Some Aspects of Antarctic Geophysics*

By H. WEXLER, Chief Scientist, US-IGY Antarctic Program, National Academy of Sciences, Washington, D. C.

(Manuscript received July 5, 1957)

1. Introduction

This paper is concerned mostly with the Antarctic Ice Sheet—first, the time required for the ice to build up to its present mass; second, its present budget in terms of annual import and export; and third, its important role in the manufacture of cold air.

The discussion will be suggestive rather than conclusive and will attempt to illustrate the need for the type of data which will be collected in the Antarctic during the International Geophysical Year.

2. Time Required to Build Up the Antarctic Ice

The transfer of water from the oceanic reservoir through the narrow bottle-neck of the atmosphere to the polar ice sheets must be a very slow process, since at any one time the atmosphere contains only 10^{-5} of the water found in the ocean, while the present land ice sheets have locked up as much as 2% of the water contained in the oceans. To estimate the time required for the Antarctic Ice to build up to its present mass we must first estimate this mass.

The area covered by the thick (non-annual) inland and shelf ice attached to Antarctica has been estimated by KLEBELSBERG (1948) to be $13.5 \cdot 10^6$ km². An earlier figure of 1,600 meters for the average thickness is thought to be too small, SHARP (1956), GOULD (1957). Recent observations of ice: 2,800 meters thick 400 km inland from Maudheim (71° S, 11°W), (ROBIN, 1953), figure 1; 3,000 meters thick in the vicinity of the Byrd IGY Station, 80° S, 120° W, (1,515 meters m.s.l.), (BENTLEY and CRARY, 1957); and 3,000 to 3,500 meters thick in the vicinity of the Pioneerskaya IGY Station, 69° 44′ S, 95°30′ E (2,700 meters m.s.l.), 375 km inland from Mirny (AVSIUK, 1957) all point to thicker ice than formerly believed. An average thickness of ice of 2,000 meters over the $13.5 \cdot 10^6$ km² area is assumed which, taking an average density of 0.9 for the ice, amounts to a mass of $2.43 \cdot 10^{22}$ gm.

If we now visualize an idealized Antarctic continent bounded by the 70° S latitude circle let us estimate the transport of water vapor across this boundary. If we use the value of

* Paper presented at Fourth CSAGI Conference on the Antarctic, Paris, France, 13 June 1957.

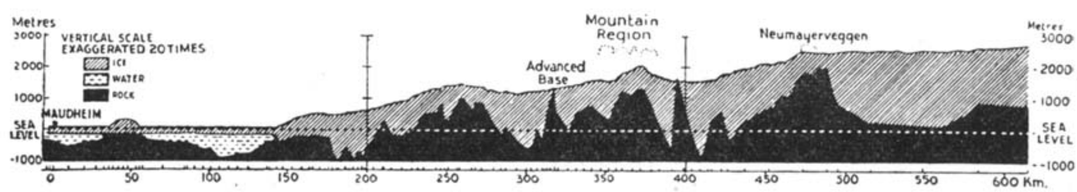


Fig. 1. The main seismic profile showing the ice and rock profiles inland from Maudheim, Antarctica. The vertical strokes above the distance scale indicate points at which seismic soundings were made [after Robin (1952]).

$0.8 \cdot 10^{11}$ grams per second crossing the 70° *North* latitude circle computed from Northern Hemisphere observations during 1950 by STARR and WHITE (1954) and assume that all the water is deposited as snow, this transfer process would take 9,650 years. Another estimate made by LOEWE (1956) for transport across the 70° *South* latitude circle is two-thirds as large, or $0.52 \cdot 10^{11}$ gm/sec, giving 14,800 years as the time required for the ice to build up to its present size. Since both these figures assume no loss during the period of ice deposition, these times must be regarded as *minimum* values provided the transport of water vapor across latitude 70° South remains the same throughout the whole period.

3. Present Antarctic Ice Budget

If we use the Starr and White Northern Hemisphere water vapor transport figure the import across 70° S is $2.52 \cdot 10^{18}$ gm/yr and, if we use Loewe's figure, it is $1.62 \cdot 10^{18}$ gm/yr; the latter figure is equivalent to an average liquid precipitation of 12 cm/yr over Antarctica.

According to LOEWE, the export by blowing snow, extrapolated from the values measured at the notoriously windy Adélie Land coast and therefore probably too high as a mean for the entire coastline, is $0.28 \cdot 10^{18}$ gm/yr and that due to calving of ice bergs is $0.04 \cdot 10^{18}$ gm/yr.

This later figure is based on an estimate by Loewe of the annual movement northward of 20 meters per year of a 150 meter thick shelf ice whose northern boundary is at 70° S. Other estimates, SHARP (1956), GOULD (1957), for the Ross Ice Shelf (in the vicinity of the Bay of Whales) are more than ten times larger.

Loss by run-off from melting snow or evaporation is nil. But the melting of the shelf ice by the sea may be appreciable and to estimate this we use Sverdrup's figure of the heat transport by that component of the wind-driven ocean current directed into the ice shelf near Maudheim (SVERDRUP, 1953). The annual average temperature of the surface layer of the ocean is 0.3°C above the freezing point of sea-water and if all the heat thus transported into the ice barrier were used to melt ice it would melt $1.30 \cdot 10^{18}$ gm/yr. The budget is summarized in Table 1.

Table 1. Antarctic Ice Budget (in 10^{18} gm/yr)

Import	
By water vapor transport across 70° S (Loewe)	1.62
Export	
By blowing snow (Loewe)	.28
By calving of ice bergs (Mawson & Loewe)	.04
By melting of ice (Sverdrup)	1.30
	1.62

Using these figures, a balanced budget is achieved but the agreement of the two numbers is probably fortuitous because of the many uncertain factors. For example, not all of the energy transported into the barrier may melt ice—some of it after sinking may not push under the ice shelf but may turn northward as illustrated in Sverdrup's figure (figure 2). Sverdrup estimates that only 10 % of the southerly transport of oceanic heat into the barrier would be required to off-set the annual accumulation of 40 cm of water equivalent along a 30 km wide strip of the shelf ice at Maudheim. But if the entire Antarctic Ice is to be in balance on the basis of the above budget, then the amount of ice to be melted each year would have to be the equivalent of a *strip of ice one meter thick, 100 kilometers wide of an ice shelf whose northern terminus is the 70° South latitude circle.*

Referring to Robin's Queen Maud Land Ice Profile in figure 1, there is evident a slight increase of the ice thickness near the 100 km mark which perhaps may be interpreted as evidence of such melting to the north.

If, however, future observations show melting of the bottom of the ice shelf to be negligible or even negative (i.e., accretion by freezing of sea water) then the above budget can be balanced only by a much larger "calving" of ice from the ice barrier than observed by Mawson and Loewe in the Adélie Land coastal area. To achieve a balanced budget by the calving process and not by melting, each year a 500 meter wide strip of shelf ice 200 meters thick would have to break away all around the 70° S latitude circle as compared to 30 meters estimated by Mawson, and 20 meters by Loewe. There is additional evidence, (CRARY, radio message, 30 May 1957 and HAWKES, private communication, June 1957, based on

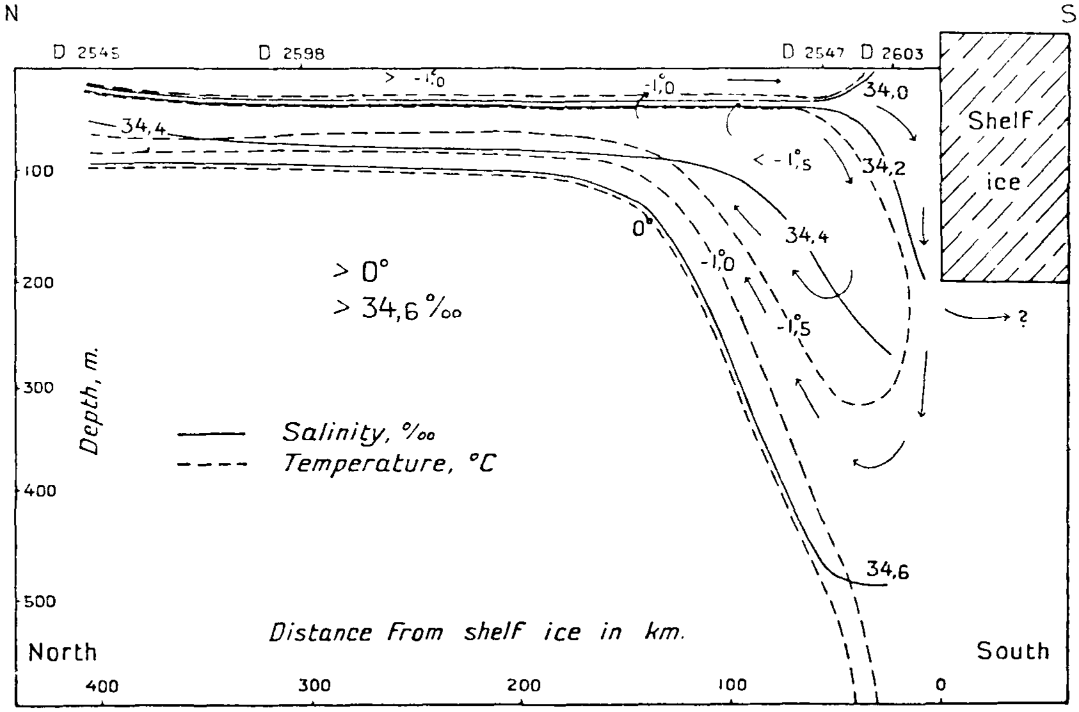


Fig. 2. Vertical section at right angles to the coast line in about longitude 2° E (Queen Maud Land), showing distribution of temperature, salinity, and probable vertical circulation [after Sverdrup (1953)].

observations made in 1947 and 1955) which supports Gould's measurement of 1929—30 that near the former Bay of Whales at Little America the ice edge is moving northward and presumably breaking off at nearly the 500 meter/year rate required but because of the influence of Roosevelt Island it is questionable whether this value is representative of the remainder of the Ross Ice Shelf and other ice shelves.

Observations taken in the International Geophysical Year should throw considerable light on the annual import of water vapor and whether the principal loss of the Antarctic ice is from melting by the sea or by the calving process.

4. The Ice as a Source Region for Polar Air

Antarctica as a whole averaged over a year is a radiative cold source. For example, Liljequist (1956) showed that at Maudheim the average net radiative loss (taking into account the effective incoming solar radiation and outgoing infra-red radiation) is 25 ly day^{-1}. (1 langley (ly) equals 1 cal/cm^2). At Port Martin (3° farther north) Loewe (1956) found a net loss 20 ly day^{-1} and for the inland ice as a whole he computed a net radiative loss of 100 ly day^{-1}.

Liljequist showed the net radiative loss at Maudheim is off-set by the turbulent transport of heat downward from atmosphere to the surface and the upward conduction of heat from the interior of the snow, but still leaves a deficit of 4.5 ly day^{-1}, which must be balanced by hoarfrost deposit of 2.4 grams per year.

What happens to mild maritime air as it moves over such an enormous cold source as Antarctica? This problem was studied under the assumption that only infra-red radiative exchanges between snow surface, atmosphere and space are involved (Wexler, 1936). The computation therefore neglected (i) solar radiation (the cooling occurred during the polar night); (ii) turbulent transport of heat downward (calm conditions were assumed); and (iii) no heat conducted upward from the snow (considered to be a perfect insulator).

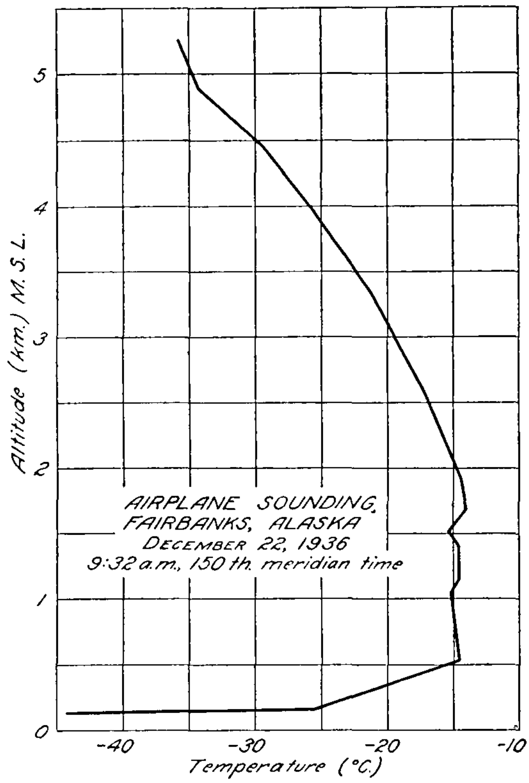


Fig. 3. Airplane sounding, Fairbanks, Alaska, December 22, 1936.

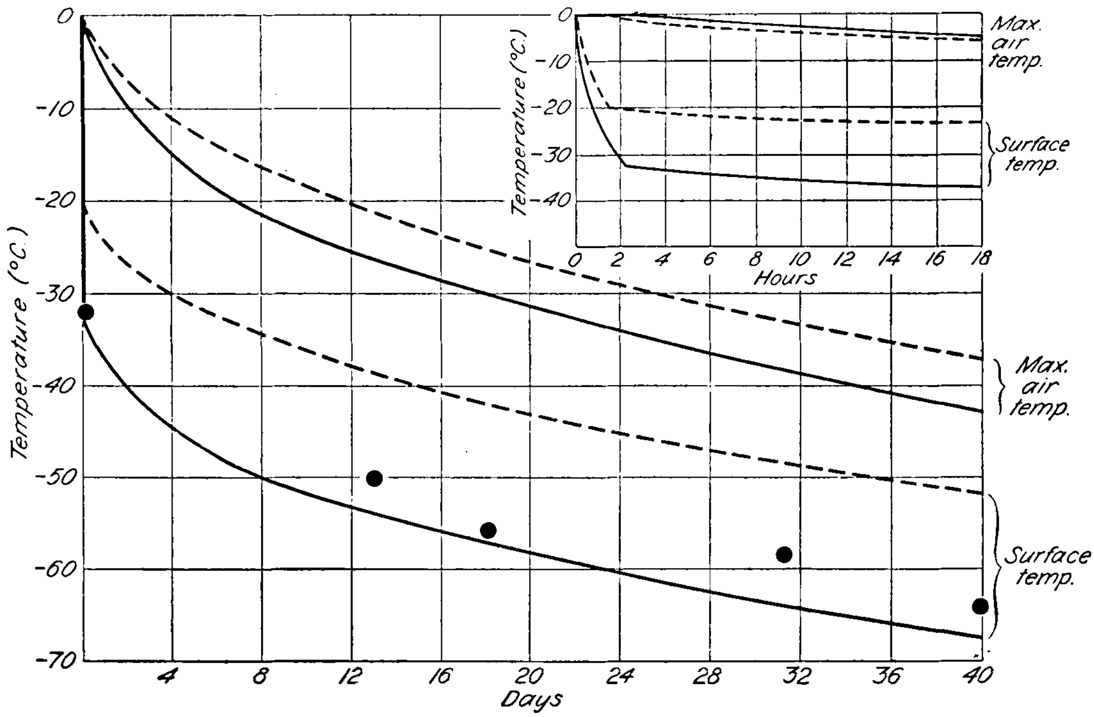
5. Rate of Cooling of the Air

Under these conditions the atmosphere cools mainly from below, undergoing a succession of quasi-radiative equilibrium states characterized by a strong increase of temperature with height above the surface (surface inversion) and isothermal conditions above to the top of the cooled layer as illustrated in figure 3 (WEXLER, 1937). Since as time proceeds, thicker and thicker layers of air are cooled accompanied by a smaller and smaller energy loss, the rate of cooling decreases asshown in figure 4 (WEXLER, 1936). Considering only the full lines (which apply to an atmosphere of normal infra-red radiative properties), the cooling initially (shown in the inset diagram) is very rapid until a "critical" temperature of —33°C is reached and progressively thicker layers of air join in the cooling. The cooling rate then slows down appreciably as shown in the larger diagram. Plotted in this diagram are large black dots showing the downward progression of surface air temperatures at the Amundsen-Scott IGY (South Pole) Station. During the past Antarctic summer (December and January) the temperatures were between —18°C and —30°C and first reached the critical value of —33°C on February 12, 1957, and successively lower temperatures at later dates as indicated by the black dots. It is interesting to note that none of the dots fell below the computed curve although this was constructed for an atmosphere resting on sea-level and not for one resting on the 2,800 meter high South Polar Plateau; the latter atmosphere should have much less water vapor and therefore be capable of cooling more rapidly than a sea-level based atmosphere.

6. Upper Air Conditions over the South Pole

On May 11, at 1445 GMT, 88 days after the "zero" day of February 12, 1957, the South Pole surface temperature dropped to —73.6°C to establish a new world's record low temperature. On September 17, 1957 the temperature fell to — 102.1° F to establish a new record. A radiosonde ascent made at 0000 GMT on May 10, thirty-nine hours before the record low temperature was measured, is shown in figure 5. The strong surface temperature inversion called for in theory is clearly present to a degree never before observed—an increase of 31°C in 850 meters. Above this height the normal temperature decline with height is found terminating in a well-marked tropopause inversion of 3°C at 8,500 meters above sea level or 5,700 meters above the station. After maintaining near-isothermalcy at approximately —62°C for the next 4 kilometers, the temperature drops to —77°C at 20 km above which another inversion, suggestive of a second tropopause, is found. (The same phenomenon was also observed 1 kilometer lower in the sounding taken 24 hours later.)

The maximum temperature of —60°C at the bottom of the stratosphere represents a drop from the —40° characteristic of polar stratospheres—both Antarctic and Arctic—in the summer. The cooling rate of the 11 to 15 km layer of air which averages 0.35°C per day from late March to April 1957, is very close to the value of 0.30°C per day computed by GOWAN (1947) by night-time radiative cooling from the ozone, water vapor and carbon dioxide present in the lower stratosphere.



Computed thermograms based on (a) Hettner's data in atmosphere of abnormal CO_2 content (shown by broken lines; (b) Weber and Randall's data in atmosphere of normal CO_2 content (shown by solid lines).

Fig. 4. Air temperatures versus time - computed (1936) (solid lines) and observed (black dots) at IGY South Pole Station (1957).

7. Stratospheric Versus Tropospheric Cooling

Another radiosonde report from the South Pole taken on June 17 at 1200 GMT was sent to Washington and is plotted on figure 5. The lower half of this sounding is almost identical with that on May 10th but is considerably cooler in the stratosphere. If the June sounding is taken as representative of June conditions at the Pole it would indicate that unequal cooling has occurred—namely, the troposphere temperatures are virtually the same but the stratosphere has cooled by 8° to 10°C. This unequal cooling decreases greatly the intensity of the tropopause inversion and would account for the absence of the winter tropopause observed in Antarctica by COURT (1942), and more recently by SCHUMACHER (1955). The cooling rate in the lower stratosphere from May 10 to June 17 is 0.25°C per day, again very close to Gowan's computed value.

The lack of a corresponding temperature drop in the troposphere may perhaps be indicative of a very strong advection of warm air in this layer but not in the stratosphere. The very rapid fall of surface air temperature at the South Pole from February to May and recovery to higher values thereafter is believed to be indicative of a strongly overcompensating horizontal heat advection arising from the increasing winds caused by unequal radiative cooling of Antarctica and the surrounding oceans. For example, at the South Pole, the average surface air temperature for May 1957 was —55.7°C, or 0.8° higher than the —56.5°C value observed in April. At the Byrd IGY Station at 80° S, 120° W, the average surface air temperatures for April and May were exactly the same, —35.8°C, but both the minimum and maximum air temperatures for May were higher than those for April. These values, indicating a reversal of what one would expect to be a strong seasonal trend downward, has

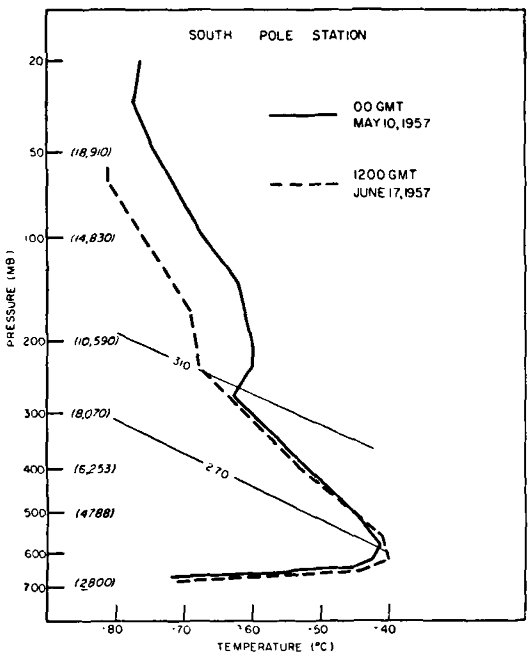


Fig. 5. Radiosondes at the IGY South Pole Station 0000 GMT, 10 May 1957 and 1200 GMT, 17 June 1957. Figures on the right hand side of the ordinate refer to the height above sea level in geopotential meters.

its counterpart in Little America where, on the basis of six years of observations, the June temperature averages 5°C higher than the May temperature (COURT, 1949 and unpublished data for 1956 and 1957). If, after a few years more of observations, this reversal of the "normal" seasonal decline of temperature in the autumn and early winter is found to be characteristic of much of Antarctica, it may reveal that horizontal advection of heat from lower latitudes more than makes up for the loss by outgoing radiation, thus requiring far stronger northerly winds aloft than formerly believed. It is of interest to note that at the same time that the South Pole IGY Station had its —73.6°C temperature, Little America, 1,200 km to the north, was enjoying a temperature of —1°C with a 60-knot gale from the ocean.

8. Micrometeorology of the Record Low Temperature

The time-sequence of the vertical air temperature profile 10 meters above the snow, wind and cloud amount is shown in figure 6. The temperatures at the snow surface, 2 meters (shelter level), 5 meters, and 10 meters are plotted in a series of vertical profiles starting at 0000 GMT on May 9th and ending at 1800 GMT on May 11th.

The wind speed is given in meters per second, the wind direction is the meridian along which the air blows to the south and the extent of cloud cover is shown by the partial filling of the circle. Initially, starting with a wind speed of 5.7 m/sec from 110° East and the skies clear, there are some unexplained variations of the temperature profile culminating in a large surface inversion of 6°C in 10 meters. However, when the wind speed dropped to the low value of 2.1 m/sec the air temperature at the shelter height of 2 meters achieved its record low of —73.6°C while the snow surface temperature fell to —74.2°C ($T_c \sim -84$°C refers to the snow surface temperature which would have been observed if there had been no eddy flux of heat downward from the atmosphere or conduction upward from within the snow).

However, in the next few hours strong advection of air from the Ross Sea, which was clearly indicated on the 500 mb and 300 mb weather charts drawn at the IGY Antarctic Weather Central at Little America, brought in clouds which covered half the sky. The black-body radiation from this cloud, which can be no colder than the tropopause temperature of —62°C, warms the snow surface temperature from its minimum of —74.2°C to —65.3°C in less than 4 hours. Compared to the effect of clouds the slight increase in wind speed makes a negligible contribution to the observed increase of the surface temperature from 1445 to 1800 GMT. The increased radiation from clouds to the snow surface is the actual mechanism by which heat, brought in by the compensating advection mentioned earlier, warms the snow surface and adjacent air.

In closing this brief account of some aspects of Antarctic geophysics I wish to pay particular tribute to the observers, both those at the present IGY Stations and those who manned the earlier stations, who, under most difficult conditions, took the observations which formed the basis of this paper. I wish also to thank my colleagues Mr. R. A. McCormick and Mr. M. J. Rubin for their assistance in the preparation of this paper.

6—709370

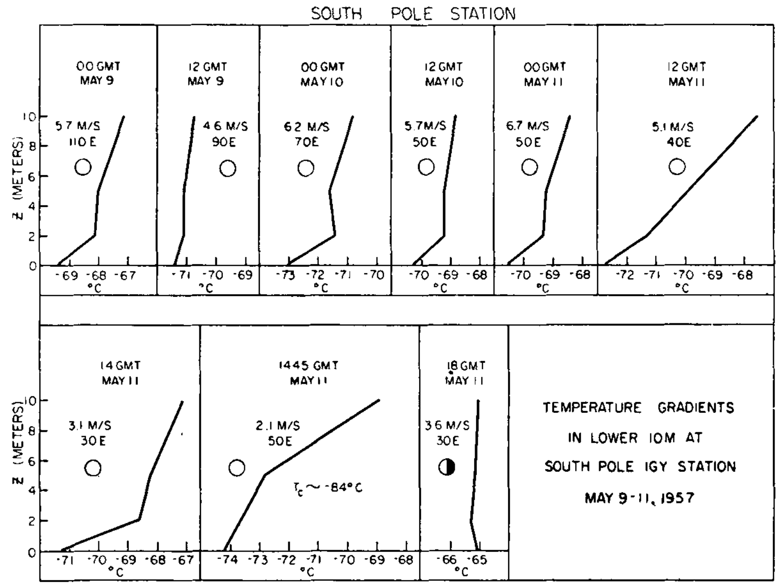


Fig. 6. Time sequence, lower 10 meters temperature profile, winds and sky cover at IGY South Pole Station.

REFERENCES

AVSIUK, G. A., 1957: Études Glaciologiques Faites par L'Expedition Antarctique Soviétique, paper presented at IV CSAGI Antarctic Conference, Paris, 13 June 1957.

BENTLEY, C. R., and CRARY, A. P.: radio message, 31 March 1957.

COURT, A., 1942: Tropopause Disappearance during the Antarctic Winter, *Bull. Amer. Met. Soc.*, **23**, pp. 220—238.

— 1949: Meteorological Data for Little America III, *Mo. Wea. Rev.* Suppl. 48.

GOULD, L. M., 1957: Antarctic Prospect, *Geogr. Rev.*, XLVII, No. 1, pp. 1—28.

GOWAN, E. H., 1947: Night Cooling of the Ozonosphere, *Proc. Roy. Soc.*, *A*. **190**, pp. 227—231.

KLEBELSBERG, R. V. 1948—49: *Handbuch der Gletscherkunde und Glazialgeologie*, Wien.

LILJEQUIST, G. H., 1956: Energy Exchange of Antarctic Snow Field, Long-Wave Radiation and Radiation Balance, Norwegian-British-Swedish Antarctic Expedition, 1949—52, *Scientific Results*, II.

LOEWE, F. 1956: Études de Glaciologie en Terre Adélie, 1951—52, Act. Scient. et Industr. 1247, Exp. Pol. Fran., Hermann & Cie, Paris.

ROBIN, G. de Q., 1953: The Norwegian-British-Swedish Antarctic Expedition, 1949—52. Part II: Summary of Seismic Shooting Investigations in Dronning Maud Land, *Jour. Glaciol.*, **2**, n. 13, pp. 204—211.

SCHUMACHER, N. J., 1955: Upper Air Temperatures over an Antarctic Station, *Tellus*, **7**, pp. 87—95.

SHARP, R. P., 1956: Objectives of Antarctic Glaciological Research, Chapter in *Antarctica in the Geophysical Year*, Geophys. Monogr. No. 1, American Geophysical Union, Wash., D. C., pp. 27—35.

STARR, V. P., and WHITE, R. M., 1954: Balance Requirements of the General Circulation, in *Studies of the Atmospheric General Circulation*, Mass. Inst. Technol., Final Report, Par i, Gen'l Circ. Proj. pp. 186—242.

SVERDRUP, H. U., 1953: The Currents off the Coast of Queen Maud Land, *Norsk Geogr. Tidsskrift*, Bd XIV, nr. 1—4.

WEXLER, H., 1936: Cooling in the Lower Atmosphere and the Formation of Polar Continental Air, *Mo. Wea. Rev.*, **64**, pp. 122—136.

— 1937: Absorption of Radiation by Water Vapor as Determined by Hettner and by Weber and Randall, *Mo. Wea. Rev.*, **65**, pp. 102—104.