

Barometric pressures on Mt. Everest: new data and physiological significance

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West, John B. Barometric pressures on Mt. Everest: new data and physiological significance. *J. Appl. Physiol.* 86(3): 1062–1066, 1999.—Barometric pressures (P_B) near the summit of Mt. Everest (altitude 8,848 m) are of great physiological interest because the partial pressure of oxygen is very near the limit for human survival. Until recently, the only direct measurement on the summit was 253 Torr, which was obtained in October 1981, but, despite being only one data point, this value has been used by several investigators. Recently, two new studies were carried out. In May 1997, another direct measurement on the summit was within ~1 Torr of 253 Torr, and meteorologic data recorded at the same time from weather balloons also agreed closely. In the summer of 1998, over 2,000 measurements were transmitted from a barometer placed on the South Col (altitude 7,986 m). The mean P_B values during May, June, July, and August were 284, 285, 286, and 287 Torr, respectively, and there was close agreement with the P_B-altitude (h) relationship determined from the 1981 data. The P_B values are well predicted from the equation $P_B = \exp(6.63268 - 0.1112 h - 0.00149 h^2)$, where h is in kilometers. The conclusion is that on days when the mountain is usually climbed, during May and October, the summit pressure is 251–253 Torr.

extreme altitude; maximal oxygen uptake; acclimatization; work capacity; extreme hypoxia

BAROMETRIC PRESSURES near the summit of Mt. Everest (altitude 8,848 m) are of great interest to high-altitude physiologists because the pressure is so low that the P_{O₂} is very near the limit for human survival. Until recently, only one direct measurement of barometric pressure had been made on the Everest summit. This was done by Dr. Christopher Pizzo on October 24, 1981 during the American Medical Research Expedition to Everest (AMREE), and the value he obtained was 253 Torr (8). The measurement was made with a crystal sensor that was calibrated in the field against a mercury barometer.

Despite being only one data point, the value of 253 Torr has been extensively used in high-altitude physiology. For example, it was the pressure selected for the “summit” in the long-term low-pressure chamber study Operation Everest II (1). In addition, the summit

measurement and additional measurements just above the South Col at an altitude of 8,050 m were used to define the relationship between barometric pressure and altitude on high mountains at latitudes near the equator with good predictive power (5). Mt. Everest is especially suitable for determining the pressure-altitude relationship because not only is its summit at 8,848 m the highest point on Earth but also the South Col (altitude 7,986 m) is a well-defined saddle, and therefore its altitude has been accurately determined.

Clearly, it would be desirable to have additional data on barometric pressures at extreme altitudes on Mt. Everest, and in the last 3 yr two new studies have been carried out. The present paper describes the results, compares the new information with that already available, and discusses the physiological implications.

1997 NOVA EVEREST EXPEDITION

In the spring of 1997, the television science program NOVA organized an expedition to Mt. Everest, and five people reached the summit. The scientific program included measurements of neuropsychological function at extreme altitude, and these were compared with the results from brain imaging before and after the expedition. Cardiopulmonary studies were also made.

We were not aware of the expedition until the last minute but were able to send a handheld barometer in the hope that it would be possible to obtain a measurement on the summit. The instrument was a Pretel Alti Plus K2 barometer (Groupe Pretel, Claix, France). Although we had used the barometer extensively at altitudes up to ~5,000 m at normal ambient temperatures, there was not time before the expedition to calibrate it for the very low pressure expected on the summit and for the very low temperature.

A single measurement was made by David Breahears at 7:00 AM Nepalese time on May 23, 1997. The value was 346 mbar, which corresponds to 259.5 Torr. The barometer was carried in his backpack and so was exposed to the ambient temperature. This was not measured directly, but according to weather balloon soundings made at the same time (see WEATHER BALLOON SOUNDINGS) the temperature was approximately –22°C.

When the barometer was returned to University of California San Diego, it was directly calibrated against a mercury column at barometer temperatures of 21, –6, and –20°C. The graph of barometer reading against

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mercury height showed excellent linearity. However, the barometer read 1–2 Torr low at 760 Torr and 5.3 Torr high at barometric pressures between 232 and 283 Torr at a temperature of 21°C. When the measurements were made after the barometer had been left overnight in a –20°C cold room, the error increased to 7 Torr in the pressure range of 232–283 Torr. Therefore, the corrected pressure was 259.5 Torr minus 7 Torr, that is, 252.5 Torr. This is in close agreement with the value of 253 Torr obtained by Pizzo on October 24, 1981.

WEATHER BALLOON SOUNDINGS

Additional information on barometric pressures at an altitude of 8,848 m in the vicinity of Mt. Everest at the time of the direct measurement was obtained from weather balloon soundings. These radiosondes are released from many locations all over the world at 0000 and 1200 UTC (Universal coordinated time) every day. We used data from radiosondes released from the 14 stations closest to Mt. Everest at 0000 UTC on May 23, 1997. This corresponds to 5:40 AM local time and so is close to the time when the direct measurement was made. The latitude and longitude of the Everest summit are 27°59'N and 86°56'E, and the weather stations were all between 22 and 38°N and between 74 and 95°E. The data for each radiosonde were retrieved by Laurence G. Riddle of the Scripps Institution of Oceanography, University of California San Diego.

Altitudes for barometric pressures of 150, 200, 250, 300, 400, 500, and 700 mbar were obtained for each radiosonde (from knowledge of its ascent rate) and plotted as log barometric pressure vs. altitude. Figure 1 shows an example for the station at Gorakhpur, which is near Everest at 26.75°N, 83.37°E (Fig. 2). The data points lay almost on a straight line but an even better fit was obtained by using a parabola, and the pressure for altitude 8,848 m was then obtained by interpola-

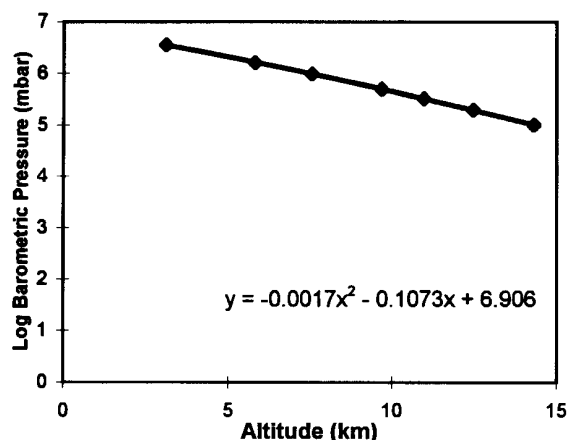


Fig. 1. Derivation of barometric pressure at 8,848-m altitude from radiosonde data. Data points are from balloon that was released from Gorakhpur 26.75°N, 83.37°E at 0000 UTC (Universal coordinated time), May 23, 1997. Altitudes for barometric pressures of 700, 500, 400, 300, 250, 200, and 150 mbar were 3,166, 5,880, 7,600, 9,720, 11,020, 12,540, and 14,390 m, respectively. Data points were fitted with a parabola ($R^2 > 0.9999$), and pressure for 8,848 m was interpolated to be 338.16 mbar. This is equivalent to 253.6 Torr.

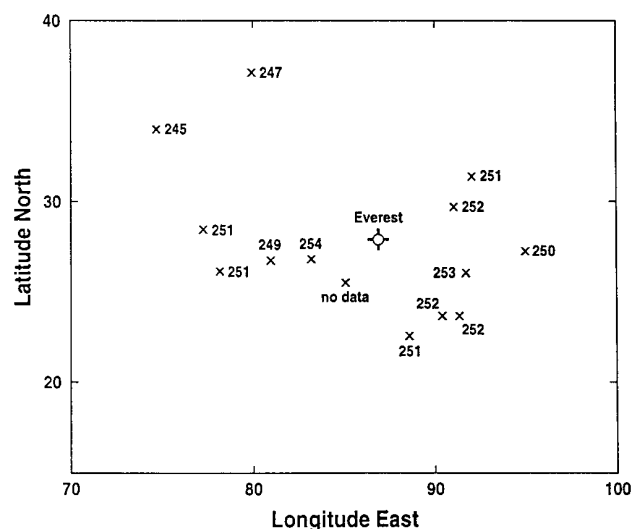


Fig. 2. Barometric pressures at an altitude of 8,848 m in vicinity of Mt. Everest at 0000 UTC on May 23, 1997 as determined from radiosonde data. There are 14 nearby stations indicated by crosses, but 1 did not transmit data above 5,850 m. Gorakhpur is the station southwest of Everest where the pressure at 8,848-m altitude was 253.6 Torr. At Gauhati station, southeast of Everest, pressure at 8,848 m altitude was 252.7 Torr. Note the high-pressure system extending from just west of Everest in a southeasterly direction.

tion. For Gorakhpur, this was 338.2 mbar. These pressures in millibars were converted to Torr by multiplying by 0.7500, and the results are shown in Fig. 2. Other data are also available from the radiosondes, including temperature, humidity, wind direction, and wind velocity. The temperature data showed that, at an altitude of 8,848 m, the temperature was about –22°C, and therefore this was used to calibrate the barometer as indicated under 1997 NOVA EVEREST EXPEDITION.

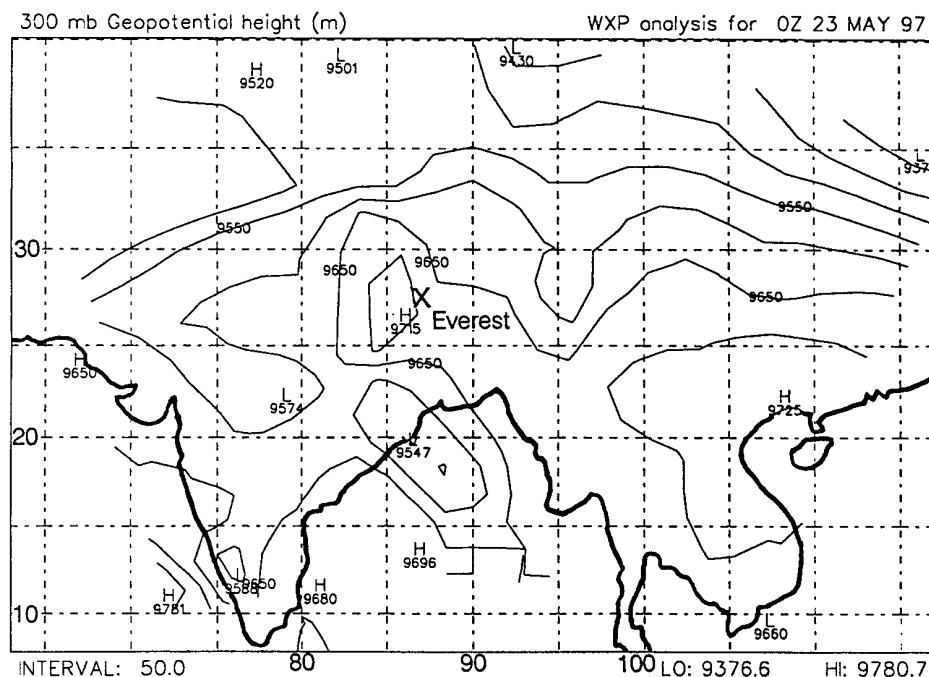
Figure 2 shows that the barometric pressure at an altitude of 8,848 m above Gorakhpur just to the south and west of Everest was 254 Torr, whereas above Gauhati just to the south and east of Everest the pressure was 253 Torr. There is another close station at Patna at 25.60°N, 85.10°E, but unfortunately this radiosonde failed and no data were reported above 5,850 m. The agreement between the radiosonde pressures and the direct measurement is close.

An interesting feature of the radiosonde data is that a high-pressure system was located near the summit of Mt. Everest at the time of the direct measurement. This is apparent from Fig. 2 but is more easily seen in plots of the altitude for a barometric pressure of 300 mbar (225 Torr), which are available from the radiosonde data. Figure 3 shows that, at the coordinates of the Everest summit, the altitude of the 300-mbar pressure was 9,715 m, which corresponds to almost the highest altitude on the chart.

BAROMETRIC PRESSURES ON THE SOUTH COL OF EVEREST (ALTITUDE 7,986 M) OBTAINED IN THE SUMMER OF 1998

An Everest study organized by the Media Laboratory of the Massachusetts Institute of Technology placed a

Fig. 3. Altitudes for a pressure of 300 mbar (225 Torr) in vicinity of Mt. Everest at 0000 UTC on May 23, 1997 as determined from radiosondes. Coastline of India, Pakistan, and southeast Asia is shown by thick line. Note that Everest was near the center of a high-pressure system. L, low; H, high; mb, mbar; WXP, weather processor; OZ, 0000 UTC.



weather station on the South Col (altitude 7,986 m) (3) in early May 1998. Barometric pressure was measured with a Motorola sensor (MPX 5100AP, Motorola, Schaumburg, IL), which has a pressure range of 0–760 Torr and can operate at temperatures down to -40°C . The data were transmitted up to one of three polar orbiting National Oceanic and Atmospheric Administration satellites and then to a ground station. These data were posted on the Web site <http://janson.media.mit.edu/weather/14836>, and up to 30 measurements of pressure and time of day were available every day from May 4 to August 26. The probe also transmitted temperature, wind speed, and degree of lightness or darkness.

In general, the data were internally very consistent with small daily and monthly SDs. However, there were 23 rogue measurements that were clearly outliers. For example, on May 7 all but one of the measurements were between 10.7 and 11.27 in. Hg, whereas one at 0246 UTC was 3.11 in. Hg. Again on July 1, all the measurements were between 10.93 and 11.27 in. Hg except for one of 25.88 in. Hg, which was clearly an outlier. In addition, the measurements at the start of the data transmission on May 4 and early on May 5 were erroneously high because the barometer was still being carried up at this time. If these outliers are rejected, the total number of measurements between May 6 and August 26 was 2,572.

The mean and SD pressures for May, June, July, and August, respectively, were as follows: 11.17 ± 0.10 , 11.24 ± 0.05 , 11.27 ± 0.04 , and 11.30 ± 0.03 in. Hg. Note that the monthly SDs were $<0.5\%$ of the means. When these pressures were converted to Torr, the monthly means for May, June, July, and August were 283.7, 285.5, 286.3, and 286.9 Torr. The gradual increase in barometric pressure from May to July is to be

expected because of the well-known seasonal variation (e.g., see Fig. 3 in Ref. 8).

COMPARISON WITH PREVIOUS DATA AND PHYSIOLOGICAL SIGNIFICANCE

Direct measurement on the Everest summit by the 1997 NOVA Everest Expedition. The agreement within ~ 1 Torr of this measurement with that made by Pizzo in October 1981 is gratifying. There is a substantial seasonal variation in barometric pressure at an altitude of 8,848 m (as shown in Fig. 3 of Ref. 8). The highest pressures are seen in July and August and the lowest pressures in January. May and October are at approximately the same height on the descending limbs of the plot of pressure against month. Therefore, we can expect the pressures in these 2 mo to be similar.

The fact that the pressure was as high as 253 Torr does not mean that this is the mean pressure at the summit during May or October. Climbers tend to choose high pressure days for their summit bid, and, for example, October 24, 1981 was unusually warm with the temperature directly measured on the summit being -9°C (8). In the case of Breashears' measurement on May 23, 1997, Fig. 3 shows that Everest was near the center of a high-pressure system. Radiosonde measurements made from New Delhi show that the mean monthly barometric pressure for an altitude of 8,848 m at latitude 28°N is ~ 251 Torr for both May and October (8). In July and August the mean monthly pressure is between 254 and 255 Torr, whereas in January it falls to as low as 243 Torr.

Radiosonde measurements for 0000 UTC on May 23, 1997. Again, the agreement between the radiosonde data and the direct measurement is close. The isobars

for the pressure of 300 mbar (Fig. 3) show that a high-pressure zone extended from the weather stations at Gorakhpur and Gauhati to include Everest. The same pattern is seen in the altitudes for the 500-mbar pressure, which is not reproduced here. Therefore, we can conclude that the radiosonde value at the Everest summit was close to 253 Torr.

Barometric pressures on the Everest South Col, May to August 1998. The South Col of Mt. Everest is ~860 m below the summit, and it might therefore be argued that barometric pressure data from that location are not valuable in determining the summit pressure. However, the altitude of the South Col is accurately known, and therefore the barometric pressure data can be used to locate the line relating pressure to altitude.

The weather probe measurements can be compared with those made at Camp 5 during the AMREE in 1981. The altitude of this camp was ~60 m above the South Col at 8,050 m, and six barometric pressure measurements were made between October 12 and October 25, the range of values being 281.5 to 285.1 Torr. The mean and SD was 283.6 ± 1.5 Torr (8). The mean pressure recorded from the Massachusetts Institute of Technology (MIT) weather probe for May 1998 (when the seasonal variation is comparable with October) was 283.7 Torr so agreement between the two studies was close. At this altitude, an increase in altitude of 60 m corresponds to a fall in pressure of ~2 Torr.

Relationship between barometric pressure and altitude on Mt. Everest. Table 1 summarizes the barometric pressure data available from the 1997 NOVA Everest Expedition, the 1998 Everest study organized by MIT, and the 1981 AMREE. After the 1981 expedition, a line relating barometric pressure to altitude was derived on the basis of the measurements made at 8,848, 8,050, and 5,400 m as shown in Table 1 (Fig. 2 of Ref. 8). The line used the logarithm of barometric pressure because the data then almost fall on a straight line. Subsequently, the Model Atmosphere equation was derived that fitted these data together with barometric pressures measured at many high-altitude stations, the altitudes of which are accurately known (5). Many of these measurements were from locations within 30° of the equator, and most were in the summer. These locations and time of year were chosen because the barometric pressures are lower at higher latitudes and

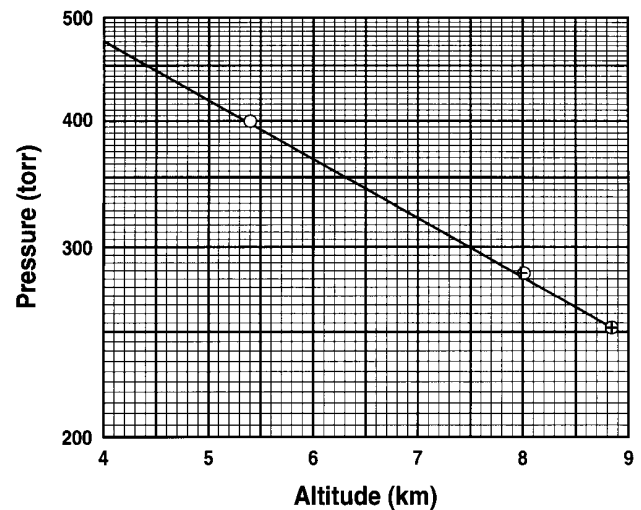


Fig. 4. Barometric pressure-altitude relationship. Circles, data from 1981 American Medical Research Expedition to Everest; cross at summit altitude (8,848 m), data point from 1997 NOVA expedition; cross at altitude of 7,986 m, from 1998 Massachusetts Institute of Technology expedition. SDs are too small to show on the graph. Line corresponds to Model Atmosphere equation: $P_b = \exp(6.63268 - 0.1112 h - 0.00149 h^2)$, where P_b is barometric pressure in Torr and h is altitude in km.

in the winter months. The Model Atmosphere equation is $P_b = \exp(6.63268 - 0.1112 h - 0.00149 h^2)$ where P_b is barometric pressure in Torr and h is altitude in kilometers. It was shown that barometric pressures of most locations were predicted within 1%.

Figure 4 shows the line for the Model Atmosphere equation for altitudes over 4,000 m. The circles show data points from AMREE, and the crosses show the new data. At the highest altitude of 8,848 m, the cross indicating the NOVA measurement is superimposed on the AMREE data point. At the altitude of ~8,000 m, the cross indicating the mean of the MIT measurements during May is at a slightly lower altitude than is the AMREE point and at the same barometric pressure. However, agreement is clearly very close.

Physiological significance of the new data. The new data greatly increase our confidence in the barometric pressure-altitude relationship at altitudes of 8,000 m and above on Mt. Everest where there was previously so little data. The new measurements confirm that the inspired P_{O_2} is only 42–43 Torr on the summit and justify the use of this value in determining the maximal oxygen consumption ($\dot{V}O_{2\max}$) on the summit (4, 7). The measurements further emphasize the extreme sensitivity of $\dot{V}O_{2\max}$ to barometric pressure at these great altitudes.

Measurements during AMREE on very well-acclimatized subjects at inspired P_{O_2} values of 48.5 and 42.5 Torr, respectively, showed that the $\dot{V}O_{2\max}$ declined from 1,450 to 1,070 ml/min (see Table 6 in Ref. 7). This means that the slope of the line relating $\dot{V}O_{2\max}$ to inspired P_{O_2} was ~63 ml·min⁻¹·Torr⁻¹. A very similar result was found in Operation Everest II (4; see Fig. 11.17 in Ref. 6).

Table 1. Barometric pressures on Mt. Everest

Altitude, m	AMREE	NOVA	MIT	Model Atmosphere Equation
8,848 (Summit)	253	253		253
8,050	284			282
7,986			284	284
5,400	400			399

Values are in Torr. AMREE, October 1981 American Medical Research Expedition to Everest; NOVA, May 1997 NOVA Everest Expedition; MIT, May 1998 Massachusetts Institute of Technology Everest Study; Model Atmosphere equation: $P_b = \exp(6.63268 - 0.1112 h - 0.00149 h^2)$, where P_b is atmosphere pressure in Torr and h is altitude in km (5).

The extreme steepness of the line relating $\dot{V}O_{2\max}$ to inspired PO_2 has some interesting physiological implications. For example, if the barometric pressure on the summit were 236 Torr, as predicted from the International Civil Aviation Organization Standard Atmosphere (2), the inspired PO_2 on the summit would be only 39.5 Torr. Therefore, the reduction in inspired PO_2 from the value of 43 Torr, which would exist for a summit pressure of 253 Torr, would be 3.5 Torr. The reduction of oxygen consumption would therefore be ~ 222 to a value of ~ 848 ml/min, or a reduction of $\sim 21\%$. It seems very unlikely that the mountain could be climbed under these conditions.

In fact, even the reduction of barometric pressure of only 10 Torr, such as occurs between summer and winter on the Everest summit, is predicted to reduce $\dot{V}O_{2\max}$ by ~ 133 ml/min. In other words, $\dot{V}O_{2\max}$ on the summit would fall from 1,070 to ~ 940 ml/min, that is, by $\sim 12\%$. This is presumably one reason why the mountain has not yet been climbed in midwinter without supplementary oxygen.

In summary, the new direct measurement of barometric pressure made in May 1997 and the very extensive series of measurements of barometric pressure on the South Col in 1998 greatly increase our confidence in the barometric pressure-altitude relationship at altitudes of 8,000 m and above on Mt. Everest. They provide additional evidence that humans at these altitudes are very close to the limit of tolerance to hypoxia.

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