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THE METEOROLOGICAL AIRPLANE ASCENTS OF THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

I

On the Technique of Meteorological Airplane Ascents

BY

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II

Aircraft Instruments in Meteorological Flying

BY

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I. ON THE TECHNIQUE OF METEOROLOGICAL AIRPLANE ASCENTS

BY K. O. LANGE

A. Purpose, Regularity and Cost of Ascents

In November 1931 the Meteorological Division of the Massachusetts Institute of Technology established a meteorological airplane station at the East Boston airport. Since that time regular ascents to heights of from 17,000 to 27,000 feet have been made daily at about 8 A.M. during the academic year, or from October 1 to the end of May. Part of the temperature and humidity observations obtained through these flights have been published in tabular form in the Monthly Weather Review [1].* The final and detailed publication of all flights will be included in a subsequent report in the form of reproductions of adiabatic charts and Rossby diagrams. These charts show, for each significant point, pressure in millibars, altitude in dynamic meters, temperature in °C, relative humidity, vapor-pressure in millibars, mixing ratio ($0.622\ e/p-e$) in grams per kilogram, potential and equivalent potential temperature, supplemented by observations on clouds, haze, bumpiness, ice formation, high winds and other meteorological phenomena.

The aerological flights at Boston are part of the general research program of the Meteorological Division of Massachusetts Institute of Technology, which program since 1929 has been directed especially toward the study of American air masses and fronts. Recently, some results of these studies were published by Willett [2], who based his investigations on a series continuous over three years of morning and evening weather maps, analyzed at the Institute, together with upper air soundings from the United States Weather Bureau stations at Dallas, Omaha, Chicago, Groesbeck, Atlanta and from the United States Navy at Seattle, Anacostia, Pensacola and San Diego. These upper air data facilitated the determination of the properties of the air masses and so proved of inestimable value for the study. But the use of the data also showed that improvement both in the number of stations and in the quality of observations was highly desirable. Ascents in the northeastern part of the United States were lacking. Knowledge of the vertical structure of air masses reaching this region, however, is of special interest in forecasting for this densely populated district. For these reasons and since the direct comparison of actual local weather developments with upper air conditions is also considered to be very valuable, the Institute started its own airplane station at Boston. In addition to "regular" ascents at the time of the morning surface observations, special flights were made when particularly interesting weather situations prevailed. On a number of days series of ascents were carried out to obtain cross sections through fronts passing over Boston. Other special flights were made to obtain information on atmospheric turbulence. For this same purpose and also in order to study the diurnal changes of temperature in the lowest 5,000 feet, several series are planned of a number of comparatively low altitude flights at short intervals throughout the day.

Particular attention was devoted to the study of aerological observational technique. Observation methods and instruments had to be improved and reliable calibration equipment developed. It is this part of the work that will be treated in the present paper.

* References are indicated by figures within brackets and are listed at the end of the paper.

The educational value of practical experience in good aerological technique is an important consideration in the program of the airplane station. Realizing that in the future much greater use will be made of upper air observations for weather forecasting, the Institute gives its students in meteorology a thorough training in the technique and the use of data of meteorological ascents. Every regular flight observation is at once made available to the U. S. Weather Bureau station at the East Boston airport and distributed over the teletype system for use in the synoptic service.

Besides meteorological investigations a number of other problems were attacked in cooperation with the United States Department of Agriculture and with other departments of Massachusetts Institute of Technology. During the time of the development of the gypsy moth larvae in the spring, insect catchers were mounted on the plane and taken up to determine the altitude which the gypsy moth larvae reach while spreading. A report on these investigations has recently been published by Collins and Baker [3]. Since January 1933 a device for collecting bacteria and pollen is regularly carried up and exposed at different altitudes. A preliminary report on this work has been published by Proctor [4]. Air samples were taken at the top of climb for the determination of the composition of the air at this height and attempts were made to collect sufficient dust at high altitudes to permit a study of the amount of meteoric dust in the atmosphere.

During the National Glider Contests of 1932, 1933, and 1934 at Elmira, New York, aerological ascents were carried out with the aid of grants from the Soaring Society of America. Since these ascents were not a definite part of the program of the Boston station, they are not included in the tables to follow.

The airplane station is under the direction of Professor C. G. Rossby, and under the direct supervision of the writer, who was invited to the Institute mainly to establish and maintain the aerological and instrumental work of the division. During 1931–32, the research pilot was D. C. Sayre, Assistant Professor of Aeronautical Engineering, and during 1932–33 the late Lt. H. B. Harris. Professor Sayre left Massachusetts Institute of Technology at the end of the year 1932 due to ill health. The writer wishes to express his appreciation for the splendid cooperation given by both these men. Their excellent advice on all technical questions, their ability to establish contacts with all sources of help for the establishment of the station, and above all their courageous flying, even in hazardous weather conditions, contributed in a great measure to the success of the work from the very beginning. While the chief pilots flew five days a week, spare pilots made the remaining ascents. In 1931–32 the spare pilots were Lt. Pierson and Lt. Harris, in 1933 Mr. Joseph Barber. To assist in the meteorological part of the work Messrs. C. Harmantas, S. Lichtblau, and J. Namias worked regularly at the airport.

Due to the former connection of the writer with the Deutsches Forschungsinstitut für Segelflug (Rhoen-Rossitten-Gesellschaft) and with the Technische Hochschule Darmstadt, our airplane station has profited to a large extent from the experiences of the German aerological stations. It is here in Boston however, that the first attempt was made to run aerological ascents to high altitudes regularly with a "small airplane." The German system is to carry, besides the pilot, a meteorologist who completes the meteorograph records by eye observations and by such interpretation as only a trained observer can furnish. This procedure is what really makes the airplane superior to other kinds of aerological carriers, such as kites, captive balloons and sounding balloons. However, also a small single seated airplane can be used advantageously if flown by the meteorologist himself. This means a saving not only in running expenses but also the saving of one salary. The "small plane station" with a meteorologist as pilot thus represents the ideal method if the purpose is solely to collect accurate and complete upper air observations such as are used in weather forecasting especially in forecasting for air traffic. If additional research work is planned a larger crew and a double seated airplane are essential.

During the flying period 1931–32, the Institute worked with a Cessna plane with a 110 H.P. Warner engine. Fully equipped with meteorological and navigation instruments and flown without passengers this ship had an absolute ceiling of over 20,000 feet and a service ceiling of about 17,000 feet attainable in 1½ hours. Prof. Sayre quickly acquired the familiarity with observational aspects of aerological meteorology necessary to furnish valuable eye observations. Only on exceptional cases did the writer take part in the flights, for instance when particularly interesting weather situations required interpretation or when cloud photographs had to be taken.

At the beginning of the period 1932–33 the Cessna airplane was replaced by a Curtiss-Robin with a 185 H.P. Challenger engine. This was a step towards the two place plane which permits the ascent of two persons, one of whom concentrates completely on all the problems bearing on the exploration of the atmosphere which have been taken up since the establishment of the station. A special glass-encased cabin and the installation of new equipment made this plane a real "flying laboratory" capable of reaching 15,000 feet within one hour with two persons and 17,000 to 18,000 feet with one person.

For the chief purpose of the ascents, the determination of the vertical temperature and humidity distribution, the additional altitude of nearly 3,000 feet attainable by leaving the meteorologist on the ground seemed more valuable than the contributions of a trained meteorological observer. Therefore, during the period 1932–33 most regular ascents were made by the pilot alone. In the second half of May 1933 observers were carried up regularly, the altitude sometimes being increased by extending the time of climb to 90 minutes. During this period studies with psychrometers and dew point indicators were made and dust samples were taken. Careful manometric measurements on Venturi tubes and Gyro pumps were made. Moving pictures of the behavior of the navigation instruments in extreme flying positions and at different elevations were taken. Results of these tests are discussed by C. S. Draper in another section of this report. Unfortunately, the financial situation did not allow the acquisition of a plane of higher performance, which would have facilitated studies of this kind throughout the year.

During the years 1931 and 1932 the station was maintained by a special fund from the Institute, a contribution from the Joseph Henry Fund of the National Research Council and a special appropriation from the Daniel Guggenheim Research Fund in meteorology, which had previously been placed at the disposal of the Meteorological Division. At the end of 1932 the Rockefeller Foundation made possible the continuation of the work through a special grant for the year 1933. On account of the restricted means available for the work, utmost economy had to be observed from the beginning. A short survey is given below of the financial side of the work. For comparison with similar ascents of other institutions the following tables present also the technical results since 1931. All the data in these tables are separated into the period of the "small plane station" and the later period.

Table I, column IV shows the regularity of the ascents as the ratio between the number of flights actually made to the number of scheduled flights. It should be noted here that there were no ascents made on Sundays and holidays during the first three months. Since February 1932 every day was scheduled for a flight with the exception of the sum-

TABLE I

REGULARITY OF THE METEOROLOGICAL FLIGHTS AT BOSTON
November 1931–May 1932; October 1932–May 1933

		I No. of regular flights to be made	II No. of flights missed due to weather	III No. of flights missed due to technical reasons	IV regularity $\frac{I-(II+III)}{I}\cdot 100$
1931	Nov. 17–30	12	2		83
	Dec. 1–19	17	1		94
1932	Jan. 4–31	25	5	1	77
	Feb.	29	4		86
	Mar.	31	2	1	91
	Apr.	30	3		90
	May 1–16	16	1		94
Flying Period 1931/32		160	18	2	88
1932	Oct.	31	3		91
	Nov.	30	3		90
	Dec. 1–23	23	2		91
1933	Jan. 3–31	29	2		93
	Feb.	28	3		90
	Mar.	31	5		84
	Apr.	30	4		87
	May	31	2		94
Flying Period 1932/33		233	24		90
Total 1931–1933		393	42	2	89

mer vacation and a few days at Christmas for top overhaul of the engine. The regularity has a minimum of 77% in January 1932. From then on it increases to 90% and 94% due in part to more favorable flying weather, in part to our increased experience in cloud flying and to the gradual completion of our flying and safety equipment. The mean regularity during the two years was 89%, in other words, we missed three to four flights per month. At first glance this seems to be a fairly poor average. However, it must be taken into account that the work at the aerological station was only a part time job for both pilot and meteorologist. Consequently, when for any reason an ascent could not be made in the early morning hours, in general it had to be cancelled altogether. Only if there was a particular interest in the weather situation, flights were arranged later in the day. In these cases the ascent at the time nearest to 8 A.M. was designated a "regular flight" and included in the tables as such.

The regularity of aerological observations is of course of the same importance as the regularity of ground observations. Nevertheless, the fact that no attempt was made to force the regularity of the Massachusetts Institute of Technology station to 100%, is due to our belief that the value of an individual meteorograph ascent is not to be compared with the value of human life or even a serious risk of plane and instruments. During the first period there occurred two emergency landings outside the home airport due to very bad weather. In one case expensive repairs were caused. In both cases it became impossible to fly on the following day on schedule. The even more conservative attitude observed after these incidents probably helped considerably to avoid similar mischief later on. Decisions not to fly were made only after a careful study of the weather map and

TABLE II

DIURNAL DISTRIBUTION OF METEOROLOGICAL FLIGHTS AT BOSTON

The plain numbers refer to the "regular" flights. The numbers in parenthesis give the special flights.

		Number of Ascents at 6^h	7^h	8^h	9^h	10^h	11^h	12^h	13^h	14^h	15^h	16^h	17^h	18^h	Total
1931	Nov.		0	8	1	0	1	0	0	(1)	0	0	0	0	10(1)
	Dec.		0	6	8	1	1	(2)	(1)	(1)	(2)	(1)	0	0	16(7)
1932	Jan.		0	10	7	(2)	0	1	1	(1)	(1)	0	(1)	0	19(5)
	Feb.		0	9	10	2	1	2	0	(1)	1	0	(1)	0	25(2)
	Mar.		0	22	4	1	(3)	(1)	1	(2)	(3)	1(1)	0	0	28(10)
	Apr.		2	16	6	0	1	0	1(1)	(1)	0	0	0	0	27(2)
	May		8	7	0	0	0	0	0	(1)	0	0	0	0	15(1)
1931/32			10	78	36	4(2)	4(3)	3(3)	3(2)	0(8)	1(6)	1(2)	0(2)	0	140(28)
1932	Oct.			25	1	1	1		(1)		(1)		(1)		28(3)
	Nov.			24	3	(1)		(1)							27(3)
	Dec.			19	1					1					21(0)
1933	Jan.			24	3										27(0)
	Feb.			18	3		1	1	1	(2)	1	(1)	(1)		25(4)
	Mar.			23	1		2			(1)		(1)	(1)	(1)	26(4)
	Apr.			19	2	2		(1)	2	1		(1)			26(2)
	May			26	2			1							29(0)
1932/33				178	16	3(1)	4	2(2)	3(1)	2(3)	1(1)	(3)	(3)	(1)	209(16)
1931–33			10	256	52	7(3)	8(3)	5(5)	6(3)	2(11)	2(7)	1(5)	(5)	(1)	349(44)

the latest available airway observations. On account of the regulations of the insurance company flights had to be cancelled when there was a ceiling of less than 500 feet of a thick solid overcast nature. This includes dense fog over large areas. Furthermore, flights were not made when there was continuous precipitation out of thick solid clouds, causing a visibility of less than 1 kilometer together with considerable danger of ice formation. This situation is encountered rather frequently in New England with a low pressure center to the East and northeasterly winds. It frequently stops all flying for two or three successive days.

As already pointed out, the ascents lose considerable value for their main purpose if not made at the time of the morning ground observations and if not available for the students' synoptic laboratory course. Table II shows the diurnal distribution of the ascents. During the first period 124 out of 140 flights were started before 9:30 A.M., during the second period 194 out of 209, that is 91% of all regular flights.

Next to regularity the mean altitude of ascents is the most important characteristic of an aerological station. It is generally given as the sum of the individual tops of climb divided by the number of ascents carried out. This ratio is lowered when ascents are made in very bad weather to low heights, although the efficiency of the station really is higher than if no flights are made. A more significant number is the ratio between the sum of all heights over the number of flights which should have been made. These ratios are given for the individual months in Table III, column I. Column II shows the mean altitudes as the first mentioned ratio between sum of altitudes of the regular flights over the number of regular flights to be compared with the corresponding data of other stations. Finally, in column III there are shown the average altitudes of all the flights including the special ones. The mean cost of one ascent as computed below, is related to all the flights, in other words it corresponds to the average altitude of 4680 meters.

TABLE III
MEAN ALTITUDES OF THE METEOROLOGICAL FLIGHTS AT BOSTON

		Regular Flights I		Regular Flights II		All Flights III	
		Number of days when flights should have been made	Ratio of sum of alt. over no. of scheduled flights	Number of regular flights carried out	Mean alt. of the flights carried out	Number of all flights carried out	Mean alt. of all flights made
1931	Nov.	12	3440	10	4120		3970
	Dec.	17	4650	16	4940	23	4690
1932	Jan.	25	3780	19	4980	24	4590
	Feb.	29	3200	25	3720	27	3780
	Mar.	31	3900	28	4320	38	4120
	Apr.	30	3880	27	4320	29	4330
	May	16	4160	15	4440	16	4460
1931–32		160	3820	140	4370	168	4260
1932	Oct.	31	4670	28	5170	31	5050
	Nov.	30	4450	27	4950	30	4450
	Dec.	23	4650	21	5090	21	5090
1933	Jan.	29	4460	27	4790	27	4790
	Feb.	28	4550	25	5100	29	4980
	Mar.	31	4290	26	5110	30	4650
	Apr.	30	4730	26	5460	28	5400
	May	31	4870	29	5220	29	5220
1932–33		233	4580	209	5100	225	5000
1931–33		393	4280	349	4810	393	4680

The survey of the cost of the ascents had to be restricted to the first period, since the inclusion of the later activities would have delayed publication of this report.

The expenses were separated into three groups:

1. Running expenses
   a) regular
   b) caused by forced landing
2. Expenses for instruments and parachute
3. Salaries

The running expenses should be the same within narrow limits for similar stations. The expenses for the instruments are primarily determined by the choice of a rate of depreciation. It is assumed that the average life of the instruments exceeds five years, which seems to be very reasonable, especially since a considerable amount for instrument repair and overhaul is included in the running expenses. The item for instrument depreciation is entered separately, so that it might be modified to agree with the policy of other institutions, if desired. The expenses for personal compensation form the third group. They are mentioned separately, since the very favorable arrangements at the Massachusetts Institute of Technology during the first period hardly can be expected to obtain at other stations. There is practically no salary paid, since the work at the station is considered as an addition to regular duty at the Institute. To give an idea of expenses for personnel, it might be mentioned that the amount paid to relief pilots is now $5 to $7 per ascent.

The Running Expenses were:

Cessna airplane bought for $1,200		
sold for 600		$ 600
Liability Insurance for 7 months		135
Storage of plane and daily service of mechanic—6½ months per $35		228
Seven 20-hour checks on engine (average price $20)		154
Top overhaul		79
Repairs on plane and engine, caused by regular use		218
Installation and repairs on instruments (including supplies which became worthless after the plane was taken out of service, such as meteorograph brackets, etc.)		268
Gas and oil		441
Office material, furniture, telephone, hydrogen, oxygen, dry ice, photo material, etc.		147
		$2,270
Expenses, mainly repairs, caused by an emergency landing		354
Total Running Expenses		$2,624
Meteorological instruments:		
Two Bosch airplane meteorographs	$237	
Pressure-temperature chamber built at Massachusetts Institute of Technology	150	
Humidity calibration apparatus	10	
Ventilation shelter built at Massachusetts Institute of Technology	40	
	$437	
Depreciation for one year		$87
Flying instruments:		
Artificial Horizon		
Altimeter		
Bank and Turn indicator		
Cup-speedometer		
Wing thermometer		
Gyro compass		
Climb indicator		
Radio set and shielding		
Oxygen device		
Parachute	$1,310	
Depreciation for one year		$ 262
Total depreciation of equipment		$ 349
Pay to spare pilots and assistants		$ 292
Total expenses		$3,265

With a total amount of $3,265, which covered all expenses including the airplane and a five years' depreciation of all instruments the Massachusetts Institute of Technology "small plane station" carried out within six months 168 ascents to an average altitude of 4,670 m. This gives an average total expense of $19.43 for one flight.

B. Measurements of Temperature

Surface air temperatures are usually measured with standard mercury thermometers which are protected from radiation and kept properly ventilated. Temperatures of the free atmosphere are normally recorded with the aid of bimetal elements. What really is determined in both cases is not the air temperature but the temperature of the mercury or the bimetal. We assume that air temperature and instrument temperature are sufficiently equal. They never are absolutely the same when the air temperature is changing, since a heat transfer from the air to the instrument has to take place in order to change the instrument temperature accordingly and since this heat flow is possible only when there exists a temperature difference between the two media. The temperature difference between air and instrument will be larger, the larger the heat capacity of the instrument is and the quicker the air temperature changes. Temperature changes at the ground are generally rather slow. The heat capacity of all standard thermometers is roughly the same. Thus the error in taking air temperature in this way is small and of the same order of magnitude for all stations. This makes it permissible for many purposes, especially for temperature comparisons of different locations, to use the thermometer readings without corrections. The conditions for upper air soundings are different. No matter which one of the aerological methods is used, whether balloon, kite, airplane or parachute, the velocity with which the thermometer is carried vertically through the atmosphere is so high that the instrument always undergoes large and rapid temperature changes. Moreover, the different types of meteorographs are equipped with thermometers of quite different heat capacities. The ventilation conditions of different carriers and different meteorographs differ among themselves. The errors in these temperature indications are therefore likely to be larger than in the surface readings, and data gathered at different aerological stations are not readily comparable. It is therefore essential that a careful investigation of these effects be made at each individual station. In many cases temperature corrections should be applied in order to keep the errors within reasonable limits. Since the application of corrections is a tedious procedure and since even a very careful correction can not eliminate all the errors, efforts should be directed towards the designing of thermometer elements for aerological soundings which do not require corrections.

Thermometers are influenced by two different types of temperature changes, namely, those caused by the rapid change of elevation of the carrier and those caused by certain quick changes of temperature which seem to take place in the air all the time. Investigations with highly sensitive thermocouples prove that the temperatures indicated by the standard thermometers actually represent mean values of temperature fluctuations of short periods and variable amplitudes. A certain type of such fluctuations, having amplitudes of the order of magnitude of 1°C and periods of, roughly, one second, have been registered by Barkow [8]. Fluctuations of larger size can easily be measured anywhere with sensitive thermographs. Measurements of this kind made by J. Namias at East Boston Airport in June 1932 showed fluctuations up to 4°C near the ground. Doubtless similar temperature oscillations prevail throughout the turbulent layer of the atmosphere. Even at 5,000 meters, "horizontal gradients" of 1.5°C (Boston, April 6, 1933) were registered by the Standard Bosch meteorographs. It is reasonable to assume that they are even more frequent than our present observation methods indicate.

It would be of the highest importance for the study of turbulence to measure the temperature structure of the atmosphere regularly at different altitudes. This would require thermometers of extremely high sensitivity. Such thermometers could be developed in the form of recording thermocouples, probably even for use in airplanes. Since the temperature changes due to turbulence are faster than the temperature changes due to the climb of the fastest climbing meteorograph carriers now in regular use, thermometers of this kind would naturally register the vertical temperature changes without noticeable lag. It is nevertheless questionable whether such a record of the actual air temperature structure as could be obtained by our ordinary aerological soundings would be of much use for research in turbulence. Our aerological soundings give us, not a simultaneous, but a successive, record of the temperatures at the different elevations. Balloons, kites and especially airplanes change their location during the ascent. Thus, the temperature records would present the air temperature in a rather complicated form, as a function of time, height and location. For the study of turbulence with the help of exact temperature measurements it seems to be necessary to abandon our usual aerological methods. Temperature—time records from highly sensitive thermographs placed at certain elevations must be taken. This has already been done by mounting resistance thermometers or thermocouples at different heights on towers. It should not be impossible to extend this method to kites. Thermographs could be carried on an airplane and on cables hanging down from an airplane, the plane flying at constant altitude. The difficulty will consist in keeping the altitude constant.

The use of such sensitive thermometers in regular aerological ascents implies considerable disadvantages. The temperature traces would represent a superposition of horizontal, vertical and time temperature structure. At our present state of knowledge, we would not be able to differentiate correctly between these effects. Most aerological soundings are carried out to gather information to be used immediately in forecasting. The vertical temperature and humidity distribution are the most important data gained from the ascents and to distribute them quickly is often more vital than to collect additional scientific information. For this reason too detailed temperature traces are not desirable. However, it would facilitate computations if the lag of the thermometers could be kept low enough to get records of the vertical temperature distribution without marked errors. In the following an attempt is made to show to what extent it is possible to reach this goal with the help of an ordinary mechanically recording bimetal thermometer.

It is well known that the indicated temperature T_i differs from the actual temperature T by an amount which is proportional to the time rate of change of the indicated temperature, thus

$$T - T_i = \alpha \frac{d\ T_i}{d\ t}.$$

α represents the lag coefficient of the thermometer expressed in minutes. α is known to be 0.38 minutes for a mercurial thermometer of the standard Assmann psychrometer at a ventilation velocity of 2 meters per second. This means that the indications of the thermometer lag 0.38°C behind the actual air temperature provided the actual temperature changes at the rate of 1°C per minute. Changes of 3°C per minute are encountered rather frequently when making aerological ascents, the plane climbing at the rate of 300 meters per minute through layers with dry adiabatic lapse rates. Even changes of more than 7°C per minute (Boston, May 28, 1933) are not rare when the ascents are carried out at early morning hours with radiation inversions. In these cases, readings of a standard mercury thermometer (if ventilated at the rate of 2 m.p.s.) would be 1.1°C or 2.6°C too high or too low respectively.

The lag coefficients of some of the types of meteorographs which are used in aerological observations in the United States were determined in the Massachusetts Institute of Technology wind tunnel at an air speed of 63 miles per hour. The standard Bosch Meteorograph as used in the Massachusetts Institute of Technology ascents has a lag coefficient of $\alpha = 0.27$. The same type of meteorograph, but equipped with a bimetallic test strip of a thickness of 0.01″, gives $\alpha = 0.10$. The lag coefficient of a standard Friez aerograph was found to be $\alpha = 0.75$. Another Friez aerograph, which was kindly put at our disposal for these investigations by the U. S. Weather Bureau, has a lag coefficient of $\alpha = 1.04$. Kopp [19] gives the lag factor of a Marvin kite meteorograph, used as an airplane meteorograph by the Berlin aerological station, as $\alpha = 0.17$. Based on the above mentioned frequently encountered rate of a temperature change of 3°C per minute, these five instruments reach their state of equilibrium when the deviations from the true air temperature are the following:

Standard Friez I	3.1°C
Standard Friez II	2.3°C
Standard Bosch	.8°C
Marvin Kite	.5°C
Bosch with Test Strip	.3°C

These examples show clearly that without the application of corrections the upper air data, especially those obtained with Friez aerographs, may frequently differ from real conditions and not be comparable among themselves. The Friez company is now developing a meteorograph with greatly reduced temperature lag.

Assuming that the meteorograph registers the correct temperature at the moment of take off ($t = 0$) and assuming furthermore that the actual temperature encountered during the flight drops at a linear rate,

$$T = T_0 - \beta t,$$

then the lag formula shows that the indicated temperature will drop at the rate

$$T_i - T = \Delta = \alpha\beta[1 - e^{-t/\alpha}] = \Delta_\infty[1 - e^{-t/\alpha}].$$

Δ_∞ represents the constant difference between indicated and actual temperature listed above for five different instruments. If the actual temperature changes at a rate of 3°C per minute (actual lapse rate, 1°C/100 m, rate of climb 300 m per minute) the indicated average lapse rates for the first 300 m and for the first 600 m will differ considerably from the true lapse rate, as may be seen from the following table.

TABLE IVa

Indicated Lapse Rates

Instrument	0–300 m $\frac{dT_i}{dz}$ in $\frac{°C}{100\,m}$	0–600 m $\frac{dT_i}{dz}$	Adiabatic Atmosphere, Rate of Climb 300 m per minute
Standard Friez I	0.36	0.56	
Standard Friez II	0.45	0.65	
Standard Bosch	0.74	0.87	
Marvin Kite	0.83	0.91	
Bosch with Test Strip	0.90	0.95	

By reducing the rate of climb during the first ten minutes to, say, 100 m. per minute the final constant differences between indicated and actual temperatures would be reduced to one third of their listed values. Under those conditions the indicated lapse rates would come closer to the actual, as seen in Table IVb.

Besides showing the disastrous effect of lag in masking the true lapse rate, these two tables indicate the necessity of maintaining a very slow rate of climb near the ground. Since most aerological stations carrying out routine observations do not correct their records for lag, one is probably justified in assuming that adiabatic and superadiabatic lapse rates are much more common than is generally assumed.

The determination of the lag coefficient is a comparatively simple experiment. The instrument has to be heated or cooled to not more than 6°C [5] off the actual constant temperature T and then exposed to an air current of the temperature T and a speed corresponding to that encountered during aerological ascents. A trace representing T_i as a function of time is thus obtained. From this trace corresponding values of T_i and $\frac{dT_i}{dt}$ may be taken and substituted into the above formula in order to get α.

TABLE IVb

INDICATED LAPSE RATES

Instrument	0–300 m $\frac{dT_i}{dz}$	ɔ–600 m $\frac{dT_i}{dz}$	Adiabatic Atmosphere, Rate of Climb 100 m per minute
Standard Friez I	0.67	0.83	
Standard Friez II	0.75	0.87	
Standard Bosch	0.91	0.95	
Marvin Kite	0.94	0.97	
Bosch with Test Strip	0.97	0.98	

Integration between the time limits t_2 and t_1 gives

$$\alpha = \frac{t_2 - t_1}{\ln \frac{T_{i_1} - T}{T_{i_2} - T}}.$$

If T_{i_1} and T_{i_2} are chosen so that $T_{i_2} - T$ equals $1/2\ (T_{i_1} - T)$, a certain value $t_2 - t_1$ will be obtained. α becomes equal to $\frac{t_2 - t_1}{\ln 2}$ or, $t_2 - t_1 = \alpha \cdot \ln 2$. This value $\alpha \cdot \ln 2$ often is noted instead of α. Since, in most cases, the temperature deflection of bimetal thermographs is a linear function of temperature for the small range of 6°C, this latter method has the advantage of simplicity. The lag coefficient is obtained graphically by dividing a distance in half and multiplying the time interval thus determined with $\ln 2 = 0.695$. Compare Fig. 1.

As has been pointed out before, a transfer of heat from the air to the thermometer has to take place in order to equalize the temperatures of the two. The time required represents the lag of the thermometer. The heat transfer takes place at the surface of the thermometer. The larger this surface A is, the smaller the lag. The heat capacity of the thermometer is given by its mass times its specific heat, or volume V times density s times specific heat c. The smaller this heat capacity is, the less time will be required to change the temperature of the thermometer. Finally a factor H representing the heat exchange per cm² at the surface of the thermometer regulates the heat flow. The larger

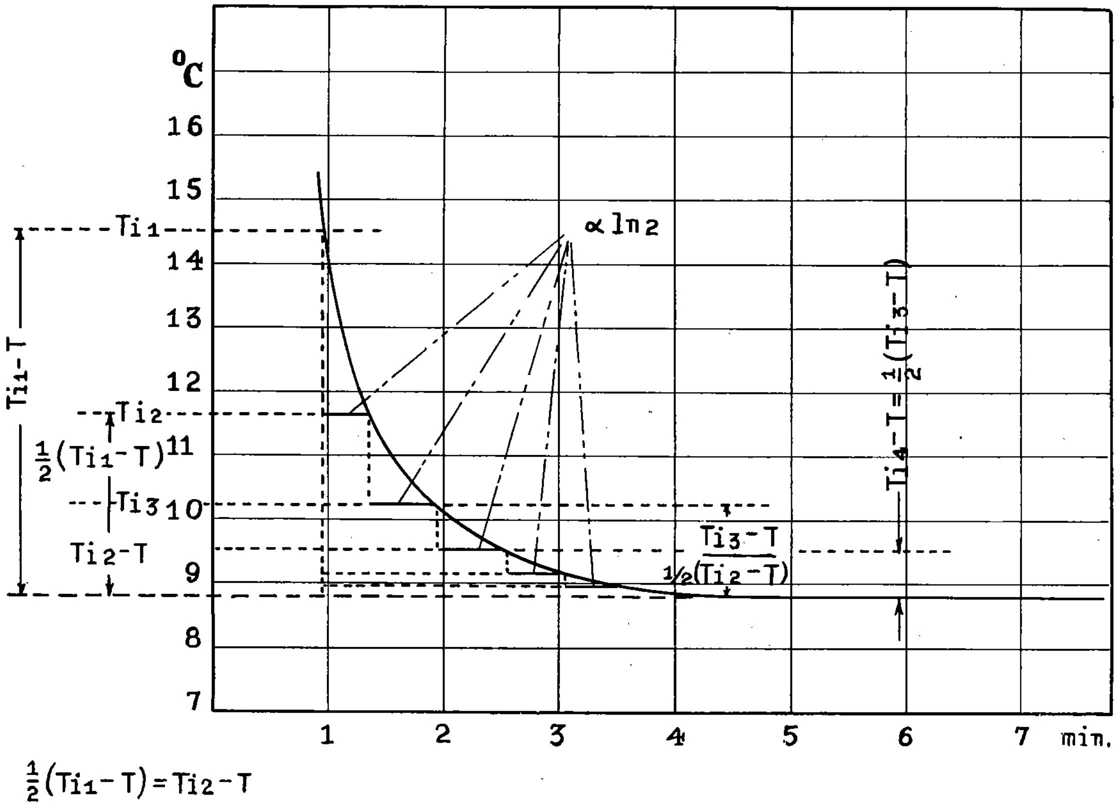

FIG. 1.—Graphical determination of thermometrical lag.

H, the smaller the lag. The lag coefficient is thus represented by the following equation:

$$\alpha = \frac{V \cdot s \cdot c}{A \cdot H}.$$

This relation does not permit the determination of the numerical value of α. V, A, c and s are known, but the factor H depends not only on the surface condition of the thermometer, but also on the ventilation velocity and air density and includes in addition heat conductivity within the thermometer and radiational effects. H has been com-

TABLE V

	Heat Capacity $c \cdot s$	Expansion Coefficient
Alcohol	0.46	$11 \cdot 10^{-6}$
Mercury	0.41	$60 \cdot 10^{-6}$
Glass	0.44	30 to $80 \cdot 10^{-6}$
Aluminum	0.58	$23 \cdot 10^{-6}$
Brass	0.75	$19 \cdot 10^{-6}$
Copper	0.80	$16 \cdot 10^{-6}$
Iron	0.86	$12 \cdot 10^{-6}$
Steel	0.86	1 to $19 \cdot 10^{-6}$

puted by theoretical considerations, but the great variation in exposure in different meteorographs seldom permits the use of the values of H found under greatly simplified assumptions. However, the formula does indicate how one has to proceed in order to reduce the lag. There are three possibilities:

1. Choose thermometer material of small heat capacity $s \cdot c$.
2. Make the ratio A/V large.
3. Increase H, the heat transfer, by increasing the ventilation speed.

The choice of materials is restricted since not only heat capacity but also expansion coefficient must be taken into account; in order to obtain reasonably large temperature deflections and actuating forces it is necessary to join one high expansion metal with one of low expansion coefficient. Table V shows the heat capacities and expansion coefficients for a number of materials used in thermometer construction. The heat capacities of glass covered liquid thermometers are about one half of the heat capacities of ordinary bimetal strips. Thus, liquid thermometers would have only half the lag of bimetal thermometers of the same shape. Bourdon tubes of the same shape would have intermediate values. Aluminum has a comparatively low heat capacity and a high expansion coefficient. A superior bimetal combination could be obtained if it were possible to join aluminum to a low expansion metal.

It is well known that mercury thermometers with spherical bulbs are less sensitive than the ones with cylindrical bulbs. The explanation is that the ratio V/A of the sphere is a maximum. The disadvantage of the large heat capacity of bimetal strips is made up for by the more favorable ratio V/A obtainable with bimetal strips. This ratio can be decreased still further by decreasing the thickness of the element. Since the thickness usually is negligibly small compared with length and width, the surface A remains practically constant, while V decreases as a linear function of the thickness. Using strips of smaller thickness however, produces effects, described later, part of which are not desirable. For this reason it was considered desirable to check the formula by a number of tests in order to find out if the decrease of lag actually is proportional to the thickness. For the experiments the following bimetals were put to our disposal by the General Plate Co., Attleboro, Massachusetts:

TABLE VI

NAME	CHARACTER	THICKNESS (h) inches	cm.
#1 Precision Metal	Invar Steel—Chromium nickel steel	0.010	0.0254
#2 Precision Metal	Invar Steel—Chromium nickel steel	0.008	0.0206
#3 Precision Metal	Invar Steel—Chromium nickel steel	0.006	0.0152
#4 Lotemp Metal	Invar Steel—Brass	0.009	0.0229
#5 Lotemp Metal	Invar Steel—Brass	0.007	0.0178
#6 Lotemp Metal	Invar Steel—Brass	0.005	0.0127

The experiments were made with the help of a recorder having a recording drum of 30 cm. length and 15 cm. diameter, a displacement of 4.5 cm. representing 1 minute. On this device the 6 bimetal strips of 10 cm. length were mounted so that they furnished temperature traces on lamp-blacked paper, the deflections of the bimetal being enlarged by a 15 cm. recording lever. Several series of such traces were obtained by first bringing the temperature of the whole device to about 10°C. below room temperature and then exposing it to room temperature. Two ventilation conditions were used: (1) the ordinary motion of air in a closed heated room, which may amount to an average of 1 or 2 meters per second, and (2) the ventilation by an electric desk fan, which stirred the air at about 5 meters per second. It proved to be necessary to direct the air current produced by the fan through a paper tunnel in order to get uniform ventilation for all the six elements. Without the tunnel the values of the lag coefficient α, determined from different parts of one and the same trace and from corresponding traces of different tests, had a dispersion as high as 33%. Using the tunnel the maximum dispersion of 10 determinations of α from each thermometer at the rate of 2 meters per second and 5 meters per second did not exceed 13%. The mean values of the lag coefficients found from these tests are given in table VII. Kleinschmidt [6] finds $\alpha = 0.15$ for bimetals of 0.5 mm. thickness at a ventilation of 5 mps, but already Raethjen and Huss [7] have stated that this value seems to be too small. Extrapolation of our tests also shows that this lag must be 0.4 to 0.5.

TABLE VII

Coefficients of Thermometrical Lag

Bimetal		Lag coefficient α in minutes			
		Nat. Vent. = ab. 2 mps		Fan Vent. = ab. 5 mps	
Type	Thickness in inches	Measured	Computed from formula	Measured	Computed from formula
#1 Steel-steel	$10 \cdot 10^{-3}$	0.98	(0.98)	0.22	(0.22)
#2 Steel-steel	8	0.75	0.78	0.17	0.18
#3 Steel-steel	6	0.66	0.58	0.14	0.13
#4 Steel-brass	9	0.76	(0.76)	0.17	(0.17)
#5 Steel-brass	7	0.66	0.59	0.14	0.13
#6 Steel-brass	5	0.59	0.46	0.07	0.09

If the formula $\alpha = \frac{V \cdot s \cdot c}{A \cdot H}$ is correct, the lag coefficients of the two groups of bimetals must have the ratios of the thicknesses, i.e., 10:8:6 and 9:7:5 respectively. The coefficients computed this way as related to #1 and #4, are shown for comparison in table VII.

Figure 2 is the graphical representation of the tests. It indicates that the lag of the steel-steel thermometers is approximately 15% higher than the one of the steel-brass thermometers which is in accordance with the heat capacities of the materials (compare table V). With merely room ventilation, the lag does not decrease as rapidly as expected. These curves for low ventilation are hard to explain. Lack of precision in the thicknesses of the thermometers used may play a rôle but should show the same effects in both tests. Heat conduction or radiation from the frame of the device can not be made responsible for these differences either, since only thermometer #6 was mounted near the solid frame. The most probable explanation is that the arrangement of the bimetal elements on the frame caused a systematic protection of the elements #3, #5, and #6 from the irregular little air currents in the room. How strong the influence of the ventilation is, can easily be seen from the big difference in the lag coefficients due to the two different ventilation conditions of the experiments. A check on the results obtained could have been made by repeating the tests with a different arrangement of the thermometers on the frame. At the time when the results were computed, however, the whole apparatus had already been changed for other experiments. The lag coefficients obtained using the ventilation current of the fan, conform reasonably with the theory. The tests show that the *lag decreases with decreasing thickness of the bimetal strips at a linear rate*, when sufficient ventilation is used. That means that improvements as to the lag may be obtained by constructing the bimetal elements as thin as possible.

A limit to this procedure is set since for mechanically recording thermometers there must be a certain force available to overcome the friction of the recording pen and neces-

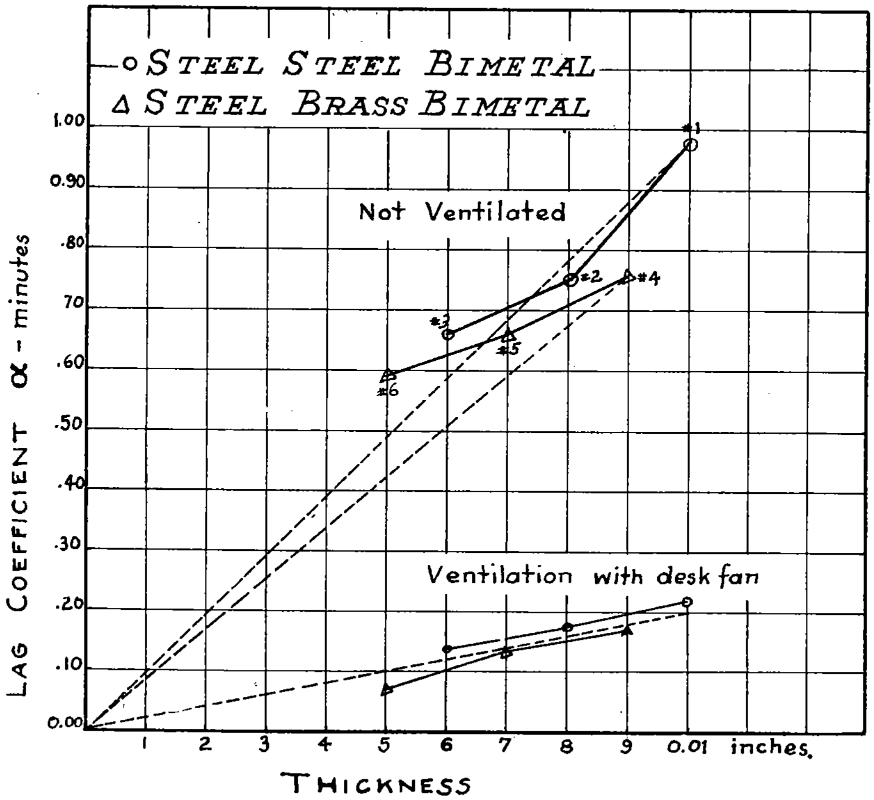

FIG. 2.—Lag coefficient vs. thickness of bimetal strips.

sary enlarging gears. The bimetal strip must be stiff enough to withstand a steady or oscillating deformation by the ventilation current. If the meteorograph changes its position, the bimetal must be stiff enough not to bend under its own weight and the weight of the enlarging mechanism.

A measure of the stiffness of the strip is the deflection of the free end under the influence of these forces. Friction of the pen and of the enlarging mechanism may be represented by a small force P acting at the free end of the strip in a direction opposite to the temperature change. If the length of the element is L, its width l and its thickness h, the deflection may be represented by the equation

$$\Delta S = \frac{4PL^3}{E \cdot l \cdot h^3},$$

where E is Young's modulus of the metal used.

The ventilation current produces forces upon the bimetal strip which vary con-