# NATIONAL HURRICANE CENTER TROPICAL CYCLONE REPORT

# HURRICANE WILLA

(EP242018)

20–24 October 2018

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National Hurricane Center
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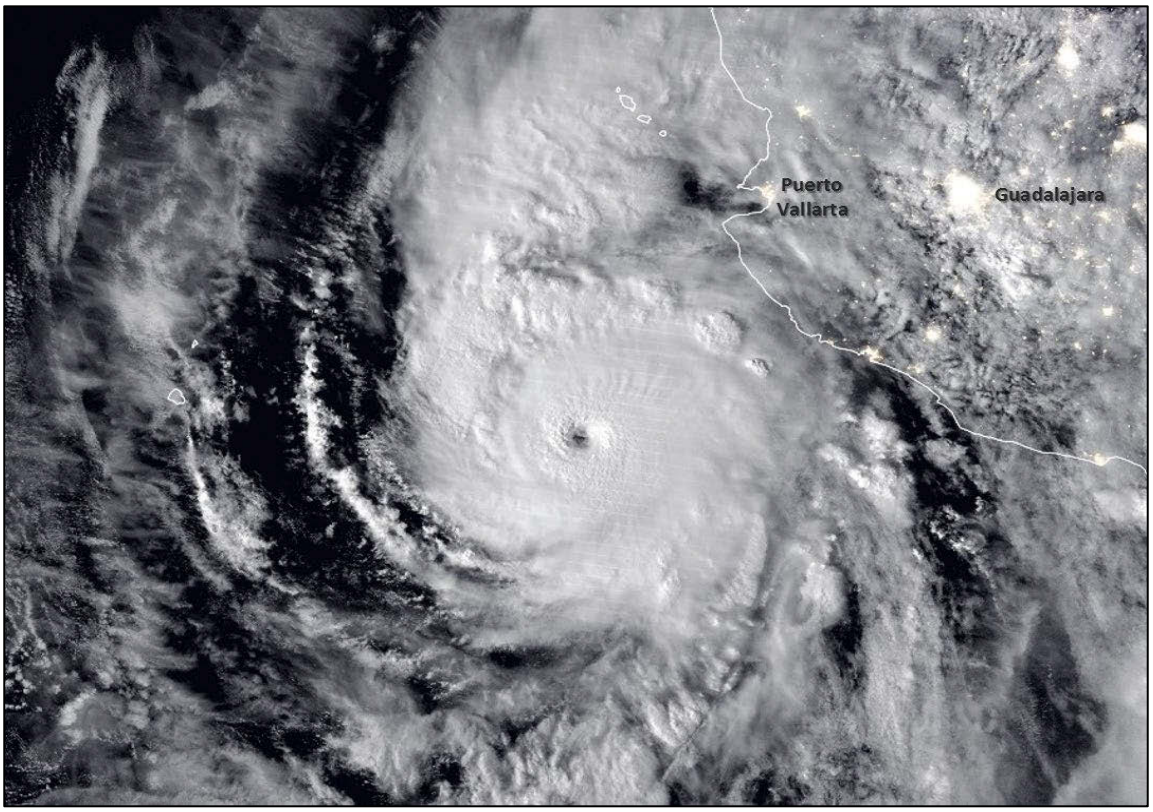


NIGHTTIME VISIBLE IMAGE AT 0850 UTC 22 OCTOBER 2018, SHOWING HURRICANE WILLA NEAR CATEGORY 5 INTENSITY WHEN IT WAS APPROACHING SOUTHWESTERN MEXICO. NOAA-NASA SUOMI NPP SATELLITE IMAGE COURTESY OF NASA.

Willa became a category 5 hurricane (on the Saffir-Simpson Hurricane Wind Scale) before it weakened and made landfall along the west-central coast of Mexico as a category 3 hurricane. In the states of Nayarit and Sinaloa, Willa's heavy rains produced widespread lowland and river flooding along with mudslides that severely damaged and isolated several communities. Four direct deaths occurred as a result of the floodwaters.

# Hurricane Willa

**20–24 OCTOBER 2018**

## SYNOPTIC HISTORY

The tropical wave that subsequently spawned Hurricane Willa moved off the west coast of Africa on 2 October at fairly low latitude around 5°N. The wave initially showed some signs of organization, but the associated convection waned considerably the next day. Intermittent bursts of deep convection developed near a well-defined mid-level circulation center between 4 and 6 October, but all convection was stripped away by strong southwesterly and westerly deep-layer vertical wind shear by 8 October. The wave moved quickly westward at forward speeds of 15–20 kt for the next several days, reaching Central America on 15 October. The wave crossed into the far eastern portion of the North Pacific basin on 16 October, with a significant flare-up of deep convection occurring along the wave axis on 17 October when the disturbance was located over the southern Gulf of Tehuantepec. The intense thunderstorm activity aided in the formation of a broad low pressure system by early on 18 October about 250 n mi southeast of Acapulco, Mexico. Over the next 36 h, the low continued its westward motion and steadily became better defined, and by 0000 UTC 20 October, deep convection had increased enough and became sufficiently organized for the disturbance to be designated a tropical depression when it was centered about 230 n mi south of Manzanillo, Mexico. By late that day, the depression slowed down and turned toward the west-northwest and northwest as the cyclone moved around the southwestern periphery of a deep-layer ridge located over central and southeastern Mexico. The "best track" chart of the tropical cyclone's path is given in Fig. 1, with the wind and pressure histories shown in Figs. 2 and 3, respectively. The best track positions and intensities are listed in Table 1[1].

Convection steadily increased and became better organized over the next 12 h, including the development of a central dense overcast above the center of the small cyclone, and the depression strengthened into a tropical storm by 1200 UTC 20 October when the system was located about 250 n mi south-southwest of Manzanillo. The combination of low 850–200-mb vertical wind shear, a moist mid-level environment, and sea-surface temperatures (SSTs) exceeding 29°C (Fig. 4), in conjunction with Willa's small radius of maximum winds $\leq$ 25 n mi, resulted in an incredible 42-h period of rapid intensification (RI) with the cyclone's winds increasing by 105 kt during that period. During the RI phase, the tropical cyclone moved northward between the ridge over Mexico and an approaching deep-layer trough to its west, remaining 150–170 n mi off the coast of southwestern Mexico. Willa reached hurricane status around 0600 UTC on 21 October, became a major hurricane 12 h later, and achieved its peak intensity of 140 kt by

[1] A digital record of the complete best track, including wind radii, can be found on line at ftp://ftp.nhc.noaa.gov/atcf. Data for the current year's storms are located in the *btk* directory, while previous years' data are located in the *archive* directory.

0600 UTC 22 October when the powerful category 5 hurricane was located about 170 n mi south-southwest of Cabo Corrientes, Mexico (cover photo).

Shortly after reaching peak intensity, Willa began a steady weakening trend due to an an eyewall replacement cycle (ERC) and possibly cold waters (Fig. 4). Data from the SHIPS model suggest that the hurricane moved over a pool of low upper-ocean heat content (UOHC) values of less than 20 kJ $cm^{-2}$, however other UOHC analyses did not indicate a minimum in this area (not shown). Although the depth of the warm water beneath Willa steadily increased after 1200 UTC 22 October according to SHIPS analyses, and southwesterly vertical wind shear remained generally less than 15 kt, the ERC overwhelmed these favorable environmental conditions. The result was steady weakening until about 12 h prior to landfall, with the eye expanding in size from a diameter of around 10 n mi at peak intensity to about 60 n mi by 0043 UTC 23 October (Fig. 5). However, passive microwave satellite imagery during much of this time indicated that Willa maintained a small, remnant inner eyewall (Fig. 5c).

A U.S. Air Force Reserve Unit reconnaissance aircraft investigated Willa the morning of 23 October just prior to the hurricane moving across the Islas Marías archipelago (Fig. 6). Wind and pressure data obtained during the flight confirmed that significant weakening had occurred based on equivalent surface wind speeds of about 100 kt and an estimated central pressure of 963 mb. Concentric eyewalls 16 n mi and 37 n mi in diameter were reported at the beginning of the mission, an indication that the ERC was still ongoing at that time. Toward the conclusion of the flight, however, the ERC had ended, resulting in a relatively large eye that was about 26 n mi wide.

Now moving northeastward around the western periphery of a mid-level ridge located over central Mexico, Willa took aim on the westernmost islands of the Islas Marías archipelago, with the relatively large and ragged eye passing over Isla San Jaunito and Isla María Madre around 1745 UTC 23 October (Fig. 7), bringing sustained hurricane-force winds to the entire archipelago. The tropical cyclone continued its northeastward motion toward southwestern Mexico, making landfall as a category 3 hurricane along the coast near Palmito del Verde, Sinaloa, Mexico, at 0120 UTC 24 October. Increasing southwesterly steering flow ahead of an encroaching deep-layer trough accelerated Willa across southwestern and central Mexico, and the combination of strong southwesterly shear of more than 20 kt (Fig. 4) and mountainous terrain resulted in rapid weakening over the next 12 h. Willa became a tropical storm by 0600 UTC 24 October when the cyclone was located inland about 10 n mi southeast of Durango, Mexico, and dissipated 6 h later when the system was moving over northeastern Mexico. The remnant moisture plume spread northeastward into the coastal plain region of southeastern Texas and southwestern Louisiana, aiding the development of locally heavy rainfall late that day.

## METEOROLOGICAL STATISTICS

Observations in Willa (Figs. 2 and 3) include subjective satellite-based Dvorak technique intensity estimates from the Tropical Analysis and Forecast Branch (TAFB) and the Satellite Analysis Branch (SAB), and objective Advanced Dvorak Technique (ADT) estimates and Satellite

Consensus (SATCON) estimates from the Cooperative Institute for Meteorological Satellite Studies/University of Wisconsin-Madison. Observations also include flight-level, stepped frequency microwave radiometer (SFMR) surface-based winds, and dropwindsonde observations from one flight conducted on 23 October by the 53rd Weather Reconnaissance Squadron of the U.S. Air Force Reserve Command, which yielded two eye penetrations and fix positions. Data and imagery from NOAA polar-orbiting satellites including the Advanced Microwave Sounding Unit (AMSU), the NASA Global Precipitation Mission (GPM), the European Space Agency's Advanced Scatterometer (ASCAT), and Defense Meteorological Satellite Program (DMSP) satellites, among others, were also useful in constructing the best track of Willa.

Ship reports of tropical-storm-force winds associated with Hurricane Willa are given in Table 2.

## *Winds and Pressure*

Hurricane Willa's peak intensity of 140 kt at 0600 UTC 22 October is based on UW-CIMSS SATCON and ADT satellite intensity estimates of T7.0/140 kt, which was coincident with a relatively small eye diameter of 5–10 n mi. The minimum pressure of 925 mb is based on the KZC pressure-wind relationship.

An Air Force Reserve reconnaissance aircraft conducted a mission into Willa's eye between 1400 and 1600 UTC 23 October indicated a central pressure of 963 mb and equivalent surface wind speeds of around 100 kt, with the latter intensity being maintained until landfall (Fig. 2).

It is worth noting that a reconnaissance mission into Willa had been scheduled for the previous day on 22 October 2018, but the mission was aborted shortly after crossing the southwestern coast of Mexico due to the aircraft taking a lightning strike during transit of an outer rain band. The intense electrical surge disabled the nose radar that is used in critical navigation through the intense inner-core region of tropical cyclones, especially in powerful Category 4 hurricanes like Willa was on that particular day.

Willa's eye moved across the two westernmost islands in the Islas Marías archipelago, with the eastern eyewall passing over or very near an automated Mexican Navy weather station on Isla María Madre, Nayarit, Mexico (21.63°N 106.54°W; elevation: 37 m ASL) at 1745 UTC 23 October. A 15-minute-average wind speed of 77 kt (and a gust to 97 kt) was measured at that time, which yields an equivalent 1-minute wind speed of approximately 85 kt at 10-m elevation above sea level after adjusting for both the 15-minute averaging period and the elevation of 37 m. Observations from the Isla María Madre airport and aircraft reconnaissance indicate that Willa produced at least category-2 sustained winds across those two islands, with category-1 sustained winds likely occurring across the remainder of the archipelago (Figs. 6, 7).

The landfall intensity of 100 kt at 0120 UTC 24 October is based on extrapolation of the reconnaissance data and satellite imagery. The landfall pressure of 968 mb is based on *in situ* pressure data of 968 mb measured around 0129 UTC by Josh Morgerman of the *iCyclone.com* storm chasing team which was located near the coast at Palmito del Verde, Sinaloa, Mexico (Fig. 8). His eyewitness report indicates that Willa's eye took about 30 minutes to pass over Palmito

del Verde. Given that the hurricane's forward speed at landfall was 11–12 kt suggests that the along-track width of the eye was about 6 n mi. Location C likely experienced Willa's strongest winds due to its position within the southeastern eyewall. It is also worth noting that an eyewall mesocyclone probably occurred at location B around 0145 UTC (724 PM MDT) based on the 5-mb pressure drop noted in the pressure trace (see inset, Fig. 8). This small-scale phenomenon is rarely observed with standard meteorological instruments.

### *Storm Surge*

No official storm surge heights are available. However, reports from the *iCyclone* storm chasing team and the media indicate that a significant storm surge, along with large battering waves, occurred in the landfall region between Isla del Bosque and Teacapan in the Mexican state of Sinaloa. The high surf breached the 8-ft seawall in the Malecón district of Teacapan, Mexico.

### *Rainfall and Flooding*

Widespread heavy rainfall in excess of 4 inches caused significant inland freshwater floods and major river flooding across much of the Mexican states of Colima, Durango, Jalisco, Michoacán, Nayarit, and Sinaloa. Rainfall totals exceeding 10 inches were reported in localized areas of the Mexican states of Jalisco and Nayarit. The highest rainfall amounts reported were 15.39 inches and 13.17 inches, observed at Milpillas San Andrés and Cihuatlán, Mexico, respectively (Fig. 9).

The remnants of Willa also produced locally heavy rainfall late on 24 October and early 25 October across portions of southeastern Texas and extreme southern Louisiana, with the highest rainfall totals confined mainly to the immediate coastal areas of southeastern Texas. The Houston metropolitan area received rainfall amounts exceeding 4 inches in Santa Fe, Dickinson, and Bayou Vista in Galveston County. At the Galveston Scholes International Airport (KGLS), 4.90 inches of rain was measured, while 4.36 inches of rainfall was observed in League City, Texas.

## CASUALTY AND DAMAGE STATISTICS

Willa caused 4 direct deaths[2] along with significant damage to homes and infrastructure, which resulted in more than 100,000 people being displaced from their homes according to media reports and the Government of Mexico.

[2] Deaths occurring as a direct result of the forces of the tropical cyclone are referred to as "direct" deaths. These would include those persons who drowned in storm surge, rough seas, rip currents, and freshwater floods. Direct deaths also include casualties resulting from lightning and wind-related events (e.g., collapsing structures). Deaths occurring from such factors as heart attacks, house fires, electrocutions from downed power lines, vehicle accidents on wet roads, etc., are considered "indirect" deaths.

The four deaths occurred in the state of Nayarit. Three people drowned in the Rio San Pedro, and the other individual was washed downstream by floodwaters and was found by local fishermen.

Reports from the media and the *iCyclone.com* storm chasing team indicate that some buildings along with utility poles and other infrastructure incurred modest damage along and close to where Willa's eye made landfall along the Mexican coast, especially between Isla del Bosque and Teacapan. The seawall in the Malecón district of Teacapan was damaged by Willa's storm surge along with large waves that battered the harbor area (Figs. 10 and 11).

Heavy rainfall and hurricane-force wind gusts, along with floods and mudslides, devastated the municipalities of Escuinapa, Rosario, Los Sandovales, and Acaponeta. Large stretches of roads were washed out and even some bridges collapsed (Figs. 12–14). In addition to the devastating freshwater flooding, Willa's strong winds knocked down numerous trees that took down power lines and blocked roads across those states. The hospital and the municipal water system were damaged in Escuinapa. More than 96,000 people were left without power in the states of Sinaloa, Nayarit, Durango, and Michoacán.

In addition to the damage caused by Willa, the hurricane also forced the airport in Mazatlan to close, which disrupted travel and hindered the evacuation of tourists. Several oil tankers were unable to unload fuel at the ports in Manzanillo and Tuxpan due to inclement weather associated with Willa's outer rain bands. Pemex — the state oil company of Mexico — was forced to close a major pipeline that transports oil to Guadalajara due to the effects of Willa. The pipeline closure, along with delay in unloading fuel from tankers, caused a fuel shortage that affected more than 500 gas stations across southwestern Mexico.

Total damage costs in Mexico are estimated to be at least USD$536 million, with the overwhelming majority of those losses, USD$510 million, occurring in the state of Narayit.

In the United States, the remnants of Willa produced locally heavy rainfall across portions of southeastern Texas and extreme southern Louisiana on 24 October. These rains fell on ground that was already saturated from recent significant rainfall events, resulting in extensive flooding of roads and highways across the southern portion of the Houston-Galveston metropolitan area, especially in League City, Hitchcock, and Bayou Vista in Galveston County.

## FORECAST AND WARNING CRITIQUE

The genesis of Willa was extremely well forecast (Table 3). The tropical wave from which Willa developed was introduced in the Tropical Weather Outlook in the 120-h (5-day) period with a low chance (<40%) of genesis 150 h prior to formation as a tropical cyclone. The 120-h probabilities were increased to the medium (40–60%) and high (>60%) categories 132 h and 108 h, respectively, prior to the development of a tropical depression. The disturbance from which Willa formed was given a low chance of development in the 48-h (2-day) forecast period 90 h before genesis occurred. The 48-h probabilities were increased to the medium and high categories 84 h and 66 h, respectively, prior to the formation of Willa.

A verification of NHC official track forecasts (OFCL) for Willa is given in Table 4a. Official forecast track errors were lower than the mean official errors for the previous 5-yr period at 12 h and 24 h, and above average after that time, particularly at 72 h and 96 h; however, the sample size is small at those times. The reasons for the larger-than-normal errors at 72 h were an initial westward track bias (which was corrected within 12 h after the first advisory was issued) and a slow forward speed bias. Despite the large overall errors, the cross-track errors around the landfall location were remarkably small, consisting of only a 30-n mi spread. A homogeneous comparison of the official track errors with selected guidance models is given in Table 4b. OFCL forecasts were bested by nearly all of the available model guidance at all time periods, including the GFS (GFSI), the GEFS ensemble-mean (AEMI), as well as the simple consensus models TVCE, TVCX, TCON, and GFEX, due to those models having a much smaller track speed bias. In contrast, the ECMWF (EMXI) and UKMET (EGRI) models, especially the latter model, had errors larger than OFCL at nearly every forecast time. This is significant since those two models comprise 40% and 60% of the multi-model consensus aids TVCE and TVCX, respectively. The more sophisticated corrected-consensus models HCCA and FSSE (Florida State Superensemble) had errors that were comparable to OFCL.

A verification of NHC OFCL intensity forecasts for Willa is given in Table 5a. OFCL errors were greater than the mean official errors for the previous 5-yr period at all time periods. These large errors were due to a combination of a low bias early in the forecast cycle during the rapid spin-up of the hurricane and a high bias during Willa's weakening phase. Despite the large intensity errors, the OFCL intensity forecasts were quite accurate in forecasting rapid intensification to occur beginning with the first advisory that was issued. Subsequent forecasts maintained the RI trend, just not at the incredible rate that Willa intensified, with the cyclone strengthening 60 kt in 24 h compared to the RI threshold of 30 kt in 24 h. This is a very challenging forecast scenario, since current model guidance struggles to predict many RI events, much less such extreme ones. A homogeneous comparison of the official intensity errors with selected guidance models is given in Table 5b. Although the OFCL intensity errors were higher than average, they were still better than all of the individual intensity aids through 48 h. However, the HCCA and FSSE corrected consensus aids out-performed OFCL at 24-48 h and 24-36 h, respectively. At 72 h, OFCL was beaten by most of the guidance, with the exception of the HWRF (HWFI) and HMON (HMNI) regional hurricane models and the global models GFSI and EMXI, which did not perform well for Willa.

Watches and warnings associated with Willa are given in Table 6.

# ACKNOWLEDGMENTS

Josh Morgerman and his chase team from *iCyclone.com* provided important detailed pressure observations and eyewitness accounts of conditions along the southwestern coast of Mexico during Willa's landfall between Isla del Bosque and Teacapan, especially at the landfall point of Palmito del Verde. The Servicio Meteorológico Nacional (Mexican Meteorological Service) provided rainfall data and damage reports for Mexico. Special thanks to Senior Hurricane Specialist John Cangialosi for preparing the 'best track' figure.

Table 1. Best track for Hurricane Willa, 20–24 October 2018.

| Date/Time (UTC) | Latitude (°N) | Longitude (°W) | Pressure (mb) | Wind Speed (kt) | Stage |
|---|---|---|---|---|---|
| 19 / 0000 | 14.2 | 98.9 | 1007 | 25 | low |
| 19 / 0600 | 14.5 | 100.4 | 1007 | 25 | " |
| 19 / 1200 | 14.7 | 101.7 | 1007 | 25 | " |
| 19 / 1800 | 14.8 | 102.8 | 1007 | 25 | " |
| 20 / 0000 | 14.8 | 103.6 | 1007 | 30 | tropical depression |
| 20 / 0600 | 14.7 | 104.5 | 1006 | 30 | " |
| 20 / 1200 | 14.9 | 105.1 | 1005 | 35 | tropical storm |
| 20 / 1800 | 15.1 | 105.5 | 1001 | 45 | " |
| 21 / 0000 | 15.5 | 105.9 | 996 | 55 | " |
| 21 / 0600 | 16.0 | 106.3 | 987 | 70 | hurricane |
| 21 / 1200 | 16.4 | 106.6 | 975 | 85 | " |
| 21 / 1800 | 16.8 | 106.9 | 962 | 100 | " |
| 22 / 0000 | 17.5 | 107.1 | 945 | 120 | " |
| 22 / 0600 | 17.9 | 107.1 | 925 | 140 | " |
| 22 / 1200 | 18.7 | 107.2 | 928 | 135 | " |
| 22 / 1800 | 19.4 | 107.2 | 934 | 130 | " |
| 23 / 0000 | 20.2 | 107.2 | 943 | 120 | " |
| 23 / 0600 | 20.6 | 107.2 | 952 | 110 | " |
| 23 / 1200 | 21.1 | 107.1 | 960 | 105 | " |
| 23 / 1800 | 21.7 | 106.7 | 965 | 100 | " |
| 24 / 0000 | 22.5 | 106.0 | 968 | 100 | " |
| 24 / 0600 | 23.8 | 104.6 | 990 | 45 | tropical storm |
| 24 / 1200 | | | | | dissipated over Mexico |
| 24 / 0120 | 22.7 | 105.8 | 968 | 100 | landfall near Palmito del Verde, Sinaloa state, Mexico |
| 22 / 0600 | 17.9 | 107.1 | 925 | 140 | minimum pressure and maximum intensity |

Table 2. Selected ship reports with winds of at least 34 kt for Hurricane Willa, 20–24 October 2018.

| Date/Time (UTC) | Ship call sign | Latitude (°N) | Longitude (°W) | Wind dir/speed (kt) | Pressure (mb) |
|---|---|---|---|---|---|
| 21 / 1500 | VRCY8 | 19.0 | 104.9 | 110 / 40 | 1011.0 |
| 22 / 0000 | A8SI8 | 19.7 | 106.2 | 120 / 36 | 1017.0 |

Table 3. Number of hours in advance of formation associated with the first NHC Tropical Weather Outlook forecast in the indicated likelihood category. Note that the timings for the “Low” category do not include forecasts of a 0% chance of genesis.

| | Hours Before Genesis | |
|---|---|---|
| | 48-Hour Outlook | 120-Hour Outlook |
| Low (<40%) | 90 | 150 |
| Medium (40%-60%) | 84 | 132 |
| High (>60%) | 66 | 108 |

Table 4a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) track forecast errors (n mi) for Hurricane Willa, 20–24 October 2018. Mean errors for the previous 5-yr period are shown for comparison. Official errors that are smaller than the 5-yr means are shown in boldface type.

| | Forecast Period (h) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 12 | 24 | 36 | 48 | 72 | 96 | 120 |
| OFCL | **19.6** | **31.9** | 47.5 | 66.0 | 168.9 | 350.2 | |
| OCD5 | 37.7 | 71.7 | 110.4 | 177.4 | 353.4 | 579.3 | |
| Forecasts | 16 | 14 | 12 | 10 | 6 | 2 | |
| OFCL (2013-17) | 21.8 | 33.2 | 43.0 | 53.9 | 80.7 | 111.1 | 150.5 |
| OCD5 (2013-17) | 34.9 | 70.7 | 109.1 | 146.1 | 213.8 | 269.0 | 339.7 |

Table 4b. Homogeneous comparison of selected track forecast guidance models (in n mi) for Hurricane Willa, 20–24 October 2018. Errors smaller than the NHC official forecast are shown in boldface type. The number of official forecasts shown here will generally be smaller than that shown in Table 4a due to the homogeneity requirement.

| Model ID | Forecast Period (h) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 12 | 24 | 36 | 48 | 72 | 96 | 120 |
| OFCL | 15.9 | 30.4 | 42.5 | 64.5 | 142.4 | | |
| OCD5 | 27.1 | 49.0 | 88.7 | 140.0 | 309.2 | | |
| GFSI | **14.2** | 31.2 | **40.1** | **40.3** | **87.8** | | |
| EMXI | 17.8 | **30.3** | 45.3 | 82.5 | 147.8 | | |
| EGRI | 23.3 | 51.6 | 93.8 | 151.3 | 312.9 | | |
| CMCI | 33.1 | 46.9 | 78.9 | 130.7 | 261.1 | | |
| NVGI | 23.6 | 44.3 | 63.8 | 66.4 | **126.5** | | |
| AEMI | **12.7** | **24.7** | **28.3** | **30.7** | **65.2** | | |
| HWFI | 18.8 | 30.4 | 52.3 | 73.4 | **121.3** | | |
| HMNI | 16.7 | **23.7** | **29.1** | **45.3** | **43.7** | | |
| GFEX | **15.2** | **29.1** | **38.7** | **53.8** | **72.2** | | |
| TCON | **12.8** | **27.4** | 51.2 | 80.8 | **134.5** | | |
| TVCE | **15.2** | **28.7** | **41.6** | **61.0** | **114.8** | | |
| TVCX | **15.5** | 30.6 | 43.4 | 69.6 | **141.1** | | |
| HCCA | **15.5** | 32.7 | 44.8 | 74.5 | **140.2** | | |
| FSSE | 17.1 | 31.4 | **39.2** | 64.9 | **127.6** | | |
| TABD | **14.0** | **28.3** | 48.8 | **42.2** | **101.5** | | |
| TABM | 18.2 | **24.7** | **34.8** | **32.3** | **77.3** | | |
| TABS | 30.1 | 52.5 | 71.7 | 79.9 | **115.1** | | |
| Forecasts | 12 | 10 | 9 | 6 | 3 | | |

Table 5a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) intensity forecast errors (kt) for Hurricane Willa, 20–24 October 2018. Mean errors for the previous 5-yr period are shown for comparison. Official errors that are smaller than the 5-yr means are shown in boldface type.

| | Forecast Period (h) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 12 | 24 | 36 | 48 | 72 | 96 | 120 |
| OFCL | 9.1 | 17.1 | 21.2 | 22.5 | 20.0 | 32.5 | |
| OCD5 | 16.8 | 28.9 | 38.8 | 49.3 | 47.5 | 30.5 | |
| Forecasts | 16 | 14 | 12 | 10 | 6 | 2 | |
| OFCL (2013-17) | 5.8 | 9.6 | 11.8 | 13.2 | 15.1 | 15.1 | 14.6 |
| OCD5 (2013-17) | 7.6 | 12.4 | 15.6 | 17.7 | 19.8 | 20.8 | 19.6 |

Table 5b. Homogeneous comparison of selected intensity forecast guidance models (in kt) for Hurricane Willa, 20–24 October 2018. Errors smaller than the NHC official forecast are shown in boldface type. The number of official forecasts shown here will generally be smaller than that shown in Table 5a due to the homogeneity requirement.

| Model ID | Forecast Period (h) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 12 | 24 | 36 | 48 | 72 | 96 | 120 |
| OFCL | 9.6 | 17.1 | 18.0 | 12.5 | 15.0 | | |
| OCD5 | 18.1 | 29.3 | 36.4 | 40.2 | 37.5 | | |
| HWFI | 13.1 | 19.0 | 23.4 | 25.0 | 16.8 | | |
| HMNI | 15.2 | 23.2 | 23.7 | 21.5 | 22.2 | | |
| HCCA | 11.3 | **16.4** | **17.8** | **12.2** | **7.5** | | |
| FSSE | 12.2 | **16.0** | **17.9** | 17.0 | **10.2** | | |
| DSHP | 12.6 | 19.0 | 21.9 | 20.0 | **13.5** | | |
| LGEM | 12.8 | 20.8 | 29.2 | 28.5 | **13.5** | | |
| IVCN | 14.4 | 19.0 | 22.7 | 20.1 | **11.8** | | |
| ICON | 13.2 | 19.2 | 22.9 | 22.6 | **13.2** | | |
| GFSI | 15.6 | 23.7 | 27.5 | 24.4 | 20.5 | | |
| EMXI | 23.4 | 38.8 | 49.0 | 48.4 | 43.2 | | |
| Forecasts | 14 | 12 | 10 | 8 | 4 | | |

Table 6. Watch and warning summary for Hurricane Willa, 20–24 October 2018.

| Date/Time (UTC) | Action | Location |
|---|---|---|
| **21 / 1500** | Tropical Storm Watch issued | Playa Perula to San Blas |
| **21 / 1500** | Hurricane Watch issued | San Blas to Mazatlan |
| **21 / 2100** | Tropical Storm Watch issued | Mazatlan to Bahia Tempehuaya |
| **22 / 0300** | Tropical Storm Watch changed to Tropical Storm Warning | Playa Perula to San Blas |
| **22 / 0300** | Tropical Storm Watch changed to Tropical Storm Warning | Mazatlan to Bahia Tempehuaya |
| **22 / 0300** | Hurricane Watch changed to Hurricane Warning | San Blas to Mazatlan |
| **22 / 0300** | Hurricane Warning issued | Islas Marias |
| **24 / 0300** | Hurricane Warning discontinued | Islas Marias |
| **24 / 0600** | Tropical Storm Warning discontinued | All |
| **24 / 0600** | Hurricane Warning discontinued | All |

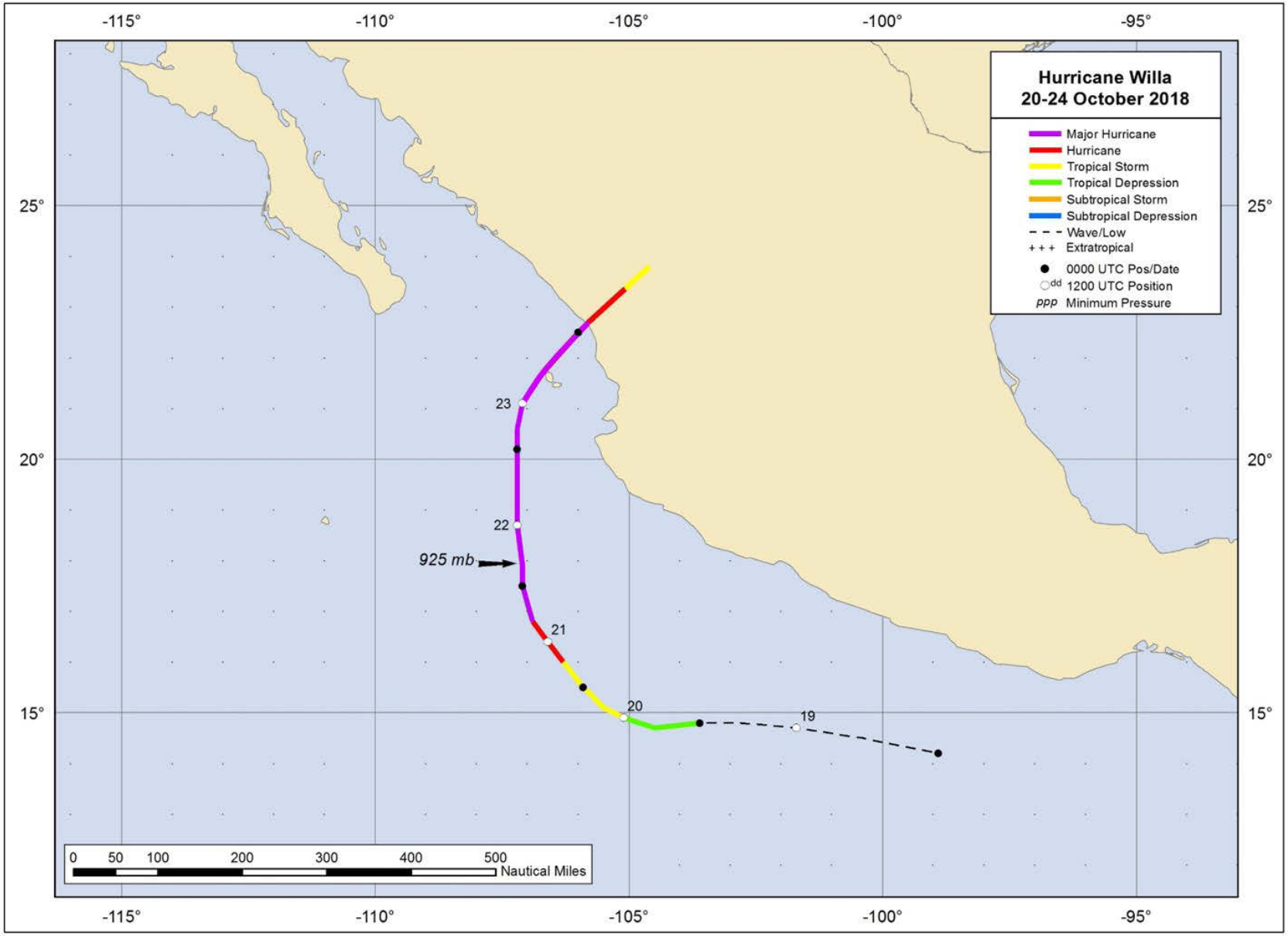


Figure 1. Best track positions for Hurricane Willa, 20–24 October 2018.

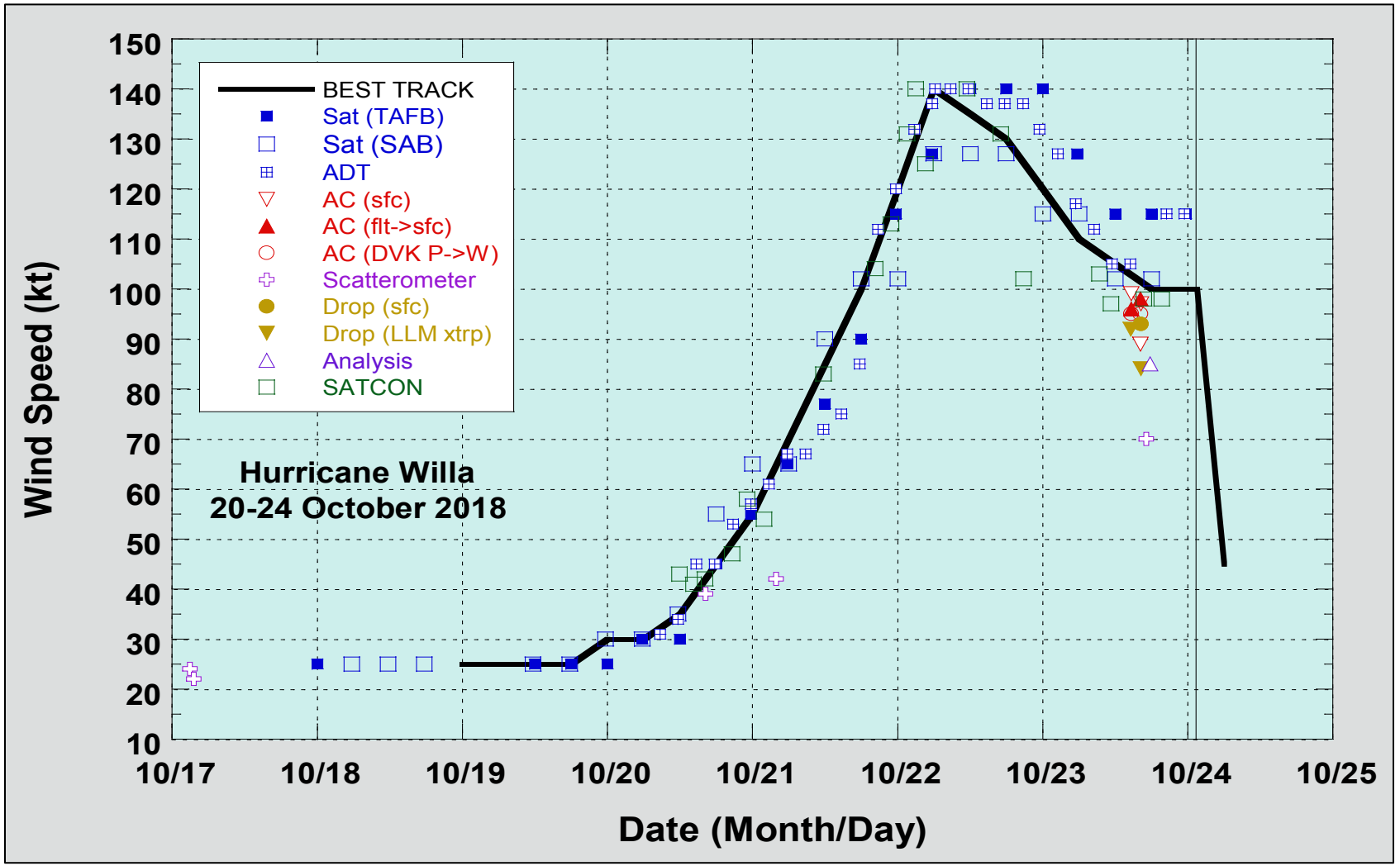


Figure 2. Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Willa, 20–24 October 2018. Aircraft observations have been adjusted for elevation using a 90% adjustment factor for observations from 700 mb. Dropwindsonde observations include actual 10 m winds (sfc), as well as surface estimates derived from the mean wind over the lowest 150 m of the wind sounding (LLM). Advanced Dvorak Technique estimates represent the Current Intensity at the nominal observation time. SATCON intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies. Dashed vertical lines correspond to 0000 UTC, and the solid vertical line corresponds to landfall along the coast of Mexico.

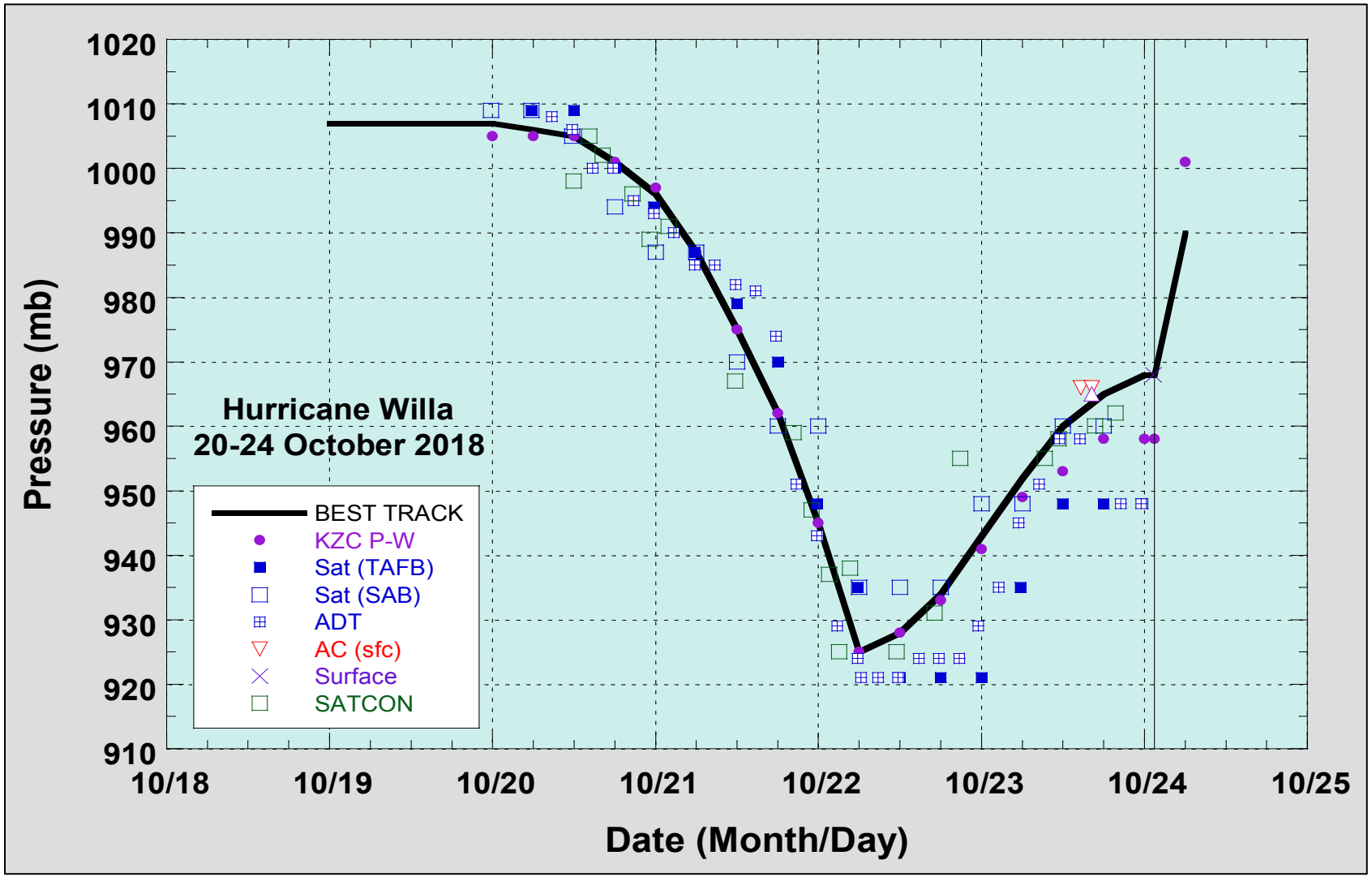


Figure 3. Selected pressure observations and best track minimum central pressure curve for Hurricane Willa, 20–24 October 2018. Advanced Dvorak Technique estimates represent the Current Intensity at the nominal observation time. SATCON intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies. KZC P-W refers to pressure estimates derived using the Knaff-Zehr-Courtney pressure-wind relationship. Dashed vertical lines correspond to 0000 UTC, and the solid vertical line corresponds to landfall along the coast of Mexico along the coast of Mexico.

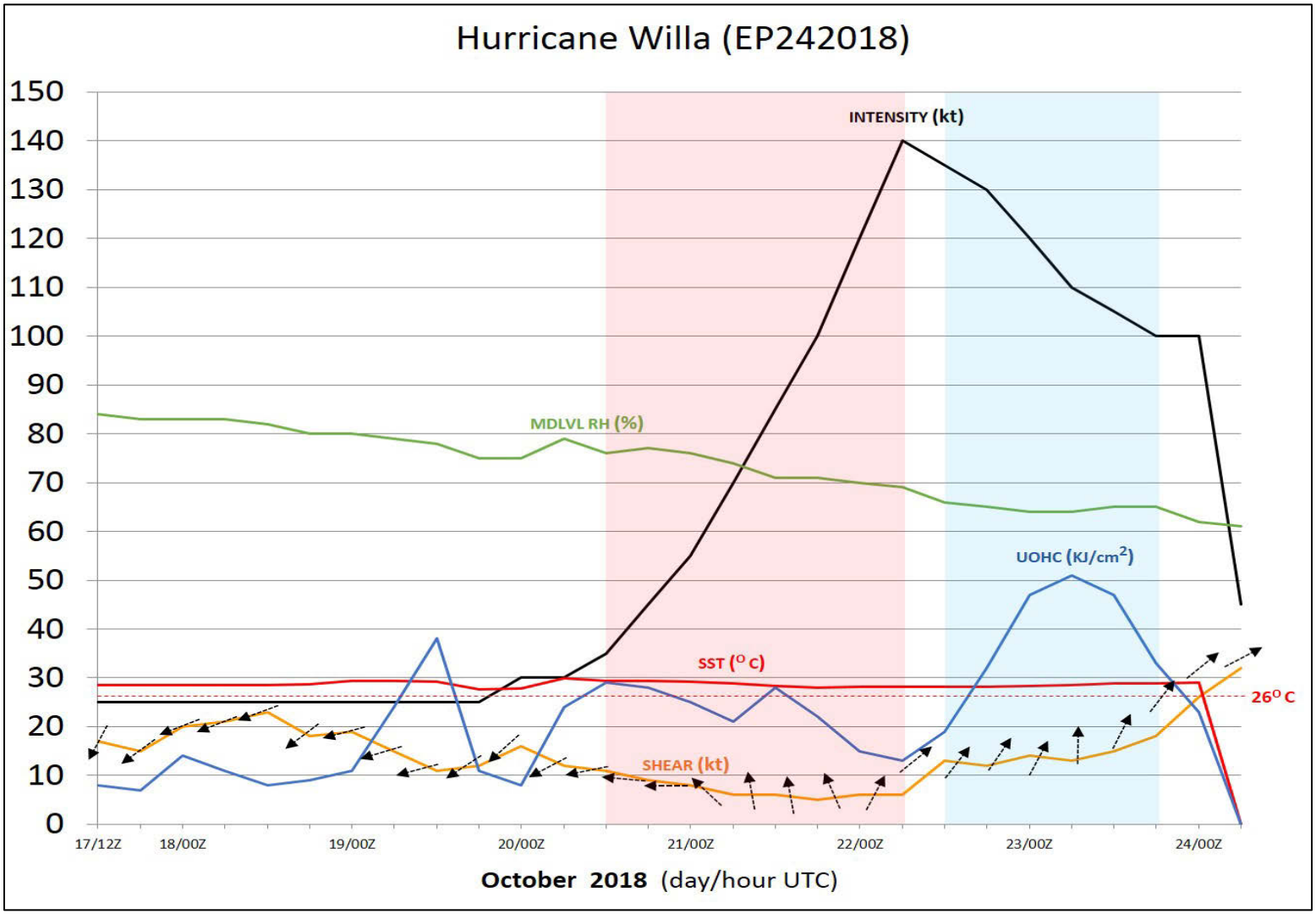


Figure 4. Graph of Hurricane Willa's actual intensity versus GFS-based SHIPS model analyzed environmental parameters: 850−200-mb vertical wind shear (**SHEAR**, kt), sea-surface temperature (**SST**, °C), upper-ocean heat content (**UOHC**, kJ $cm^{-2}$), and 700−500-mb average relative humidity (**MDLVLRH**, percent). Direction of vertical wind shear vectors (black dashed arrows) is relative to true north, with north being at the top of the page. Time period covered is from 1200 UTC 17 October to 0600 UTC 24 October 2018, which includes the rapid intensification phase (red shading) and the eyewall replacement cycle (blue shading).

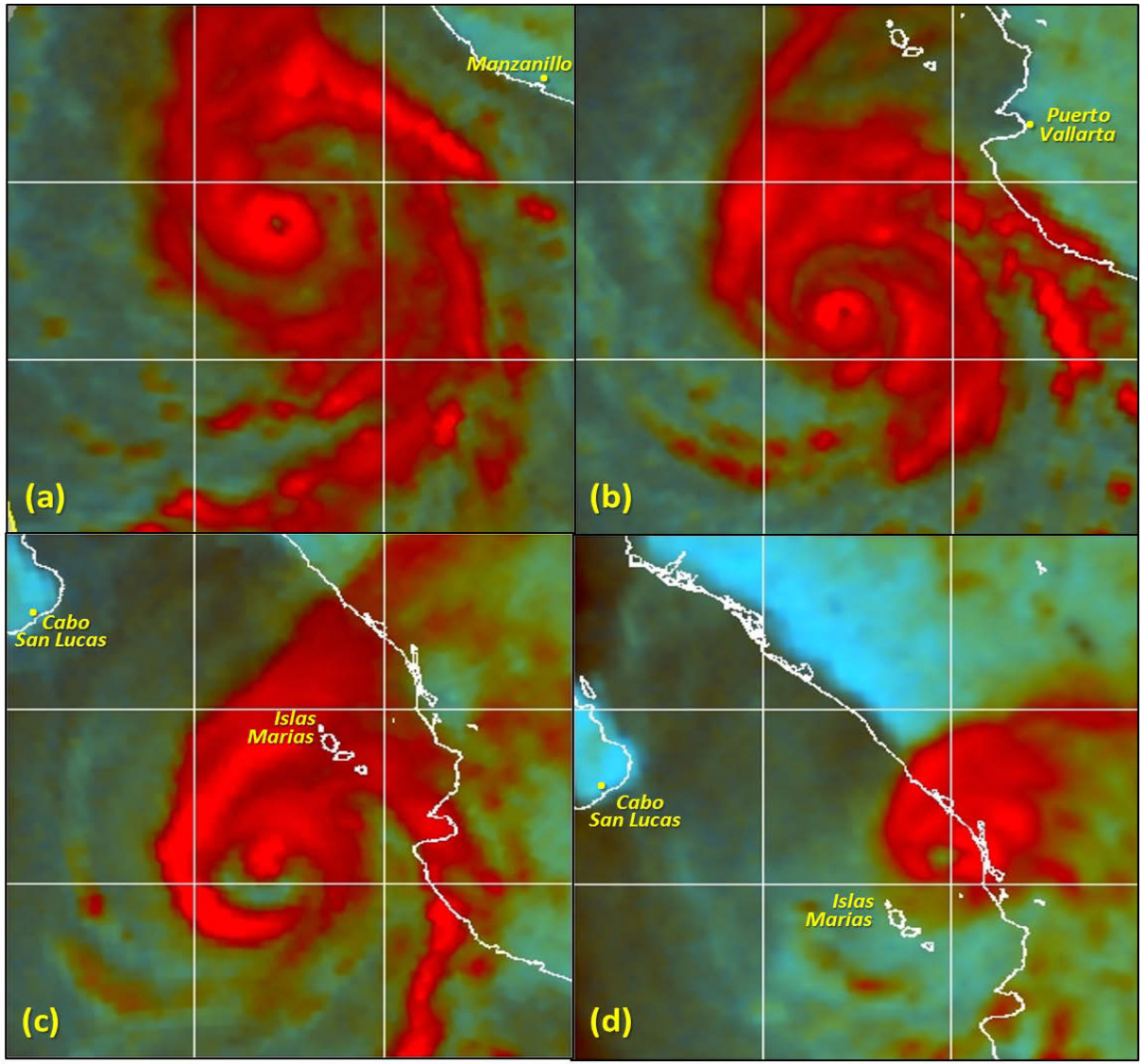


Figure 5. Passive microwave satellite images showing the evolution of Hurricane Willa's eyewall replacement cycle: (a) 0113 UTC 22 October SSMI/S 91-GHz, Willa near peak intensity of 140 kt associated with small eye; (b) 1058 UTC 22 October SSMI/S 91- GHz, beginning of ERC; (c) 0049 UTC 23 October SSMI/S 91-GHz, full ERC underway with a small inner eyewall still intact; (d) 2158 UTC 23 October SSMI 85-GHz, ERC completed, resulting in larger eye diameter.

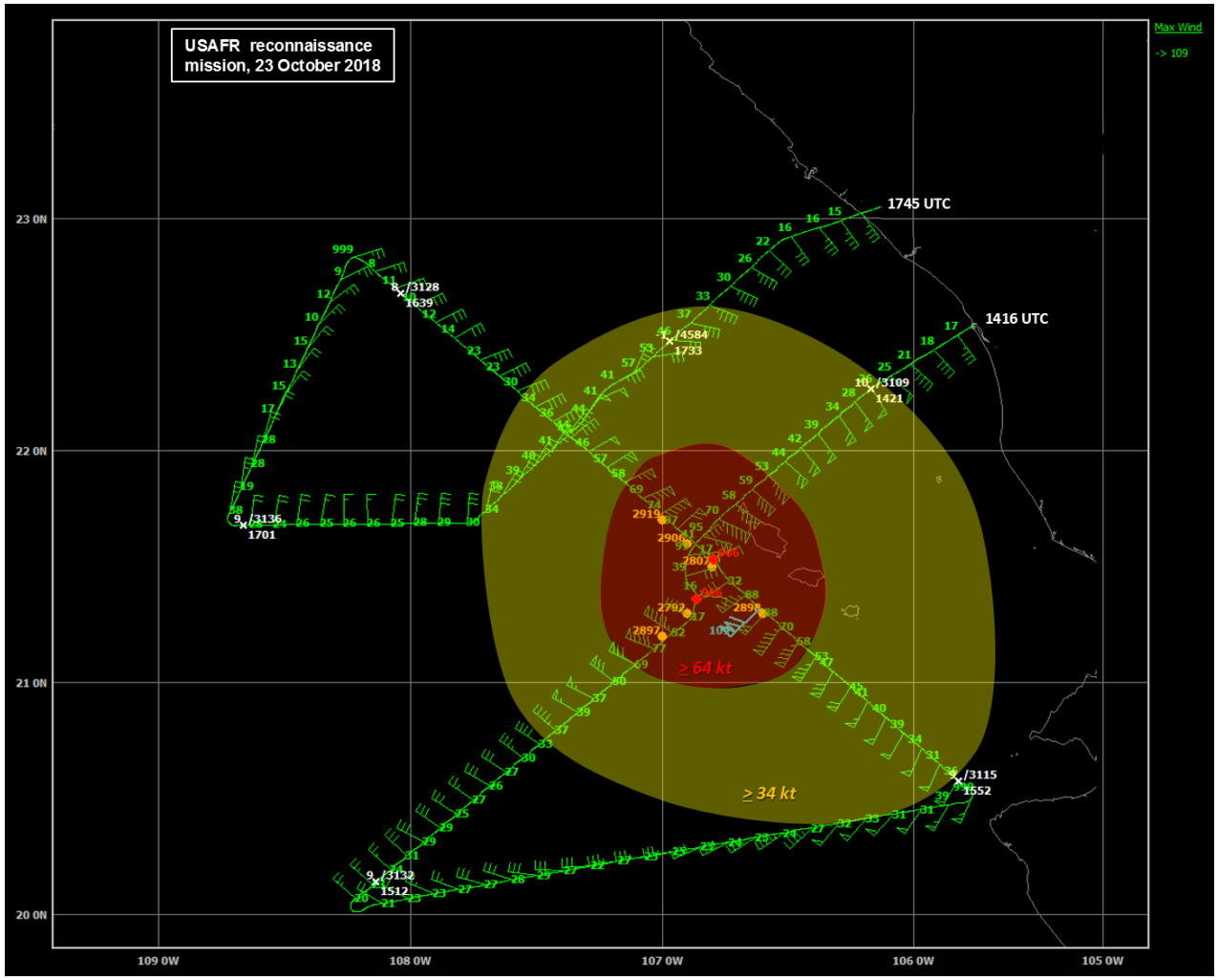


Figure 6. Flight-track of USAFR WC-130 aircraft (AF309) over water during reconnoiter of Willa from 1416-1745 UTC on 23 October 2018 as the hurricane was approaching the Isla Marías archipelago. Flight-level winds (kt) are indicated by the green wind barbs and SFMR surface winds (kt) are shown in green text next to the wind barbs. The peak 700-mb flight-level wind was 109 kt and the peak SFMR surface wind speed was 99 kt during the mission. Analyses of estimated sustained surface-based tropical-storm-force winds (≥34 kt) are indicated by the yellow-shaded region and hurricane-force winds (≥64 kt) are indicated by the red-shaded region.

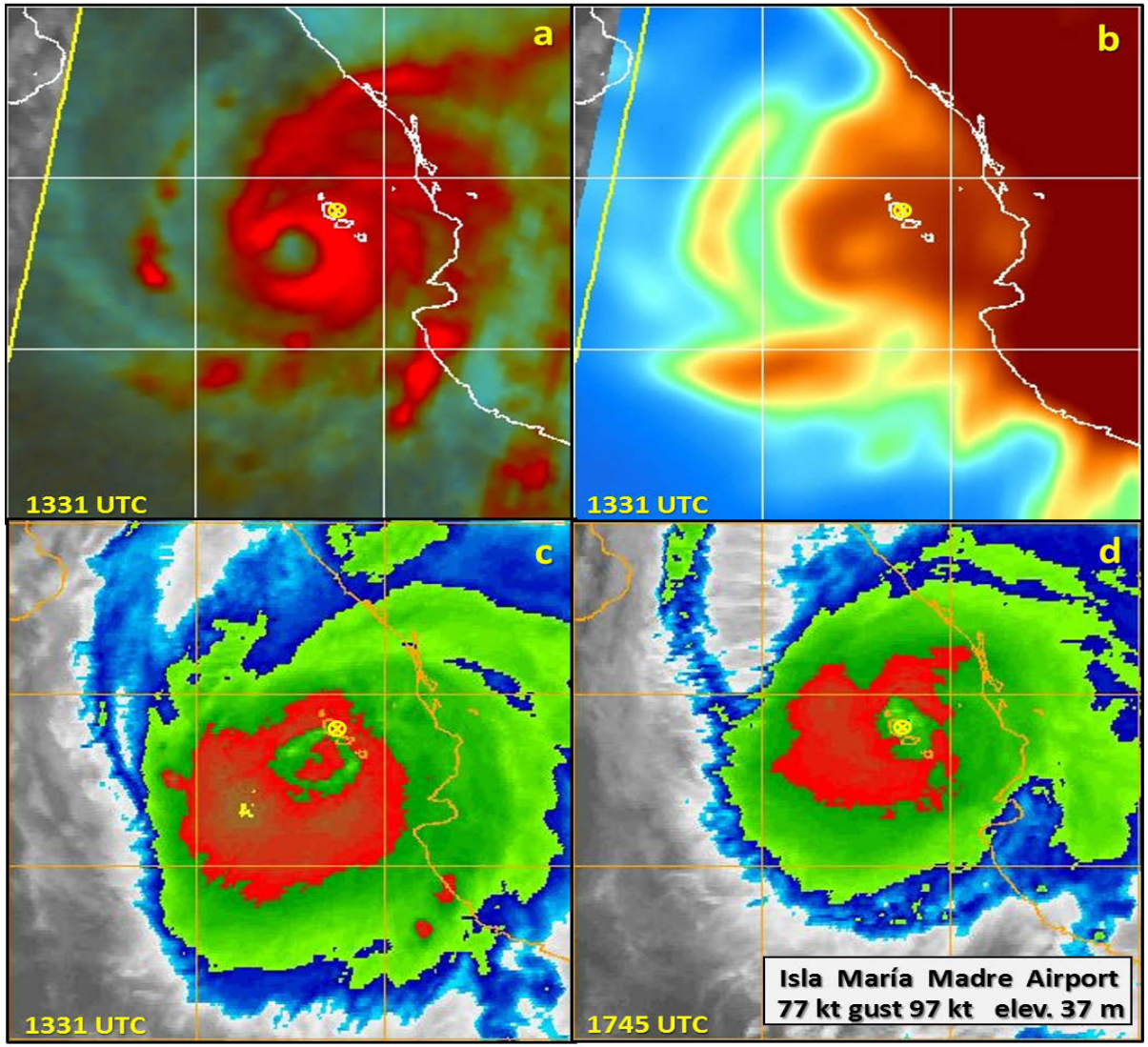


Figure 7. Passive microwave and infrared (IR) satellite mosaic of Hurricane Willa's ragged eye passing over the westernmost islands off the Isla María archipelago on 23 October at (a) 1331 UTC SSMI/S 91-GHz, (b) 1331 UTC SSMI/S 37-GHz-H, (c) 1331 UTC GOES-15 color-enhanced IR, and (d) 1745 UTC GOES-15 color-enhanced IR. Eye passage near the Isla María Madre airport (yellow circled-X) occurred around 1745 UTC (d), resulting in a 15-minute-average wind speed of 77 kt and a gust to 97 kt.

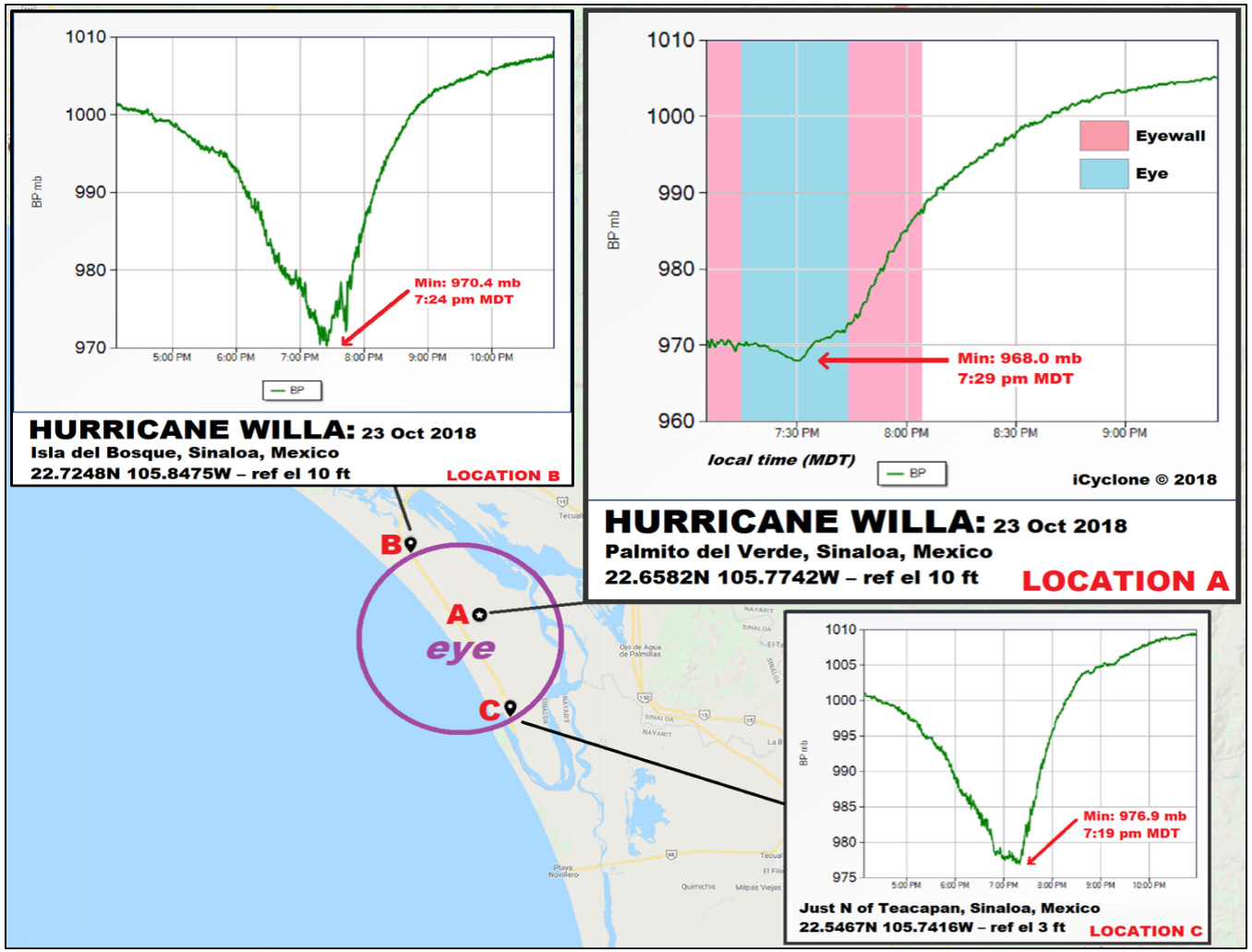


Figure 8. Hurricane Willa landfall with center of the eye crossing the coast near Palmito del Verde, Sinaloa, Mexico (location A), around 0120 UTC 24 October 2018 based on surface pressure data and eyewitness accounts from the *iCyclone.com* storm chasing team. Complete eye passage occurred between 0115–0144 UTC 24 October 2018 at location A. Location C likely experienced the strongest winds due to its position in/near the southeastern eyewall. Note: add 6 h to local MDT to convert to UTC. Graphic courtesy of Josh Morgerman, *iCyclone.com*.

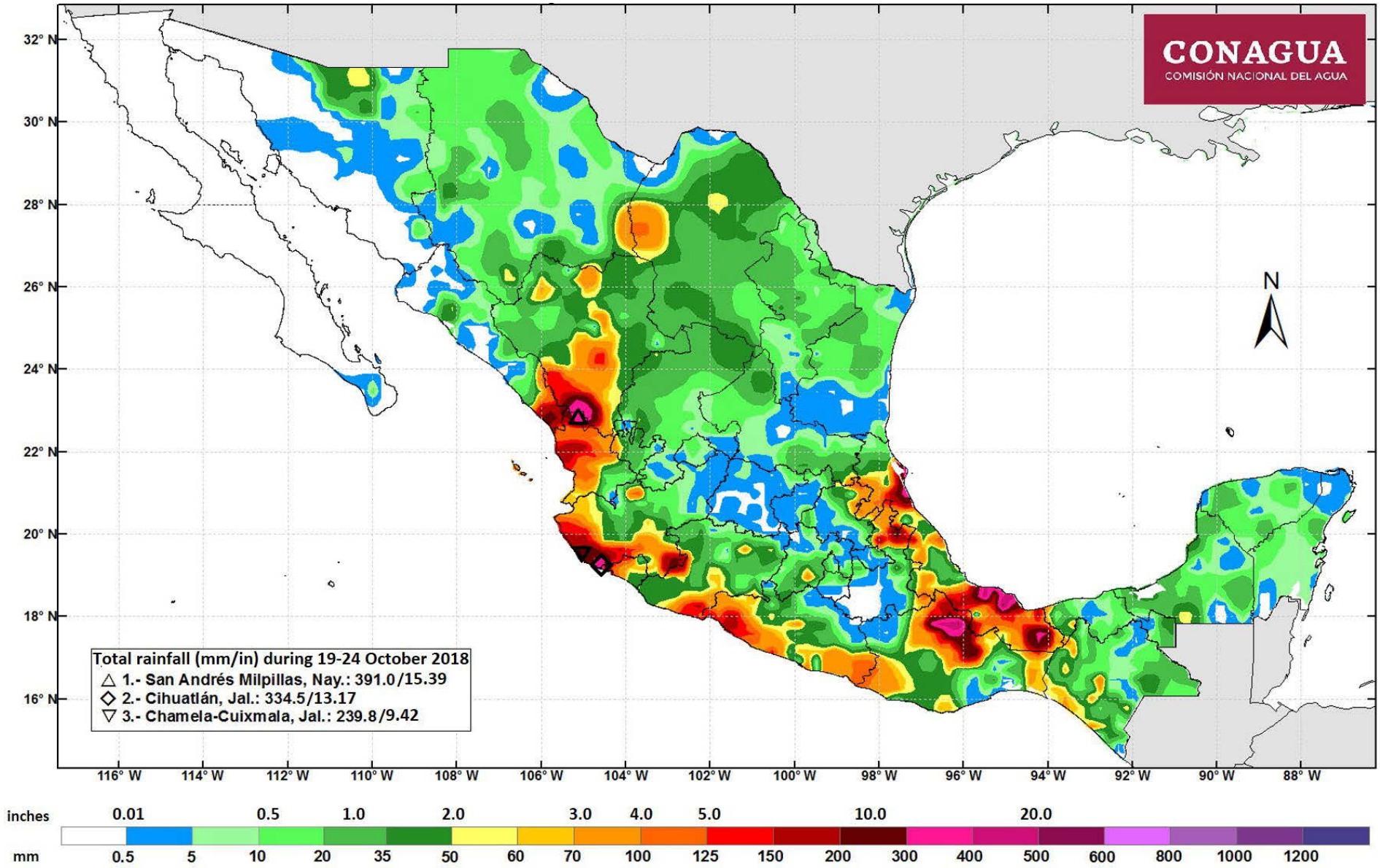


Figure 9. Total rainfall (mm/inches) during the period 19–24 October 2018 when Willa was a disturbance and a tropical cyclone. Map courtesy of the Servicio Meteorológico Nacional (Mexican Meteorological Service).

Figure 10. Damage to the seawall in the Malecón district of Teacapan, Mexico, where the eastern eyewall of Willa accompanied by the strongest winds and highest storm surge likely occurred – (left) viewing southeast along the coast and (right) viewing northwest along the coast. Images taken on 24 October 2018 courtesy of Josh Morgerman, *iCyclone.com*.

Figure 11. Damage to the promenade in the Malecón district of Teacapan, Mexico – (left) viewing southeast along the coast and (right) viewing northwest along the coast. Images taken on 24 October 2018 courtesy of Josh Morgerman, *iCyclone.com*.

Figure 12. Bridge collapse and highway eroded over the Rio Acaponeta in Nariyat state, Mexico. Picture courtesy of *Informador.mx*.

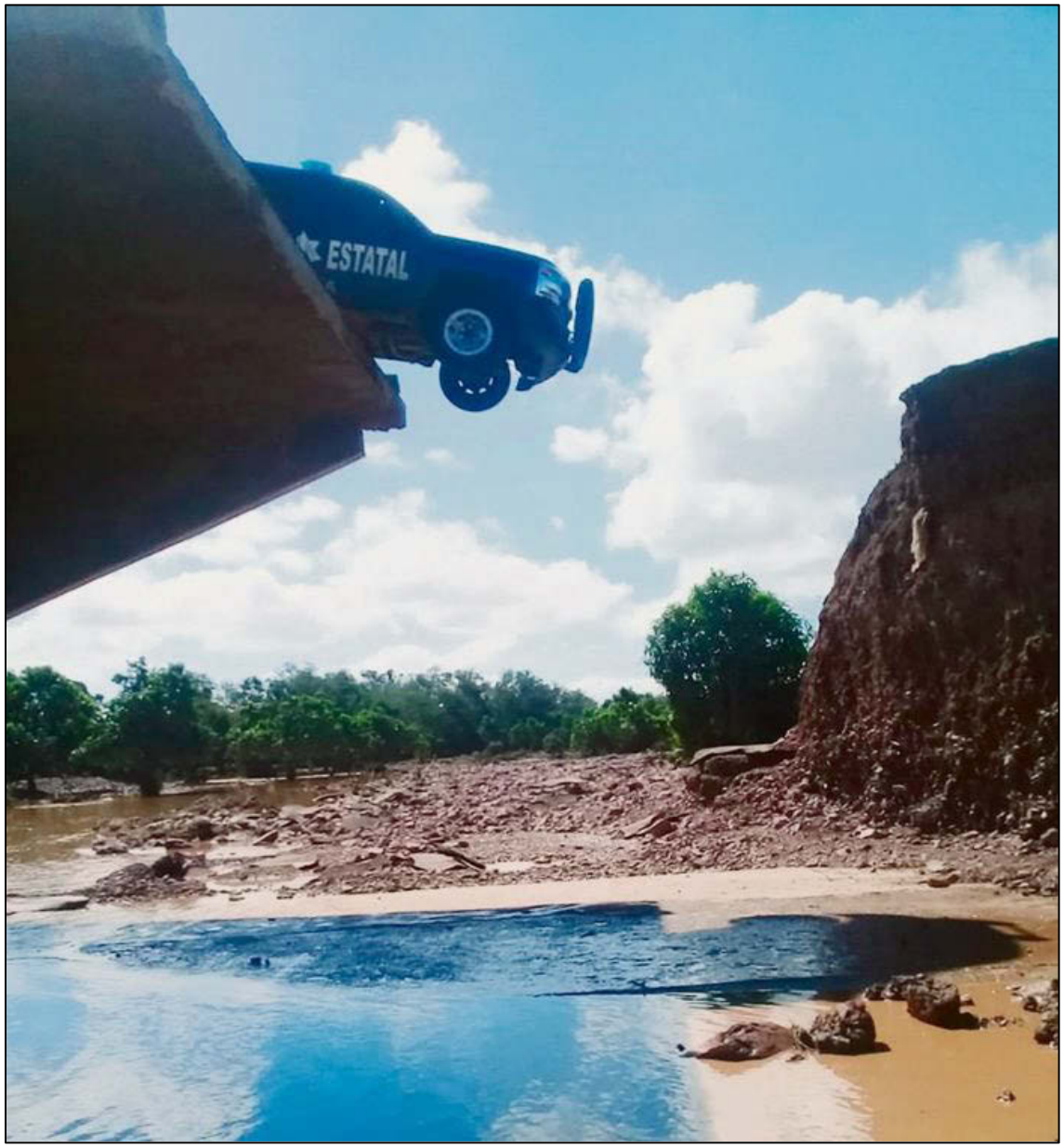


Figure 13. Bridge and highway collapse in Sinaloa state, Mexico. Picture courtesy of *Informador.mx*.

Figure 14. Home buried in mud in Los Sandovales, Narayit state, Mexico. Picture courtesy of *Informador.mx*.