Antarctic Stratospheric Warmings During 1963 Revealed by 15- μ TIROS VII Data^{1,2}

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ABSTRACT

TIROS VII 15- μ radiation data were used to study Southern Hemisphere stratospheric warmings during the winter of 1963 over regions which had little conventional data. Three significant warmings could be mapped despite the latitudinal limit of 60S. The first, from 20 July to 13 August, and the second from 26 August to 16 September each reached a maximum in the Australian sector with temperature increases of 10C and 24C near Campbell Island. The warmings moved eastward from Australia and the South Indian Ocean. The third, or final warming, occurred in the western South Pacific from 16 October to 10 November with a temperature increase of 21C. This warming travelled southeastward toward the South Atlantic Ocean. This study demonstrates the validity and usefulness of single-day satellite data. It is strongly suggested that future observations of the same narrow CO₂ band be carefully processed to filter out only the random time fluctuations in order that potentially high resolution in time and space of this system can be realized. The 15- μ radiation can indeed provide mid-stratospheric temperature data over the major portion of the globe which now has no upper-air observational network at all. A truly polar orbit such as that of Nimbus, would further provide such data over the central polar regions where this atmospheric layer experiences dramatic changes and is of most interest.

1. Introduction

Following the discovery of sudden stratospheric warmings by Scherhag (1952), numerous reports (for example, Finger and Teweles, 1964; Wilson and Godson, 1962) have appeared describing their behavior and characteristics in the Northern Hemisphere. Several warmings of various intensity usually occur each winter. In addition to these, in the springtime, there is a final warming which is associated with the seasonal reversal of meridional thermal gradient and the replacement of the cold polar vortex by a warm anticyclone. Similar events have been observed in the Southern Hemisphere (Godson, 1963). However, the sparseness of observations, particularly in the southern oceans, makes analysis and subsequent description of stratospheric events difficult.

The 1963 stratospheric warmings of the Southern Hemisphere were first pointed out by Nordberg *et al.* (1965) using 15- μ data. They found that a warm region over the southeastern Indian Ocean persisted throughout the winter and then spread to make one-half of the hemisphere almost 15K warmer than the other. However, no details of the warming were given. Phillpot (1964) discussed the 1963 final warming in the Antarctic region using radiosonde data. Teweles (1966) compared the

TIROS 15- μ temperatures with the radiosonde temperatures at two stations and indicated two stratospheric warmings. Using rocketsonde data Briggs (1965) found the final warming in the spring but failed to detect the mid-winter warmings. Quiroz (1966) reanalyzed Briggs' data and demonstrated that a major warming occurred in July-August, and concluded that the same warming was delayed until September at lower levels.

The problem of evaluating the Southern Hemisphere warmings can be improved by using more detailed satellite radiometric measurements from the 15- μ CO₂ emission band. The sensor characteristics and theoretical evaluation of the 15- μ temperatures³ have been described by Nordberg *et al.* (1965) and Bandeen *et al.* (1965). These temperatures are vertically weighted mean temperatures; 65% of the radiative energy in the band centered at 15- μ originates from 15 to 35 km. The maximum emission at low nadir angles is at 23–25 km. It has been shown that the 15- μ temperatures are well correlated with the 20- or 30-mb temperatures (Belmont *et al.*, 1968). The near global coverage from 60N to 60S, of these stratospheric temperatures, makes them an important source for studying Southern Hemispheric and oceanic events. The purpose of this paper is to investigate the features of the sudden warmings in the Southern Hemisphere winter and spring of 1963 revealed by the 15- μ TIROS VII temperatures.

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³ In this paper the temperatures derived from the 15- μ channel radiation intensities will be referred to as 15- μ temperatures.

2. Data

Three different sets of $15\text{-}\mu$ temperature maps were used. One set was the 10-day mean maps compiled by Kennedy (1966) which were spatially filtered and had isotherms drawn by a computer. The possible effect of clouds was not considered. Two spatial filters were used to retain the longest waves unchanged in amplitude and phase, but to eliminate short waves. The filters effectively eliminated waves shorter than about 20° in the zonal direction, and from 20° to 10° in the meridional direction for 0 to 60° latitude, respectively. The advantage of averaging over time and space was to smooth the random noise of the radiation signal and to extrapolate over gaps between orbital paths and regions not covered by the satellite. All observations that are located in a rectangular area are averaged and the average value applied to the center of the area. For the 1:40 million Mercator map used for this set of maps, the length of the rectangle is constant at 5° of longitude, but the width varies from about 5° of latitude at the equator to 2.5° of latitude at 60° . A 10-day period consolidates 20-70 orbits and, as a result, each grid-point average generally contains several hundred observations. If the grid-point average contained less than 40 observations, it was discarded from the automated isotherm analysis. A disadvantage of the 10-day maps is, of course, that temperature variations with periods less than 10 days are averaged out. To recover some of the lost information from the 10-day maps, single-day maps were examined.

The second set was a group of 50 usable individual day maps over a 127-day period from 15 July to 19

November. The maps were the normal Mercator grid-print maps of 1:40 million scale (Staff Members, 1962) and the same as used in the first set of maps above. On these maps isotherms were drawn by hand using grid-point averages of 10 or more observations. The data for these maps were not filtered.

The third set consisted of 7 single-day maps selected from the 127-day period of set two, to show the temperature minima and maxima before and during the three warmings; they are reproduced in this paper. These maps were plotted and analyzed using the same computer program that produced the 10-day mean maps with two exceptions: grid-point averages from 10 or more observations were retained, and the isotherms were in increments of 5C instead of 2C .

All of the temperatures in the three above sets were corrected for instrumental degradation by NASA's Data Center (Staff Members, 1965). Although each map extends from approximately 60N to 60S there are certain silent areas and data coverage depended upon the number and location of orbits which were available for single days. The number of orbits per day varied from 4 to 8 and the number of observations used in each grid-point value varies from 10 to 100. For the remainder of this paper, " $15\text{-}\mu$ temperatures" will be understood to be from the 10-day mean maps unless individual day maps are specifically referred to.

Radiosonde data, which covered the Australian sector plus four Antarctic stations, were obtained from the Environmental Science Services Administration. Only a few of the soundings extended beyond 70 mb and thus analysis of these temperatures was restricted to 70 mb. Additional data were extracted from pub-

FIG. 1. The $15\text{-}\mu$ and 30-mb temperatures at Campbell Island.

lished reports by Phillpot (1964), Briggs (1965) and Teweles (1966).

It was impractical to consider the effect of cloudiness although the 8–12 μ TIROS VII channel also observed cloud top temperature. To do so would require close estimates of the ground temperature averaged over the precise region “seen” by this channel, in order to estimate cloud height. The effect of clouds is to reduce the 15- μ temperatures, and the higher the clouds the greater this decrease. However, it is considered unlikely that the influence of cloudiness can change the general results of this paper, as the available radiosonde data confirm the 15- μ temperature trends, and the 15- μ data at 60S agree with those at 50S. Furthermore, by taking 10-day means the effect of cloudiness is reduced.

3. Southern Hemisphere warmings

The 15- μ temperatures at 60S, 170E, taken from the 10-day mean maps, were plotted as a function of time as shown in Fig. 1. The plotted point applies to the mid-day of the 10-day period. Since the data were smoothed by averaging and filtering, they do not show the short quasi-periodic oscillations demonstrated by Teweles (1966). They retain only longer period waves. Fig. 1 also contains a time plot of 15- μ temperatures for the same geographic point taken from the single-day maps, as well as for 50S, 170E for every other day from 15 July to 12 November except for a period from 30 July to 15 August when complete data were not available. Both of these curves show short-period oscillations that are not found in the 10-day mean time plot.

The 30-mb radiosonde temperatures for Campbell Island (53S, 169E) taken from Fig. 1 of Teweles' (1966) paper are included to verify that the short-period temperature waves found in the single-day maps are real and not a result of the random noise of the radiation signal. These single-day 15- μ values thus permit a more accurate determination of the warming period than the 10-day means.

Figure 1 shows three major temperature waves from July to November 1963. The approximate dates of the warmings at 60S, 170E are:

First warming	20 July–13 August
Second warming	26 August–16 September
Third warming	16 October–10 November

a. First (mid-winter) warming. As the Southern Hemisphere winter progressed, the stratospheric temperatures decreased, especially in the Antarctic region, due to the seasonal reduction of solar heating. A very strong cyclonic vortex developed near the south pole.

From the middle of June to early August the 10-day mean maps show that the isotherms south of 40S were practically parallel to latitude circles with the coldest temperatures at high latitudes. Slight deviations from a zonal pattern occur in the isotherms in the eastern South Pacific and south Indian Oceans. These areas are somewhat cooler than adjacent areas. The Pacific cold trough is much more persistent than the one in the Indian Ocean. It will be seen later that the western side of the Pacific cold trough is a site for stratospheric warmings in this year. Fig. 2 shows the typical stratospheric thermal pattern for the Southern Hemisphere

FIG. 2. 15- μ temperatures ($^{\circ}$ K), TIROS VII from 2330 GMT on 14 July to 1442 GMT on 15 July 1963.

winter on 15 July. By early August, it appears that a warm air pocket had developed and by 12-13 August definite warm areas were located over the Australia-New Zealand and the South Atlantic sectors as shown in Fig. 3.

During this mid-winter warming of early August, the warm air region over southeastern Australia expanded eastward and apparently southward. It was centered at 40S, 175E on the 10-day mean isotherm map of 9-18 August. The southern vortex shifted to the Weddel Sea while the warm pocket intensified reaching its peak values. Afterward, the southern vortex retrogressed to the South Pacific and the warm center weakened. The temperatures returned to normal by the 18-27 August map period.

The $15\text{-}\mu$ temperature change determined from the 10-day mean maps during an 18-day period from 26 July to 13 August, is summarized in Fig. 4. The $15\text{-}\mu$ temperature increased 10C near the center located near 45S, 170W. The warming is predominantly zonal along 45S. The periphery of the warming extended as far east as Argentina, and westward to the Indian Ocean. On the other hand, no significant temperature increase is seen equatorward of 30S. (Note that the location of a warm center need not coincide with that of the maximum temperature change.)

Although this first warming was not as remarkable as the more intense warming observed with the $15\text{-}\mu$ data in the Northern Hemisphere in January 1964 (Nordberg *et al.*, 1965), the rate of warming was nevertheless appreciable. The 10-day mean $15\text{-}\mu$ tempera-

tures at 60S, 170E reached a minimum of -64C on 26 July as shown in Fig. 1. The temperatures increased to -55C on 9 August, a mean warming of 9C. By 27 August they had returned to the original level of -64C , suggesting that the warming was dynamic in nature, associated with wave perturbation.

The daily temperature curve in Fig. 1 shows an increase of 16C from 20 July to 13 August at the same location and a subsequent cooling of 20C by 26 August. According to rocketsonde temperature measurements at McMurdo Sound (78S, 168E), the warming was greatest at 30 km, perhaps 40C from mid-July to mid-August according to Quiroz (1966). This mid-winter warming was also observed by radiosonde at Macquarie (55S, 159E) and Wilkes (66S, 111E) as illustrated in Fig. 5. The 70-mb temperatures at Macquarie show the warming occurring in two waves with an increase of 6C from 21 July to 4 August and a subsequent decrease of 9C in the next nine days with another surge of warm air that increased the temperature 8C from 13 August to 18 August. The daily $15\text{-}\mu$ temperatures at 50S, 170E also show this warming to occur in two waves as the temperature increased by 12C from 28 July to 13 August, decreased by 6C to 17 August, then increased again by 5C to 22 August. There were no data available at Wilkes between 18 July and 2 August, but after this time, the temperature at 70 mb decreased by 9C to 8 August; afterward, an increase of 12C occurred by 23 August. At 50 mb (not shown) the temperature increased by 14C from 8-23 August. Although the 10-day mean $15\text{-}\mu$ temperatures indicate

FIG. 3. $15\text{-}\mu$ temperatures ($^{\circ}\text{K}$) TIROS VII, from 1423 GMT on 12 August to 0526 GMT on 13 August 1963.

FIG. 4. The $15\text{-}\mu$ temperature change from 26 July to 13 August 1963 in the Southern Hemisphere taken from 10-day mean maps.

that some increase of temperatures should have occurred at Hobart (43S , 147E), the radiosonde data does not show an increase during late July and early August. Unfortunately, there were insufficient daily $15\text{-}\mu$ data at this time and place to help clarify the situation. A significant warming of 14C , however, occurred earlier, between 16–22 July, and may be the same one which appeared about 10 days later, some 20° eastward and downstream of Hobart. The only data in the interior of the Antarctic continent is for 70 mb at Amundsen-Scott (Fig. 5) which shows no warming.

Fig. 6 shows the trajectory of the warm air pockets for all three warmings of 10-day mean periods. The solid curve shows a reasonably reliable trajectory and the dashed curve an extrapolated trajectory. The first warming originated in the Australian region, and moved eastward from the end of July to mid-August. On 18 August this wide warm center divided into two cells with a second center in the southern Indian Ocean. This bipolar temperature wave affirms Godson's (1963) climatology that bipolarity over the southern oceans, but not over Antarctica, may accompany the final warming. This dual warm stratospheric wave was evident in the 10-day maps from this time to the end of the final warming at mid-latitudes. Only a single wave was evident, however, around the 60S latitude circle.

b. Second warming. The $15\text{-}\mu$ temperatures at 60S , 170E reached a minimum of -64C as shown by the 10-day mean map centered at 28 August. The middle stratosphere had warmed to -40C at this location by the map time centered at 16 September, a warming of 24C . The same maps show a warming of 15C and 9C at 50S , 170E and 40S , 170E , respectively. The single-day map of 26 August shown in Fig. 7 indicates that the $15\text{-}\mu$ temperatures at 60S , 170E had experienced a considerable decrease from 12–13 August, reaching values less than -73C , much below what they were before the warming in July. This cooling is verified by the 30-mb temperatures at Campbell Island in Fig. 1. Fig. 8 shows that the middle stratosphere at this same location had warmed to about -38C by 15 September, an increase of 35C .

The 10-day mean maps reveal that a definite warm center had developed near 40S , 75E by 18 August. It moved east from 31 August to 16 September when it was located near 52S , 150E . It then veered to the northeast and by 20 September the warm center was located near 35S , 165E , at which time it disappeared. A 13C warming near 45S , 90E from 17–22 August, moving westward, was reported by Barbé and Reininger (1966) using data from Kerguelen and New Amsterdam. This seems to correspond to the westward portion of the

trajectory of warming II shown in Fig. 6 from 15- μ data. Alt *et al.* (1965) also reported a 20C warming at Campbell Island, to 16 September, agreeing well with warming II from TIROS data.

Fig. 9 shows that the maximum 15- μ temperature change from the 10-day maps from 28 August to 20 September was +24C at 60S, 170E. Increases of 8C or more occurred as far north as 35S in the New Zealand area. Significant warmings, however, occurred almost entirely around the globe at 60S. It should be made clear

that this is not the final warming when the stratospheric winter circulation pattern changes to a summer pattern. The 15- μ temperature maps demonstrate that substantial cooling occurred over most of the Southern Hemisphere before the final warming reached a climax in mid-November. However, this second warming may be considered a preliminary surge of the final warming because its final temperature was warmer than its initial value. A first indication of the final warming appears afterward in the Indian Ocean sector where a

FIG. 5. Radiosonde temperatures during the Southern Hemisphere winter of 1963 for selected available stations and pressure levels.

FIG. 8. $15\text{-}\mu$ temperatures ($^{\circ}\text{K}$) TIROS VII, from 0345 GMT to 1841 GMT on 15 September 1963.

FIG. 9. The $15\text{-}\mu$ temperature change from 28 August to 20 September 1963 in the Southern Hemisphere taken from 10-day mean maps.

FIG. 10. The 70-mb temperature change from 30 August to 16 September 1963 for available stations in the Southern Hemisphere.

warm center (III) starting about 25 September permanently reverses the poleward temperature gradient in that area.

From the limited number of radiosonde stations available, the 70-mb temperature change chart (Fig. 10) places the center of maximum warming, 26°C, toward Macquarie Island (55S, 159E). This center is slightly to the southwest of the center indicated by the 15- μ temperatures. One would have expected Campbell Island (53S, 169E) to show the maximum warming to be consistent with the locations of the 15- μ temperature changes. This small inconsistency may be due to the different levels in the atmosphere represented by the two temperatures. It is possible that the maximum warming occurred further to the southeast at levels above 70 mb, and these levels would be represented better by the 15- μ temperatures. It may be, too, that the maximum warming of the 10-day average, 15- μ temperatures would shift the center slightly from the single day observation at 70 mb. Considering these reasons, and in view of the radiosonde confirmation, the 15- μ mean temperatures still established the location of the maximum warming with excellent accuracy.

The 24°C warming of the 15- μ temperatures and the 26°C warming at 70 mb for Macquarie Island indicate that a much larger warming may have occurred at

higher levels. The change of +13°C in the 70-mb temperature at Campbell Island is exceeded only slightly at the 15-mb level (Fig. 5), indicating that almost equal warming occurred through a deep layer to low levels. On the other hand, Wilkes, which is much farther from the indicated maximum warming center than Campbell Island and beyond the 15- μ temperature coverage, had a warming of 56°C at 10 mb compared to only 5°C at 70 mb. Wilkes and Campbell Island were the only two stations available that had enough data above 70 mb to permit discussion of the vertical structure of the warming. From this limited data, one might conjecture that the warming reached considerably lower altitudes at its northernmost excursion, but was confined to much higher altitudes at its southern extreme.

It is interesting to note that Quiroz (1966) interpreted the McMurdo rocket data as showing a high-level warming from mid-July to mid-August, and a delay of this same warming until September at 20 km. He also says "It is interesting to conjecture that if the warming at 20 km were examined without benefit of the higher-altitude rocket data, it could easily be construed as the beginning of the final (springtime) warming." The interpretation that is made here of the 15- μ temperatures which depict the thermal events

FIG. 11. 15- μ temperatures ($^{\circ}$ K) TIROS VII, from 2334 GMT on 30 September to 1255 GMT on 1 October 1963.

very near 25 km, is that the July–August (first) warming took place at lower latitudes than McMurdo, and that the mid-September (second) warming was in fact the beginning surge of the springtime warming.

c. Third warming. The third warming may be considered as the last phase of the final warming of the 1963 Southern Hemisphere winter. The second and third warmings reported here are considered together as the final warming, following the description of the spring warmings by Godson (1963). Maenhout and Van Mieghem (1964), on the other hand, state that the antarctic final warmings start after the spring equinox; by their criterion, the third warming discussed here would be the final warming and the second would not be a part of it, i.e., a mid-winter warming. In the opinion of the authors, the second warming is one surge of two that constitutes the final warming, because the cooling that occurred after the peak of the second warming did not produce temperatures as low as they were before the onset of the second warming. At 60S, 170E the 15- μ temperatures from the 10-day map decreased from -40°C to -50°C from 16 September to 14 October before the onset of the third warming. After 14 October these temperatures increased by 19°C reaching a maximum of -31°C on 15 November.

The single-day 15- μ temperature map for 1 October is presented in Fig. 11. The thermal pattern shows that warm air had spread into the South Atlantic and western Indian Oceans by 1 October, and the warm air over the western South Pacific had been replaced with relatively cool air. There is no zonal symmetry in the

isotherms now and little south-to-north temperature gradient. Nevertheless, it appears that the spring reversal has not occurred as there is some general cooling around the globe at the higher southern latitudes until 14–15 October (Fig. 12). At 60S, 170E and 50S, 170E the temperatures decreased by 16°C and 15°C , respectively, from the 1 October single-day map. The map for 19 November is given in Fig. 13, which shows that the spring reversal is complete and the isotherms have become organized in a symmetrical pattern along latitude circles except over the area west of the Aleutian chain which, as usual, remains warmer than elsewhere at its latitude. The temperature at high southern latitudes increased to values of -23°C to -33°C . The stratosphere cooled by about 5°C after this time, and then maintained its normal summer pattern indicating that the final warming of the winter had occurred.

The third warming followed the path shown in Fig. 6. The solid curve from 25 September to 28 October indicates the track established by the 15- μ temperatures, and its continuation to 30 November, was determined by extrapolating the 15- μ temperature pattern southward of its field of view, and supplemented by the available radiosonde stations on the Antarctic continent. Indications are that the center continued to move to the southeast after it reached the southern limit of satellite coverage on 11 November, as it was near 75S, 130W on 30 November, the latest date that the warm center could be located from available data. This center was also a division of the previous one, and from 31 August moved westward from the South Indian Ocean

FIG. 12. 15- μ temperatures ($^{\circ}$ K) TIROS VII, from 1844 GMT on 14 October to 0617 GMT on 15 October 1963.

into the Atlantic, recurving eastward after mid-September. At Kerguelen the temperature decreased to -56°C the first half of September and then rose to -45°C by 10 October, apparently as warm center III passed eastward and south of the island.

Fig. 14 gives the 15- μ temperature change from the 10-day mean map centered at 14 October to the one centered at 21 November. Between these dates, a maximum warming of 21°C occurred at 60°S , 170°W . Substantial warming had taken place almost around

FIG. 13. 15- μ temperatures ($^{\circ}$ K) TIROS VII, from 0652 GMT to 2206 GMT on 19 November 1963.

FIG. 14. The $15\text{-}\mu$ temperature change from 14 October to 21 November 1963 in the Southern Hemisphere taken from 10-day mean maps.

the Southern Hemisphere by this time, except in the eastern South Atlantic and southeastern Indian Ocean. The 10-day mean maps show that the latter area, which was warmer initially than the Australian sector, did not reach its maximum temperature until the map centered at 5 December when a -27°C isotherm ran along the 60°S latitude circle between about 30°E and 60°W .

The 70-mb temperature change chart between 15 October and 20 November (Fig. 15) is strikingly similar to the $15\text{-}\mu$ temperature change chart. At 70 mb the maximum warming extended along the 180° meridian from the pole to 65 or 70°S . The location of the warming north of 60°S is in good agreement with the location established by the $15\text{-}\mu$ temperatures. From the stations along the Antarctic coast, it is quite obvious that the eastern South Atlantic and southwestern Indian Oceans had not obtained their maximum temperature by this time and subsequent warming occurred which is in agreement with the $15\text{-}\mu$ temperatures. In a review of antarctic final warmings, Godson (1963) states "it is general observation that temperatures tend to be warmer and final warmings to be earlier in the Australian sector than in South Atlantic sector." Maenhout and Van Mieghem (1964) also

conclude that antarctic stratospheric final warmings propagate across the south pole from the Antarctic coast opposite Australia up to the Antarctic coast opposite South America. The year 1963 appears to be no exception.

4. Comparison of the two hemispheric vortices

During the winter months, the stratospheric polar circulation is dominated by an intense cyclonic vortex centered close to the pole. The formation of the cold cyclonic vortex is the direct result of reduction and withdrawal of solar radiation. The circulation is predominately westerly. The antarctic and arctic vortices are similar in nature but not in detail. Satellite $15\text{-}\mu$ temperature measurements make it possible to follow the variation of mean temperatures in the mid- and lower-stratosphere from winter to summer at high latitudes (60°) from which inferences can be made about the polar circulation.

The distribution of the satellite temperatures in an antarctic vortex is shown in Fig. 16, which was derived from the 10-day mean temperatures established by Kennedy (1966). A large temperature gradient is seen from 45°S southward toward the pole. The true polar-

FIG. 15. The 70-mb temperature changes from 15 October to 20 November 1963 for available stations in the Southern Hemisphere.

night circulation takes place south of 45S. Another feature of interest is a warm belt between 15–45S. Two warm centers are present in this warm belt during 9–18 August 1963, one near New Zealand and another in the south Atlantic and Indian Oceans. The warm belt shifts with season and the warm air pockets move predominately to the east.

To compare the stratospheric polar vortices in the Northern and Southern Hemispheres, two periods, January–June 1964 and July–December 1963, were examined. The 10-day mean satellite temperatures along 60N and 60S from winter to summer were plotted, respectively, in Figs. 17 and 18. There were several interesting differences between antarctic and arctic winter circulations:

- 1) In early winter the antarctic vortex is symmetrical while the arctic vortex is predominately asymmetrical to the pole. The variation of temperature along a latitude circle is insignificantly small in the Southern Hemisphere and large in the Northern Hemisphere along 60°. The latter is as large as the temperature difference between summer and winter at 60N, 180° longitude.

- 2) In mid- and later winter, warm centers occur near New Zealand and in the southern Indian Ocean. The southern polar vortex shifts toward the Weddell Sea. The asymmetry of the southern polar vortex is evident from increasing longitudinal temperature difference (10–12C at 60S). However, the degree of asymmetry of the antarctic vortex is always weaker than that of the arctic vortex. The asymmetry of the antarctic vortex of 1966 was also observed by the Nimbus II satellite (Nordberg *et al.*, 1966). Furthermore, no bipolar pattern of the antarctic vortex was observed along 60S during the whole period.
- 3) The antarctic vortex was more persistent throughout the winter than the arctic one. In 1963, the breakdown of the southern vortex took place 9 weeks after the spring equinox (i.e., the end of November). On the other hand, the breakdown of the arctic vortex occurred only one week after the spring equinox. The difference in timing may be due to stronger baroclinicity of the arctic vortex and the greater annual variability of final warmings in the Northern Hemisphere.

FIG. 16. 10-day mean 15- μ temperatures for 9–18 August 1963. FIG. 17. Temporal variation of 15- μ 10-day mean temperature along 60N (January–June 1964). Months are numbered consecutively from 1–6.

FIG. 18. Temporal variation of $15\text{-}\mu$ 10-day mean temperature along 60S (July–December, 1963). Months are numbered consecutively from 7–12.

- 4) The distribution of the summer stratospheric temperatures along 60S is uniform. This pattern is similar to the temperature pattern along 60N latitude. However, in the southern summer, cooling of about 8C occurred after the peak of the final warming in late November, whereas in the northern summer no cooling is observed after the spring warming in this year and the high temperatures persisted through June. Data from Engberg and Belmont (1964) demonstrate that in some years such temperature decreases are observed there also.

5. Conclusions and recommendations

Rocketsonde, radiosonde and $15\text{-}\mu$ temperature data show that during the 1963 winter the antarctic area experienced one mid-winter minor warming in addition to two warmings that constituted the final one. Although the preliminary satellite values in uncorrected form have already been used to show one apparent warming in the antarctic, this is the first application of the corrected $15\text{-}\mu$ TIROS VII data to investigate the nature of the three warmings in some detail. This study also demonstrates the validity and usefulness of single-day satellite data. It is strongly suggested that future observations of the same narrow CO_2 band be carefully processed to filter out only the random time fluctuations with frequencies less than a few seconds and not to filter data spatially, in order that this system's potentially high resolution in time and space can be realized. The $15\text{-}\mu$ radiation can indeed provide mid-stratospheric temperature data over the major portion of the globe which now has no upper-air observational network at all. Only a truly polar orbit

would further provide such data over the central polar regions where this atmospheric layer experiences dramatic changes and is of most interest.

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