2019-03

EFFECTS OF TEMPERATURE GRADIENT ON THE DEVELOPMENT AND SUSTAINMENT OF LOW-LEVEL COASTAL JETS

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THESIS

EFFECTS OF TEMPERATURE GRADIENT ON THE DEVELOPMENT AND SUSTAINMENT OF LOW-LEVEL COASTAL JETS

by

Phillip B. Smith

March 2019

Thesis Advisor: Wendell A. Nuss

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REPORT DOCUMENTATION PAGE				*Form Approved OMB No. 0704–0188*
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1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** March 2019	**3. REPORT TYPE AND DATES COVERED** Master's thesis		
4. TITLE AND SUBTITLE EFFECTS OF TEMPERATURE GRADIENT ON THE DEVELOPMENT AND SUSTAINMENT OF LOW-LEVEL COASTAL JETS				**5. FUNDING NUMBERS**
6. AUTHOR(S) Phillip B. Smith				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000				**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A				**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.				**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

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14. SUBJECT TERMS low-level coastal jet			**15. NUMBER OF PAGES** 43
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540–01-280-5500 Standard Form 298 (Rev. 2–89) Prescribed by ANSI Std. 239–18

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EFFECTS OF TEMPERATURE GRADIENT ON THE DEVELOPMENT AND SUSTAINMENT OF LOW-LEVEL COASTAL JETS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND PHYSICAL OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

Over the summer of 2016, a total of 92 days were reviewed; 22 were determined to meet the requirements of this study for having the presence of a low-level coastal jet (LLCJ). Cross sections were taken to investigate the thermal structure and evidence of the vertical circulation pattern. In each of these examples, a clear jet is present just below a sloping inversion except for one. June 27–29 found the presence of a LLCJ but with no sloping inversion, and the jet was found to be above the inversion. Several factors about this case seem to contribute to its unique structure with the jet above the inversion. In order for this structure to occur, the thermal structure above the inversion becomes very important. Above the inversion, there is a stronger than normal thermal gradient that is not present in the other more typical LLCJ cases. This result suggests that a thermal gradient is a necessary condition for the development of the LLCJ no matter how it is developed.

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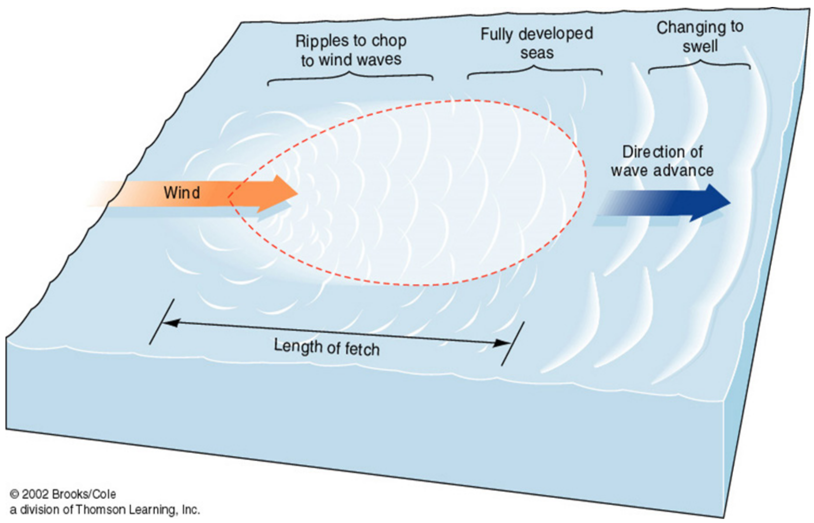
I. INTRODUCTION

Low-level jets (LLJ) have been extensively studied over the years. They can seemingly come out of nowhere and provide dangerous conditions with little warning. The meteorological term LLJ describes multiple types of wind maxima near the surface. The most well-known and studied LLJ is the one over the plains of the United States. The Great Plains LLJ is driven by an ageostrophic process with maximum wind speeds happening just after midnight due to inertial oscillations from a decrease of frictional forcing during the night (Bonner and Paegle 1970). However, the low-level coastal jet (LLCJ) that is found along the U.S. West Coast in the summertime is thought to develop due to a different physical process. In this case, thermal wind balance set up by land-sea heating contrasts leads to an increase in flow toward the surface (Parish 2000). While other papers have demonstrated the influence of hydraulic effects in producing local wind maxima (Munoz and Garreaud 2005), the larger-scale flow seems to be more of a feature of thermal wind balance (Parish 2000). This paper explores the balanced flow processes that led to the LLCJ development and sustainment on the California coast in the summer of 2016.

Due to space constraints and shoal water, threat to small craft from winds and waves can be much greater close to shore. When a LLCJ is present it is often not well represented in the models, and thus predicted waves can be underestimated by a large degree. This is a danger to any operation, civilian or military. A great asset the military has is its ability to transport personnel, equipment and supplies onto any coastline in the world. An amphibious landing could be in support of direct military action or a humanitarian operation. If the prediction of winds and seas are incorrect, lives can be put at risk as well as the supplies and equipment being transported. Many amphibious vehicles have low tolerances related to sea state and their safe operation. So, even if the sea state does not threaten the main force afloat, there could be a serious threat to the landing craft. Specifically, the LLCJ can increase the wind over the ocean and lead to the creation of larger-than-expected waves in a short period of time. These smaller but potentially strong fetch areas (Figure 1) are not always captured in the standard global models used for forecasting. This is mainly due to the LLCJ being a relatively small feature and contained within the boundary layer. The height potential of the waves resulting from the fetch area depend on the strength of the winds and the duration of those winds from the same direction. With the winds from a LLCJ being relatively high and the duration of several days, the potential for dangerous sea states is very high. The need to determine the driving dynamics of the LLCJ is key to being able to better predict their development and provide better forecasts for the safety of navigation.

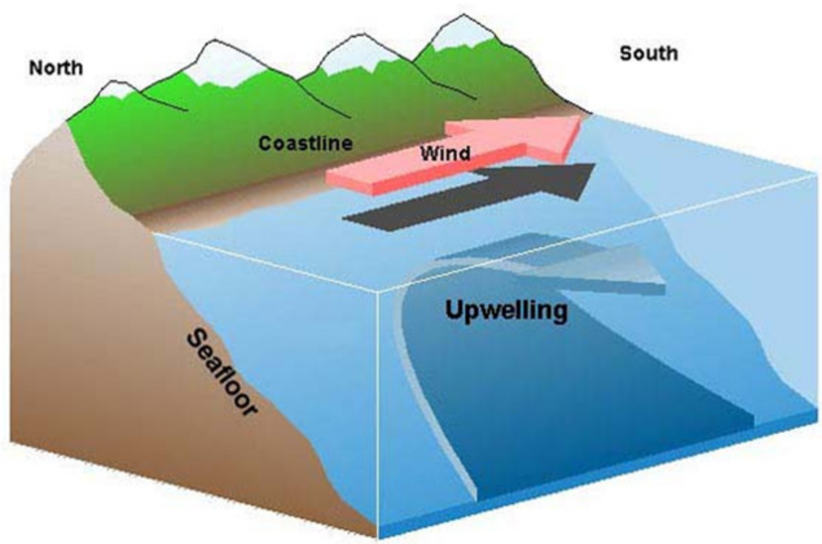


The combination of high and persistent winds from a consistent direction, a fetch area, can produce larger-than-expected waves in a relatively short time.

Figure 1. Fetch Area

The atmospheric setup associated with the LLCJ is fairly simple for the California coast, where this study is focused. The subtropical high occurs offshore and strong warming in the interior produces a pronounced thermal trough of low pressure. The synoptic setup produces a strong cross-coast pressure gradient and a northerly wind, usually from the northwest, at the surface. There also exists a persistent temperature gradient with cooler temperatures over the ocean and warmer over the land. Unique to this case, the temperature gradient is unaffected by the diurnal heating cycle. This thermal gradient is made possible during the summer months in California due to the cold coastal waters and much warmer surface temperatures over land that persist even through the night and day heating changes. This gradient can even be enhanced through cold water upwelling

(Figure 2) driven by Ekman transport offshore due to the northerly wind. Ekman transport is the transport of surface and near surface ocean water 90 degrees to the right of the prevailing wind direction (Pond and Pickard 1978). With this mass transport, the surface water is replaced from the water below, decreasing the overall surface temperature of the water. The thermal gradient can now be enhanced when the low-level inversion that occurs above the cold, up-welled water is forced to slope down towards the coast. This paper will explore the processes that influence the thermal gradient and thermal wind balance that result in the development of a strong LLCJ that, when not predicted correctly, can be a danger to both civilian and military operations.



Due to Ekman transport, the northerly wind along the West Coast leads to colder water at depth to be brought to the surface. This decreases the surface temperature of the water and can increase the temperature gradient between the ocean and land.

Figure 2. Upwelling. Source: Sanctuary Quest (2019).

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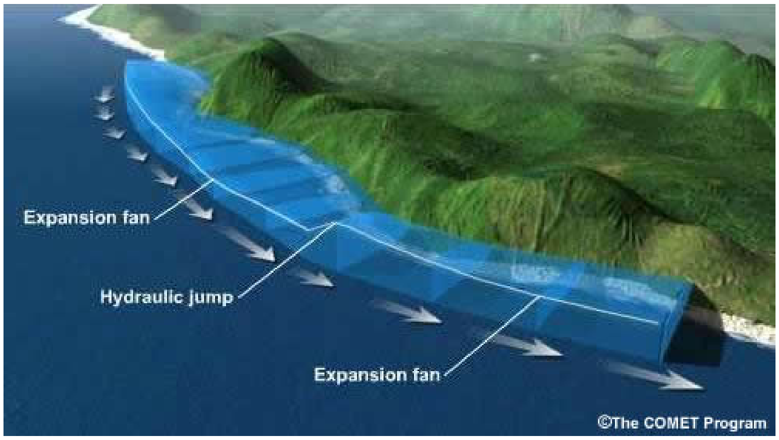
II. BACKGROUND

Several studies have examined the causes of the LLCJ, each providing a piece of the puzzle as to the dynamic effects that result in its development and sustainment. In Chao (1985), it was presented that zonal flow that interacted with coastal topography could produce topographic blocking that would provide a LLCJ of wind speeds similar to those that were measured. This LLCJ was the result from the development of Kelvin waves as the zonal wind interacted with the coastal mountains. When large-scale zonal flow was inserted into the models, the LLCJ that was produced purely from topographic blocking was determined to be an underestimation of the wind. Thus, the influence of coastal topography such as the California coastal mountain ranges can clearly have an effect on the LLCJ but does not fully explain its strength.

A study by Parish (2000) took observations of the LLCJ in the hopes of determining the kinematics and dynamics of the LLCJ. Using flight-collected data on two days during the summer, rough conclusions were made as to the driving factors of the LLCJ. The results of this study describe conditions and circumstances that led to the development of the LLCJ on the two observed days. First, the size of the LLCJ was found to be within the scale of the Rossby radius of deformation. Second, the observed depth of the boundary layer and the associated inversion height slopes downward with progression landward. The reason for this slope is thought to be the large temperature gradient between the land and sea. With this thermal gradient in place, a resultant thermal wind would be set up. Third, there was no observed evidence that topographic effects are necessary to the development of the LLCJ.

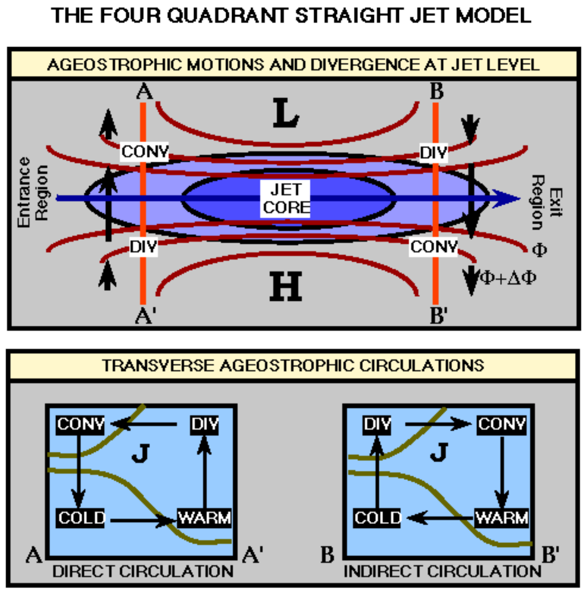
The development of a LLCJ along the west coast of South America strictly due to hydraulic effects is detailed in a paper by Munoz and Garreaud (2005). Topographic or hydraulic effects (Figure 3) occur where the specific topography of the coastline squeezes and relaxes the pressure of the alongshore wind field, creating focused areas of wind maximums. Munoz and Garreaud (2005) concluded that hydraulic effects were the driving factor due to the unique topography of the South American coast. In the area of study, there are long stretches of vertical cliffs that rise out of the ocean and are greater in height than the boundary layer or top of the inversion. With these physical features, there is no way to have the effects of a sloping inversion through the difference in land and sea temperatures. Purely topographic forcing resulting in a LLCJ is a unique situation specific to the west coast of South America and is not considered the driving factor of LLCJs on the U.S. west coast.

If the jet is in thermal wind balance and there is a persistent low pressure over the land and high pressure over the water, the four-quadrant jet model can be applied to theorize what type of vertical circulation should be expected. The four-quadrant jet model, shown in Figure 4, describes the convergent and divergent areas surrounding a jet core. In these areas, a circulation develops due to the sinking and rising air in the different quadrants surrounding the jet core. One way to determine this circulation could be to look for the distinct slope in the height of the inversion layer as observed by Parish (2000). If the four-quadrant model holds true, there should be an observable difference in the slope of the inversion both upstream and downstream of the jet core. The greatest slope should be just downstream from the entrance region of the jet, where the sinking air due to convergence would be pushing down on the inversion landward, and rising air seaward of the entrance region would lead to an increase in the inversion height. The convergent and divergent areas are opposite in the exit region. This would theoretically lead to less of a slope, or possibly a slight upslope structure, of the inversion height downstream of the jet core.



Coast variations in the topography can create local maximum and minimum in wind speed.

Figure 3. Hydraulic Effects. Source: Comet MetEd (2018).



Using this model, there should be evidence of the convergence and divergent areas in any straight jet. For this study, we are treating the LLCJ as a straight jet.

Figure 4. Four-Quadrant Model. Source: NC State University (2019).

With the inversion height being sloped, a strong horizontal temperature gradient has been created. This increases the thermal wind, which can strengthen and maintain the jet. Due to the tightly packed potential temperature contours in the inversion, even a small slope to the inversion can lead to a large horizontal temperature gradient over a short distance.

By examining cross-sections before, during, and after the jet core, there should be evidence of the convergence and divergence sectors according to the four-quadrant model. The greatest slope of the inversion should be found upstream of the jet core; the least amount of slope to the inversion should be downstream of the jet core. This assumes that the dominant factor in the development of the LLCJ is the horizontal thermal gradient created by the sloping inversion. However, there could be circumstances that allow for an LLCJ to be elevated above the inversion, which will also be examined in this paper.

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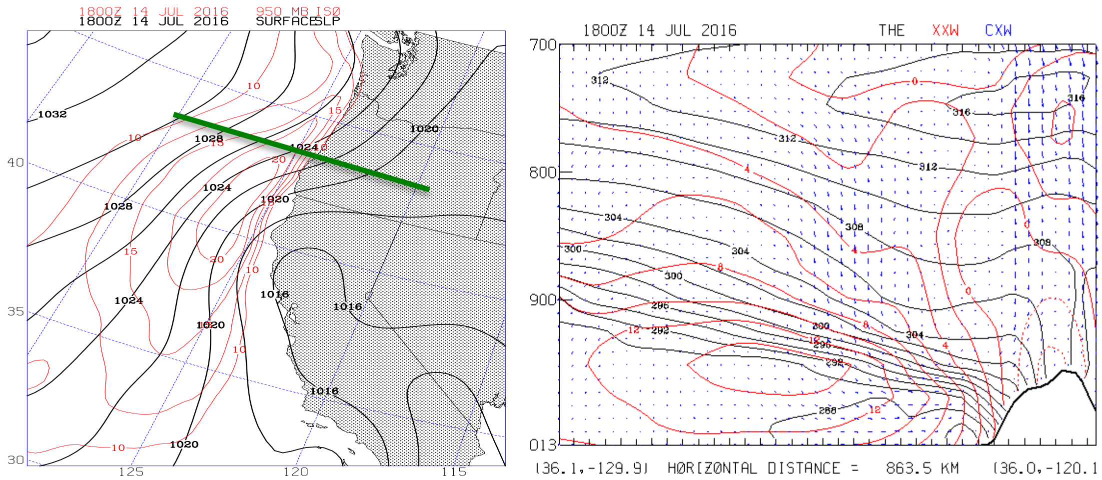
III. METHODS

In order to study the characteristics of LLJs on the California coast, the Climate Forecast System Reanalysis (CFSR) model was used. The National Center for Atmospheric Research (NCAR) describes the model as follows.

> The CFSR is a third generation reanalysis product. It is a global, high resolution, coupled atmosphere-ocean-land surface-sea ice system designed to provide the best estimate of the state of these coupled domains over this period. The CFSR includes (1) coupling of atmosphere and ocean during the generation of the 6 hour guess field, (2) an interactive sea-ice model, and (3) assimilation of satellite radiances. The CFSR global atmosphere resolution is ~38 km (T382) with 64 levels. The global ocean is 0.25° at the equator, extending to a global 0.5° beyond the tropics, with 40 levels.(Saha et al. 2010)

Data was taken from June through August of 2016, as displayed using the system Visual. Described by its creators, Dr. Wendell Nuss and Dr. Steve Drake (1980), in its user manual "visual is a meteorological diagnostic and display program that uses GKS primitives and NCAR graphics utility routines to examine meteorological grids and observations" (p. 3). CFSR data over the summer of 2016 was used to look at both the vertical and horizontal structure of the LLCJ on the U.S. west coast. The procedure to determine the presence of a LLJ was initially done by looking at isotachs on a 950mb surface, such as the one in Figure 5. This subjective analysis was used to narrow down the number of days that were analyzed in order to focus on the specific conditions that indicated a LLJ. The LLCJ days were defined as having a jet core of at least 15kts at 950mb, where the core remained relatively close to shore, and the jet persisted for at least two days. With a 15kt jet core, the ability for that energy to be transferred to the ocean surface is significant enough to produce an increase in wave height. Similarly, a persistent jet of two days produces a significant fetch area, which results in the development of dangerous wave heights. With these combined factors, only the strongest and most stable jets are left to be analyzed. Each day was observed at 18 UTC for consistency and to eliminate diurnal changes in intensity of the LLJ. Per these criteria, 22 days of a LLCJ occurred from June through August of 2016.



Figures 5–7 show top-down view (left) as an approximation of the location of the cross section (right) where the red contours are wind speed.

Figure 5. July 14 Jet Upstream of Core

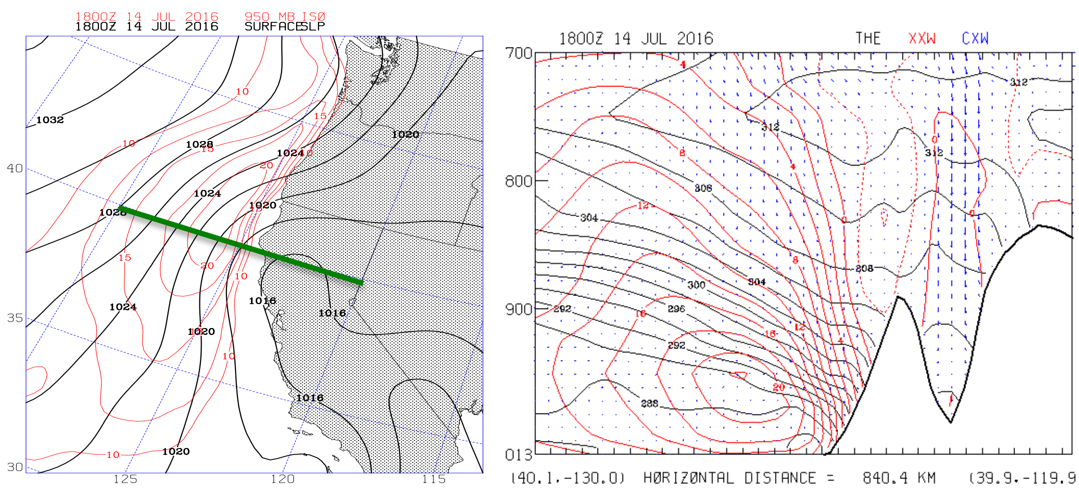


Figure 6. July 14 in Jet Core

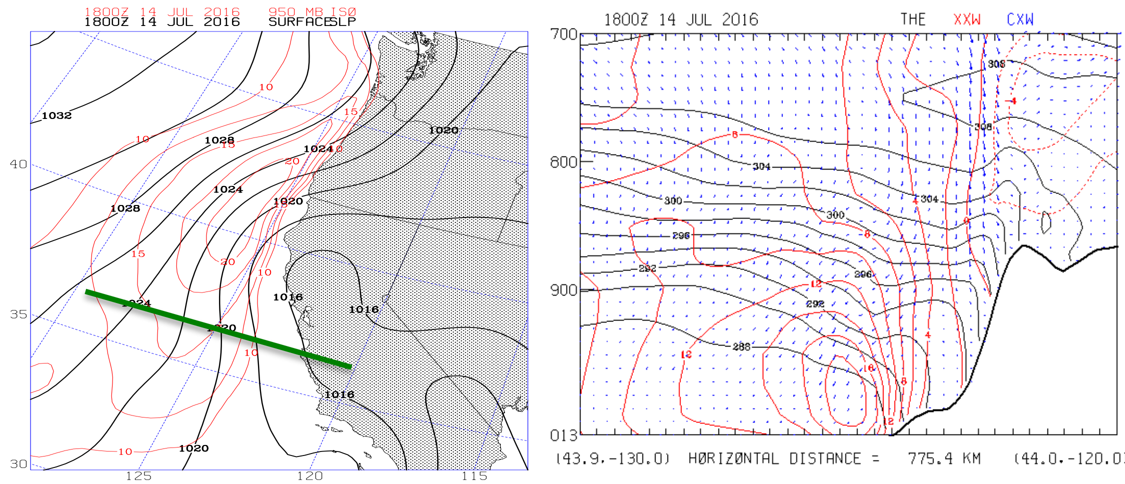
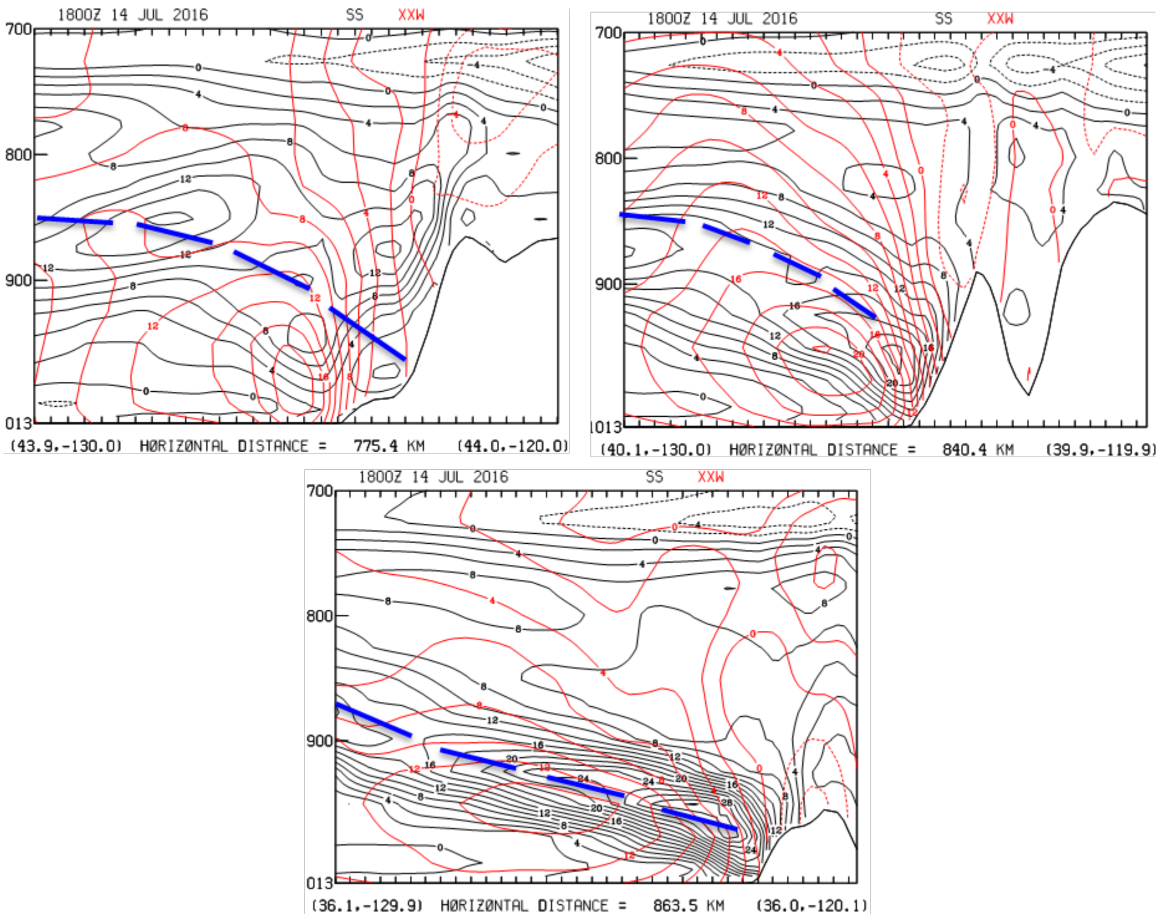


Figure 7. July 14 Jet Downstream of Core

Once the days were chosen, several vertical cross-sections were taken each day. Cross sections were taken across the length of the jet, both upstream and downstream of the jet max, as well as in the jet max itself (Figures 5–7). This was done in order to determine a conceptual 3-D picture and idea of the structure of the LLJ. By overlaying both isotachs and potential temperature, an idea of how the LLJ and the top of the inversion were related was gained. Based on the idea that the jet is in thermal wind balance the expectation is to find the core of the jet close to the largest horizontal temperature gradient. This is most likely just below the inversion, where the slope of the inversion and the land sea difference are greatest. Potential temperature contours provide the ability to see the general slope of the inversion, but specifically locating the inversion relative to the jet core was difficult. For example, in Figure 6 the general location of the inversion can be seen somewhere between 950mb and 850mb above the jet core. Visually, the approximate height of the inversion can be determined, but in cases with weaker vertical gradients, determining its height and slope was difficult. By its definition, by the AMS (American Meteorological Society) glossary, the characteristics of a temperature inversion imply strong thermodynamic stability, and so these maximum stabilities could be used to identify the inversion. The static stability was calculated for both above and below each jet core as well as in a cross-section through the LLCJ core. Figure 8 shows the static stability on the cross sections through the jet entrance, core and exit regions. The axis of strongest stability is in the inversion and its slope can clearly be seen in the cross sections. This depiction indicates where static stability max is in a 3-D relation to the LLJ. There was now a way to compare the position of the LLJ and the location of the greatest atmospheric stability and thus the approximate location of the inversion.



Upstream of the jet core (top left) and in the jet core (top right) show a sloping inversion (dashed line) while downstream of the jet core (red contours) has much less slope to the inversion.

Figure 8. Static Stability July 14

The importance was not only where did the jet core relate to the highest static stability, but also how it compared both up and downstream of the jet core. By comparing the different cross-sections, there should be evidence of the changing vertical circulation and thermal structure patterns associated with the four-quadrant model. Specifically, the slope of the inversion should be less downstream of the jet max due to the upward vertical motion expected on the landward side, or more likely, from the downward vertical motion seaward. Similarly, the LLCJ core should be the location of the greatest slope of the inversion in order to produce the strongest horizontal thermal gradient.

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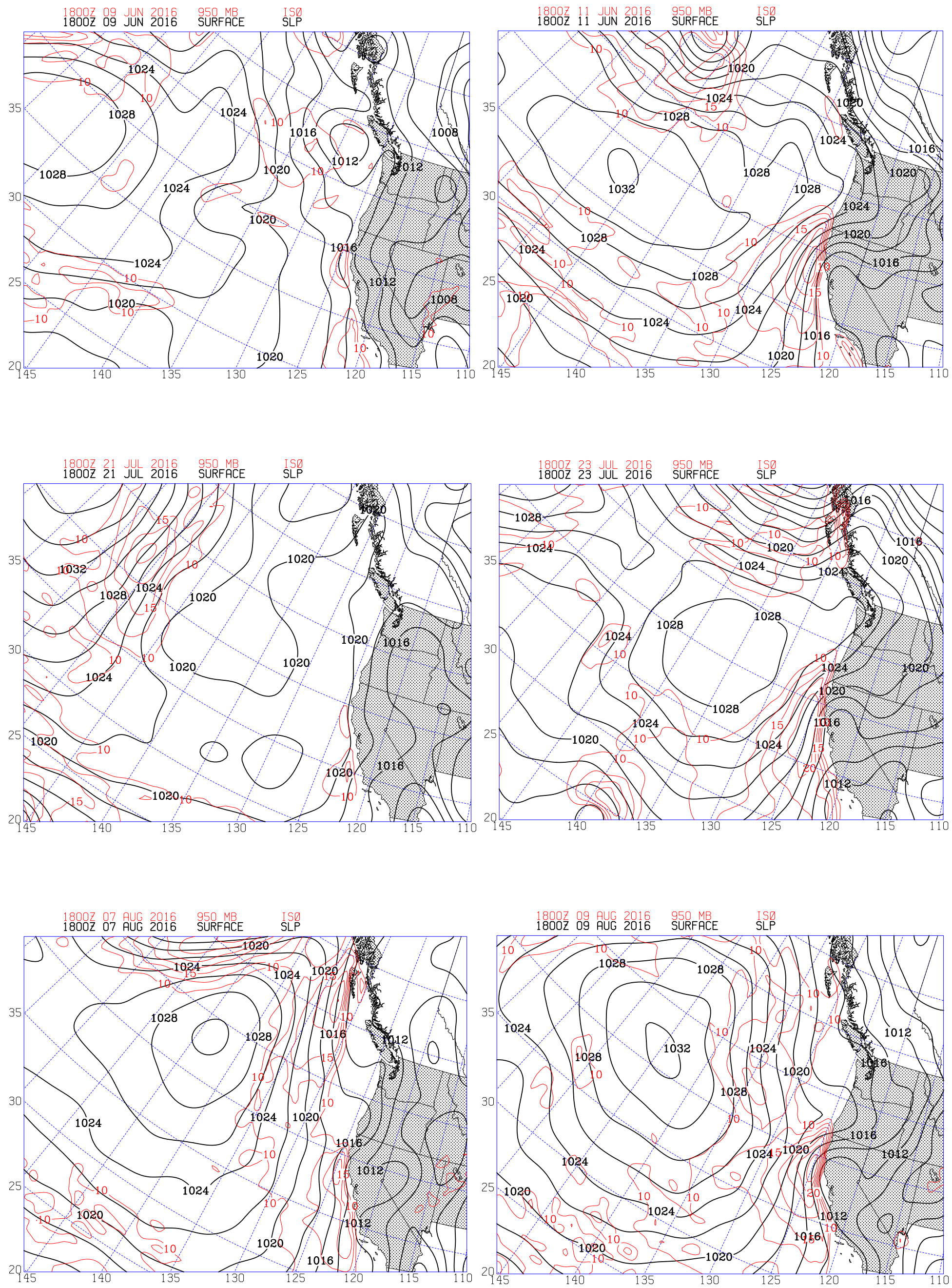
IV. RESULTS

Over the summer of 2016, a total of 92 days were reviewed; 22 were determined to meet the requirements of this study for having the presence of a LLCJ. A quick look at the large-scale synoptic overview clearly shows the differences in a jet and non-jet setup. Shown in Figure 9 is the sea-level pressure (SLP) and 950mb winds for jet versus non-jet case for each month. For June (Figure 9, top left), the high is centered well to the west of 150W for the non-jet day and moves close to 145W. However, more important is the intensification of the high on the jet day. The 1028mb line moves from 150W to 130W, which significantly increases the pressure-gradient force (PGF) near the coast. In July (Figure 9, top right) the high is located not only west of 150W but is quite strong for a non-jet day. Due to its location being so far west, though, there is little coastal PGF. During the July jet day, the high has weakened significantly but has made a large move to the east. Because of this extreme shift east, the 1028mb line is at 130W, which results in similar conditions for the jet day in June. August (Figure 9, bottom) has little movement of the high between the two days, with a location near 145W. The main difference is the intensification and size of the high. Not only does the central pressure rise by over 2mb, the size increases which increases the PGF felt at the coast. Although the center of the Pacific high is not always closer to the coast when there is a confirmed LLCJ, the high does extend towards the coast and increase the PGF for jet days. This agrees with what is expected given that when the high is closer to the coast, there is an increase in the PGF in the area of the jet maximum.

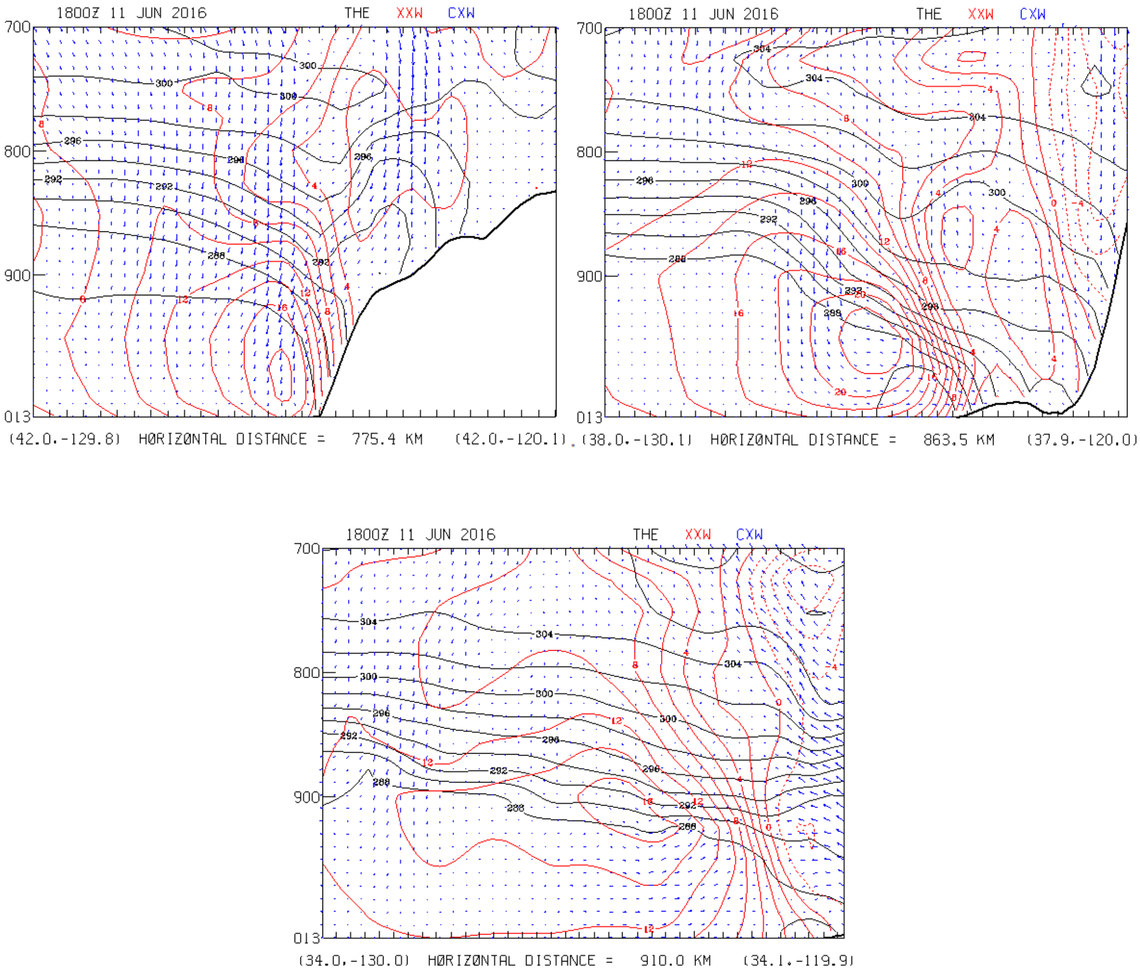
The vertical structure of the jet, Figures 10 to 12 show cross-sections for June 11, July 23 and August 23, as representative cases for each month. After examining Figure 9, for all three cases common east-west cross sections were chosen to represent the jet upstream region (42 degrees North), jet core (38 degrees North), and downstream region (34 degrees North). Figure 10 shows the jet for June 11 and the associated thermal structure. On this day, the inversion is relatively high, above 900mb, and only moderately strong. The cross-sections show less slope in the inversion for upstream (Figure 10, top left) and downstream (Figure 10, bottom) than near the jet core (Figure 10, top right). This structure fits the thermal wind paradigm rather well with the stronger wind speed and greatest slope (thermal gradient) near the jet core. The height of the inversion in July (Figure 11) is lower than the June case. It is also stronger than in June as evident by the more tightly compacted potential temperature lines. Just as in the other cases the slope of the inversion is less in the upstream (Figure 11, top left) and downstream (Figure 11, bottom) cross-sections. The July case also fits with the thermal wind paradigm, where the strongest wind speed is found in conjunction with the largest thermal gradient in the core (Figure 11, top right). The August cross-sections (Figure 12) show a very similar story to that of July. Less slope to the inversion is upstream (Figure 12, top left) and downstream (Figure 12, bottom) of the core (Figure 12, top right), which holds the highest wind speeds and the largest horizontal thermal gradients.

In each of these examples, a clear jet is present just below a sloping inversion. In most cases, the slope is approximately 75mb of drop from west to east over approximately 700km, typically from 850mb to 925mb in the jet core. This is expected and confirms what is currently understood with where the LLCJ core should be found. With the understanding of the four-quadrant model, the expectation should be that a relaxation in the slope of the inversion downstream of the jet core will be found. This could be from either the upward vertical motion on the east or the downward vertical motion to the west. From the days observed, it is more visually apparent that the downward vertical motion is more responsible for the decrease of the inversion's slope. In a few cases, a slight upward (west to east) slope can be seen, but they are not as common. Out of all of the cases, there was one, however, that did not fit into the expected results.



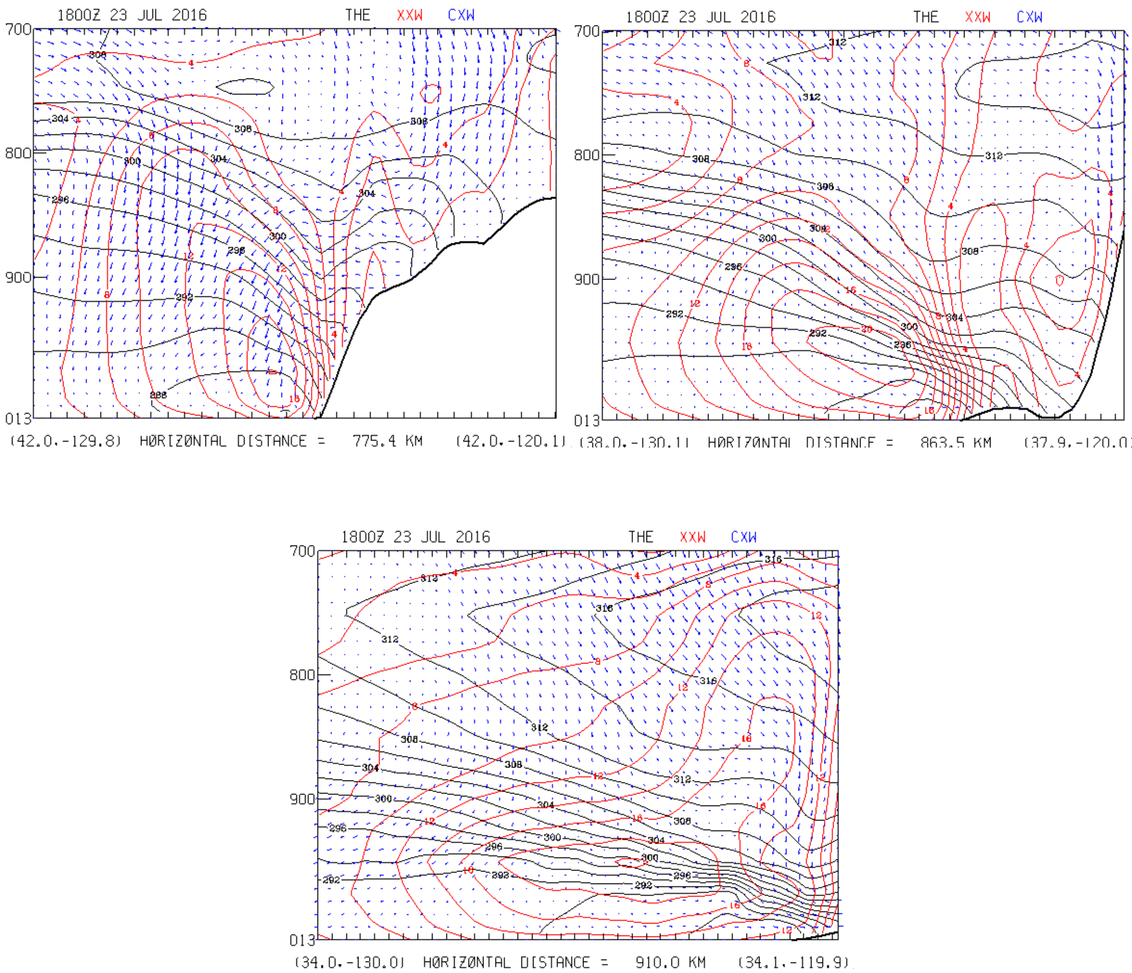
Three non-jet days are depicted (left panels) along with jets that occurred after development over the succeeding two days (right panels). Note the change in intensity and position of sea-level pressure (SLP) centers.

Figure 9. Location of Pacific High for LLCJ



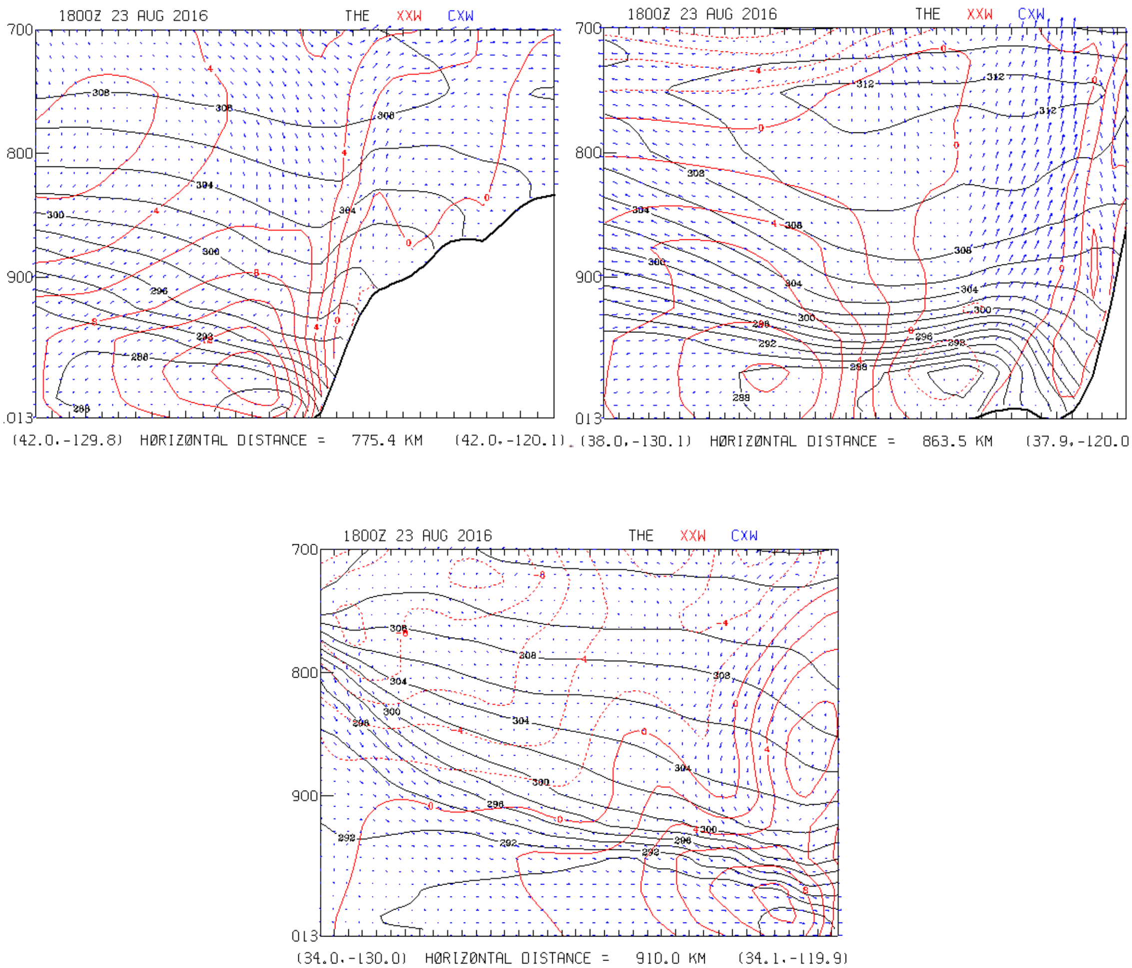
Upstream of the jet core (top left), in the jet core (top right), and downstream of the jet core (bottom).

Figure 10. June 11 Jet Case



Upstream of the jet core (top left), in the jet core (top right), and downstream of the jet core (bottom).

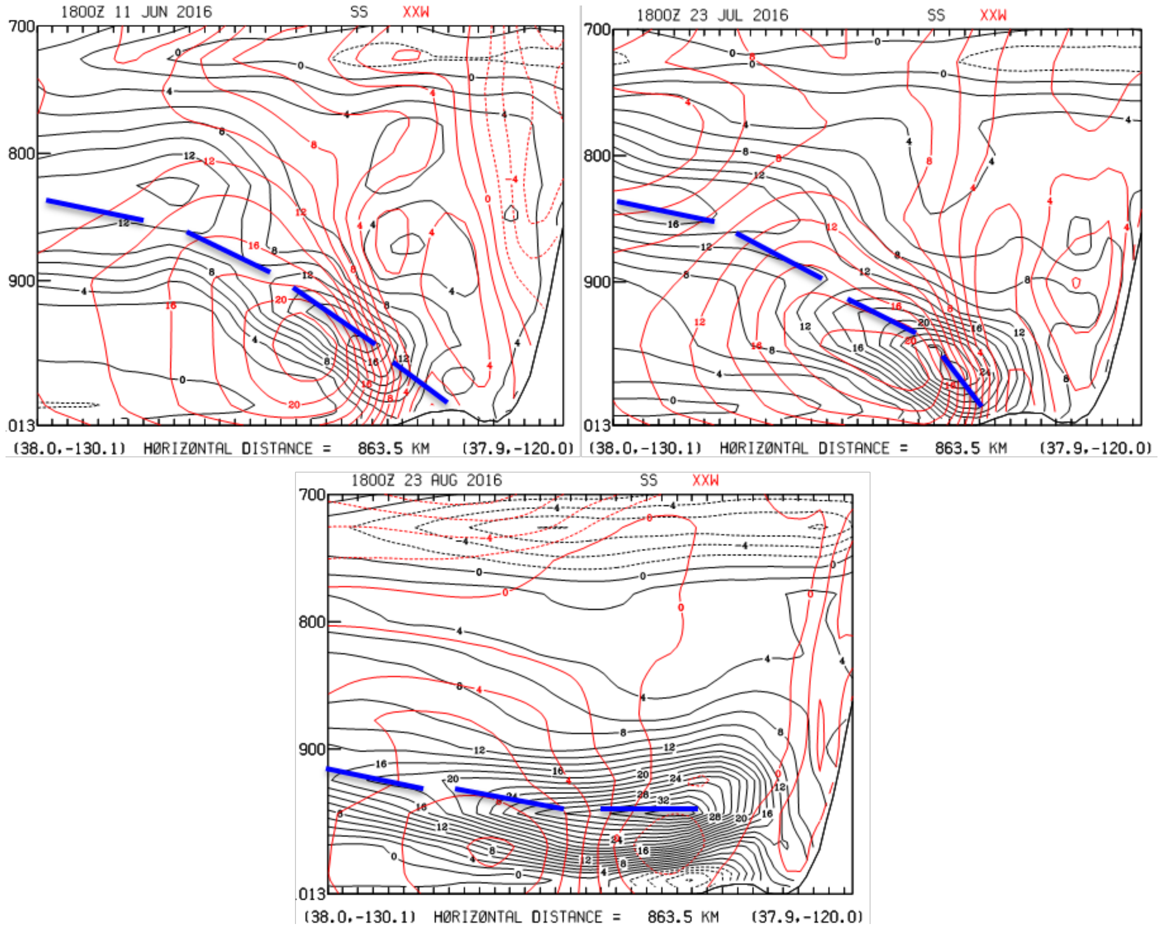
Figure 11. July 23 Jet Case



Upstream of the jet core (top left), in the jet core (top right), and downstream of the jet core (bottom).

Figure 12. August 23 Jet Case

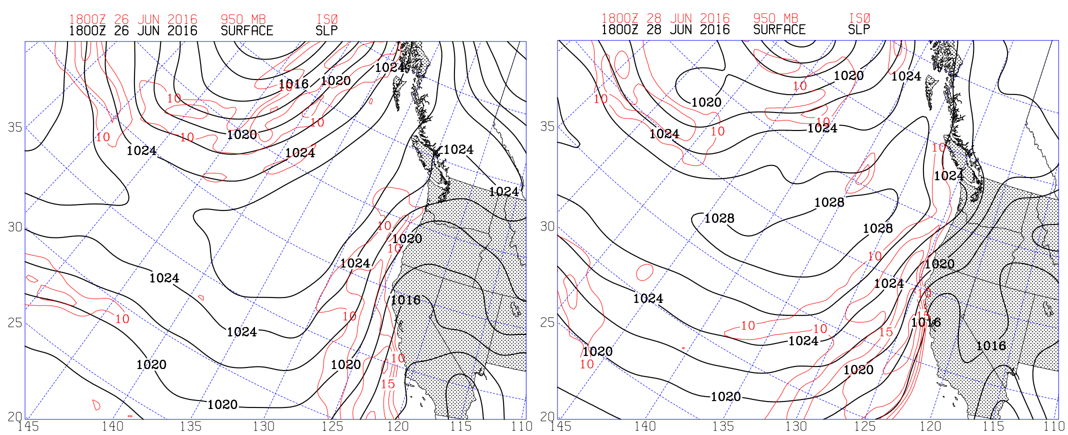
As discussed previously, it is difficult to directly relate the specific location of the inversion using only potential temperature. Figure 13 is a comparison of cross sections of each of the chosen days with their static stability. In each case, it is clearly visible that the jet core is typically at the same level or below the inversion as defined by the highest static stability. The axis of highest stability is marked on Figure 13 to highlight the sloping inversion. In each case, the jet core occurs just below or near the steepest slope of the inversion. This was fairly typical and fits with previous research about the jet structure. There is a different example examined later showing that some conditions do allow a jet to be located completely above the inversion.



June (top left) core of the jet is at the same level as the highest Static Stability. July (top right) and August (bottom) show a jet clearly below the inversion. The bold blue dashes indicate the axes of highest stability (solid black lines). Wind speed is shown in the solid red lines.

Figure 13. June–August Static Stability

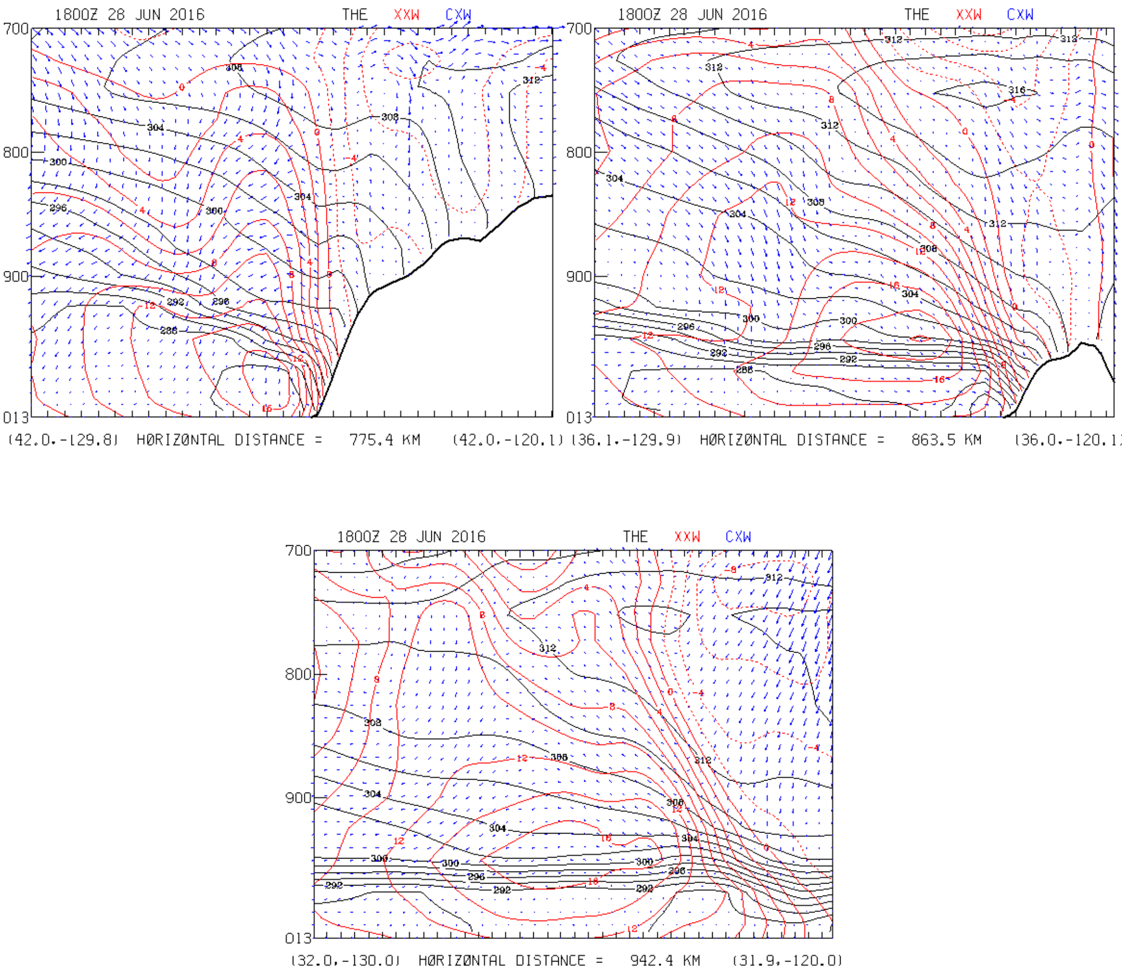
Out of the 22 days of a LLCJ, there were three days in June that had a clear LLCJ, but the location of the jet core occurred well above a non-sloping inversion. In all previous examples of the LLCJ, the jet core was at or below a clearly sloping inversion. During June 27–29, there is a fundamental departure from this structure, and June 28 has been chosen as a good representation of all three days. The synoptic setup for these days is not as largely different in terms of the location or intensity of the pacific high compared to the other cases that were studied. Each of the days in Figure 14 are comparable to those in the non-jet days looked at in Figure 9. June 26 (Figure 14, left) does show some SLP gradient near the coast with a weak or non-existent LLCJ. By June 28 (Figure 14, right), the synoptic pattern is similar to June 26 with a slight relocation of the SLP gradient south of its previous position. However, a more pronounced jet occurs on this day just slightly offshore. This setup would indicate that the synoptic pattern may help in the development of the LLCJ, but is not necessarily the only requirement. On June 28, the upstream, core and downstream cross-sections (Figure 15) provide a very different picture than the other cases that have been studied. Looking first at the cross-sections of potential temperature, the inversion has little to no slope. This results in no thermal gradient except in the cross-section upstream of the jet core (Figure 15, top left). In both the core (Figure 15, top right) and downstream (Figure 15, bottom) of the jet, the inversion is at a much lower level and has a decreased slope. Without this slope, the inversion provides little to the horizontal temperature gradient. However, this case still supports a three-day persistent LLCJ, despite the lack of a sloping inversion.



There is little to no real change in the sea-level pressure field when comparing the no LLCJ day (left) to that of the LLCJ (right) on June 28.

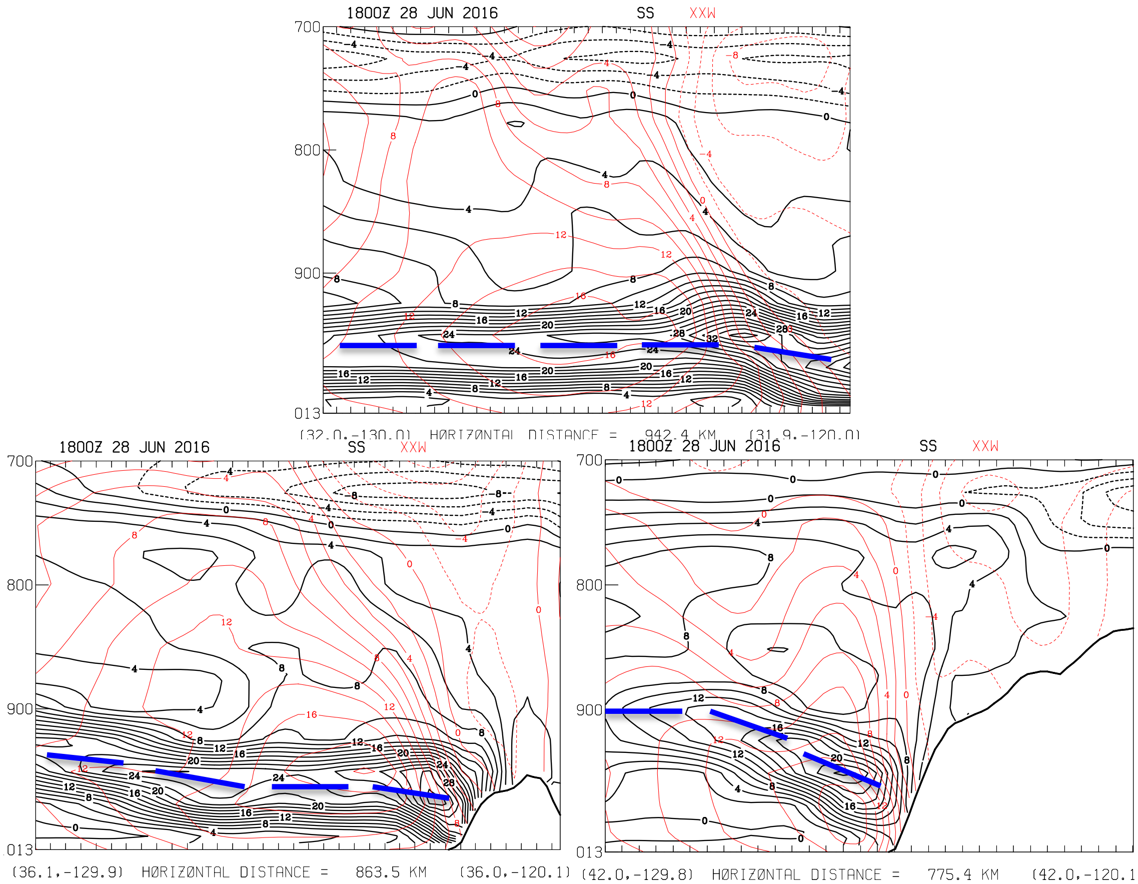
Figure 14. June Special Case Synoptic Look

Several factors about this case seem to contribute to its unique structure with the jet above the inversion. When looking at the height of the inversion in this case (Figure 16), it is much lower in the atmosphere than the other cases (Figure 13). In typical cases that produce a LLCJ, the top of the inversion is around 875–900mb, and the jet core is found at or just below the inversion. For June 28, the inversion height is 50mb lower and the jet core is clearly above the inversion. In order for this structure to occur, the thermal structure above the inversion becomes very important. Above the inversion, there is a stronger than normal thermal gradient that is not present in the other more typical LLCJ cases (compare to Figure 9). It is also recognized that this jet is one of the weakest out of all that were studied. The core itself is spread out over a larger area and seems to be much less compact than other examples of the LLCJ, consistent with the broad baroclinic structure above the inversion. The broad jet structure is most likely due to the lack of horizontal temperature gradient provided by a sloping inversion. The atmosphere above the inversion supports the development of a jet through thermal wind balance. While a sloping inversion provides the most efficient way to create a strong horizontal temperature gradient and concentrated jet core, it can be created above the inversion when the thermal gradient is strong enough to support a LLCJ.



Upstream of the core (upper left) has a more typical profile. In the core (upper right) is much lower and has little to no slope compared to the other examples. Downstream of the core (bottom) there is a slight upward slope to the inversion. This is evidence of the upward vertical motion predicted by the four-quadrant jet model.

Figure 15. June 28 Special Case Jet



Upstream of the jet core (top left) shows the jet just below a sloping inversion where in the core (top right) and downstream of the core (bottom) show a flat inversion and the jet residing above. Contours are the same as in Figure 8.

Figure 16. June 28 Static Stability

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V. SUMMARY

The reasons for the development of the LLCJ are fundamentally different from other, more studied, LLJ phenomena. Different papers have presented explanations ranging from topographic blocking resulting from zonal flow (Chao 1985), hydraulic effects (Munoz and Garreaud 2005), and the thermal gradient formed from a sloping inversion (Parish 2000). This study examined an entire summer season to determine the primary physical and dynamic reasons for the development of the LLCJ on the U.S. West Coast. The most likely of dominant factors were thought to be 1) a synoptic setup with the summer Pacific high being located further to the east and 2) a strong horizontal temperature gradient due to a sloping inversion. With this setup, the potential for a strong LLCJ is a high possibility. The resulting fetch area can quickly produce hazardous wind and wave conditions that are missed by the global weather models, used to force wave models. The threat to vessels of the civilian sector includes not only the small pleasure craft but commercial shipping and is a threat to public safety. On the military side, anything from special operations, including small-boat operations and intelligence gathering, to full-scale beach landings of an amphibious ready group, could be adversely affected from the waves generated by a fetch area produced by a LLCJ.

Looking at the U.S. west coast during the summer of 2016, there were 22 days that met the requirements of a strong LLCJ. A strong jet required at least a core wind speed of 15kts, needed to persist for two days, and needed to be reasonably close to the coast. In most of these cases, the conditions producing the LLCJ aligned with the conclusions of the Parish paper, which suggests that thermal wind balance is primarily responsible for the jet. The core of the LLCJ was found to be at or just below the elevated inversion. In these typical cases, there is also evidence of the circulation predicted by the four-quadrant model with the vertical circulation leading to changes in the slope of the inversion. By looking at several locations along the jet, the relaxation of the inversion slopes up, and downstream of the jet core suggests that thermal wind balance is a primary factor. This seemingly confirms the results and conclusions from Parish (2000). However, the June 27–29 case found evidence of a LLCJ with a flat inversion. The unique circumstances of a very low inversion height combined with a stronger-than-normal horizontal thermal gradient above the inversion results in a dynamic situation capable of developing and sustaining a LLCJ. This result suggests that a thermal gradient is a necessary condition for the development of the LLCJ no matter how it is developed. This paper recognizes that the best way to achieve a horizontal gradient is with a sloping inversion as suggested by Parish (2000), but it is not a necessary requirement. It is the conclusion of this paper that, while a sloping inversion provides the best opportunity for the development of a LLCJ, the only actual requirement is the presence of a strong and persistent horizontal temperature gradient. The relative contribution of inversion slope and deeper thermal gradient was not examined for each case but their importance likely varies.

In order to obtain a complete understanding of the structure and circulations of the LLCJ more studies need to be completed. The addition of more cases, like the one from June 27–29, where the LLCJ is found to be above the sloping inversion, would provide a greater insight into the true physical processes that lead to the LLCJ. Factors such as possible topographic effects of flow blocking and the role a larger synoptic setup has on the LLCJ were outside the scope of this study but should be more thoroughly examined. Furthermore, the vertical circulation and its impact on inversion slopes needs to be more completely examined in a future study. The four-quadrant model implies the thermal gradient changes at the entrance and exit of a jet are due to the vertical circulation. How that occurs in the LLCJ is not clear and should be examined to develop a complete conceptual model.

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