

The Extratropical Transition of Tropical Storm Ophelia (2005): Summary of Forecasts and Meteorological Observations

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10 November 2005

1. Storm history

Hurricane Ophelia formed from a tropical depression that developed over the northwestern Bahamas on 06 September 2005 (see Fig. 1). Ophelia first attained hurricane status with winds near 65 knots on 08 September east of Cape Canaveral, Florida. After stalling there, the storm weakened back to tropical storm strength, and then moved to the north where it regained hurricane status (maximum sustained winds (MSW) near 75 knots) with a minimum sea level pressure (MSLP) of 977 mb on 10 September. Ophelia then weakened while stalled well south of Cape Hatteras. On 13 September the storm began to move toward the South Carolina coast, away from the cool water it had upwelled, and regained hurricane strength once again. The hurricane moved slowly toward the north, then northeast, paralleling the outer banks of North Carolina on 14 and 15 September with MSW reaching 80 knots and a MSLP of 979 mb.

On 16 September, Ophelia weakened to a tropical storm and began accelerating toward the north-northeast. During this time, the early stages of extratropical transition (ET) were beginning to take place as dry air began wrapping into the storm circulation from the west. The storm continued to accelerate toward the northeast on 17 September while the deep cloud pattern became heavily sheared toward the northeast by upper-level winds. The MSW dropped to 45 knots as it tracked not far south of western Nova Scotia. The storm made landfall near Sheet Harbour, Nova Scotia near 06 UTC 18 September by which time it was declared an extratropical (post-tropical) storm. The remnant low pressure area crossed eastern Newfoundland on 18 September.

2. Synoptic analysis

Figure 2 shows a composite of satellite images from late on 16 September as Ophelia was beginning to undergo ET. Conventional GOES-12 infrared and visible images, shown in panels a and b, reveal a front or “cloud tail” forming to the south of the storm. Passive microwave imagery from the Special Sensor Microwave/Imager (SSM/I) instrument, shown in panels c and d, indicate that the deep, rain-producing convection had shifted toward the northeast sector of the storm. The red colors (in the color version) of Fig. 2d denote the heavy precipitation area while shallower cloud/moisture shows up as green tones (color version). A more complete explanation of the microwave imagery and how to interpret it is available at the Naval Research Laboratory tropical cyclone page at http://www.nrlmry.navy.mil/tc_pages/tc_home.html.

A research aircraft was also investigating Tropical Storm Ophelia near the time valid in the satellite images. Data from dropsondes showed that dry air was wrapping around the storm center from the west, encircling $\frac{3}{4}$ of the storm core. This was also apparent in land-based radar at 18 UTC 16 September (hereafter 18/16) shown in Fig. 3. The radar and satellite signatures became much more “ragged” by 21/16, a sign that the storm was weakening. More information and analyses from the dropsondes will be presented in the following section.

Analyses of sea level pressure and 500-mb geopotential heights and vorticity valid at 00/17 are shown in Fig. 4. Images are from the DIFAX archive of weather charts at the Canadian Meteorological Centre (CMC). In Fig. 4a, a baroclinic wave and associated low pressure area were situated over western Pennsylvania, while a 500-mb trough was migrating eastward across the Great Lakes (Fig. 4b). A general northeastward flow was seen in the vicinity of Ophelia, which was responsible for moving the storm in a direction toward Nova Scotia.

The low level circulation of Ophelia had become completely exposed by the morning of 17 September when the storm was passing to the southeast of Cape Cod. Satellite imagery from GOES and the SSM/I in Fig. 5 show the sheared cloud pattern. Deep convection and precipitation was confined to the north-northeast of the low-level center, which can be discerned from the curvature in low-level cloud bands in Fig. 5d (green tones in color version). Throughout the day, the shear appeared to become more westerly. For instance, the skewness of deep convection had rotated anticyclonically to the east-northeast of the low level center. This is consistent with the storm moving faster than the shortwave trough over the Great Lakes and beginning to move into the more zonal flow pattern closer to a ridge located downstream near Newfoundland.

By 00/18, Ophelia had almost completed transition to an extratropical low. Analyses of sea level pressure and 500-mb geopotential heights and vorticity from CMC valid at 00/18 are shown in Fig. 6. The center of Ophelia was moving south of Nova Scotia at that time, with a quasi-stationary warm front situated north of the storm’s circulation (Fig. 6a) where heavy rain had been falling throughout much of the day on 17 September. At the time of aircraft observations (17-22 UTC) and based on the 500-mb analysis, the circulation center of Ophelia no longer existed at that level. The top of the storm had essentially been blown off. Also, the storm moved out ahead of the 500-mb shortwave trough as shown in Fig. 6b, leading to a more eastward track.

The center of post-tropical storm Ophelia arrived at the coast on the eastern mainland of Nova Scotia and moved very near a private weather station operated by Danny McInnis in the Country Harbour area of Guysborough County. Figure 7 shows a sea level pressure trace from that station, showing the gradual fall and rise of pressure. This is evidence that the once tight pressure pattern of the tropical storm had broadened, and thus had undergone ET.

Occasionally the weather office will prepare summaries of weather events, such as tropical cyclones. These summaries are usually brief, and serve as a timely source of information for media. Below is the operational storm summary for this event, prepared by the hurricane forecasters, with wind and rainfall data:

AWCN11 CWHX 190048
 SPECIAL STORM SUMMARY MESSAGE FOR NOVA SCOTIA ISSUED BY ENVIRONMENT
 CANADA AT 9:48 PM ADT SUNDAY 18 SEPTEMBER 2005.

TROPICAL STORM OPHELIA TRACKED JUST SOUTH OF WESTERN NOVA SCOTIA AND HALIFAX SATURDAY NIGHT AND MADE LANDFALL AS A POST-TROPICAL STORM NEAR SHEET HARBOUR..HALIFAX COUNTY WITH MAXIMUM SUSTAINED WINDS OVER WATER NEAR 45 KNOTS. THE CENTER WENT OVER SYDNEY THEN MOVED THROUGH SOUTHEASTERN NEWFOUNDLAND SUNDAY EVENING.

THE PREDICTED HEAVY RAINFALLS DID OCCUR FOR THE MOST PART ..HOWEVER..STRONG WINDS WERE NOT EXPERIENCED OVER NOVA SCOTIA BECAUSE THE STORM GENERALLY TRACKED SOUTH OF THE PROVINCE WHICH WAS FURTHER SOUTH THAN WE EXPECTED BEFORE THE WEEKEND. HAD THE TRACK BEEN A BIT FURTHER NORTH..THERE WOULD VERY LIKELY HAVE BEEN SOME HIGH WIND GUSTS OVER NOVA SCOTIA. THE STRONGEST WIND GUST IN NOVA SCOTIA WAS 80 KM/H FROM THE EAST-SOUTHEAST..REPORTED AT THE WELL-EXPOSED BEAVER ISLAND WEATHER STATION IN EASTERN HALIFAX COUNTY.

IN NEWFOUNDLAND..THERE WERE SOME STRONG COASTAL WIND GUSTS. AT BURGIO..A GUST OF 96 KM/H WAS REPORTED FROM THE NORTHEAST. THIS WOULD HAVE BEEN A LOCAL EFFECT DUE TO CHANNELING OF WIND FROM HIGHER TERRAIN.

HEAVIEST RAINFALL AMOUNTS WERE OVER NOVA SCOTIA. HERE ARE THE STORM TOTAL RAINFALLS AND MAXIMUM WIND GUSTS FOR SELECTED STATIONS:

NOVA SCOTIA...

| | RAINFALL | WIND GUSTS | LAT/LON (minutes) | | ELEV |
|--------------------|----------|------------|-------------------|---------|------|
| CAPE SABLE ISLAND | 88.0 MM | 72 KM/H | 43' 27N | 65' 28W | 13m |
| YARMOUTH | 69.4 MM | 37 KM/H | 43' 52N | 66' 06W | 9m |
| KEJIMKUJIK | 28.6 MM | | 44' 26N | 65' 12W | 125m |
| GREENWOOD | 20.6 MM | 32 KM/H | 44' 59N | 64' 55W | 28m |
| WESTERN HEAD | 46.0 MM | 41 KM/H | 43' 59N | 64' 40W | 9m |
| LIVERPOOL | 67.3 MM | | 44' 00N | 64' 50W | 90m |
| SHEARWATER | 60.7 MM | | 44' 38N | 63' 30W | 51m |
| CLAYTON PARK | 60.0 MM | | 44' 39N | 63' 45W | 90m |
| LOWER SACKVILLE | 47.0 MM | | | | |
| OSBORNE HEAD | | 65 KM/H | | | |
| HALIFAX INT'L ARPT | 62.0 MM | 39 KM/H | 44' 53N | 63' 31W | 145m |
| BEAVER ISLAND | | 80 KM/H | | | |
| SYDNEY | 31.0 MM | 57 KM/H | 46' 10N | 60' 03W | 62m |
| NEW GLASGOW | 36.8 MM | 31 KM/H | 45' 36N | 62' 42W | 37m |
| CARIBOU POINT | 53.2 MM | 44 KM/H | 45' 46N | 62' 41W | 2m |
| TRACADIE NS | 29.6 MM | 54 KM/H | 45' 33N | 61' 52W | 10m |
| PARRSBORO | 27.6 MM | 35 KM/H | 45' 21N | 64' 24W | 30m |
| DEBERT | 55.0 MM | 37 KM/H | 45' 22N | 63' 16W | 40m |
| INGONISH BEACH | 82.6 MM | 65 KM/H | 46' 38N | 60' 27W | 100m |
| HART ISLAND | | 70 KM/H | 45' 21N | 60' 59W | 4m |

NEW BRUNSWICK...

| | | | | | |
|---------------|---------|---------|---------|---------|------|
| MONCTON | 18.8 MM | 41 KM/H | 46' 07N | 64' 41W | 72m |
| FREDERICTON | 19.5 MM | 32 KM/H | 45' 52N | 66' 32W | 20m |
| SAINT JOHN | 14.0 MM | 33 KM/H | 45' 19N | 65' 53W | 109m |
| POINT LEPREAU | 17.1 MM | 52 KM/H | 45' 04N | 66' 28W | 1m |
| SAINT STEPHEN | 20.7 MM | 37 KM/H | 45' 13N | 67' 15W | 26m |
| BATHURST | 12.0 MM | | 47' 38N | 65' 45W | 59m |
| ST LEONARD | 17.2 MM | | 47' 09N | 67' 50W | 241m |

PRINCE EDWARD ISLAND...

| | | | | | |
|---------------|---------|---------|--------|--------|-----|
| ELMWOOD | 42.4 MM | | | | |
| CHARLOTTETOWN | 39.4 MM | 28 KM/H | 46°17N | 63°08W | 54m |
| SUMMERSIDE | 39.2 MM | 39 KM/H | 46°26N | 63°50W | 21m |
| EAST POINT | 38.7 MM | 50 KM/H | 46°27N | 61°58W | 13m |

ILES DE LA MADALEINE...

| | | | | | |
|-------------------|---------|---------|--------|--------|-----|
| GRINDSTONE ISLAND | 33.6 MM | 56 KM/H | 47°25N | 61°47W | 10m |
|-------------------|---------|---------|--------|--------|-----|

NEWFOUNDLAND...

| | | | | | |
|------------------|---------|---------|--------|--------|------|
| PORT-AUX-BASQUES | 38.5 MM | 63 KM/H | 47°34N | 59°10W | 40m |
| BURGEO | 50.6 MM | 96 KM/H | 47°37N | 57°37W | 12m |
| ST LAWRENCE | 32.5 MM | 67 KM/H | 46°55N | 55°23W | 49m |
| ARGENTIA | 21.8 MM | 65 KM/H | 47°18N | 54°00W | 13m |
| CAPE RACE | 17.5 MM | 74 KM/H | 46°39N | 53°04W | 28m |
| SAINT JOHNS | 29.0 MM | 37 KM/H | 47°37N | 52°45W | 140m |
| STEPHENVILLE | 28.2 MM | | 48°33N | 58°34W | 60m |
| DEER LAKE | 13.2 MM | | 49°13N | 57°23W | 22m |
| SAGONA ISLAND | | 63 KM/H | | | |
| GANDER | 41.2 MM | | 48°57N | 54°34W | 151m |
| BONAVSITA | 37.0 MM | 93 KM/H | 48°40N | 53°07W | 29m |
| TWILLINGATE | 15.8 MM | | | | |
| TERRA NOVA | 53.7 MM | | 48°45N | 54°00W | 50m |

OVER THE OCEAN ..MAXIMUM WINDS OF 40 KNOTS WERE REPORTED BY LAHAVE BANK BUOY WITH A MAXIMUM WAVE OF 11.0 M AS THE STORM PASSED BY TO THE NORTH.

END MCILDOON/FOGARTY

3. Research aircraft observations

Two ET research flights into Tropical Storm Ophelia were conducted by the Hurricane Research Division (HRD) in Miami in collaboration with Jim Abraham at the Meteorological Service of Canada using a P3 research aircraft. Several GPS dropsondes were deployed in the vicinity of the storm and its environment during the missions. The first mission was flown on 16 September and the second on 17 September while Ophelia was approaching Nova Scotia. More information on these flights can be found at http://www.aoml.noaa.gov/hrd/Storm_pages/ophelia2005/mission.html.

As noted in the previous section, signs of ET were evident in satellite imagery and dropsonde profiles on 16 September. A cross section of relative humidity along a southwest-to-northeast transect through the storm center is shown in Fig. 8. Although the cruising altitude of the aircraft was quite low, there is a hint of tilt toward the north in the humidity pattern below ~700 mb. Drier air can also be seen intruding into the low levels on the north side of the core, consistent with the warp-around of dry air suggested in the coastal radar (Fig. 3) reflectivity pattern at 18/16. The cross section was constructed from 5 sondes launched between 1713 UTC and 1850 UTC.

A highly asymmetric wind field with considerable boundary layer wind speed shear was observed on the second day of flights. In addition, the aircraft did not observe a circulation at 500 mb. A dropsonde profile of wind speed and direction located ~200 km east-southeast of the storm's surface center is shown in Fig. 9. Hurricane force winds (33

m s^{-1} / 64 knots) were observed at 200 m above the ocean surface, while winds were much less (18.5 m s^{-1} / 36 knots) at the surface (12 m). This shear was comparable to that observed during Hurricane Michael (Abraham et al. 2004). Had Ophelia tracked over land, these winds could have been possible at the surface in the form of wind gusts. This may seem surprising for a 997-mb low, but forecasters should be aware of the likelihood of these strong winds above the boundary layer in transitioning tropical systems, particularly over cool sea surface temperatures where wind shear becomes enhanced. In October, 2001, Tropical Storm Karen made landfall over western Nova Scotia as a 998-mb storm, but maximum coastal wind gusts reached 100 km/h (54 knots / 28 m s^{-1}) east of the center in Halifax Harbour. Winds near hurricane force were observed by aircraft near the top of the boundary layer (Fogarty et al. 2002).

4. Summary of numerical model forecasts

Various numerical forecast model results are available to forecasters at the Canadian Hurricane Centre (CHC). Forecasters have access to track and intensity forecasts from models run at various agencies around the world which are available on the internet. The primary numerical guidance in Canada is the Canadian Global Environmental Multiscale (GEM) model. Generally speaking, the GEM model does not predict tropical cyclones very well, primarily due to the scarcity of storm observations necessary to provide good initial conditions for the model. During Ophelia, some aircraft data were being assimilated into the model, and since the storm had passed close to the coastal buoy network off Cape Hatteras, more data from the storm region was available for improving the model initial conditions than is normally the case. Therefore, the GEM model appeared to be resolving the storm circulation reasonably well during its forecast cycles, however, it over-predicted Ophelia's intensity and tracked it too far to the north across Nova Scotia.

Track predictions issued at 12/16 from various sources are shown in Fig. 10, showing the storm tracking over or near Nova Scotia. This plot is courtesy of Dr. Krishnamurti at Florida State University (Williford et al. 2003). These models predicted maximum sustained winds between 45 and 55 knots at the 36-HR mark. The Global Forecast System (GFS) model turned out to have one of the best tracks for any of the numerical models for this event.

The operational CHC forecast (discussed in more detail in the following section) followed a scenario that would bring the remnants of Ophelia across Nova Scotia (worst case scenario). This situation was being predicted by the GEM model, but did not materialize. The failed forecasts lead to many questions following the event.

Several forecasters were (somewhat) surprised by the degree to which the storm became sheared/decoupled. Upon closer inspection of the output from the GEM model, it was no surprise that the storm became sheared apart. For instance, the 24-HR GEM forecast valid at 00/18 depicted the intrusion of dry air into the storm circulation by stronger winds above 700 mb (Fig. 11a). This pattern compares with the cross section of relative

humidity from dropsonde data (Fig. 11b). The cross sections were taken along a 350-km line from northwest to southeast, not far ahead of the storm.

Although the model represented the sheared moisture pattern reasonably well, there were some fundamental differences in the “mass fields” compared with data at the surface and aloft. The difference between analyzed sea level pressure from the CMC global analysis and the 24-HR GEM forecast is shown in Fig. 12. The model predicted lower than observed pressures west of the storm and higher than observed pressures to the east. This could explain why the model track had a westward tendency. The 500-mb winds from the CMC analysis valid at 00/18 (which are a good representation of steering flow) had a stronger eastward component than forecast by the model, as shown in Fig. 13.

The GEM model has been noted for tracking tropical type systems too far to the west in the past (personal experience). This happened during the ET of Wilma in late October, 2005, and during Hurricane Michael in October, 2000 (Abraham et al. 2004, Fogarty 2002). Further study is needed to determine the source of this bias.

5. Summary of Canadian Hurricane Centre forecasts

As with most extratropically-transitioning tropical storms in this region, the CHC had a challenging job forecasting Ophelia. This was complicated by the fact that the storm was approaching Nova Scotia at an oblique angle (see track in Fig. 1). The Centre erred on the side of caution with regard to track and intensity guidance by going with the scenario of a 50-kt storm moving along or just inland from the coast of Nova Scotia. This was suggested by the GEM, the Geophysical Fluid Dynamics Laboratory model (GFDL, Bender and Ginis 2000) (see Fig. 10) and an in-house experimental hurricane model using a weak cyclone bogus for initial conditions. A landfalling tropical cyclone of 50 knots typically brings inland gusts to 50 knots or more, which is the threshold for wind warnings in this region. Wind and heavy rainfall warnings were issued for Nova Scotia, Prince Edward Island and parts of southern New Brunswick. In addition, tropical storm warnings were posted for many regions. This was the first time that tropical-type warnings were used in Canada, which generated extra media attention. In hindsight, traditional rainfall warnings would have sufficed given the actual track and extratropical state of the storm.

During the morning of 17 September it became apparent that Ophelia was moving faster and farther east than expected. The forecast track was moved just off the coast of Nova Scotia, but most weather warnings were retained *with the expectation that there may be some modest reintensification* in the weakly baroclinic environment. That behavior was suggested by the GEM and GFDL models, which had been resolving the storm quite adequately up until that time. The strongest winds remained well offshore to the right of the storm’s motion, so Ophelia would probably had to have tracked over central or northern Nova Scotia for some of those winds to be experienced.

By the time forecasters realized the winds with this system were not going to materialize, it was “too late” - the media had already been going full force with their story of a nasty wind and rain storm forecast to hit Nova Scotia.

In hindsight, the forecast rationale during this event was reasonable and justifiable. Specific lessons learned from this storm are summarized below:

1. Forecasters should be aware of the known westward bias in the GEM model for storms undergoing ET. More study is needed on this.
2. Refrain from speaking of details of impacts until the situation becomes clearer. For example, mention was made of the possibility of tree branches breaking and power outages. The media had blown this out of proportion by occasionally mentioning “trees blowing down” and “widespread power outages”. A lot of this is unfortunately outside the forecaster’s control.
3. Only initiate tropical-type warnings for high-end tropical storms and hurricanes that are not expected to be well into the ET phase. This is, however, a very difficult and inherently subjective decision. When tropical-type warnings or watches are issued, media interest increases markedly.
4. Begin downplaying the storm as soon as data indicate a less threatening scenario. Quick action was taken during the ET of Wilma once it became clear that it would track well south of inland regions. It is important to react quickly, because there will be a lapse in time before the changes get relayed to the public.

More analyses and information on this storm are available at:

<http://projects.novaweather.net/work.html>

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- Bender, M.A., and I. Ginis, 2000: Real-case simulations of hurricane-ocean interaction using a high-resolution coupled model: effects on hurricane intensity. *Mon. Wea. Rev.*, **128**, 917-946.
- Fogarty, C. T., Abraham, J., and W. Strapp, 2002: Extratropical transition of Hurricanes Michael and Karen: Storm reconnaissance with the Canadian Convair 580 aircraft. Preprints, 25th Conf. on Hurricanes and Tropical Meteorology, 29 April - 3 May 2002, San Diego, CA, Amer. Meteor. Soc., 497-498.

Fogarty, C. T., 2002: Hurricane Michael, 17-20 October, 2000: Summary report and storm impact on Canada. Meteorological Service of Canada, Atlantic Region Science Report Series 2002-01, 35 pp. [Available online at http://www.novaweather.net/Hurricane_Michael_files/Michael_MSC.pdf].

Williford, C. E., T. N. Krishnamurti, R. C. Torres, S. Cocks, Z. Christidis, and T. S. Vijaya Kumar, 2003: Real-Time multimodel superensemble forecasts of Atlantic tropical systems of 1999. *Mon. Wea. Rev.*, **131**, 1878–1894.

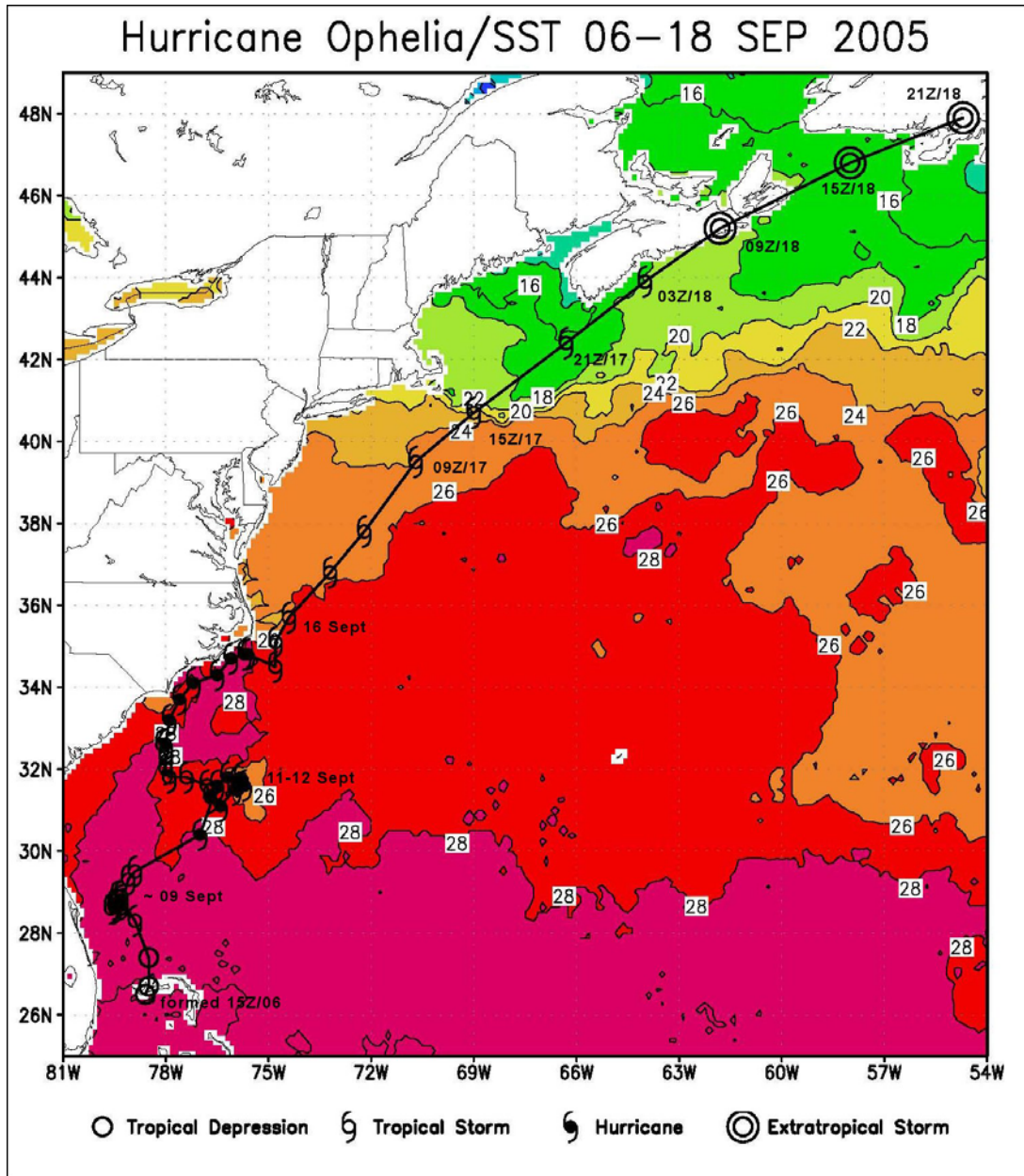


Fig. 1. Storm track for Hurricane Ophelia from National Hurricane Center and Canadian Hurricane Center bulletins. Sea surface temperature analysis from the National Environmental Satellite, Data, and Information Service at <http://www.class.noaa.gov/nsaa/products/welcome> (contoured every 2°C) valid at 00/16 is also shown.

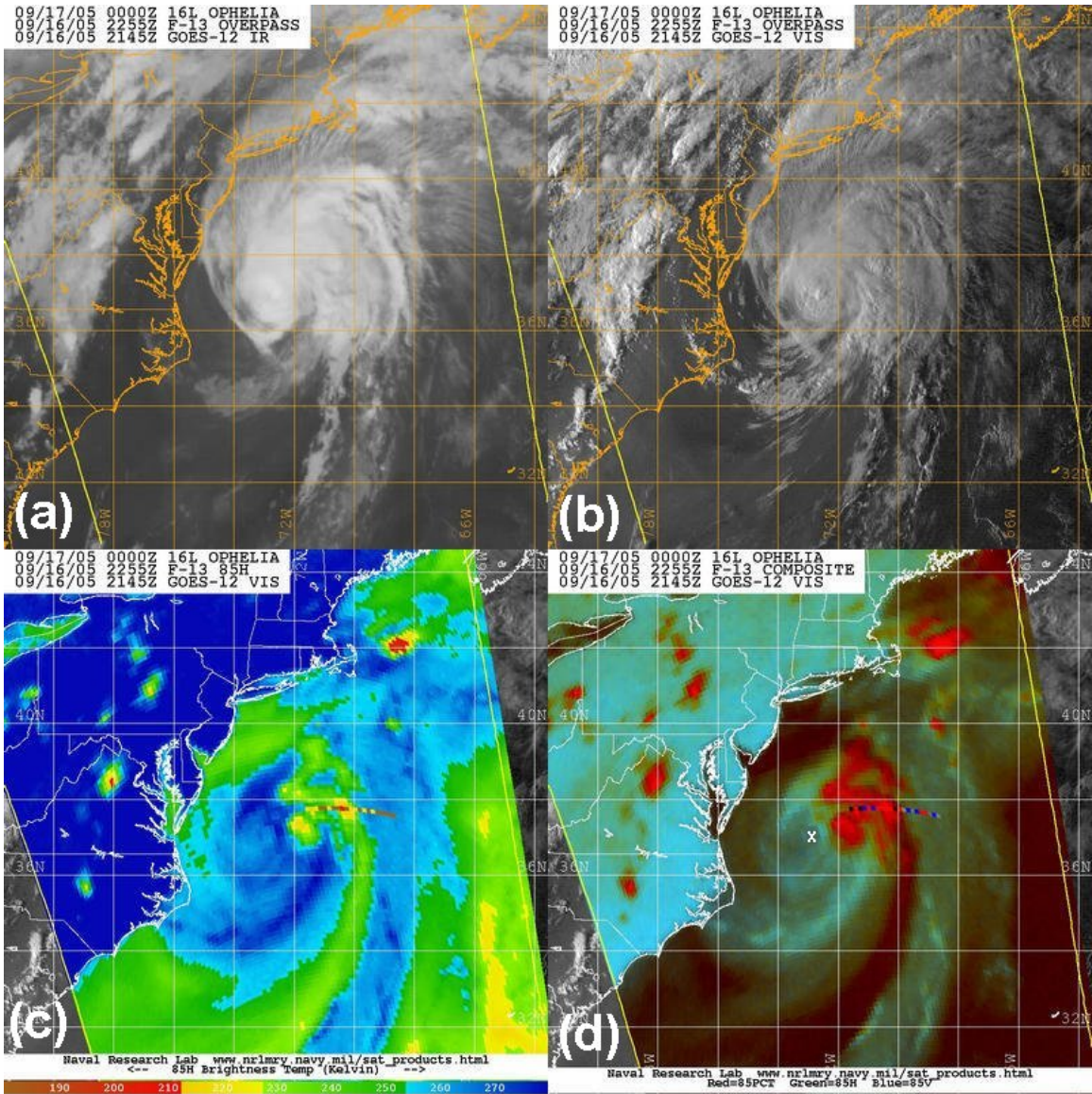


Fig. 2. Multisensor satellite imagery from the Naval Research Laboratory tropical cyclone webpage from 2145/16 and 2255/16. The location of the surface center of TS Ophelia is indicated with a white X in panel d.

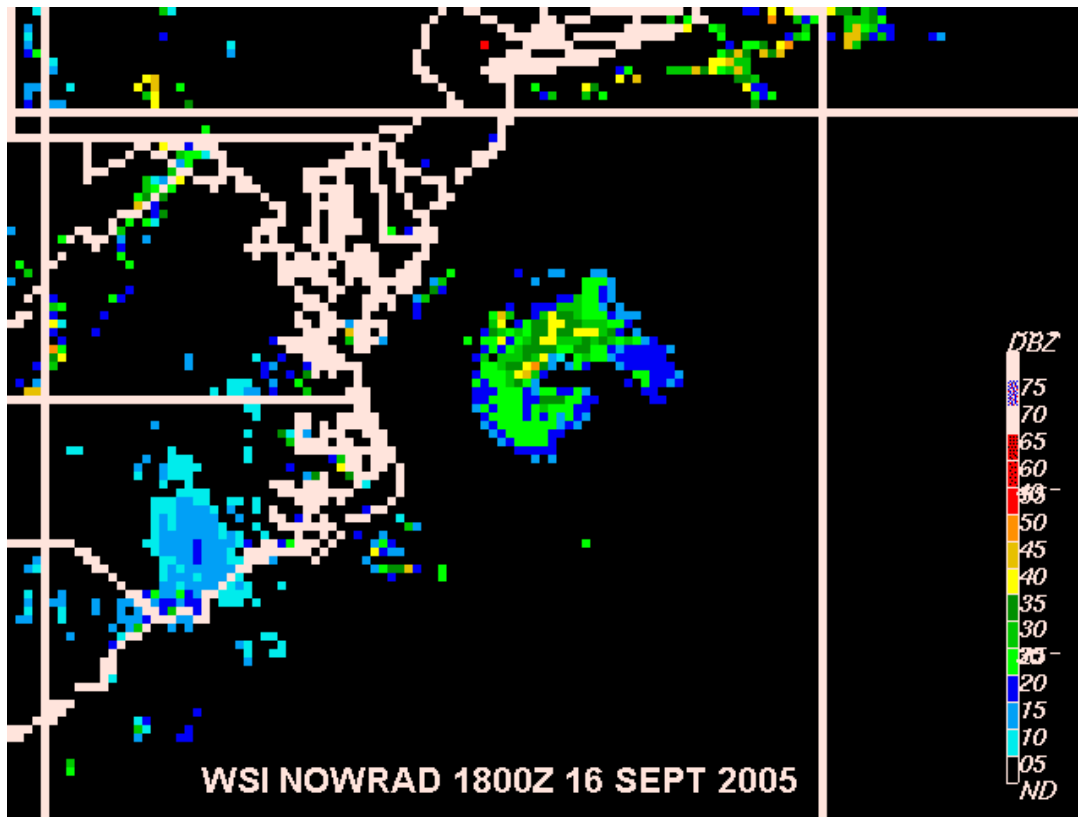


Fig. 3. WSI NOWRAD radar reflectivity valid at 18/16.

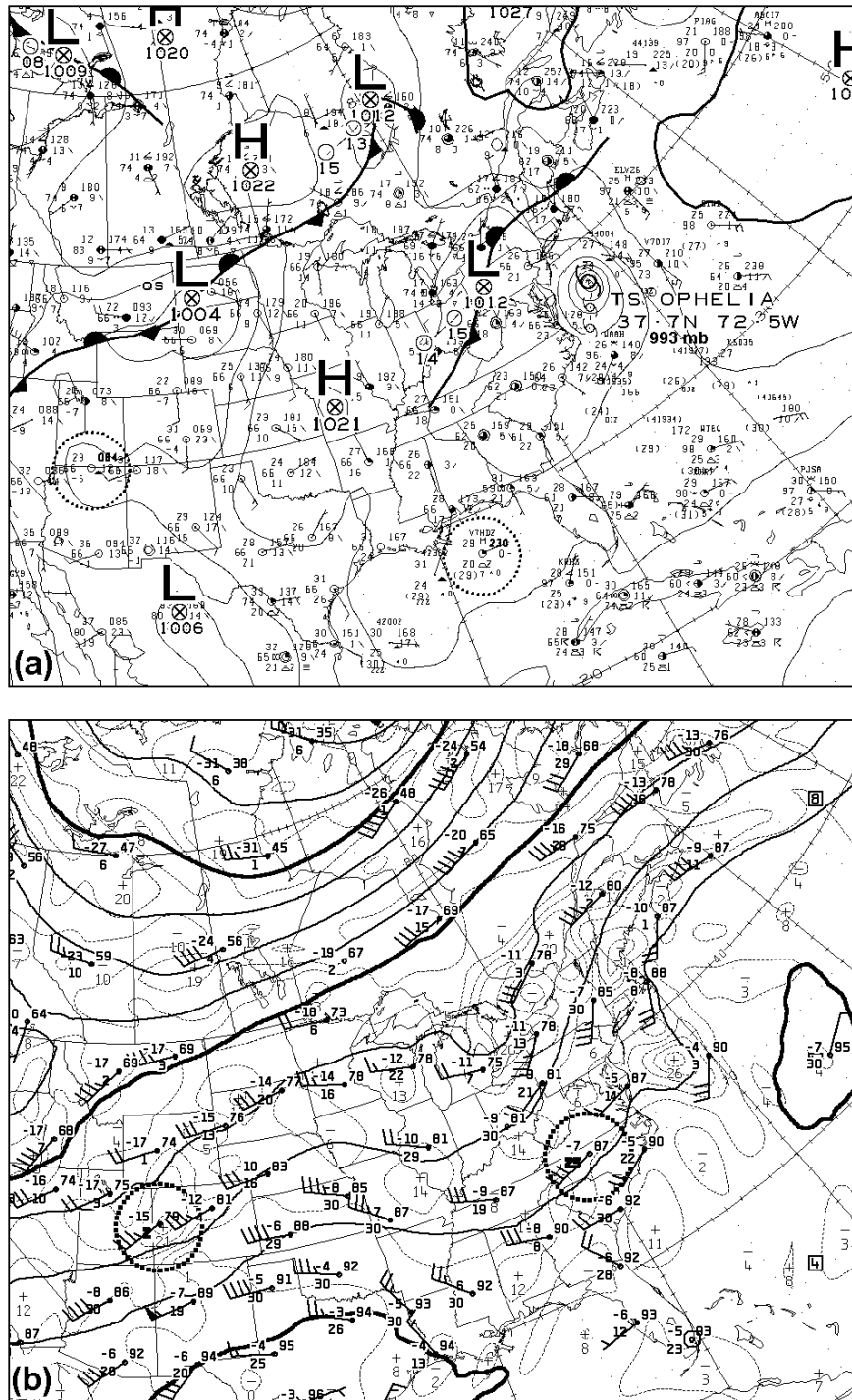


Fig. 4. Surface synoptic weather plot (conventional notation) with sea level pressure analysis (a), and 500-mb geopotential height and vorticity analysis (b), valid at 00/17. Analyses are taken from the Canadian Meteorological Centre DIFAX chart archives.

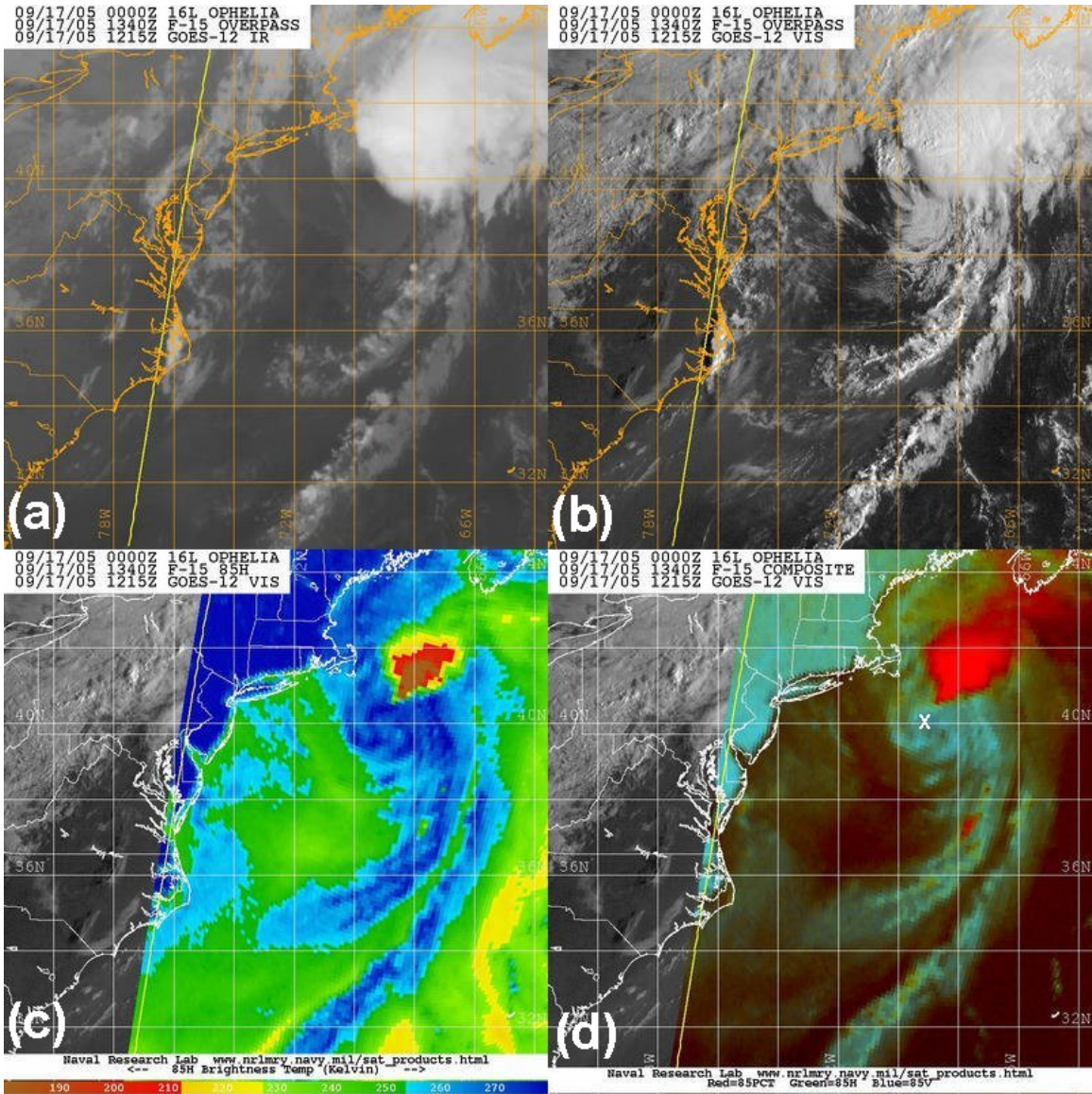


Fig. 5. Multisensor satellite imagery from the Naval Research Laboratory tropical cyclone webpage from 1215/17 and 1340/17. The location of the surface center of TS Ophelia is indicated with a white X in panel d.

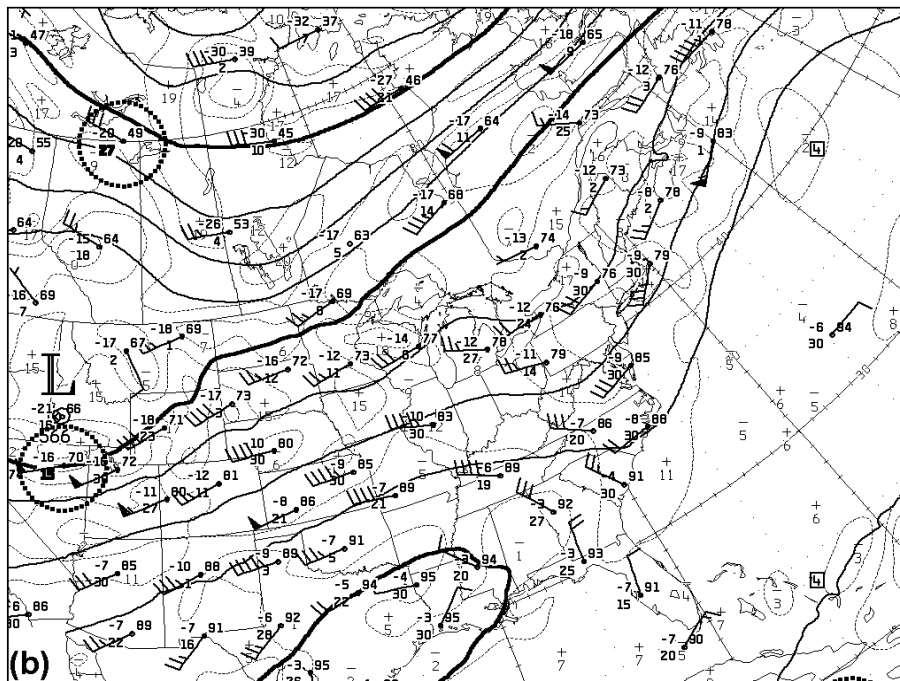
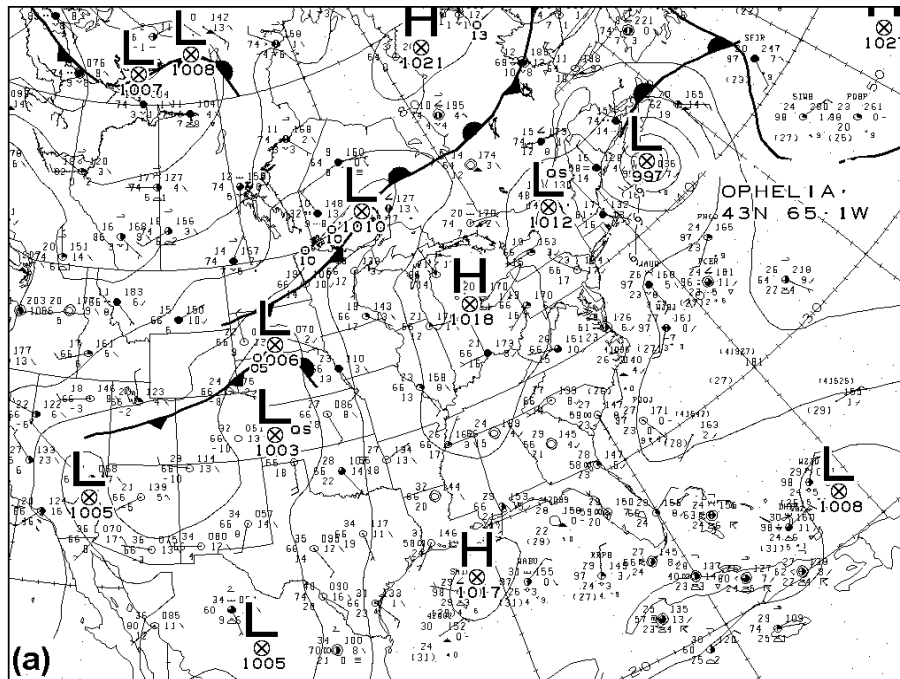


Fig. 6. Surface synoptic weather plot (conventional notation) with sea level pressure analysis (a), and 500-mb geopotential height and vorticity analysis (b), valid at 00/18. Analyses are taken from the Canadian Meteorological Centre DIFAX chart archives.

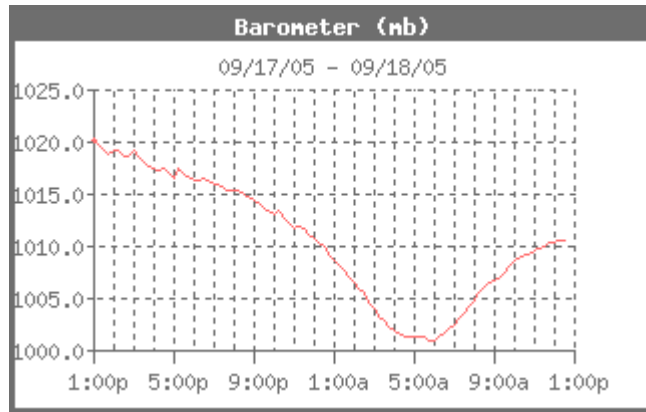


Fig. 7. Sea level pressure trace (mb) versus local time at a private weather station located near where Ophelia made landfall.

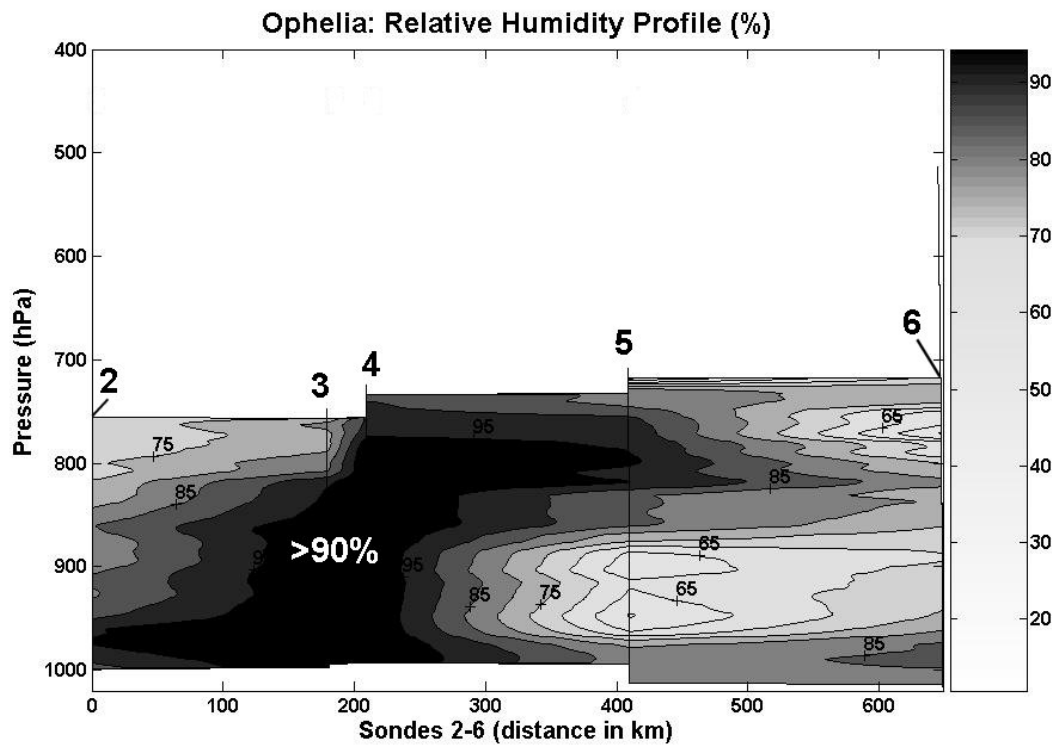


Fig. 8. Cross section (southwest to northeast) of relative humidity (every 5%) from dropsonde data between 1713/16 and 1850/16. Dropsonde locations are shown by numbers (2 through 6) in the plot.

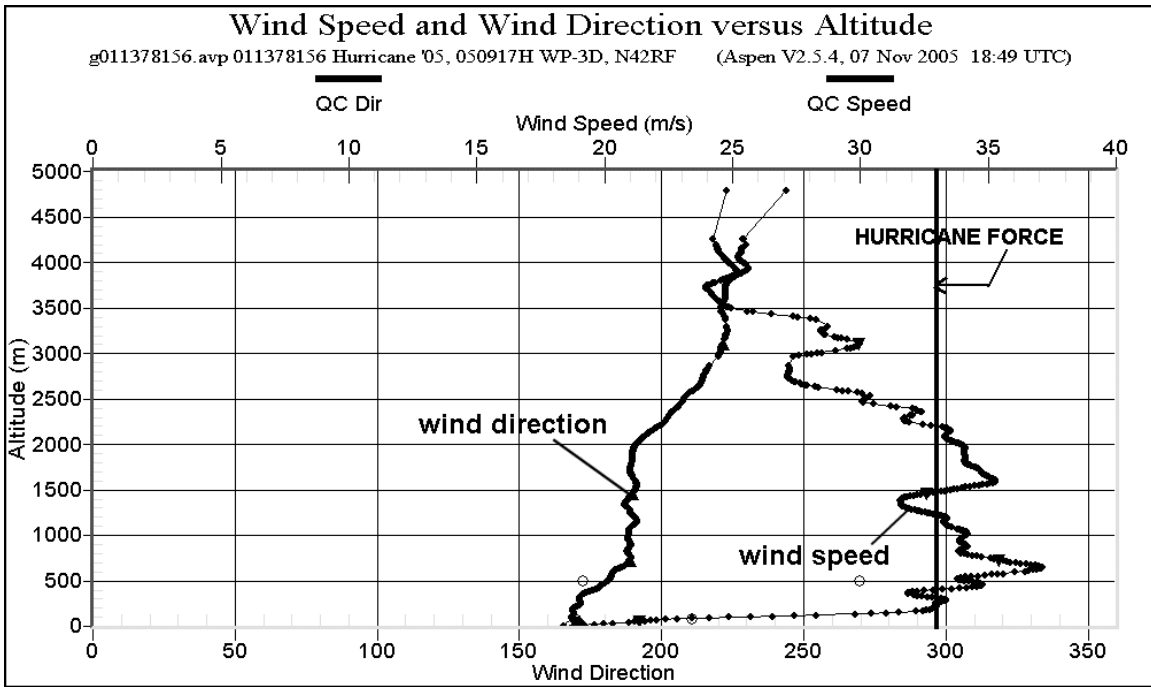


Fig. 9. Vertical wind speed and direction profile from a dropsonde located 200 km east-southeast of the storm center at 1718/17.

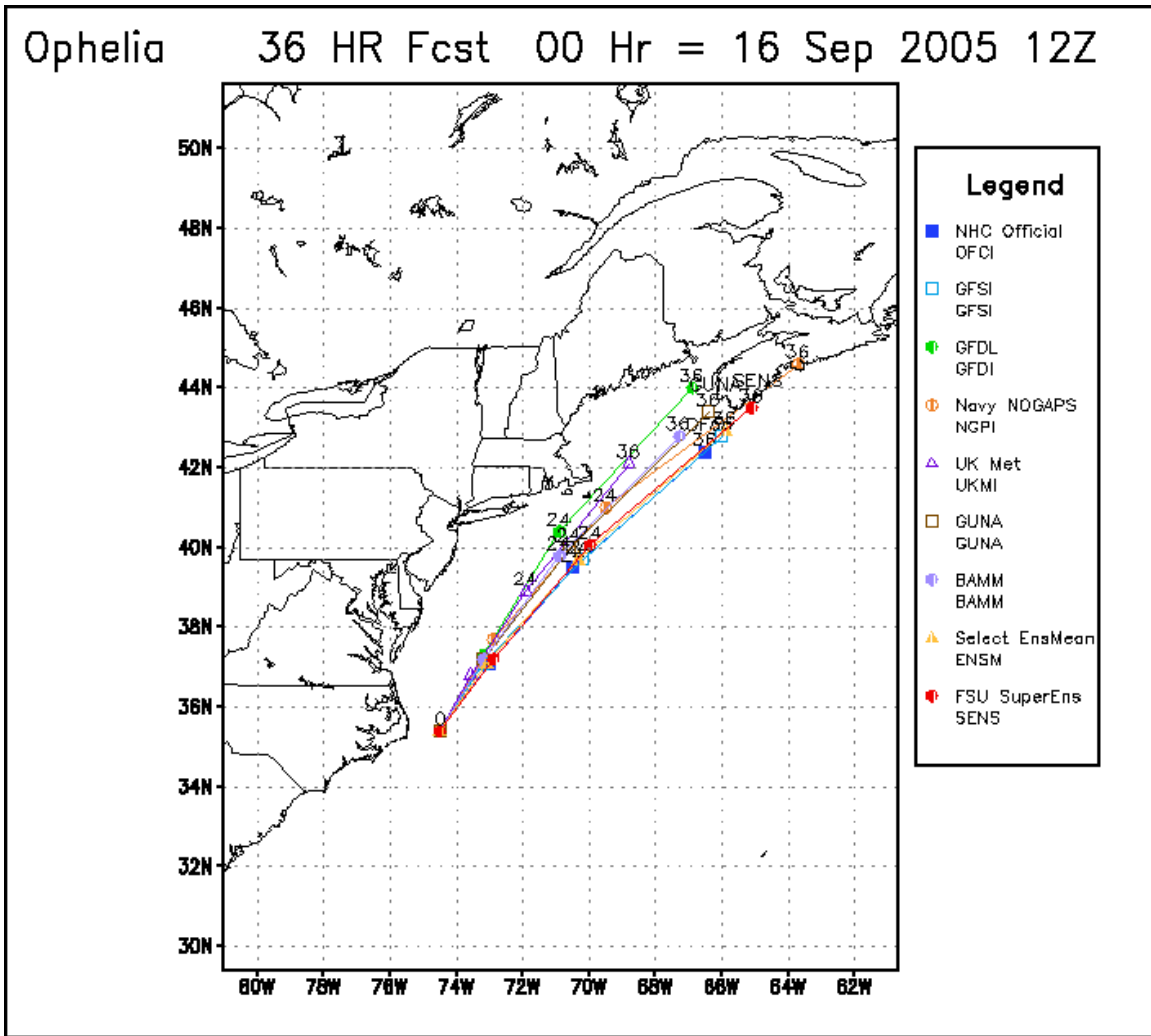


Fig. 10. Track forecasts with initial time 12/16 from various numerical models including the official National Hurricane Center (NHC) forecast and the Florida State Superensemble (FSU).

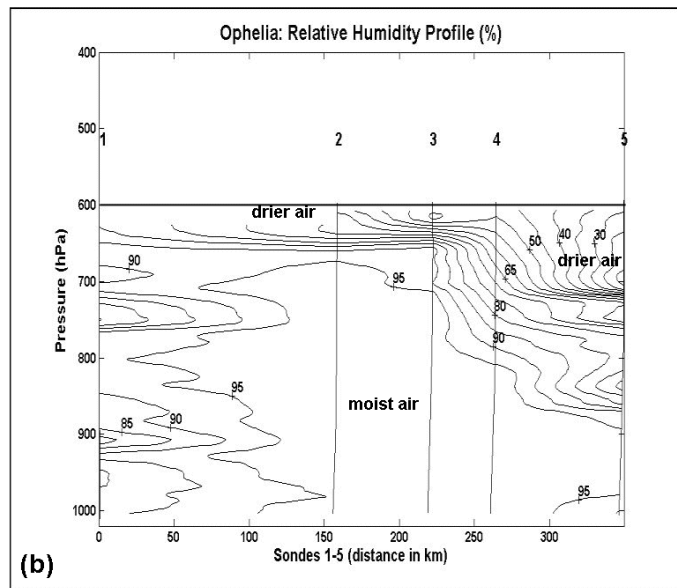
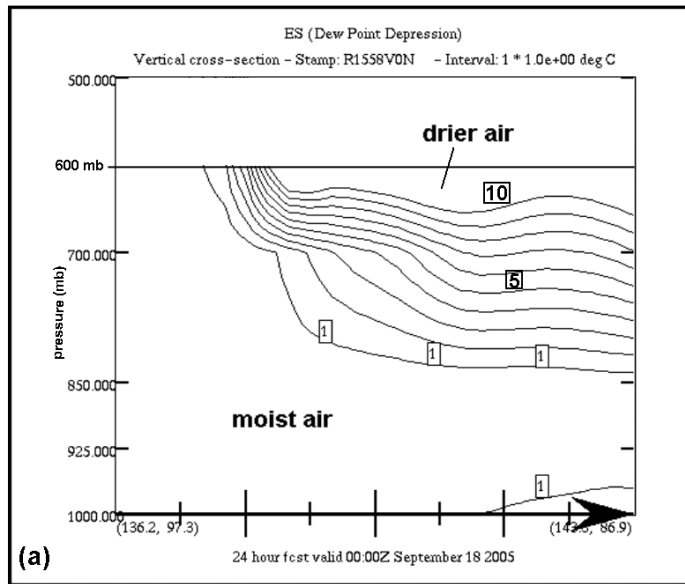


Fig. 11. Cross-sections showing vertical moisture structure ahead of Tropical Storm Ophelia on 16 September: (a) dew point depressions (every 1°C) from the 24-HR GEM forecast, and (b) relative humidity (every 5%) from dropsonde data. Low relative humidity correlates with large dew point depressions. The location of the dropsondes are shown with numbers and vertical lines in panel b. The center of the storm is near the middle of the cross-sections.

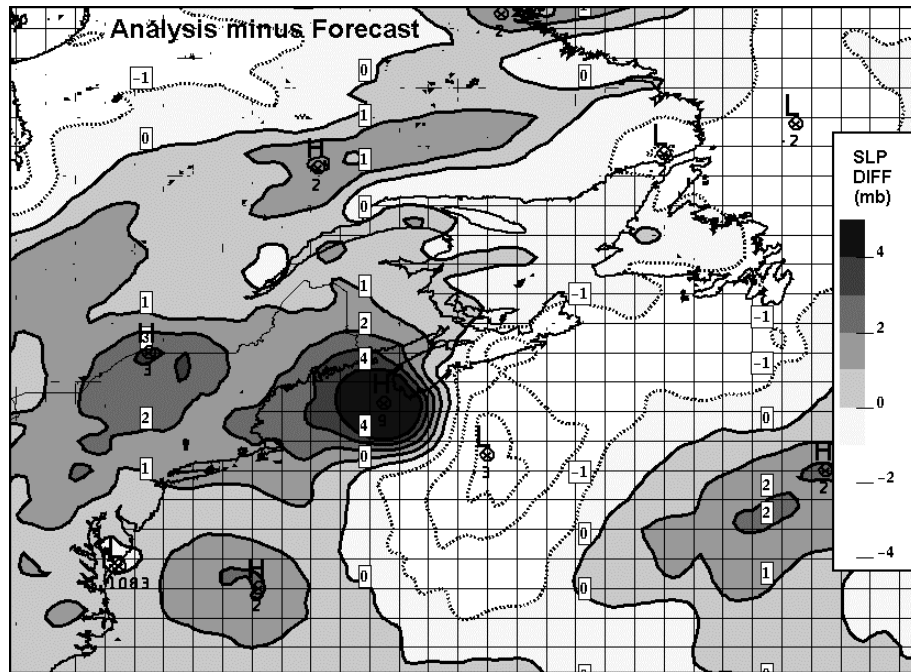


Fig. 12. Difference in sea level pressure between analysis and 24-HR GEM forecast (analysis minus forecast) valid at 00/18. Negative values are outlined with dotted contours (every 1 mb).

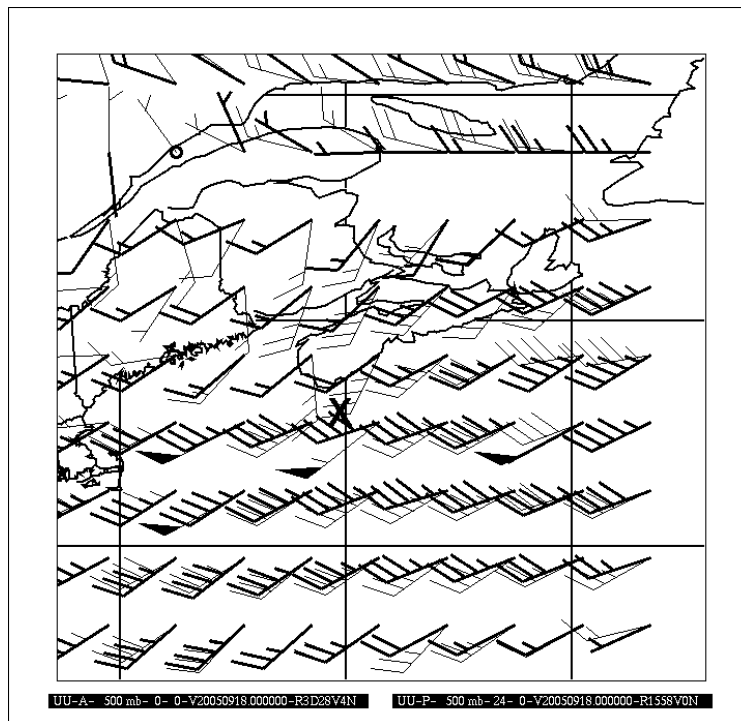


Fig. 13. Plot of 500-mb winds from the CMC analysis (bold barbs) and 24-HR GEM forecast (thin barbs) valid at 00/18. The observed surface position of Ophelia is denoted with a black X.