Synoptic Meteorology I: Jets and Jet Streaks

4, 9 December 2014

Introduction

As previously discussed, a jet (or jet stream) is an intense, narrow, quasi-horizontal current of wind that is associated with strong vertical wind shear. The qualifiers "intense" and "narrow" are somewhat subjective, however. A jet streak is a localized maximum of wind speed embedded within a jet stream.

A jet stream can refer to one of two features:

- A climatological maximum in the zonal wind. The temporal duration of the climatology can vary from on the order of one week to on the order of one year.
- A localized corridor of high wind speed at one given analysis time. This manifestation of a jet stream is that which is typically analyzed on synoptic-scale weather maps and that which we will consider within this class.

In the context of this course, we will primarily focus upon upper tropospheric manifestations of jet streams. We will only cursorily discuss the low-level jet, a lower tropospheric manifestation of a jet stream. Likewise, we will focus primarily upon jet streams located within the middle and higher latitudes. There exist jet streams within the tropics, such as the African easterly jet and tropical easterly jet, but the study of these features is beyond the scope of this course.

The Polar Jet

The polar jet (sometimes referred to as the polar-front jet) is located along the tropopause. In isobaric coordinates, this typically corresponds to between 200-300 hPa. It is associated with strong quasi-horizontal temperature gradients in the lower troposphere and strong vertical wind shear. These features are often associated with the polar front, the name given to cold fronts that trail cyclones in polar front theory.

The link between the polar jet and the aforementioned quasi-horizontal temperature gradients is manifest through the thermal wind relationship. Winds along the polar jet typically have a westerly component to them; concordantly, given westerly vertical wind shear and thus a westerly thermal wind, relatively cold lower tropospheric air is found poleward of the polar jet and relatively warm lower tropospheric air is found equatorward of the polar jet. Meridional undulations of the jet stream are associated with poleward and equatorward displacements of warm and cold air, respectively.

Presuming that the polar jet is a westerly jet, the height of the tropopause is lower poleward and higher equatorward of the polar jet. This can be viewed in the context of thickness arguments, with greater (lesser) tropospheric depth where it is relatively warm (cold). Climatologically, the height of the tropopause gently slopes upward from the pole to the equator through the polar jet.

A vertical cross-section through the polar jet and associated polar front is depicted in Figure 1. The polar front slopes northward with height, from south of Norman, OK (OUN) toward North Platte, NE (LBF), as indicated by the sloping corridor of tightly-packed isentropes. Winds are out of the north beneath the polar front and primarily out of the west-southwest ahead of and atop the polar front. The polar jet is centered at around 300 hPa at Dodge City, KS (DDC) and OUN and has maximum wind speeds of 140-150 kt at the height of the tropopause. The tropopause itself is higher to the south, in the warm air, and lower to the north, in the cold air. The tropopause is locally depressed downward, or folded, at its intersection with the polar front. Note the relationship between the polar jet and the lower tropospheric polar cold frontal zone: the polar jet is found atop the cold frontal zone, as we would expect from thermal wind balance.

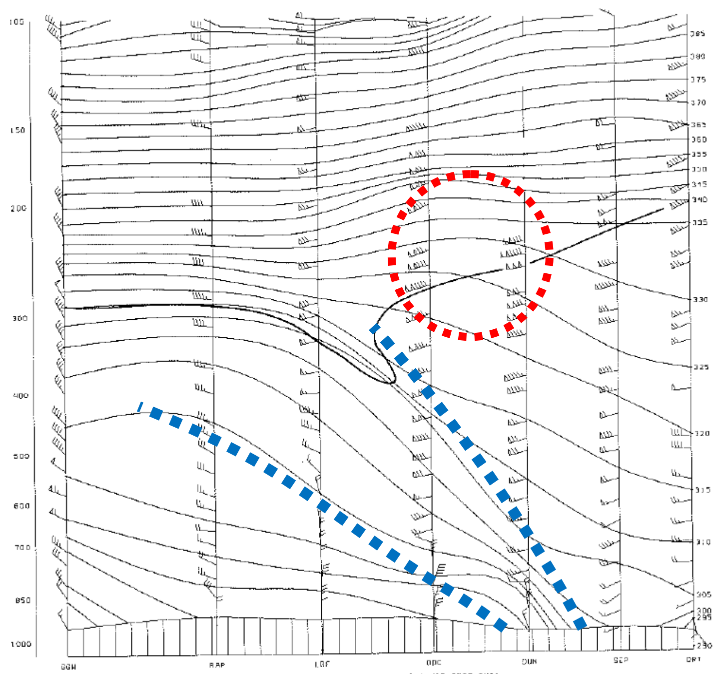

Figure 1. Vertical cross-section of potential temperature (contoured every 5 K) and wind (half-barb: 5 kt, full barb: 10 kt, pennant: 50 kt) through a strong polar front (blue annotation) and polar jet (red annotation) system. The thicker black line denotes the approximate location of the tropopause. The northern extent of the cross-section, at left, is at Glasgow, MT. The southern extent of the cross-section, at right, is at Del Rio, TX. Reproduced from *Synoptic-Dynamic Meteorology in Midlatitudes (Vol. II)* by H. Bluestein, their Figure 2.86.

The Subtropical Jet

Like the polar jet, the subtropical jet is located along the tropopause. In isobaric coordinates, this typically corresponds to around 200 hPa. The subtropical jet is primarily a wintertime phenomenon found between 20-35°N/°S latitude. In the time-mean view of the subtropical jet, it can have the appearance of being a continuous jet around the globe within the subtropics. Consequently, the subtropical jet can be viewed as a quasi-steady or quasi-persistent feature of the cold season climatology. On a day-to-day basis, however, the subtropical jet may merge with or become indistinct from the polar jet, particularly when the latter protrudes equatorward.

A vertical cross-section through the subtropical jet is depicted in Figure 2. Unlike the polar jet, there is no well-defined frontal boundary that slopes toward the cold air with height in association with the subtropical jet. The meridional temperature gradient associated with the vertical wind shear underneath the subtropical jet (again through the thermal wind relationship) is largely confined to a shallow vertical layer within the middle to upper troposphere. The subtropical jet itself is centered at around 200 hPa at Waycross, GA (AYS) and has maximum wind speeds of 120-125 kt at the height of the tropopause. The tropopause itself, though not depicted on this figure, is higher to the south and lower to the north.

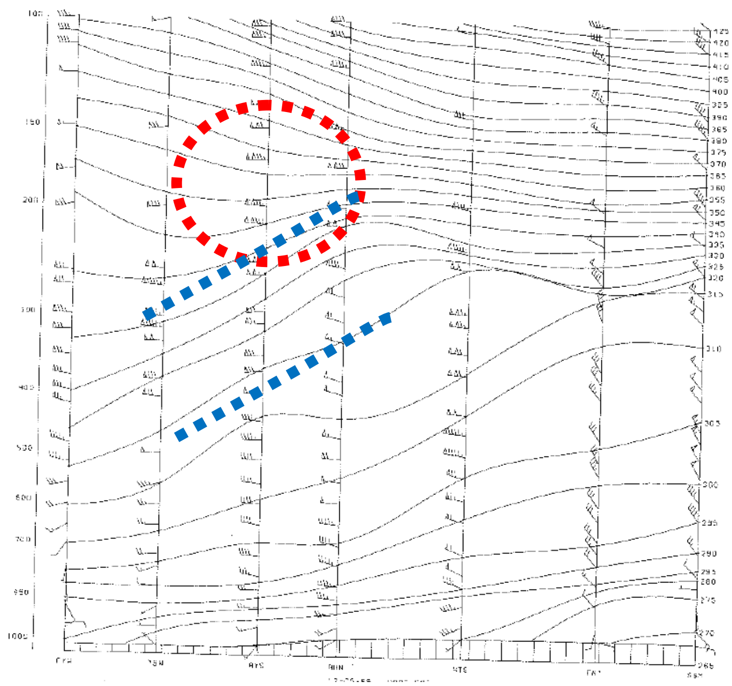

Figure 2. As in Figure 1, except for a south-to-north (left-to-right) vertical cross-section through the subtropical jet. Here, the blue annotation reflects the region of largest horizontal temperature gradients rather than a true frontal zone. Reproduced from *Synoptic-Dynamic Meteorology in Midlatitudes (Vol. II)* by H. Bluestein, their Figure 2.92.

Because the subtropical jet is found at relatively low latitudes, a relatively weak horizontal temperature gradient can nevertheless be accompanied by relatively large vertical wind shear. In the context of the thermal wind approximation, this is due to the inverse relationship between the magnitude of the thermal wind (and thus vertical wind shear) and the Coriolis parameter f, which is smaller at lower latitudes.

The presence of the subtropical jet can be viewed from two somewhat complementary perspectives. The first relates to the Hadley and Ferrell general circulation cells. The Hadley cell, the meridional vertical circulation that characterizes the tropical latitudes, is associated with poleward flow in the upper troposphere and equatorward flow in the lower troposphere. The Ferrell cell, the meridional vertical circulation that characterizes the mid-latitudes, is associated with equatorward flow in the upper troposphere and poleward flow in the lower troposphere. This promotes convergence aloft and divergence at the surface, acting to intensify the meridional temperature gradient aloft and weaken it at the surface. The latter explains why there is often little or no frontal structure at the surface beneath the subtropical jet. From thermal wind balance, the stronger meridional temperature gradient aloft, with warmer air toward the equator and colder air toward the poles, gives rise to the westerly subtropical jet.

The second relates to the conservation of absolute angular momentum in the context of the Hadley cell. Absolute angular momentum is a function of both the rotation of the Earth and the velocity of the air parcel; following the motion, in the absence of friction, an air parcel generally strives to conserve absolute angular momentum. Consider an air parcel that is initially at rest at the Equator within the upper troposphere. If this parcel is displaced poleward from the Equator, such as within the poleward flow aloft found with the Hadley cell, it will accelerate (to ~100-200 kt) in order to conserve absolute angular momentum. It will also deflect toward a westerly flow due to the effects of the Coriolis force, with rightward deflection in the northern hemisphere and leftward deflection in the southern hemisphere, thus giving rise to the subtropical jet.

The Low-Level Jet

There are two types of low-level jets (or LLJs) that are of particular interest:

- Nocturnally-driven LLJs.
- LLJs induced by upper tropospheric and/or synoptic-scale forcing.

Nocturnally-driven LLJs are at their maximum intensity at night; there may be little to no evidence of a nocturnal LLJ during the daytime hours. They owe their existence to sloping topography, such as is found across the Great Plains of the United States (with higher terrain to the west gradually sloping downward toward the east), and to inertial oscillations. Nocturnal LLJs are typically found at or just above the surface. In the Great Plains, they are typically associated with southerly winds of >15 m s^{-1} and may influence thunderstorm development, maintenance, and upscale growth.

LLJs induced by upper tropospheric and/or synoptic-scale forcing are often found in association with upper tropospheric jets and synoptic-scale cyclones. The conveyor belts of a mature mid-latitude synoptic-scale cyclone that we will examine in the next lecture can be viewed, to first approximation, as manifestations of LLJs. The presence of such LLJs is not dependent upon the time of the day; rather, they can appear at all times of the day. Likewise, these LLJs can be every bit as strong as their nocturnal counterparts. As compared to nocturnal LLJs, however, LLJs induced by other forcing are typically found at slightly higher altitudes (~850 hPa).

It should be noted that the two types of LLJs are not mutually exclusive of one another; in the presence of synoptic-scale forcing, a given southerly LLJ over the Great Plains may have structural characteristics of both types of LLJs.

The Four Quadrant Jet Model

We first consider an idealized view of an upper tropospheric jet streak, one that is associated with primarily "straight" (or non-curved) flow through the jet itself. This is depicted in Figure 3. Before we proceed, two minor terminology notes. The jet entrance region is the region where the wind accelerates. Conversely, the jet exit region is the region where the wind decelerates. Likewise, the "right" and "left" sides of the jet are defined as to the right and left of the jet with your back to the wind. Thus, for a westerly jet streak, the right side of the jet streak is to the south and the left side of the jet streak is to the north.

When we introduced the concept of the ageostrophic wind earlier this semester, we stated that it could be expressed in terms of parcel accelerations following the flow, such that:

$$\frac{Du}{Dt} = fv_{ag} \tag{1a}$$

$$\frac{Dv}{Dt} = -fu_{ag} \tag{1b}$$

For the case of the westerly jet streak depicted in Figure 3, it is Equation (1a) that we are most interested in. However, the following analysis can be generalized to a straight jet streak of any particular orientation.

As a parcel enters into the jet, it moves from west to east at a progressively faster rate of speed, meaning that it accelerates. Thus, following the flow, the left-hand side of (1a) is positive as u becomes more westerly. Let us presume that we are in the Northern Hemisphere, such that $f > 0$. As a result, v_{ag} must be positive, indicating a south-to-north flow across the jet within its entrance region. From continuity, this implies upper tropospheric divergence and middle tropospheric ascent in the right entrance region and upper tropospheric convergence and middle tropospheric descent in the left entrance region.

Conversely, as a parcel exits the jet, it moves from west to east at a progressively slower rate of speed, meaning that it decelerates. Thus, following the flow, the left-hand side of (1a) is negative as u becomes less westerly. Again presuming that $f > 0$, v_{ag} must be negative, indicating a north-to-south flow across the jet within its exit region. From continuity, this implies upper tropospheric convergence and middle tropospheric descent in the right exit region and upper tropospheric divergence and middle tropospheric ascent in the left exit region.

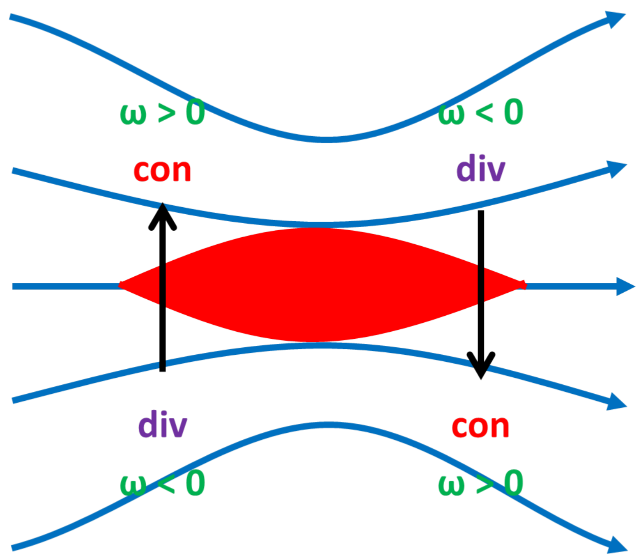

Figure 3. Idealized view of a westerly "straight" upper tropospheric jet streak (in red). Hypothetical streamlines are depicted in blue, the ageostrophic flow is depicted in black, the resultant convergence and divergence are depicted in red and purple respectively, and the resulting sign of omega is depicted in green.

In the lower troposphere, the patterns of ascent and descent within the jet entrance and exit regions promote the opposite sense of ageostrophic flow – negative (north-to-south) within the jet entrance region and positive (south-to-north) within the jet exit region. Thus, vertical circulations exist within the jet entrance and exit regions. As rising motion is found equatorward of the jet streak, where it is relatively warm, in its entrance region, the jet entrance region circulation is known as a thermally-direct circulation. Conversely, as rising motion is found poleward of the jet streak, where it is relatively cold, in its exit region, the jet exit region circulation is known as a thermally-indirect circulation.

Surface cyclones tend to develop – or develop most rapidly – when they are located within the right entrance or left exit region of an upper tropospheric jet. We will explore why this is the case in more detail next semester.

The Inclusion of Jet/Flow Curvature

To this point, we have considered the distribution of ageostrophic flow for a "straight" jet streak. However, jet streaks and the synoptic-scale flow accompanying them often exhibit at least weak curvature. An example of a weakly curved jet streak is depicted within Figure 4.

In a qualitative sense, the interpretation is identical to that of the straight jet streak example described above. In a quantitative sense, however, the interpretation changes slightly. In the example posed below, there is strong synoptic-scale difluence in the left exit region and strong synoptic-scale confluence in the left entrance region of the jet streak. In the right entrance and exit regions, there is comparatively little synoptic-scale confluence or diffluence.

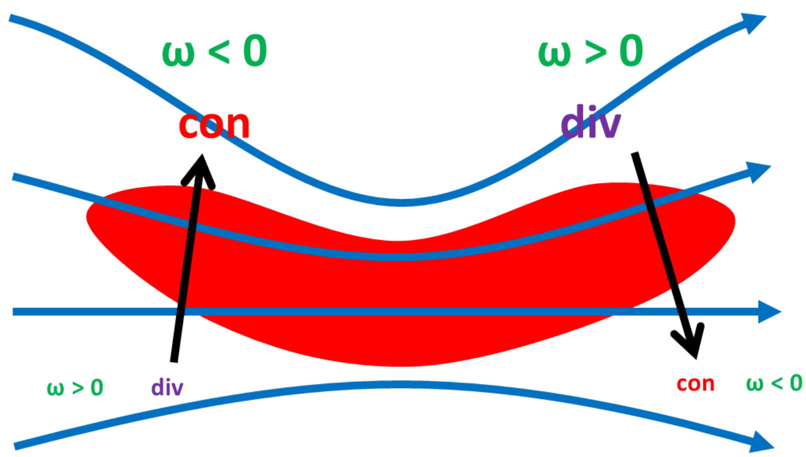

Figure 4. As in Figure 3, except for a slightly curved (along the streamlines) upper tropospheric jet streak. The relative size of the text on the right and left sides of the jet is indicative of the relative magnitudes of divergence and omega on each side of the jet.

Thus, in this example, the superposition of the synoptic-scale forcing (from continuity) and that associated with the across-jet vertical circulations enhances descent and ascent in the left entrance and exit regions of the jet streak, respectively. There is minimal impact upon ascent and descent in the right entrance and exit regions of the jet streak, respectively.

The Four Quadrant Jet Model Applied to Low-Level Jets

Let us consider the four quadrant jet model applied to low-level jets from the standpoint of the parcel acceleration-based interpretation. For ease of interpretation, let us consider a southerly low-level jet, as depicted within Figure 5. Note, however, that the basic interpretation can be applied to a low-level jet of any horizontal orientation. From Equation (1b), the sign of the ageostrophic wind is the same in the entrance and exit regions of the low-level jet as it is in the entrance and exit regions of the upper tropospheric jet: from east to west and from west to east, respectively. This implies lower tropospheric divergence in the right entrance and left exit regions of the jet and convergence in the left entrance and right exit regions of the jet.

In the upper troposphere, the tropopause is the quasi-rigid bound on vertical motions. This bound is located at and above the level of the jet. In the lower troposphere, the situation is flipped: the ground is the quasi-rigid bound on vertical motions. Lower tropospheric divergence, then, is associated with sinking motion from continuity, whereas lower tropospheric convergence is associated with rising motion. Thus, the pattern of ascent and descent is flipped from that seen with upper tropospheric jets: ascent is favored in the left entrance and right exit regions of low-level jets and descent is favored in the right entrance and left exit regions of low-level jets.

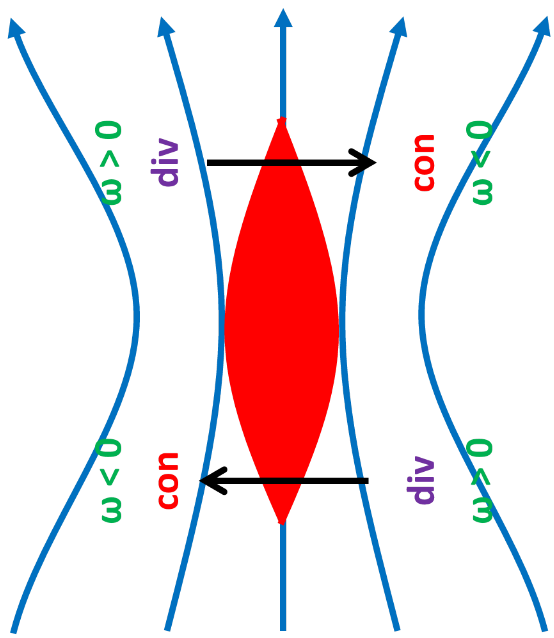

Figure 5. As in Figure 3, except for a low-level jet. Note that the only change between Figures 3 and 5, apart from the direction of the jet, is the sign of omega in each quadrant.

For Further Reading

Sections 2.7 and 2.8.2 of *Synoptic-Dynamic Meteorology in Midlatitudes, Vol. II* by H. Bluestein go into extensive detail regarding the structure of jets. Jets and their relationship with horizontal temperature gradients are discussed in Chapter 11 of *Weather Analysis* by D. Djurić.