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A BARE ICE FIELD IN EAST QUEEN MAUD LAND, ANTARCTICA, CAUSED BY HORIZONTAL DIVERGENCE OF DRIFTING SNOW

by

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ABSTRACT

The horizontal divergence of drifting snow was estimated from the ice-sheet topography on Mizuho Plateau, East Antarctica. The calculation was made by using a relationship between the snow-drift transport rate and wind speed estimated from the surface slope. The divergence thus estimated for Mizuho Station (70°42′S, 44°20′E) was consistent with observations of surface net mass balance, precipitation and sublimation. Around the southern region of the Yamato Mountains, a large divergence was predicted and this is believed to be the principal cause of the bare ice field. Other factors in the formation and preservation of the bare-ice area are discussed.

INTRODUCTION

On inclined terrain in Antarctica, katabatic winds are formed by gravitational forcing of cold air masses and generate drifting snow throughout the year. Along the wind stream line, if the wind speed increases to leeward, the drift transport rate increases and there is horizontal divergence of drifting snow. Compensating for the divergence, the density of drifting snow should increase along the wind stream line as a result of erosion of the surface-snow layer. Thus divergence is an important factor in establishing the surface mass balance.

It has been reported that local mass balance is closely related to local topography on inland ice sheets (Schytt 1955, Swithinbank 1959, Black and Budd 1964, Gow and others 1972). These observations can be explained in terms of horizontal divergence of drifting snow because the speed of the wind, in particular the katabatic wind (which is predominant over the Antarctic ice sheet), shows a close correlation with the surface slope. Whillans (1975) discussed mass movement by drifting snow in Marie Byrd Land in terms of a relationship between changes in snow-drift transport rate and changes in surface slope.

In this paper, the divergence of drifting snow is estimated two-dimensionally over Mizuho Plateau, East Antarctica, from the surface topography of the ice sheet (Fig. 1).

SURFACE MASS BALANCE AT MIZUHO STATION

Precipitation

At Mizuho Station, Kobayashi and others (1985) obtained from the drift density at 30 m height a value of 140 mm (all values of surface mass balance are given as

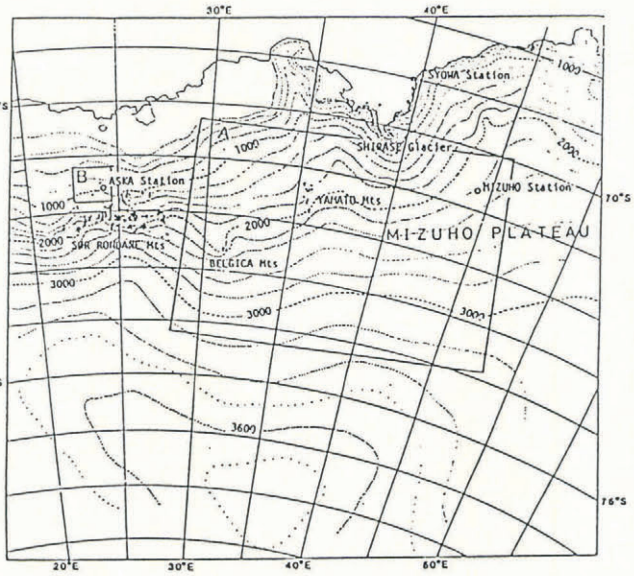

Fig. 1. Map of East Queen Maud Land, showing surface-elevation contours. A: area for calculation of drifting-snow divergence around the Yamato Mountains, B: area around Aska Station.

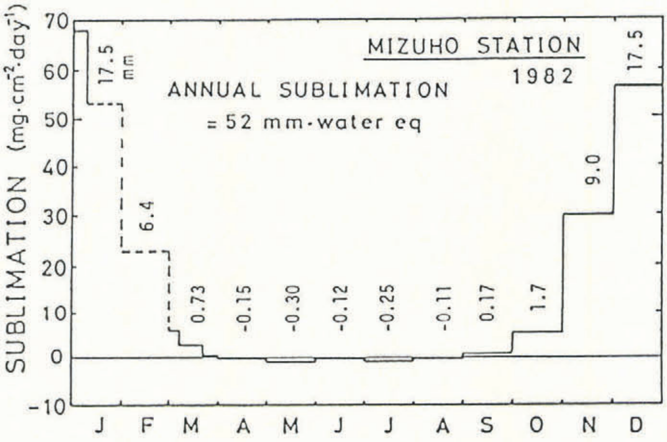

Fig. 2. Sublimation at Mizuho Station in 1982, measured by means of an evaporimeter filled with ice.

water equivalent) for the annual precipitation in 1980, where all the drift was assumed to be attributable to precipitation. By the same method, Takahashi (1985b) obtained 260 mm as the precipitation in 1982, and 230 mm by attempting to distinguish precipitation from drift flux at 1 m height. We conclude that precipitation was roughly 200 m at Mizuho Station, although it could be within a wide range between 100 and 300 mm.

Sublimation from the surface

In 1982, the rate of sublimation was measured at Mizuho Station by weighing an evaporimeter filled with ice (Fig. 2). A small amount of sublimation from vapor to ice was predominant in the winter season, from April to the middle of September, whereas a large amount of sublimation from ice to vapor was predominant during the rest of the year. A value of about 50 mm was obtained for the net loss from the surface. Fujii and Kusunoki (1982) obtained a similar result for 1977–78.

Surface mass-balance deficiency

On Mizuho Plateau, the annual net mass balance has been measured since 1968 by means of snow stakes along various traverse routes. Yamada and others (1978) represented the annual net balance as a function of altitude. According to this understanding, the net balance ranged from 0 to 100 mm at the altitude of Mizuho Station (2230 m a.s.l.).

Narita and Maeno (1979) obtained an annual net balance of 70 mm from data on crystal-grain distribution in a snow core.

Around Mizuho Station, therefore, the surface net balance should be less than 100 mm. This is less than the sum of precipitation (about +200 mm) and sublimation (about −50 mm). The deficit can be explained by mass export from the area, caused by the horizontal divergence of drifting snow carried by katabatic winds that are deflected by surface topography. This will be discussed in the following section.

DIVERGENCE OF DRIFTING SNOW AT MIZUHO STATION

Katabatic wind and surface inclination

Katabatic winds depend on surface slope and inversion intensity (Ball 1960, Adachi 1983, Schwerdtfeger 1984, Parish, unpublished). In the two-layer model, the wind speed of the lower layer is determined by balancing the Coriolis force F_c, the friction force F_f and the gradient force of the dense layer on a slope F_g (Fig. 3). If the x-axis is aligned with the direction of maximum slope, the equations of this model are:

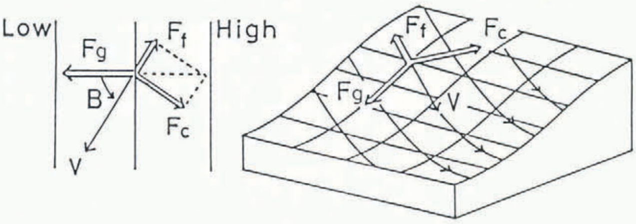

Fig. 3. Equilibrium of Coriolis force $\boldsymbol{F_c}$, friction force $\boldsymbol{F_f}$ and slope gradient force $\boldsymbol{F_g}$ in the two-layer model for katabatic winds.

$$0 = -kVu + fv + g(\Delta\theta/\bar{\theta}) \sin A \qquad (1a)$$

$$0 = -kVv - fu \qquad (1b)$$

where k is the friction coefficient, V is the absolute wind speed, u and v are x- and y-wind components, f is the Coriolis parameter, g is the gravity acceleration, A is the surface slope, $\Delta\theta$ is the inversion intensity (the potential temperature difference of the two layers), and $\bar{\theta}$ is the mean potential temperature of the low layer. Geostrophic winds are neglected as a first approximation in considering the annual mean wind speed. The solutions of these equations are:

$$V = (F_g/k) \cos B \qquad (2a)$$

$$\cos B = -f^2/2F_g k + \{(f^2/2F_g k)^2 + 1\}^{\frac{1}{2}} \qquad (2b)$$

where the gradient force F_g is $g(\Delta\theta/\bar{\theta}) \sin A$: the third term on the right-hand side of Equation (1a).

At Mizuho Station, the annual mean wind speed was 11.1 m s^{-1} and B was about 45°. Since $A = 4 \times 10^{-3}$ and $f = -1.387 \times 10^{-4}$ s^{-1}, F_g is given by 2.18×10^{-3} m s^{-2} and k is 1.25×10^{-5} m^{-1} from Equations (2a) and (2b). From these values, the relation between wind velocity V and inclination A is obtained as shown in Figure 4, where V is normalized by the wind speed at Mizuho Station V_0. The wind-speed data obtained by Inoue and others (1983) on various slopes on Mizuho Plateau agreed with this relation (Fig. 4).

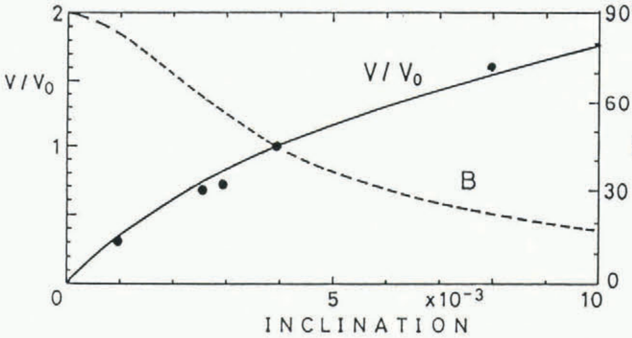

Fig. 4. Ratio of wind speed to that of Mizuho Station V/V_0 and deflection angle B as a function of surface inclination, obtained from Equations (2a) and (2b). Solid circles denote the ratio quoted from Inoue and others (1983).

From F_g and the mean annual temperature of −33°C, the inversion intensity $\Delta\theta$ was 13.5 K at Mizuho Station. Since $\Delta\theta$ is not as large near sea-level, it should be a function of altitude. When the intensity at sea-level is assumed to be one-third of that at Mizuho Station, the ratio $\Delta\theta/\bar{\theta}$ is given by

$$\Delta\theta/\bar{\theta} = \left[p + (1 - p)H/H_0\right] \Delta\theta_0/\bar{\theta}_0 \qquad (2c)$$

where p = one-third and subscript 0 represents the value at Mizuho Station. This is based on an assumption that the lapse rate in the upper layer is 0.6°C/100 m and in the lower layer is 1.0°C/100 m, as we would expect from 10 m depth snow-temperature observations. As a result, the $\Delta\theta$ of 13.5 K at Mizuho Station is reduced to 4.7 K at sea-level. From Equations (2a), (2b) and (2c), the katabatic wind speed can be obtained at any place from its surface inclination and altitude.

Drifting-snow divergence at Mizuho Station

At Mizuho Station, Takahashi (1985a) obtained a snow-drift transport rate from March 1982 to January 1983 by integrating the drift flux from the surface to a height of 30 m. The relation between the drift transport rate Q (kg m^{-1} d^{-1}) and wind speed V (m s^{-1}) at 1 m height was as follows:

$$Q = 6.2 \times 10^{-2} V^{5.17} \qquad (3)$$

The annual drift transport rate at Mizuho Station Q_0 was estimated as 3×10^6 kg m^{-1} a^{-1}. From this value and Equation (3), the transport rate Q of another region with a different wind speed V can be given by

$$Q = Q_0 (V/V_0)^m \qquad (4)$$

where m is 5.17 and V_0 is the average wind speed at Mizuho Station, about 11 m s^{-1}.

The horizontal divergence of drifting snow at Mizuho Station was one-dimensionally estimated as follows. If the gradient of the ice-sheet topography changes one-dimensionally, the drifting-snow divergence can be given by the difference in the transport rate at two different places, 1 and 2, along a wind stream line.

$$\begin{aligned} \operatorname{div} Q &= (Q_2 - Q_1)/\Delta L \\ &= Q_0\left[(V_2/V_0)^m - (V_1/V_0)^m\right]/\Delta L \end{aligned} \tag{5}$$

where ΔL is the horizontal distance between the two points.

The surface topography around Mizuho Station is convex upward. The surface inclination in the windward region 50 km away from Mizuho Station is about 3×10^{-3}, and that in the leeward region 50 km away is about 6×10^{-3}. From the relation between V/V_0 and A in Figure 4, V/V_0 was 0.83 in the windward region and 1.30 in the leeward region. Since ΔL is 100 km, the drifting-snow divergence was obtained as 105 kg m^{-2} a^{-1} from Equation (5). In other words, annual mass export from the surface was about 100 mm. The annual balance of 70 mm was hence established for precipitation of 140–260 mm, sublimation of 50 mm, and drifting-snow divergence of 100 mm, as illustrated in Figure 5.

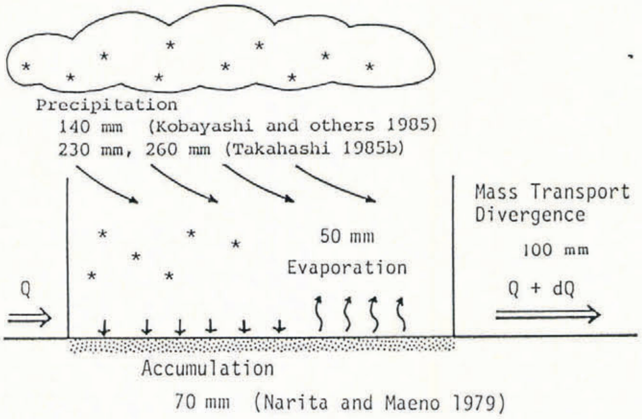

Fig. 5. Surface mass-balance model at Mizuho Station.

TWO-DIMENSIONAL DRIFTING-SNOW DIVERGENCE ON MIZUHO PLATEAU

Equations of two-dimensional divergence

At grid points for calculation as shown in Figure 6, a gradient of surface slope $\boldsymbol{n}$, defining a descending direction positive, is given by

$$\boldsymbol{n}(i,j) = \begin{bmatrix} n_x \\ n_y \end{bmatrix} = -\begin{bmatrix} \partial H/\partial x \\ \partial H/\partial y \end{bmatrix}$$

$$= -\frac{1}{2\Delta x}\begin{bmatrix} H_{i+1,\,j+1} + H_{i+1,j} - H_{i,j+1} - H_{i,j} \\ H_{i+1,\,j+1} + H_{i,j+1} - H_{i+1,j} - H_{i,j} \end{bmatrix} \tag{6}$$

where $H_{i,j}$ is an altitude of the grid point (i,j) and Δx is the distance of a grid point in the x- and y-axis directions. For small inclination, the inclination A is $|\boldsymbol{n}|$ $(= (n_x^2 + n_y^2)^{\frac{1}{2}})$. Wind speed V and deflection angle B are obtained from this A by Equations (4a), (4b) and (4c). Hence the wind speed in a vector $\boldsymbol{V}$ is given by

$$\boldsymbol{V}(i,j) = \frac{V}{A}\begin{bmatrix} \cos B & -\sin B \\ \sin B & \cos B \end{bmatrix}\begin{bmatrix} n_x \\ n_y \end{bmatrix} \tag{7}$$

Similarly to Equation (4), the annual transport rate of drifting snow in a vector is represented by

$$\boldsymbol{Q}(i,j) = KV^{m-1}\boldsymbol{V}(i,j) \tag{8}$$

where K is $Q_0/V_0{}^m$ and m is 5.17. The horizontal divergence of drifting snow is, therefore, given as follows:

$$\operatorname{div} \boldsymbol{Q} = \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y}$$

$$= \frac{1}{2\Delta x}\Big[Q_x(i,j) + Q_x(i,j-1) - Q_x(i-1,j) - Q_x(i-1,j-1)$$

$$Q_y(i,j) + Q_y(i-1,j) - Q_y(i,j-1) - Q_y(i-1,j-1)\Big] \tag{9}$$

Thus the drifting-snow divergence at a grid point can be obtained from its altitude and the altitudes of adjacent points.

Drifting-snow divergence and bare ice

Over an area 600 km × 450 km on Mizuho Plateau, the two-dimensional drifting-snow divergence was calculated at a 15 km grid interval. From Equation (7), the annual mean wind speed was obtained at each grid point (Fig. 7).

The horizontal divergence of drifting snow was thus obtained from the wind speed using Equation (9), as shown in Figure 8. Substantial divergence was found on the windward part of the bare ice field around the Yamato Mountains, which indicates a considerable amount of mass export from the surface. If the mass export due to divergence exceeds the precipitation minus sublimation, the net mass balance becomes negative and a bare ice field can be generated. We conclude that the large divergence is the

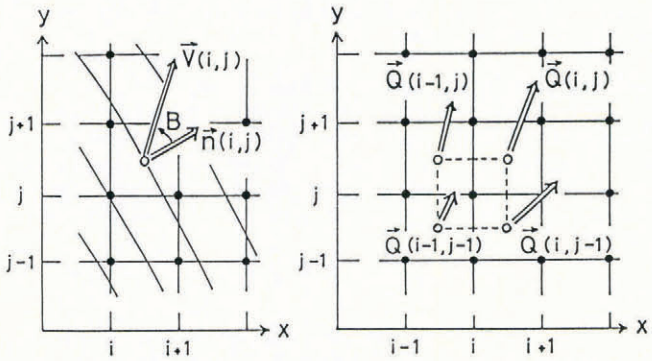

Fig. 6. Notation of grid points for calculation of the surface gradient $\boldsymbol{n}$, katabatic wind vector $\boldsymbol{V}$ and snow-drift transport rate $\boldsymbol{Q}$. B is the deflection angle between $\boldsymbol{n}$ and $\boldsymbol{V}$.

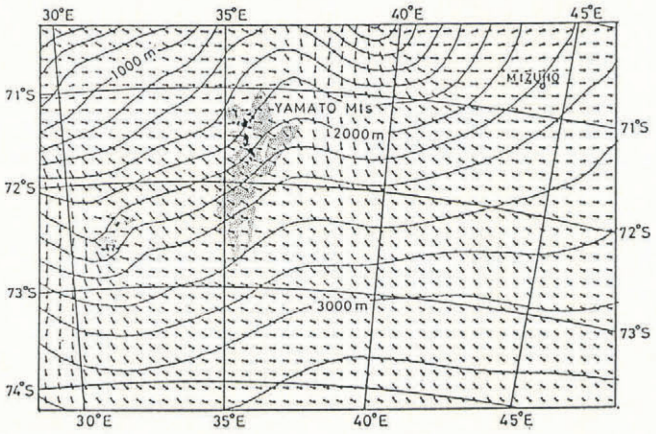

Fig. 7. Katabatic wind vector at 42 × 28 grid points, with a 15 km grid interval calculated from the topography around the Yamato Mountains. Dark areas denote the bare ice field.

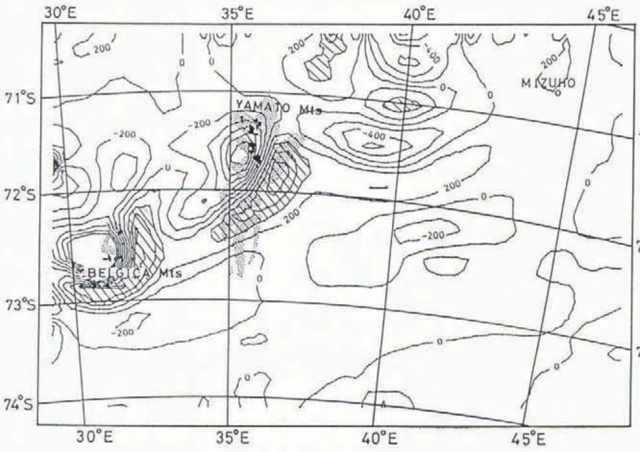

Fig. 8. Horizontal divergence of drifting snow with 200 kg m^{-2} isopleth interval, calculated from the wind speed shown in Figure 7. The hatched area defines values above 400 kg m^{-2}. The isopleth below −1000 kg m^{-2} is not shown. Dark areas denote bare ice.

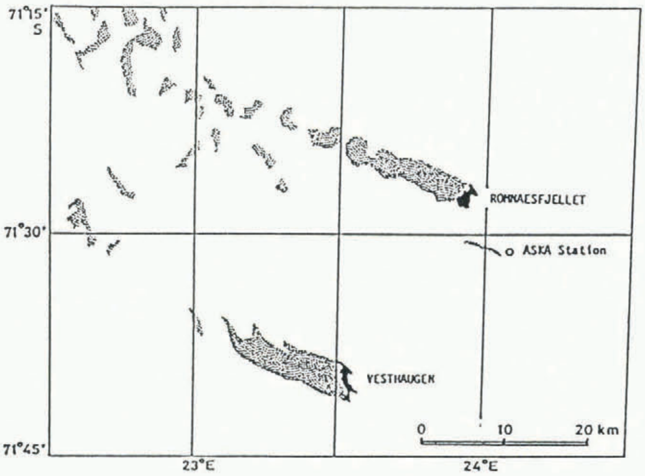

Fig. 9. Elongated bare ice fields (dark area) in the lee of Romnaesfjellet and Vesthaugen in the Sør Rondane Mountains.

principal cause of the bare ice field. In the leeward area, however, the divergence was small or even negative (deposition), as shown in Figure 8. This will be discussed later.

Around the Belgica Mountains, the divergence was large in the windward area despite the fact that no prominent bare ice has been found, except near the mountains. One problem is the inaccuracy of the contour lines. Recent satellite doppler surveys suggested corrections from several tens of meters to 100 m in altitude.

DISCUSSION

Unsaturation of drifting snow

A large divergence of more than 800 kg m^{-2} was found in the windward part of the Yamato bare ice field. This value, however, could not indicate net mass loss from the surface because no snow would be available from the bare ice surface, and the drifting snow could not be saturated. The divergence should therefore be smaller than 800 mm a^{-1}.

In the leeward part of the bare ice field, the calculated divergence shows small or even negative values, as mentioned above. Since the drifting snow should be unsaturated in this area, the decrease in wind speed does not necessarily imply negative divergence of drifting snow. Negative divergence could only take place after the drifting snow became saturated. In this area, the calculation cannot represent exactly the actual divergence, and a further study (in which unsaturated drifting snow is analyzed along a stream line of katabatic flow) will be necessary.

Other factors affecting bare ice fields

The acceleration of wind over the smooth surface of the bare ice should be taken into account. The roughness parameter of bare ice is expected to be smaller than that of a snow surface with sastrugi, dunes and barchans. The lesser roughness should lead to acceleration of the wind and thus divergence of drifting snow.

The low albedo of drifting ice would be another factor. Substantial sublimation has been observed on the bare ice field around the Yamato Mountains. The reason would be the low albedo of bare ice rather than the accelerated wind speed. Once the bare ice has been formed, the low albedo would increase the surface temperature and promote sublimation.

Both these factors have a feed-back effect on the development of a bare ice field. Once bare ice is formed for any reason, the reduced roughness and lowered albedo promote bare-ice formation and the effect extends to leeward, elongating the ice field. Thus the leeward part of a bare ice field can be explained by its lesser roughness and low albedo in addition to unsaturated drifting snow.

The orographic effect is a different kind of factor. Owing to turbulence around the mountains, the diffusion coefficient must increase and the stable profile of absolute humidity is broken by mixing of the air mass, which also promotes sublimation. Bare ice fields are commonly found in the lee of mountains. A prominent example can be seen around the Sør Rondane Mountains (Fig. 9). On the leeward side of Romnaesfjellet and Vesthaugen, bare ice fields are elongated to about 50 km.

CONCLUDING REMARKS

At Mizuho Station, the annual net accumulation of about 70 mm is smaller than the precipitation of about 200 mm minus the sublimation of 50 mm. This deficit in surface mass balance is explained by the mass export of about 100 mm from the surface, due to the horizontal divergence of drifting snow, which is caused by the convex surface topography around the station.

Because of the dependence of katabatic winds on slope gradient, drifting-snow divergence appears on a convex surface and results in mass export from the area. The two-dimensional divergence of drifting snow was calculated at 15 km grid intervals over an area 400 km × 600 km on Mizuho Plateau. Large divergence of drifting snow was seen on convex surface topographies, especially on the windward part of the bare ice field around the Yamato Mountains.

The large divergence of drifting snow could be a cause of the bare ice field. If mass export due to divergence exceeds the precipitation minus sublimation, the surface mass budget would be negative and bare ice would be exposed.

The low roughness and low albedo of bare ice would have a feed-back effect on the development of the ice field, which could explain the leeward elongation reported.

For another cause of bare ice fields, the orographic effect could be considered. In the leeward region of a mountain, bare ice commonly develops. This could be explained by turbulence due to the mountain. A prominent example is seen in the region of the Sør Rondane Mountains.

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