The Katabatic Winds of Adélie Land and King George V Land

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Abstract

The principle features of the katabatic wind in the neighbourhood of Commonwealth Bay, Antarctica, are described with particular emphasis on the sudden onsets and cessations of the wind. The unusual features are explained on the hypothesis that a quasistationary pressure jump line, forming a sharp boundary between the strong katabatic winds of the ice slope and the comparitively calm conditions over the sea, occurs near the coast. Movement of this pressure jump line across the causes a sudden change in wind conditions there. Quantitative predictions on this hypothesis are of the correct magnitude.

1. Introduction

Early voyagers in the Antarctic Region, such as Wilkes, D'Urville and Ross, found that the winds in the neighbourhood of the coast blew strongly off the continent sometimes bringing with them much drift snow. These observations were confirmed at the beginning of the twentieth century by the first expeditions to land on the continent. Exploring parties that climbed the ice slope, led for examply by Armitage 1902, Scott 1903, Shackleton 1909 and David 1909, found that the winds, apart from a slight deviation due to the earth's rotation, almost always blew down the slope, regardless of the direction of the slope, and that the sastrugi[1] indicated that these winds were the prevalent ones. These facts clearly demonstrate the katabatic nature of the winds. The meteorological glossary defines katabatic as an adjective applied to winds which blow down slopes that are cooled by radiation, the direction of flow being controlled almost entirely by orographic features.

These winds, though occasionally reaching blizzard strength, were not exceptionally strong. However when the Australasian Antarctic expedition of 1911–1914, under the leadership of Sir Douglas Mawson, established a base at Cape Denison on the coast of Adélie Land[2], exceptionally strong and persistent katabatic winds were encountered. Adélie Land had been sighted about 80 years previously by D'Urville who named it after his wife. No landings had been made and Mawson's party were the first to establish a base on the coast of Adélie Land. Indeed Mawson's Cape Denison base was the first established anywhere along the foot of the main antarctic ice slope. Other stations had been separated from continental conditions by mountain

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[1] Ridges on the ice aligned in the direction of the prevalent wind.

[2] Now officially King George V Land, Adélie Land being used only for the neighbouring French Sector.

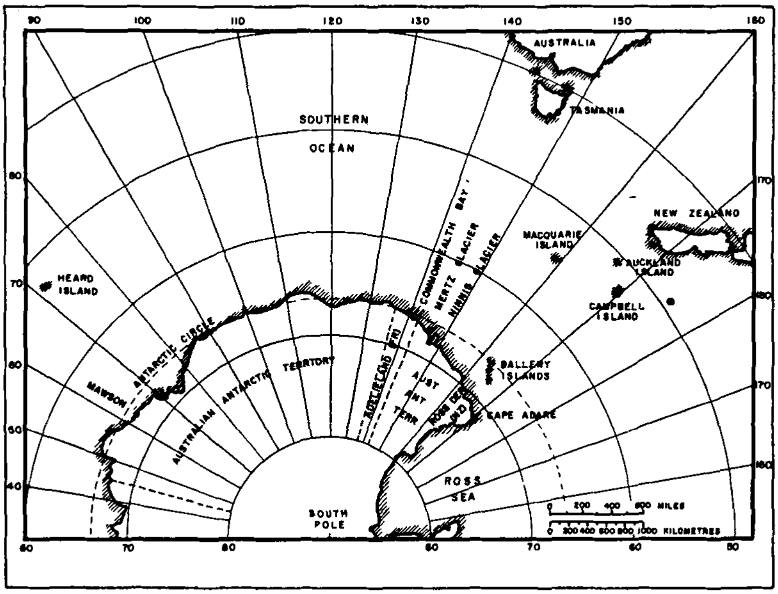

Fig. 1. Location map.

ranges or ice shelves or had been established in regions where the coast is much more broken up.

2. General description of the wind

Cape Denison is situated in Commonwealth Bay at latitude 67° 00′ S and longitude 142° 40′ E. The coast in the vicinity runs roughly east and west though it is indented by broad bays. The hut and meteorological instruments were placed at the foot of the ice slope on the rocky outcrop which constitutes Cape Denison. The following figures give some indication of the violence of the winds experienced there. The mean wind speed for the whole 22 months of observation was 44.2 m.p.h. On the Beaufort scale 43 m.p.h. is a gale so that the average wind speed at Cape Denison is a gale. The highest monthly mean was 55.6 m.p.h. for July, 1913 and the highest daily mean was 80.6 m.p.h. for August, 1913.

A more vivid picture of meteorological conditions at the station can be obtained from the original accounts by Sir Douglas Mawson and C.T. Madigan the chief meteorological officer of the expedition. From MADIGAN (1929) we cite:

"The wind was the most remarkable feature of the meteorology or indeed of the locality. It is the outstanding characteristic of Adélie Land. Commonwealth Bay is probably the windiest place on earth and certainly appears to be so as far as records up to the present indicate. For nine months of the year an almost continuous blizzard rages, and for weeks on end one can only crawl about outside the shelter of the hut unable to see an arm's length owing to the blinding snow drift..."

Madigan also describes the extreme steadiness of the wind in both speed and direction. Any wind stronger than 20 m.p.h. came from between SE and S, the usual direction being S by E. Only in comparative calms were other directions recorded.

In recent years the French Antarctic Expeditions have observed similar violent katabatic winds a few miles west of Cape Denison at Port Martin (66° 40′ S, 141° 24′ E) where the annual mean wind speed was 42 m.p.h. Wind strength and drift are however not the only peculiarities of the meteorological conditions along the Adélie Land coast. The end and particularly the onset of the strong wind is frequently very sudden, with the wind rising from almost calm to gale strength in a few minutes. These curious lulls have excited comment from numerous authors, in particular C. T. Madigan makes the following remarks:

"Considerable interest attaches to these periods of comparative calm and variable winds. Several phenomena were peculiar to them, including small whirlwinds raising snow like miniature 'willy-willys' with their dust columns in Australia, and also low fracto-cumulus cloud forming rapidly over the coast line, swirling round, drifting north and quickly re-evaporating. This is shown diagrammatically in the sketch (fig. 2). During the calms the wind could frequently be heard roaring on the plateau to the south, and sometimes snow drift could be seen whirling down to the coast to the west, showing the coastal calm to be local. Often too clouds of drift were observed passing overhead at the 1,000 foot level or higher. On several occasions sledging parties coming in from 5 miles south reported strong winds at about this level and walked down into calm at the hut."

It is clear from the preceding account and from that of MAWSON (1915) that the occasional comparatively calm conditions at Cape Denison were frequently local and that the katabatic winds persisted a short distance up the slope and sometines also a short distance along the coast. In addition observations made at sea when strong winds were blowing at the coast showed that these winds did not usually extend more than a few miles from the coast. These facts together with the sudden onset and end of the blizzard suggest that there is a sharp boundary between the strong katabatic winds and the comparatively stagnant air over the sea.

At Port Martin the end of the strong wind is accompanied by a sudden rise in pressure and the onset by a sudden drop in pressure. During the period of the lull the barograph has the appearance of being displaced upwards by about 3 mb. Sudden movements of the barograph were also observed at Cape Denison but the Scientific Reports do not state whether or not these movements coincided with changes in wind speed. Indeed KIDSON (1946), ascribes these vertical movements to stiffness in the bearings of the barograph. However in view of the more recent evidence of sudden pressure changes in both Greenland and Antarctica it is perhaps desirable to re-examine the original records.

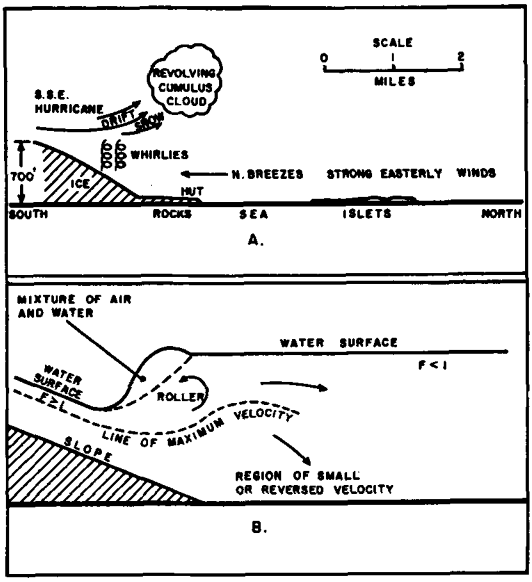

Fig. 2. Comparison between Madigan's diagram and flow in a roller type hydraulic jump.
A. Madigan's diagram.
B. Roller type hydraulic jump.

When the British Arctic Air-Route expedition 1930–31 established a base station on Kangerdlua fjord in East Greenland, katabatic winds and strong southerlies from the sea were both experienced. S.T.A. Mirrlees original account (Geophysical memoires No. 61) shows the striking similarity between the katabatic winds of Antarctica and Greenland.

Concerning the behaviour of the barograph at the base station he writes:

"During the northerly gales irregular changes of pressure were usually shown on the barograph... The course of events seems to be as follows: before the gale reaches the base small oscillations appear on the barogram; at about the time of arrival perhaps shortly after, when some critical velocity is reached, the sudden downward displacement of the trace occurs. During the continuance of the gale the barogram shows rapid oscillations due to gusts of wind, the trace on occasions when the pen was writing finely presenting the appearance of a gusty anemogram. Occasional larger irregular oscillations may also be superposed. When the extreme force of the gale abates the barogram suddenly rises, the trace appearing at times as if a change of base line had been made during the period of the gale. . ."

"During the few gales from southerly or easterly points the large irregular oscillations and 'displacements' do not appear on the barograms; the traces present the appearance ordinarily associated with a building exposed to moderate gusts of wind."

As to the possibility that the pressure change is merely a result of the violent motion of the air past the hut ('house effect'), this is improbable for several reasons. Firstly, the pressure and velocity changes would be exactly simultaneous if the 'house effect' were the cause. This is not confirmed by observation indicating that the pressure changes are caused by other means. Secondly, pressure changes were recorded at Port Martin by a barograph in the meteorological screen outside the hut, where 'house effects' would be much reduced. Thirdly the difference in behaviour between the katabatic winds and the southerly winds in Greenland suggests a pressure structure peculiar to the katabatic winds. Finally, the longer period pressure fluctuations observed in both Greenland and Antarctica, which are independent of fluctuations in wind speed, indicate the presence of some mechanisms for causing pressure fluctuations.

Pilot balloon measurements at Port Martin show that the depth of the rapidly moving air is not very great. It is usually about 300 metres. This value is roughly confirmed by observations of drift at Cape Denison.

The behaviour of the katabatic wind in the neighbourhood of Commonwealth Bay can be summarised as follows:

1. Normal wind characteristics
    (i) Persistence – almost continuous for nine months of the year
    (ii) Strength – about 30 metres $\sec^{-1}$
    (iii) Steadiness in both speed and direction.
2. Lull characterteristics
    (i) Sudden end and sudden onset
    (ii) Roar up slope
    (iii) Over-riding of the rapidly moving air
    (iv) Abrupt pressure changes.

3. Explanation

The observations indicate that the katabatic wind in the neighbourhood of Commonwealth Bay can be regarded as a relatively thin layer of cold air flowing down the ice slope under the influence of gravity. High up on the slope the air must pass through an accelerating stage. Probably before reaching the foot an approximate equilibrium is set up between the frictional resistance and gravity, in which case the flow is said to be uniform. For simplicity it will be assumed that the cold air has a definite depth, i.e. it is surmounted by a discontinuity in temperature which will be referred to as the inversion, and that the velocity and potential temperature in the cold air are independent of height. The behaviour of the air on reaching the foot of the slope will depend, in the first place, on whether the Froude number of the uniform flow, F_n say, is greater or less than unity, where $F_n = \frac{\Theta Q^2}{\Theta' g h_n^3}$ and the symbols are defined as follows:

h_n = normal depth, i.e. the depth of cold air in uniform flow.
(h = local depth of cold air)
Θ = potential temperature of the cold air.
Θ' = potential temperature deficit of the cold air, i.e. the difference in temperature between the cold air and the warm air above.
Q = rate of flow = hu where u is the velocity.

If $F_n < 1$ then the flow will smoothly retard to a new depth over the sea. If however $F_n > 1$ then the flow will jump abruptly at some stage to a new flow regime with a much lower velocity and correspondingly much greater depth of cold air. A jump of this type can be seen, for instance, near the foot of a weir. The water flowing over the weir is accelerated so that the Froude number exceeds unity and, where it is retarded on the weir apron, it changes abruptly at a hydraulic jump to flow with Froude number less than unity.

The flow will in future be referred to as shooting or tranquil according as the Froude number is greater or less than unity. To determine whether the strong katabatic winds of Commonwealth Bay are shooting or tranquil we may take as typical values: $h_n = 3 \times 10^4$ cm, $u = 3 \times 10^3$ cm $\sec^{-1}$ and $\Theta'/\Theta = 1/60$ giving a Froude number of 18. There is consequently little doubt that the katabatic flow is shooting and there must therefore normally be a discontinuity in the flow somewhere in the neighbourhood of the coast. The atmospheric phenomenon analogous to a hydraulic jump is usually referred to as a pressure jump since its passage over a station causes a sudden change in depth of the cold air at the station and a corresponding sudden change in pressure, often large enough to be detected on a standard barograph. The position of the jump depends not only on the value of F_n, which is determined by upwind conditions, but also on the depth, H say, of the cold air out to sea, which is in turn determined by downwind conditions. If H is less than a certain value then the jump will be situated seaward of the coast and a coastal station will be in the region of violent winds. On the other hand if H is greater than this value then the coastal station will be 'drowned' in the comparatively deep and stagnant air over the sea.

The general explanation of the curious behaviour of the katabatic wind is now clear. The sudden onset of the wind accompanied by a pressure drop occurs when the jump moves seaward past the observing station and the sudden end and pressure rise occurs when the jump moves landward past the station. Even in the most favourable circumstances it is unlikely that the jump will be situated more than a few miles out to sea so that the violent winds will be confined to coastal waters. When the jump is near the coast a slight change in value of either H or F_n may be sufficient to make the jump cross the coast and so cause a complete change of conditions at a coastal station. Two stations on or near the coast will experience quite different frequencies of strong winds if in one case the jump is usually situated inland and in the other it is usually situated out to sea. Furthermore only a small difference in the position of the station in relation to the slope or in steepness or roughness of the slope etc. will be sufficient to achieve this.

Madigan's description of conditions during a lull, with strong winds both audible and visible higher up the slope, describes exactly what one would expect at a pressure jump. This is shown in fig. 2.

The existence of a pressure jump near the coast explains most of the peculiarities described above; some features however deserve further comment. Consider first the roll cloud; the uplift at the jump may be sufficient to cause condensation and so produce the cloud, particularly if the katabatic flow is kept nearly saturated by evaporation from suspended snow drift. If the air above the katabatic flow is at or near saturation then the mixing caused by turbulence generated at the jump will also tend to produce condensation.

When the Froude number is fairly close to unity the flow tends to be irregular. Waves of various types readily occur since a small change in energy corresponds to a big change in depth. In these conditions the wind would be very unsteady and gusty. Though this is observed at some places along the coast it is not the case at Cape Denison where the wind is exceptionally steady, indicating in agreement with the preceding rough estimate that the Froude number is not very close to unity there.

The characteristics of a hydraulic jump and probably also of a pressure jump are determined by the Froude number, F say, upstream of the jump. Three cases can be distinguished (Binnie and Orkney 1955)

(i) $1 < F < 1.26$. This is the so-called smooth undular jump which takes the form of a train of smooth unbroken waves.

(ii) $1.26 < F < 1.55$. In this case a wave train still forms but turbulence also appears, the extent of the turbulence increasing with increase in Froude number.

(iii) When the Froude number is greater than about 1.55 the stationary waves disappear and the jump takes on a typical highly turbulent roller form.

The jump near the coast of Adélie Land will almost certainly be of type (iii).

If the Froude number of the uniform flow is greater than four the katabatic flow is theoretically unstable and 'roll' waves should occur. The wind should then be characterised by violent gusts at fairly regular intervals (JEFFREYS 1925, CORNISH 1934). Observations indicate that roll waves do not occur except on steeper slopes than predicted by the theory (i.e. higher Froude numbers) probably because a very great length of slope would be required for the waves to build up on slopes near the minimum. Waves of this type apparently occurred in the evening of May 24, 1913 at Cape Denison. MAWSON (1915) describes conditions on this occasion in the following words:

"Having failed to demolish us by dogged persistence the gale tried new tactics on the evening of May 24, in the form of a series of Herculean gusts. As we learned afterwards, the momentary velocity of these doubtless approached 200 miles per hour. After the passage of each gust, the barometer dropped, rising again immediately afterwards."

The mean flow kinetic energy decreases suddenly at a jump. The energy lost is either 'radiated' away by the standing wave system, appears as turbulent kinetic energy or is used in entraining and mixing warm air from above. The relative amounts depend on the intensity of the jump. At Cape Denison some of this energy takes the form of small but violently rotating vortices. The development of vortices instead of chaotic turbulence is possibly caused by the air entering the jump at an angle, having been deflected by the earth's rotation during its movement down the slope. There is then a sudden change in wind direction as well as in wind velocity and conditions are suitable for the production of vortices. Tornadoes in U.S.A. which often appear behind pressure jump lines may originate in a similar manner.

The vast quantities of suspended snow which almost invariably accompany a strong wind in Adélie Land, must exert an influence in various ways. Firstly, as remarked previously the air is kept at or near saturation by the finely divided ice particles and the evaporation which takes place during the downward movement will cause lower temperatures than those which would occur in a similar dry air stream. This increases the density difference between the katabatic wind and the air above and so tends to produce stronger winds. The density of the katabatic flow is also directly increased by the presence of the drift. Rough figures given by LOEWE (1953) for the amounts of snow transported suggest that the density increase in the lower layers produced in this way is of the order of one percent and is therefore comparable with the increase in density caused by the temperature difference. The violent katabatic winds can therefore be regarded in some ways as large scale avalanches of low intensity. The relative proportions of the air snow mixture in an avalanche proper are quite different, the density being three or four times that of the surrounding air. The presence of drift snow also increases the surface friction to a certain extent but the effect is small compared with the influence of the density increase. From these considerations it seems likely that the availability of drift snow in the 'catchment' of the katabatic wind can have a considerable effect on the intensity and frequency of the winds at the coast.

4. Numerical predictions

If it is assumed that the frictional force per unit area acting on the air moving down the slope is proportional to the square of the velocity, together with certain other simplifying assumptions, then a complete theory of the behaviour of the wind near the foot of the slope can readily be developed (BALL 1956). The frictional force can now be written $\varrho k u^2$ where ϱ is the air density and k is a dimensionless constant. The Froude number for uniform flow is then related to k by the following equation:

$$F_n = \alpha / k$$

where α is the angle of inclination of the ice slope. In Commonwealth Bay α is about 10^{-1} and F_n has been shown to be about 18. This leads to a value for k of about 5.6×10^{-3} compared with 2.3×10^{-3} for surface friction deduced from measurements on ice made at Maudheim (71° 03′ S, 10° 56′ W) in Dronning Maud Land, Antarctica during the Norwegian-British-Swedish Antarctic Expedition, 1949–52 (LILJEQUIST 1953). It is to be expected that the k value for the katabatic wind will be higher than the k value for surface friction alone, since the wind is presumably retarded at its upper as well as its lower boundary.

According to the simple theory there are three possible types of steady flow which can occur near the foot of the ice slope, namely:

type (1) in which no jump occurs
type (2) where the jump occurs inland
type (3) » » » » over sea

These three flow types are shown in figure 3. If $F_n < 1$ then the flow is always of type (1), the air is retarded before reaching the coast and a coastal station will be in a region of light winds. If $F_n > 1$ the flow will be either type (2) or (3). To determine which of these

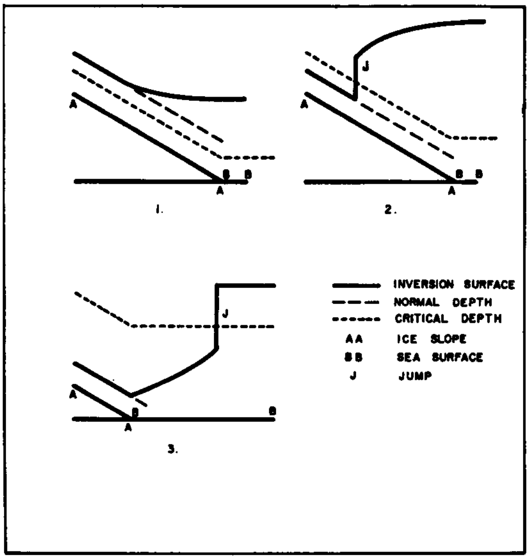

Fig. 3. The three types of steady flow.

types will occur it is necessary to know the characteristic depth, H say, of the cold air over the sea. Flow type (2) will occur if the following inequality is satisfied:

$$H > (h_n/2)\{(1 + 8\,F_n)^{\frac{1}{2}} - 1\}$$

In these circumstances light winds will be experienced at the coast but strong winds may be audible or visible a short distance inland in the neighbourhood of the jump. If the above inequality is not satisfied then flow type (3) will occur. It is only in this case that strong winds will be experienced at the coast. When the flow changes from type (2) to type (3) or vice versa the jump crosses the coast and the inequality becomes an approximate equality. Using the previous values for F_n and h_n the corresponding value of H is 1,700 metres. In Adélie Land apparently H is usually less than 1,700 metres causing strong winds at the coast. Furthermore the change in depth of the cold air from 300 metres to 1,700 metres at the jump corresponds to a pressure change of about 3 mb at the surface, in agreement with the observed pressure change of 3 mb at Port Martin. The above considerations apply strictly to steady flow, whereas in fact when the jump moves past the station the flow is clearly not steady. A landward moving jump will be more intense than a stationary jump in the same situation and a seaward moving jump less intense. A landward moving jump causes an abrupt cessation of the wind when it passes a station, consequently the biggest pressure changes should occur at the commencement of a lull. This prediction is also confirmed by the observations at Port Martin where the pressure change tends to be larger at the commencement of a lull than at the end (BOUJON 1954).

When the inversion height out to sea is 100 metres less than the critical height, i.e. 1,600 metres, then calculation indicates that in the steady state the jump is situated about 5 km. from the coast. On the other hand when the inversion height out to sea is 1,800 metres then the jump is situated about 400 metres inland. Thus the seaward movement of the jump in response to a decrease in H is much larger than the landward movement in response to a similar increase in H. This suggests that the jump will generally be most nearly stationary just inland of the coast and conditions there will be most suitable for the observational study of the jump.

The deviation of the wind from the lines of greatest slope caused by the Earth's rotation is given by the equation:

$$\sin\beta = \frac{2\,\Omega \sin\Phi\,\Theta\,u}{\Theta'\,g\,\alpha}$$

where Ω is the angular velocity of the Earth and Φ is the latitude. This equation gives β approximately equal to 14° compared with 10° – 15° observed at Cape Denison.

The removal of cold air from the ice cap by the katabatic wind is equivalent to a net heat flux poleward given by $C_p\,u\varrho\Theta' h_n$, where C_p is the specific heat of air at constant pressure. This is approximately equal to 1.3×10^4 calories per second per centimetre of coast which together with a latent heat flux of about 0.4×10^4 effected by the suspended snow gives a total of 1.7×10^4 calories per second per centimetre. On the assumption that the flux at Adélie Land is representative, the total flux across about 15,000 km of coast line is 2.5×10^{13} calories per second. The rate of loss of heat by radiation in winter in Antarctica is probably of the order of 0.2 calories per square centimetre per minute which gives a total rate of loss over the whole (Liljequist 1953) of the continent of 4×10^{14} calories per second. This rough calculation does no more than indicate the orders of magnitude of the quantities involved. It does not exclude the occasions when the wind starts and stops possibility that the katabatic winds, in spite of their extreme shallowness, can play a significant part in the energy balance of Antarctica.

5. Concluding remarks

The preceding results show that the simple theory gives not only a good qualitative explanation of the puzzling features of strong katabatic winds but also a fair quantitative one. The chief fault of the theory lies in the fact that it does not explain the frequent gradually in Commonwealth Bay. This arises from the various factors which have been neglected. In particular the existence of a strong gradient wind above the katabatic flow must exert a considerable influence on the behaviour of the cold air beneath.

Throughout this paper attention has been confined to Polar katabatic winds. The phenomenon discussed here also occurs in other situations, e.g. on a much smaller scale around Ayer's Rock, Central Australia. This mountain consists of a rounded dome of rock about one mile in radius, rising 1,100 feet from the plains. The katabatic wind in the neighbourhood of the rock often sets in with great suddenness and violence usually in the late evening when the rock has cooled appreciably after the heat of the day.

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