The Relationship Between Vertical Sounder Radiances and Mid-Latitude 300 mb Flow Patterns

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ABSTRACT

The direct synoptic application of radiances measured in the 695 cm^{-1} channel of the 15 μm carbon dioxide band by the vertical sounding instruments aboard the NOAA operational satellites is described. The radiation measured in this channel is emitted from a layer centered around 150–100 mb, or above the level of the polar jet stream and tropopause. In this region above the baroclinic zone of the polar front, the horizontal temperature gradient is the reverse of that found in the troposphere. It is demonstrated that mapped radiance patterns are quite useful for describing the upper tropospheric circulation features at 300 mb, and that the gradients are well related to 300 mb wind speeds in and near the polar jet stream.

1. Introduction

Vertical temperature sounding instruments were developed for retrieving temperature profiles of the atmosphere. It has also been found that the patterns in the mapped fields of radiances from certain channels have direct synoptic application. As one example, the radiance patterns from the 695 cm^{-1} channel measurements in the 15 μm carbon dioxide band closely resemble the middle and upper tropospheric flow patterns in mid-latitude regions. The gradients in this radiance field appear to offer considerable information on the location and strength of the polar jet stream. This note describes a research effort to relate the mapped radiances from the operational vertical sounding instruments (VTPR) to the mid-latitude 300 mb flow.

The weighting function curve for the 695 cm^{-1} channel of the VTPR instruments (hereafter referred to as channel 3) shows that the emitted radiation in this channel arises from a layer extending from 15 to 20 mb down to 350 to 400 mb and centered around 150 to 100 mb. The radiance emitted by this layer is a function of its mean temperature. For the purpose described above, it would appear that the three CO_2 channels (4, 5 and 6) whose weighting functions peak in the troposphere would be more appropriate; however, these channels are strongly cloud-contaminated and present considerable problems in application. Channel 3 is affected to a much smaller extent by high clouds and, as will be described in the next section, the adjacent channel (4) that peaks lower ($\sim$400 mb) can be used to make generally rather small empirical corrections for the contamination. The two most opaque channels (1 and 2) peaking above channel 3 are completely in the stratosphere and do not reflect the tropospheric synoptic-scale pattern as does channel 3.

It is not obvious why radiances emanating from a layer mostly in the lower stratosphere are useful for describing the character of tropospheric flow patterns. An heuristic explanation is as follows: In mid-latitudes a large portion of the channel 3 radiant energy emanates from warmer, lower stratospheric polar and mid-latitude air masses at one extreme and from colder, upper tropospheric and lower stratospheric tropical air masses at the opposite extreme. The former are the vertical extension of mid-tropospheric cold lows and troughs, while the latter are associated with the warm highs and ridges. Separating the two is the area of the jet stream. The net effect of this structure on the horizontal temperature gradients in the layer contributing to the channel 3 radiances is a reversal of the pattern normally found in the tropospheric layers, i.e., the warmer temperatures and radiances are found toward the pole and the colder ones toward the equator.

Physically, such a temperature pattern leads to thermal winds supporting flow opposite in direction to the westerly flow and thermal winds found in the troposphere. Just as the thermal winds in the troposphere are associated with the building of the polar jet stream in the vertical, the reversal of the thermal winds above the tropopause is associated with the breaking down of the jet in the lower stratosphere. Since the jet stream speeds are closely related to the strength of the thermal winds in the troposphere, it is also logical for the reverse thermal winds above the jet level to be proportional in magnitude to the strength of the jet. Finally, just as thermal winds are related to thickness gradients for a given layer, so the thickness (mean temperature) pattern is related to the radiance pattern. Thus, the radiance pattern for channel 3 provides a direct indication of the thickness and thermal wind patterns in a layer primarily above the polar jet level and so gives important information about the jet level or upper tropospheric flow itself.

2. Cloud contamination correction

As noted in the preceding section, the channel 3 radiances are to some extent contaminated by high clouds, particularly those in areas of convection or associated with deep multi-layered clouds such as frontal bands. The latter regions, especially, can result in enhanced radiance gradients that lead to erroneous estimates of the flow field. The channel 4 radiances can be used to alleviate this difficulty using the property that they are much more strongly cloud-contaminated than channel 3. On examining the radiances from the two channels, it was observed that the differences between them are closely related to the type of cloudiness. In comparing with IR pictures, the smaller the differences (channel 4—channel 3) the more solid, cold or convective the clouds appear.

Full-resolution radiance data were used to determine a correction for cloud-contaminated channel 3 radiances in carefully selected areas where a clear column radiance could be estimated. This correction was correlated with the observed differences between channel 4 and channel 3 for 412 points gathered in winter and early spring periods of 1975 over the North American region. These points and a third-order polynomial fit to them are shown in Fig. 1. Clearly, the smaller the positive or the larger the negative difference between the two channels (along the abcissa) the greater the correction to be applied to channel 3 (on the ordinate). An explained variance of 79% is obtained with the polynomial. The computed error for the scatter of points about the curve is 0.39 mW. This relationship may be applied to eliminate the cloud-enhanced gradients in the radiance data.

3. A case study

The resemblance of the analyzed channel 3 radiance pattern to the 300 mb flow pattern is shown by the example presented in Fig. 2. The radiance contour analysis on the upper half of the figure was made from grid point values computed from a weighted average of full-resolution radiance values. The observation times for the satellite data change from near 0000 GMT in the eastern portion of the chart to approximately 0600 GMT in the northwestern portion. Radiance isopleths are broken where there are gaps in the coverage of the VTPR instrument; however, north of 45–50° latitude the coverage is continuous. The 300 mb height contour map at 0000 GMT is that nearest in time to the satellite data; the polar jet axis from the 300 mb analysis is placed on the radiance analysis to facilitate comparison.

There is a striking correspondence between the upper tropospheric pressure systems at 300 mb and the radiance thermal systems equatorward of an axis defined by the warm centers and the relatively warm connections between them in the 45–60°N latitude belt. Cold radiance "ridges" and warm radiance "troughs" agree well in location to the 300 mb ridges and troughs, particularly when the time difference in the northwest portion is taken into account. The closed warm radiance center near the southwest California coast is in excellent agreement with the 300 mb closed low. Poleward of the warm axis described above, the pronounced cold pool is associated with the stratospheric polar vortex and therefore relates well to the mid-stratospheric circulation.

Correspondence between the location of the jet stream axis and areas of strongest gradient in the radiance pattern can also be noted. This correspondence is especially marked around the region of the large warm radiance centers. Jet stream maxima in the northeast Pacific and in the northeastern United States agree with areas of the tightest gradient in the radiance contours. Exceptions occur in regions between the primary centers, for example over western Canada, where the somewhat cooler lower stratospheric air and

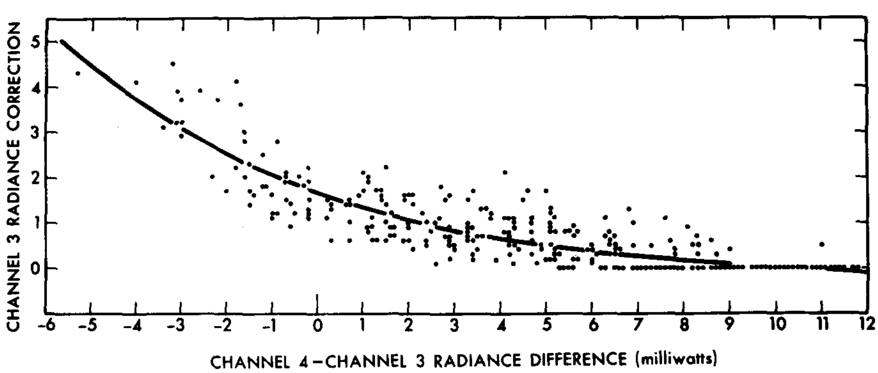

FIG. 1. Estimated channel 3 radiance correction versus measured channel 4 minus channel 3 radiance difference (mW).

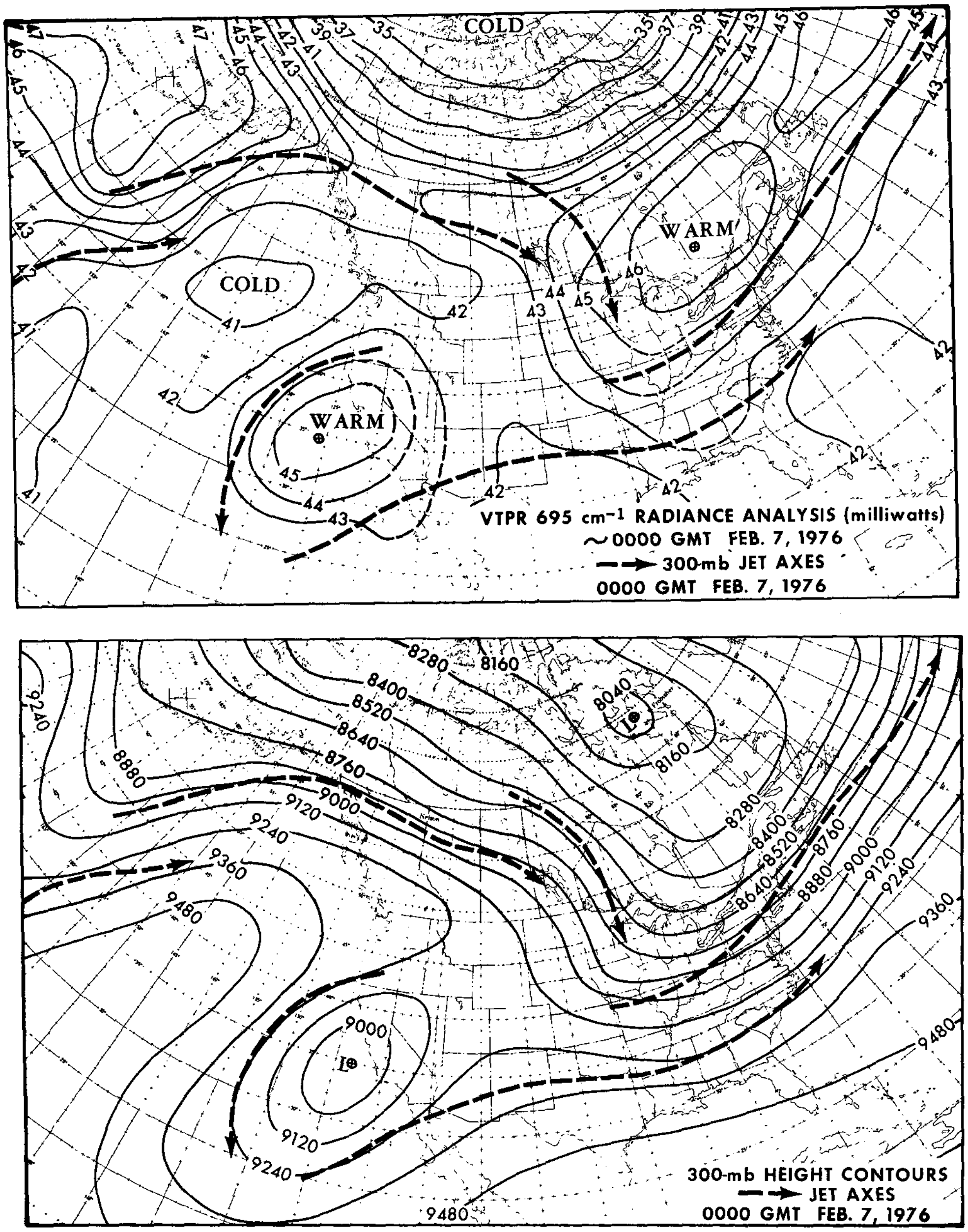

Fig. 2. Upper portion, channel 3 radiance analysis [mW/(m² sr cm⁻¹)] and lower portion is NMC 300 mb height field (m) for 0000 GMT 7 February 1976.

cooler middle stratospheric air associated with the polar vortex combine to produce lower radiance values than are generally expected north of the jet axis. This results in a much weaker radiance gradient. Another exception is through the southern United States where the subtropical jet stream dominates.

4. Jet stream axis position

The correspondence between the position of the jet stream axis and the zone of the tight gradients in the radiance patterns has been examined more precisely with some 20 case studies from the winters and early springs of 1975 and 1976. To accomplish this, an estimated jet axis was positioned in the center of the band with the tightest concentration of channel 3 radiance isopleths wherever the gradient was greater than ~2 mW (440 km)$^{-1}$. It should be noted that this allows the estimated axis to cross radiance isopleths. Then an observed jet axis position was taken from the 300 mb National Meteorological Center analyzed wind speed axis wherever the speed was greater than 35 m s^{-1}. (A time-interpolated axis position was constructed when the time difference between the satellite data and the conventional analysis made it necessary to account for a shift in location.) The two axes were

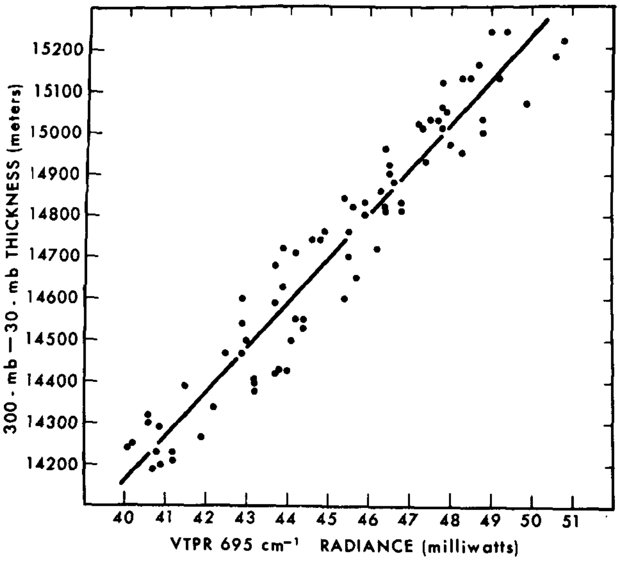

FIG. 3. Scatter diagram of channel 3 radiances [mW/(m^2 sr cm^{-1})] versus radiosonde 300–30 mb thickness values. Solid line is linear regression for the data.

then superimposed, and measurements, in kilometers, were made of the separation between them at intervals of 550 km along the analyzed axis. In this manner, 120 comparison points were assembled. The estimated (radiation analysis) jet axis was positioned within 100 km of the 300 mb analysis axis in 87% of the comparisons. In no case was the separation greater than 200 km.

5. Thermal wind speeds

As mentioned in the Introduction, the radiances are a function of the mean temperature through some layer from which they arise. To illustrate this relationship, channel 3 radiance measurements were compared with the 300–30 mb radiosonde thickness values at the same location for 80 points from 10 dates in the periods mentioned in the preceding section. The layer is centered symmetrically about the weighting function curve for channel 3 and one can see in Fig. 3 that the two parameters are strongly related. The scatter is small and evenly distributed about the regression line in the figure. From the regression relationship, a thickness difference can be determined for a given radiance difference. Thus, radiance gradients can be converted into thickness gradients, and a thermal wind speed for the layer can be computed. This has been done and the result is shown by the broken line in Fig. 4, which is discussed in detail in the next section.

6. Jet stream wind velocity

As a means of determining whether any useful relationship exists between the magnitude of the radiance gradients and the 300 mb wind speeds along and near a maximum wind axis, differences of the radiances at a 440 km spacing normal to the radiance isopleths were taken at observed wind locations and compared to the measured 300 mb wind speeds. The observed winds are mostly from rawinsonde reports over North America with some oceanship and aircraft wind reports over the Pacific Ocean during the first three months of 1976. Wind speeds from certain jet regions were excluded from the data. Regions of confluent jet axes tend to produce wind speeds that are too high compared with the bulk of the data and comparisons were made at least 10° of longitude downstream from the area of confluence. Wind speeds in regions of pronounced cyclonic curvature are generally too low by comparison with the data and were excluded if the radius of curvature of the contours was less than ~500 km.

The result of 165 comparisons is shown as a scatter diagram. In Fig. 4, the channel 3 radiance difference (normalized to 43° latitude using the Coriolis parameter) is on the horizontal axis with the wind speeds on the vertical axis. The solid line is the linear regression fitting the data with a positive correlation coefficient of ~0.85 and a scatter of 7.74 m s^{-1}. The thermal wind computation, shown as a broken line (using the same wind speed scale on the left), supports the validity of this result. The agreement between the two lines is excellent and both supports the 300 mb wind speed vs

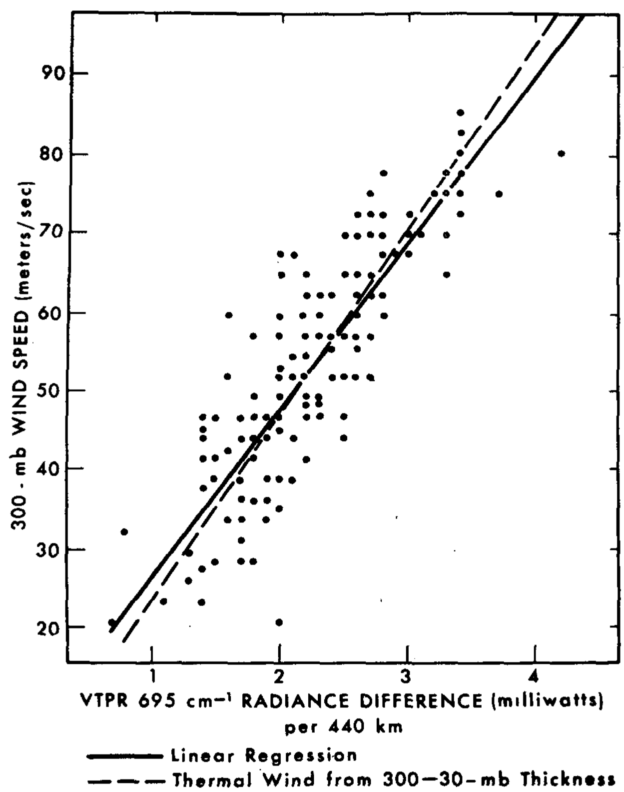

FIG. 4. Scatter diagram of channel 3 radiance gradients [mW (440 km)$^{-1}$] versus 300 mb wind speeds. Solid line is linear regression for the data and the broken line represents thermal wind speeds computed from thickness differences taken from Fig. 2.

radiance gradient relationship and indicates that the 300–30 mb thermal wind speed is approximately equal to the 300 mb wind speed itself, even though the directions are opposite. For operational use this regression has been used to develop a wind-speed scale (resembling a geostrophic wind scale) so that 300 mb wind speeds may be obtained directly from radiance analyses.

The direction portion of the wind velocity is specified by the orientation of the radiance isopleths. Generally, the wind directions may be taken as parallel to these isopleths or to the estimated jet axis when it is cutting across radiance isopleths at some angle.

7. Conclusion

This study shows that it is entirely feasible to obtain 300 mb wind estimates in and around the polar jet stream from mapped radiance data. At present, the National Environmental Satellite Service is using channel 3 radiance analyses operationally to obtain wind estimates over ocean areas where little if any other direct evidence of wind speeds is available. Such estimates may also prove useful over land areas where conventional radiosonde data are too sparse to correctly position and define the areas of maximum gradient.

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