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Hunting Phenomena of the Balloon Motions Observed over Antarctica

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It was reported that the strong hunting motions of the balloons were observed just after reaching the ceiling altitude for the balloons launched at Antarctica in the daytime. Such hunting motions are observed at middle latitude only for the nighttime launching. In this article, the thermal analysis of the balloon motions is performed by considering the atmospheric temperature and the environmental radiation conditions at the balloon altitudes. We found that the hunting phenomena over summer Antarctica are caused by the fact that the balloons over Antarctica encounter similar thermal conditions of flights at night over the midlatitude.

Nomenclature

A = albedo coefficient
D = diameter of the balloon
e = expansion coefficient of gas, $1/T$
Gr = Grashoff number
g = constant of gravity, 980 cm/s^2
$J0$ = radiation from the sun
$J1$ = infrared radiation from the ground
K = thermal conductivity of gas
Nu = Nusselt number
P = pressure of the atmosphere
Pr = Prandtl number
Qc = heat flow by the convection process
Qr = heat flow by the radiation process
R = radius of the balloon
Re = Reynolds number of the balloon
T = temperature
Tf = temperature of the balloon film
Tr = radiation temperature
$T0$ = radiation temperature at nighttime
α = variation coefficient of infrared radiation with altitude, it is zero over the altitude of 20 km
γ = ratio of specific heat of gas, 1.67 for He gas
ΔT = temperature difference
ε = absorption coefficient of polyethylene film for the visible light
θ = elevation angle of the sun
κ = absorption coefficient of polyethylene film for the infrared radiation
μ = viscosity coefficient of gas
ρ = density of gas
σ = Stephan-Boltzmann constant

Introduction

RECENTLY, two major balloon campaigns have been conducted in Antarctica. One is the so called "Polar Patrol Balloon" program, which has been carried out by the collaboration of the National Polar Institute and the Institute of Space and Astronautical Science (ISAS).[1,2] The purpose was to observe the geophysical phenomena in the polar region by performing circumpolar flight taking 2–3 weeks. The balloon launchings are made at Showa Station (69°00′S, 39°35′E). Another campaign has been conducted by NASA at McMurdo Station (77°51′S, 166°40′E), the purpose of which is also to accomplish the circumpolar flight lasting 1–2 weeks.[3]

In these programs, the hunting motions are observed for the balloons just after they reached the ceiling altitude in the daytime. Such phenomena have been observed for the balloons launched at nighttime at midlatitude, but have never been observed for the balloons of daytime launching.

In this article, we analyze the balloon motions based on the thermal conditions for the balloons at each latitude. We find that thermal conditions encountered by the balloons at daytime in the polar region is quite similar to those of night flights at midlatitude. It is shown that the particular hunting motions observed in the polar region can be explained by these thermal conditions encountered by the balloons.

Hunting Motion Observed at Antarctica

In the balloon flights performed at McMurdo, it was reported that the hunting motions were observed after reaching their ceiling altitude, even though they were launched during the daytime. Those flight curves for the balloons performed by the group of Houston University are shown in Fig. 1.[3] In these flights, four balloons began to descend after reaching the ceiling altitude of around 30 km. The last example in Fig. 1 does not show any hunting motion because of the slow ascending speed of the balloon as explained in the following sections.

Thermal Analysis of the Balloon Motions

Since the lift of the balloons is closely connected with the temperature difference between He gas and the atmosphere,

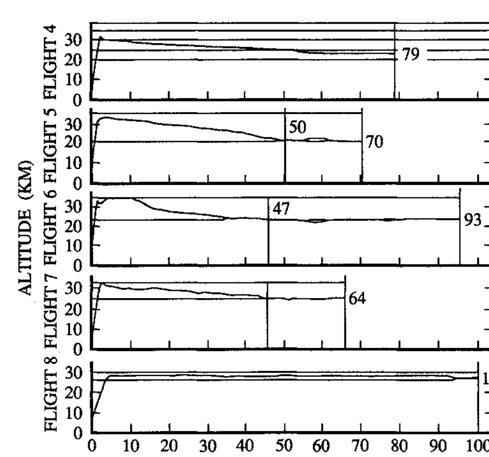

Fig. 1 Hunting motions observed for the balloons over Antarctica.

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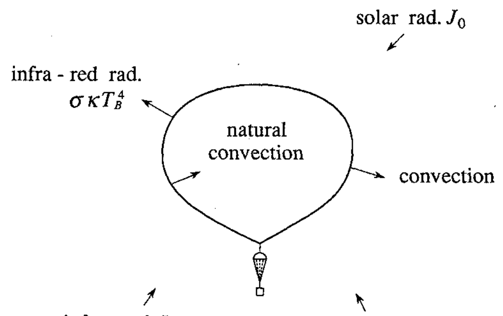

Fig. 2 Thermal processes of the balloons.

the balloon motion is controlled by the thermal conditions of the balloons and atmosphere. For this reason, thermal analyses of the balloon motions have been widely studied by many authors. Here, we briefly summarize the results of the analysis following the paper of Ref. 4.

An ascending or descending balloon in the atmosphere is affected by several thermal processes, such as radiation, convection, and adiabatic processes as shown in Fig. 2.

As we shall see later, the radiation and adiabatic processes play an important role in controlling the balloon motions at high altitudes.

Radiation Process

For the radiation process, it is convenient to introduce the concept of radiation temperature.[4]

The temperature of the balloon film determined by the environmental radiation ignoring the convention effect of the atmosphere. Tr is given by

$$4\pi R^2\sigma Tr^4 = \pi R^2[2J1(1 + \alpha) + (1 + A)\varepsilon/\kappa J0] \quad (1)$$

The first term of the right side of Eq. (1) indicates the contribution of the infrared from the ground, and the second term is due to the visual light from the sun and its albedo from the ground.

From Eq. (1), we have for Tr

$$Tr = T0\{(1 + \alpha) + [(1 + A)/2](\varepsilon/\kappa)(J0/J1)\}^{1/4} \quad (2)$$

By introducing the concept of radiation temperature, we can treat the radiation process of the balloon in a simple manner. The energy absorbed by the balloon Qr, is given in terms of the radiation temperature as

$$Qr = 4\pi R^2\sigma\kappa(Tr^4 - Tf^4)$$

The radiation temperature was observed for the polyethylene balloons at midlatitude, and reported as

Tr (Mid. Lat.):

about 240 K at daytime (3)

about 215 K at nighttime (4)

Estimation of Radiation Temperature at Night

There are no observed data for the radiation temperature over Antarctica, however, it can be estimated in the following way. First, we estimate the radiation temperature at night, which is due to the infrared given in the first term of formula (2). Figure 3 shows the infrared flux emitted from the Earth at midlatitude observed by satellites. The strong absorption is observed in the molecular bands of water and carbon dioxide in the atmosphere. The flux is roughly interpreted as the equal mixture of blackbody radiation of 288 and 218 K. The physical meaning is that the atmospheric window in this wave range is about 50%, and the blackbody radiation of 288 K from the ground is contributed through this window. While the wave range in the absorption bands, the blackbody radiation of the atmospheric temperature of 100–200 mb contributes to the top of atmosphere, since the average absorption mean free path in the air in this wave range is 100–200 g/cm^2.

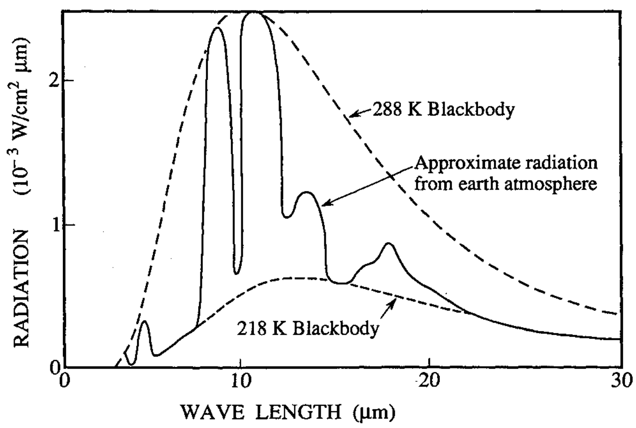

Fig. 3 Infrared radiation emitted at midlatitude observed by satellite.

The effective temperature for infrared radiation is then given by

$$T_{\rm eff} = [(288^4 + 218^4)/2]^{1/4}\ {\rm K} = 260\ {\rm K} \quad (5)$$

Then the radiation temperature at night is derived by using Eq. (2) as

$$T0 = T_{\rm eff}/2^{1/4} = 218\ {\rm K}$$

which agrees well with the observed data of 215 K as given in Eq. (4).

In the summer seasons at Antarctica, the average ground temperature is about 270 K, and atmospheric temperature around 100–200 mb is about 240 K. The ground temperature is lower, but the atmospheric temperature is higher than those of midlatitude. The effective temperature of the blackbody radiation over Antarctica is thus estimated as

$$T_{\rm eff} = [(270^4 + 240^4)/2]^{1/4}\ {\rm K} = 256\ {\rm K} \quad (6)$$

This is almost the same as the effective temperature at midlatitude shown in Eq. (5). Then we would expect almost the same radiation temperature at night over Antarctica to that of midlatitude, and it is estimated as $T0 = 215$ K at Antarctica.

Estimate of the Radiation Temperature in Daytime

We next discuss the radiation temperature at daytime. In the polar region, the elevation angle of the sun is always low. We need to take into account the atmospheric absorption for visible light together with the possible change of the albedo coefficient. For the circumpolar flight balloons, the albedo comes from the reflecting area of sea when the sun angle is high. On the other hand the albedo comes from the ground area covered by the snow when the sun angle is low. For the representative values of A, we take 0.15 (sea) for the high angle, and 0.8 for low angles of the sun.

The estimated flux of the visual light is shown in Table 1 at the balloon altitude of 10 mb. Here, the effective flux of the visual light is estimated as $(1 + A \sin\theta)$ in the last column. At midlatitude, we have this flux value of 1.30 for $\theta = 90$ deg with $A = 0.30$.

Putting these figures to Eq. (2), we estimate the radiation temperature in daytime over Antarctica as $Tr = 236$ K, which is a little lower than 240 K of midlatitude that is shown in Eq. (3).

Table 1 Absorption and albedo of visual lights in the polar region

Sun angle	Effective depth	Transparency[a]	A	$(1 + A \sin \theta)$
30 deg	20 mb	0.996	0.15	1.07
20 deg	29 mb	0.994	0.30	1.10
10 deg	57 mb	0.987	0.70	1.11
5 deg	100 mb	0.978	0.80	1.05
3 deg	200 mb	0.956	0.80	1.00

[a]We estimate this value by taking the observed data at Nemuro City located at the northern part of Hokkaido, Japan.

Table 2 Atmospheric temperature and radiation temperature over Sanriku and Showa Station

	Sanriku	Showa
Atmospheric temperature, 30 km altitude	230 K	250 K
Radiation temperature in the daytime	240 K	236 K
Radiation temperature at nighttime	215 K	215 K

Table 3 Deviation of the atmospheric temperature from the radiation temperature ΔT, ΔT = atmospheric temperature—radiation temperature

	ΔT	
Location	Day	Night
Sanriku	−10°C	+15°C
Showa	+14°C	+35°C

Convection Process

Heat flux Qc by the convection process is generally written as

$$Qc = K/D \times Nu\Delta T$$

For the convection between the balloon films and the atmosphere, we take the following formulas for Nu[4]

$$Nu = 0.03Re^{0.8} \quad \text{for turbulent flow}$$

$$Nu = 0.52Re^{1/2} \quad \text{for laminar flow}$$

For the natural convection between He and balloon films, we take

$$Nu = 0.65(PrGr)^{1/4}$$

where Gr is given by

$$Gr = \rho^2 geD^3\Delta T/\mu^2$$

and Pr is a constant of 0.6 for He gas.

Adiabatic Effect

Due to the change of the gas pressure ΔP, the gas temperature changes by the adiabatic effects. The amounts of the temperature change, ΔT is given by

$$\Delta T/T = [(\gamma - 1)/\gamma]\Delta P/P$$

In case of He gas, the temperature change near the ground is

$$\Delta T/T = -13.9°\text{C/km}$$

Atmospheric Temperature and the Radiation Temperature over Showa Station and Sanrika Balloon Center

The average atmospheric temperature and radiation temperature over Antarctica and midlatitude are summarized in Table 2. We take Sanriku Balloon Center (141°49′E, 39°09′N) as a representative location of midlatitude.

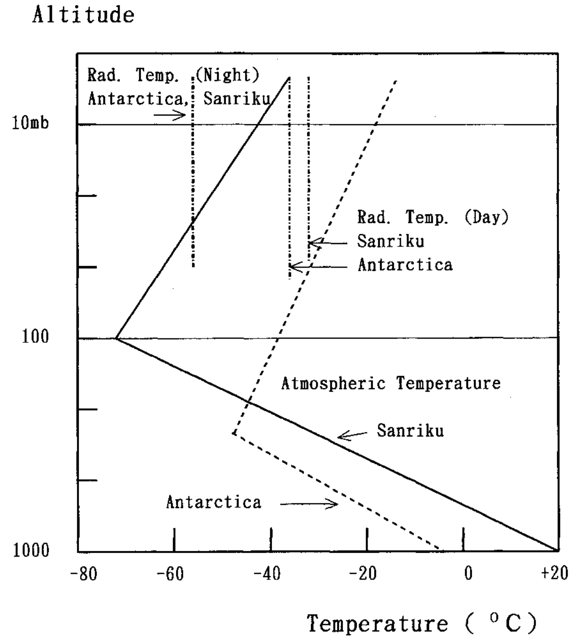

Fig. 4 Atmospheric and radiation temperature over Antarctica and midlatitude.

The most important parameter for the balloon motions is the difference between the atmospheric temperature and the radiation temperature, since the He gas temperature of the balloons at level altitude approaches the radiation temperature, and the total lift of the balloon is determined by the difference of those temperatures. The differences of those temperatures are shown in Table 3. From this table, we see that the thermal conditions are quite similar to each other for the balloons at daytime in the polar region and the nighttime in midlatitude. The thermal condition in the atmosphere is also shown in Fig. 4.

Numerical Examples for Balloons of 30,000 m³ Launched in the Polar Region and Midlatitude

In order to see the thermal conditions more quantitatively, we examine the case of a 30,000 m³ balloon ascending with a speed of 5 m/s. The numerical values from various processes are shown in Table 4.

From this table, we see that the most dominant contributions are due to the radiation and adiabatic processes. The convection process contributes only about 10% to those processes mentioned above. During ascending, He gas is cooled by the adiabatic process, but after reaching the level altitude, its temperature approaches the radiation temperature. Deviation of He gas temperature from the radiation temperature is estimated to be as small as only 1 or 2°C. The potential lift shown in the last column is expected because of the increase of the gas temperature after reaching the ceiling altitude that was cooled down by the adiabatic process during the ascending phase.

When a balloon reaches the ceiling altitude, the He gas is exhausted. Because of the ascending inertia of the balloons,

Table 4 Contribution of various thermal processes. Unit, μcal/cm^2 s

	Sanriku		Showa
	Day	Night	Day
Atmospheric temperature	230 K	230 K	250 K
Radiation temperature	240 K	215 K	236 K
Radiation process[a]	$141 - 13.2\Delta Tf$-He	$-180 - 13.2\Delta Tf$-He	$-218 - 17.0\Delta Tf$-He
Natural convection[a]	$3.7\Delta Tf$-He$^{5/4}$	$3.7\Delta Tf$-He$^{5/4}$	$3.7\Delta Tf$-He$^{5/4}$
Forced convection	$6.79\Delta Tf$-air	$6.79\Delta Tf$-air	$6.79\Delta Tf$-air
Adiabatic effect	140	140	130
Deviation from atmospheric temperature			
Balloon film temperature	0°C	−16°C	−14.6°C
He temperature	−18.3°C	−34.3°C	−31.9°C
Deviation from radiation temperature			
He temperature	−28°C	−19°C	−17.9°C
Potential lift[a]	12%	8%	7%

[a]Here we take the following abbreviations: ΔTf: Difference of the film and atmospheric temperature. ΔTf-He: Difference of the temperature of film and He gas. ΔTf-air: Difference of the temperature of film and atmosphere potential lift. Potential lift: Potential lift due to the increase of the He gas temperature after the balloon gets into the level flight.

extra He gas is exhausted in addition to the He gas for the free lift. The hunting phenomena are caused by this overexhausting of the He gas. In the daytime of midlatitude, this overexhaust is compensated by the potential lift due to the increase of the He temperature after the balloon reached the level altitude. The amount of the potential lift is shown in the last column of the table. However, at nighttime in midlatitude, and at daytime in the polar region, the extra lift is only several percent of the total weight of the balloons as shown in Table 4, and it is not enough to compensate for this negative lift. If the ascending speed is lower, the overexhaust of He gas is reduced and we might not expect the hunting phenomena to occur. This is what happened in the last balloon in Fig. 1.

In summary, we note that the balloons launched at daytime in the polar region encounter similar thermal conditions of the balloons launched at night at midlatitude. The particular hunting phenomena observed at polar region is thus interpreted in the same way as the hunting phenomena for the balloons launched at night in midlatitude.

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