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Satellite pictures in the study of snow hydrology over Western Himalayas

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ABSTRACT. Satellite APT pictures for the past few years were examined to study snow cover and snowline over the Western Himalayas. Selected pictures for different months were studied in detail and a suitable method of snow measurements over the Himalayas for operational use was evolved. The results obtained relate to snow cover, appearance of snow, snowline and its variations from place to place. The periods of maximum and minimum snow cover and maximum snow melt are pointed out. The activity of western disturbances with reference to snow cover in winter and the water budget of the Himalayan rivers in summer are also touched upon. The snowline measurements compare well with the measurements made by other methods—Gemini V pictures, trigonometrical observations and estimates by ground-based personnel. At times in winter, the snowline comes down as low as 900 m a.s.l. An interesting observation is the location of snowline at a higher elevation on the Tibetan side than on the Indian side. The influence of thick glaciers on the snowline in the west Uttar Pradesh region of the Himalayas is pointed out. The accuracy of the various measurements involved in the method are also discussed in detail. The study establishes the feasibility of reliable measurements of the Himalayan snow from APT pictures and focusses attention on the vast wealth of data that can be derived from these pictures.

1. Introduction

An important application of satellite data is in the field of snow hydrology. Satellite TV pictures and infrared data over cloud free-portions of the globe provide information about the extent of snow cover over the earth, its depth, the condition of snow as well as snow melt. From the time of the early TIROS satellites, the importance of snow and ice studies using satellite pictures had been recognised and many of the early studies in the field (Fritz 1962 and 1963; Wark and Popham 1962 a, 1962 b) brought out the usefulness of satellite pictures for this purpose and also indicated the direction in which the studies should proceed. With the improved type of satellites after 1965, research was intensified to use satellite pictures for snow studies, and techniques have been developed in USA and USSR to utilise the data on an operational basis (Barnes and Bowley 1968, 1969; Popham 1968; MaClain and Baker 1969; MaClain 1970; Ramey 1970 and Temnikov 1970). Satellite data in the form of TV pictures (AVCS and APT) as well as in the digitised form have been utilised for this purpose.

The only area in India, covered by snow is the Himalayas where some of the major rivers of the subcontinent have their origin. Knowledge of snow cover over this region is, therefore, of importance to hydrological interests. Any information that can be derived from satellite data regarding the snowline, estimates of snow accumulation and snow melt, the periods when they occur as well as the areas involved will be of great use to hydrologists. At present, the information collected for the purpose is very meagre and quite unrepresentative. Since satellite pictures (APT) are now being received in our country every day, it is only logical that we should look into the problem of utilisation of satellite data for snow hydrology over the inaccessible areas of the Himalayas. An examination of APT pictures received during the last five years shows that some useful information about snow cover can be obtained from these pictures. This study was, therefore, undertaken to find out how best these pictures can be put to use for this type of work.

2. Method of analysis

The APT pictures for the past few years (available at Poona) were scanned through and a selection was made of representative samples of useful pictures in each month. The conditions imposed on this selection were:

(*i*) that a large area over the Himalayas is to be cloud-free,

(*ii*) the picture quality should be high, and

(*iii*) the area to be studied is not towards the edge of the picture.

These conditions limited the number of available pictures. Since it was found that it is more difficult to obtain cloud-free pictures of the Eastern Himalayas, the study was confined only to the Western Himalayas. Out of the selected pictures, one typical of each month of the year was chosen for detailed study. In all, nine pictures (seven APT and two Nimbus AVCS*) belonging to 1969 and 1970, were studied.

The method used by the authors to delineate the snow cover and the snowline in the satellite pictures is essentially the same as the one developed by Barnes and Bowley (1968, 1969) and the method was modified to the extent necessary for application to suit the region under study. The method** is briefly outlined below.

The portion of the picture covering the Western Himalayas was enlarged to about sixteen times the size of the original APT picture (without causing any fuzziness) and the prints were taken on a superior quality paper. On the enlarged picture, the latitude/longitude lines were interpolated at each degree interval from the operational grids drawn at 5° interval and the one degree interval grids were drawn on an overlay over the picture. From the recognisable landmarks on the picture (particularly in and near the snow cover area under study†), a mean correction to the latitude/longitude grids was obtained and it was applied to the grids drawn on the overlay. An analysis of the pictures was made on the following lines to delineate the snow cover and snowline —

(*i*) The area of snow coverage was marked after identifying the snow on the picture and examining the pattern appearance and pattern stability of the snow cover.

(*ii*) The boundary of snow cover was transferred to the overlay and the area enclosed by the boundary line was measured with a planimeter.

(*iii*) The geographical coordinates‡ of selectted points along the snow boundary‡‡ were determined and by referring to Survey of India maps on a large scale (1: 1,000,000) the contour heights at these selected points were read off. The contour heights are available on the Survey of India maps at 300 m interval. The heights thus read off from the contour charts are the heights of the snow line approximately at the different geographical locations. Such snowline height delineation was made on each picture at half a dozen to dozen points over the Western Himalayas.

3. Snow Cover

The features of snow cover observed on the nine satellite pictures (Figs. 1-9) and the inferences that could be drawn from the snow cover and snowline measurements made from the pictures are discussed in the next few paragraphs.

The main features†† of snow cover noticed on the pictures are as follows —

(*i*) *Pictures for 28 January 1970 and 17 February 1970*

Figs. 1 and 2 show Himalayan snow at its maximum. The snow cover is quite bright. The valleys are dark in contrast and the pictures thus bring out the ridge-valley pattern of the Himalayan region very clearly. Srinagar valley could be well recognised with the Pir Panjal Range to the southwest being snow bound.

The picture of 28 January 1970 (Fig. 1) was taken immediately after a spell of heavy snowfall over the entire Western Himalayas caused by a series of active western disturbances. On 17 Feburary 1970 (Fig. 2) there was no recent snowfall. An examination of these two pictures bring out some significant contrast. In Fig. 1 more area is covered by snow than in Fig. 2. In particular, the snow boundary on the Tibetan side of the Himalayas, is more to the east in January than in February. Apparently this is due to the freshly fallen snow in January having been blown off downwind by the prevailing strong winds and spreading eastwards before it finally melted. Many river valleys (for instance, *Sutlej* river valley) which are

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*The Nimbus AVCS pictures were obtained through courtesy of Mr. Lewis J. Allison of NASA, Greenbelt, Md., USA.

**For greater details about identification of snow cover, its mapping etc the reader may refer to the references listed at the end.

†This is necessary as corrections may vary from portion to portion of the picture and we will have to determine the geographical locations of points along the snow boundary correct to very nearly one minute.

‡See further discussion on this point in sub-sec. (*iv*) of Sec. 5.

‡‡It is necessary to choose the points at places where the boundary is quite sharp.

††These features are as seen in the original APT/AVCS and their enlargements. It is quite possible that in the printed diagrams, many of the details noticeable in the original pictures are lost. Such loss of detail in second or third generation prints is unavoidable.

clearly seen in February picture can only be faintly seen in the January picture, particularly their upper reaches; the dark areas associated with the valleys are also somewhat narrower in January picture suggesting that parts of the valleys also have become heavily snow-covered. Pir Panjal Range has heavier snow cover than in February picture. In contrast to February picture where the edge of the snowline is sharp, there is a certain blurring of the snow boundary in January picture. This indicates that a small depth of snow deposited by the western disturbances in the lower ranges has not yet melted away. The snowline determined from the January satellite picture was as low as 900 m a. s. l. at some places.

(*ii*) *Picture for 2 April 1969* — Fig. 3 is in many respects similar to the pictures of January and February. A very important difference, however, is the mottled appearance (*i.e.*, white areas being interspersed with grey to dark holes) of the snow-covered area which is indicative of the snow getting old and gradually thawing at places. This mottled appearance was absent in the picture for 20 March 1969 (not presented) suggesting that the thawing must have started only towards the end of March. This agrees with the monthly river discharge data presented by Gupta and Abbi (1971).

(*iii*) *Picture for 22 May 1970*—Fig. 4 shows a large contrast from the earlier ones. Considerable snow melt has occurred by this time and the snow-covered area has been broken into a dendritic pattern. We could also recognise (particularly south of 35°N) bright spots of snow, surrounded by relatively grey coloured snow cover, indicative of the melting in the lower ranges (around the peaks) while the higher ridges are still heavily snow bound. To the north of 35°N, many rivers and valleys which were not clearly seen in the earlier pictures show themselves up as the snow has melted (for instance, river *Oxus* and its tributaries).

(*iv*) *Pictures for 19 July 1969, 4 August 1969 and 2 October 1970* — Pictures shown in Figs. 5 to 7 are in complete contrast to the winter time pictures. While a certain amount of snow cover persists over the Karakoram and Pamirs, a gradual decrease can be noticed from July to October. From this set of pictures, October (Fig. 7) appears to be the month of minimum snow cover. The snow cover seen in October picture is the permanent snow over the Himalayas.

(*v*) *Pictures for 18 November 1970 and 3 December 1969* — Figs. 8 and 9 when compared with October picture (Fig. 7), indicate the beginning of accumulation of snow particularly north of

Fig. 1

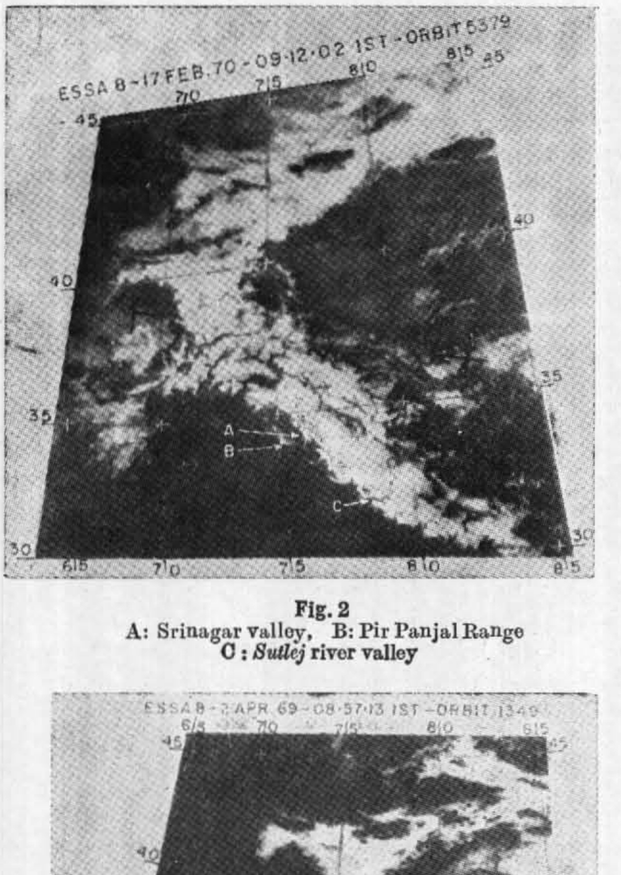

Fig. 2
A: Srinagar valley, B: Pir Panjal Range
C : *Sutlej* river valley

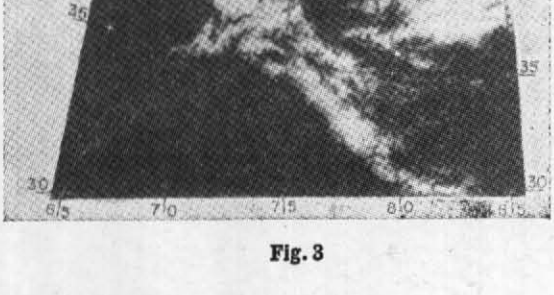

Fig. 3

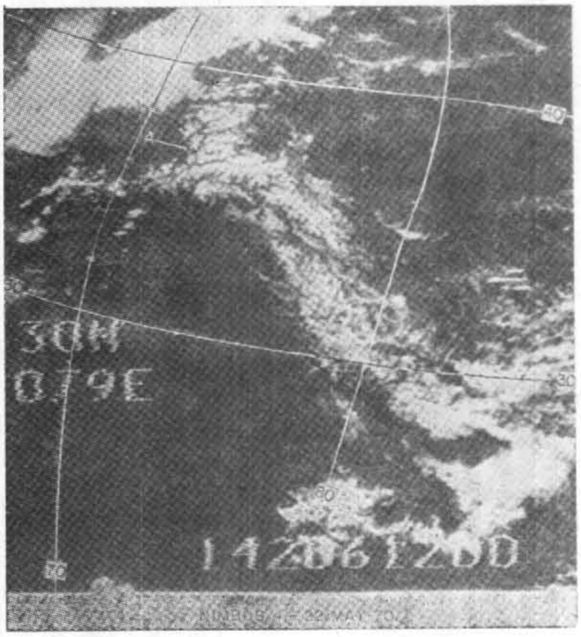

Fig. 4

A : River *Oxus*

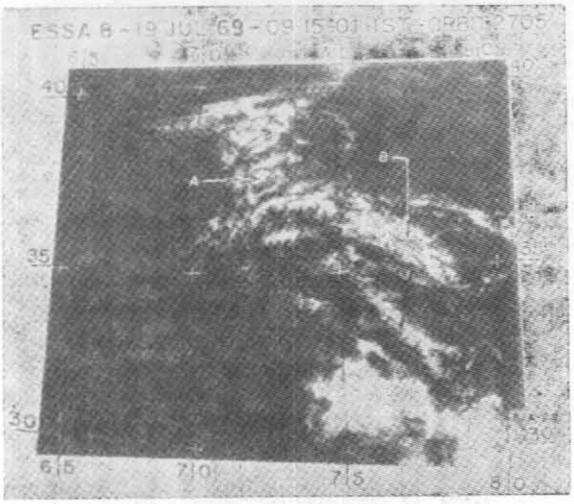

Fig. 5

A : Pamir Plateau, B : Karakorum Range

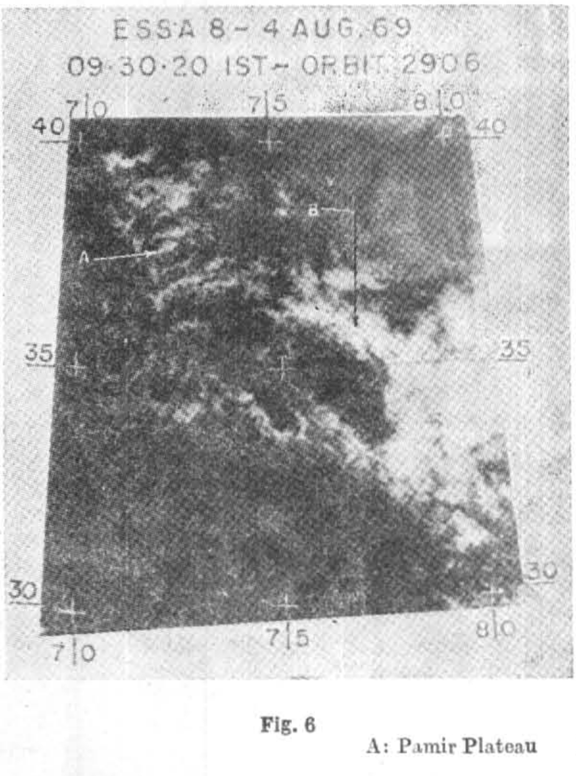

Fig. 6

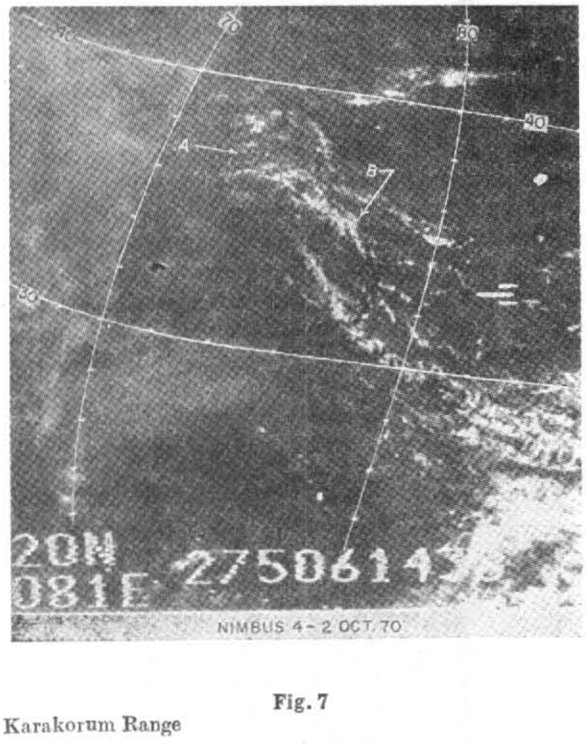

Fig. 7

A: Pamir Plateau B: Karakorum Range

35°N. The relatively larger snow coverage in November 1970 south of 35°N (in contrast to December 1969) is due to early western disturbance activity in November 1970.

The areas of snow cover over Western Himalayas as determined from these nine pictures, using a planimeter, are shown in Fig. 10, from which the following conclusions can be drawn.

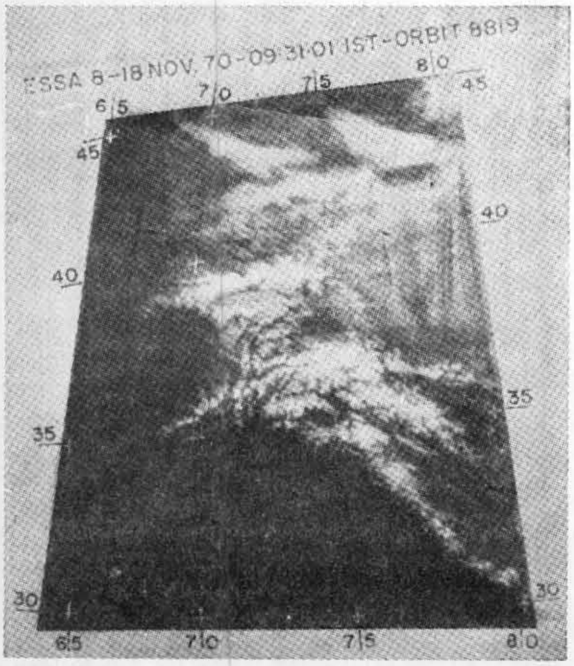

Fig. 8

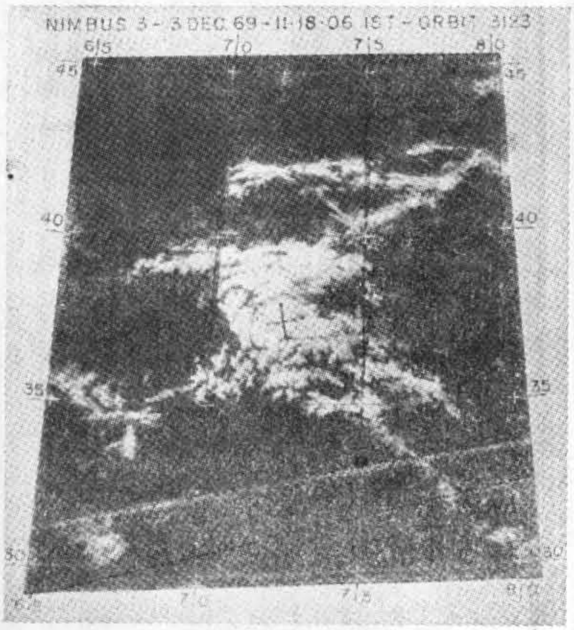

Fig. 9

(*i*) The area covered by snow reaches a maximum in the second half of winter, when the activity of western disturbances is pronounced over the area. It is nearly one lakh sq. km.

(*ii*) This extensive snow cover persists till spring, when melting of snow begins (as seen from the appearance of snow cover in April picture).

(*iii*) May and June are the months when the maximum snow melt takes place; significant snow melt continues even in July, though the amount may be less than in the previous two months.

(*iv*) August, September and October are the months of minimum snow cover. In these months all the snow left over the Himalayas is apparently only the permanent snow. This covers only just one tenth of the coverage in winter.

(*v*) Though winter* conditions set in over this area by November, still the snow accumulation is very small in the early part of winter (November-December).

(*vi*) Even in the winter months, there is a temporary increase in the snow coverage in association with active western disturbances. The snow area once again shrinks well after the effect of the western disturbances is over and the temperatures begin to rise subsequently, as illustrated by January and February pictures. In the first half of January 1970, there was no precipitation worth mentioning in the Western Himalayas. However, in the second half of the month on account of passage of western disturbances in quick succession there were three spells of widespread and heavy snow fall over the Western Himalayas causing accumulation of snow over the areas. This large accumulation has been depicted very clearly in the satellite picture for 28 January 1970. However, after 1 February, for the subsequent two weeks or so, weather was nearly dry over the Western Himalayas. Apparently on account of the increased insolation due to the absence of any major synoptic system, the snow in the lower reaches melted during this fortnight and the snow boundary receded upwards, particularly on the Tibetan side.

(*vii*) Fig. 10 also gives us an idea of the approximate snow accumulation during winter caused by the western disturbances and the snow melt during summer. Even though the depth of the snow could be widely varying from place to place, this

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*According to the convention in India Meteorological Department winter period consists of January and February. In the present paper, however, the period November—February has been taken as winter, as winter conditions prevail over the Western Himalayas, even from November.

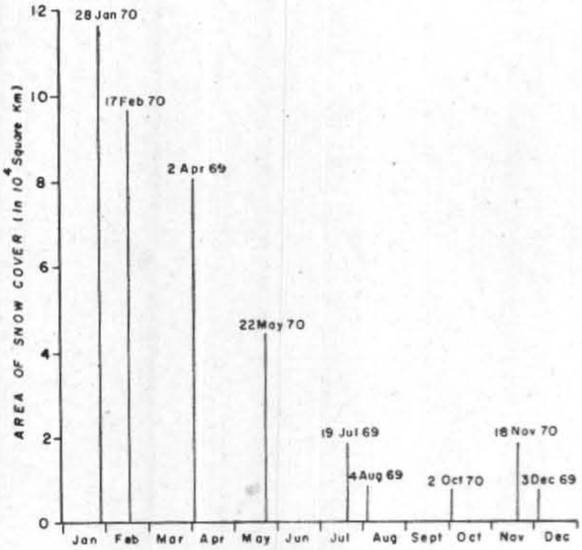

Fig. 10

Snow cover over Western Himalayas

diagram suggests that the volume of snow deposited by the western disturbances over the Himalayas is at least 10 times the permanent snow over the place and nearly 75 per cent of this melts and flows into the river systems of the Indian sub-continent in the three months April to June. On an average, during April to June the flow in the *Indus* and its tributaries is estimated to be 30 per cent of the annual mean flow (Misra 1970). Since the rainfall during these three months (except towards the end of June) in the Western Himalayas is not substantial, a significant contribution to the river flow comes apparently from snowmelt. Thus the western disturbances of the winter contribute significantly to the water budget in the Himalayan rivers in summer before the onset of southwest monsoon.

The approximate* boundaries of the snow-covered area in the Western Himalayas on five of the nine representative dates are shown in Fig. 11. From this figure we see the permanent snow-cover over the Western Himalayas forms a backbone around which snow accumulates in winter and the area of snow cover spreads on either side, as winter advances.

4. Snowline

The heights (a.s.l.) of snowline at selected locations as determined from satellite pictures have also been indicated in Fig. 11. An examination of the snowline data as given by this figure shows—

(*i*) During winter and spring months the snowline in the southwestern face of Western Himalayas is distinctly at a lower elevation than on the northeastern face. It is at about 2 to 3 km on the southwestern face and 3 to 5 km in the northeastern face. This difference in the heights of the snowline on the two faces is because of relatively more moist air and more precipitation on the western side of the Himalayas and drier air and less precipitation on the Tibetan (eastern) side (*see* Leon Bertin 1961 and Burrard and Hayden 1933). In the January picture the snowline has come as low as 0·9 km at some places on the Indian side, after the spell of a prolonged and heavy snowfall.

(*ii*) By May, when snow melt is well in progress, there is appreciable receding of the snowline on the southwestern face where it rises to 3 to 4 km. On the northeastern face it remains between 4 and 5 km.

(*iii*) During August to October, the snowline recedes to its maximum height of about 4-5 km.

(*iv*) The mean heights of the snowline on the southwestern and northeastern faces of Western Himalayas (during January to May) are given in Table 1. By August the snow area becomes too narrow to significantly distinguish its eastern and western faces.

(*v*) The height of snowline is not uniform all along the range but varies from place to place, depending upon the snow accumulation, temperature and wind regimes.

Hill (1881) has reported the snowline heights over northwestern Himalayas as follows —

Winter—1700 m (lowest 900 m which is very rare); Autumn—4700 m on the western face to 5200 m over the eastern face (as determined by trigonometrical observations).

From Gemini V (end of August 1965) photographs of the Himalayas, the elevation of the snow-line has been shown to be between 5500 and 5800 m (Popham 1968).

The satellite derived values of snowline heights are in agreement† with these figures. Satellite derived figures are also in fair agreement† with the snow line observations received from observers in the

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*The approximate boundary is shown in this figure for facility of easy representation. In planimetering the area, however, the exact boundary line was used.

†In this context we should bear in mind the orders of accuracy in the estimation of snowline by the various methods (also *see* sec. 5 sub sec.(*iv*) on page 342.

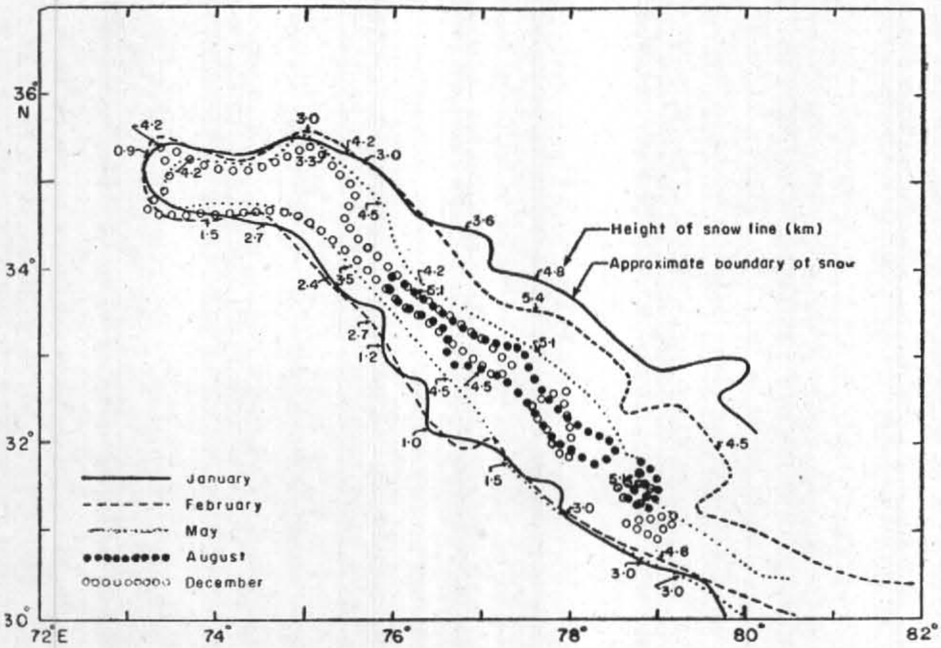

Fig. 11
Snow cover and snowline in May, a number of large gaps were present inside the boundary indicated in the figure

Himalayan region. Table 2 gives a comparison of the heights of snowline estimated by ground observers in Chamba district area (between Lat. 32° and 33°N, Long. 76° and 77°E) of Himachal Pradesh with those computed from satellite pictures.

(*vi*) An interesting feature in Fig. 11 is that the snow boundary along west Uttar Pradesh portion of the Great Himalayas remains quasi-stationary during the period January to May, though large variations in snow boundary are noticed in the other portions during the same period. This appears to be due to the very thick glaciers and the high snowclad peaks in the area which are believed to have an influence over local weather and climate by way of local reduction in temperature and increased snowfall. These, in turn, affect the snowline and produce only a slow variation in the height of the snowline (Burrard and Hayden 1933).

5. Accuracy of the method

This study has indicated that APT pictures can be utilised on an operational basis for the delineation of snow cover over the Himalayan region and the marking of the snowline. The superiority of the satellite method lies in the fact that the cost involved in this method is negligible when compared to other methods, such as aerial survey, spot observations etc. Besides, the satellite gives a synoptic view over very large areas day after day. It would, therefore, be appropriate here to discuss the extent of accuracy of this method.

TABLE 1

	Mean height (km) of snowline	
	On SW face (Indian side)	On NE face (Tibetan side)
January 1970	2·1	4·0
February 1970	2·3	3·6
April 1969	2·6	3·7
May 1970	3·1	4·3

TABLE 2

	Snowline (km) as determined from	
	Satellite pictures	Ground based observations* in Chamba Dist. of H.P.
January 1970	1 to 2	0·9 to 2·4
February 1970	2·5 to 4·0	1·7 to 2·7
April 1969	2 to 3·5	2·4
May 1970	3 to 4·5	3·0
July 1969	4 to 5	4·0
August 1969	4 to 5	4·0
November 1970	3·5 to 4·5	3·4

*Collected from snowfall statements available with Deputy Director General of Observatories (Climatology & Geophysics), Poona-5.

The accuracy depends on the following factors —

(*i*) Scale of satellite pictures and resolution of the TV camera system,

(*ii*) Accuracy of gridding of APT pictures,

(*iii*) Accuracy with which snow boundary can be located, and

(*iv*) Accuracy in reading the contour heights at various geographical coordinates.

In the light of our experience in the present study we shall discuss the above-mentioned factors and also offer a few suggestions.

(*i*) *Resolution of TV camera system and scale of satellite picture*

(*a*) The maximum resolution of the APT camera system is about 4 km near the centre of the picture, gradually decreasing towards the boundaries. As we are dealing with relatively large areas of the order of thousands of square km, an error of the order of a few km in delineating the boundary is not likely to be significant. However, an error of a few kilometres may introduce large errors in the snowline determination. But, since the snowline can be determined at a number of contiguous points on a number of consecutive days, we get a large number of observations which yield a mean picture in which the error due to resolution and scale may be expected to be filtered out.

(*b*) The APT picture received on facsimile paper is on a scale of about 1 : 17·5 million in the latitudes of the Himalayas. However, by enlarging the APT picture, we can reduce the error in measuring the distances and areas on the satellite picture. In the present case, the APT picture was enlarged by a factor of about 16. Barnes and Bowley (1968) feel that APT picture can be used as such without enlargement. Temnikov (1970) has mentioned an enlargement of 10 times being used in USSR. The present authors are of opinion that moderate enlargement will greatly facilitate measurement and reduce errors, but further experiments need to be made to decide upon the optimum enlargement as a compromise between increase of scale of the picture on the one hand and the introduction of fuzziness on the other.

(*ii*) *Accuracy of gridding*

Although the grids on the APT pictures are subject to certain errors (Srinivasan 1970) which may be too large for snow cover and snowline delineation, these errors do not enter into the present method. For, here we correct the operational grids by reference to recognizable geographical landmarks in and near the area of snow cover and once this correction is applied and enlarged pictures are used, the accuracy of location of any line or point on the picture is as good as can be obtained from any comparable map reading.

(*iii*) *Accuracy of snow boundary location*

The snow boundary as seen in the satellite picture is quite sharp so long as fuzziness is not introduced due to over-enlargement. In the case of the Himalayas, the "Terai" region on the southern slopes of the mountain are very densely forested and they appear distinctly black on the satellite pictures. The bright snow cover lies just to the north, adjacent to this dark area. This contrast in the brightness on the picture greatly facilitates the placement of the snow boundary with confidence.

(*iv*) *Accuracy of contour heights at various geographical co-ordinates.*

(*a*) The error in reading the contour heights arises out of the fact that in mountainous regions the elevation varies considerably through small horizontal distances. From the grids drawn on the overlays on satellite pictures, Lat./Long. of points along the snow boundary were determined correct to one place of decimal. While this accuracy was sufficient for mapping the snow cover area, it was found to be not good enough for snowline determination, for in a distance equal to 0·1 of a degree (*i.e.*, roughly 10 km), the elevation of the terrain can vary through as much as 2.0 km in regions of steep gradient of contours. Hence we had to read the latitudes/longitudes of the points to a greater degree of accuracy — correct to 1/50 of a degree*. On the scale of enlargement we used, we could measure distances to this accuracy. A distance of 1/50 of a degree corresponds to a horizontal distance of 2 km and the variation of height elevation through this distance is only about 500 metres even in the regions of steep gradient. The accuracy of the snow line determined in this study can, therefore, be assumed to be of this order, *viz.*, 300 m (about 1000 ft) in the regions of weak contour gradient and nearly double this magnitude in the regions of steep gradient.

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*In view of para (*c*) on p 343, an accuracy of 1/25 of a degree corresponding to a horizontal distance of 4 km (limit of resolution of the TV camera system) might have been sufficient (*b*) The differences between the two sets of satellite derived values (with readings correct to 0·1 of a degree and 0·02 of a degree) were within 900 m on all the occasions except three. They were within 300 m on 50 per cent of the occasions. It was also found that discrepancies of higher magnitudes were in the regions of steep contour gradient. This clearly brings out the necessity to select points in areas of weak contour gradient.

(*c*) The satellite derived height values (utilising readings correct to 0·02 of a degree) were compared with more accurate values obtained from the Director, Survey of India, Dehra Dun. It was encouraging to note that the two sets of readings differed by more than 600 m in hardly 5 per cent of the cases and in a little over 50 per cent of the cases they were within 300 m. This suggests that Survey of India map on 1 : 1 million scale is sufficient for the purpose of snowline delineation by this method.

(*d*) Any refinement in the readings of latitudes/longitudes of points, beyond a particular limit will not yield greater accuracy, as horizontal distance measured on the satellite pictures less than the limit of resolution of the camera system, has no meaning. But, with improved resolution cameras in future satellites, we can hopefully proceed to finer measurements and obtain snowline determination with greater accuracy.

(*e*) Use of larger scale contour maps and snowline measurements in areas where the contour gradient is not steep, will reduce this source of error to a minimum. In addition, if we determine the heights of snowline at a number of points on a few consecutive days, the random errors introduced in measurements can be evened out.

6. General remarks and conclusions

1. The satellite offers a very simple and inexpensive method for determining snow cover and snowline over the Himalayas and the present study has shown that the method is feasible and the results obtained are consistent. We have presented a method for collecting a wealth of observations regarding snow cover and snowline and their daily and seasonal variations. Such a large number of observations derived from the satellite pictures will turn out to be a great boon to studies on Himalayan snow cover from the point of view of meteorology as well as other geophysical disciplines.

2. We are primarily concerned with snow cover during winter and early spring when snow accumulation is high and also late spring and early summer when snow melt is very important. During these periods, the Himalayas are not much clouded nor so persistently clouded over the same area. Hence, even from pictures with parts of Himalayas alone cloud-free, we can derive sufficient information required for operational work by compositing the data over a period of a few days.

3. In such studies, the quality of the APT pictures and the enlargements should be quite high and the changes in brightness should be faithfully reproduced. A poor quality picture is absolutely of no use for this work.

4. Another important factor is familiarization with the geographical background of the area as it appears in the satellite pictures on cloud-free days. This will facilitate easy recognition of landmarks and snow boundaries quickly on the picture and also avoid confusion with clouds or other spurious features.

5. From the present study, the following conclusions can be drawn in respect of the snow over the western parts of the Great Himalayas—

(*i*) Although snow accumulation starts from the beginning of the winter season (November), the area covered by snow reaches a maximum in the second half of winter (January-February). The snowmelt begins in spring (April) and is highest in May and June. The minimum snow cover occurs in August-October and almost coincides with the permanent snow over the area.

(*ii*) The area of snow cover at its maximum (in winter) is about one order of magnitude greater than the minimum coverage (in late summer and autumn).

(*iii*) The accumulation of snow is caused by the western disturbances of the winter season, particularly in the second half. In association with active western disturbances, the area of snow coverage may increase temporarily and extend to lower altitudes. The seasonal strong westerly winds over this area help to spread the snow towards the east.

(*iv*) The snowline is at 2-3 km a.s.l. in winter rising upto about 5 km a.s.l. in August, September and October. In winter, after a spell of heavy snowfall the snowline comes down to as low as 900 m a.s.l. at some places. At any particular time, the snowline varies from place to place within certain limits.

(*v*) The snowline on the southwestern face (Indian side) is lower than on the northeastern face (Tibetan side).

(*vi*) The snowline over west Uttar Pradesh portion shows some special features, which is believed to be due to the profound influence of the thick glaciers over the area.

6. When the Earth's Resources Technology Satellite (ERTS) with improved resolution imagery system and Geostationary Operational Environmental Satellite (GOES) with multi-spectral sensoring go into orbit within a year or two, hydrologists can obtain more detailed snow measurements leading to greater application of satellite data in operational snow hydrology.

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