UNITED STATES MARINE CORPS

LESSON PLAN

VERTICAL MOTIONS

INTRODUCTION:

1. Gain Attention. Have you ever wondered why bad weather is always associated with low pressure and good weather is always associated with high pressure? In general, the type of vertical motions that are occurring in the atmosphere determines weather.

2. Overview. During this period of instruction, the student(s) shall be introduced to the assumptions and limitations of the Quasi-Geostrophic Theory, how to determine vertical motion by utilizing the Omega Equation, the Trenberth version of the Omega Equation, and Q-Vectors.

3. Introduce Learning Objectives.

a. Terminal Learning Objective. With the aid of, but in accordance with the instruction, discuss the Quasi-Geostrophic theory, list the assumptions and limitations associated with the Quasi-Geostrophic theory, discuss the Omega equation and how it applies to vertical motion, discuss the Trenberth form of the Omega equation and how it can be used as an alternate to the classic Omega equation, and discuss Q-Vectors and how they can be used to aid in the determination of vertical motion.

b. Enabling Learning Objective(s). Without the aid of, but in accordance with the instruction, complete the following:

(1) Given a 500 millibar (mb) vorticity chart; analyze for Positive, Negative, and Neutral Vorticity Advection and determine vertical motion for those areas according to the Omega equation.

(2) Given a 1000-500 millibar (mb) thickness chart; analyze for cold, warm, and neutral temperature advection and determine vertical motion for those areas according to the Omega equation.

(3) Given an analyzed 500 mb vorticity chart and thickness chart; determine the vertical motion for an area comparing the vorticity and thermal advection for a given location.

(4) Given a 1000-500 mb thickness chart and 500mb vorticity chart; determine the vertical motion of an area utilizing the thermal wind (V_t) and the relative vorticity isopleths according to the Trenberth form of the Omega equation.

(5) Given various constant pressure charts; determine the vertical motion utilizing Q-Vectors.

(6) Given an area where the vertical motion cannot be determined from utilizing the classic Omega equation; determine the vertical motion by comparing the Q-Vectors with vorticity and thermal advection for a given location.

4. Method/Media. This period of instruction will be taught using the lecture method with the aid of a Macromedia Flash presentation "QMMPH1-Introduction to the Dynamics of the Earth's Atmosphere".

5. Evaluation. The student(s) shall be evaluated by successfully demonstrating the terminal learning objective(s).

TRANSITION. Determining vertical motions in the atmosphere is of critical importance. Correctly analyzing and forecasting vertical motions on a mesoscale or synoptic scale allows the forecaster to determine if systems will intensify or weaken. The next topic introduces a theory that several different methods of determining vertical motions have been derived from.

BODY:

1. Quasi-Geostrophic (Q-G) Theory. Q-G Theory states that the atmosphere strives to maintain a hydrostatic and geostrophic balance. Hydrostatic balance is the struggle between the pressure gradient acting upwards, due to decreasing pressure with height, and the force of earth's gravity acting in the opposite direction, it is reached when the pressure gradient is equal and opposite to Earth's gravitational force. Geostrophic balance is the struggle between the pressure gradient and the Coriolis force. Geostrophic balance can be reached when the Coriolis force is equal and opposite of the pressure gradient force. When these balances are destroyed by various forcing mechanisms (temperature advection or movement of circulations), horizontal and vertical ageostrophic motions occur in an effort to restore the balance. When utilizing the Q-G Theory, there are several assumptions and limitations that apply.

a. Assumptions.

(1) The atmosphere is in hydrostatic balance, or thermodynamically stable. Hydrostatic balance is destroyed near thunderstorms where the atmosphere is unstable.

(2) The wind is quasi-geostrophic, meaning the air flows parallel to the height contours. Advantages to this assumption are that height contour patterns may replace the actual wind flow and that no actual wind observations are necessary.

(3) No small-scale weather features are required.

(4) Only single analysis of vorticity, isobaric heights, and temperatures are required.

(5) Divergence and/or convergence is small (regions of inactive weather and small vertical motions).

(6) Vorticity is represented by geostrophic vorticity, which can be derived from the height pattern on isobaric surfaces. Vorticity advection can be inferred from the intersection of vorticity isopleths and height contours (similar to analyzing for temperature advection on the thickness chart).

b. Limitations.

(1) Provides only a first interference of where and why vertical motion may be occurring in the atmosphere.

(2) Should not be applied in the tropics where the synoptic scale flow is more ageostrophic in nature.

(3) Should be used with great caution in active weather regions where divergence is large and non-hydrostatic conditions may exist.

(4) Vertical motion produced by topography (i.e. friction), latent heating (i.e. convection), evaporative cooling, radiational heating/cooling, and small-scale processes will not be represented by the Q-G theory and the Omega equation.

(5) Strictly a diagnostic equation. The disadvantage to this is that it cannot be used to predict future vertical motions patterns. On the other hand, the advantage is that the Omega equations methods and Q-vector method may be used to diagnose vertical motion in model forecast patterns (i.e. the model generates the forecast pattern and the omega equation and Q-vector methods are then applied).

(6) Some error is introduced in the Omega equation when smoothed contour patterns are used.

TRANSITION. There is an equation in atmospheric physics known as "the Omega equation". It allows synoptic-scale vertical motion to be accurately estimated by analyzing temperature and wind fields above the boundary layer, leading to a value for vertical velocity (allocated the greek letter omega (Ω)), in pressure coordinates (dp/dt).

2. The Omega Equation. The Omega Equation can estimate regions of synoptic scale vertical motion. It is represented by the equation below that shows the relationships between vertical motion, vorticity advection, and temperature advection. In the simplest form the equation states vertical motion is equal to the vorticity advection plus the lowest tropospheric thermal advection.

$$VM = \frac{[\Delta(\acute{\eta}_g \text{Advection})]}{\Delta z} + [\text{T Adv}]_{(\text{lower tropospheric})}$$

a. Vorticity Advection ($[\Delta(\acute{\eta}_g\text{Advection})]/\Delta z$). Vorticity advection (VA) equals the change in absolute vorticity advection with change in height. PVA increasing with height is positive; NVA increasing with height is negative. Vorticity advection is typically measured using the 500 millibar (mb) vorticity chart. The following discusses the possible resultants from the equation for vertical motions.

$$VA = \frac{[\Delta(\acute{\eta}_g Advection)]}{\Delta z}$$

$$VA = \frac{[(\acute{\eta}_g Advection_{500mb})-(\acute{\eta}_g Advection_{SFC})]}{z_{500mb}-z_{SFC}}$$

(1) The change in height (Δz) will always be a positive number because the height of 500 mb will always be greater than that of the surface (0 feet). The change in height corresponds to the change in vorticity with height. Wind speeds are generally higher in the upper levels of the troposphere, as compared to the low levels of the troposphere. A forecaster can usually take for granted that vorticity increasing with height due to the increasing wind speeds; thus, the change in height, or Δz, is usually positive.

(2) "$\Delta(\acute{\eta}_g Advection)$" is the absolute vorticity at the 500mb level minus the absolute vorticity at the surface. Vorticity changes from the low levels of the troposphere to the upper levels of the troposphere.

(a) Positive Vorticity Advection (PVA). Positive vorticity advection will occur when the vorticity advection in the upper levels (500mb) is greater than the vorticity advection in the lower levels, which produces a positive number for this portion of the equation. In other words, vorticity advection is usually higher at 500 millibars than in the low levels of the troposphere because the wind speeds tend to increase with height (500 millibar winds near a trough will often be stronger than low-level winds). Because of this, the resultant will be positive (+).

$$VA = \frac{[(A) - (B)]}{(C - 0)} = \frac{+}{+} = +$$

1. PVA leads to rising air on the synoptic scale. Thus, a forecaster locates these regions of enhanced uplift in order to determine areas that are most likely to receive precipitation. Precipitation as a result of PVA alone is often termed dynamic precipitation. This precipitation tends to be high based also since the lifting is most intense in the upper troposphere (assuming PVA is primary lifting mechanism). Severe weather is enhanced where strong PVA that overrides low level moisture, instability and low level WAA.

2. Positive vorticity advection contributes to upward vertical motion. The spin up of vorticity causes the troposphere to cool since air typically cools as it ascends in the atmosphere. This cooling causes height to decrease aloft. Cooling the middle and upper levels of the troposphere causes the troposphere to become unstable because colder air will then overlay warmer air (a situation indicative of instability). PVA is associated with upward vertical motion and upper level divergence above the level of non-divergence (lnd).

(b) Negative Vorticity Advection (NVA). Negative vorticity advection will result when the upper-level (500mb) advection is less than the lower-level advection resulting in a negative number. NVA can be calculated as shown below:

$$VA = \frac{[(A) - (B)]}{(C - 0)} = \frac{-}{+} = -$$

1. NVA is a process that is indicative of upper-level convergence and downward vertical motion (subsidence) above the level of non-divergence (lnd).

2. This leads to an increase of isobaric heights, surface pressure rises, and possible anticyclogenesis that produce stable weather conditions (i.e. clear skies and dry conditions).

(c) Neutral Vorticity Advection. Neutral vorticity indicates areas where the vorticity and upper height isopleths are parallel, meaning that there is no vorticity advection occurring. It could also mean that the wind is too weak to advect any vorticity. In each case, little to no convergence or divergence is occurring aloft. No distinct vertical motion can be identified.

$$VA = \frac{[(0) - (0)]}{(C - 0)} = \frac{0}{+} = 0$$

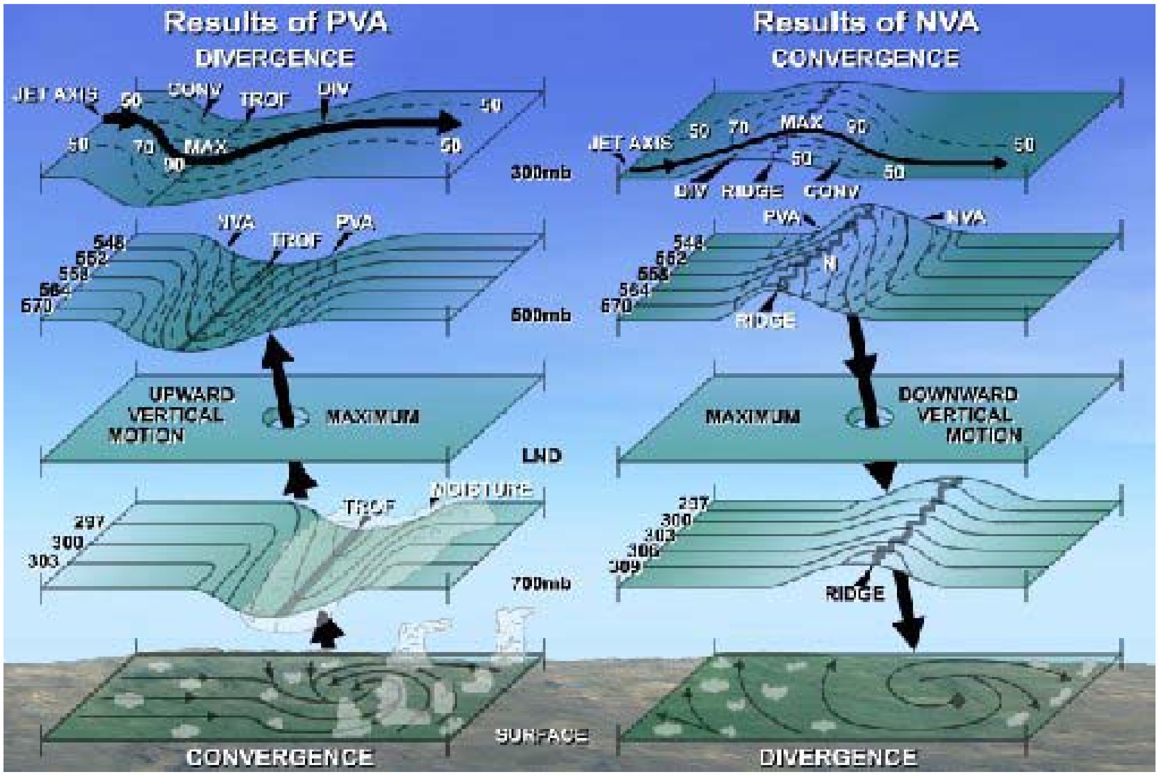

Figure 1 - Three-dimensional view of the atmosphere where surface convergence/divergence is associated with upper-level divergence/convergence.

b. Temperature Advection ($[T\ Adv]_{(lower\ tropospheric)}$). This part of the equation represents the temperature advection (Tadv) occurring in the lower troposphere. Warm air advection (WAA) is positive; cold air advection (CAA) is negative. Temperature advection is usually at its maximum at or just above the gradient level. Several charts may be used to evaluate temperature advection in the lower troposphere, any one or combinations of the following charts are utilized: (1) 1000mb-500mb thickness, (2) 1000mb-850mb thickness, (3) the 925mb analysis, or (4) the 850mb analysis. The 700mb chart may also be used in mountainous regions.

(1) Cold Air Advection (CAA). Recall that cold air is denser than warm air and therefore its tendency is to sink or subside. Because of this CAA is associated with downward vertical motion and can be represented mathematically as:

VM = [Temp Advection]

VM = [CAA]

VM = [-] = -

VM = Downward Vertical Motion (VM)

(2) Warm Air Advection (WAA). Recall that warm air is less dense than cold air and therefore its tendency is to rise.

Because of this, WAA is associated with upward vertical motion and can be represented mathematically as:

VM = [Temp Advection]

VM = [WAA]

VM = [+] = +

VM = Upward

(3) Neutral Advection. With neutral advection, the thickness/isotherms are parallel to the wind flow. The wind flow could also be so weak that there is little to no advection occurring. Mathematically, neutral advection is stated below:

VM = [Temp Advection]

VM = [Neutral]

VM = [0] = 0

VM = 0

c. Vertical motion (VM). Lifting occurs when VM is positive (+), which indicates divergence in the upper troposphere and convergence in the lower troposphere. Sinking occurs when VM is negative (-), which indicates convergence in the upper troposphere and divergence in the lower troposphere. VA and Tadv may have like signs (i.e. both positive or both negative). If both VA and Tadv are positive, this indicates an enhanced magnitude in lifting. If both are negative, this indicates an enhanced magnitude in sinking.

(1) VA and Tadv may often have opposite signs (i.e. one positive and one negative). This can result in an offset, reducing the magnitude of lifting or sinking. This all depends on the value of each term.

(a) If VA has a value of positive 10 and Tadv has a value of negative 5, the offset has reduced the magnitude by half. This offset can also result in a reverse in lifting.

(b) If VA has a value of positive 5 and Tadv has a value of negative 10, the overall vertical motion would be negative. Because these two variables can offset each other, it is important to evaluate each term's influence individually.

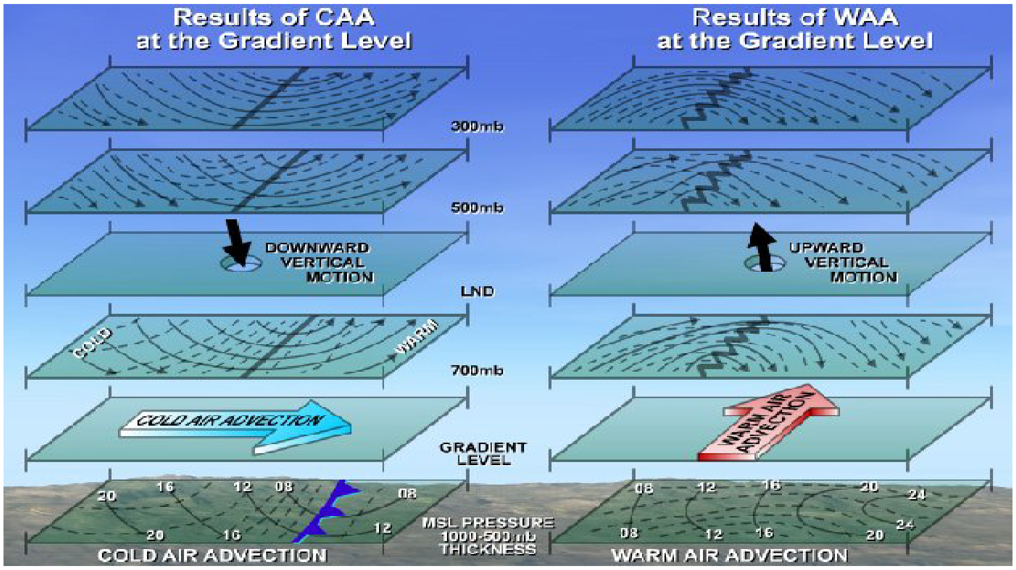

Figure 2 – The results of warm and cold air advection at the gradient level.

c. <u>The Sum of Vorticity and Thermal Advection</u>. As VA and Tadv change, so will the vertical motion. The chart below displays all the possible combinations.

↑ = upward vertical motion
↓ = downward vertical motion
0 = neutral
? = undeterminable (further analysis is needed to determine vertical motion)

Table 1 – The resulting atmospheric vertical motion with respect to vorticity and thermal advection.

		VORTICITY ADVECTION		
TEMPERATURE ADVECTION		**NEUTRAL (0)**	**PVA (↑)**	**NVA (↓)**
	NEUTRAL (0)	0	↑	↓
	WAA (↑)	↑	↑	?
	CAA (↓)	↓	?	↓

<u>TRANSITION</u>. There are several different ways to determine the vertical motions occurring in the atmosphere. The "Trenberth" form of the Omega Equation will be the next topic of discussion that provides an alternate way to determine vertical motions.?

2. <u>Trenberth form of the Omega Equation</u>. The Trenberth form of the Omega equation can be used as an alternate to the traditional Omega equation described above. Trenberth showed that for synoptic scale weather patterns, vertical motion is more sensitive to the advection of

relative vorticity (ζ) rather than to absolute vorticity. Trenberth also showed that the effect of thermal advection on vertical motion could be captured better by the veering or backing of the geostrophic wind with height, rather than the actual isotherms or thickness isopleths by the geostrophic wind in the lower troposphere. Also, vertical motion was more sensitive to vorticity advection by the thermal wind (V_t), rather than the geostrophic wind (V_g). Thus, Trenberth showed that VA and Tadv in the classic Omega equation could be combined into a single variable, eliminating the often-confusing cancellation of VA and Tadv of the classic Omega equation. The Trenberth form of the Omega Equation is represented as VM = (ζAdvection by V_t), where "VM" is the vertical motion, "ζAdvection" is the relative vorticity advection, and V_t is the thermal wind.

a. Vertical motion (VM) can be determined by the advection of relative vorticity (ζAdvection) by the thermal wind (V_t). The V_t at 500mb is parallel to the 1000-500mb thickness isopleths, with lower thickness values to the left of the V_t and higher thickness values to the right of the V_t. Quasi-geostrophic vertical motion may be visually estimated by the intersection of the 1000-500mb thickness isopleths with the 500mb relative vorticity isopleths.

b. Upward vertical motion occurs when the V_t blows across isopleths of higher relative vorticity toward isopleths of lower relative vorticity. VM = (ζAdvection by V_t) = PVA = +.

c. Downward vertical motion occurs when the Vt blows across isopleths of lower relative vorticity toward isopleths of higher relative vorticity. VM = (ζAdvection by V_t) = NVA = -.

d. Note: All the assumptions and limitations of the Q-G theory still apply to the Trenberth form of the Omega equation.

3. Q-Vectors. Q-Vectors are not a real measurable quantity like temperature and wind. They are a derivative of a mathematical formula that was derived from the Omega Equation. Q-Vectors allow forecasters to better visualize vertical motions within the atmosphere. They are dependent upon the strength of the horizontal temperature gradient brought about solely by the horizontal change in the geostrophic wind field. The concept of the Q-vector is a mathematical representation of the atmosphere's attempt to restore the thermal field once it has been disturbed from its 'equilibrium' state of both hydrostatic and geostrophic balance. Q-Vectors can be derived on an isobaric surface from the strength of the horizontal temperature gradient and the vector manipulation of the horizontal shear of the geostrophic wind. They can be calculated on a single isobaric level or for multiple isobaric levels (i.e. 850mb, 700mb, 500mb, etc…). Examination of Q-vectors allows a forecaster to assess vertical motions at each isobaric level; therefore, it requires interpretation of Q-Vectors from several isobaric levels in order to determine the overall tropospheric Q-G vertical motion pattern.

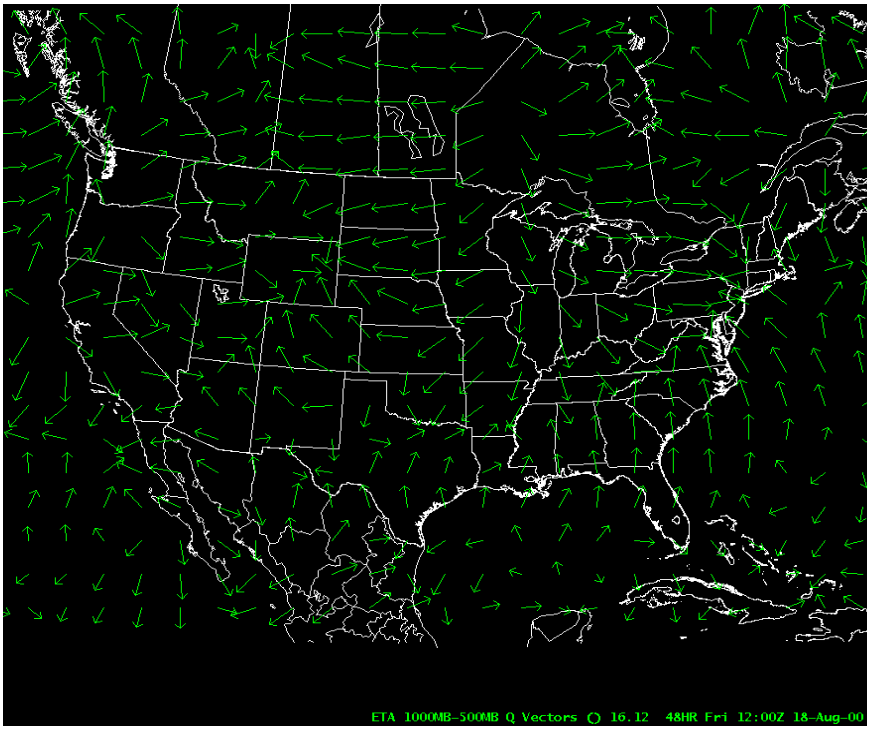

Figure 1 - Example of a chart depicting Q-Vectors. This chart was produced by AWIPS based off of complex mathematical formulas.

a. Interpreting Q-Vectors. The convergence of Q-Vectors represents upward vertical motion and the divergence of Q-Vectors represents downward vertical motion. One of the most significant limitations of using a chart of Q-Vectors is that there is no way of determining why the vertical motion depicted is occurring. All the assumptions and limitations of the Q-G theory still apply to Q-Vectors.

b. Q-Vector vertical motion patterns should be used together with classic Omega equation indicators, such as vorticity and thermal advection patterns, for a better recognition of the processes that may be forcing the vertical motion. Ideally, utilizing the classic Omega equation, when the vertical motion is indeterminable because VA and Tadv oppose each other (i.e. PVA in an area of CAA), the Q-Vector convergence/divergence patterns can aid in determining which process is dominating. In the examples provided below, it is assumed that 700mb represents the LND.

Example 1.

(1) Omega Equation: VM = PVA (↑) + CAA (↓) = ? for VM.
(2) 700mb Q-Vector pattern is Q-Vector convergence which = ↑.
(3) The resultant hypothesis is that PVA (↑) dominates over CAA (↓).

Or

(1) 700mb Q-Vector pattern = Q-Vector divergence = ↓.
(2) The resultant hypothesis is that CAA (↓) dominates over PVA (↑)

Example 2.

(1) Omega Equation: VM = NVA (↓) + WAA (↑) = ?
(2) 700mb Q-Vector pattern = Q-Vector divergence = ↓
(3) The resultant hypothesis is that NVA (↓) dominates over WAA (↑)

Or

(1) 700mb Q-Vector pattern = Q-Vector convergence = ↑.
(2) The resultant hypothesis is that WAA (↑) dominates over NVA (↓)

TRANSITION. Are there any questions over Q-vectors or how to determine vertical motions from them?

OPPORTUNITY FOR QUESTIONS:

1. Questions from the Class.

SUMMARY: All the methods for determining vertical motion described above only provide a first guess as to where and why synoptic scale vertical motions may be occurring. Utilizing all the described methods in tandem will provide the forecaster with a better idea of the vertical motions over a given region.

REFERENCES:

Meteorology and Oceanographic Analyst Forecaster Course Text Book (N61RCB1-ST-102), Physics I, Chapter 5, pgs. 5-11-12, Rev. October 2002.

Cloud Formation Processes, Chapter 8 Introduction to the Hydrosphere. Dr. Michael Pidwirny. Department of Geography, Okanagan University College 1999-2004. Last updated 2/16/2004. Last accessed 8/9/2004. http://www.physicalgeography.net/fundamentals/8e.html

Q-Vectors. Meteorology Education and Training. Last updated 9/27/04. Last accessed 9/28/04. http://meted.ucar.edu/awips/validate/qvector.htm

Using Q-Vector difference to forecast the location of heavy snow with lifting southwest U.S. Lows. Michael J. Bodner, NWS/WFO Pleasant Hill, Missouri. Last accessed 9/28/04. http://www.crh.noaa.gov/eax/amsqvc1.htm