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Yukimarimo at Dome C, Antarctica

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ABSTRACT. Balls of frost (yukimarimo) up to 12 cm in diameter and weighing up to 14 g were observed forming in light winds in the temperature range, −70 to −60 °C at Dome Charlie, Antarctica, during the 2014 winter. Their density ranged from 15 to 60 kg m^{-3}. Meteorological conditions during four formation periods are tabulated. Their formation seems to be due to a clumping of crystals caused by electrostatic attraction, followed by the collection of hoarfrost crystals while rolling along the snow surface.

KEYWORDS: Antarctic glaciology, atmosphere/ice/ocean interactions, snow/ice surface processes

1. INTRODUCTION

'*Yuki*' means snow in Japanese, and 'marimo' are balls of algae that grow in only a few lakes in Hokkaido (Japan), Iceland, Scotland, Estonia, Austria and Australia. Kameda and others (1999) found a resemblance between these algal balls and an unusual phenomenon, balls of snow, that they observed at Dome Fuji station (77°19′S; 39°42′E; 3810 m a.s.l.) on the Antarctic Ice Sheet, during the 36th Japanese Antarctic Research Expedition (JARE-36) in 1995. They termed these balls of snow 'yukimarimo'. Yukimarimo are a naturally occurring phenomenon observed at sites at very low temperature. According to Kameda and others (1999), fine frost layers had formed on the snow surface at air temperatures <−60 °C and humidity above normal levels when these frost balls formed. 'Solid needle' surface hoar crystals were found growing on the snow surface during yukimarimo formation. When a light wind blew after the formation of this hoarfrost, it broke apart and the frost crystals clumped and stuck together. They then rolled over the snow surface, collecting snow to form yukimarimo, which, at Dome Fuji were 5–30 mm in diameter. The yukimarimo were fragile, but did not break apart when handled carefully. Later, Nelson and Baker (2003) suggested a model involving the charging of ice/vapour interfaces to explain yukimarimo formation. They suggested an electrostatic attraction between the rapidly formed ice crystals, which is high due to growth charging during formation, and subsequent fusing of ice crystals.

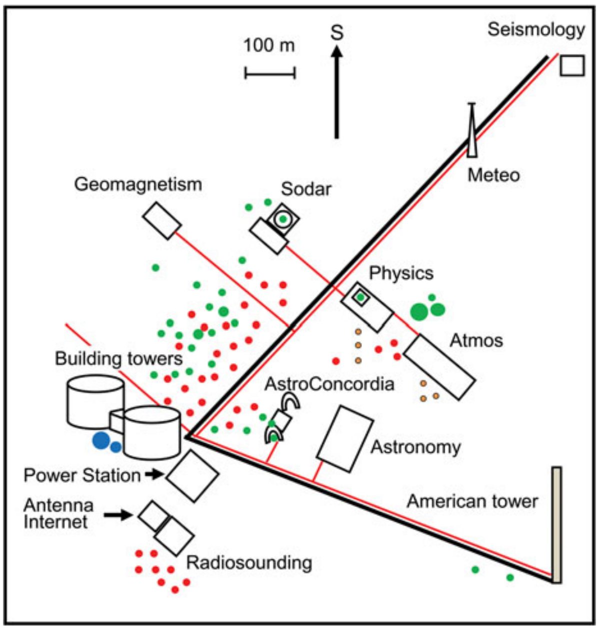

Fig. 1. Plan of Concordia station. Electrical lines are shown in red. Coloured dots indicate areas where yukimarimo were found: red – first case, blue – second case, green – third case and orange – fourth case. The distance scale refers to the distance between the centres of the objects, but not to their dimensions.

According to Kameda and others (1999), a similar phenomenon had been described only twice from earlier observers. Amundsen (1912) reported cylindrical objects of snow during his journey to the South Pole in 1911. Siple (1959) presented observations at South Pole in 1957, of 'wispy frost balls' with diameters up to 50 mm, which immediately disintegrated when touched. Much later, in 1995, Kameda and colleagues discovered and clearly registered these 'intriguing' natural formations (Kameda and others, 1999). Further information on yukimarimo in Antarctica can be found at http://www.yukimarimo.com and at http://www.en.wikipedia.org/wiki/Yukimarimo. One observation of yukimarimo in Greenland is documented at https://www.youtube.com/watch?v=C7R_DOibCxQ. To our knowledge until now, no other literature or Internet sources are available to provide further information on this phenomenon.

In this paper, we describe observations of yukimarimo, made during the tenth overwintering at the French/Italian Concordia station (Dome Charlie (Dome C), Antarctica) in 2014. Video and photographs can be found at https://www.youtube.com/watch?v=XazcOcrJIRQ and http://www.italiantartide.it.

2. SITE AND METEOROLOGICAL CONDITIONS

Concordia station is located at Dome C, Antarctic plateau, 900 km inland of the nearest coast (75°06′S; 123°21′E; 3233 m a.s.l.). The plan of the station is shown in Figure 1. The sun was below the horizon from 5 May to 12 August. Weather conditions during winter are characterised by the presence of a strong temperature inversion of 35 °C. Air temperature at a height of 1.4 m ranged from ~−80 °C to −60 °C and wind speed at 3.5 m varied between 1 and 6 m s^{-1}.

Episodic synoptic perturbations due to maritime air intrusions are characterised by stronger winds up to 12 m s^{-1}, significantly higher temperatures (up to −30 °C) and considerable cloudiness (e.g. Argentini and others, 2001; Genthon and others, 2013).

Some unusual phenomena observed just before the first yukimarimo appearance are described:

(1) On 6 April 2014, we observed that the snow surface exhibited small areas (spots) of different (apparent) brightness. These spots disappeared within 2 days. A similar phenomenon repeated on 8 May 2014, and more careful observations were made. Two large oblong shaped spots were observed. Visual inspection near the boundaries of the spots showed significant differences in the structure of the surface across the spot boundaries. One surface was smooth, the other covered with ice rounded cones of 5–10 mm. The boundary between these two structures was sharp, without any transition zone. The difference in brightness across the two zones turned out to be an optical illusion; the apparent 'darkness'/'lightness' of the surface was found to depend upon the direction of the observation relative to the direction of the sun. We are unable to suggest any explanation of the formation and distribution of these 'pimples' on the snow surface.

(2) On 7 and 8 April 2014, in the vicinity of the main buildings, we observed many hovering large (several centimetres) snowflakes. They could be referred to as A1 (aggregation of column-type crystals) or A3 (aggregation of column- and plane-type crystals) of the classification by Kikuchi and others (2013).

3. MAIN OBSERVED CHARACTERISTICS OF YUKIMARIMO

3.1. First case, 08 April 2014

In the first case, on 8 April 2014, yukimarimo were found in the vicinity of Dome C station (Fig. 1; red dots). For several days before this event, the weather had been calm with slight cloudiness. Meteorological measurements are shown in Figure 2 (LT is local time at Dome C = coordinated universal time (UTC) + 8 h). The night of 5 April was characterised by slightly stronger winds of 5 m s^{-1}; on all other days leading up to the event, wind speed was 2–4 m s^{-1}. There were no large variations in humidity or pressure, but a slight increase in temperature, humidity, wind speed and downward longwave radiation was observed on the afternoon of 7 April 2014. A further increase in these parameters occurred during morning hours on 8 April 2014.

The yukimarimo had diameters principally in the range 10–50 mm. They were fragile, however, did not fall apart when carefully touched. The day before, no sign of yukimarimo was observed, i.e. they formed within a time span <24 h. This is in agreement with results by Kameda and others (1999). During the first 2 days they were distributed around the base over an area of radius up to ~500 m. Along with some large (30–50 mm) non-moving yukimarimo, some small ones of ~10–20 mm in diameter were rolled by the wind. The average density of several yukimarimo with diameters of 35–45 mm was measured to be ~45 ± 5 kg m^{-3}. This value is the same as obtained by Kameda and others (1999). Table 1 summarises the average values of the density for all cases of yukimarimo occurrence. Over the next 2 days, some yukimarimo (10–20 mm) grouped into heaps containing up to several tens of pieces.

3.2. Second case, 28 and 29 April 2014

Another case occurred on 28 April 2014, after some days of non-steady cloudy weather. The evening prior to the yukimarimo occurrence was characterised by clear sky, but many ice crystals were visible in the air. During the night, a large amount of hoarfrost formed. At the same time, the wind direction changed from north-northeast to southeast. Meteorological measurements during this period are shown in Figure 2. Large yukimarimo concentrated directly under the building towers not more than 20 m from the base as shown in Figure 1 (blue dots). Two of these yukimarimo are shown in Figure 3. The number density of yukimarimo was less than in the first case; however, they were larger. Many of them had diameters of 40–60 mm, and several had diameters in the range 60–120 mm. The weight of the heaviest yukimarimo was 14.5 g. Some of the largest yukimarimo had a slightly oblate form. The average density, ~55 kg m^{-3} was higher than in the first case. On the next day, only a few yukimarimo, size 50–90 mm were found under the buildings, and several of 20–30 mm were located ~30 m from the buildings.

3.3. Third case, 2–5 June 2014

Many yukimarimo of different sizes, in the range 20–100 mm were observed in the period 2–5 June 2014. Weather conditions were characterised by the passage of a cyclonic perturbation that was accompanied by an increase in cloudiness, temperature and humidity, which began at 04:00 local time (LT) on 2 June 2014. Meteorology is summarised in Figure 2. Many ice crystals similar to types C1–C3 from the column group (Kikuchi and others, 2013) were present in the air. The observed yukimarimo were mainly concentrated at the South-southwest sector as shown in Figure 1 (green dots). There were many heaps consisting of large and small yukimarimo (Fig 4). Contrary to the first two cases, the surface was not smooth, but exhibited wind-carved hollows, depth up to 30 cm. A large amount of accumulated initial material resembling 'fluff' ('candy floss', 'cotton candy') was present.

This fluff-like mass was not uniform, but was structured in contiguous rounded pieces and was found in a variety of locations. Some small yukimarimo and 'fluff' accumulated within a 2 m high sound isolation enclosure surrounding the sodar antenna (Fig 1). Yukimarimo accumulated and moved within a protecting enclosure on a heated glass window of the lidar at a height of 6 m (Figs 1 and 5). They looked slightly melted and resembled hail stones. 'Fluff' was also found near a radiometer rack at the top of a wooden tower, Astroconcordia, at 5 m height (Figs 1 and 6). Over the next 6 days, 3–9 June 2014, some new large yukimarimo were found in other areas. The density of these yukimarimo was markedly less than in the previous two cases, ~15–30 kg m^{-3}. On 13 June 2014, two isolated balls with diameters of ~55 and 65 mm, density ~60 kg m^{-3}, were found in the vicinity of the base.

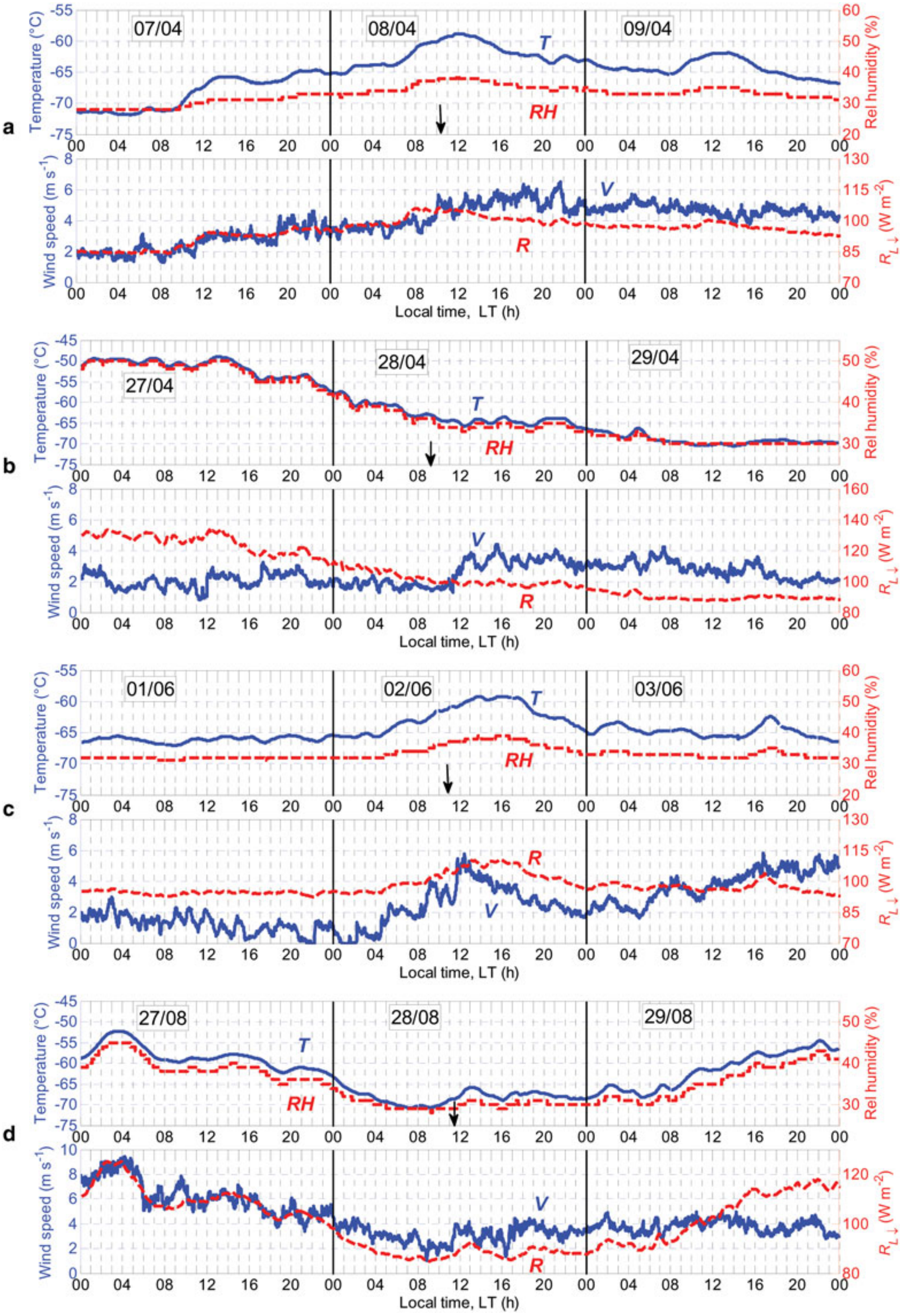

Fig. 2. Time behaviour of meteorological parameters. *a* 07–09 April 2014 *b* 27–29 April 2014 *c* 01–03 June 2014 *d* 27–29 August 2014 Date format on plots is dd/mm. The top panels display temperature *T* (blue solid curve) and relative humidity RH (red dash curve). The bottom panels display wind speed *V* (blue solid curve) and longwave downward radiation $R_{L\downarrow}$ (red dash curve). Black arrows indicate the times after which yukimarimo were observed.

3.4. Fourth case, 28 August 2014

In the fourth case, on 28 August 2014, the initial stage only of yukimarimo formation was observed. The temperature during the night and morning of 28 August varied between −70 °C and −60 °C, the wind velocity was 2–4 m s^{-1} from the south. The day before, cloudiness and a moderate wind of 4–7 m s^{-1} were observed; temperature and humidity values were slightly higher than normal, at −55 °C to −60 °C and 50 to 70%, respectively.

Some surface zones covered with pimples were found north of the Atmos shelter (Fig. 1; orange dots). After careful searching, several accumulations of small yukimarimo balls were found 20 m from the Atmos shelter, mostly with diameters of 10–20 mm. They had been rolled by the wind into spiral trajectories, accumulating in hollows. Later, a quantity of rolling small frost balls, diameter ~20 mm, were found. They concentrated within a band downwind of the Physics shelter to a distance up to 80 m

Table 1. Yukimarimo and meteorological parameters

	Characteristics of yukimarimo		Variables	18:00 LT	00:00 LT	04:00 LT	12:00 LT
First case 8 April	Diameter (mm)	20–50	T (°C)	−67	−65	−63	−60
	Density (kg m^{-3})	45	V (m s^{-1})	2.5	3.5	3.9	5.8
			Direction (°)	183	185	182	185
			H, %	31	33	34	38
			P (hPa)	636	636	636	635
			LW↓ (W m^{-2})	75	75	76	80
Second case 28 April	Diameter (mm)	50–120	T (°C)	−54	−57	−60	−64
	Density (kg m^{-3})	50–60	V (m s^{-1})	2.7	2.2	2.3	2.7
			direction (°)	315	300	280	270
			H (%)	46	42	40	34
			P (hPa)	640	638	637	636
			LW↓ (W m^{-2})	80	80	79	77
Third case 2 June	Diameter (mm)	20–100	T (°C)	−66	−65	−65	−62
	Density (kg m^{-3})	15–60	V (m s^{-1})	1.5	1.2	0.5	3.5
			Direction (°)	185	180	190	180
			H (%)	32	32	32	37
			P (hPa)	641	640	639	638
			LW↓ (W m^{-2})	77	76	75	80
Fourth case 28 August	Diameter (mm)	5–20	T (°C)	−60	−63	−68	−68
	Density (kg m^{-3})	NA	V (m s^{-1})	4.8	5.0	3.0	3.5
	*		Direction (°)	180	170	160	160
			H (%)	38	35	30	30
			P (hPa)	638	639	642	644
			LW↓ (W m^{-2})	73	70	67	68

* Not well developed.

(Fig. 1). From this we hypothesise that some foreign objects (e.g. a metallic container) can trigger yukimarimo formation processes; it seems the interaction between ice crystals carried by the wind and metallic surfaces covering some electrical instruments can produce specific charging of the snow surface. A search near other Concordia constructions revealed no trace of yukimarimo and observations over the next day failed to find any development or growth of yukimarimo.

Weather conditions at Dome C station during the periods of yukimarimo occurrence are summarised in Table 1. Measurements made at 1800 LT in the day before, and at 00:00, 04:00 and 12:00 LT in the day of the yukimarimo appearance are presented. Considering all cases, we note that yukimarimo occurrence was accompanied mainly by fair weather soon after perturbations causing a small increase in temperature and humidity. The values are typical of the winter period, and it seems unlikely that the weather itself is the principal factor for yukimarimo formation. At most, some specific snow or atmospheric conditions may be required to trigger formation processes. Favourable wind speeds can be roughly estimated as >2 m s^{-1} at 3.5 m height. Our observations and conclusions concerning temperature and wind regimes favouring the yukimarimo formation are in agreement with those of Kameda and others (1999).

Based on our observations, we suggest a rough classification of yukimarimo:

(1) *'Spherically rolling'* – balls, 10–30 mm diameter rolling fast, driven by wind, as observed by Kameda and others (1999), in Greenland, and by us.
(2) *'Heaped up'* – a few tens of balls, 20–30 mm diameter, gathered in hollows in the snow surface.


28/04/2014 11:55

Fig. 3. Two yukimarimo found under the building towers between footstalls.


02/06/2014 10:34

Fig. 4. Large and small yukimarimo among 'fluff'.

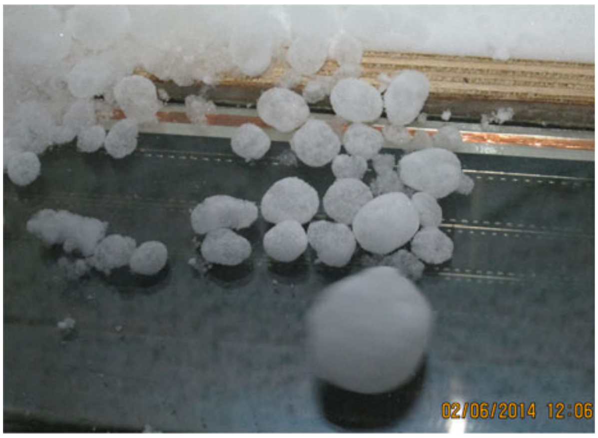

Fig. 5. Slightly melted yukimarimo accumulated inside the enclosure of the lidar heated glass window (height, 6 m).

(3) '*Light soft*' – soft balls, 30–60 mm diameter and density, 15–30 kg m^{-3}.
(4) '*Heavy medial*' – consistent and steady balls with diameter, 30–50 mm and density, 40–50 kg m^{-3}.
(5) '*Light giant*' – large balls with diameter, 60–100 mm and density, 15–30 kg m^{-3}, as found in the third case.
(6) '*Heavy giant*' – large balls, diameter, 60–120 mm and density, 40–60 kg m^{-3} as found only under the main building structures in the second case (Fig. 1).

We hypothesise a two-step process for yukimarimo formation:

(1) At the initial stage, an electrostatic attraction (Nelson and Baker, 2003) favours the formation of small non-dense and soft balls or a 'fluff' with a rounded structure.
(2) These 'nucleus' balls begin to roll with the wind, accumulating mass on their external surface.

In addition, Kameda (2007) presented microscope photographs of crystals forming yukimarimo with a cross-like form. So, it seems that such shaped crystals can hitch to each other, and subsequently form yukimarimo.

4. SUMMARY

Yukimarimo were observed during the tenth overwintering at Concordia (Dome C) station in 2014. They appeared suddenly and existed over a few days on the snow surface. Yukimarimo were observed four times showing different behaviour and properties. Although similar in form (spherical or oblate), they had different characteristics in terms of their total number, size, density and distribution over the area. Their density varied from 15 to 60 kg m^{-3}. The largest had an equatorial diameter of ~120 mm; the heaviest had a weight of ~14 g.

There are some essential differences between our observations and previous observations. Amundsen (1912) described snow cylinders; we found only balls. Siple (1959) described very fragile balls 'so delicate that the slightest touch caused them to collapse into nothing'. Ours were stronger; it was possible to take them by hand without destroying them (!) The yukimarimo diameters observed by Kameda and others (1999) ranged in diameter from 5 to 30 mm. We observed many yukimarimo with larger diameters up to 120 mm. Some yukimarimo were found in previous overwintering campaigns at Dome C station, but they were smaller than those in 2014.

The most favourable meteorological conditions for the formation of yukimarimo were air temperature between −70 and −60 °C and wind speed from 2 to 4 m s^{-1}, the same as reported by Kameda and others (1999).

We are unable to suggest any new hypothesis to explain yukimarimo, and that suggested by Nelson and Baker (2003), that an electrostatic attraction is required as an initial mechanism to trigger the formation of nuclei, remains the best. The described phenomenon needs to be understood and described thoroughly. We believe it indicates the presence of some yet little known processes concerning electrical properties of ice and air in polar regions at low temperature.

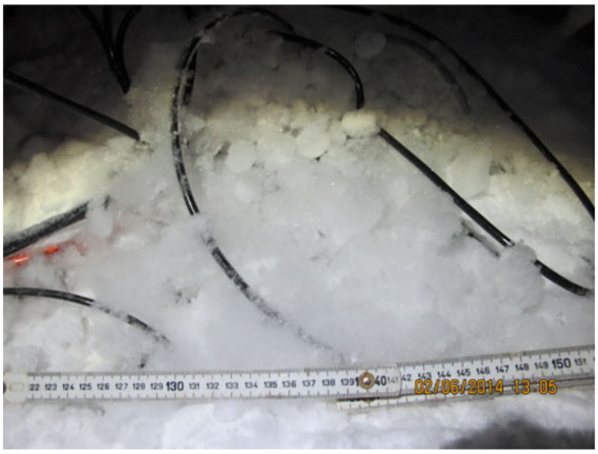

Fig. 6. 'Fluff' accumulated at the tower Astroconcordia (height, 5 m).

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