) a jet retraction, (f) a poleward shift, and (h) an equatorward shift regime. The numbers in the bottom right of each panel indicate the number of cases included in each composite. Stippled areas represent locations where the 250-hPa geopotential height anomalies or 850-hPa temperature anomalies are statistically distinct from climatology at the 99% confidence level. Figure and caption are from Winters et al. (2019a; their Fig. 5).
3. Categorical Analysis of Landfalling ARs

3.1 AR Landfall as a Function of Season

During autumn, a maximum of AR landfall is located in British Columbia, with a smaller, secondary maximum in western Mexico (Fig. 3.1). During jet extensions, jet retractions and poleward shifts, a local maximum in AR landfall is observed in British Columbia (Figs. 3.2a–c). During an equatorward shift, AR landfall is observed to be evenly distributed along the entire west coast of North America (Fig. 3.2d). Additionally, during jet extensions and retractions, there is a notable lack of AR landfall in southern California (Figs. 3.2a,b). As the year progresses to the winter months, the location that experiences the maximum number of landfalling ARs moves equatorward and is focused in the Pacific Northwest and California (Fig. 3.3). In each NPJ regime, a local maximum in AR landfall is observed in the Pacific Northwest and California (Figs. 3.4a–d). Finally, during spring, landfalling ARs occur most often in British Columbia and central California (Fig. 3.5). At the end of winter and beginning of spring, the NPJ is located at its most equatorward climatological position, explaining the maxima of AR landfall in central California. As spring progresses, the NPJ begins to retreat poleward, eventually reaching its climatological resting place near 50°N. Climatologically, the NPJ remains confined near 50°N during a large fraction of spring, which explains the second maxima in AR landfall in British Columbia. Ultimately, the progression of the NPJ from south to north explains the two AR landfall maxima during spring. While there are a similar number of ARs making landfall during jet extensions and retractions during spring (Figs. 3.6a,b), there are many more ARs making landfall during poleward shifts than equatorward shifts (Figs. 3.6c,d). Furthermore, as the seasons progress from autumn to
winter and eventually spring, there is a noted southward progression of AR landfall maxima, which agrees with Mundhenk et al. (2016) (Figs. 3.1, 3.3, and 3.5).

Although most categories that will be described throughout the rest of this chapter contain a large number of ARs making landfall during the neutral phase, the goal is to discuss the most common NPJ regimes outside of neutral that precede AR landfall. As discussed in chapter 2, the neutral phase occurs when the projection onto the NPJ phase diagram is less than the Euclidian distance of at least one standard deviation from the origin. In autumn, the average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet retraction or a poleward shift (Fig. 3.7a). The phrase “most often”, in this example and in the rest of this chapter, refers to the NPJ regime/regimes (other than neutral) that are most common prior to AR landfall. Out of 261 non-neutral landfalling ARs (731 total landfalling ARs) in autumn, there were 70 and 71 that made landfall during a jet retraction and a poleward shift, respectively. During winter, the average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet extension or a poleward shift (Fig. 3.7b). Out of 394 non-neutral (615 total landfalling ARs) landfalling ARs in winter, there were 105 and 111 that made landfall during a jet extension and a poleward shift, respectively. Throughout spring, the average state of the NPJ during the five days prior to AR landfall is most often characterized by a poleward shift (Fig. 3.7c). Out of 206 non-neutral (419 total landfalling ARs) landfalling ARs in spring, there were 78 that made landfall during a poleward shift.

In autumn, there is a very weak tendency for the NPJ to evolve toward a poleward shift and a jet retraction prior to AR landfall (Fig. 3.8a). The composite NPJ phase diagram trajectory in Fig. 3.8a ends at approximately the point (−0.03, 0.06). During winter there is a very weak tendency for the NPJ to evolve toward a jet extension prior to AR landfall (Fig. 3.8b). The
composite NPJ phase diagram trajectory in Fig. 3.8b ends at approximately the point (0.06, 0.01). During spring, there is a weak tendency for the NPJ to evolve toward a poleward shift and a jet extension prior to AR landfall (Fig. 3.8c). The composite NPJ phase diagram trajectory in Fig. 3.8c ends at approximately the point (0.08, 0.13). The stronger signal of a poleward shift prior to AR landfall may be attributed to the seasonal poleward retreat of the NPJ.

For the three seasons, the strongest projection onto the composite NPJ phase diagram occurs during spring. However, the differences between the composite NPJ phase diagram trajectories for each season are small. Using a statistical analysis can illuminate whether small differences are meaningful. The composite NPJ phase diagram trajectory difference for each season can be further understood using a Welch’s $t$-test. This $t$-test assesses the significance of differences in the evolution of the NPJ by comparing the means of the distance traveled by PC1 and PC2 in the composite NPJ phase diagram prior to AR landfall. Welch’s $t$-test utilizes the means of samples, $\bar{X}_1$ and $\bar{X}_2$, their standard deviations, $s_1$ and $s_2$, and sample size $N_1$ and $N_2$. The $t$ statistic is given in Eq. (1):

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}}$$

(1)

Application of Welch’s $t$-test shows that the small differences between the trajectories in Figs. 3.8a–c are not statistically significantly different from each other at the 95% confidence level.

3.2 AR Landfall as a Function of Latitude
Unlike section 3.1 and future sections, landfall locations for ARs in each latitude band only occur in each respective latitude band making this diagnostic uninformative. For this reason, landfall locations for ARs in each latitude band are omitted. Instead, the focus will be placed on the state of the NPJ during the five days prior to AR landfall and the evolution of the NPJ in the 10 days prior to AR landfall. In the southern domain, the average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet retraction (Fig. 3.9a). Out of 131 non-neutral (273 total landfalling ARs) landfalling ARs in the southern domain, there were 52 that made landfall during a jet retraction. While the average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet retraction, the signal is weak, as less than 20% of landfalling ARs in the southern domain occur during a jet retraction. In the central domain, the average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet extension and poleward shift (Fig. 3.9b). Out of 382 non-neutral (588 total landfalling ARs) landfalling ARs in the central domain, there were 107 and 104 that made landfall during a jet extension and a poleward shift, respectively. In the northern domain, the average state of the NPJ during the five days prior to AR landfall is most often characterized by a poleward shift (Fig. 3.9c). Out of 417 non-neutral (904 total landfalling ARs) landfalling ARs in the northern domain, there were 134 that made landfall during a poleward shift. While average state of the NPJ during the five days prior to AR landfall is most often characterized by a poleward shift, the signal is weak, as less than 20% of landfalling ARs in the northern domain occur during a poleward shift.

In the southern domain, during the 10 days prior to AR landfall there is a weak tendency for the NPJ to evolve towards a jet retraction and an equatorward shift (Fig. 3.10a). The composite NPJ phase diagram trajectory in Fig. 3.10a ends at approximately the point (−0.13, −0.05) In the central domain, during the 10 days prior to AR landfall there is a weak tendency for the NPJ to
evolve towards a jet extension and a poleward shift (Fig. 3.10b). The composite NPJ phase diagram trajectory in Fig. 3.10b ends at approximately the point (0.12, 0.04). In the northern domain, during the 10 days prior to AR landfall there is a weak tendency for the NPJ to evolve towards a poleward shift (Fig. 3.10c). The composite NPJ phase diagram trajectory in Fig. 3.10c ends at approximately the point (0, 0.1). Similar to the seasonal variation of composite NPJ phase diagram trajectories prior to AR landfall, the differences between each domain are not statistically significantly different (Eq. 1) at the 95% confidence level.

3.3 AR Landfall as a Function of Phase of the PNA

During a positive PNA, AR landfall occurs most frequently in British Columbia, with a secondary maximum in the southern Pacific Northwest and northern California (Fig. 3.11). Most ARs characterized by a jet extension or poleward shift during a positive PNA make landfall in British Columbia and the Pacific Northwest (Figs. 3.12a,c), with very few ARs making landfall during jet retractions and equatorward shifts (Figs. 3.12b,d). During a negative PNA, AR landfall occurs most frequently in California (Fig. 3.13). During a negative PNA, ARs more frequently make landfall in northwestern Mexico following jet retractions than following equatorward shifts (Figs. 3.14b,d), with very few landfalling ARs occurring during jet extensions and poleward shifts (Figs. 3.14a,c).

During a positive PNA, the average state of the NPJ during the five days prior to AR landfall is most often characterized by jet extensions and poleward shifts (Fig. 3.15a). Out of 157 non-neutral (266 total landfalling ARs) landfalling ARs during a positive PNA, there were 83 and 55 that made landfall during a jet extension and a poleward shift, respectively. Additionally, during
During a positive PNA there were only 8 and 11 ARs that made landfall during a jet retraction and an equatorward shift, respectively. Having predominantly jet extensions and poleward shifts during a positive PNA agrees with the results of Winters et al. (2019a). During a negative PNA, the average state of the NPJ during the five days prior to AR landfall is most often characterized by jet retractions and equatorward shifts (Fig. 3.15b). Out of 102 non-neutral (171 total landfalling ARs) landfalling ARs during a negative PNA, there were 55 and 38 that made landfall during a jet retraction and an equatorward shift, respectively. Additionally, during a negative PNA there were only 4 and 5 ARs that made landfall during a jet extension and a poleward shift, respectively. Having predominantly jet retractions and equatorward shifts during a negative PNA agrees with the results of Winters et al. (2019a). During a positive PNA, an upper-level trough-over-ridge pattern spans most of the Pacific basin. This upper-level pattern allows for the eastward extension of the jet exit region. Additionally, an upper-level ridge is positioned on the west coast of North America during a positive PNA. The upper-level ridge causes the exit region of the jet to be shunted poleward, hence the poleward shift. In contrast, during a negative PNA, an upper-level ridge-over-trough pattern spans most of the Pacific basin. With a strong blocking pattern over the Pacific, the jet is retracted. Additionally, an upper-level trough is positioned on the west coast of North America during a negative PNA. This upper-level pattern can often lead to a split flow pattern and aid in the development of an equatorward shift of the jet exit region. Further discussion on these features is found in chapter 4.

During a positive PNA, there is a strong tendency for the NPJ to evolve towards a jet extension and a poleward shift in the 10 days prior to AR landfall (Fig. 3.16a). The composite NPJ phase diagram trajectory in Fig. 3.16a ends at approximately the point (0.58, 0.29). During a negative PNA, there is a strong tendency for the NPJ to evolve towards a jet retraction and an
equatorward shift in the 10 days prior to AR landfall (Fig. 3.16b). The composite NPJ phase diagram trajectory in Fig. 3.16b ends at approximately the point \((-0.31, -0.52)\). Unlike the differences between the composite NPJ phase diagram trajectories in sections 3.1 and 3.2, during a positive and negative PNA the composite NPJ phase diagram trajectories are statistically significantly different (Eq. 1) at the 95% confidence level.

3.4 AR Landfall as a Function of Phase of the AO

During a positive AO, AR landfall occurs most frequently in British Columbia and the Pacific Northwest (Fig. 3.17). Most ARs characterized by a jet retraction or poleward shift during a positive AO also make landfall in British Columbia and the Pacific Northwest (Figs. 3.18b,c), with fewer ARs making landfall during jet extensions and equatorward shifts (Figs. 3.18a,d). During a negative AO, AR landfall occurs most frequently in northern California (Fig. 3.19). Additionally, during a negative AO, ARs infrequently make landfall in southern California and northwestern Mexico during all NPJ regimes (Figs. 3.20a–d).

During a positive AO, the average state of the NPJ during the five days prior to AR landfall is most often characterized by jet retractions and poleward shifts (Fig. 3.21a). Out of 114 non-neutral (168 total landfalling ARs) landfalling ARs during a positive AO, there were 40 and 30 that made landfall during a jet retraction and a poleward shift, respectively. Having a maximum of jet retractions during a positive AO agrees with the results of Winters et al. (2019a). During a positive AO, a weak blocking pattern occurs over the Pacific with an anomalous anticyclone typically occurring near the Aleutian Islands. This blocking pattern impedes the eastward progression of the jet and often results in a jet retraction. An anomalous anticyclone near the
Aleutian Islands, signaling a positive AO, matches the anomalous anticyclone location from Fig. 2.5d for the composite jet retraction. During a negative AO, the average state of the NPJ during the five days prior to AR landfall is most often characterized by jet extensions and equatorward shifts (Fig. 3.21b). Out of 112 non-neutral (186 total landfalling ARs) landfalling ARs during a negative AO, there were 42 and 33 that made landfall during a jet retraction and an equatorward shift, respectively. Having a maximum of jet extensions during a negative AO agrees with the results of Winters et al. (2019a). During a negative AO, an anomalous surface cyclone resides near the Aleutian Islands. An anomalous surface cyclone in this region coincides with the location of the poleward jet exit region. The location of the poleward exit region of the NPJ near the Aleutian Islands is consistent with a jet extension. An anomalous surface cyclone near the Aleutian Islands, signaling a negative AO, matches well with the anomalous surface cyclone location from Fig. 2.5b for the composite jet extension.

During a positive AO, there is a moderate tendency for the NPJ to evolve towards a jet retraction in the 10 days prior to AR landfall (Fig. 3.22a). The composite NPJ phase diagram trajectory in Fig. 3.22a ends at approximately the point (−0.23, 0). During a negative AO, there is a weak tendency for the NPJ to evolve towards a jet extension and a poleward shift in the 10 days prior to AR landfall (Fig. 3.22b). The composite NPJ phase diagram trajectory in Fig. 3.22b ends at approximately the point (0.12, 0.05). The differences between the composite NPJ phase diagram trajectories during a positive and negative AO are statistically significantly different at the 95% confidence level. However, the differences between the composite NPJ phase diagram trajectories during a positive and negative AO are notably weaker than the differences during a positive and negative PNA.
3.5 AR Landfall as a Function of the Top 10% of IVT

For landfalling ARs that rank in the 90th percentile of IVT, landfall occurs most frequently in British Columbia and in western Mexico (Fig. 3.23). The strongest ARs making landfall during a jet retraction or poleward shift most often do so in British Columbia and the Pacific Northwest (Figs. 3.24b,c). Additionally, during all NPJ regimes, there is a notable lack of AR landfall in southern California and a signal for AR landfall in western Mexico (Figs. 3.24a–d). For landfalling ARs that rank in the 90th percentile in terms of their IVT, the average state of the NPJ during the five days prior to AR landfall is most often characterized by a poleward shift (Fig. 3.25). Out of 100 non-neutral (176 total landfalling ARs) landfalling ARs that rank in the 90th percentile of IVT, there were 38 that made landfall during a poleward shift. For landfalling ARs that rank in the 90th percentile in terms of their IVT, there is a weak tendency for the NPJ to evolve towards a poleward shift in the 10 days prior to AR landfall (Fig. 3.26). The composite NPJ phase diagram trajectory in Fig. 3.26 ends at approximately the point (−0.01, 0.13). Typically, ARs that make landfall in British Columbia or the Pacific Northwest receive moisture transport connected to the tropical western Pacific (Knippertz et al. 2013). In order to transport moisture from the tropical western Pacific to British Columbia or the Pacific Northwest, an eastward and northward transport must occur. This transport is achieved through the eastward extension and poleward shift of the jet. Although an extension is not evident in Fig. 3.26, more details on the evolution of the NPJ will be discussed in chapter 4.
Fig. 3.1. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during autumn.

Fig. 3.2. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during autumn and (a) a jet extension, (b) a jet retraction, (c) a poleward shift, and (d) an equatorward shift.
Fig. 3.3. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during winter.

Fig. 3.4. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during winter and (a) a jet extension, (b) a jet retraction, (c) a poleward shift, and (d) an equatorward shift.
Fig. 3.5. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during spring.

Fig. 3.6. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during spring and (a) a jet extension, (b) a jet retraction, (c) a poleward shift, and (d) an equatorward shift.
Fig. 3.7. The average position of the NPJ within the NPJ phase diagram five days prior to those ARs that make landfall during (a) autumn, (b) winter, and (c) spring.

Fig. 3.8. Composite NPJ phase diagram trajectory 10 days prior to those ARs that make landfall during (a) autumn, (b) winter, and (c) spring. The jet position starts at the green diamond and ends at the red diamond.
Fig. 3.9. The average position of the NPJ within the NPJ phase diagram five days prior to those ARs that make landfall at (a) 22.5°N–32.5°N, (b) 32.5°N–45.0°N, and (c) 45.0°N–57.5°N.

Fig. 3.10. Composite NPJ phase diagram trajectory 10 days prior to those ARs that make landfall at (a) 22.5°N–32.5°N, (b) 32.5°N–45.0°N, and (c) 45.0°N–57.5°N. The jet position starts at the green diamond and ends at the red diamond.
Fig. 3.11. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during a positive PNA.

Fig. 3.12. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during a positive PNA and (a) a jet extension, (b) a jet retraction, (c) a poleward shift, and (d) an equatorward shift.
Fig. 3.13. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during a negative PNA.

Fig. 3.14. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during a negative PNA and (a) a jet extension, (b) a jet retraction, (c) a poleward shift, and (d) an equatorward shift.
Fig. 3.15. The average position of the NPJ within the NPJ phase diagram five days prior to those ARs that make landfall during (a) a positive PNA and (b) a negative PNA.

Fig. 3.16. Composite NPJ phase diagram trajectory 10 days prior to those ARs that make landfall during (a) a positive PNA and (b) a negative PNA. The jet position starts at the green diamond and ends at the red diamond.
Fig. 3.17. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during a positive AO.

Fig. 3.18. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during a positive AO and (a) a jet extension, (b) a jet retraction, (c) a poleward shift, and (d) an equatorward shift.
Fig. 3.19. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during a negative AO.

Fig. 3.20. Frequency of AR landfall along the west coast of North America for those ARs that make landfall during a negative AO and (a) a jet extension, (b) a jet retraction, (c) a poleward shift, and (d) an equatorward shift.
Fig. 3.21. The average position of the NPJ within the NPJ phase diagram five days prior to those ARs that make landfall during (a) a positive AO and (b) a negative AO.

Fig. 3.22. Composite NPJ phase diagram trajectory 10 days prior to those ARs that make landfall during (a) a positive AO and (b) a negative AO. The jet position starts at the green diamond and ends at the red diamond.
Fig. 3.23. Frequency of AR landfall along the west coast of North America for those ARs that make landfall in the 90th percentile of IVT.

Fig. 3.24. Frequency of AR landfall along the west coast of North America for those ARs that make landfall in the 90th percentile of IVT and (a) a jet extension, (b) a jet retraction, (c) a poleward shift, and (d) an equatorward shift.
Fig. 3.25. The average position of the NPJ within the NPJ phase diagram five days prior to those ARs that make landfall in the 90th percentile of IVT.

Fig. 3.26. The evolution of the NPJ within the NPJ phase diagram 10 days prior to those ARs that make landfall in the 90th percentile of IVT. The jet position starts at the green diamond and ends at the red diamond.
4. Composite Evolutions and Illustrative Cases

4.1 Positive PNA Composite Evolution

A zonal NPJ is present at day –6 (Fig. 4.1a), along with a surface cyclone positioned in the Bering Sea beneath the left jet-exit region and a surface anticyclone positioned just southwest of California (Fig. 4.1b). The positioning of a surface anticyclone to the southeast of a 1000 hPa surface cyclone in the Bering Sea focuses a corridor of elevated IVT that originates from the tropical western Pacific and is directed towards western North America. At day –4, the NPJ extends eastward compared to day –6 in conjunction with the amplification of an upper-tropospheric trough near 160°W (Fig. 4.2a). An upper-tropospheric ridge is also firmly positioned over western North America. The surface cyclone remains at 1000 hPa beneath the left jet-exit region and continues to reside near the Aleutian Islands (Fig. 4.2b), accompanied by the surface anticyclone remaining nearly stationary compared to day –6. With little change in the strength and position of the surface cyclone and anticyclone, the IVT corridor remains relatively unchanged in intensity and location as well. At day –2, the NPJ extends farther eastward and strengthens, as the previously mentioned trough over the central North Pacific continues to amplify (Fig. 4.3a). On the equatorward side of the NPJ, an amplifying subtropical ridge is present. The surface cyclone over the Aleutian Islands begins to deepen beneath the left jet-exit region and downstream of the upper-tropospheric trough and features a minimum central pressure of 996 hPa (Fig. 4.3b). At this time, the surface anticyclone remains positioned to the southeast of the surface cyclone. As the surface cyclone deepens, the pressure gradient increases in the area between the surface cyclone and anticyclone, over the central and eastern North Pacific. This increased pressure gradient results in stronger lower-tropospheric westerly winds over the central North Pacific compared to days –4.
and –6 and, consequently, higher IVT values over the central eastern Pacific. At day 0, the NPJ is strongly extended and is associated with an upper-tropospheric ridge over western North America, characteristic of a positive PNA (Fig. 4.4a). Additionally, the presence of an upper-tropospheric trough-over-ridge pattern over the North Pacific is consistent with an extension of the NPJ. The surface cyclone reaches a peak intensity of 992 hPa (Fig. 4.4b) beneath the left jet-exit region and downstream of the upper-tropospheric trough over the central North Pacific, which is negatively tilted at this time (Fig. 4.4a). Given the presence of the negatively tilted trough, this composite suggests that landfalling ARs within the positive PNA category may be associated with cyclonic RWB over the eastern North Pacific. The surface anticyclone has remained unchanged in intensity and position since day –6 and is now positioned to the south-southeast of the surface cyclone. With the further strengthening and eastward progression of the surface cyclone, the strong IVT corridor impinges along the coast of the Pacific Northwest and British Columbia, signaling AR landfall.

The composite NPJ phase diagram trajectory in Fig. 3.15a indicates that during the 10 days prior to AR landfall during a positive PNA, the NPJ transitions towards a jet extension and poleward shift. The upper-tropospheric composite evolution discussed earlier in this section during a positive PNA supports the interpretation of a jet extension but does not capture a strong poleward shift. The well-defined upper-tropospheric trough-over-ridge pattern in Fig. 4.4a is reminiscent of the composite jet extension–poleward shift pattern in Figs. 2.5a,e. Additionally, the strong surface cyclone in the Gulf of Alaska in Fig. 4.4b matches the composite lower-tropospheric pattern during a jet extension in Fig. 2.5f.

4.2 Positive PNA Illustrative Case
At 0000 UTC 3 Nov. 2016, the NPJ phase diagram indicates an NPJ that does not project strongly onto PC 1 or PC 2, with the position lying inside the unit circle (Fig. 4.5). Through 9 Nov., the NPJ remains within the unit circle. However, during the final 96 h prior to AR landfall, the NPJ phase diagram indicates a transition towards a poleward shift. Through the entire 10-day period, the NPJ phase diagram indicates a transition towards a weak jet extension and a more robust poleward shift. The composite NPJ phase diagram trajectory in Fig. 3.16a indicates that during the 10 days prior to AR landfall during a positive PNA, the NPJ transitions towards a jet extension and poleward shift. Although in this case the NPJ phase diagram exhibits a transition towards a poleward shift, a jet extension is not indicated, as the PC 1 value is less than one PC unit away from the origin.

At 0000 UTC 13 Nov. 2016, a weak extension and strong poleward shift of the exit region of the NPJ are observed (Fig. 4.6a). Typical of a poleward shift pattern, an upper-tropospheric trough-over-ridge pattern resides over the central North Pacific. Additionally, an upper-tropospheric ridge is in place over western North America, indicative of a positive PNA. Just downstream of the upper-tropospheric trough in the poleward exit region, an 850 hPa cyclone, which closely represents a surface cyclone, is present near the Aleutian Islands (Fig. 4.6b). Based on the position and orientation of the IVT vectors, it appears that they are aligned along a cold front that originates from the surface cyclone near the Aleutian Islands. This cold front extends from the central Pacific to the western shore of the Pacific Northwest and British Columbia. Although there is a broad region of Q-vector convergence and positive Q-vector forcing in the Gulf of Alaska, it remains well offshore and is likely not enhancing ascent along the coast of the Pacific Northwest and British Columbia (Fig. 4.6c). However, there are likely areas of orographically induced ascent along the west coast of the Pacific Northwest and British Columbia,
evidenced by some component of the surface isobars crossing the mostly northwest-to-southeast oriented mountain ranges along the west coast of the Pacific Northwest and British Columbia (Fig. 4.6d). Additionally, there is likely a broad area of warm air advection and implied ascent just west of the Pacific Northwest and British Columbia, inferred from the orientation of the isobars and the implied geostrophic wind directed toward colder air (lower thickness values). The area of warm air advection also is located near the jet exit region indicative of forcing for ascent. With the combination of tropical moisture and robust ascent, an AR is likely present in the Pacific Northwest and British Columbia.

The geographic landfall location in Figures 3.12a,c indicate that ARs making landfall during a positive PNA and a jet extension or poleward shift often make landfall in the Pacific Northwest and British Columbia. This case fits the overarching theme. Additionally, the state of the NPJ in Figure 3.15a indicates that during the 5 days prior to AR landfall during a positive PNA, the state of the NPJ is most often characterized by jet extensions and poleward shifts. While in this case a transition towards a weak jet extension did occur, a strong poleward shift was more evident.

4.3 Negative PNA Composite Evolution

At day –6, a weak NPJ, along with a strong upper-tropospheric ridge, is positioned to the east of the Dateline (Fig 4.7a). Additionally, a weak upper-tropospheric trough is centered on the Dateline at subtropical latitudes. A broad surface cyclone in the exit region of the weak NPJ is positioned in the North Pacific, along with a surface anticyclone centered at 140ºW (Fig. 4.7b). Due to the juxtaposition of the surface cyclones and anticyclone, a corridor of elevated IVT extends across the central North Pacific. However, moisture is also being transported from the eastern
North Pacific, around the western periphery of the surface anticyclone located over the eastern North Pacific. At day –4, the NPJ remains weak and retracted, as the upper-tropospheric ridge and trough at high and low latitudes, respectively, amplify and broaden compared to day –6 (compare Fig. 4.8a with Fig. 4.7a). An upper-tropospheric trough begins to form over western North America at this time as well. Consequently, the large-scale flow pattern strongly resembles a negative PNA. A broad surface cyclone still remains in the North Pacific, with the strength and position of the surface anticyclone remaining unchanged (Fig. 4.8b) compared to day –6 (Fig. 4.7a). The IVT corridor is similar in intensity and position compared to day –6 due to little change in position and strength of the surface cyclone and anticyclone. At day –2, the NPJ continues to remain retracted, with split flow observed to the east of the Dateline (Fig. 4.9a). The upper-tropospheric ridge and trough over the central North Pacific continue to amplify and broaden compared to day –4. Meanwhile, the upper-tropospheric trough over western North America continues to amplify as well. The lower-tropospheric flow pattern depicts two separate pressure minima, one centered near Kamchatka and the other in the Gulf of Alaska (Fig. 4.9b), with the surface anticyclone and associated IVT corridor once again remaining unchanged in intensity and position compared to day –4. At day 0, the NPJ is fully retracted. The meridional juxtaposition of the strong upper-tropospheric ridge and upper-tropospheric trough over the central Pacific is strongly indicative of a retracted NPJ (Fig. 4.10a). This upper-tropospheric pattern strongly resembles that in Fig. 2.5c, which exemplifies a jet retraction/equatorward shift pattern. A 984 hPa surface cyclone is located in the Gulf of Alaska at this time (Fig. 4.10b), which is deeper than that observed in the Gulf of Alaska at day –2 (Fig. 4.9b). The presence of the surface anticyclone in the subtropics facilitates moisture transport from the tropical eastern North Pacific, while the combination of the surface cyclone and anticyclone facilitate moisture transport from the tropical western Pacific. This
moisture impinges along the Pacific Northwest and California, signaling AR landfall. The signal for AR landfall during the negative PNA composite is much weaker compared to the positive PNA composite (compare Fig. 4.10b with Fig. 4.4b).

The composite NPJ phase diagram trajectory in Fig. 3.15b indicates that during the 10 days prior to AR landfall during a negative PNA, the NPJ transitions towards a jet retraction and equatorward shift. The previously discussed upper-tropospheric composite evolution during a negative PNA supports the interpretation of the composite trajectory for a jet retraction, but does not capture the equatorward shift. In addition to this evolution of the NPJ, the well-defined upper-tropospheric ridge-over-trough pattern in Fig. 4.10a is reminiscent of the composite jet retraction pattern in Fig. 2.5c.

4.4 Negative PNA Illustrative Case

At 1200 UTC 8 Feb. 2011, the NPJ phase diagram indicates an NPJ that does not project strongly onto PC 1 or PC 2, with the position lying inside the unit circle (Fig. 4.11). By 12 Feb., the NPJ phase diagram indicates a rapid transition towards a jet retraction. Although during the next 48 h the NPJ begins to transition away from a jet retraction, by 18 Feb. the NPJ phase diagram indicates that the NPJ firmly resides in a jet retraction and equatorward shifted pattern. The composite NPJ phase diagram trajectory in Fig. 3.16b indicates that during the 10 days prior to AR landfall during a negative PNA, the NPJ transitions towards a jet retraction and equatorward shift. In this case, the NPJ phase diagram exhibits a transition towards a jet retraction and equatorward shift.
At 1200 UTC 18 Feb. 2011, a substantially amplified NPJ is present over the central North Pacific, typically indicative of a jet retraction (Fig. 4.12a). While there is a strong upper-tropospheric ridge spanning most of the central North Pacific, the feature of interest is the deep upper-tropospheric trough centered just off the west coast of North America, indicative of a negative PNA. Owing to a positively tilted trough, a weak 850 hPa cyclone is present near the Pacific Northwest (Fig. 4.12b). Moreover, there is a very weak corridor of IVT, which emanates from the tropical eastern Pacific and is focused onshore in southern California and northwestern Mexico. An area of Q-vector convergence is featured near southern California (partially shown), indicating forcing for quasigeostrophic (QG) upward vertical motion (Fig. 4.12c). In the same area as the Q-vector convergence, some component of the isobars is directed perpendicular to the mostly north-to-south oriented mountain ranges in California, likely supporting orographic ascent (Fig. 4.12d). Without the presence of warm air advection, i.e., isobars crossing 1000–500 hPa thickness contours, this AR is likely weakening. However, with the combination of weak tropical moisture and some ascent, a weak AR is likely present in southern California.

The geographic landfall location in Figures 3.14b,d also indicate that ARs making landfall during a negative PNA and a jet retraction or equatorward shift often make landfall in southern California and northwestern Mexico. This case fits the overarching theme. Additionally, the state of the NPJ in Figure 3.15b indicates that during the 5 days prior to AR landfall during a negative PNA, the state of the NPJ is most often characterized by jet retractions and equatorward shifts. In this case a jet retraction and equatorward shift occurred.

4.5 Top 10% of IVT Composite
For this category, only the final landfall time is selected for the composite evolution due to a lack of differences between prior times. Overall, this lack of differences may be indicative of considerable variability that is inherent to this category. In other words, the variability averages out to yield the observed similarity between times. At day 0, the composite NPJ features a weak extension and poleward shift. In particular, the composite analysis features an upper-tropospheric trough over the Gulf of Alaska and an upper-tropospheric ridge downstream over the west coast of North America (Fig. 4.13a). The presence of this upper-tropospheric ridge along the west coast shifts the exit region of the NPJ northward, resulting in a poleward shift of the NPJ. Immediately downstream of the upper-tropospheric trough, a compact 996 hPa surface cyclone resides in the Gulf of Alaska (Fig. 4.13b). The surface cyclone features a corridor of elevated IVT on its southwestern flank that impinges along the west coast of the Pacific Northwest and British Columbia, signaling the landfall of an AR. The composite flow pattern at the time of AR landfall appears similar to the positive PNA category, but with much weaker upper- and lower-tropospheric flow anomalies.

The composite NPJ phase diagram trajectory in Fig. 3.17 indicates that during the 10 days prior to AR landfall for ARs in the top 10% of IVT, the NPJ transitions towards a poleward shift. The previously discussed upper-tropospheric composite evolution for ARs in the top 10% of IVT supports the interpretation of a poleward shift. However, the composite evolution shows a weakly extended jet through the six-day period (not shown), but Fig. 3.17 did not. In addition to the evolution of the NPJ, the weakly-defined upper-tropospheric trough-over-ridge pattern in Fig. 4.13a has some similarity to the composite jet extension/poleward shift pattern in Figs. 2.5a,e. However, the upper-tropospheric features in Fig. 4.13a are much weaker in amplitude than Figs. 2.5a,e.
4.6 Top 10% of IVT Illustrative Case

At 1200 UTC 16 Nov. 2011, the NPJ phase diagram indicates an NPJ that does not project strongly onto PC 1 or PC 2, with the position lying inside the unit circle (Fig. 4.14). However, over the next 4 days, the NPJ transitions towards a jet retraction. By 24 Nov. the NPJ has transitioned away from a jet retraction, and now resides in a poleward shift. By the time of AR landfall on 26 Nov., the NPJ phase diagram trajectory has looped clockwise back around, once again residing in a jet retraction, along with a poleward shift. The composite NPJ phase diagram trajectory in Fig. 3.26 indicates that during the 10 days prior to AR landfall for those ARs in the top 10% of IVT, the NPJ transitions towards a weak poleward shift. In this case there was a similar weak transition towards a poleward shift.

At 1200 UTC 26 Nov. 2011, a highly amplified NPJ is present over the eastern North Pacific (Fig. 4.15a). In addition to a deep upper-tropospheric trough centered near 150°W, a strong upper-tropospheric ridge is located over the west coast of North America. This amplified ridge is consistent with a poleward-shifted NPJ exit region. The juxtaposition of an 850 hPa cyclone in the Gulf of Alaska and an 850 hPa anticyclone over the Intermountain West focuses a strong corridor of IVT towards the Pacific Northwest and British Columbia (Fig. 4.15b). A region of Q-vector convergence dominated by the across-front component of the Q vector is present in the Pacific Northwest and British Columbia, suggesting that some of the QG ascent is due to frontogenetical processes (Fig. 4.15c). The mostly across-front Q-vector convergence pattern, with Q-vectors pointing towards larger values of 700-hPa temperature, is supported by the southwest-to-northeast oriented cold front in the eastern North Pacific (Fig. 4.15d). The previously mentioned corridor of
IVT resides along the warm side of the cold front, evidenced by the pool of precipitable water originating from the tropical eastern North Pacific. Additionally, there are likely contributions to the ascent stemming from forced ascent over orography in the Pacific Northwest and British Columbia, as evidenced by surface isobars exhibiting some component crossing the mostly northwest-to-southeast oriented mountain ranges along the west coast of the Pacific Northwest and British Columbia. Finally, in the same area as the Q-vector convergence exists an area of strong warm air advection, inferred from the orientation of the isobars and the implied geostrophic wind directed toward colder air (lower thickness values). With the combination of high IVT values and substantial ascent, a strong AR is likely present in the Pacific Northwest and British Columbia.

The geographic landfall location in Fig. 3.24c also indicates that ARs in the top 10% of IVT that make landfall during a poleward shift overwhelmingly do so in the Pacific Northwest and British Columbia. This case fits the overarching theme. The state of the NPJ in Figure 3.25 indicates that during the 5 days prior to AR landfall for those ARs in the top 10% of IVT, the state of the NPJ is most often characterized by poleward shifts. In this case, the NPJ spent a considerable amount of time in a poleward shift, with the position ultimately ending within the unit circle.
Fig. 4.1. Composite upper- and lower-tropospheric flow pattern 6 days prior to those landfalling ARs that occur during a positive PNA. (a) 250-hPa wind speed (shaded, every 10 m s\(^{-1}\)), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 0.25σ in solid red contours, negative standardized geopotential height anomalies every −0.25σ in dashed red contours). (b) IVT (shaded, kg m\(^{-1}\) s\(^{-1}\)) and vectors (reference vector bottom right), mean sea level pressure (black contours, every 4 hPa), and 850-hPa temperature (dashed blue contours, every 5°C).

Fig. 4.2. Composite upper- and lower-tropospheric flow pattern 4 days prior to those landfalling ARs that occur during a positive PNA. (a) 250-hPa wind speed (shaded, every 10 m s\(^{-1}\)), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 0.25σ in solid red contours, negative standardized geopotential height anomalies every −0.25σ in dashed red contours). (b) IVT (shaded, kg m\(^{-1}\) s\(^{-1}\)) and vectors (reference vector bottom right), mean sea level pressure (black contours, every 4 hPa), and 850-hPa temperature (dashed blue contours, every 5°C).
Fig. 4.3. Composite upper- and lower-tropospheric flow pattern 2 days prior to those landfalling ARs that occur during a positive PNA. (a) 250-hPa wind speed (shaded, every 10 m s\(^{-1}\)), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 0.25σ in solid red contours, negative standardized geopotential height anomalies every \(-0.25\sigma\) in dashed red contours). (b) IVT (shaded, kg m\(^{-1}\) s\(^{-1}\)) and vectors (reference vector bottom right), mean sea level pressure (black contours, every 4 hPa), and 850-hPa temperature (dashed blue contours, every 5°C).

Fig. 4.4. Composite upper- and lower-tropospheric flow pattern at landfall for those landfalling ARs that occur during a positive PNA. (a) 250-hPa wind speed (shaded, every 10 m s\(^{-1}\)), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 0.25σ in solid red contours, negative standardized geopotential height anomalies every \(-0.25\sigma\) in dashed red contours). (b) IVT (shaded, kg m\(^{-1}\) s\(^{-1}\)) and vectors (reference vector bottom right), mean sea level pressure (black contours, every 4 hPa), and 850-hPa temperature (dashed blue contours, every 5°C).
Fig. 4.5. The evolution of the NPJ in the context of the NPJ Phase Diagram during the 10-day period, 0000 UTC 3 Nov.–13 Nov. 2016. Each diamond corresponds to 0000 UTC on a particular day. The green and red diamonds indicate the start and end of the trajectory, respectively.
Fig. 4.6. Maps valid at 0000 UTC 13 Nov. 2016 depicting: (a) 250-hPa wind speed (shaded, m s\(^{-1}\)), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 1σ in solid red contours, negative standardized geopotential height anomalies every −1σ in dashed red contours). (b) IVT (shaded, kg m\(^{-1}\) s\(^{-1}\)) and vectors (reference vector bottom right), and 850-hPa geopotential height (black contours, every 60 dam). (c) 700-hPa geopotential height (blue contours, every 60 dam), 700-hPa temperature (dashed red contours, every 3°C), Q vectors (vectors, plotted for values greater than 5 × 10\(^{-7}\) Pa m\(^{-1}\) s\(^{-1}\)), and forcing term (−2\(\nabla\cdot\mathbf{Q}\)) of the Q-vector form of the QG omega equation (shaded, 10\(^{-12}\) Pa m\(^{-2}\) s\(^{-1}\)). (d) 1000–500 hPa thickness (dashed contours, every 60 dam), precipitable water (shaded gray, mm), sea level pressure (solid contours, every 4 hPa), and 250-hPa wind speed (shaded colors, m s\(^{-1}\)).
Fig. 4.7. Composite upper- and lower-tropospheric flow pattern 6 days prior to those landfalling ARs that occur during a negative PNA. (a) 250-hPa wind speed (shaded, m s\(^{-1}\)), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 0.25σ in solid red contours, negative standardized geopotential height anomalies every \(\sim 0.25\sigma\) in dashed red contours). (b) IVT (shaded, kg m\(^{-1}\) s\(^{-1}\)) and vectors (reference vector bottom right), mean sea level pressure (black contours, every 4 hPa), and 850-hPa temperature (dashed blue contours, every 5°C).

Fig. 4.8. Composite upper- and lower-tropospheric flow pattern 4 days prior to those landfalling ARs that occur during a negative PNA. (a) 250-hPa wind speed (shaded, m s\(^{-1}\)), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 0.25σ in solid red contours, negative standardized geopotential height anomalies every \(\sim 0.25\sigma\) in dashed red contours). (b) IVT (shaded, kg m\(^{-1}\) s\(^{-1}\)) and vectors (reference vector bottom right), mean sea level pressure (black contours, every 4 hPa), and 850-hPa temperature (dashed blue contours, every 5°C).
Fig. 4.9. Composite upper- and lower-tropospheric flow pattern 2 days prior to those landfalling ARs that occur during a negative PNA. (a) 250-hPa wind speed (shaded, m s\(^{-1}\)), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 0.25\(\sigma\) in solid red contours, negative standardized geopotential height anomalies every \(-0.25\sigma\) in dashed red contours). (b) IVT (shaded, kg m\(^{-1}\) s\(^{-1}\)) and vectors (reference vector bottom right), mean sea level pressure (black contours, every 4 hPa), and 850-hPa temperature (dashed blue contours, every 5°C).

Fig. 4.10. Composite upper- and lower-tropospheric flow pattern at landfall for those landfalling ARs that occur during a negative PNA. (a) 250-hPa wind speed (shaded, m s\(^{-1}\)), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 0.25\(\sigma\) in solid red contours, negative standardized geopotential height anomalies every \(-0.25\sigma\) in dashed red contours). (b) IVT (shaded, kg m\(^{-1}\) s\(^{-1}\)) and vectors (reference vector bottom right), mean sea level pressure (black contours, every 4 hPa), and 850-hPa temperature (dashed blue contours, every 5°C).
Fig. 4.11. The evolution of the NPJ in the context of the NPJ Phase Diagram during the 10-day period, 1200 UTC 8 Feb.–18 Feb. 2011. Each diamond corresponds to 1200 UTC on a particular day. The green and red diamonds indicate the start and end of the trajectory, respectively.
Fig. 4.12. Maps valid at 1200 UTC 18 Feb. 2011 depicting: (a) 250-hPa wind speed (shaded, m s\(^{-1}\)), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 1σ in solid red contours, negative standardized geopotential height anomalies every −1σ in dashed red contours). (b) IVT (shaded, kg m\(^{-1}\) s\(^{-1}\)) and vectors (reference vector bottom right), and 850-hPa geopotential height (black contours, every 60 dam). (c) 700-hPa geopotential height (blue contours, every 60 dam), 700-hPa temperature (dashed red contours, every 3°C), Q vectors (vectors, plotted for values greater than 5 \(\times\) 10\(^{-7}\) Pa m\(^{-1}\) s\(^{-1}\)), and forcing term \((-2\nabla \cdot \mathbf{Q})\) of the Q-vector form of the QG Omega equation (shaded, 10\(^{-12}\) Pa m\(^{-2}\) s\(^{-1}\)). (d) 1000–500 hPa thickness (dashed contours, every 60 dam), precipitable water (shaded gray, mm), sea level pressure (solid contours, every 4 hPa), and 250-hPa wind speed (shaded colors, m s\(^{-1}\)).
Fig. 4.13. Composite upper- and lower-tropospheric flow pattern at landfall for those landfalling ARs that are in the top 10% of IVT. (a) 250-hPa wind speed (shaded, m s$^{-1}$), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 0.25σ in solid red contours, negative standardized geopotential height anomalies every −0.25σ in dashed red contours). (b) IVT (shaded, kg m$^{-1}$ s$^{-1}$) and vectors (reference vector bottom right), mean sea level pressure (black contours, every 4 hPa), and 850-hPa temperature (dashed blue contours, every 5°C).

Fig. 4.14. The evolution of the NPJ in the context of the NPJ Phase Diagram during the 10-day period, 1200 UTC 16 Nov.–26 Nov. 2011. Each diamond corresponds to 1200 UTC on a particular day. The green and red diamonds indicate the start and end of the trajectory, respectively.
Fig. 4.15. Maps valid at 1200 UTC 26 Nov. 2011 depicting: (a) 250-hPa wind speed (shaded, m s$^{-1}$), 250-hPa geopotential height (black contours, every 120 dam), and 250-hPa standardized geopotential height anomalies (positive standardized geopotential height anomalies every 1σ in solid red contours, negative standardized geopotential height anomalies every −1σ in dashed red contours). (b) IVT (shaded, kg m$^{-1}$ s$^{-1}$) and vectors (reference vector bottom right), and 850-hPa geopotential height (black contours, every 60 dam). (c) 700-hPa geopotential height (blue contours, every 60 dam), 700-hPa temperature (dashed red contours, every 3°C), Q vectors (vectors, plotted for values greater than 5 × 10$^{-7}$ Pa m$^{-1}$ s$^{-1}$), and forcing term (−2$\mathbf{\nabla} \mathbf{\cdot} \mathbf{Q}$) of the Q-vector form of the QG Omega equation (shaded, 10$^{-12}$ Pa m$^{-2}$ s$^{-1}$). (d) 1000–500 hPa thickness (dashed contours, every 60 dam), precipitable water (shaded gray, mm), sea level pressure (solid contours, every 4 hPa), and 250-hPa wind speed (shaded colors, m s$^{-1}$).
5. Discussion and Suggestions for Future Work

5.1 Discussion

ARs play an important hydrological and societal role along the west coast of North America. This research is centered on the NPJ phase diagram and NPJ regimes prior to AR landfall, motivated by the lack of discussion in previous literature on the relationship between NPJ regimes and ARs. Examining ARs through an NPJ regime/NPJ phase diagram lens has provided new insights into the dynamics and variability of ARs, which may lead to improved forecasts of these features and the extreme precipitation associated with them. This method of investigating ARs was adopted to improve the understanding of: 1) the average state and evolution of the NPJ prior to AR landfall for selected categories of landfalling ARs; 2) the dynamical processes applicable to the aforementioned categories of landfalling ARs that are linked to NPJ variability in (1).

Landfalling ARs were organized into five different categories: landfalling ARs as a function of season, landfalling ARs as a function of latitude, landfalling ARs as a function of the phase of the PNA, landfalling ARs as a function of the phase of the AO, and landfalling ARs in the top 10% of IVT. Each category was investigated in terms of three metrics: the geographical landfall position of ARs as a function of NPJ regime, the average state of the NPJ in the five days prior to AR landfall, and the evolution of the NPJ in the 10 days prior to AR landfall.

5.1.1 AR Landfall as a Function of Season

The seasonal progression of the NPJ from north to south is noted in AR landfall location as the season changes from autumn to winter. From winter to spring, the NPJ retreats north,
denoted by a double maximum in AR landfall location during spring in California and British Columbia. The remainder of this section will document the results from each season beginning with autumn.

During autumn, AR landfall is most common in British Columbia. The average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet retraction and poleward shift. The evolution of the NPJ during the 10 days prior to AR landfall has a weak tendency to evolve towards a jet retraction and a poleward shift. Next, during winter, AR landfall is most common in the Pacific Northwest. The average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet extension and poleward shift. The evolution of the NPJ during the 10 days prior to AR landfall has a weak tendency to evolve towards a jet extension. Finally, during spring, AR landfall is most common in California and British Columbia. The average state of the NPJ during the five days prior to AR landfall is most often characterized by a poleward shift. The evolution of the NPJ during the 10 days prior to AR landfall has a weak tendency to evolve towards a jet extension and poleward shift.

5.1.2 AR Landfall as a Function of Latitude

In the southern domain (22.5°N–32.5°N), the average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet retraction. The evolution of the NPJ during the 10 days prior to AR landfall has a weak tendency to evolve towards a jet retraction and an equatorward shift. ARs making landfall in the southern domain are most commonly associated with jet retractions. As a result of the NPJ undergoing a jet retraction, a meridionally oriented NPJ and/or a split flow pattern often result. In order for the NPJ to impact southern California and northwestern Mexico, latitudes where the NPJ typically does not reach, a highly amplified upper-tropospheric flow pattern must result. A highly amplified upper-
tropospheric flow pattern is consistent with the composite upper-tropospheric pattern during a jet retraction in Fig. 2.5c.

In the central domain (32.5°N–45.0°N), the average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet extension and poleward shift. The evolution of the NPJ during the 10 days prior to AR landfall has a weak tendency to evolve towards a jet extension and a poleward shift. ARs making landfall in the central domain are most commonly associated with jet extensions and poleward shifts. Unlike the southern domain, the central domain and the typical latitude of the NPJ during winter are collocated. In order for the NPJ to impact California and the Pacific Northwest, a highly zonal upper-tropospheric flow pattern must result. A highly zonal upper-tropospheric flow pattern is consistent with the composite upper-tropospheric pattern during a jet extension or poleward shift in Figs. 2.5a,e.

In the northern domain (45.0°N–57.5°N), the average state of the NPJ during the five days prior to AR landfall is most often characterized by a poleward shift. The evolution of the NPJ during the 10 days prior to AR landfall has a weak tendency to evolve towards a poleward shift. ARs making landfall in the northern domain are most commonly associated with poleward shifts. ARs making landfall during poleward shifts makes physical sense as most of British Columbia is north of the typical latitude of the NPJ during all three seasons. Thus, in order for ARs to make landfall at latitudes poleward of 47.5°N, the NPJ must undergo a poleward shift.

5.1.3 AR Landfall as a Function of Phase of the PNA (Positive)

During a positive PNA, AR landfall is most common in British Columbia. The average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet
extension and poleward shift. The evolution of the NPJ during the 10 days prior to AR landfall has a strong tendency to evolve towards a jet extension and a poleward shift.

A composite analysis was performed in addition to the geographical landfall analysis and the average state and evolution of the NPJ for the positive PNA phase. During the six days prior to AR landfall, the NPJ undergoes a transition towards a jet extension and poleward shift. As the NPJ extends across the North Pacific, an upper-tropospheric trough-over-ridge pattern prevails across the North Pacific, consistent with the findings of Griffin and Martin (2017) and Winters et al. (2019). Downstream of the upper-tropospheric trough-over-ridge pattern, a surface cyclone and anticyclone are positioned in the Gulf of Alaska and southwest of California, respectively, which focus a strong corridor of IVT towards British Columbia and the Pacific Northwest that emanates from the tropical western Pacific. Consistent with a positive PNA pattern, an upper-tropospheric ridge is also positioned over the west coast of North America at AR landfall. This composite evolution featured a transition towards a jet extension and a poleward shift, which matches well with the composite NPJ phase diagram trajectory in section 3.3.

5.1.4 AR Landfall as a Function of Phase of the PNA (Negative)

AR landfall is most common in California. The average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet retraction and equatorward shift. The evolution of the NPJ during the 10 days prior to AR landfall has a strong tendency to evolve towards a jet retraction and an equatorward shift.

Similar to section 5.1.3, a composite analysis was performed for the negative PNA phase. During the six days prior to AR landfall, the NPJ undergoes a transition towards a jet retraction
and equatorward shift. When the NPJ undergoes a jet retraction, an upper-tropospheric ridge-over-trough pattern prevails across the North Pacific, consistent with the findings of Griffin and Martin (2017) and Winters et al. (2019). Downstream of the upper-tropospheric ridge-over-trough, a surface cyclone and anticyclone are positioned in the Gulf of Alaska and west of California. In contrast to the positive PNA composite, IVT corridors are found to emanate from both the tropical western Pacific and the tropical eastern Pacific. The IVT corridors originating from the tropical western Pacific and the tropical eastern Pacific are both directed towards the Pacific Northwest and California. The composite IVT values and the resultant strength of the AR are much weaker during a negative PNA than during a positive PNA. This composite evolution featured a transition towards a jet retraction but failed to capture an equatorward shift, which was a feature highlighted by the composite NPJ phase diagram trajectory in section 3.3.

5.1.5 AR Landfall as a Function of Phase of the AO (Positive and Negative)

During a positive AO, AR landfall is most common in British Columbia and the Pacific Northwest. The average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet retraction and a poleward shift. The evolution of the NPJ during the 10 days prior to AR landfall has a moderate tendency to evolve towards a jet retraction and a poleward shift. A positive AO typically features a weak blocking pattern over the North Pacific, with an anomalous surface anticyclone near the Gulf of Alaska. This blocking pattern acts to impede the eastward progression of the NPJ and often results in jet retractions. The location of the anomalous surface anticyclone matches the location of the surface anticyclone in the jet retraction composite, (Fig. 2.5d).
During a negative AO, AR landfall is most common in northern California. The average state of the NPJ during the five days prior to AR landfall is most often characterized by a jet extension and an equatorward shift. The evolution of the NPJ during the 10 days prior to AR landfall has a moderate tendency to evolve towards a jet extension. During a negative AO, an anomalous surface cyclone resides near the Aleutian Islands, which coincides with the location of the poleward exit region of the NPJ. The location of the poleward exit region of the NPJ near the Aleutian Islands is consistent with a jet extension and matches the location of the surface cyclone in the jet extension composite (Fig. 2.5b).

5.1.6 AR Landfall as a Function of the Top 10% of IVT

AR landfall is most common in British Columbia and the Pacific Northwest. The average state of the NPJ during the five days prior to AR landfall is most often characterized by a poleward shift. The evolution of the NPJ during the 10 days prior to AR landfall has a weak tendency to evolve towards a poleward shift.

Similar to the positive and negative PNA phases, a composite analysis was conducted for landfalling ARs that ranked in the top 10% of IVT. Given the considerable variability in the large-scale flow pattern prior to these events, only the time of AR landfall was investigated. The NPJ is weakly extended and poleward shifted at the time of AR landfall. In particular, an upper-tropospheric ridge is observed along the west coast of North America, which positions the exit region of the NPJ farther north and translates to a poleward shift. A surface cyclone located in the Gulf of Alaska directs an IVT corridor towards British Columbia and the Pacific Northwest. The top 10% of IVT composite evolution is similar to the positive PNA category composite evolution,
but with weaker upper-tropospheric features. The top 10% of IVT composite evolution exhibits a weak jet extension and poleward shift. However, the composite NPJ phase diagram trajectory in section 3.5 only exhibits a weak poleward shift.

5.2 Suggestions for Future Work

Previous work by Winters et al. (2019) has demonstrated that forecasts verifying during jet retractions and equatorward shifts exhibit less skill than those that verify during jet extensions and poleward shifts. Given this finding, additional forecast skill evaluations that involve ARs could be performed. These additional evaluations could include the forecast skill of: ARs during each NPJ regime, ARs during a positive/negative PNA as a function of each NPJ regime, and ARs during a positive/negative AO as a function of each NPJ regime.

Since teleconnection patterns such as the PNA and AO can be predicted relatively skillfully in the medium range, combining these teleconnection indices with the NPJ phase diagram and the results from this work may allow for more skillful prediction of ARs in the medium range. Additionally, the NPJ phase diagram could be used to examine the antecedent NPJ structure prior to periods such as Feb. 2017, where several ARs make landfall along the west coast of North America in rapid succession.
References


Neiman, P. J., F. M. Ralph, G. A. Wick, J. D. Lundquist, and M. D. Dettinger, 2008: Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the West Coast of North America based on eight years of SSM/I satellite observations. J. Hydrometeor., 9, 22–47.


