Seasonal Snow Extent and Snow Volume in South America Using SSM/I Passive Microwave Data

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ABSTRACT

Seasonal snow cover in South America was examined in this study using passive microwave satellite data from the Special Sensor Microwave Imagers (SSM/I) on board Defense Meteorological Satellite Program (DMSP) satellites. For the period from 1992-1998, both snow cover extent and snow depth (snow mass) were investigated during the winter months (May-August) in the Patagonia region of Argentina. Since above normal temperatures in this region are typically above freezing, the coldest winter month was found to be not only the month having the most extensive snow cover but also the month having the deepest snows. For the seven-year period of this study, the average snow cover extent (May-August) was about 0.46 million km^2 and the average monthly snow mass was about 1.18 x 10^{13} kg. July 1992 was the month having the greatest snow extent (nearly 0.8 million km^2) and snow mass (approximately 2.6 x 10^{13} kg).

1. INTRODUCTION

In the Northern Hemisphere, the land masses are situated much closer to the poles than they are in the Southern Hemisphere. The land not only acts as a source area for cold air, but because of its lower thermal inertia compared to water, it does not modify the cold temperatures nearly as much as does water, even cold Antarctic waters. Thus, in the middle latitudes temperatures during the winter months are much cooler in the Northern Hemisphere than in the Southern Hemisphere, and snowfall occurs more frequently. Associated with this is the fact that high pressure systems or anticyclones occur less often in the Southern Hemisphere than in the Northern Hemisphere. Because there is less land in the mid latitudes of the Southern Hemisphere, the southern westerlies are stronger than their northern counterpart, and large nearly stationary "high" systems such as the "Siberian High" are less frequently established. These large "highs" are important in refrigerating surface air and influencing the strength and tracks of storm systems (Chang at al., 1990). Despite these drawbacks, however, snow does occur in the middle latitudes of the Southern Hemisphere and occasionally even in the sub-tropics at elevations below 1,000 m.

Using data from the SSM/I on board DMSP satellites, snow extent and snow depth (snow mass) have been calculated for the period from 1992-1998 in the middle latitudes of the Southern Hemisphere. It should be noted that in mid winter approximately 99% of the snow cover in the Southern Hemisphere is confined to Antarctica. The data record shows that South America is the only continent in the Southern Hemisphere (other than Antarctica) where an extensive, non mountainous, winter snow cover may occur. Therefore, the emphasis in this study is on South America. The objectives are to map the seasonal snow cover during the cold months of the year using passive microwave satellite data and to generate a snow record comparable to the record for North America and Eurasia.

Although a considerable amount of effort has been devoted to developing and refining passive microwave snow algorithms for North America and Eurasia, for example, Chang at al. (1987), Goodison et al. (1993), Pulliainen et al. (1993), Grody and Bassist (1996), Foster et al. (1997), and Armstrong and Brodzik, (1999), very little work has been expended for algorithm development of seasonal snowfields in the Southern Hemisphere.

II STUDY AREA

Figure 1 is a map of South America showing the location of the Patagonia region of Argentina and the Tierra del Fuego region of Argentina and Chile. In southern Argentina, snow may accumulate as early as May and as late as October. Each winter, snow is a regular feature south of about 45 degrees latitude, and in the snowiest years, over 1 million square km of snow has been measured (Dewey and Heim, 1983). A single storm may cover the ground with several hundred thousand km^2 of snow. Snow can fall at locations much further north than expected, and it can even lay on the ground for a few days as far north as 27 degrees south latitude. Snow here is usually confined to elevations greater than 1,000 meters above sea level, where as much as 30 cm of snow has been observed in southern Brazil. In July 2000, freezing temperatures and snowfall in southern Brazil and Paraguay damaged coffee crops (Prohaska, 1976).

Although the Andes in southern Chile and Argentina can be snow covered throughout the year (Williams and Ferrigno, 1998), again, we are mainly interested in seasonal, non mountainous snow. Figures 2 and 3 show plots of July 1994 temperature versus snow cover for the cities of Lago Argentino and Rio Gallegos, respectively (Figure 1). For Rio Gallegos, snow covered the ground from the 17th onward, and according to meteorological data for this station a coastal storm deposited approximately 60 cm (2 ft) of snow on the 26th of July, 1994!

Typically, snow cover in southern South America results from disturbances embedded in the westerly air streams. East winds and heavy precipitation during the winter in southern South America are caused by quasi-stationary high pressure systems at high latitudes over the western South Atlantic Ocean (Kidson, 1988).. These anticyclones block the normally zonal air flow in such a way that normal sea level cyclonic systems are steered around the "high" toward Patagonia (the South American states of Rio Negro, Chubut, Santa Cruz and Tierra Del Fuego). In southeastern Brazil, snow can fall when incursions of polar air from the south push northward, coincident with a weakening of the normally dominant sub- tropical high pressure belt.

Although snow cover may be significant in South America in terms of its effects on weather, especially emperature and agriculture, it is variable from year-to-year. This is to be expected when accumulations generally are shallow. According to Dewey and Heim (1983), over a 7-year period from 1974-1980, snow cover reached a maximum extent of about 1 x 10^6 million km^2 in 1980, but in 1979, the maximum extent was only about 70% of this amount. For comparison, during the 1980 snow season, snow covered an area about the size of the country of Boliva in South America (about the size of the states of Texas and Oklahoma in the US and about the size of the states of New South Wales and Victoria in Australia).

III PASSIVE MICROWAVE DATA

The study years used for this investigation (1992-1998) match the years of coverage for the DMSP 11 and 12 satellites, launched in November 1991 and August 1994, respectively. Data were acquired from the SSMI on board the DMSP satellites. While only 7 years of data were used, it is worth noting that this period includes one very snowy year and one year with little snow. For this investigation, brightness temperature differences between the 19 GHz and 37 GHz channels were multiplied by a coefficient related to the average grain size (1.60) to derive the thickness of the snow (Chang at al., 1987). The simple algorithm is then

$$SD = 1.6\,[(19\text{ GHz} - 37\text{ GHz}) - 5]\text{ cm} \qquad [1]$$

Where SD is snow depth in cm and 19 GHz and 37 GHz are the brightness temperatures at 19 GHz and 37 GHz horizontal polarizations, respectively.

To derive snow water equivalent, the above algorithm can be multiplied by 3.0 – the average density of mid winter, mid latitude snowpacks is approximately 300 kg^{-3} . This is expressed as follows:

SWE = 4.8 [(19 GHz - 37 GHz) –5] mm **[2]**

where SWE is snow water equivalent in mm. If the 18 GHz channel is less than the 37 GHz channel, then the SWE is defined to be zero.

Using data from a study by Van Der Veen and Jezek (1993), it was found that a -5 K offset exists between Scanning Multichannel Microwave Radiometer (SMMR) data and SSMI observations over Antarctica. The above equations include this offset. The nominal resolution for the 19 GHz (actually 19.35 GHz) channel is 69 x 43 km^2 and for the 37 GHz channel it is 37x 28 km^2 (Naval Research Laboratory, 1987). Equal Area SSMI Earth Grid (EASE-grid) Southern Hemisphere projections, used in this study, were provided by the National Snow and Ice Data Center. During the colder winter months, the atmosphere is generally transparent in the 19 and 37 GHz frequency range, and thus atmospheric corrections were not made.

Landsat, which has a 16-day repeat period, or even the Moderate Resolution Sprctroradiometer (MODIS) on-board the Terra satellite, available every 2 days at the latitude of southern South America, can be rendered nearly useless by the persistent clouds that often cover Patagonia. Even daily NOAA/AVHRR visible data may not obtain cloud free imagery over Patagonia for periods of a week or longer. Figure 4 shows snow cover in Patagonia from an Advanced Very High Resolution Radiometer (AVHRR) image - one of only a few relatively cloud free AVHRR images available during July 1995.

Passive microwave remote sensing, therefore, is particularly advantageous in this kind of environment, not only because clouds and darkness do not preclude snow detection, but also because Patagonia has few forests. The emission from trees can confound the scattering signal of snowpacks, and thus if forests are present, adjustments would need to be made to the retrieval algorithms in order to account for the forest emission and resulting increase in brightness temperature.

Disadvantages of using passive microwave radiometry in Patagonia are related to the continental shape of southern South America and the general shallowness of the snow in this region. Because the southern part of South America tapers to a point, a number of SSMI pixels at the tip, include water from the Atlantic and Pacific Oceans. Pixels having more than 20% water render snow retrieval algorithms useless because the very low brightness temperatures characteristic of open water in the microwave portion of the spectrum are emission-based and not scattering-based. Shallow snow, less than about 3 cm in thickness, is often transparent to microwave radiation, and therefore no snow may be indicated when employing an algorithm when, in fact, a thin veneer of snow is present.

IV DATA ANALYSIS AND RESULTS

SSMI snow data were acquired from May through August for the years 1992-1998. In order to construct snow maps, 19 GHz and 37 GHz (horizontal) radiances were converted to brightness temperatures. Both average monthly and monthly maximum maps of snow cover extent and snow depth (mass) were generated for the 28-month period using equation **1**. Average monthly snow depth is given as ½ of the maximum observed on any day. Thus, if 24 mm of snow was the maximum daily snow for any given pixel during the month, the average snow depth for the month was 12 mm. This procedure was used because, while the snow in Patagonia is generally quite shallow and transient, the snow thickness seems to be rather consistent – pixel-to-pixel variance is low. Several different categories are noted on the maps. If the 37 H brightness temperature is greater than 250 K or if the 37 GHz and 19 GHz frequency gradient is greater than 10 K, then no snow is assumed. Furthermore, if the snow water equivalent (SWE), from equation **2,** is less than 10 mm, the surface is considered snow free. For the microwave maps, we selected land areas south of 25 degrees south latitude. Areas to the north of this were labeled as "climatologically impossible snow."

In order to assure that the SSMI algorithm is sufficiently sensitive to detect snow on the ground, Figure 5 shows a plot of the monthly average temperature (departure from normal) during the months of May through August for 1992-1998 versus the number of snow covered SSMI pixels for these same months. The temperatures are averaged from four meteorological stations; Gobernator Gregores, Rio Gallegos, and Lago Argentino, Argentina and from Punto Arena, Chile (Figure 1). It is quite evident that an extensive snow cover (~300 SSMI 0.5 degree x 0.5 degree pixels) exists only when the average daily temperatures are colder than normal, and in this region, when the temperatures are above normal, they are almost always above freezing (0 C), quickly melting the snow. This result, and comparison of the estimates with the station data when a snow cover exists, demonstrates that the algorithm is indeed able to discern snow, even shallow snow (< 5 cm).

Thus, equation 1 was used to determine the monthly average and monthly maximum snow extent and snow mass values from SSMI for the years 1992-1998 (Table 2). The most snow for any year (average and maximum) occurred in 1992, and the year with the least amount of snow was 1996. July 1992 was the month having the greatest snow cover extent (nearly 0.8 million square km) and snow mass (approximately 2.58×10^{13} kg).

Figures 6-8 show the seasonal build up of snow in Patagonia during the fall and winter of 1992. Table 1 gives the monthly (May-August) snow cover and snow mass for the 1992-1998 period.

DISCUSSION

Normally, in May, the seasonal snow cover is confined to the higher elevations inland as opposed to coastal areas (Figure 6). Snow cover may be absent in the higher latitudes near sea level, but further to the north, more equatorward, in the highland areas of Boliva, for example, snow may be extensive. As fall progresses into winter, lowland coastal areas also become snow covered (Figures 7-9), even as far as 45 °south in interior areas, in some years. Note that because the pixels in the vicinity of Tierra del Fuego (Figure 1) are mixed with water, they are not mapped as snow covered, even though they are, in fact, likely to be at least partially snow covered. Although, the snow depths are generally less than about 10 cm across most of Patagonia in mid winter, coastal storms can produce significant snowfalls. In the coastal city of Rio Gallegos (51° south), for example, approximately 50 cm of snow fell during a storm in July of 1994 (Figure 2).

Since the snow cover in Patagonia is generally quite shallow, the month having the maximum snow coverage can vary from one year to the next. With few exceptions, however, the coldest month is the month with the greatest snow cover extent. Consequently, July is the month that usually has the greatest snow cover, but in some years August has the most snow. This is the case in North America and Eurasia as well; the greatest snow cover extent occurs during the coldest month (January) or the second coldest month (February).

With respect to snow volume, in the Northern Hemisphere, because the snow accumulates throughout the winter months at the higher latitudes and at highest elevations, the greatest snow volume typically occurs in February or March. In South America, the snowpack is deepest in July and August. By September, much of the snow in the higher latitudes is already melting. In many years, a storm will deposit a layer of snow that melts before another storm arrives. So, the month with the deepest snowpack is almost always the month with the greatest snow extent – the coldest month.

On occasion, the snow volume and mass may be greater in a month when the snow extent is less than a month having a greater area of snow cover. In May of 1995, for example, only 77 SSMI pixels were snow covered, and the average snow depth per SSMI pixel was approximately 6.3 cm, whereas in June of that year, 246 pixels were snow covered, but the average snow depth per SSMI pixel was slightly less.

For the 7 years studied, the average maximum thickness per pixel was approximately 10.5 cm (August 1992). Approximately 5% (352 pixels) of South America was snow covered during the month having the maximum snow extent (July, 1992). In contrast, for the month of maximum snow extent in North America (January) and Eurasia (February), the maximum snow extent encompasses approximately 62% and 53% of the land area, respectively. Of course, the land mass configurations are very different in the Northern and Southern Hemisphere. If South America were turned upside down, perhaps 30% or more of its surface would be snow covered in mid winter.

Our estimates of snow extent were slightly less than the values measured by Dewey and Heim (1983) for the late 1970s through the mid 1980s. However, their measurements included snow in the Andes Mountains, south of 10 degrees south latitude. For our measurements, we included only snow cover south of 25 degrees south latitude.

CONCLUSIONS

Exclusive of Antarctica, seasonal snow in the Southern Hemisphere is, for the most part, confined to South America. Though snow may fall and even persist on the ground for several days in Africa and Australia, on those continents, however, snow is basically a novelty. The 7-year period investigated in this study demonstrates that passive microwave radiometry is especially useful in estimating the snow cover extent and snow mass in areas where clouds are a near-constant problem and where the snow is typically ephemeral. The passive microwave observations show that there are sharp year-to-year differences that exist in the seasonal snow extent over the Patagonia region of South America. This agrees with earlier findings in the work of Dewey and Heim (1983).

In terms of future plans, the seasonal snow extent and snow volume will be derived for Patagtonia for each year of the passive microwave record (1979-present). In addition, the current algorithm will be fine-tuned to ensure that shallow snow depths, which are typical of Patagonian winters, can be accurately and reliably identified. To this end, in order to more fully evaluate the passive microwave-estimates of snow cover extent and snow volume, data from meteorological stations and, when possible, from airborne and satellite visible data (Ramsay, 1998) will be compared with the passive microwave maps.

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Table 1

Snow cover and snow mass in South America (1992-1998)

		Snow Extent (x 10^5 km^2)	Snow Mass (x 10^{13} kg)
1992	May	4.26	0.85
	June	7.08	1.70
	July	7.96	2.58
	August	6.95	2.36
1993	May	2.94	0.63
	June	5.32	1.24
	July	5.70	1.36
	August	4.01	0.93
1994	May	3.87	0.94
	June	5.26	1.70
	July	6.44	2.01
	August	5.21	1.55
1995	May	1.89	0.39
	June	5.60	1.17
	July	6.54	1.60
	August	6.59	1.80
1996	May	1.53	0.27
	June	3.19	0.62
	July	3.07	0.62
	August	3.46	0.68
1997	May	2.17	0.42
	June	5.20	1.34
	July	7.34	2.12
	August	5.67	1.49
1998	May	1.99	0.43
	June	2.43	0.56
	July	3.45	0.76
	August	3.55	0.82
28 month average		4.59	1.18

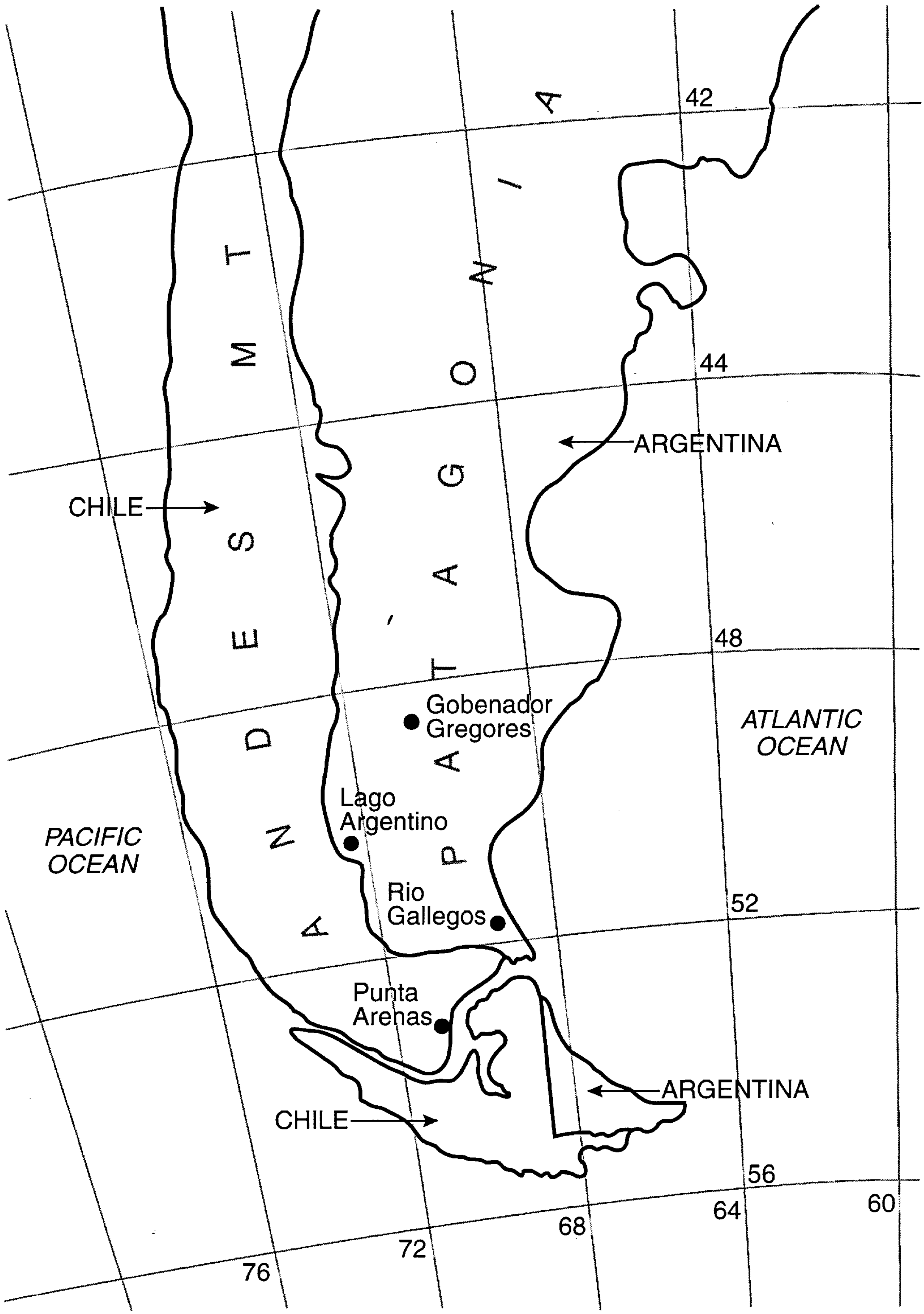

ANDES MT
PATAGONIA
CHILE
ARGENTINA
PACIFIC OCEAN
ATLANTIC OCEAN
Gobenador Gregores
Lago Argentino
Rio Gallegos
Punta Arenas
ARGENTINA
CHILE
42
44
48
52
56
60
64
68
72
76

Fig 1

Lago Argentio - Average Maximum Temperature Versus Snow Depth on the Ground for July 1994

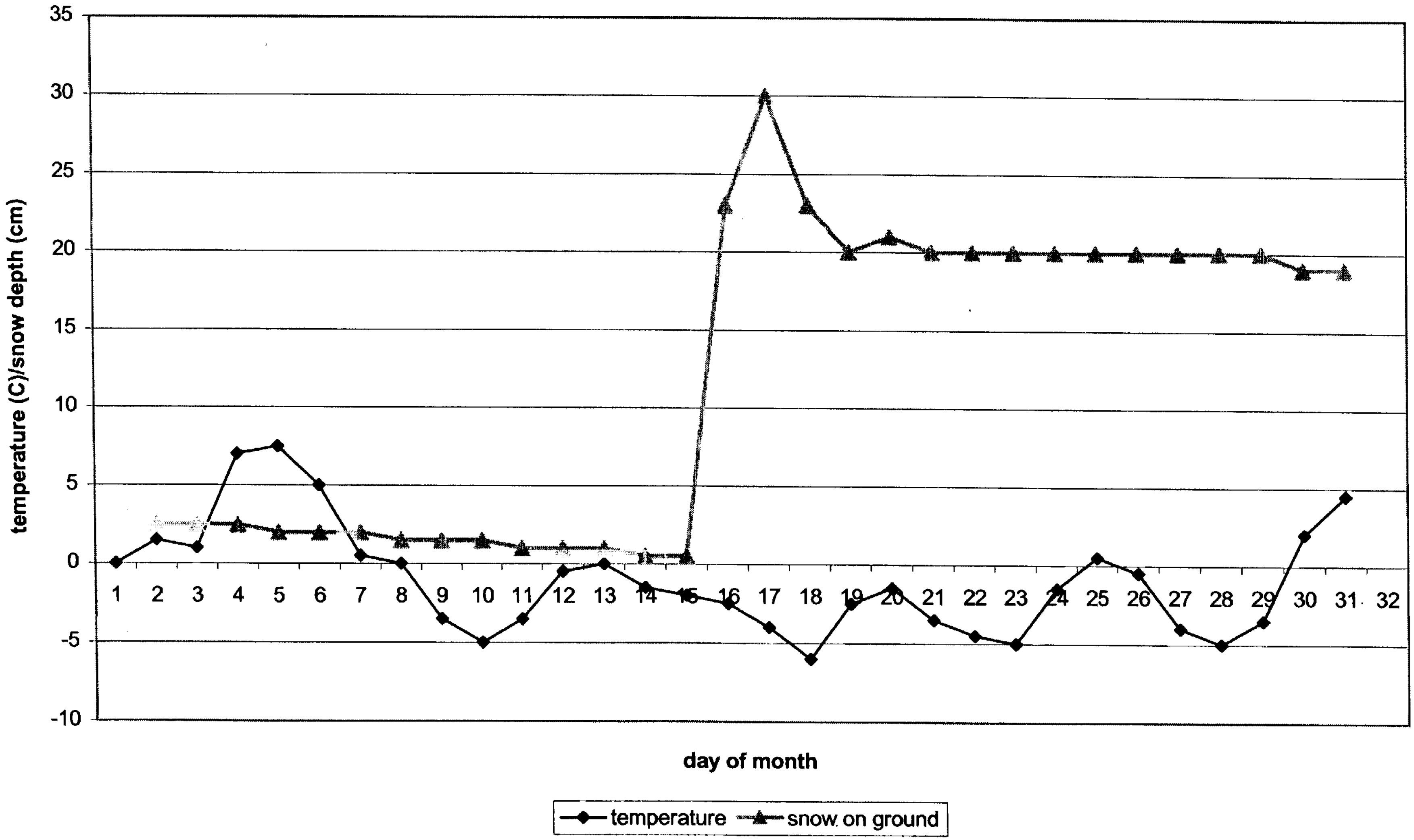


Fig 2

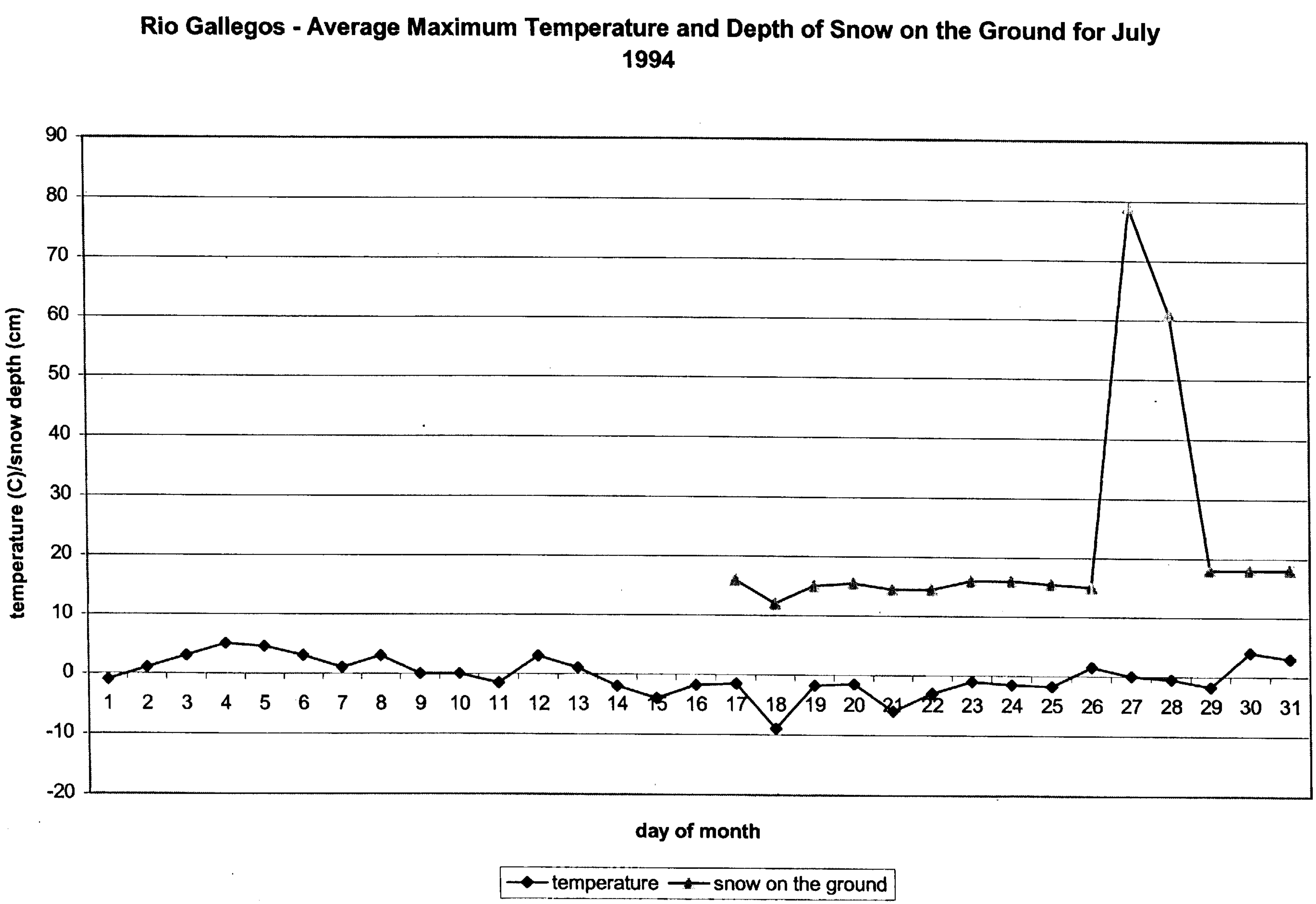

Rio Gallegos - Average Maximum Temperature and Depth of Snow on the Ground for July 1994
temperature (C)/snow depth (cm)
90
80
70
60
50
40
30
20
10
0
-10
-20
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
day of month
temperature
snow on the ground

Fig 3

Fig 4

Fig 4

Average Monthly (May-Aug) Temperature vs Number of SSMI Snow Covered Pixels in Patagonia

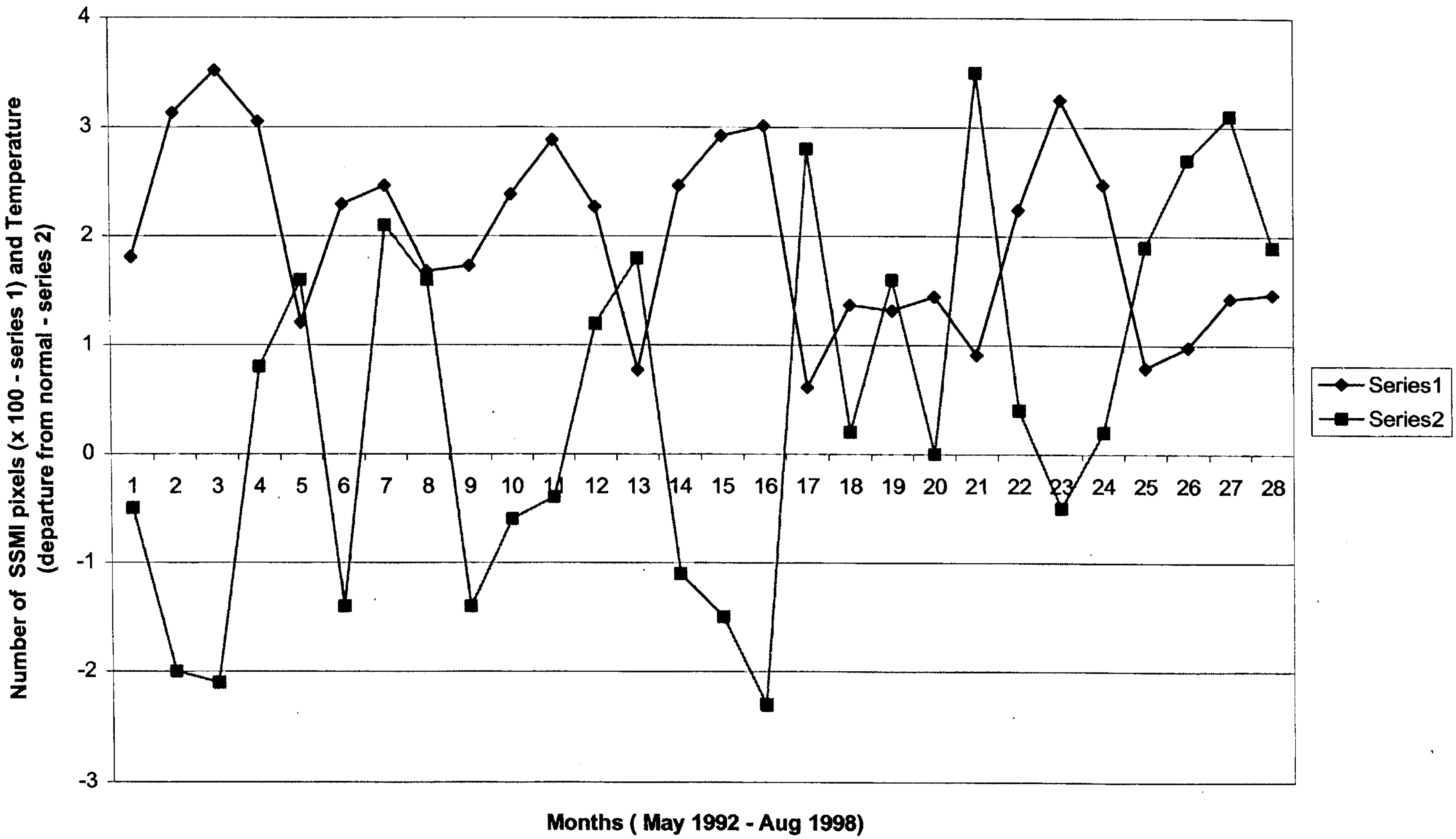
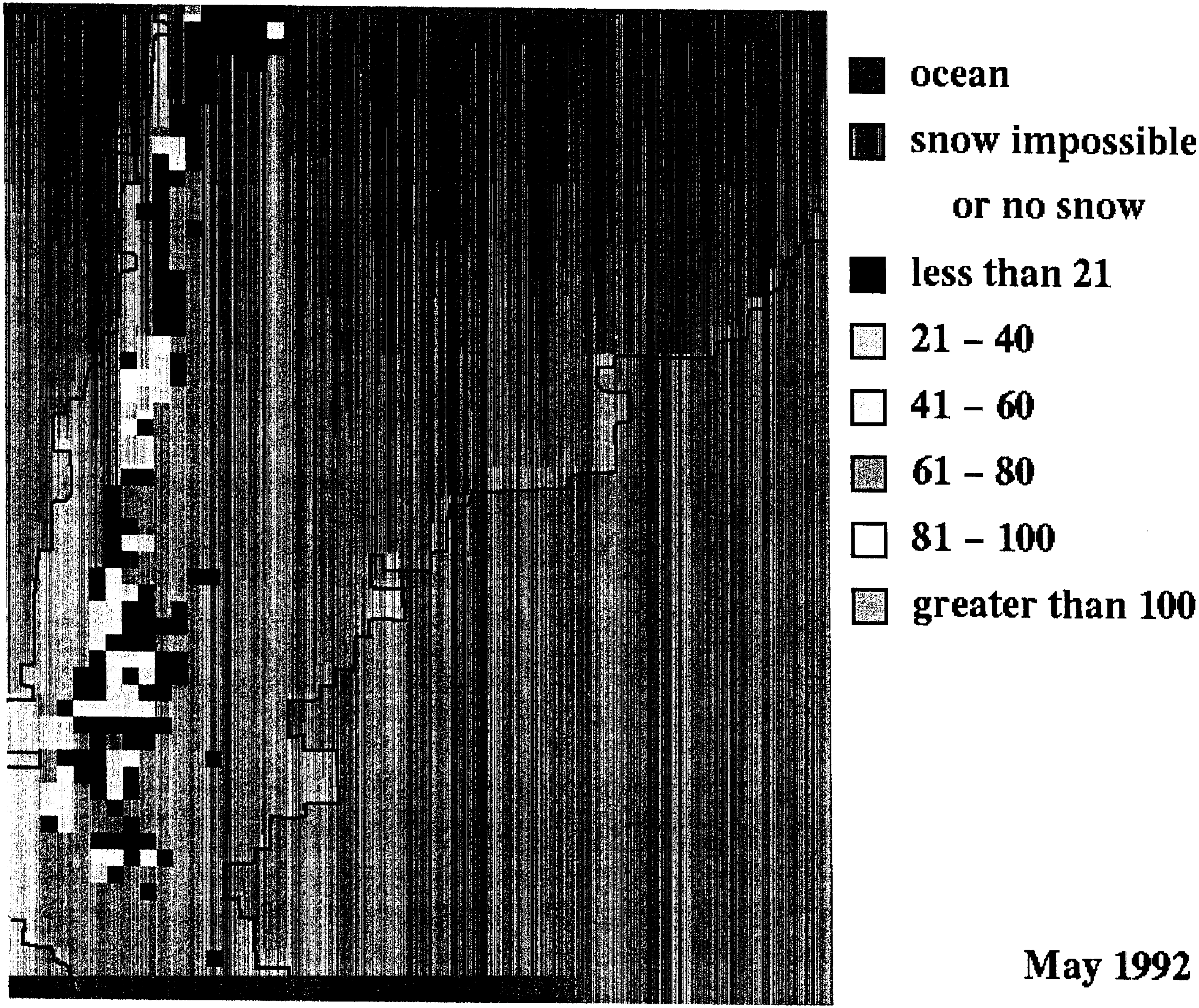
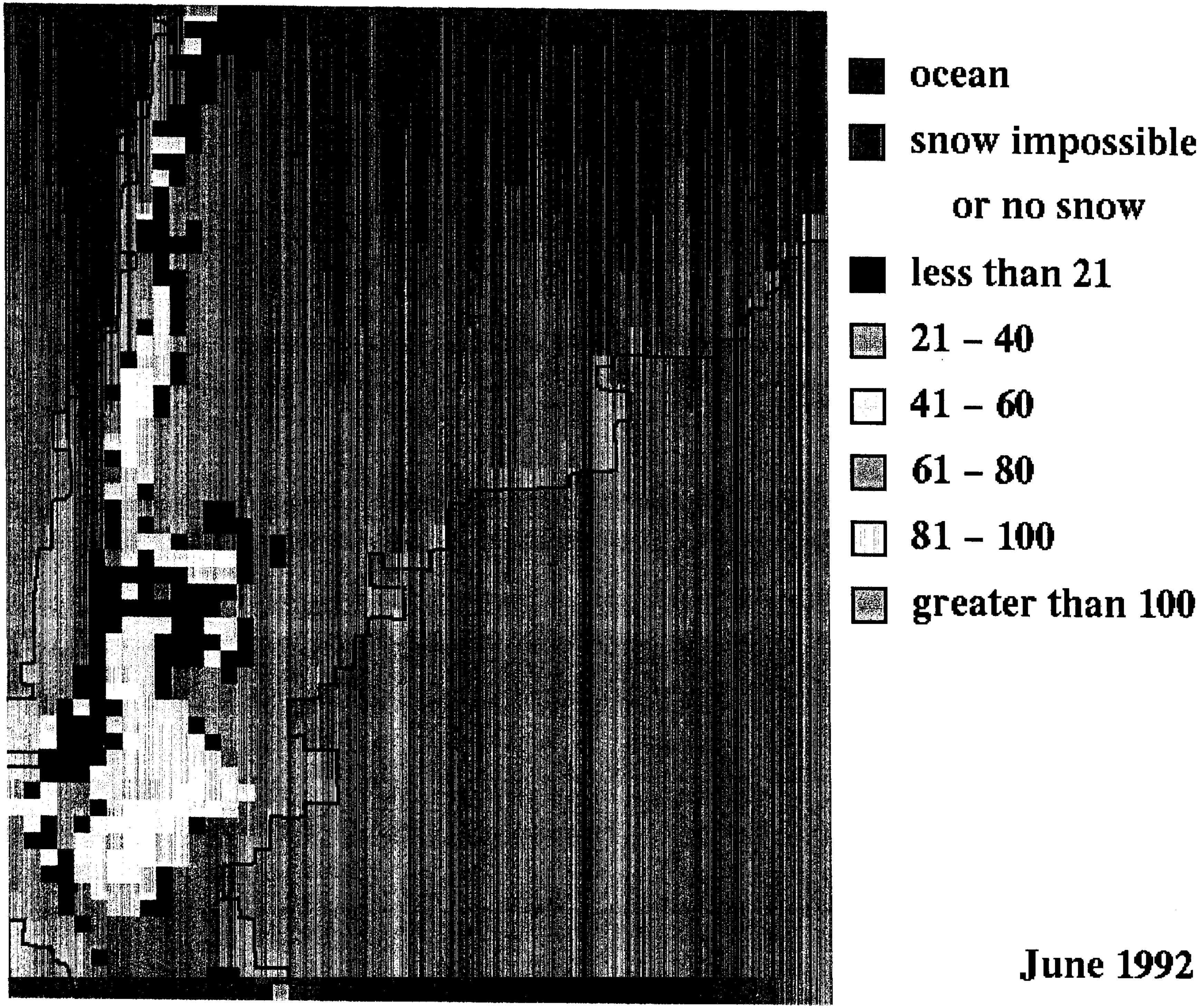


Fig 5



May 1992

Fig 6



June 1992

Fig 1

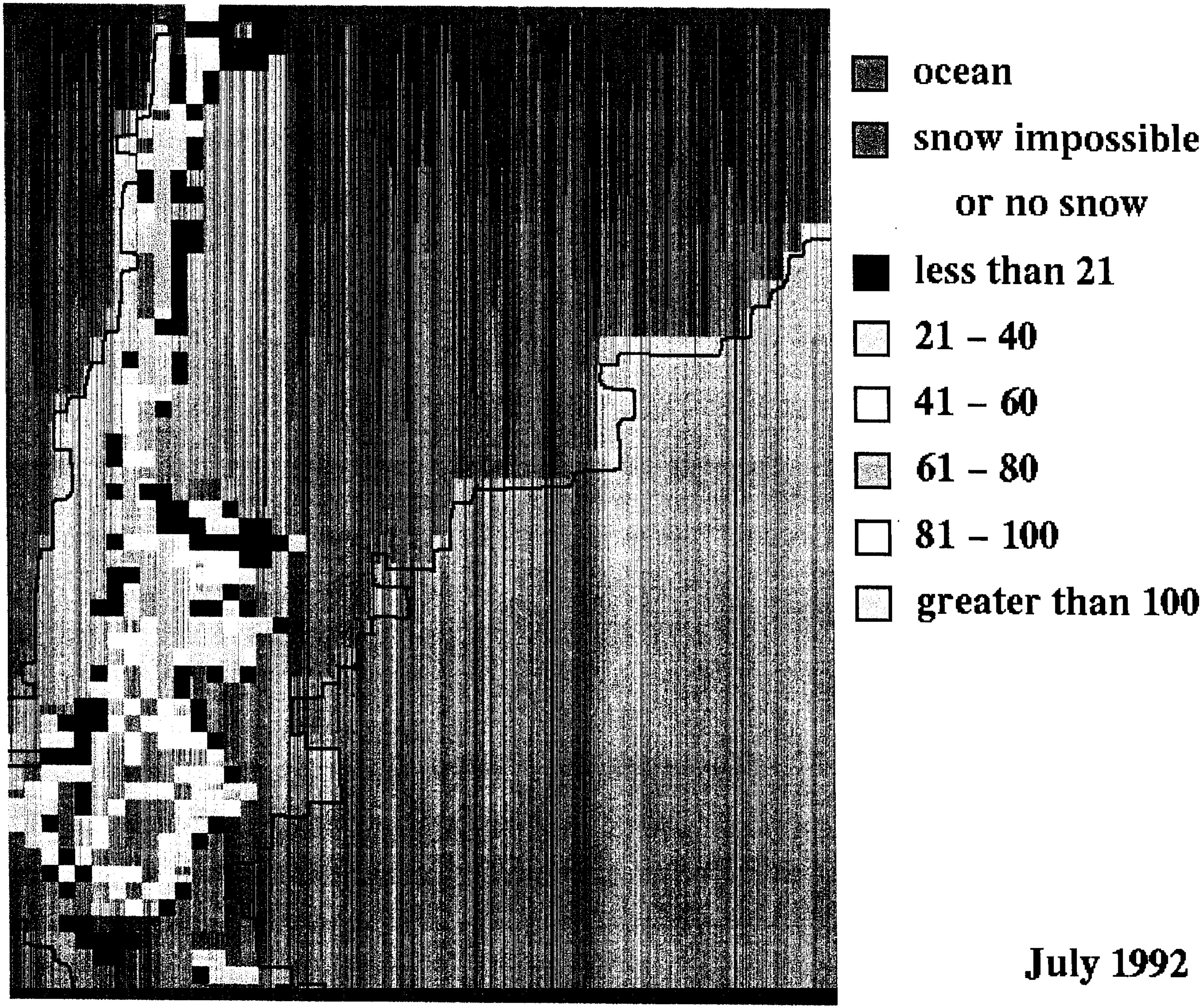

ocean
snow impossible
or no snow
less than 21
21 - 40
41 - 60
61 - 80
81 - 100
greater than 100
July 1992

Fig 8

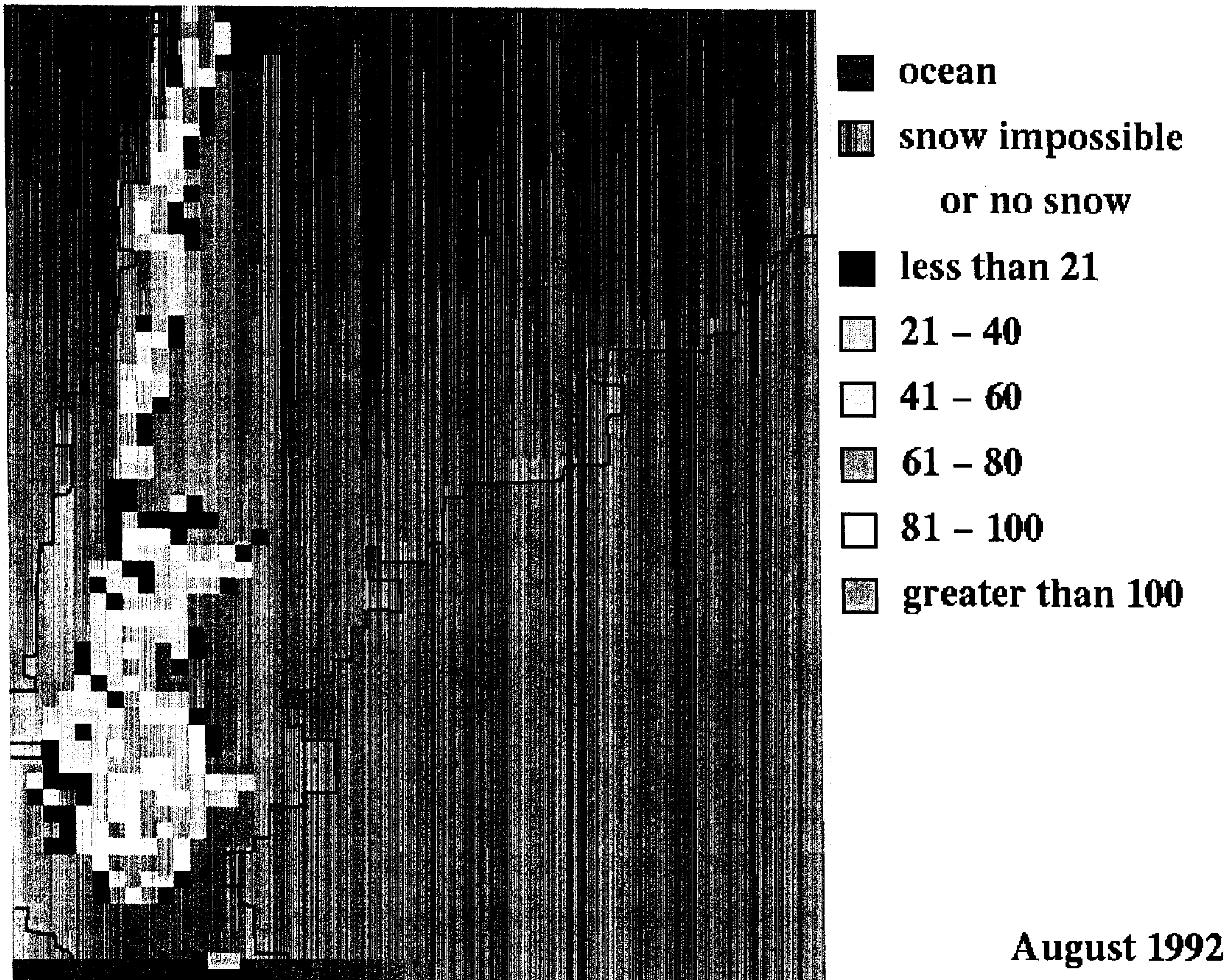

ocean
snow impossible
or no snow
less than 21
21 – 40
41 – 60
61 – 80
81 – 100
greater than 100
August 1992

Fig 9