TIROS II Window Radiation and Large Scale Vertical Motion

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ABSTRACT

The difference between observed window radiation and radiation expected without clouds was related to various synoptic parameters. The best correlation, 0.72, was obtained with vertical motion computed by the adiabatic methods at 700 mb. Other variables tested were meridional flow and vertical motion at other levels.

1. Introduction

One of the purposes of infrared data from satellites is to estimate certain meteorological quantities that are difficult to ascertain from conventional weather information in sparse data regions. Estimates of cloud cover distribution have been made by Bandeen, Hanel, Licht, Stamfl and Stroud (1961), and cloud height studies have been made by Fritz and Winston (1962) and by Rao and Winston (1963). Also, Weinstein and Suomi (1961) conducted a study which related infrared measurements to surface weather systems.

Since the infrared region outside the atmospheric window is affected by both the water vapor and temperature distributions in a complex manner the radiation in these wavelengths was not considered here. Wark, Yamamoto and Lienesch (1962) have concluded from their extensive studies of the effects of water vapor and ozone that the absorption due to water vapor is not negligible, even in the window. Nevertheless, radiation in the window is closely related to the surface temperature or cloud top. The specific purpose of this investigation is to determine to what extent infrared measurements from a satellite in the atmospheric window can supply information about the atmospheric circulation and temperature field in regions of sparse data coverage. Even in sparse data areas, other information can supplement the satellite measurements provided that it can be supplied from climatology or by very simple means.

2. Treatment of window radiation

Since water vapor, ozone and particulate matter affect the transparency of the window, no single radiating surface can be defined. Nevertheless, it is possible to define an effective temperature: i.e., that temperature which a blackbody would have if it were to give the observed radiation. The relation between window radiation and effective temperature is found in the *TIROS II Radiation Data User's Manual* (Staff members, 1961b) and has been illustrated in Fig. 1. Because of the intervening water vapor and other radiators the relation between the temperature of the actual surface and window radiation is different. This will be established empirically later. It will be seen that the window radiation is a function of the temperature at the ground in a clear area or of the top of a cloud. The same radiation intensity could be obtained from a high cloud over warm ground or from the ground in a cold region with a clear sky. As a result, window radiation intensity by itself is ambiguous and should be combined with some other parameter to eliminate the ambiguity.

One of the most easily obtainable quantities over areas of little meteorological information is an estimate of surface temperature. Over the oceans the surface temperature varies little from year to year, and is given in climatic atlases. Even, over isolated areas, a crude surface temperature estimate is often possible.

First, a relation between window radiation and surface temperature in clear areas must be established. Observations were obtained in the United States east of the Rocky Mountains, and in Canada east of the Continental Divide. All forms of meteorological data are plentiful in this area but the area west of the Continental Divide was eliminated because of the strong local effects on temperature introduced by mountain ranges. To maintain continuity throughout the study, the same area was used for all data collections.

Maps of window radiation measurements have been published by the Goddard Space Flight Center in Greenbelt, Md. (Staff members, 1961a). Surface temperatures were read from North American surface charts for 3-hr intervals at all reporting stations. The

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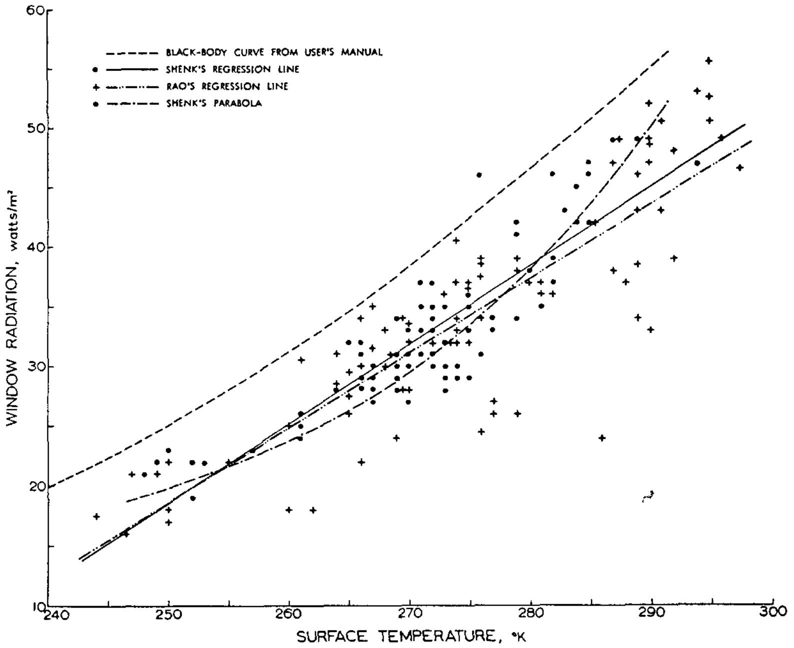

FIG. 1. The relation between TIROS II window radiation and surface temperature. The curves of Shenk and Rao were fitted by least squares.

average distance between stations was approximately 200 miles. In many cases, the temperature values are interpolated as the satellite would make its pass between map times.

Fig. 1 shows the relation between window radiation and surface temperature for 88 points between 23 Nov. 1960 and 23 Dec. 1960. We will now denote the curve called Shenk's parabola by $f(T)$ and will assume that it represents the best relation between the temperature of the "surface" and window radiation. The curve was fitted by least squares. In the presence of clouds, we will take $f(T)$ as the relation between the temperature of the cloud tops and window radiation. Rao and Winston (1963) have shown that the window radiation measurements are a good indicator of cloud height. As can be seen in the graph there appears to be some slight curvature, somewhat similar to that of the blackbody curve in the *User's Manual*, also reproduced in this figure. However, the curvature is so small that the difference between the linear and parabolic correlation is quite small, the linear correlation being 0.88 and the parabolic correlation 0.89. The difference between the blackbody curve and the observed curve can be partially explained by the effects of water vapor, ozone and particulate matter, all of which reduce the radiation intensity. The scatter about the curve might be explained to some extent by varying moisture content or by thin layers of moisture drops or dust. Also any errors in the surface temperature interpolation would produce scatter, but this should be of smaller magnitude than any error induced by the uncertainty of the effective temperature of the surface. An error analysis revealed a standard error of 4C in the surface temperature.

Krishna Rao of the National Weather Satellite Center carried out a similar investigation with strikingly similar results.[2] The results of the two studies are shown in Fig. 1. The linear correlation coefficient for Rao's data was 0.85. Rao included 92 points and his points were selected from the same TIROS II catalog that was used in this study. As a result, many of the synoptic situations that Rao included in his study were also included here.

Thus, there seems to be a definite relation between surface temperature and the window radiation values. This result was also found by Wark, Yamomoto and Lienesch (1962). Unfortunately, TIROS II made nearly all of its passes during November and December 1960 over the United States and Canada at night so that the above correlation was established from nighttime observation only. One of the difficulties of nighttime observations is that thin cirrus may be present even though the observer reports a clear sky. The presence of cirrus clouds could lower the effective temperature and the satellite would record a lower radiation intensity than in the absence of cirrus. Daytime testing would be desirable, but only a few measurements were available.

The symbol *DV* will be defined as the window radiation intensity that would be received if there were no clouds minus the observed window radiation intensity. In general, the larger the *DV* value, the higher the clouds.

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[2] Rao, Krishna, 1962: Personal communication, May.

The DV charts were obtained at all stations where surface temperatures were given. These temperatures were entered into Fig. 1, and observed radiation was subtracted from the clear-air radiation read from Shenk's Parabola in Fig. 1. The DV values thus obtained were computed to the nearest watt m^{-2}, and isoplethed every 2 watts m^{-2} to give a smooth field. A total of 9 synoptic situations during November and December, 1960 were processed.

3. Properties of DV values

Since DV is the radiation intensity at the ground minus the radiation intensity at the cloud top and radiation is related to "surface" temperature by $f(T)$ we may write:

$$DV = f(T_g) - f(T_s),$$

where T_g = temperature at the ground and T_s = temperature at the cloud top.

Let $\bar{T}$ be the average temperature and be expressed by $(T_g + T_s)/2$ and let $\Delta T = T_g - T_s$. Then let R_g be the energy emitted by the ground and R_s the energy emitted by the "surface." Then:

$$R_g = f\left(\bar{T} + \frac{\Delta T}{2}\right)$$

$$R_s = f\left(\bar{T} - \frac{\Delta T}{2}\right).$$

Expanding $f(T_g) - f(T_s)$ about $\bar{T}$ in a Taylor series we have:

$$R_g = f(\bar{T}) + \frac{\Delta T}{2} f'(\bar{T}) + \frac{(\Delta T)^2}{8} f''(\bar{T})$$

and higher order terms.

A similar expression can be written for R_s. After substituting in the relation $DV = R_g - R_s$ the Taylor expansion for DV becomes:

$$DV \propto \Delta T.$$

Multiplying and dividing the right side by h, the height of the cloud top above the ground, we have

$$DV \propto h\gamma,$$

where γ = the average existing lapse rate.

Vertical motion is one meteorological quantity that is related both to the lapse rate and to cloud height. With large scale upward motion the air tends to be relatively unstable and with subsidence a stable atmosphere is more likely. When upward motion is present clouds are formed and it can usually be expected that the more vigorous the upward motion the higher the cloud tops. Since vertical velocity is related to both the above meteorological parameters it would seem likely that it would be related to the DV values. Hence, vertical motion might be inferred from DV values.

Another meteorological quantity the knowledge of which would be desirable is the meridional component of flow. If this quantity were known it would be possible to give an estimate of the position of the trough and ridge lines. Since north-south flow is related to vertical motions (Miller, 1958) a relation between north-south flow and the DV values seems probable, provided a relationship between DV values and vertical motion can be demonstrated.

4. Relation of DV values to synoptic variables

Altogether, nine different synoptic situations were analyzed in this study beginning with the first orbit on 23 November 1960, and ending with the case on 21 December 1960. This month is almost the entire period covered by the Goddard Flight Center TIROS II catalogue.

For the study of the relation between DV values and synoptic data, a 2-deg grid of latitude and longitude was established. With this point selection system, the largest number for a given synoptic situation was 108 points and the smallest number was 12 points. Although the various parameters change significantly over 2 deg latitude or longitude, the observations at such points cannot be regarded as independent of each other.

Interpolation between map times became a considerably greater problem when upper air charts with a 12-hr time spacing were used than when the 3-hr surface charts were processed in the derivation of the DV values. Linear interpolation was still the primary method, but development and non-linear variations had to be considered on some occasions.

5. Relationship of DV values and vertical motion

Vertical motions were computed by the adiabatic method at 700, 500 and 300 mb in an effort to find which of the three levels would yield the best relation between vertical motion and DV values.

The adiabatic method produces a 12-hr average of the vertical motion. The adiabatic assumption is the only restrictive assumption in the method. An equation for computing the vertical motion by the adiabatic method is (Miller, 1948):

$$W = \frac{-\dfrac{\delta T}{\delta t}}{\gamma_d - \gamma}$$

where δT is the 12-hr temperature difference at a given level along an isobaric projection of a trajectory, γ_d = adiabatic lapse rate and γ = existing lapse rate.

In this study the dry adiabatic lapse rate was always used in the denominator of the adiabatic equation $\gamma_d-\gamma$. In thick clouds, the moist adiabatic lapse rate would have been more appropriate but is too difficult to handle in practice. One difficulty with saturated air is the prevailing lapse rate leads to underestimates of vertical motions when they are large and positive.

The largest error in obtaining the vertical motion from the adiabatic equation results from measuring the 12-hr temperature difference along an isobaric trajectory. Errors in both wind and temperature contribute to these errors. In particular, the trajectories around closed centers are not very accurate. Further, the steeper the lapse rates and the stronger the winds at higher levels the smaller the precision of the computations. As a result, the accuracy of the vertical motions is greatest at 700 mb and decreases with height. The 700-mb standard error is estimated of order 1 cm sec^{-1} in agreement with conclusions reached by Miller (1958).

First, a linear correlation coefficient between vertical motion and *DV* values was computed with the 138 points in cloudy areas only. If the results looked promising at any or all of the three levels, the size of the data sample was to be increased and points were selected regardless of sky condition.

The linear correlation coefficients between *DV* values and vertical motion at the 700-, 500- and 300-mb levels were 0.768, 0.569 and 0.564, and the standard errors were 0.7, 1.0 and 1.5 cm sec^{-1}, respectively.

The fact that the correlation between *DV* values and the vertical motion at 700 mb is better than at the other levels substantiates the hypothesis that vertical velocity charts at 500 and 300 mb are less accurate than those at 700 mb, since there is no obvious physical reason why the correlation between vertical motion should deteriorate with increasing height. On the other hand, since the average vertical velocity between the cloud top and the ground should be used, the 700-mb level by virtue of its location near 10,000 ft is probably a good approximation. Since the 700-mb results were quite good with limited data, the relationship was examined on a larger scale without regard to sky conditions at that level only.

The relation between *DV* values and vertical motion at 700 mb for all sky conditions is shown in Fig. 2. The linear correlation coefficient was 0.721. The regression line is above the mean in the extreme right portion of Fig. 2, but the dry adiabatic lapse rate that was used in computing the vertical motion led to underestimates of the vertical motion in that portion of the figure. Thus, the regression line may give a good estimate of the actual vertical motion even when *DV* values are large and positive.

It is interesting to notice the rather wide scatter of points below the zero line in the left hand portion of Fig. 2. A reason for the scatter is that in clear areas there may be weak or strong subsidence. Negative *DV* values occasionally occur and may be due to radiation errors but they also can be produced by inversions. In inversions, γ is negative so that $DV \propto h\gamma$ is negative. Since h is a measure of vertical motions, *DV* values of zero or less cannot be used in quantitative estimation of vertical motion except to say that there is subsidence.

6. Relationship between *DV* values and meridional flow

Since meridional flow is correlated with vertical motion (Miller, 1958), the *DV* values might be expected

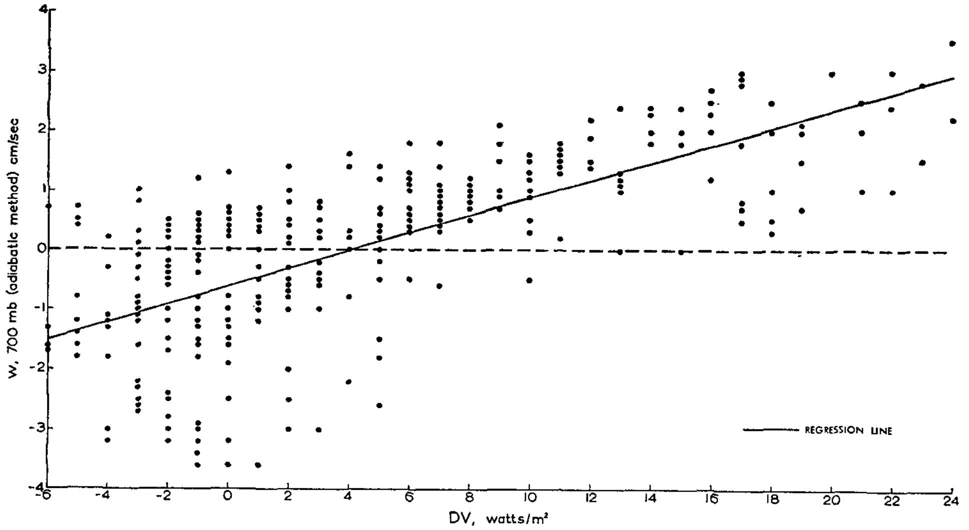

FIG. 2. The relation between *DV* values and vertical motion at 700 mb computed by the adiabatic method. The regression line was fitted by least squares.

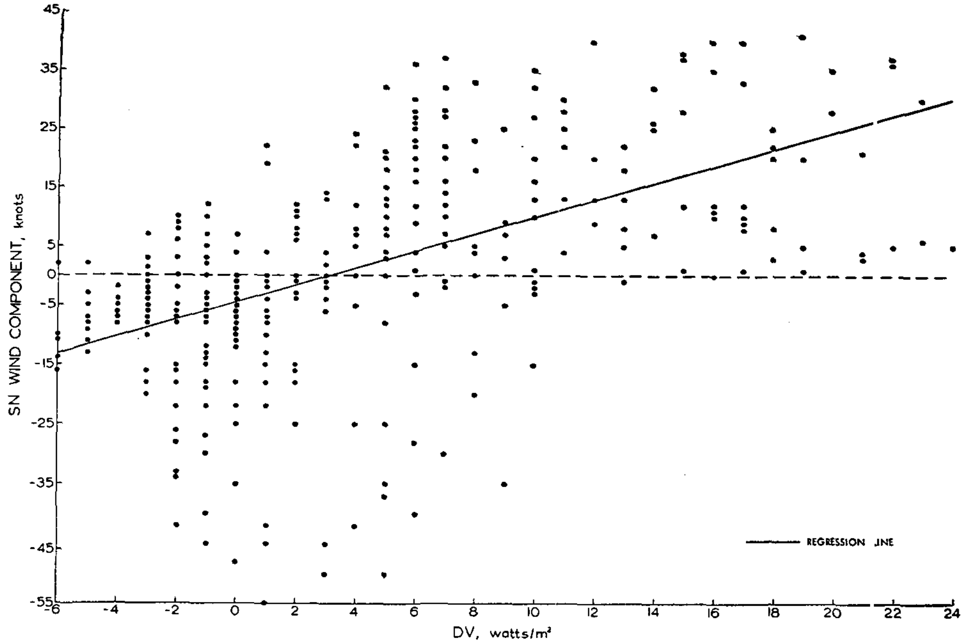

FIG. 3. The relation between *DV* values and meridional flow. The regression line was fitted by least squares.

to be well correlated with north-south component. Such a relationship would permit estimates of the trough and wedge line positions on constant pressure charts from satellite data which would be an aid in forecasting in sparse data areas where no rawinsonde reports are received. Meridional flow is related to the vertical motion in that upward motion is expected in areas of southerly component and subsidence is anticipated in regions of northerly component. Thus low *DV* values should be related to northerly component and high *DV* values to southerly component.

North-south geostrophic wind components were computed at every intersection of 5-deg intervals of latitude and longitude.

The graphical relation between meridional flow and *DV* values is shown in Fig. 3. The linear correlation coefficient is 0.557. The graph shows considerable scatter, but when *DV* values are greater than 10 watts m^{-2} the flow definitely has some southerly component with one minor exception.

The relation between vertical motion and north-south component frequently breaks down in closed lows. Even to the west of such centers, where northerly flow prevails, clouds are quite common. The asymmetrical shape of some of the troughs was another reason for the scatter, in particular troughs with a NE-SW axis. The flow east of the axis was weak southerly components and strong northerly components west of the axis. When, in such situations, strong upward motion occurs east of the axis, as in the case of 23 November 1960, the quantitative relation between *DV* values and meridional flow is not good.

7. Conclusions

The basic conclusions of this investigation are:

1) That a high linear correlation exists between surface temperature and window radiation measurements in areas of clear skies at the time of the satellite passage.

2) A good linear relationship was found between the difference of observed window radiation and that derived from surface temperatures, and vertical motion computed by the adiabatic method at 700 mb.

3) A smaller linear correlation was found to exist between meridional flow and the *DV* values. This relation can be used for estimating the position of the trough and wedge lines in sparse data areas.

Since only nine synoptic situations were studied and these occurred at night, over land areas, in the middle latitudes, and in the months of November and December 1960, and because the results are statistical, different relations may apply in other periods.

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REFERENCES

Bandeen, W. R., R. A. Hanel, J. Licht, R. A. Stamfl and W. G. Stroud, 1961: Infrared and reflected solar radiation measurements from the TIROS II meteorological satellite. *J. geophys. Res.*, **66**, 3169–3185.

Fritz, Sigmund, and Jay S. Winston, 1962: Synoptic use of radiation measurements from satellite TIROS II. *Mon. Wea. Rev.*, **90**, 1–9.

Miller, Albert, and H. A. Panofsky, 1958: Large scale vertical motion and weather in January, 1953. *Bull. Amer. meteor. Soc.*, **39**, 8–14.

Miller, J. E., 1948: Studies of large scale vertical motions of the atmosphere. *Meteor. papers*, New York University, **7–12**.

Rao, P. Krishna, and J. S. Winston, 1963: An investigation of some synoptic capabilities of atmospheric 'window' measurements from satellite TIROS II. *J. appl. Meteor.*, **2**, 12–23.

Staff Members, Aeronomy and Meteorology Division, Goddard Space Flight Center, NASA and National Weather Satellite Center, U. S. Weather Bureau, 1961a: *TIROS II radiation data catalog*. Vol. 1, Greenbelt, Md., Goddard Space Flight Center, NASA, 356 pp.

——, 1961b: *TIROS II radiation data user's manual*. Greenbelt, Md., Goddard Space Flight Center, NASA, 57 pp.

Wark, D. Q., G. Yamomoto and J. H. Lienesch, 1962: Methods of estimating infrared flux and surface temperature from meteorological satellites. *J. atmos. Sci.*, **19**, 369–384.

Weinstein, Melvin, and V. E. Suomi, 1961: Analysis of satellite infrared radiation measurements on a synoptic scale. *Mon. Wea. Rev*, **89**, 419–428.