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ROYAL OBSERVATORY, HONG KONG

Technical Note (Local) No. 10

FROST, RIME, SLEET AND OTHER WINTER PHENOMENA IN HONG KONG

by

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1970

C O N T E N T S

I. FROST

Despite the fact that Hong Kong is situated within the tropics, the occurrence of frost in the Colony is by no means a rare event, although it is definitely a news-worthy one. However, the frost reported by local newspapers invariably refers to visible hoar frost and not to invisible ground frost.

The following discussion on frost is sub-divided into two sections:-

(A) hoar frost
and (B) ground frost

(A) HOAR FROST

Hoar frost is a crystalline icy deposit formed by the process of sublimation, i.e. the direct transformation of water vapour into ice without going through the intermediate stages of liquefaction. It generally assumes the shape of scales, needles, feathers or fans and can form only when the surface temperature of objects in contact with the air falls below the frost point. The frost point is the lowest temperature to which moist air must be cooled in order that it shall be saturated with respect to ice at its existing pressure, and it is always below 0°C. In fact, hoar frost is produced in the same manner and under the same circumstances as the more familiar deposit known as dew, except that the temperature of the surface on which it forms is below 0°C.

Fourteen reports (mainly from newspapers) of hoar frost during the 20-year period 1949-1968 are summarized in Table I, together with the associated meteorological conditions at the Royal Observatory. However, it is probable that frost occurred during the period without being reported and so the total of 14 reports in 20 years is likely to be an underestimate of the actual frequency of occurrence.

From Table I, one can generalize that the following conditions are favourable for the occurrence of hoar frost in Hong Kong:-

(1) Location

Hoar frost usually occurs in the New Territories, especially on high ground, and seldom on Hong Kong Island.

(2) Season

Hoar frost, essentially a winter phenomenon in Hong Kong, has been reported only in January and February.

(3) Cloud and Rainfall

Usually no rain occurs at the Royal Observatory on occasions when frost is reported. However, the state of sky may vary from clear to overcast.

(4) Wind

Winds are usually from the north to northeast, and are light to moderate in strength.

(5) Temperature and Humidity

Apart from 2 doubtful occasions on 5th and 6th Jan., 1956, frost has never been reported on a day when the minimum air temperature at the Royal Observatory on the same morning was above 10°C. These two reports have been omitted in Table II, which shows the frequency of occurrence of frost under various humidity conditions when the minimum temperature at the Royal Observatory was below 10°C during the 20-year period 1949-1968.

The table indicates that:-

(i) When the temperature at the Royal Observatory dropped below 7°C, then frost occurred 9 times out of a possible 37, but when the temperature fell below 4°C then frost occurred 3 times out of a possible 4.

(ii) Relative humidity appears to be less significant in dictating the formation of hoar frost although frost occurred twice as frequently when the mean relative humidity was less than 50%.

(iii) When the minimum temperature was below 6°C and the mean relative humidity was below 50%, then frost occurred on 4 out of the 7 recorded occasions.

(B) GROUND FROST

Frost is an economic hazard to fruit and vegetable growers in Hong Kong where the winter is usually relatively mild. The critical temperature varies not only with the different types of plants but also with a specific plant depending on its stage of growth, water content, etc.

Since injury to the tissues of plants is not normally caused until the temperature has fallen appreciably below 0°C, a 'ground frost' used to be regarded as having occurred only when the reading of a thermometer, placed with its bulb just touching the tips of short grass, (i.e. the grass minimum temperature), had fallen to -0.9°C. This definition of ground frost was adopted by the British Meteorological Office from 1906 to 1960. With effect from 1st Jan., 1961, however, the term 'ground frost' was redefined as a grass minimum temperature below 0°C[1].

During the 10-year period from 1959 to 1968 the grass temperature at the Royal Observatory fell to zero or below on only three occasions:-

(1) 0°C, on 10th Jan., 1963,
(2) -1.3°C, on 17th Jan., 1967,
(3) -0.2°C, on 15th Feb., 1968.

The frequency of occurrence of ground frost over the New Territories should be much higher since it is usually colder there. Unfortunately, there was no direct measurement of ground temperatures in the New Territories until June, 1969 when grass minimum temperatures were first measured daily at an experimental farm of the Agriculture and Fisheries Department at Ta Kwu Ling.

Due to the lack of direct observations of ground frost, one cannot carry out an examination of past weather conditions in order to formulate any forecasting tool. However, an indirect method for forecasting ground frost is proposed, as follows:-

(1) Forecast the minimum air temperature, T_{min}, expected at the Royal Observatory,

(2) Forecast the mean cloud cover, m, between midnight and 7 a.m.,

(3) With T_{min} and m, forecast the grass minimum temperature, G_{min}, expected at the Royal Observatory. A method for doing this is presented in Section II.

(4) If G_{min} is expected to be below freezing, then ground frost is forecast to occur at the Royal Observatory and in the New Territories. If G_{min} is just above freezing, then ground frost is likely to occur anywhere in the Colony where the over-night minimum temperature will be lower than that at the Royal Observatory by at least $(T_{min} - G_{min})$ degrees. The variation of air temperature over the Colony is given by Sham[2] and Fig. I which shows the minimum air temperatures recorded at various places on the morning of 5th Feb., 1969, presents an indication of such variation.

It must be stressed that the occurrence of frost can be very localized as nocturnal ground cooling is very dependent on exposure. Sheltered valleys can be much colder than exposed ground because cold air there, being relatively heavy, forms a stagnant pool and is cooled continuously, being unaffected by the light winds above. Hence, a knowledge of local conditions is essential for the forecast of frost in a particular locality.

Of equal importance is the nature of the surface of the ground. Gloyne[3] has found that the night temperature on different surfaces but with the same weather conditions decreases in the following order:-

long grass
short grass
bare soil

The effect of the nature of the surface of the ground on nocturnal cooling will be further discussed in Section VII.

DATE	LOCATION	MIN. TEMP. T_{min} (°C)	GRASS MIN. TEMP. G_{min} (°C)	TOTAL RAINFALL FROM MIDNIGHT TO 7 a.m. (mm)	MEAN CONDITIONS FROM MIDNIGHT TO 7 a.m.				
					RELATIVE HUMIDITY (%)	CLOUD AMOUNT (oktas)	DEW POINT (°C)	WIND	
								DIRECTION	SPEED (knots)
9 Jan 1949	FANLING	5.9	NO RECORD	NIL	40	NIL	-5.0	N TO NNE	16
10 Jan 1949	FANLING	6.7	NO RECORD	NIL	73	3	3.9	ENE	4
9 Jan 1955	FANLING	7.3	3.0	NIL	50	3	1.7	NNW TO NNE	7
12 Jan 1955	SHEK KONG VALLEY, HAPPY VALLEY RACE COURSE	5.2	-2.7	NIL	33	NIL	-7.8	NNE	5
5 Jan 1956	MT. NICHOLSON	15.3	10.6	NIL	81	6	12.4	N TO E	13
6 Jan 1956	MT. NICHOLSON	12.2	15.3	TRACE	90	7	15.6	ENE TO ESE	10
7 Jan 1956	MT. NICHOLSON	6.4	8.5	2.9	89	8	7.8	N TO NNW	10
8 Jan 1956	SHEK KONG, HILLS IN N.T., BY THE SIDES OF HIGHWAYS IN N.T.	5.7	5.1	TRACE	58	8	-1.1	N TO NNE	12
9 Jan 1956	HIGH HILLS	3.9	1.7	NIL	46	TRACE	-5.4	NNE	12
10 Feb 1957	CASTLE PEAK, TAI MO SHAN, TAI PO.	3.8	7.1	NIL	82	8	4.4	N TO NNE	10
11 Feb 1957	LANTAU PEAK, NGONG PING, ROUTE TWISK, PADDY FIELDS IN N.T.	2.4	0.8	NIL	64	7	-2.6	N TO NNE	8
25 Jan 1964	TAI MO SHAN, HILLTOPS AROUND YUEN LONG	9.2	10.7	NIL	74	7	6.4	NNE TO ENE	3
21 Feb 1964	KAI SHAN, NEAR PING SHAN	7.0	8.3	NIL	85	8	6.4	N TO NE	4
16 Jan 1967	HILLTOPS IN N.T.	4.6	2.3	NIL	29	TRACE	-10.2	NNE	12

Table I. HOAR FROST AND ASSOCIATED WEATHER CONDITIONS AT THE ROYAL OBSERVATORY

MEAN R.H. MIDNIGHT TO 7 a.m.(%) \ MIN.AIR TEMP. (°C) — FROST TOTAL CASES	2.0 - 2.9	3.0 - 3.9	4.0 - 4.9	5.0 - 5.9	6.0 - 6.9	7.0 - 7.9	8.0 - 8.9	9.0 - 9.9	2.0 - 9.9
11 - 20	0/0	0/0	0/0	0/0	0/0	0/1	0/0	0/0	0/1
21 - 30	0/0	0/0	1/1	0/0	0/1	0/0	0/6	0/1	1/9
31 - 40	0/0	0/1	0/0	2/2	0/0	0/2	0/7	0/4	2/16
41 - 50	0/0	1/1	0/1	0/1	0/2	1/2	0/5	0/7	2/19
51 - 60	0/0	0/0	0/1	1/2	0/2	0/3	0/7	0/5	1/20
61 - 70	1/1	0/0	0/2	0/4	0/3	0/6	0/9	0/12	1/37
71 - 80	0/0	0/0	0/1	0/0	1/1	0/4	0/11	1/12	2/29
81 - 90	0/0	1/1	0/1	0/2	1/6	1/8	0/7	0/13	3/38
91 -100	0/0	0/0	0/0	0/0	0/0	0/1	0/4	0/4	0/9
11 -100	1/1	2/3	1/7	3/11	2/15	2/27	0/56	1/58	12/178

$\frac{5}{45} = \frac{2}{18}$

$\frac{7}{133} \rightarrow \frac{1}{18}$

Table II. FREQUENCY DISTRIBUTION OF OCCURRENCE OF HOAR FROST IN RELATION TO RELATIVE HUMIDITY AND MINIMUM AIR TEMPERATURE AT THE ROYAL OBSERVATORY.

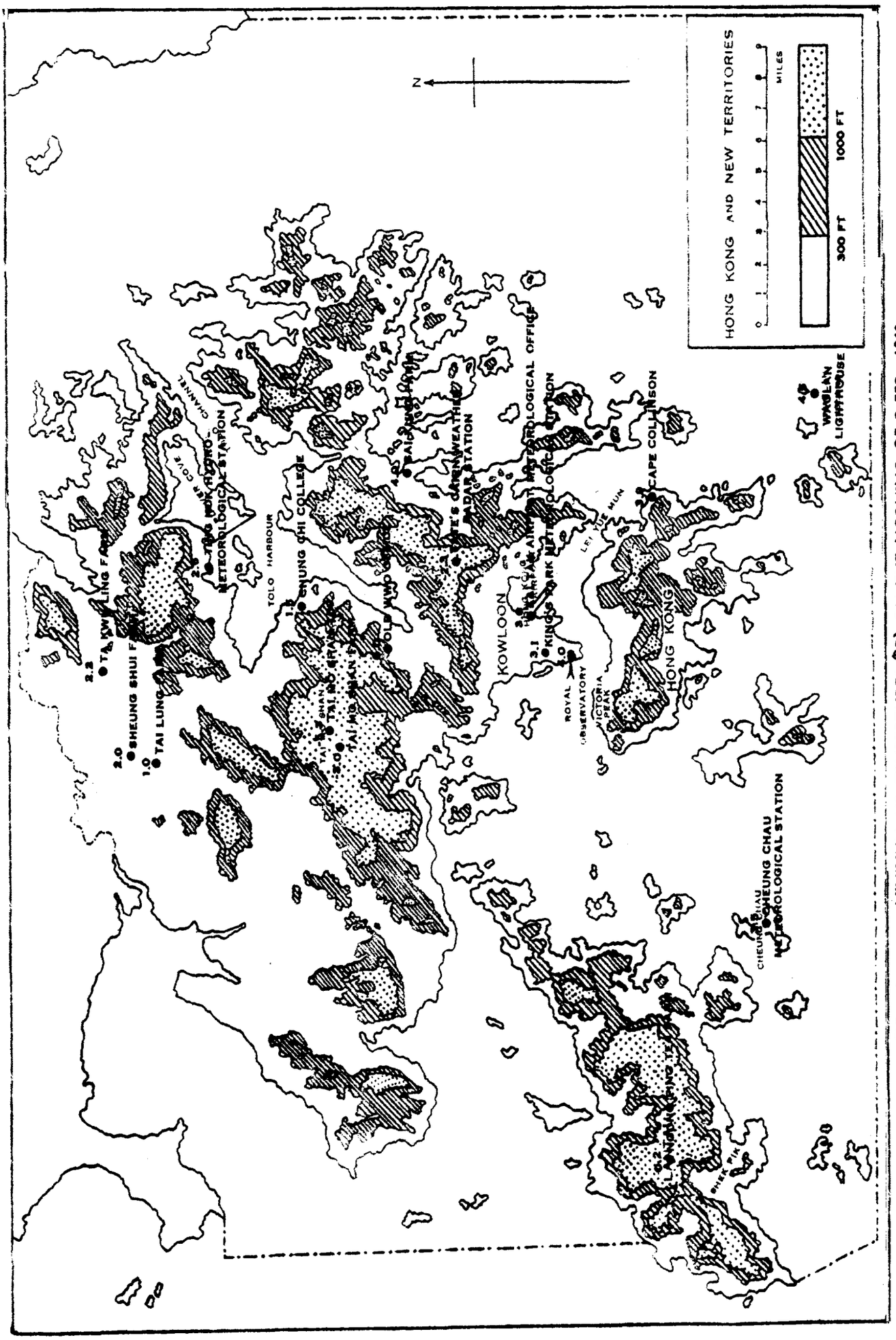

FIG. 1. MINIMUM AIR TEMPERTURES (°C) ON THE MORNING OF 5 FEB., 1969

II. FORECAST OF GRASS MINIMUM TEMPERATURE

During the night, heat is lost from the ground in the form of long-wave radiation, but this loss will be reduced if there is water vapour or cloud in the atmosphere, since both absorb the outgoing radiation from the ground, are heated, and, in turn, emit radiation in all directions part of which returns to the ground. However, water vapour is transparent to certain wave-lengths of the earth's radiation and this means that whatever the humidity, nocturnal cooling of the ground can still take place provided that the downward radiation from clouds is less than the upward radiation from the earth. In fact, Byers[4] has stated that the night-time cooling of the ground is modified more by cloudiness than by any other factor.

Tables III and IV have been prepared to assist in the forecast of the temperature ($T_{min} - G_{min}$).

Table III gives the difference as a function of the mean cloud coverage, m, between midnight and 7 a.m. and in Table IV the mean differences are tabulated in relation to the mean wind speed between midnight and 7 a.m. Both tables have been prepared from observations made at the Royal Observatory during the 10-year period 1959 - 1968.

Table IV shows that, with the exception of overcast conditions, the difference is usually greater in calm or light winds. This is because wind causes mixing and so the drop in temperature is spread through a thicker layer of air.

The relative frequency of the mean cloud amount from midnight to 7 a.m. for the months of January, February and December during the period 1959 to 1968 is given in Table V.

MEAN CLOUD AMOUNT m, BETWEEN MIDNIGHT & 7 a.m.	NIL	NIL < m ≤ 1/8	1/8 < m ≤ 2/8	2/8 < m ≤ 3/8	3/8 < m ≤ 4/8	4/8 < m ≤ 5/8	5/8 < m ≤ 6/8	6/8 < m ≤ 7/8	7/8 < m ≤ 8/8
$T_{min} - G_{min}$ (°C) / MONTH	MEAN ABS. MAX. ABS. MIN.	MEAN ABS. MAX. ABS. MIN.	MEAN ABS. MAX. ABS. MIN.	MEAN ABS. MAX. ABS. MIN.	MEAN ABS. MAX. ABS. MIN.	MEAN ABS. MAX. ABS. MIN.	MEAN ABS. MAX. ABS. MIN.	MEAN ABS. MAX. ABS. MIN.	MEAN ABS. MAX. ABS. MIN.
DECEMBER	5.9	5.3	4.2	4.4	3.8	3.4	3.6	2.4	1.2
	7.9 2.6	8.5 1.3	6.7 2.9	7.4 1.7	7.5 1.4	5.1 2.0	9.6 1.5	6.8 0.2	4.9 -0.7
JANUARY	5.6	5.5	4.5	4.5	3.5	4.2	3.1	2.1	1.3
	8.8 2.6	8.3 2.0	7.5 1.9	8.8 1.7	5.4 1.5	7.0 1.9	6.5 0.1	6.4 -0.2	7.6 -1.1
FEBRUARY	4.3	4.6	3.2	4.0	3.5	2.9	2.1	1.7	0.7
	7.0 1.7	8.7 2.1	4.8 1.4	8.1 0.1	6.3 1.2	5.1 1.5	3.6 -0.3	4.5 -0.3	3.3 -0.7
DECEMBER JANUARY FEBRUARY	5.5	5.3	4.1	4.3	3.6	3.5	3.0	2.1	1.0
	8.8 1.7	8.7 1.3	7.5 1.4	8.8 0.1	7.5 1.2	7.0 1.5	9.6 -0.3	6.8 -0.3	7.6 -1.1

Table III. $(T_{min} - G_{min})$ IN RELATION TO MEAN CLOUD AMOUNT

WIND STRENGTH / CLOUD AMOUNT	F 0-2 (0-6 Knots)		F 3 (7-10 Knots)		≥ F 4 (≥ 11 Knots)	
	NO. OF CASES	MEAN $T_{min} - G_{min}$ °C	NO. OF CASES	MEAN $T_{min} - G_{min}$ °C	NO. OF CASES	MEAN $T_{min} - G_{min}$ °C
NIL	39	5.0	13	4.6	6	3.8
0/8 < m ≤ 1/8	71	5.8	25	4.7	12	4.1
1/8 < m ≤ 2/8	26	4.1	12	4.5	4	2.4
2/8 < m ≤ 3/8	16	4.6	17	4.0	2	4.9
3/8 < m ≤ 4/8	24	3.8	11	3.4	5	3.2
4/8 < m ≤ 5/8	26	3.6	6	3.0	2	3.0
5/8 < m ≤ 6/8	31	3.5	20	2.9	10	1.7
6/8 < m ≤ 7/8	83	2.2	56	2.1	28	1.6
7/8 < m ≤ 8/8	98	0.8	49	1.1	27	1.1

Table IV. ($T_{min} - G_{min}$) IN RELATION TO CLOUD AMOUNT AND WIND STRENGTH.

MEAN CLOUD AMOUNT (■) / FREQUENCY (%) / MONTH	NIL	NIL < m ≤ 1/8	1/8 < m ≤ 2/8	2/8 < m ≤ 3/8	3/8 < m ≤ 4/8	4/8 < m ≤ 5/8	5/8 < m ≤ 6/8	6/8 < m ≤ 7/8	7/8 < m ≤ 8/8
DECEMBER	6.1	12.9	5.5	5.2	7.7	3.5	11.0	30.6	17.4
JANUARY	10.3	16.8	6.8	4.5	4.5	5.2	8.1	21.9	21.9
FEBRUARY	2.8	7.8	3.9	3.9	4.6	3.9	7.1	20.5	45.6

Table V. FREQUENCY DISTRIBUTION OF MEAN CLOUD AMOUNT FROM MIDNIGHT TO 7 a.m.

III. RIME

The International Cloud Atlas[5] defines rime as "a deposit of ice, composed of grains more or less separated by trapped air, sometimes adorned with crystalline branches. Rime is produced by the rapid freezing of supercooled, very small water droplets; it sometimes grows to thick layers. Near the ground, rime is deposited on objects, mainly on the side exposed to the wind and mostly on points and edges, by the freezing of supercooled fog droplets or (in mountainous regions) of supercooled cloud droplets". If the process persists, rime may grow out to an inch or more to the windward side of exposed objects but the deposit is usually so delicate that it can be dislodged by a slight shake.

A necessary condition for rime formation is the occurrence of wet fog or drizzle with the air temperature below 0°C.

So far, the Royal Observatory has received two authenticated rime reports:-

(1) Rime was reported at 12, Mt. Kellet Road Hong Kong Island on 23rd Mar., 1968. When the Royal Observatory personnel arrived at 10.15 a.m. the site was enshrouded in low stratus (hill fog) and some rime was still visible in the garden.

(2) Rime persisted near the top of Tai Mo Shan for two consecutive days from 4th to 5th Feb., 1969 when the minimum air temperature there was -3.5°C and -5.0°C respectively and the site was in cloud. The photographs in Fig. II and Fig. III were taken around noon on the 4th.

IV. ICE

During the winter months, ice sometimes forms in pools or fish ponds, while buckets of water left out of doors overnight become covered with a layer of ice by the next morning.

Reports of ice and the associated weather conditions at the Royal Observatory during the years 1948 to 1968 are summarized in Table VI.

The table indicates that ice was often associated with temperatures at the Royal Observatory below 7 degrees and low humidity conditions, and the mean dew point from midnight to 7 a.m. was generally less than 4°C.

Although ice will form when water is exposed to air whose temperature is below 0°C, this is not a necessary condition for Hong Kong. When the air temperature falls to near freezing in winter, additional cooling due to evaporation can be sufficient to cause the formation of ice.

On 16th Jan., 1967 ice formed in the evaporation pans at King's Park Meteorological Station. The following records from that station illustrate the importance of evaporation cooling:-

Minimum air temperature	3.7°C
Minimum wet bulb temperature	- 0.6°C
Period when wet bulb temperature was below freezing	6.30 - 9.20 a.m.
Grass minimum temperature	1.1°C
Minimum evaporation pan water temperature	-0.3°C

DATE	PHENOMENON	LOCATION	MIN. TEMP. T_{min} (°C)	GRASS MIN. TEMP. G_{min} (°C)	TOTAL RAINFALL FROM MIDNIGHT TO 7 a.m. (mm)	MEAN CONDITIONS FROM MIDNIGHT TO 7 a.m.				
						RELATIVE HUMIDITY (%)	CLOUD AMOUNT (oktas)	DEW POINT (°C)	WIND	
									DIRECTION	SPEED (Knots)
27 Jan 1948	ICE FOUND ON A RIDGE	NORTH OF TSUEN WAN	4.3	NO RECORD	TRACE	93	8	3.9	N	3
9 Jan 1949	ICE FOUND IN FISH PONDS	VICTORIA PEAK	5.9	NO RECORD	NIL	40	NIL	-5.0	N	18
10 Jan 1949	ICE FOUND IN POOLS OF WATER	FANLING	6.7	NO RECORD	NIL	73	3	3.9	E	4
10 Jan 1955	ICE FILM FORMED IN TUBS OF WATER ICE FOUND IN POOLS OF WATER	UPPER LEVELS OF HONG KONG ISLAND	4.6	1.7	NIL	42	NIL	-5.6	N TO NNE	7
8 Jan 1956	1-INCH THICK ICE	MA ON SHAN, TAI MO SHAN,	5.7	5.1	TRACE	58	8	-1.1	N TO NNE	12
9 Jan 1956	1-INCH THICK ICE	AND OTHER HILLTOPS	3.9	1.7	NIL	46	TRACE	-5.4	N TO NNE	12
11 Feb 1957	ICE FORMED IN WATER TANKS	LANTAU, VICTORIA PEAK, ROUTE TWISK	2.4	0.8	NIL	64	7	-2.6	N TO NNE	8
16 Jan 1967	WATER IN BUCKETS FROZEN ICE FOUND IN EVAPORATION PAN	LANTAU PEAK, TATE'S CAIRN KING'S PARK	4.6	2.3	NIL	29	TRACE	-10.2	NNE	12
13 Feb 1968	WATER IN BUCKETS FROZEN	TAI MO SHAN	11.0	8.5	NIL	80	6	8.2	ENE	12
15 Feb 1968	ICE FOUND IN POOLS OF WATER	TAI MO SHAN	5.7	-0.2	NIL	60	TRACE	-0.1	NNE	6

Table VI. ICE PHENOMENON AND ASSOCIATED WEATHER CONDITIONS AT THE ROYAL OBSERVATORY

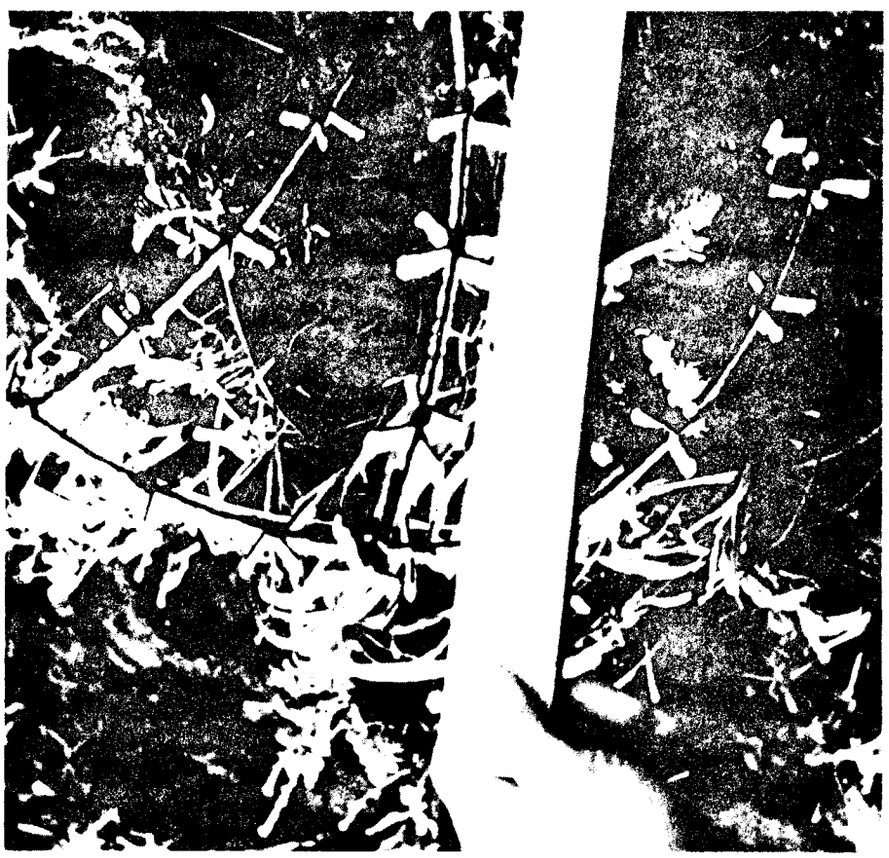

FIG. III RIME ON BARBED WIRE

FIG. II RIME ON BUSHES

V. SLEET AND SNOW

The Royal Observatory has so far received three authenticated reports of sleet or snow, particulars of each occasion are given in Table VII.

The mean freezing level for February is 4,330 metres and for December 4,600 metres. Thus the freezing levels on the days when sleet or snow was observed were lower than the average height by at least 800 metres. However, lower freezing levels have been observed without the occurrence of sleet or snow.

DATE	TIME	PHENOMENON	LOCATION	MINIMUM AIR TEMP. AT ROYAL OBSERVATORY (°C)	FREEZING LEVEL AT 8 a.m. (metres)	REMARKS
2 Feb 1967	10.30 a.m.	SNOW	CAPE COLLINSON TRAINING CENTRE	7.9	3,480	TEMPERATURE AT 10.30 A.M. AT CAPE COLLINSON METEOROLOGICAL STATION WHICH IS ABOUT 1,400 METRES FROM THE TRAINING CENTRE WAS 8.8°C.
13 Dec 1967	8.30 - 9.30 a.m.	VERY SLIGHT SNOW	NEAR TOP OF TAI MO SHAN	10.8	3,060	AMOUNT VERY SLIGHT. AIR TEMPERATURE NEAR TOP OF TAI MO SHAN AT 8.00 A.M. WAS 4.4°C.
AROUND MIDNIGHT BETWEEN FEB 12 & 13 1968		SLEET	NEAR TOP OF TAI MO SHAN	11.0	3,680 (12 FEB) 3,150 (13 FEB)	LASTED FOR ABOUT HALF AN HOUR. SNOW MELTED ON REACHING GROUND. AIR TEMPERATURE NEAR TOP OF TAI MO SHAN AT 2 A.M. WAS 5.6°C.

Table VII. SNOW OR SLEET AND ASSOCIATED WEATHER CONDITIONS

VI. FATALITIES DUE TO COLD WEATHER

Cold spells that strike the Colony have been reported to cause the deaths of some unfortunate people, mainly the aged, the very young or drug addicts. Table VIII has been compiled solely from newspaper reports during the years 1948 - 1968.

DATE	NUMBER OF PEOPLE	LOCATION	MIN. TEMP. AT R.O. (^{o}C)
26 Jan 1948	10 persons died including a 55-year old beggar	Not stated Sai Yeung Choi St., Kln.	3.8
7 - 8 Jan 1956	3 beggars died, aged 35, 40 & 45	Kowloon Walled City	6.4 5.7
11 Jan 1956	2 bodies found 1 person died	(a) Circular Pathway (b) Yuen Chau Tsai, Tai Po Pokfulam Road	8.3
6 Feb 1957	A 60-year old died	Bonham St., East	7.2
10 - 11 Feb 1957	(a) 6 died, all suspected to be drug addicts (b) A 3-year child died	Kowloon Walled City Pok Fu Lam	3.8 2.4
11 Jan 1959	More than 20 people, including 2 children, died.	mostly in Kowloon	5.8

Table VIII. REPORTS OF DEATHS DUE TO LOW TEMPERATURES

Poultry and pond fish have also been reported to have been killed in cold spells. Table IX is a summary of such occurrences, details of which have been obtained mainly from newspaper reports during the period 1948-1968. This table indicates that farmers should be especially on guard during the month of January.

DATE	TYPE OF POND FISH, POULTRY OR LIVESTOCK AFFECTED	LOCATION	MIN. TEMP. AT R.O. (^{o}C)
8 Jan 1956	Chickens and ducks	Farms in New Territories	5.7
8 - 11 Jan 1956	(a) Pond fish, mainly mud carp and mullet	Yuen Long and Castle Peak	5.7 3.9
	(b) Ducks	Tsuen Wan	5.8
	(c) A litter of pigs and a pig weighing 10-20 catties	Tsuen Wan	8.3
16 - 17 Jan 1958	Chickens	Farms in New Territories	7.5 7.3
16 Jan 1967	100 piculs of edible gold fish and common carp	New Territories	4.6

Table IX. LOSS OF POULTRY, POND FISH AND LIVESTOCK

VII. THEORETICAL NOCTURNAL COOLING OF THE GROUND

Numerous methods have been devised for calculating minimum temperature on a purely theoretical basis. Results are generally unsatisfactory, especially in hilly country or near an irregular coast line. However, the process of calculation does illustrate the importance of the various factors involved. At night, the following processes transport heat vertically through the earth's surface:-

F_N = net flux of terrestrial radiation

α = transport of heat by turbulence in the air (turbulent diffusion)

W = latent heat transfer due to evaporation, condensation or sublimation

C = heat conducted within the soil to or from the earth's surface

Since the net heat transfer across a surface of zero thickness is zero, we have

$$F_N + \alpha + W + C = 0 \quad \text{---------- (1)}$$

Assuming:

(a) W = 0 i.e. negligible condensation, evaporation or sublimation,

(b) $F_N = F_{N1}$ i.e. the net flux of terrestrial radiation remains constant throughout the night at the sunset value of F_{N1}

(c) the initial temperature distribution in the soil is isothermal (i.e. it does not vary with depth)

(d) no change in air mass,

Philips [5] has derived a solution for equation (1), as follows:-

$$T_1 - T = \frac{2}{\sqrt{\pi}} \frac{F_{N1}}{\rho_1 C_1 \sqrt{K_1} + \rho C_p K} \sqrt{t} \quad \text{---------- (2)}$$

where T_1 = initial temperature of soil

T = temperature of soil at time t after sunset

ρ_1 = density of soil

C_1 = specific heat of soil

K_1 = specific conductivity of soil (or thermal diffusivity of soil)

ρ = air density

C_p = specific heat of air at constant pressure

K = coefficient of eddy diffusivity, assumed to be constant with height.

By means of equation (2) one can obtain the nocturnal fall in temperature of any type of surface.

Effect of Variation of Different Parameters on Nocturnal Cooling

(a) Terrestrial Radiation

(i) temperature and humidity

By statistical methods, Brunt[7] has developed the following formula for F_N:

$$F_N = \sigma T^4 (1 - a - b\sqrt{e}) \quad \text{---------- (3)}$$

where σ = Stefan-Boltzmann constant

$a = 0.44$

$b = 0.08$

e = surface vapour pressure in mb

Substituting this into equation (2) we can see that the nocturnal cooling of the ground will be greater if the initial ground temperature is high or if the air is dry.

(ii) cloud cover

The net flux F_{N1}' at the earth's surface under overcast conditions may be expressed in terms of the clear sky value F_{N1} as follows:-

$$F_{N1}' = \wedge F_{N1} \quad \text{---------- (4)}$$

Angstrom[8] and Asklof[9] have shown that the scale factor $\wedge$ depends on the height of the cloud base, as shown in Table X:

CLOUD BASE (Km)	1.5	3	7
SCALE FACTOR $\wedge$	0.14	0.25	0.80

Table X. SCALE FACTOR $\wedge$

For a cloud cover of m oktas, the net flux at the earth's surface F_{N1}'' is related to the clear sky value by the following equation:-

$$F_{N1}'' = \frac{F_{N1}}{8} = (8 - m + m\wedge) \quad \text{---------- (5)}$$

Equation (5) indicates that since cloud inhibits cooling, ground temperatures will fall lower on clear nights or on nights with high clouds only.

(b) Nature of the ground

The term $\rho_1 C_1 \sqrt{K_1}$ is known as the soil product and is denoted by s. Some typical values of the soil product are as follows:-

	Joule m^{-2} deg^{-1} $sec^{-\frac{1}{2}}$
dry sand	1.89×10^{-8}
dry sandy soil	2.47×10^{-8}
clay land	3.41×10^{-8}
sandy clay (15% moisture)	6.34×10^{-8}
wet marshy soil	6.41×10^{-8}
still water	6.68×10^{-8}
wet sandy soil	6.69×10^{-8}
organic soil	6.69×10^{-8}
concrete	9.70×10^{-8}
turbulent water	2.91×10^{-7}

Since $T_1 - T$ is inversely proportional to s, surfaces with high s values will have smaller nocturnal drop in temperatures. This explains why the sea surface temperature does not fall appreciably at night.

(c) Atmospheric conditions

The coefficient of eddy diffusivity K increases (not necessarily linearly) with the wind speed and the instability of the atmosphere, so that nocturnal cooling will be greater under calm stable conditions.

Table XI lists the nocturnal cooling of the ground, as computed from equation (2), under various conditions and it shows that the following conditions favour a bigger drop in ground temperatures:-

(a) clear skies, or only high cloud,

(b) low vapour pressure, i.e. low humidity,

(c) higher initial surface temperature,

(d) light winds, stable conditions,

(e) low 's' value e.g. light dry soil.

As can be seen, the effects of (b) and (c) above are less significant than the other factors. Because of the various assumptions made in deriving equation (2), the falls of temperature listed in Table XI can serve only as a guide for comparison of nocturnal cooling although their order of magnitude is correct. In particular, it must be noted that assumption (d), which imposes a condition of no change of air mass, is seldom true for Hong Kong because of the effects of returning land breeze at night or because of the advection of cooler air from the north when the winter monsoon intensifies.

	INITIAL GROUND TEMPERATURE	DEW POINT	CLOUD COVER	NATURE OF SURFACE	ATMOSPHERIC STABILITY	NOCTURNAL COOLING IN 12 HOURS
ASSUMED STANDARD CONDITIONS	15°C	-5°C	NIL	SANDY CLAY (15% MOISTURE) OR WET MARSHY SOIL	AVERAGE	8.8°C
EFFECT OF CLOUD COVER	STANDARD	STANDARD	4/8 HIGH CLOUD	STANDARD	STANDARD	7.4°C
	- " -	- " -	8/8 - " -	- " -	- " -	6.6°C
	- " -	- " -	4/8 LOW CLOUD	- " -	- " -	4.7°C
	- " -	- " -	8/8 - " -	- " -	- " -	1.2°C
EFFECT OF HUMIDITY	STANDARD	0°C	STANDARD	STANDARD	STANDARD	7.5°C
	- " -	5°C	- " -	- " -	- " -	6.7°C
EFFECT OF TEMPERATURE	5°C	STANDARD	STANDARD	STANDARD	STANDARD	7.1°C
	10°C	- " -	- " -	- " -	- " -	7.7°C
	20°C	- " -	- " -	- " -	- " -	8.8°C
EFFECT OF ATMOSPHERIC CONDITION	STANDARD	STANDARD	STANDARD	STANDARD	STABLE	14.9°C
EFFECT OF NATURE OF SURFACE	STANDARD	STANDARD	STANDARD	DRY SANDY SOIL	STANDARD	10.3°C
	- " -	- " -	- " -	CONCRETE	- " -	6.9°C
	- " -	- " -	- " -	TURBULENT WATER	- " -	0.1°C

Table XI. NOCTURNAL COOLING UNDER VARIOUS CONDITIONS

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