A tropical disturbance made landfall near Morehead City, North Carolina, on 27 June 2006. Surface observations, Air Force reconnaissance, and Doppler velocity data suggest that the disturbance had a closed surface circulation at landfall, with maximum 1-min surface winds $>18$ m s$^{-1}$, the threshold of tropical storm strength. A cyclostrophic wind calculation using Doppler velocity data and surface observations indicates that the circulation of the disturbance likely caused the tropical storm force winds observed, rather than an environmental pressure gradient or short-lived convective process. Doppler velocity cross sections of the disturbance further suggest that the disturbance was warm core, and an analysis of the disturbance’s environment reveals that latent heat of condensation was likely a large source of energy for the disturbance, though there was some baroclinic forcing. These observations and analyses make a compelling case for the upgrade of the disturbance to a tropical storm in the best-track database.

1. Introduction

Many tropical disturbances are tracked from genesis to dissipation in the North Atlantic basin by the National Hurricane Center (NHC) every year, and some of these disturbances become tropical cyclones (TCs). Sometimes however, whether a tropical disturbance has met the requirements to be considered a TC is difficult to determine, and the disturbance is left undeclared by the NHC in real time. These borderline disturbances are reviewed by the NHC after the hurricane season is over, and a determination is made as to whether the disturbance has met the requirements to be considered a TC. This process has led to TCs being declared and added to the NHC best track database [i.e., the North Atlantic Hurricane Database (HURDAT)] postmortem, the most recent example being a vigorous tropical disturbance that was observed offshore the Canadian Maritimes during 17–18 July 2006 (Blake and Beven 2006). Additions of TCs postmortem to the HURDAT database, such as the one mentioned above, are important as HURDAT data is used for risk assessments, climate studies, TC seasonal forecasting, and forecast verification (Landsea et al. 2003).

In this paper, a potential TC that was not declared in real time has been identified. The next section outlines the methods used to analyze this cyclone. Section 3 details the structure and evolution of the cyclone using surface, upper-level, satellite, aircraft reconnaissance, and Doppler data, showing that this potential TC likely met the requirements to be considered a tropical storm by the NHC. Section 4 discusses the casualties and damages attributed to the storm. Finally, section 5 provides a summary of the findings.

2. Data and methods

Wind observations are obtained from a variety of sources which include Weather Surveillance Radar-1988 Doppler (WSR-88D), surface stations, buoys, and 10-s-averaged as well as 30-s-averaged Air Force reconnaissance flight-level data. All of these wind observations are normalized to 1-min mean surface winds using one of
two methods. Flight-level reduction factors for convective regions of the outer vortex of a TC are used to normalize all reconnaissance and WSR-88D radar observations, and these are 0.80 at 305 m, 0.75 at 915 m, 0.80 at 1500 m, and 0.85 at 3000 m (Franklin et al. 2003). The ratios of 1.12 for 10-min mean surface winds and 1.1 for 8-min mean surface winds are used to normalize all surface observations to 1-min mean surface winds (Powell et al. 1996). Also, all nonsurface observations are followed by parentheses with the height of the observation. Finally, flight-level pressure observations from the Air Force reconnaissance aircraft were converted to mean sea level pressure (MSLP). This was done through Jordan’s relation, as described in Willoughby et al. (1989).

A best track was made for the disturbance (Fig. 1, Table 1) using WSR-88D radar observations, surface observations, and satellite imagery. The location of the center of the disturbance was estimated once every 3 h using WSR-88D velocity data, with the central point of the radial velocity couplet on the lowest scan being assumed as the center (this method was used for other times throughout the paper, and is referred to as the radar center; Baynton 1979). The forward speed and heading at each 3-h storm location was then calculated. The forward speed was determined by finding the radar center of the disturbance an hour before and after the time in the best track, determining the distance between these two points, and then dividing the distance by time. The heading was calculated as the angle between the two points clockwise from due north. The maximum surface wind speed of the disturbance at each best-track point was then determined through a combined analysis of surface, Air Force reconnaissance, and WSR-88D observations.

Whether the disturbance was in the tropical, transformation, or extratropical phase was also determined every 3 h, through analyzing the characteristics of the disturbance on infrared satellite imagery as suggested by Klein et al. (2000; Fig. 2). The tropical phase is characterized by a symmetric infrared signature. The transformation phase is characterized by eroding convection in the southern and western semicircles of the circulation, along with a cirrus shield beginning to extend poleward from the circulation. The extratropical phase is characterized by further eroding of deep convection in all but the northern quadrant, resulting in an asymmetric infrared signature. The track of the disturbance is in Fig. 1, with the latitude, longitude, estimated maximum wind speed, and phase of the disturbance in Table 1.

In section 3a, potential vorticity (PV) was calculated with the following equation:

$$ PV = \frac{\xi \nabla \Theta}{\rho}, $$  

where $\xi$ is absolute vorticity, $\nabla \Theta$ is the gradient of potential temperature, and $\rho$ is the density of air. All data used in the PV equation was from the North American Regional Reanalysis (NARR), which has a resolution of 32 km.

3. Structure and evolution of the disturbance

a. Early development

An upper-level disturbance began to develop east of the Bahamas on 20 June 2006 and was clearly evident as a 200-hPa PV maximum by 0000 UTC 24 June (Fig. 3a). From 0000 UTC 24 June to 0000 UTC 26 June the upper-level disturbance moved westward through the Bahamas (Figs. 3a,d). Infrared imagery indicates that large areas of convection developed periodically in the western semicircle of the upper-level disturbance during this time (Fig. 3f), coinciding with a 0.1–0.2 PV unit (PVU) increase in 850-hPa PV across the western semicircle of the upper-level disturbance (Figs. 3b,e). The increase in low-level PV suggests that a low-level disturbance formed in association with the upper-level disturbance. The upper-level disturbance and low-level disturbance then began to head northward after 0000 UTC 26 June (Figs. 3d,e,g,h) in response to a trough approaching from the west (not shown).
b. Prelandfall and landfall observations

1) CIRCULATION CHARACTERISTICS

Convection began to increase across the low-level disturbance around 0600 UTC 27 June (Fig. 3i), 13 h prior to landfall, and 850-hPa PV increased by over 0.1 PVU from 0600 to 1200 UTC (Figs. 3h,k). This increase in convection and low-level PV suggests that the low-level disturbance (hereafter referred to as the “disturbance”) amplified early on 27 June, which coincides with the disturbance moving over the warm waters of the Gulf Stream where sea surface temperatures (SSTs) approached 28°C in a broad area from 31° to 35°N and 75° to 79°W (Fig. 4).

Around 1400 UTC 27 June, a cloud feature that displayed apparent cyclonic rotation could be seen on visible satellite imagery on the northern side of the disturbance, as denoted by the black circle in Fig. 5. Aircraft reconnaissance investigated this cloud feature and found winds...
FIG. 3. A-L NARR (courtesy of the National Climatic Data Center) (left) 200-hPa PV, (middle) 850-hPa PV, and (right) infrared satellite imagery at (from top to bottom) 0000 UTC 24 Jun, 0000 UTC 26 Jun, 0600 UTC 27 Jun, and 1200 UTC 27 Jun 2006. A PV color scale can be found at the top of the 200- and 850-hPa PV columns in each of the panels. PV images extend from roughly 20° to 40°N and 85° to 65°W, with infrared images extending roughly from 20° to 40°N and 85° to 70°W. The upper-level disturbance is boxed in on each 200-hPa PV image, with the low-level disturbance boxed in on each 850-hPa PV image, and the general area of disturbed weather is boxed in on each infrared image. (Infrared images adapted from http://vortex.plymouth.edu/sat-u.html, courtesy of Plymouth State University.)
of 28 m s\(^{-1}\) at flight level (280 m) to the southeast of it at 1651 UTC, corresponding to a 1-min mean surface wind speed of 22 m s\(^{-1}\), exceeding the tropical storm threshold. However, 30-s-averaged data, the standard resolution aircraft data that the NHC gets in real time, indicated only a sharp northeast–southwest trough associated with the disturbance between 1803 and 1810 UTC as the aircraft passed to the west of the disturbance’s radar center (not shown). The disturbance had no northerly winds based on the data, and thus no aircraft-observed surface circulation. This resulted in the NHC leaving the disturbance undeclared as seen in this excerpt from a Special Tropical Disturbance Statement (STDS) issued at 1828 UTC by the NHC:

RECENT INFORMATION FROM AN AIR FORCE RESERVE RECONNAISSANCE AIRCRAFT INDICATES THE AREA OF DISTURBED WEATHER IS CENTERED ABOUT 35 MILES SOUTHWEST OF CAPE LOOKOUT NORTH CAROLINA. WHILE THERE IS A SMALL AREA OF GALE FORCE WINDS ON ITS EAST SIDE... THE SYSTEM DOES NOT HAVE A CLOSED SURFACE CIRCULATION... AND IS THEREFORE NOT A TROPICAL CYCLONE AT THIS TIME. THE AIRCRAFT WILL CONTINUE TO INVESTIGATE THE SYSTEM THIS AFTERNOON.

The 10-s-averaged data presents a different picture. As the aircraft passed to the west of the radar center of the disturbance between 1800 and 1810 UTC, winds backed from east to west, with a northerly component observed (Figs. 6 and 7). This was concurrent with a 2–3-hPa MSLP drop (Fig. 7). Thus, the 10-s-averaged data indicate that the disturbance likely had a closed surface circulation around a surface pressure minimum.

The question then arises, what would cause such a discrepancy between 30- and 10-s data? When overlaying 10-s data from 1802 to 1806 UTC on WSR-88D Doppler velocity imagery from 1804 UTC out of Morehead City,
North Carolina (Fig. 6), it is seen that the aircraft flew on the western edge of the northerly winds associated with the circulation center, and it appears that the aircraft encountered northerly winds for such a small period of time that 30-s resolution was too coarse to resolve them. The northerly winds observed by the reconnaissance aircraft are displaced slightly to the south of the northerly Doppler winds on Fig. 6 due to the disturbance’s northward heading (Table 1) and the radar sweep occurring 40–80 s after reconnaissance traversed the center. The inability to detect the circulation of the disturbance in real time was therefore due to the small size of the circulation (Fig. 6) and the aircraft flying west of the apparent center.

The velocity couplet associated with the center of the disturbance was clearly evident as it approached within 25 km of the Morehead City WSR-88D at 1903 UTC (Fig. 8). At this range, the radar beam is centered at 250 m of altitude, with a width of 200 m. Considering that the radar beam’s altitude was centered below the altitude of the reconnaissance aircraft’s investigation earlier in the day, this radar data is further evidence that the disturbance likely had a closed surface circulation before landfall. Also, the radar indicated winds of 27 m s\(^{-1}\) (120 m) in the eastern semicircle of the disturbance as it made landfall, corresponding to 1-min mean winds of 22 m s\(^{-1}\) at the surface.

Citizens Weather Observing Program (CWOP) station C2542 (Newport, North Carolina) was in a nearly ideal position to confirm if the circulation suggested by Air Force reconnaissance aircraft and Doppler radar data existed at the surface, being only 5 km inland and about 5 km west of the radar center of the disturbance at closest approach. The station observed winds backing from east to west as the disturbance passed overhead, with a distinct northerly component observed. A 4–5-hPa pressure drop occurred simultaneously (Fig. 9). These observations strongly suggest that the disturbance had a closed surface circulation.

Surface observations were also useful in determining whether the tropical storm force winds observed by the reconnaissance aircraft and Doppler radar were present at the surface (Table 2). The strongest wind speed
FIG. 6. Reconnaissance aircraft track (wind barbs in m s$^{-1}$) overlaid on a WSR-88D velocity image out of Morehead City centered at 1804:18 UTC 27 Jun 2006. Each wind barb along the reconnaissance aircraft’s track indicates a position of a 10-s observation, and observations are plotted from 1802:00 to 1806:00 UTC, as labeled. Green pixels on the velocity image indicate wind blowing toward the radar (southerly), and red pixels indicate winds blowing away from the radar (northerly). The red tropical storm symbol indicates the approximate center of circulation based on radar data, and the black arrow extending from the center indicates storm motion. Purple pixels indicate missing data due to range folding (RF), and a table of velocity values in m s$^{-1}$ and kt can be found along the left side of the image. The aircraft was flying at an altitude of about 300 m, and the radar beam was centered at 800 m, with a beamwidth of 1100 m. The image is approximately 16 km wide and 24 km long. (Figure made with the help of GRIlevel2 radar analysis software.)

FIG. 7. Time series of 10-s-averaged reconnaissance data from 1800 to 1810 UTC 27 Jun 2008. The solid line is MSLP and the dots are wind direction. (Data courtesy of Air Force reconnaissance.)
measured by a surface station during the disturbance’s North Carolina landfall was at Coastal-Marine Automated Network (C-MAN) station CLKN7 (Cape Lookout, North Carolina), where a 10-min mean wind of 16 m s\(^{-1}\) was observed, which corresponds to a 1-min mean wind of 18 m s\(^{-1}\). Strong winds were also reported at Pine Knoll Shores and Atlantic Beach. The winds there were estimated to be sustained at 18 m s\(^{-1}\) for up to an hour (courtesy of the fire department, and confirmed through correspondence with the National Weather Service in Morehead City). The locations of stations C2542 and CLKN7 are marked on Fig. 8, in addition to Pine Knoll Shores, to give a better perspective of the position of these observation points in relation to the disturbance near landfall.

All of the preceding is evidence that the disturbance had a closed surface circulation and tropical storm force winds associated with it, but it is unclear whether the tropical storm force winds were due to the pressure gradient associated with the surface circulation or other mechanisms, such as the environmental pressure gradient or short-lived convective processes. The cyclostrophic wind equation was used to test if the surface pressure field could support tropical storm force winds, and was used rather than the gradient wind equation since the radius of the circulation was less than 25 km on Doppler velocity data (Fig. 8). The cyclostrophic wind, \(V_c\), is nearly equal to the gradient wind, \(V_g\), because of a negligible difference in the Coriolis parameter on this scale. Since pressure observations across the circulation were

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**Fig. 8.** WSR-88D velocity image out of Morehead City at 1903 UTC 27 Jun 2006. A table of velocity values in m s\(^{-1}\) and kt can be found along the left side of the image, and purple pixels indicate missing data due to RF. Green pixels on the velocity image indicate wind blowing toward the radar (southerly), and red pixels indicate winds blowing away from the radar (northerly). The blue circle is the radar center of the disturbance, which is approximately 25 km from the radar site as indicated. Additionally, locations of observation points referenced in the text are marked by black circles and labeled. (Figure made with the help of GRLv2 radar analysis software.)

**Fig. 9.** Time series of C2542 data from 1730 to 2200 UTC 27 Jun 2006. The solid line is MSLP and the dots are wind direction. (Data courtesy of the University of Utah.)
scarce, the cyclostrophic wind equation was solved for the pressure gradient assuming that storm relative Doppler radar velocity observations ($V_{ds}$, and calculated through using the storm motion in Table 1) are equivalent to $V_c$, which yields the following equation:

$$\frac{dp}{dr} = \frac{V_{ds}^2 \rho}{R},$$

(2)

where $R$ is the radius, $\rho$ is the density of air, and $dp/dr$ is the change in pressure with radial distance from the radar center (the pressure gradient).

Forty-two storm relative velocity observations, each separated by 1 km, were extracted from an 1858 UTC radar sweep at an average height of 350 m. This is one observation for every kilometer along the diameter of the circulation, minus the four closest to the center in each semicircle. The four observations closest to the center in each semicircle were excluded so that the data could be compared to station C2542 data, which only came within 5 km of the center. Also, the diameter along which the observations were taken was oriented in such a way that the wind observations would be parallel with the beam, so that most of the actual wind magnitude could be measured, since the component perpendicular to the beam would not be detected by the Doppler radar. Solving Eq. (1) for all 42 points and integrating with respect to radius across each semicircle yields a change in pressure across the circulation of

| Time (UTC) and date | Location | Type | Magnitude (m s$^{-1}$) |
|---------------------|----------|------|-----------------------|
| 1920 UTC 27 Jun     | CLKN7, Cape Lookout, NC | Sustained | 18 |
| 2340 UTC 27 Jun     | KEDE, Edenton, NC | Sustained/gust | 12/18 |
| 0220 UTC 28 Jun     | KORF, Norfolk, VA | Sustained/gust | 12/16 |
| 0300 UTC 28 Jun     | CHLV2, Chesapeake Light, VA | Sustained | 18 |
| 0300 UTC 28 Jun     | KPTV2, Kiptopeke, VA | Sustained/gust | 19/24 |
| 0640 UTC 28 Jun     | KDOV, Dover, DE | Sustained/gust | 17/23 |
| 0710 UTC 28 Jun     | SJSN4, Ship John Shoal, NJ | Sustained/gust | 21/27 |

![FIG. 10. Change in pressure profiles across the radius of the disturbance. Circles are radar data from the western semicircle, diamonds are radar data from the eastern semicircle, and squares are station C2542 data. (Data courtesy of the University of Utah and GRLevel2 radar analysis software.)](image-url)
3.9 hPa in the western semicircle and 3.6 hPa in the eastern semicircle. The pressure gradient was then calculated for station C2542 from 5 to 25 km, yielding a change in pressure of just over 3.5 hPa (Fig. 10). Considering the calculated change in pressures using Eq. (1) for both semicircles were within 0.5 hPa of the surface station’s change in pressure, the translating circulation was likely in balance with the pressure field upon landfall, and the tropical storm force winds observed at landfall can probably be attributed to this circulation.

2) THERMODYNAMIC CHARACTERISTICS

Though the preceding provides evidence that the disturbance had a closed surface circulation upon landfall with tropical storm force winds, the thermodynamic structure of the disturbance at landfall remains unresolved. Florida State University’s phase space classification technique was attempted to determine the thermodynamic characteristics of the disturbance as described in Hart (2003), but it was inconclusive because of the small size of the disturbance. Another way to assess the thermodynamic structure of a cyclone is through analyzing its wind field characteristics, assuming thermal wind balance. In a warm-core tropical cyclone the strongest winds are typically near the center and close to the surface. This is in contrast to a cold-core extratropical cyclone where the strongest winds cover a much broader area and increase with height. The strongest winds in association with the disturbance were observed to be within 10–15 km of the center on Doppler velocity data just before landfall (Fig. 8). Also, the maximum winds associated with the disturbance were below 2 km with decreasing winds above that, as seen in a vertical Doppler cross section out of Morehead City (Fig. 11). Thus, these observations are evidence that the disturbance was warm core if the observed winds are assumed to be in thermal wind balance.

The environment surrounding the disturbance at 850 hPa was then analyzed subjectively, to determine what mechanisms were powering the disturbance throughout its life. At 1200 UTC 27 June and 0000 UTC 28 June a shortwave trough was approaching the developing disturbance from...
the southwest (Figs. 12a,b), and by 1200 UTC 28 June the disturbance was along the trough axis (Fig. 12c). Considering the positions of the shortwave trough and disturbance in Figs. 12a,b, it is likely that the shortwave trough aided in the development of the disturbance through enhancing upward vertical motion across it, thus creating an environment conducive for persistent convection (Bracken and Bosart 2000).

A surface analysis was then performed for further insight into the structure of the disturbance (Fig. 13). The disturbance did not appear to be associated with frontal features at any analysis time, and surface baroclinic effects were likely small.

Though the disturbance was a discrete entity based on surface analyses, it probably derived some of its energy from baroclinic forcing due to the shortwave trough as suggested by 850-hPa analyses. However, it is common for TCs to develop in the North Atlantic with the help of baroclinic processes (McTaggart-Cowan et al. 2008). Additionally, latent heat of condensation was probably a large source of energy for the disturbance when considering the small scale of the disturbance (Fig. 8), and that the disturbance was likely warm core as shown previously in this section. It is improbable that large-scale baroclinic forcing from the shortwave trough alone could lead to such a small and vigorous warm-core vortex.
4. Casualty and damage statistics

a. Wind damage

There were six reports of wind damage in association with the disturbance, three in Virginia, and three in Maryland (high winds were reported in North Carolina too, but no damage was reported in association with them). Only tree damage occurred, with wind gusts estimated to be about 22 m s\(^{-1}\) in all of the reports based on the magnitude of damage. These damaging winds occurred as the center of the disturbance passed over each location, further suggesting that the disturbance’s strongest winds were confined to near its center. Total wind damage from the disturbance was estimated to be $12,000.

b. Storm surge

One report of damaging storm surge was received from Anne Arundel County, Maryland. Water had been rising for several days across the downwind portions of Chesapeake Bay and the Potomac River due to persistent storms embedded in the tropical flow ahead of the approaching front. Water levels in parts of the Chesapeake reached levels in excess of 0.5 m above mean sea level during high tides as the disturbance traversed the region, as observed by the Chesapeake Bay Operational Forecasting System. Storm surge damage totaled $20,000 in association with the disturbance.

c. Freshwater flooding

Radar estimates from 1100 UTC 27 June to 1200 UTC 28 June indicate that well over 3 cm of rain fell across most of the mid-Atlantic in association with the disturbance, with the most rain occurring from central Pennsylvania into central New York, where up to 20 cm of rain was estimated (Fig. 13). Part of this rainfall can be attributed to the predecessor rain event (PRE) that occurred ahead of the disturbance as the disturbance interacted with an approaching trough, which also explains why precipitation was concentrated in a swath left of the track (Atallah et al. 2007). Additionally, heavy rain from a stalled frontal system had been impacting the mid-Atlantic since 24 June, saturating the ground and resulting in flooding even before the disturbance came through. Total flood damage was an estimated $1.3 billion, with $850,000,000 of damage in New York, $450,000,000 in Pennsylvania, $31,600,000 in New Jersey, $80,000 in Maryland, and $50,000 in North Carolina. Tragically, an estimated 18 people lost their lives in the floods. All flood damage and casualties are at least partially indirect, considering that without previous heavy rainfall.

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**Fig. 13.** Surface analysis at (a) 1800 UTC 27 Jun, (b) 0000 UTC 28 Jun, (c) 0600 UTC 28 Jun, and (d) 1200 UTC 28 Jun. A wind barb is at each observation point, showing the direction of the wind and its magnitude in m s\(^{-1}\). Temperature is contoured every 2°C in black. The tropical storm symbol on each image represents the location of the disturbance, and the L on (a) represents the center of a broad area of low pressure. (Data courtesy of the National Weather Service, and the figure was made with the help of WeatherScope meteorological analysis software.)
from the stalled frontal system and the PRE, the disturbance’s rains likely would not have been as damaging.

5. Summary

A tropical disturbance made landfall in North Carolina on 27 June 2006 and reconnaissance, WSR-88D, and surface observations suggest that this disturbance had a closed circulation during and after landfall. Air Force reconnaissance traversed west of the center and the coarse temporal resolution of the aircraft’s real-time reporting combined with the small size of the disturbance explains why a closed circulation was not detected in real time. In addition, WSR-88D, surface, and reconnaissance aircraft data all indicate that the disturbance had surface winds greater than 18 m s\(^{-1}\) upon landfall in North Carolina. The tropical storm–force winds associated with the disturbance were likely a direct result of its circulation, which was in balance with the local pressure field as determined through a cyclo-

![Accumulated Rain (cm) 11UTC 27 Jun-12UTC 28 Jun 2006](image)

Fig. 14. WSR-88D estimated rainfall from 1100 UTC 27 Jun to 1200 UTC 28 Jun 2006 in cm. The best track of the disturbance is plotted on the map in black, and times starting on 27 Jun 2006 are labeled along the track in UTC. (Data courtesy of the National Climatic Data Center.)

strophic wind calculation, rather than an environmental pressure gradient or short-lived convective process. Evidence is also presented that suggests the disturbance was likely a warm-core tropical cyclone, rather than an extratropical or subtropical cyclone. A vertical WSR-88D cross section of the disturbance around landfall shows that the strongest winds were near the surface and close to the center, which suggests that the disturbance was warm core. Surface analyses reveal that the disturbance was independent of frontal features, and although 850-hPa analyses suggest that the disturbance was deriving some of its energy from baroclinic processes, it is a common occurrence among TCs in the North Atlantic and the disturbance was probably largely powered by latent heat of condensation. Finally, the disturbance’s rains are partially responsible for significant flooding damage and loss of life in the mid-Atlantic states.

Thus, Doppler, satellite, aircraft reconnaissance, upper-level, and surface observations suggest that the disturbance studied in this paper met the requirements to be
considered a tropical storm by the NHC (Federal Committee for Meteorological Services and Supporting Research 2006). In light of this evidence, the disturbance should be reviewed by the NHC best-track committee and potentially added as a 2006 tropical storm to HURDAT. Table 1 is a suggested best track for this potential tropical storm.

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