NOTES AND CORRESPONDENCE

A Record Minimum Sea Level Pressure Observed in Hurricane Gilbert

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ABSTRACT

On 13 September 1988, Hurricane Gilbert attained an extreme minimum sea level pressure, estimated to be 885 hPa from aircraft reconnaissance reports at the time. Postseason analysis indicates that the flight-level pressure, *P*, upon which this figure is based requires correction upward. In typhoons with sea level pressures < 900 hPa, comparison between sea level pressures measured by dropsonde and those estimated by the same method used in Gilbert indicates that, in addition to the error in *P*, the estimation has a bias toward low pressure. Although the aircraft did not release a dropsonde in the eye at minimum pressure, it is possible to calculate hydrostatic sea level pressures by assuming a variety of plausible thermal structures below flight level. With corrected *P*, both the statistical extrapolation with its bias removed and the hydrostatic calculations show that a revised value of 888 ± 2 hPa is closer to the true minimum sea level pressure. The standard deviation of the various approximations means that the probability is <3% that the actual minimum failed to reach a value below 892 hPa, the old record for a hurricane in the Atlantic Basin set by the Labor Day Hurricane of 1935.

1. Introduction

Hurricane Gilbert deepened at a rate > 3 hPa h^{-1} as it tracked across the Caribbean toward landfall on the Yucatan Peninsula (Lawrence and Gross 1989). At the end of the deepening, one of the NOAA WP-3D research aircraft, N43RF, conducted a reconnaissance of Gilbert at 3 km radar altitude. At 2153 UTC 13 September 1988, N43RF, flying at 632 hPa in the eye, extrapolated a 700 hPa isobaric height equivalent to a sea level pressure (SLP) of 885 hPa, a record minimum for a hurricane. The aircraft was not prepared to deploy dropsondes, making it impossible to calculate the hydrostatic SLP based upon flight-level pressure and observed virtual temperature between flight level and the surface. This note, written by participants in N43RF's flight, revises the estimate of the record SLP upward to 888 hPa through analysis of the flight-level measurements and the statistical extrapolation (Jordan 1958b) to the surface. It also suggests means to approximate the hydrostatic SLP in the absence of thermodynamic observations below flight level.

2. Observations

Table 1 presents the flight-level measurements and various estimates of surface pressure for each time N43RF approached the center of Gilbert's eye. On the left side of the table are the observed flight-level quantities: UTC, time of observation; Z, geopotential altitude in meters; T and T_d, Celsius temperature and dewpoint; and P, pressure in hPa. The instrumentation is as described by Jorgensen (1984) except that the Garrett flight-level pressure sensor has been replaced with a Rosemount Model 542K. Based upon experience during the 1988 hurricane season and postseason calibration, P required retrospective correction.

The capacitive flight-level pressure sensor exhibited a systematic error caused by defective temperature compensation. The error appeared as discrepancies between the sensor's readings and nearby rawinsonde observations when the aircraft approached or departed from its base. Although the sensor was inside the fuselage and protected to some extent from fluctuations of outside air temperature, a linear variation of the error with the outside air temperature over 1–2 h before each observation explained 79% of the variance of the error during the seven flights examined, including all of N43RF's flights in Gilbert. Because the sensor and its enclosure had large thermal inertia, the error re-

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TABLE 1. Estimated minimum SLPs and the observations upon which they are based for each time that N43RF flew into the eye of Hurricane Gilbert on 13 September 1988. Flight-level observations are: UTC, time of observation; *Z*, geopotential altitude in m; *T* and T_d, Celsius temperature and dewpoint; and *P*, corrected pressure in hPa. SLPs are estimated as follows: P_j, by statistical extrapolation (Jordan 1958b); P_{ct}, by assuming virtual temperature constant at the flight level value between flight level and sea level; P_{is}, by assuming linear variation of virtual temperature between flight level and saturation at sea level temperature T_s; and P_{it}, by assuming a saturated adiabat from 27°C at sea level to P_t and interpolating linearly from P_t to flight level.

Observations					Extrapolations			P_{is}		P_{it}	
UTC	Z	T	T_d	P	P_j	$P_j + 1.6$	P_{ct}	$T_s = 27$	$T_s = 30$	$P_t = 825$	$P_t = 700$
1756:50	3037	22.4	3.5	644.4	910.8	912.4	913.7	909.5	907.4	910.2	911.4
1913:52	2997	25.2	−1.0	642.3	902.2	903.8	904.0	901.2	899.1	902.1	903.8
2034:23	2975	23.3	2.7	638.4	893.9	895.5	897.9	894.2	892.2	894.8	896.2
2152:45	3007	27.2	−2.6	632.3	886.6	888.2	889.0	887.1	885.1	888.1	890.3
2323:24	3012	27.4	−4.8	634.9	891.4	893.0	893.1	891.3	889.3	892.3	894.5

quired 1–2 h of operation at cold temperatures to develop and a similar period at warm temperatures to disappear. Typically, the sensor indicated pressures 2–3 hPa too low at the end of a long flight at temperatures near −15°C, but agreed more closely with independently measured pressures when the aircraft departed after a long stay on the ground at temperatures > 25°C. On other occasions, when N43RF flew for several hours at temperatures of 15°–20°C, dropsonde SLPs based upon this sensor were consistent with those determined by other aircraft to within 1–2 hPa, but when it operated at higher altitudes where the temperatures were <−10°C, the error reappeared. This pattern of sensor errors was readily reproduced in the laboratory during postseason calibration.

The lowest SLP in Gilbert was extrapolated after 4 h of operation at an average temperature of 12°C, where the linear fit to temperature predicts that the sensor read 1.0 hPa low with a standard deviation ± 0.56 hPa. *P* in Table 1 reflects a +1.0 hPa correction to the flight-level pressure.

Figure 1a shows dropsonde observations in Gilbert's eye before and after N43RF's flight. An Air Force reconnaissance aircraft, AF963, observed the first sounding at 1537 UTC, 6 h before Gilbert reached minimum SLP. The sounding had a saturated, nearly moist adiabatic layer from the surface to 820 hPa. In an inversion at the top of the moist layer, the temperature increased by 5°C, and the relative humidity decreased to <50%. The temperature at 756 hPa was 27.6°C, 0.2° higher than the surface temperature. The second sounding, which the other WP-3D, N42RF, observed at 0905 UTC 14 September, 11 h after Gilbert's minimum SLP, was moist adiabatic and saturated from the surface almost to flight level. In this sounding, the surface temperature had risen to 28°C, but at that flight level had fallen from 24° to 20.1°C. Similar moistening and cooling is a well-documented feature of supertyphoons as they pass maximum intensity (Jordan 1961).

Throughout N43RF's flight, *T* and T_d at 3 km altitude in the center of Gilbert's eye were above 20°C and near 0°C, respectively. The eye was free of cloud, except for broken stratocumulus within <1 km of the surface. The inner radius of the radar eye was 8 km—too small to permit maneuvering inside the eye. On each penetration, N43RF flew directly across the eye, passing as near the center as possible and exiting on the opposite side. During the last penetration, the lowest measured wind speed was 9 m s^{-1}; consequently, the aircraft did not reach the dynamic center, and the actual minimum SLP at 2323 UTC may have been 1–3 hPa lower than the extrapolated value.

3. Statistically extrapolated surface pressures

The operational estimate of 885 hPa minimum pressure at 2153 UTC was derived from Jordan's (1958b) statistical relation between 700 hPa isobaric height and surface pressure. The first column on the right side of Table 1, labeled P_J, shows similar estimates using the corrected flight-level pressure for each time N43RF penetrated to Gilbert's center. The difference between the minimum operational SLP and P_J in Table 1 stems from the correction to the flight-level pressure.

The National Hurricane Center uses Jordan's relation routinely to extrapolate surface pressures when no dropsonde observation is available. The relation was based upon 245 typhoon eye dropsonde observations made during 1951–54. Inspection of the original scatter diagram indicates that only three of the observations had surface pressures < 900 hPa. Jordan tested the regression with 65 independent observations in Atlantic hurricanes and showed that 90% of the extrapolated pressures—admittedly higher than those of interest here—were within 3 hPa of the hydrostatic pressures. Since the extrapolated SLP at 2153 UTC is lower than most of the pressures in the original data, validation of the relation for pressures < 900 hPa is necessary.

Table 2 compares P_J extrapolated by Jordan's relation from the 700 hPa isobaric height, Z_7, with hydrostatic surface pressures, P_s, from dropsondes in 12 typhoons that had SLP < 900 hPa. Of 38 extrapolated pressures, all but seven are lower than the corresponding hydrostatic pressures. On the average, the extrapolated SLP is 1.6 hPa below the hydrostatic, a difference

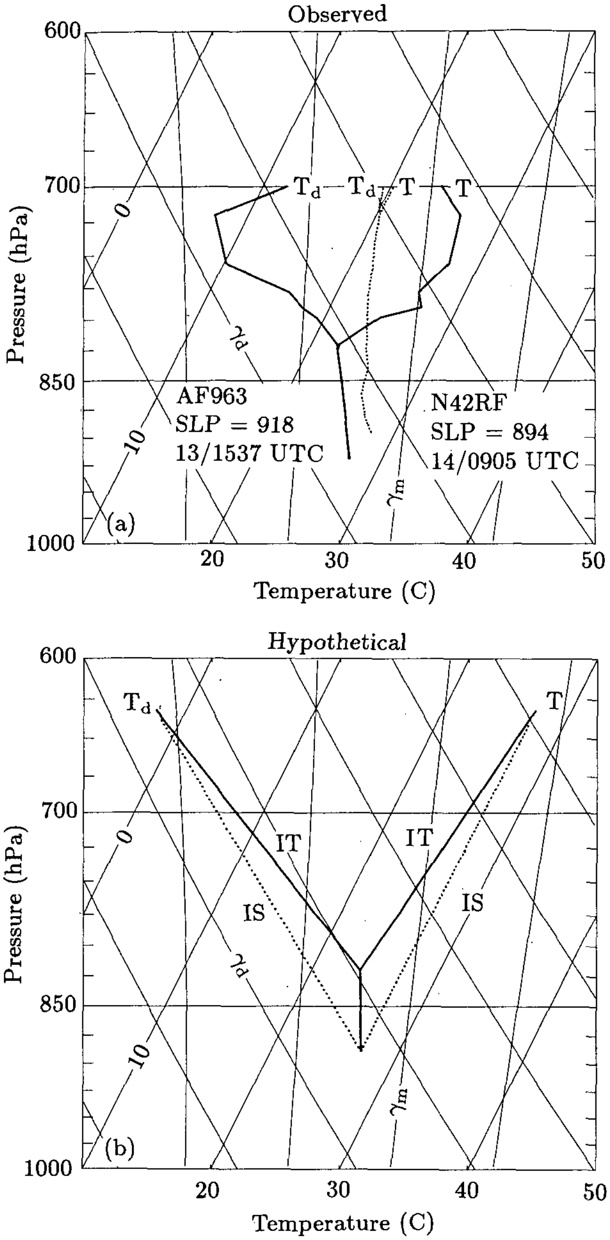

FIG. 1. Observed and hypothetical soundings in Hurricane Gilbert. The light horizontal lines are isobars, those sloping upward to the right are isotherms, those sloping upward to the left are dry adiabats, and the nearly vertical ones are moist adiabats. The heavy solid and dotted lines indicate the soundings. (a) Soundings observed as Gilbert's pressure was falling rapidly before it attained its lowest value (solid) and after the lowest value when P_s was steady at a somewhat higher value (dotted); (b) two hypothetical soundings used to extrapolate surface pressures: IS, in which temperature and dewpoint vary linearly between flight level and values assumed for the surface (dotted), and IT, in which the lower part of the sounding is saturated and follows a moist adiabat from P_s to P_t and the upper part interpolates linearly from P_t to flight level (solid).

significant at >99%, even if the observations in each typhoon were so highly correlated that they represented only a single degree of statistical freedom. Although Jordan's relation is accurate and essentially unbiased for SLP > 900 hPa, Table 2 shows that when $P_s < 900$ hPa, the extrapolated pressures require a correction of +1.6 hPa. The bias is probably caused by stronger subsidence below 700 hPa, which makes the eyes of extreme tropical cyclones warmer than the average of Jordan's sample. Thus, the best statistical estimate of minimum SLP at 2153 UTC is 888.2 hPa. Half of the difference between this value and 885 hPa comes from correction of the error in flight-level pressure and half from correction of the bias in Jordan's extrapolation.

4. Hydrostatically computed surface pressures

Even without thermodynamic observations below flight level, hydrostatic computation of SLP is a reasonable alternative to statistical extrapolation. The observed flight level T and T_d, combined with climatological or historical estimates of the thermodynamic sounding below flight level, allow estimation of the mean virtual temperature below the aircraft and, hence, SLP. This section discusses several hypothetical soundings that lead to a range of computed SLP values.

Given that T was so high in Gilbert, a reasonable "least hypothesis" sounding might have virtual temperature fixed at the flight-level value throughout the column below the aircraft. SLPs calculated using this assumption, labeled P_{ct} in Table 1, were typically 1–2 hPa higher than the corrected statistical extrapolations.

For construction of more elaborate hypothetical soundings, an estimated surface air temperature, T_s, is necessary. Jordan's (1958a) mean T_s for intense ($883 \leq P_s \leq 901$ hPa) typhoons is 27.1°C, and the observed T_s from AF963's and N42RF's soundings was within a degree of 27°C, so that little justification exists for assuming a different value. Two hypothetical soundings based upon estimated surface temperatures appear in Fig. 1b. In the sounding labeled IS, the temperature and water vapor mixing ratio are interpolated linearly from the observed values at flight level to the assumed surface temperature and saturation. The sounding labeled IT resembles the dropsonde at 1537 UTC. It is saturated and follows a moist adiabat from T_s to a specified pressure for the top of the moist layer, P_t. Above P_t, both temperature and mixing ratio are interpolated linearly to the flight-level values. If P_t equals P_s, the IT sounding is identical with the IS sounding.

The sounding with a moist layer that extends from the surface to between 800 and 850 hPa appears to be the most realistic of the hypothetical soundings. It is consistent both with observations of few clouds and low humidity in Gilbert's eye and with the moist layer present in the soundings observed earlier during Gilbert's rapid pressure fall. Averaged over the five observations in Table 1, P_{it}, the SLP computed from this sounding, is 1 hPa < P_J corrected as described above; although it agrees fortuitously at 2153 UTC. Raising the top of the moist layer to 700 hPa cools the sounding

TABLE 2. Comparison of P_s, hydrostatic surface pressures calculated from dropsonde observations in typhoons, with P_j, minimum surface pressures estimated using Jordan's (1958b) statistical relation and Z_7, 700 hPa isobaric height.

Typhoon	Time (UTC)	Date	Z_7	P_j	P_s	$P_s - P_j$	Reference
Elsie	0847	28 Oct 81	2205	898.6	898.0	−0.6	JTWC (1981)
Hope	0910	31 Jul 79	2205	898.6	898.0	−0.6	JTWC (1979)
Wynne	1437	09 Oct 80	2199	897.9	898.0	0.1	JTWC (1980)
Dot	1214	16 Oct 85	2193	897.2	897.0	−0.2	JTWC (1985)
Dot	2307	16 Oct 85	2178	895.5	897.0	1.5	JTWC (1985)
Rita	0315	24 Oct 78	2168	894.3	897.0	2.7	JTWC (1978)
Elsie	2115	23 Sep 69	2183	896.0	896.0	0.0	JTWC (1969)
Elsie	0245	23 Sep 69	2173	894.9	896.0	1.1	JTWC (1969)
Elsie	2014	28 Oct 81	2161	893.5	895.0	1.5	JTWC (1981)
Rita	1408	24 Oct 78	2151	892.4	895.0	2.6	JTWC (1978)
Nora	1020	06 Oct 73	2140	891.1	894.0	2.9	JTWC (1973)
Elsie	2120	27 Sep 81	2139	891.0	893.0	2.0	JTWC (1981)
Irma	0300	12 Nov 71	2120	888.8	893.0	4.2	JTWC (1971)
Nora	1520	05 Oct 73	2090	885.4	893.0	7.6	JTWC (1973)
Rita	2001	25 Oct 78	2128	889.7	892.0	2.3	JTWC (1978)
Joan	2152	28 Aug 59	2088	885.1	891.0	5.9	JTWC (1959)
Elsie	0300	24 Sep 69	2140	891.1	890.0	−1.1	JTWC (1969)
Nancy	0630	12 Sep 61	2130	890.0	890.0	0.0	JTWC (1959)
Wynne	0236	09 Oct 80	2130	890.0	890.0	0.0	JTWC (1980)
Rita	1902	25 Oct 78	2124	889.3	889.0	−0.3	JTWC (1978)
Judy	1921	19 Aug 79	2121	888.9	889.0	0.1	JTWC (1979)
Nancy	2145	12 Sep 61	2103	886.8	889.0	2.2	JTWC (1959)
Nancy	0415	13 Sep 61	2098	886.3	889.0	2.7	JTWC (1959)
Nancy	0045	12 Sep 61	2073	883.4	888.0	4.6	JTWC (1959)
Judy	2145	19 Aug 79	2091	885.5	887.0	1.5	JTWC (1979)
Rita	2027	24 Oct 78	2073	883.4	886.0	2.6	JTWC (1978)
Rita	1415	25 Oct 78	2061	882.0	886.0	4.0	JTWC (1978)
Irma	1555	11 Nov 71	2060	881.9	884.0	2.1	JTWC (1971)
Tip	0837	12 Oct 79	2058	881.7	884.0	2.3	JTWC (1979)
Irma	2200	11 Nov 71	2040	879.6	884.0	4.4	JTWC (1971)
Nancy	0830	13 Sep 61	2130	890.0	882.0	−8.0	JTWC (1959)
Rita	0015	25 Oct 78	2064	882.4	882.0	−0.4	JTWC (1978)
Nora	0330	06 Oct 73	2012	876.4	878.0	1.6	Holliday (1975)
Rita	0317	25 Oct 78	2007	875.8	878.0	2.2	JTWC (1978)
Nora	0015	06 Oct 73	2006	875.7	877.0	1.3	Holliday (1975)
Ida	0500	24 Sep 58	2005	875.6	877.0	1.4	Jordan (1959)
June	0843	19 Nov 75	1984	873.2	876.0	2.8	Holliday (1976)
Tip	0353	12 Oct 79	1944	868.6	870.0	1.4	Dunnavan and Diercks (1979)
Mean			2105	887.0	888.6	1.6	

and increases the SLP by about 2 hPa. Since P_t reflects a balance between vertical mixing and lateral entrainment of moisture on one hand and forced subsidence in the eye on the other, P_{it} calculated with P_t = 700 hPa is inconsistent with both the warming and drying of the eye during N43RF's flight and the visual character of the clouds. In our judgment, P_{it} with P_t = 700 hPa establishes an upper limit for plausible hydrostatic surface pressures.

The pressure from the sounding interpolated to the surface, P_{is}, with T_s = 27°C is nearly as plausible as P_{it} with the shallower moist layer. On the average, elimination of the moist layer lowers the surface pressure by nearly 1 hPa. The IS sounding with T_s = 30°C, which might have resulted from intense subsidence reaching the surface, has extrapolated pressures about 2 hPa lower than P_{is} with T_s = 27°C or 3 hPa below P_{it} with T_s = 27°C and P_t = 825 hPa. In our judgment, this very warm sounding with no moist layer is inconsistent with the observed low clouds in the eye and establishes a lower limit of plausible surface pressures. Coincidentally, this lower limit is 885 hPa, the same value estimated from Jordan's extrapolation with no correction for bias or flight-level pressure error.

The evolution of Gilbert's minimum surface pressure during N43RF's flight can be reconstructed as follows: During the first 4 h that the aircraft spent in Gilbert, the rate of pressure fall accelerated to 5 hPa h^{-1}. The surface pressure reached a calculated minimum value near 888 hPa, based upon both the corrected P_J and P_{it} with P_t = 825 hPa. The average and standard deviation of P_J + 1.6 hPa and the five hydrostatic calculations at 2153 is 888.0 ± 1.8 hPa. The uncertainty in the flight-level pressure increases the standard deviation of the estimated pressure to 1.9 hPa. The average and standard deviation mean that there is about one chance in three that the actual minimum surface pressure in Gilbert lay below 886 or above 890 hPa. The chance that it exceeded 892 hPa is <3%. The central SLP rose from the record minimum on the aircraft's last traverse of the eye. At 2323 UTC, the actual value was probably 1–3 hPa less than 892 hPa, the best estimate based upon measurements, because the aircraft missed the center.

5. Conclusion

We recommend that the meteorological community adopt 888 hPa estimated from N43RF's observation in Gilbert at 2153 UTC on 13 September 1988 at 19°30′N, 83°19′W as the new record minimum sea-level pressure in a hurricane. This pressure is 4 hPa below the previous record for a western-hemisphere tropical cyclone, 892 hPa, set in the Florida Keys Labor Day Hurricane of 1935 (McDonald 1935), but it does not rival the world record, 870 hPa, set in Typhoon Tip of 1979 (Dunnavan and Diercks 1980).

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