Hurricane Michael, 17 – 20 October 2000

Part I – Summary Report
and Storm Impact on Canada
Part II – Forecast and Warning Critique

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ABSTRACT

On 15 October, 2000, a subtropical depression formed north of the Bahamas as an upper-level low drifted southeast from the eastern United States. After several days being quasi-stationary over warm water (> 27°C), the system developed tropical characteristics and eventually became Hurricane Michael on 17 October. Michael began to track north-northeastward on 18 October ahead of a mid-tropospheric trough approaching from the northwest. During the morning of 19 October, Michael underwent rapid deepening after moving into the baroclinically-energetic region of the mid-latitude trough. The supply of this energy was enough to counteract the weakening which would have most certainly occurred over the colder waters south of Newfoundland. Consequently, Michael made landfall on the south coast of Newfoundland as a 75-knot category one hurricane with a central pressure of 965 mb.

This report, which is Part I of a two-part report, presents a comprehensive description of this unusual event of a hurricane re-intensifying at high latitudes, then making landfall in Canada. Section 1 outlines the synoptic history of the storm, section 2 contains meteorological data, section 3 summarizes damages and impacts, section 4 presents a forecast and warning summary, and information on the Convair 580 research flight appears in section 5. The report concludes with a summary in section 6.

1. Synoptic History

Between 13 and 15 October, 2000, an area of low pressure developed north of the Bahamas as an upper-level cold low drifted southeast over an old surface frontal zone. Satellite imagery revealed a wrapped-up cloud pattern around the low that was nearly stationary during that period. On 15 October the circulation appeared to be getting tighter some 500 km west-southwest of Bermuda. Late that night, the system was declared to be Tropical Depression 17 by the U.S. National Hurricane Center (NHC) as convection was beginning to wrap around the low's core. By the morning of 17 October the system had reached tropical storm strength with a ragged ring of convection enclosing an eye-like feature. Consequently, Tropical Depression 17 was renamed Tropical Storm Michael. The NHC storm track for Michael is shown in Figure 1. A "re-analysis" track will be presented in section 2 using various data collected from the storm while over Canadian territory.

Michael reached hurricane strength by late afternoon on 17 October based on satellite imagery and aircraft data. Convection was becoming more abundant and the upper level outflow pattern was improving. On 18 October the storm began moving north-northeastward ahead of a mid-latitude trough to the northwest. Early on 19 October the eye had disappeared on satellite imagery and it was becoming apparent that the storm was being sheared by the upper-level flow (see 500 mb flow in Figure 2). However, later that morning, a solid band of convection began wrapping around the storm (see Figure 3) and the eye subsequently returned. At this point Michael

was moving northeastward at approximately 35 knots, and a new low associated with the negatively-tilted trough over the U.S. Northeast formed about 150 km south of Cape Sable, Nova Scotia (see Figures 2 and 4). Additional information on this storm is available from Franklin et al. (2001) and Stewart (2000).

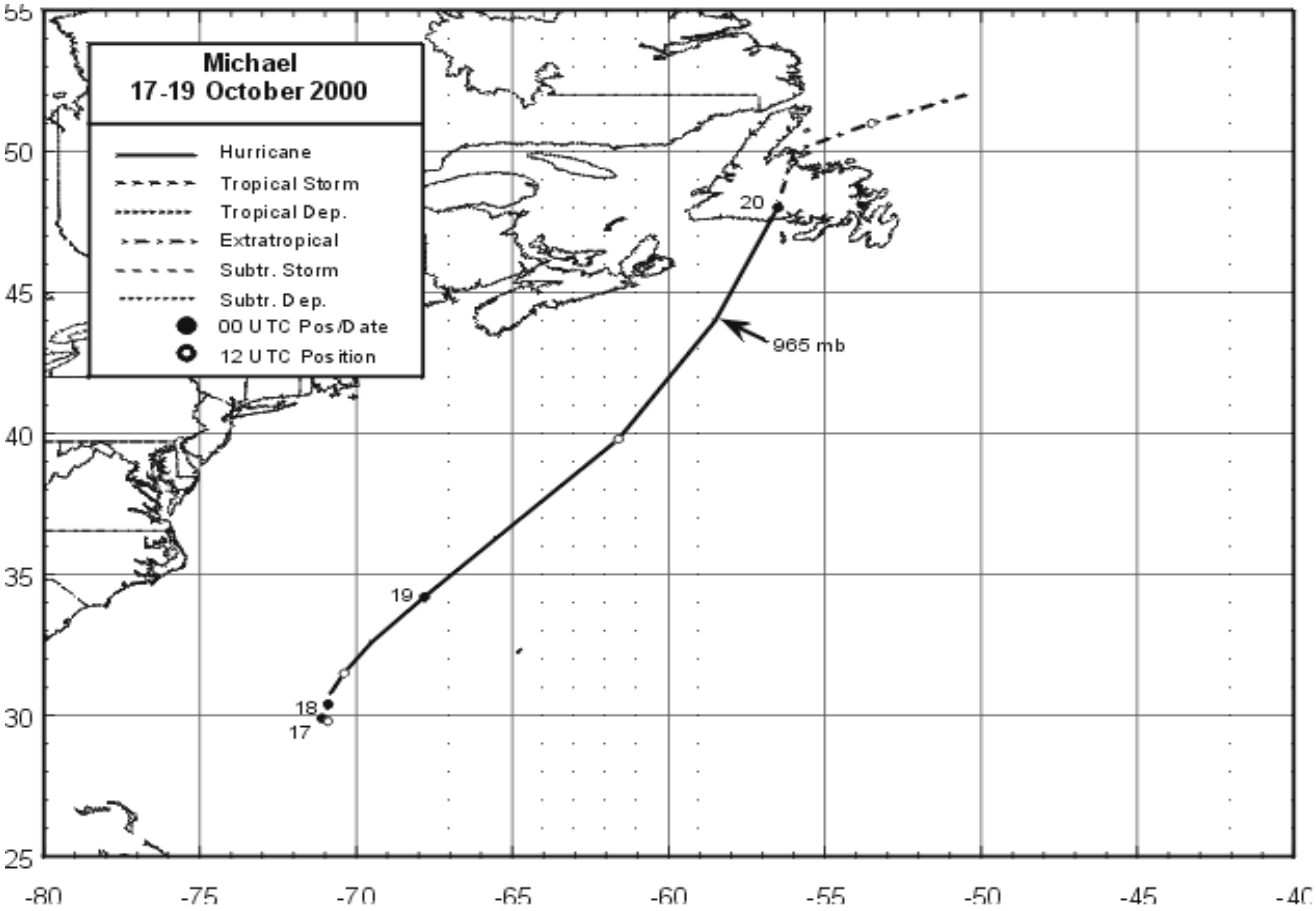


FIGURE 1 - National Hurricane Center track map for Hurricane Michael.

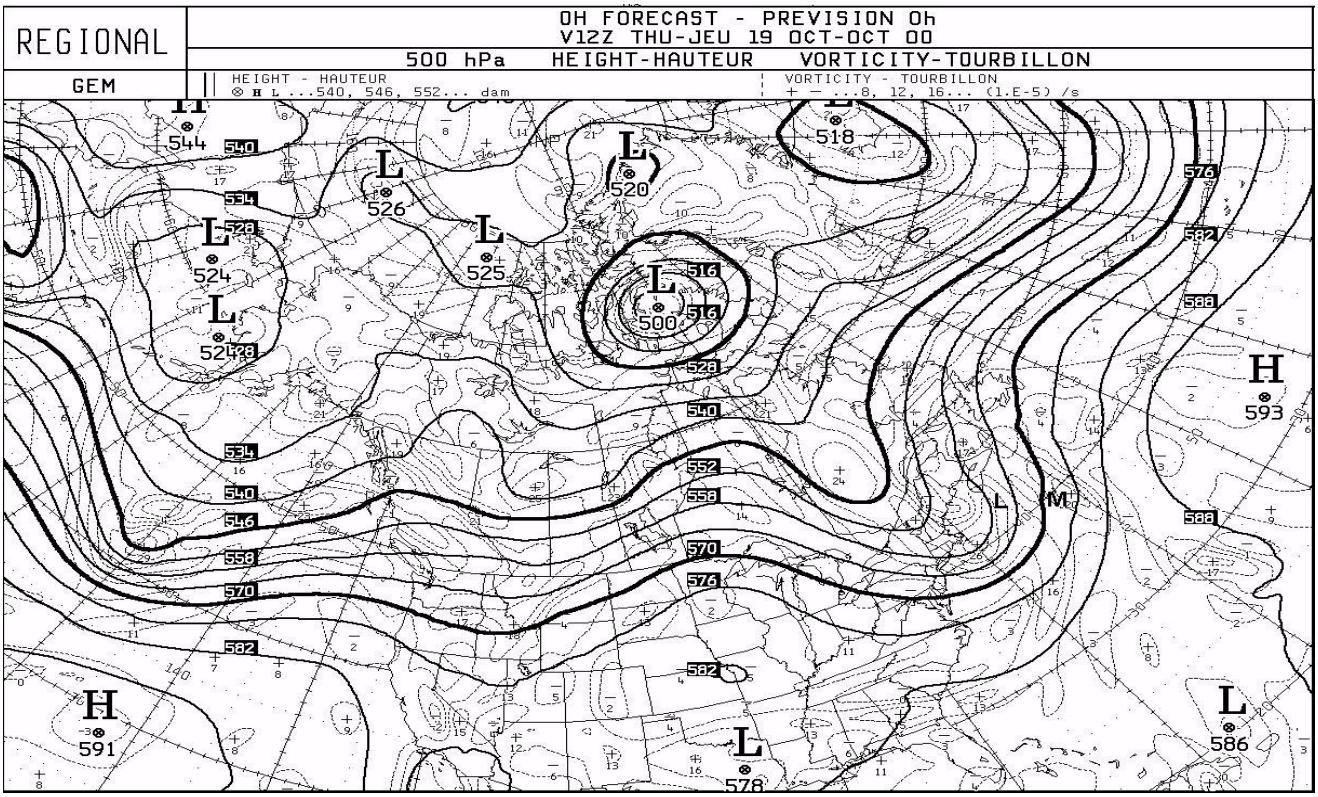


FIGURE 2 - GEM 00 HR PROG of 500 mb height and vorticity. Baroclinic low surface position marked with "L". Hurricane surface position marked with "M".

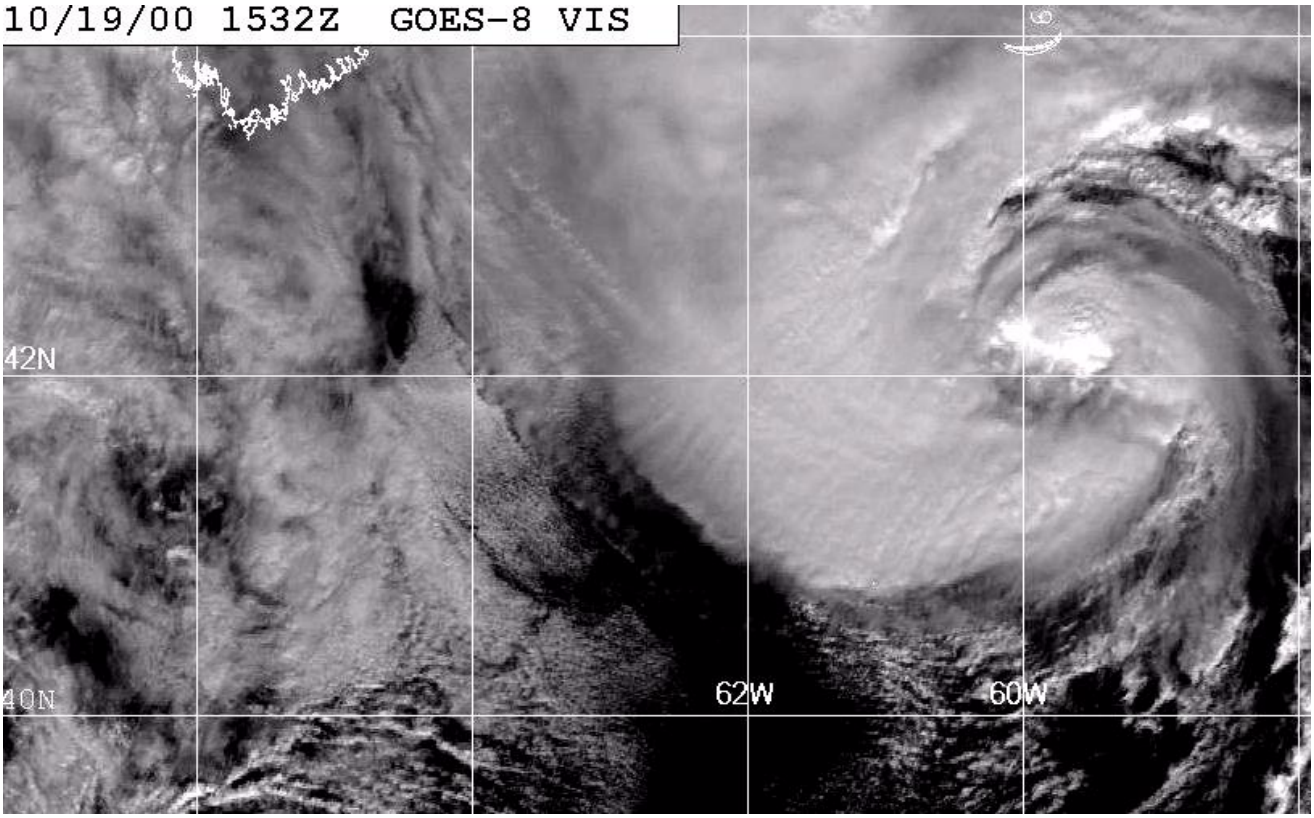


FIGURE 3 - GOES visible image of Michael at 1532 UTC 19 October.

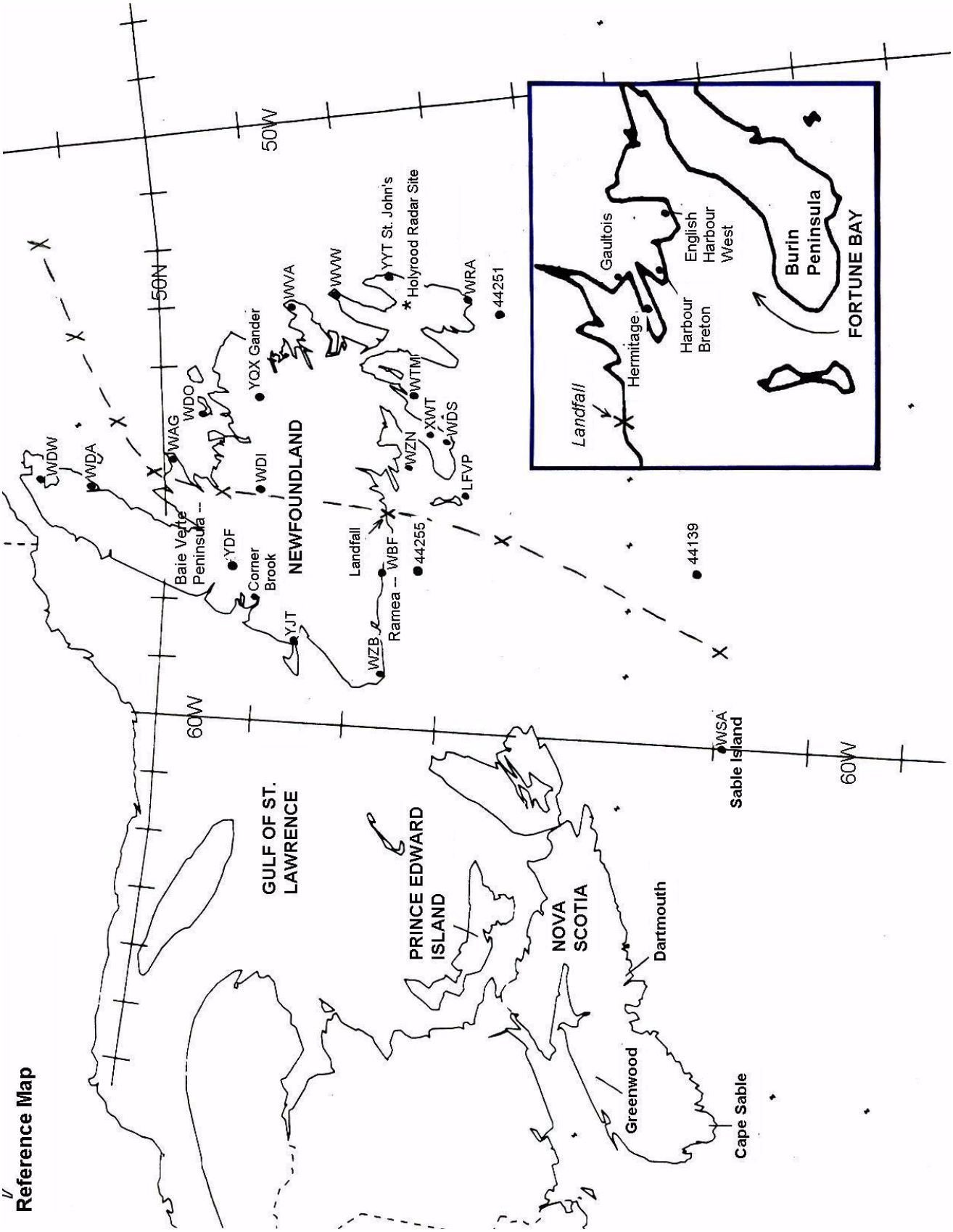


FIGURE 4 - Map of locations cited in the text.

During the afternoon of 19 October, a remarkable interaction occurring between the energetic trough and Michael resulted in explosive deepening. It is estimated that the deepening was equivalent to a rate of over 2 mb per hour in the six hours between 1200 UTC and 1800 UTC 19 October. A ship, the MSC Xingang (call sign 3EHR6), located just east of the centre at 1700 UTC reported a sea level pressure of 965.5 mb and a sustained southerly wind of 80 knots (anemometer height 30 metres - National Weather Service (2002)). At the time, Michael was racing northeastward at approximately 60 knots indicating just how quickly the cyclone was picked up by the upper-level flow. As the hurricane tracked toward the south coast of Newfoundland, the original extratropical low south of Nova Scotia became incorporated into the hurricane's circulation. Based on map data at 1800 UTC 19 October (see Figure 5) the low may have maintained its entity to the south-southwest of Michael's centre, with Michael located in the warm sector of the baroclinic wave shown. There was a line of convection and lightning along the warm front, while no convection was observed along the cold front. A new upper-level front formed in the warm airmass east of the system and extended well into the subtropics. It is believed that this was more like a moisture convergence zone acting as a stream for tropical moisture into the mid-latitudes (see the satellite image in Figure 6). There was also an abundance of convection with lightning along this front. This "hybrid" storm reached the south coast of Newfoundland just west of Harbour Breton around 8:00 p.m. local time (2230 UTC).

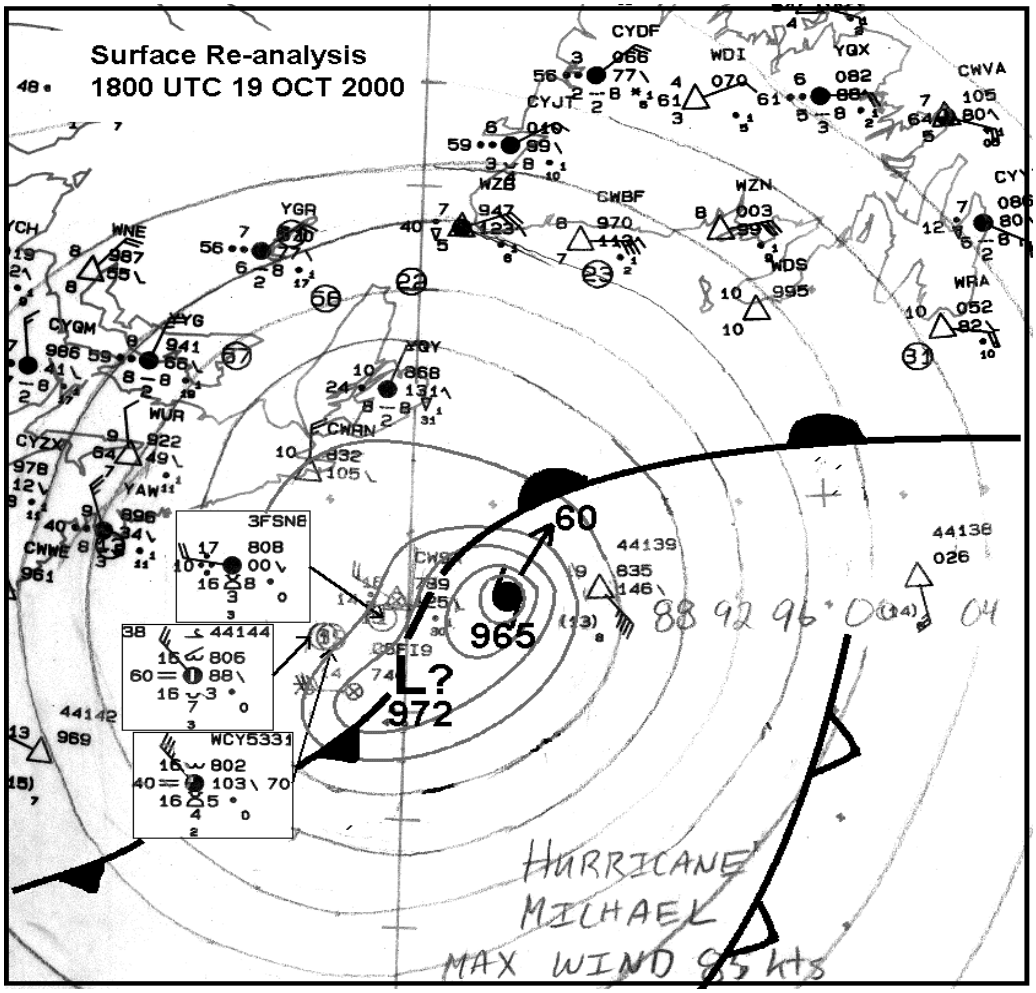


FIGURE 5 - Surface re-analysis at 1800 UTC 19 October

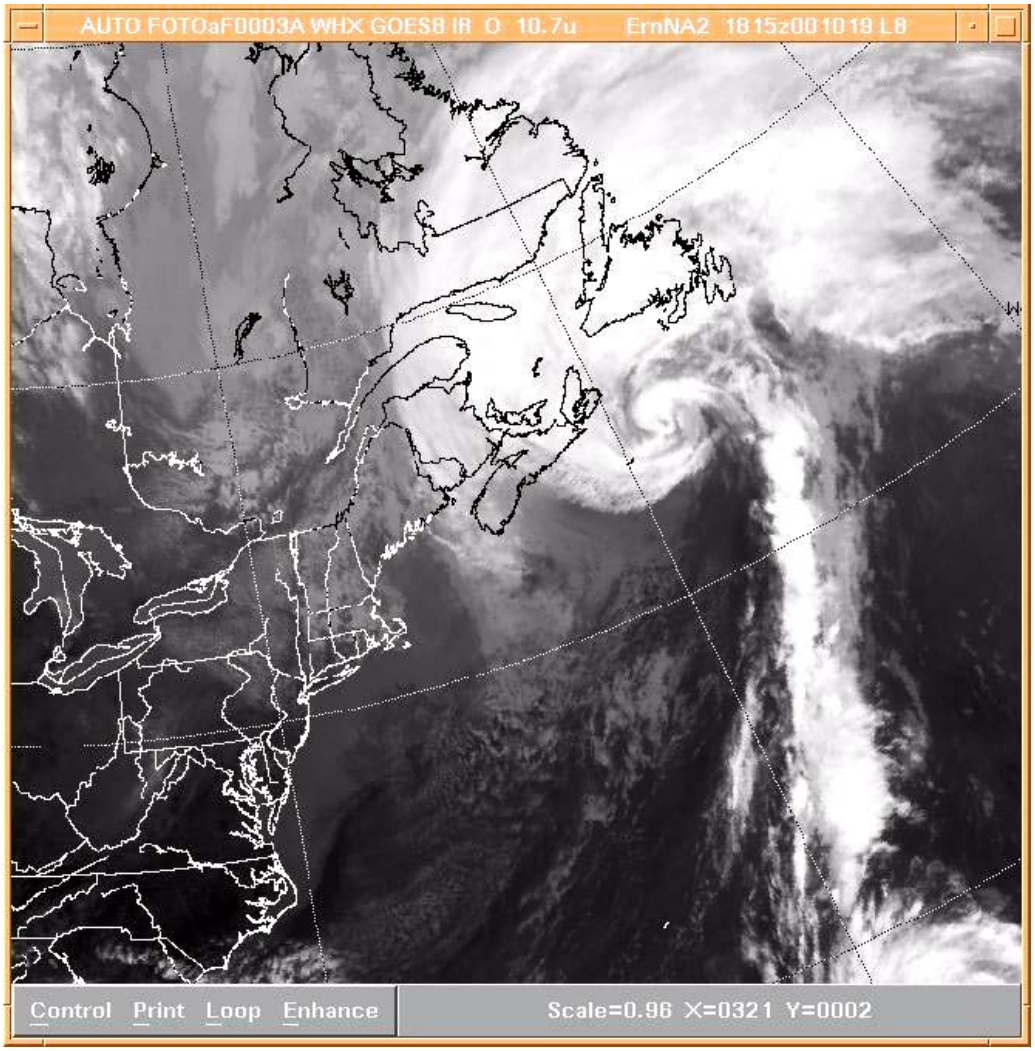


FIGURE 6 - GOES infrared satellite at 1815 UTC 19 October.

At landfall, radar imagery from Holyrood, Newfoundland (about 250 km to the east) revealed a continuous arc of echoes encircling over half of the north side of the centre (see Figure 7). This was believed to be the weakening eyewall. Convection was shallow, and almost non-existent over the southwestern quadrants of the storm. A satellite image (see Figure 8) just two hours prior to landfall shows the inner core convection beginning to erode from the southern side of the storm, exposing the low-level centre. As the storm moved inland, all deep-layered cloud and convection rushed northward leaving the characteristic comma-shaped pattern of an occluded extratropical cyclone. The trough which had accelerated Michael northward had formed a closed low over Prince Edward Island by 0000 UTC 20 October (see Figure 9) and was acting as a brake, causing the now extratropical storm to slow significantly during the six hours after landfall. By 0600 UTC, Michael had moved to lie just north of the Baie Verte peninsula. Surface analyses and observations show that the central pressure of 965 mb at landfall was maintained through the night as the storm moved inland. The sea level pressure field had expanded significantly, however, during that time. It was noted that the diameter of the 980-mb contour doubled between 0000 UTC and 0600 UTC 20 October (see Figure 10). It was also noted that at 0000 UTC 20 October just after landfall, the extratropical low which had originally formed off Nova Scotia may have still been present (see Figure 10a). Data from the Burgeo Bank Buoy (44255) indicated winds shifting to

northwesterly as Michael passed, then briefly to southeasterly between 0000 and 0100 UTC 20 October with a second small drop in sea level pressure. A similar pattern was observed three hours later at Sagona Island (WZN). These observations substantiate the theory that the extratropical low may have trailed Michael during the transition, and did not become completely absorbed until after 0000 UTC 20 October.

As the remnant hurricane became collocated with the upper-level low early on 20 October, it began to move northeastward and gradually weakened. Tropical characteristics by this time were virtually non-existent and the circulation of the storm expanded significantly in size.

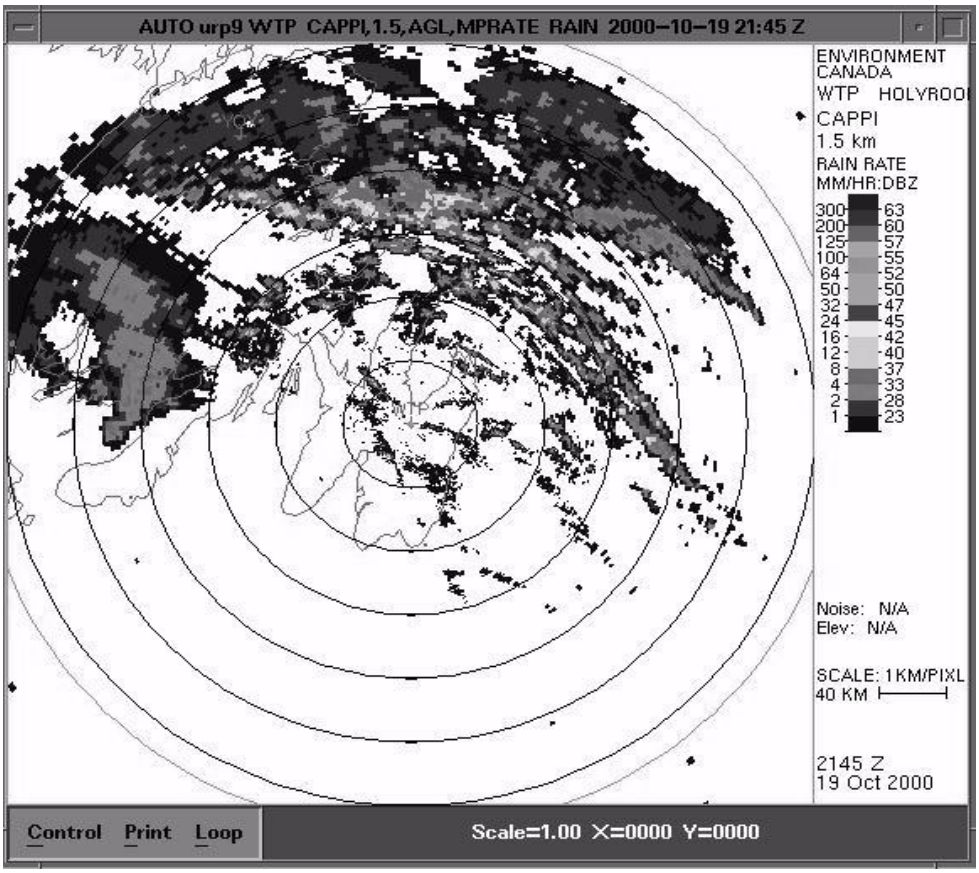


FIGURE 7 - 1.5 km CAPPI radar image from Holyrood.

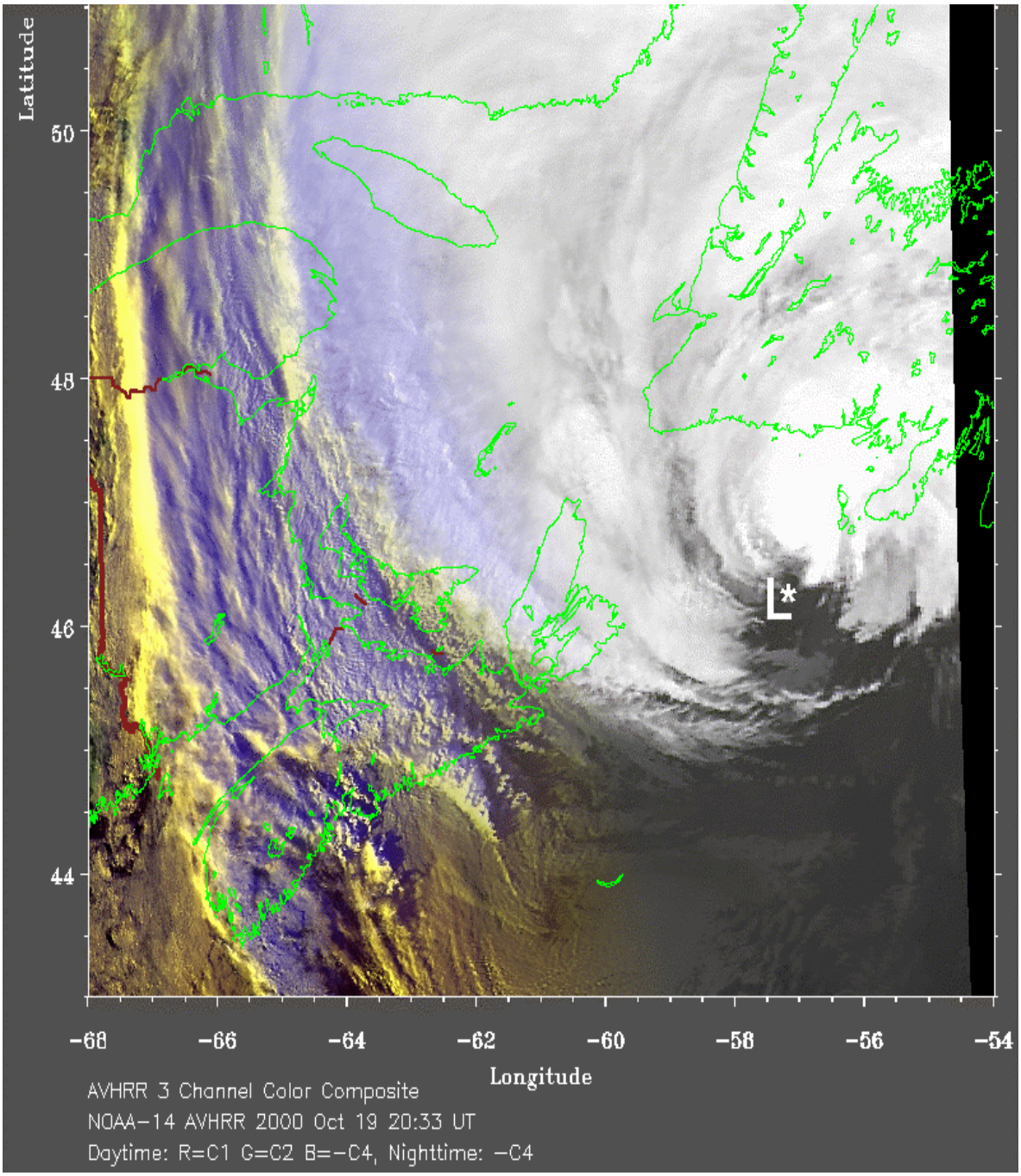


FIGURE 8. Advanced very high-resolution radiometer colour composite satellite image of Michael two hours before estimated time of landfall. Estimated surface position shown with an asterisk. *(Image courtesy of the Ocean Remote Sensing Group, Johns Hopkins University Applied Physics Laboratory)*

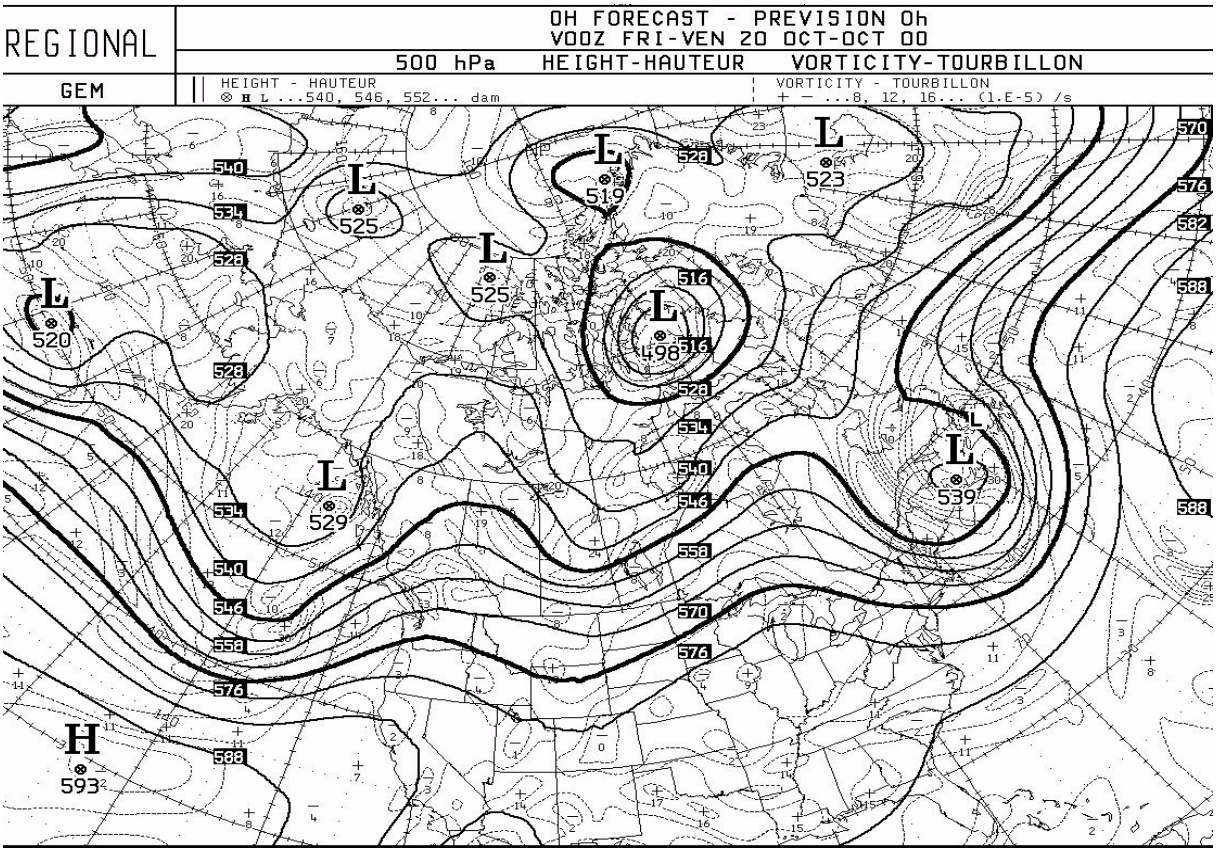
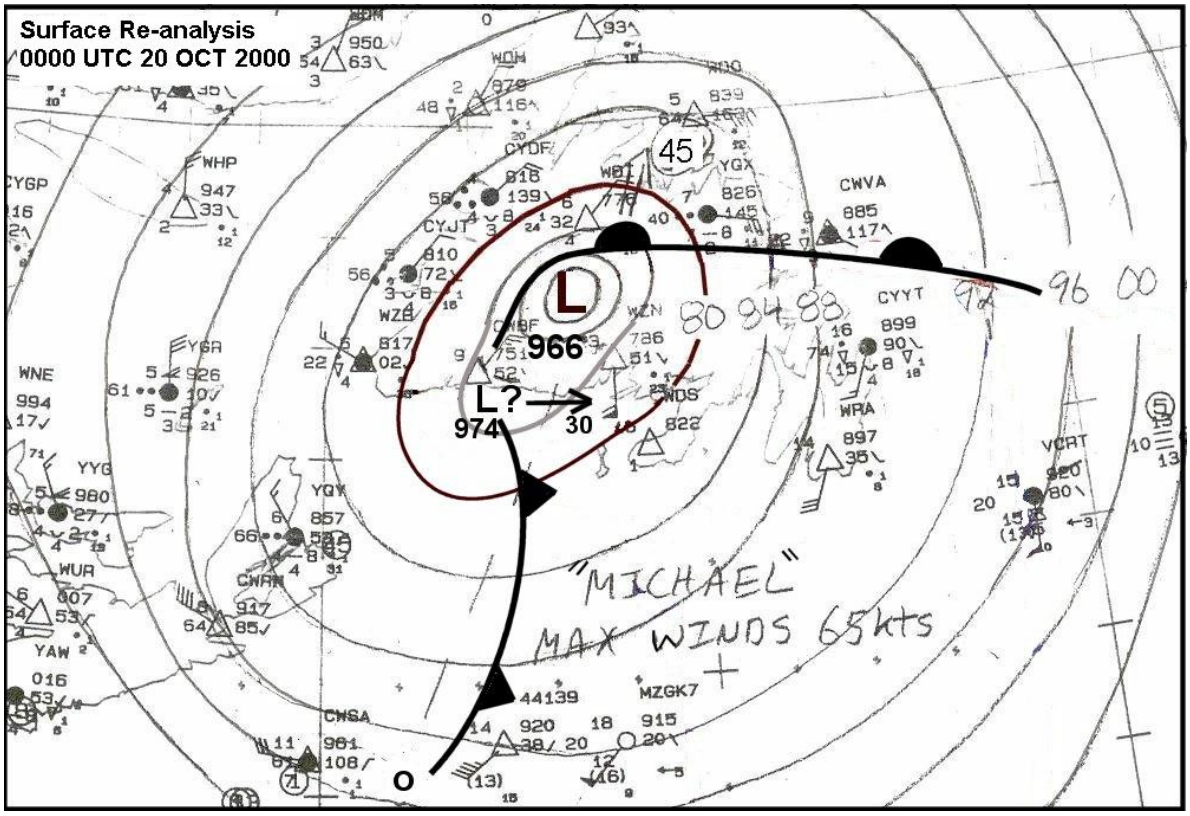
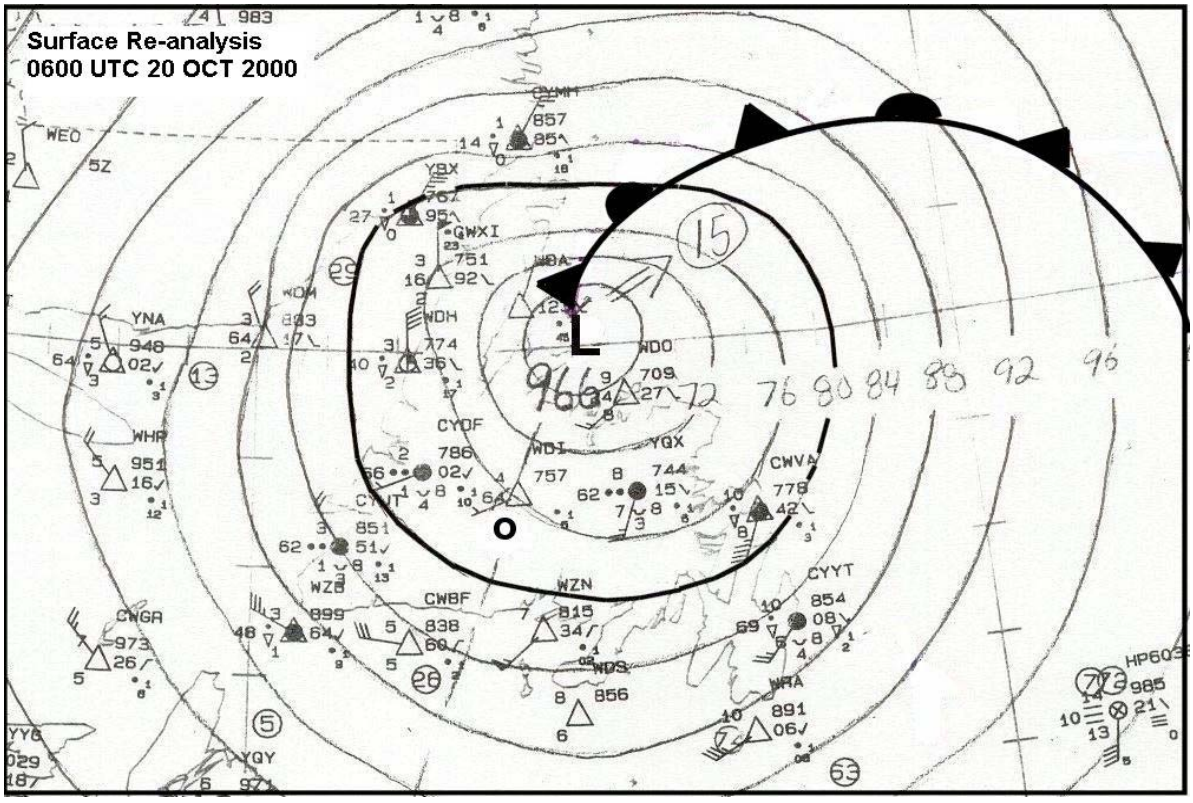


FIGURE 9 - GEM 00 HR PROG of 500 mb height and vorticity. Surface position of extratropical Michael marked with "L".



a)



b)

FIGURE 10 - Surface re-analyses at a) 0000 UTC and b) 0600 UTC 20 October.

2. Meteorological Statistics

A re-analysed track was determined for Hurricane Michael using various sources. These include data from the NHC best track archive (see storm track in Figure 1), track positions included in the Canadian Hurricane Centre (CHC) bulletins and data from all available ships, buoys, and surface weather stations used to "fine-tune" the track data during the period after 1200 UTC 19 October. Information on sea surface temperatures (SSTs) and forward speed of motion has also been added to the conventional track information. These data appear in Table 1 and are plotted on the maps in Figure 11.

TABLE 1 - Track data for Hurricane Michael

LAT	LON	TIME-UTC	WIND-KT	PRES-MB	STAT	SST-C	SPEED-KT
30.00	-71.20	10/15/12Z	30	1007	ST DEP	29	2 ENE
30.00	-71.50	10/15/18Z	30	1006	ST DEP	29	3 W
29.90	-71.80	10/16/00Z	35	1005	STS	29	3 WSW
29.90	-71.90	10/16/06Z	35	1005	STS	29	1 W
29.70	-71.70	10/16/12Z	35	1005	STS	28	3 SE
29.80	-71.40	10/16/18Z	35	1004	STS	28	3 ENE
29.90	-71.10	10/17/00Z	35	1003	TS	28	3 ENE
29.80	-71.00	10/17/06Z	45	1000	TS	28	1 SE
29.80	-70.90	10/17/12Z	55	995	TS	28	1 E
30.10	-70.90	10/17/18Z	65	988	HRCN-1	28	2 N
30.40	-70.90	10/18/00Z	65	988	HRCN-1	28	3 N
30.80	-70.80	10/18/06Z	65	986	HRCN-1	27	4 N
31.50	-70.40	10/18/12Z	65	984	HRCN-1	27	8 NNE
32.60	-69.50	10/18/18Z	70	979	HRCN-1	27	13 NNE
34.20	-67.80	10/19/00Z	75	983	HRCN-1	26	21 NE
36.30	-65.50	10/19/06Z	65	986	HRCN-1	25	28 NE
39.50	-62.00	10/19/12Z	75	979	HRCN-1	25	42 NE
41.30	**-60.20**	**10/19/15Z**	**75**	**975**	**HRCN-1**	**22**	**45 NE**
44.00	-58.90	10/19/18Z	85	965	HRCN-2	16	58 NNE
46.30	**-57.00**	**10/19/21Z**	**80**	**965**	**HRCN-1**	**13**	**53 NNE**
47.60	***-56.50***	***10/19/2230***	***75***	***965***	***HRCN-1***	***LANDFALL***	
48.50	-56.50	10/20/00Z	65	966	XT-1	INLD	44 N
49.50	**-56.30**	**10/20/03Z**	**65**	**966**	**XT-1**	**INLD**	**20 N**
50.20	-55.80	10/20/06Z	60	966	XT	10	15 NNE
51.00	-53.50	10/20/12Z	60	968	XT	8	17 ENE
52.00	-50.30	10/20/18Z	60	970	XT	8	22 ENE

LEGEND

Storm Status (STAT):
ST DEP – Subtropical Depression
STS – Subtropical Storm
TS – Tropical Storm
HRCN-1 – Hurricane Category 1 on the Saffir-Simpson Scale
HRCN-2 – Hurricane Category 2 on the Saffir-Simpson Scale
XT-1 – Extratropical Storm (Hurricane-force winds)
XT – Extratropical Storm (Storm-force winds)

WIND – Maximum sustained wind speed
PRES – Minimum central pressure
SST – Estimated Sea Surface Temperature beneath the eye/centre
SPEED - Translational speed and heading determined from previous 3- or 6-hr positions

Intermediate times are **boldface**

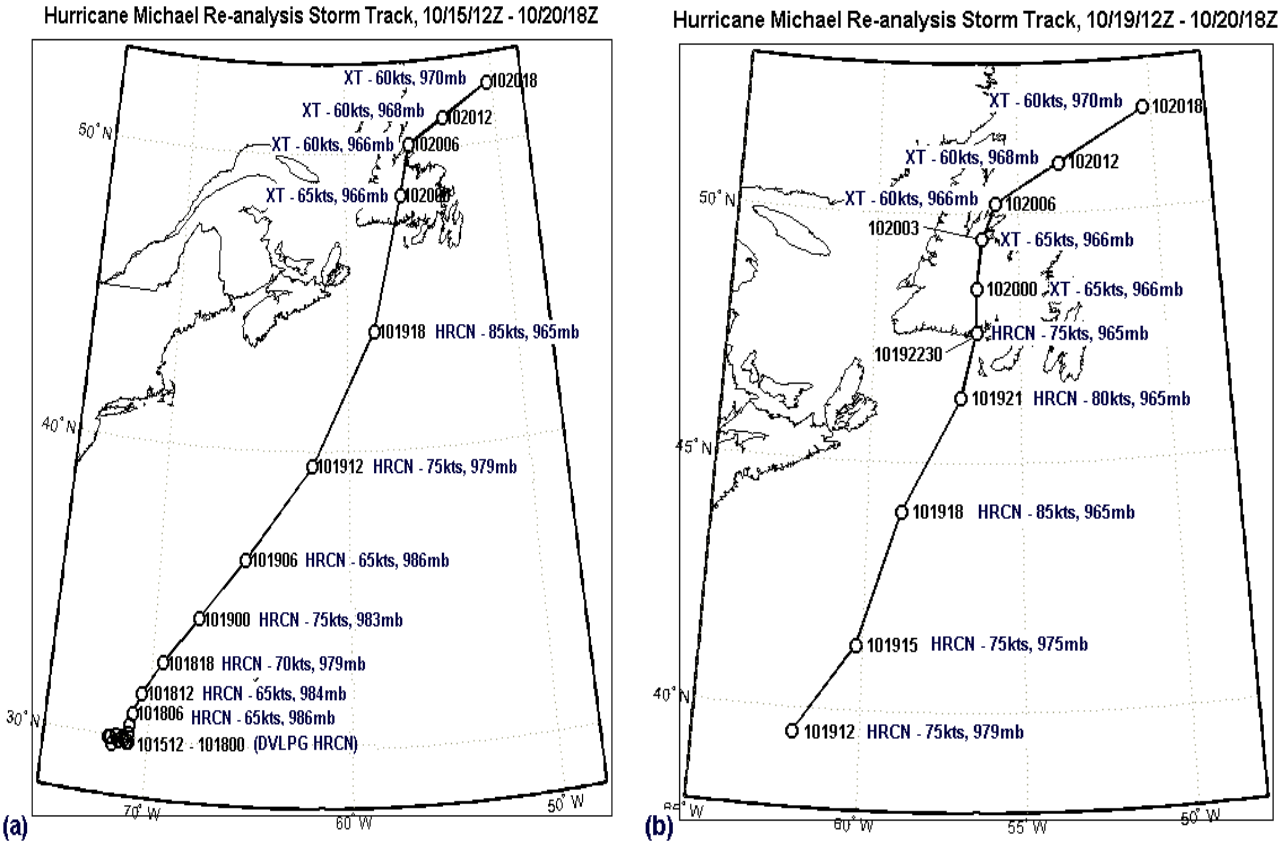


FIGURE 11 - Re-analysis track maps for Hurricane Michael for (a) the entire life cycle and (b) the latter period including re-intensification and transition. Times are UTC [mmddhh].

Michael passed close to Sable Island, ship 3EHR6, buoys 44255 and 44139, and a few automated surface stations in Newfoundland (see Figure 4). These data proved crucial in the issuing of warnings, production of surface analyses, and determination of wind speeds around the hurricane. A very crucial observation was from a ship (call sign 3EHR6) located about 120 km south-southeast of Sable Island at 1700 UTC 19 October:

```
Id     TDDHH   Lat    Long  Wind Cld  VVWX      Air  Dew  Sea Pressure DV
3EHR6 1917    43.0N  59.4W 1880   /  0R+       20.0 20.0     655 \550 W4
```

Until the time of this observation, the estimated minimum pressure was 975 mb with maximum sustained winds of 75 knots (1500 UTC 19 October). According to satellite imagery, the ship was located in the eastern portion of the eyewall; therefore, Michael was promptly upgraded to a category two hurricane with maximum sustained winds of 85 knots. This was the only observation from this particular ship during the event.

Note that the re-analyzed track takes a slight displacement to the west at the 18 UTC 19 October position, which was also around the time when Michael was meeting up with the baroclinic low to the northwest (see Figure 5). It is hypothesized that this slight "jog" to the west may have been in response to the two lows interacting. In the 1800 UTC surface analysis, the extratropical low may have been located in the trough to the southwest of Michael.

The storm tracked roughly midway between the Banquereau Bank buoy (44139—see Table 2) and Sable Island (CWSA—see Table 3) at 1800 UTC 19 October. These data were very useful in determining the pressure gradient near the centre and the evolution of the sea state. Significant wave height data from the buoy showed that seas gradually built to 4 m ahead of the storm then jumped to near 6 m as it passed. In the southwesterlies behind Michael, seas further built to near 8 m. At the Nickerson Bank Buoy (44251) about 30 km southwest of Cape Race, Newfoundland, seas built to near 5 m around the time Michael made landfall and to 7.5 m in its wake. At this point, the hurricane was moving too rapidly to allow for substantial wave growth, as noted in the evolution of seas at these buoys.

TABLE 2 - Observations from Moored NOMAD Buoy 44139, October 19-20

Id	TDDHH	Lat	Long	Wind	Air	Dew	Sea	Pressure	DV	Wave
44139	1915	44.3N	57.4W	1317/19	16.0	13.0		980 \081	0	3.7
44139	1916	44.3N	57.4W	1525/31	17.2	12.9		945 \091	0	3.4
44139	1917	44.3N	57.4W	1429/36	17.7	12.9		897 \113	0	3.3
44139	**1918**	**44.3N**	**57.4W**	**1442/54**	**18.8**	**12.9**		**835 \146**	**0**	**3.9**
44139	1919	44.3N	57.4W	-	-	-		-	-	-
44139	1920	44.3N	57.4W	2042/56	17.3	13.1		857 \040	0	5.7
44139	1921	44.3N	57.4W	2129/34	16.2	13.0		882 /046	0	5.1
44139	1922	44.3N	57.4W	2238/48	15.3	12.9		895	0	6.0
44139	1923	44.3N	57.4W	2238/54	14.6	12.8		905 /049	0	6.9
44139	2000	44.3N	57.4W	2342/56	14.0	13.0		920 /037	0	7.7
44139	2001	44.3N	57.4W	2438/48	12.7	13.3		942 /045	0	7.9

TABLE 3 - Observations from Sable Island (CWSA)

```
METAR CWSA 191700Z AUTO 06010KT 3/8SM -RA VV001 17/16 A2892 RMK PCPN  1.5MM PAST
   HR PRESFR SLP796
SPECI CWSA 191709Z AUTO 03012KT 1/8SM -RA VV001 17/16 A2889 RMK PRESFR
SPECI CWSA 191736Z AUTO 28019G25KT 1SM OVC001 16/15 A2892
SPECI CWSA 191737Z AUTO 28021KT 5/8SM -RA VV001 16/15 A2893
SPECI CWSA 191744Z AUTO 27028G35KT 3/8SM +RA VV001 17/16 A2896
SPECI CWSA 191749Z AUTO 28021G35KT 1/4SM +RA VV003 17/16 A2896
SPECI CWSA 191757Z AUTO 30018G25KT 3/8SM +RA VV004 16/15 A2892
SPECI CWSA 191759Z AUTO 31018G24KT 3/4SM RA VV004 16/15 A2890
METAR CWSA 191800Z AUTO 32021KT 1SM RA VV004 16/15 A2890 RMK PCPN 7.0MM PAST HR
   SLP789
SPECI CWSA 191804Z AUTO 32020G26KT 1SM -RA VV002 16/15 A2887
SPECI CWSA 191806Z AUTO 33021G26KT 1SM -RA VV001 16/15 A2885 RMK PRESFR
SPECI CWSA 191811Z AUTO 33017G25KT 1 1/8SM -RA VV001 16/15 A2883 RMK PRESFR
SPECI CWSA 191818Z AUTO 27018G25KT 1 3/8SM -RA VV001 16/15 A2895
SPECI CWSA 191821Z AUTO 25018G27KT 1 3/8SM -RA VV002 16/15 A2896
SPECI CWSA 191838Z AUTO 26015G20KT 2 1/2SM FEW003 FEW021 16/15 A2897 RMK PRESRR
```

Details of the time, location, and intensity at landfall are seen through an examination of the data from buoy 44255 (Table 4), the staffed station (LFVP) at St. Pierre (Table 5) and three automated surface stations (WDS, WBF, WZN - see Table 6). Key observations are boldface.

TABLE 4 - Observations from Canadian Moored Buoy 44255 (October 19–20)

TDDHH	Lat	Long		Wind	Air	Dew	Sea	Pressure
44255	1918	47.3N	57.4W	0633/42	7.9	9.4		950 \123
44255	1919	47.3N	57.4W	0633/44	8.0	8.9		902 \133
44255	1920	47.3N	57.4W	0536/46	8.1	8.9		837 \158
44255	1921	47.3N	57.4W	0436/48	8.5	8.9		760 \188
44255	1922	47.3N	57.4W	0031/44	10.1	8.9		**677 \225**
44255	1923	47.3N	57.4W	3419/25	9.8	9.0		725 \113
44255	2000	47.3N	57.4W	3203/09	9.2	9.0		762 /002
44255	2001	47.3N	57.4W	1303/07	8.7	9.0		765 /088
44255	2002	47.3N	57.4W	2611/23	8.3	9.0		762 /037
44255	2003	47.3N	57.4W	2619/23	7.5	8.9		785 /022

TABLE 5 - Observations from Staffed Station St.Pierre (LFVP) on October 19

LFVP 71805 ST. PIERRE FR 46.76N 56.17W 5m
METAR LFVP 191800Z 09023KT 1500 RA BR BKN003 09/09 Q0997
METAR LFVP 191900Z 08024KT 1500 RA BR BKN003 10/09 Q0991
METAR LFVP 192000Z 08022KT 2000 -RA BR OVC003 10/10 Q0986
METAR LFVP 192100Z 12031G44KT 2000 -RA BR OVC008 15/14 Q0977
METAR LFVP 192200Z **18051G63KT** 2000 R26/0600N -RA BR BKN006 15/14 Q0974

TABLE 6 - Observations from Automatic Stations WDS, WBF, WZN on October 19–20

WDS 71802 ST. LAWRENCE NF CN 46.92N 55.38W 49m
Following data from Thursday October 19 2000
WDS SA 1800 AUTO8 M M M 995/10/10/1026+43/M/ PK WND 0953 1736Z=
WDS SA 1900 AUTO8 M M M 944/11/11/0931+50/M/ PK WND 0850 1850Z=
WDS SA 2000 AUTO8 M M M 891/13/13/1035+44/M/ PK WND 1044 1952Z=
Following data from Friday October 20 2000
WDS SA 2100 AUTO8 M M M 836/16/16/1132+44/M/ PK WND 1045 2009Z=
WDS SA 2200 AUTO8 M M M **813**/18/08/1752+74/M/ PK WND 1574 2157Z=
WDS SA 2300 AUTO8 M M M 813/17/01/1944+60/M/ **PK WND 1793** 2210Z=
WDS SA 0000 AUTO8 M M M 822/16/01/2045+59/M/ PK WND 1972 2302Z=
WDS SA 0100 AUTO8 M M M 823/14/04/2142+59/M/ PK WND 2259 0057Z=
WDS SA 0200 AUTO8 M M M 812/13/05/2032+45/M/=
WDS SA 0300 AUTO8 M M M 806/13/13/2340+68/M/ PK WND 2268 0255Z=
WDS SA 0400 AUTO8 M M M 828/10/03<2443+57/M/ PK WND 2360 0316Z=
WDS SA 0500 AUTO8 M M M 845/09/05/2445+68/M/ PK WND 2474 0446Z=
WDS SA 0600 AUTO8 M M M 856/08/06/2547+65/M/ PK WND 2571 0532Z=

WBF 71194 BURGEO 2 (AU8) NF CN 47.62N 57.62W 12m
Following data from Thursday October 19 2000
WBF SA 1800 AUTO8 M M M 970/08/07/0833+41/M/0024 PK WND 0944 1716Z=
WBF SA 1900 AUTO8 M M M 913/07/06/0839+49/M/0040 PCPN 4.0MM PAST HR PK WND 0850 1848Z=
WBF SA 2000 AUTO8 M M M 866/07/07/0837+47/M/0120 PCPN 8.0MM PAST HR PK WND 0955 1906Z=
WBF SA 2100 AUTO8 M M M 803<08/07/0743+56/M/0191<PCPN 7.1MM PAST HR PK WND 0761 2034Z /R19/=
WBF SA 2200 AUTO8 M M M 727<08/07/0543+67/M/0259<PCPN 6.8MM PAST HR **PK WND 0767** 2157Z=
WBF SA 2300 AUTO8 M M M **725**/08/07/0335+56/M/0297<PCPN 3.8MM PAST HR PK WND 0566 2208Z /R30/=

Following data from Friday October 20 2000

```
WBF SA 0000 AUTO8 M M M 751/09/07/0427+44/M/0297<PK WND 0262 2322Z=
WBF SA 0100 AUTO8 M M M 756/08/06/0321+29/M/ PK WND 0347 0003Z=
WBF SA 0200 AUTO8 M M M 764/07/07/3503/M/ PK WND 0232 0103Z=
WBF SA 0300 AUTO8 M M M 778/07/06/2809/M/ PK WND 2819 0205Z=
WBF SA 0400 AUTO8 M M M 800/06/06/2820+29/M/0011 PCPN 1.1MM PAST HR PK WND 2829
   0354Z=
WBF SA 0500 AUTO8 M M M 822/06/05/2817+29/M/0011 PK WND 2729 0442Z=
WBF SA 0600 AUTO8 M M M 838/05/05/2828+40/M/0018 PCPN 0.7MM PAST HR PK WND 2940
   0556Z=
```

WZN 71408 SAGONA ISL (AU4) NF CN 47.37N 55.80W 35m

Following data from Thursday October 19 2000

```
WZN SA 1847 AUTO4 M M M 967/08/M/0741+48/M/0122 PCPN 3.0MM PAST HR=
WZN SA 1947 AUTO4 M M M 910/08/M/0543+50/M/0118 PCPN 11.8MM PAST HR=
WZN SA 2047 AUTO4 M M M 848<09/M/0548+57/M/0150 PCPN 3.2MM PAST HR=
WZN SA 2147 AUTO4 M M M 776<14/M/1047+63/M/0200 PCPN 5.0MM PAST HR=
WZN SA 2247 AUTO4 M M M 754/14/M/1569+81<M/0204 PCPN 0.4MM PAST HR=
WZN SA 2347 AUTO4 M M M 786/13/M/1861+73<M/0204 PRESRR 5062 ?8MMM?=
```

Following data from Friday October 20 2000

```
WZN SA 0047 AUTO4 M M M 792/12/M/1855+65<M/0204 3016 ?6MMM?=
WZN SA 0147 AUTO4 M M M 790/11/M/1850+58/M/ 0036 ?7MMM?=
WZN SA 0247 AUTO4 M M M 779/11/M/1845+52/M/ 8007 ?7MMM?=
WZN SA 0347 AUTO4 M M M 792/08/M/2247+53/M/ 5000 ?1MMM?=
WZN SA 0447 AUTO4 M M M 799/08/M/2252+63<M/0002 PCPN 0.2MM PAST HR=
WZN SA 0547 AUTO4 M M M 810/07/M/2355+63<M/0002 1031 ?8MMM?=
WZN SA 0647 AUTO4 M M M 824/07/M/2347+57/M/0002 3032 ?5MMM?=
```

Data for Sagona Island (WZN) have been graphed (see Figure 12) to show the trends in sea level pressure, winds, and temperature as the hurricane passed approximately 80 km to the west. A sudden increase in wind accompanied by an abrupt rise in temperature occurred at this time. The pressure dropped rapidly (~ 6mb/hr) up until 2247 UTC, but afterwards only rose gradually. In fact, the pressure actually dropped slightly to 978 mb near 0300 UTC. This pattern was observed at other stations as well. As mentioned before, this second minimum was likely associated with the passage of the low or trough extending to the south-southwest of Michael.

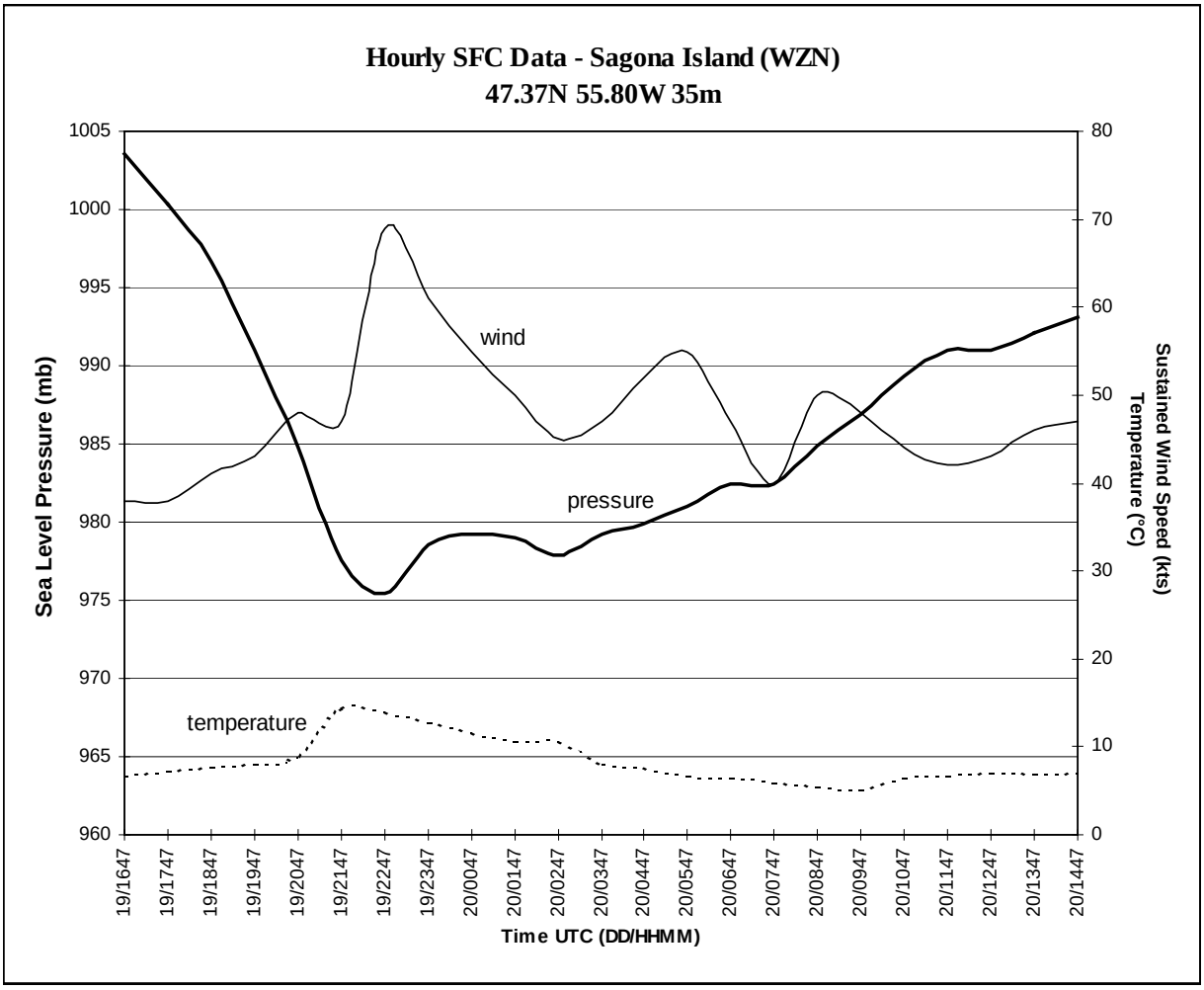


FIGURE 12 - Time series of surface data from Sagona Island (WZN)

The estimated time of landfall was 2230 UTC 19 October at 47.6N 56.5W (about 60 km west of Harbour Breton, Newfoundland). The strongest sustained winds reported by a land station were 69 knots with gusts to 81 knots from Sagona Island at 2247 UTC. Note that this station only reported data once every hour. The sustained wind is a 2-minute mean and the gusts represent the highest wind in the previous 10 minutes. A peak wind gust of 93 knots from St. Lawrence (WDS) at 2210 UTC was the highest wind speed recorded. The lowest pressure observed near landfall was 967.7 mb from the Burgeo Bank buoy (44255) at 2200 UTC with an incredible 22.5-mb drop in the preceding three hours. The estimated minimum pressure at landfall was 965 mb.

Rainfall amounts and rates from Michael were not quite typical of those found in category one hurricanes. At the time of landfall, Michael was moving very fast (approximately 50 kts) and convection—although still somewhat organized in the remnant eyewall—was becoming shallower. This is no surprise since SSTs near the coast were only 13°C (55°F). The rule of thumb used by forecasters at the National Hurricane Center for estimating rainfall amounts in hurricanes is to divide 2500 by the forward speed of the storm in knots. In Michael's case, 2500 / 50 kt = 50 mm. Amounts near 30 mm (a little over one inch) fell along the track while amounts up to 75 mm (3 inches) were recorded to the west of the track over western and northern Newfoundland. The higher amounts in these locations were attributed to the large-scale forcing associated with the interacting trough over the Gulf of St. Lawrence as well as enhancement owing to elevated terrain. A summary of total rainfall and maximum wind statistics appears in Table 7.

TABLE 7 - Wind and rainfall reports during Hurricane Michael

STATION	ID	LOCATION	ELEV	MAX WND/PK GUST	PRECIP
SABLE ISL	WSA	43.93N 60.02W	4m	280/36G50KT	30mm
SAGONA ISL	WZN	47.37N 55.80W	35m	150/**69**G81KT	33mm
ST LAWRENCE	WDS	46.92N 55.38W	49m	170/52G**93KT**	-
ST PIERRE	LFVP	46.77N 56.17W	5m	180/51G63KT	-
MARTICOT ISL	WTM	47.33N 54.58W	27m	230/54G69KT	-
WINTERLAND	XWT	48.13N 55.33W	29m	190/40G61KT	27mm
BURGEO	WBF	47.62N 57.62W	12m	050/43G67KT	34mm
CAPE RACE	WRA	46.65N 53.07W	28m	260/44G66KT	19mm
BONAVISTA	WVA	48.67N 53.12W	30m	220/44G73KT	21mm
GANDER	YQX	48.95N 54.57W	151m	180/32G45KT	19mm
BADGER	WDI	48.97N 56.07W	105m	270/19G41KT	27mm
ST JOHN'S	YYT	47.62N 52.75W	140m	230/35G63KT	27mm
GRATES COVE	WVW	48.17N 52.93W	18m	230/46G69KT	-
TWILLINGATE	WDO	49.68N 54.80W	92m	270/45G61KT	17mm
PORT AUX BASQUES	WZB	47.57N 59.15W	38m	300/36G46KT	58mm
STEPHENVILLE	YJT	48.55N 58.55W	26m	300/28G44KT	45mm
DEER LAKE	YDF	49.22N 57.38W	22m	060/20G35KT	45mm
LA SCIE	WAG	49.92N 55.67W	194m	310/30G55KT	49mm
ENGLEE	WDA	50.72N 56.12W	29m	-	**75mm**
ST ANTHONY	WDW	51.38N 56.10W	29m	010/36G59KT	-

STATION	MIN PRES	TIME(UTC)	TIME PK GUST
WSA	976.2mb	19/1811	19/2200
WZN	975.4mb	19/2247	19/2247
WDS	980.6mb	20/0300	19/2210
LFVP	974.0mb	19/2200	19/2200
WTM	978.8mb	20/0334	20/0515
XWT	977.4mb	20/0300	19/2306
WBF	972.5mb	19/2300	19/2157
WRA	988.4mb	20/0400	20/1026
WVA	978.3mb	20/0700	20/0700
YQX	973.6mb	20/0500	20/0300
WDI	972.0mb	20/0100	20/1031
YYT	984.8mb	20/0500	20/0940
WVW	982.6mb	20/0500	20/0622
WDO	969.8mb	20/1100	20/1200
WZB	979.4mb	19/2200	20/0600
YJT	980.0mb	20/0300	20/1200
YDF	977.6mb	20/0400	19/2300
WAG	**968.2mb**	20/1000	20/1305
WDA	-	-	-
WDW	972.0mb	20/0800	20/1000

3. Damage and Impacts

For the most part, damage associated with Michael was limited and caused mainly by high winds and not to coastal or inland flooding. No part of the island was left unaffected, although most of the damage was confined to a few small communities east of where Michael had made landfall (see Figure 4). Power outages, lasting a few hours, were reported in Harbour Breton, Gaultois, Hermitage, and English Harbour West. Many homeowners reported vinyl siding being peeled off, windows being smashed, and shingles torn from roofs. The community of Gaultois, located about 50 km east of landfall, appeared to sustain the most damage. A single-storey home lost its entire

roof. A large segment of the roof at a nearby hotel was also lost. Throughout the town, service lines were left dangling, trees uprooted, and fences damaged. Senior residents described the wind as being horrifying and the worst they could remember. Power interruptions were witnessed as far east as St. John's and as far west as Corner Brook, where winds were strong enough to break large tree branches.

On the water, a tug (the Atlantic Elm) in Fortune Bay lost its tow to an unmanned barge (the Portland Star) around 7:00 p.m. NDT when seas became too rough. The barge, containing 8000 metric tonnes of cement and 10000 litres of diesel fuel, was later reported to have sunk somewhere in Fortune Bay. Pleasure craft moored at ports around Fortune Bay were damaged or capsized. The storm surge from Michael caused little coastal flooding since it arrived at low tide. The tide gauge at Argentia, about 200 km east of landfall, reported a surge near 80 cm, or just less than 3 feet. It is possible that the surge in Fortune Bay may have been up to 5 feet, but there were no confirming reports. Passenger ferry service between Newfoundland and Nova Scotia was disrupted. Vessels had difficulty docking and passengers had to ride out the storm just offshore.

4. Forecast and Warning Summary

Hurricane Michael presented a great challenge for forecasters. The most challenging aspect of this event was determining how the hurricane would interact with the baroclinic low off Nova Scotia. The main question was which system would become the dominant feature. Large-scale numerical model performances on 18 October presented variations on the solution: The Canadian Global Environmental Multiscale (GEM) model appeared to be developing the remnant system, but at the expense of Michael. The U.S. Nested Grid Model (NGM) had a similar idea, but less intense with the baroclinic development. The U.S. Medium Range Forecast (MRF) model maintained Michael out to 0000 UTC 20 October but had the tropical system well south of the GEM position. Tropical models used in Miami insisted that increasing shear would cause Michael to weaken.

It was not until the morning of 19 October that there were firm indications that Michael would end up being the dominant centre. Wind warnings (for gusts to 110 km/h) were issued by the Newfoundland Weather Centre (NWC) for the Avalon Peninsula, Burin Peninsula, East Coast, and Central Newfoundland forecast regions. Heavy rainfall advisories (up to 40 mm) were also issued for the East Coast, Central Newfoundland, South Coast (except the Burin peninsula), and the West Coast forecast regions. After confirmation with the Canadian Hurricane Centre in Dartmouth on the validity of ship 3EHR6, the NWC amended the public forecast at 5:30 p.m. local time (2000 UTC). The amendment was to upgrade the wind warning for the South Coast (east of Burgeo), including the Burin Peninsula, for southerly winds of 70 km/h gusting to 130 km/h for Thursday (19 October) evening. Rainfall amounts were left unchanged. In the 10:30 p.m. (0100 UTC 20 October) public forecast update, Michael was well inland and rainfall advisories were continued only for the south coast (Burgeo and west), and the West Coast. Wind warnings remained in effect for westerlies gusting to 110 km/h on the south side of the remnant storm on 21 October.

Storm force wind warnings were in effect for the majority of Newfoundland waters in the marine forecast issued at 1800 UTC 19 October. Generally, these warnings were for winds of up to 50 knots: first in the southeasterlies ahead of, then in the westerlies behind Michael. As with the public forecast, a revised marine forecast was sent out at 5:00 p.m. after verification of the hurricane's intensity. The amendment was to upgrade the storm warning to a hurricane-force wind warning (65 to 75 knots) for the Southwest Coast east of Ramea. For the South Coast region, storm-force winds of 50 knots were upgraded to 60 knots.

In addition to these regular products issued by the NWC, three Special Weather Statements were issued. The first of these was issued at 9:50 p.m. (0020 UTC 20 October) stating where

Michael had made landfall, the maximum observed winds, and the extent of rainfall. Another was sent out at 12:55 a.m.—essentially, an update of the previous issue—with a new maximum wind report of 93 knots (172 km/h) at St. Lawrence. A third and final report was sent out at 12:14 p.m. (1444 UTC 20 October) summarizing wind and rainfall amounts observed across Newfoundland. A more complete collection of warnings and forecast verifications appears in Part II.

5. Convair Research Flight

As Michael was forming well south of Canadian waters, arrangements were being made by the Meteorological Research Branch of Environment Canada to send a research plane into Michael as it was undergoing transition. At 1521 UTC 19 October the "Convair 580"—an aircraft owned and operated by the National Research Council—departed from Greenwood, Nova Scotia, to examine the storm (Wolde et al., 2001). The aircraft was equipped with an 8-mm (K-band) radar and sophisticated sensors used to measure the microphysical properties of clouds. Sixteen GPS (Global Positioning System) dropsondes were deployed during the 3-hour, 50-minute journey. Figure 13 shows the sequence of dropsondes that were released while the Convair flew just south of the storm centre at approximately 6400 m (21,000 feet). Radar data revealed interesting vertical structure to the clouds that were topped near 10700 m (35,000 feet). Very strong headwinds of 120 knots were experienced on the return leg of the mission. Dropsonde data near the storm centre revealed a relatively deep layer of 130-knot southwesterly winds from the top of the boundary layer up to approximately 750 mb (2500 m). Details of this flight, including an in depth analysis of flight-level and dropsonde data, are planned for an upcoming article in the Bulletin of the American Meteorological Society. An article summarizing the mission appeared in the winter 2000 issue of Environment Canada's newsletter *Zephyr* (http://www.msc-smc.ec.gc.ca/cd/zephyr/winter2000/page 20_e.html).

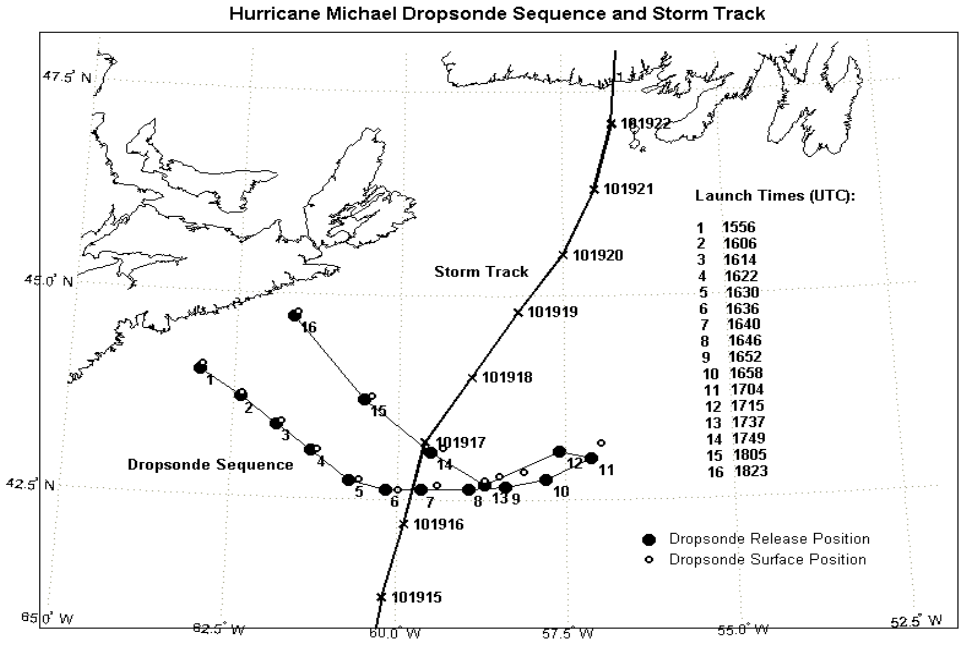


FIGURE 13. Convair dropsonde sequence and Hurricane Michael storm track segment.

6. Summary

Hurricane Michael was the third hurricane to make landfall in eastern Canada during the 5-year period from 1995 to 2000. Hurricane Luis came ashore on the Avalon Peninsula of Newfoundland on 11 September 1995 while Nova Scotia experienced the brunt of Hurricane Hortense on 14 September 1996. Michael was one of four tropical systems to affect Newfoundland and adjacent marine areas in 2000 (average is one or two per year). On 17 September Tropical Storm Florence passed just east of the Avalon Peninsula, bringing heavy rainfalls to eastern parts of Newfoundland. On 25 September the remains of Hurricane Helene crossed the northern Grand Banks, and on 8 October the remnants of Tropical Storm Leslie crossed central Newfoundland with heavy downpours between St. John's and Gander.

The highlight of the season, Hurricane Michael, made landfall in Newfoundland at 8:00 p.m. local time on 19 October just west of Harbour Breton, with maximum sustained winds of 75 knots (140 km/h) and gusts over 90 knots (165 km/h). Michael also brought between 25 and 75 mm of rain to the province. As the storm moved northeast of the island on 20 October, hurricane-force westerly winds (65 knots or 120 km/h) continued to impact some coastal areas.

Evidence that Michael was still a hurricane at landfall include the following observations:

- An apparent eyewall was seen in radar imagery (Figure 7) - note that the perceived centre was significantly displaced to the northeast of the estimated surface centre but hurricane-force winds were reaching the surface.
- The inner core appeared to remain very tight as shown in Figure 10a.
- An extratropical low which interacted with Michael may have been present near landfall suggesting Michael was still a separate entity in the warm airmass (see Figure 10a).

In general, light to moderate damage was reported to homes and trees on the south coast. Siding and shingles were removed from residential buildings in many cases. There was a report of a roof being blown off a home in Gaultois and a portion of the roof from a local hotel. Several small boats were also capsized in Fortune Bay. Newfoundland is no stranger to high winds; homes are built to withstand winter storms which often produce hurricane-force winds. Minimal amounts of tree or structural damage were reported in Newfoundland. Had Michael struck Nova Scotia, damage could have been considerably greater due to increased vulnerability to those extremes in wind. Damage due to the hurricane-force wind alone may have caused more widespread tree and property damage resulting in significant power and service disruptions comparable to that experienced along the eastern seaboard of the United States. It is a scenario like this that justifies ongoing research into the current and future frequency of hurricanes threatening eastern Canada.

Acknowledgments

The author would like to thank George Parkes, John Parker and Jim Abraham for their insightful reviews of this article. The author would also like to thank Peter Bowyer for his guidance in preparing this report and input throughout the data analysis period.

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Hurricane Michael, 17 – 20 October 2000
Part II - Forecast and Warning Critique

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ABSTRACT

This report is a follow-up to Part I "Summary Report and Storm Impact on Canada". It summarizes the various forecasts and warnings issued by the four weather offices involved in monitoring Hurricane Michael: The National Hurricane Center (NHC), Miami, FL; the Canadian Hurricane Centre (CHC), Dartmouth, NS; the Newfoundland Weather Centre (NWC), Gander, NF; and the Maritimes Weather Centre (MWC), Dartmouth, NS. Forecast verification statistics for both track and intensity are outlined for the hurricane offices. Verification of public and marine warnings issued by the NWC for the island of Newfoundland and adjacent waters is also presented. Warnings issued by the MWC are also summarized. The report concludes with a summary of coordination efforts between each of the forecast offices and a conclusion outlining the key challenges of forecasting this event.

1. National Hurricane Center Tropical Discussions

Issue times WTNT41 (intermediate bulletins italicized):
17/0300Z, 17/0900Z, 17/1500Z, 17/2100Z, 18/0300Z, 18/0900Z, 18/1500Z, 18/2100Z,
19/0300Z, 19/0900Z, 19/1500Z, *19/1800Z,* 19/2100Z, *20/0030Z*

The NHC began issuing tropical cyclone discussions on Tropical Depression 17 at 0300 UTC 17 October. This depression was estimated to be near tropical storm strength at the time, based on the fact that there was one rain-free vector of 35 knots reported by a QuikSCAT pass. Note that re-analysis data (see Table 1, Part I) show the system at tropical storm strength at this time. The depression was embedded in an upper level low, and it was thought that this would inhibit any significant strengthening in the short term. In the longer term, a trough was forecast to impart increasing shear as it approached from the northwest.

In their second advisory at 0900 UTC 17 October it was noted that the cloud pattern of now Tropical Storm Michael was becoming better organized but convection lacked vertical extent. Such a pattern would be indicative of a hurricane in the deep tropics. Michael was still not expected to gather much strength before entering the shearing environment that was expected later in the period.

The following discussions and advisories brought Michael to hurricane intensity mainly in response to the exceptional organization of the system with a well-defined eye. After receiving aircraft data from the storm on 17 October, Michael was upgraded to hurricane status in the 2100 UTC discussion. In this issue it was suggested for the first time that Michael might become absorbed by an extratropical low associated with the mid-tropospheric trough over the U.S. Northeast. At 0900 UTC 18 October the NHC was predicting that the anticipated merger between Michael and this baroclinic low would be a shear-dominated process and that the resulting cyclone would not be significant:

"...WHILE SOME STORMS THAT INTERACT WITH THE WESTERLIES STRENGTHEN AS THEY ACCELERATE...THE GUIDANCE SUGGESTS THESE WESTERLIES SHOULD PRODUCE TOO MUCH SHEAR TO ALLOW MICHAEL TO DO THAT..."

One day later, in their 0900 UTC 19 October issue, the first indication was made that the trough interaction would at least maintain a strong storm heading toward Newfoundland, but forecasters were still unclear as to which system would survive — Michael or the new baroclinic low off Nova Scotia. A significant adjustment in the intensity of Michael was made in an intermediate bulletin following the report from ship 3EHR6 and it was clear that Michael was going to remain the dominant cyclone. An excerpt from their 2100 UTC 19 October discussion follows:

"MICHAEL CONTINUES AS A HURRICANE MAINTAINING ITS COMPACT WARM CORE AND IS RACING TOWARD THE NORTH-NORTHEAST ABOUT 45 KNOTS AHEAD OF A SHORT WAVE. THE HURRICANE IS EXPECTED TO CROSS NEWFOUNDLAND WITHIN THE NEXT 6 TO 12 HOURS AS IT TRANSITIONS TO A POWERFUL EXTRATROPICAL CYCLONE.

THE SKILL IN FORECASTING THE BEGINNING AND THE END OF THE TRANSITION PROCESS IS VERY LOW. NEVERTHELESS...EITHER TROPICAL OR EXTRATROPICAL ...HURRICANE FORCE WINDS AND HEAVY RAINS WILL OCCUR TONIGHT OVER PORTIONS OF NEWFOUNDLAND. SEE LOCAL FORECASTS PROVIDED BY ENVIRONMENT CANADA."

In their final bulletin at 0030 UTC 20 October just after landfall, it was indicated that Michael had acquired frontal structures just before landfall.

The NHC's nowcasting guidance provided only a short lead-time for the hurricane-force winds reaching land due to the challenges they had faced with this storm's track and re-intensification. Their earlier assumption had been that the baroclinic trough would produce too much shear for there to be any re-intensification. Also, they did not originally anticipate that the system would reach hurricane status, demonstrating the low skill of numerical models in forecasting pre- and post-transition intensity change.

2. Canadian Hurricane Centre Prognostic Messages

Issue times FXCN05 (intermediate bulletin italicized):
17/0900Z, 17/1800Z, 18/0000Z, 18/0600Z, 18/1200Z, 18/1800Z, 19/0000Z, 19/0600Z, 19/1200Z, 19/1800Z, *19/2100Z*, 20/0000Z, 20/0600Z, 20/1200Z

The CHC began issuing prognostic messages on Michael at 0900 UTC 17 October. This was a short message and served essentially as an introduction to the storm which was expected to enter the Canadian response zone. In their second discussion at 1800 UTC 17 October the CHC was already providing details as to the possible outcome of the expected hurricane-trough merger later in the forecast period. The Global Environmental Multiscale (GEM) model was indicating that a baroclinic development would occur in about 48 hours, south of Nova Scotia. Several relevant points were made at this point: 1) the transition would occur faster than indicated by the American models; 2) a cut-off low would develop aloft; 3) a large baroclinic system would result, bringing heaviest rains to the Maritime Provinces and western Newfoundland as it decelerated. In the 0600 UTC 18 October discussion, the CHC still had a firm handle on the forecast which would end up verifying rather well.

"...BY THURSDAY NIGHT...MAJOR COMBINED BAROCLINIC LOW MOVING MUCH SLOWER OVER NEWFOUNDLAND..."

Large-scale model performances on 18 October presented variations on the solution. The GEM model appeared to be developing the remnant system, but at the expense of Michael. The Nested Grid Model (NGM) had a similar idea, but was less intense with the baroclinic development.

The Medium Range Forecast (MRF) model maintained Michael out to 0000 UTC 20 October but had the tropical system well south of the GEM position. Tropical models used in Miami insisted that increasing shear would weaken Michael.

Late on 18 October, the CHC continued with the philosophy of a faster track as suggested by the upper flow in the GEM. There was strong indication that the combination of the baroclinic low off Nova Scotia and the hurricane (whose vortex was poorly resolved by the GEM) would result in a system with very high thicknesses over its centre (about 570 dam between 1000 and 500 mb). Since the GEM was putting emphasis on the baroclinic low, the track was too far west — just brushing Cape Breton, Nova Scotia.

A change in thinking was made by the CHC at 0600 UTC 19 October:

"...GEM SHOWS 572 THKNS OVER AVALON PEN AT 20/00Z...WHICH MAY BE CLOSE TO THE REMNANTS OF MICHAEL. IT MAY MAINTAIN AN IDENTITY EVEN BEYOND AND NOT BECOME FULLY MERGED WITH THE DEVELOPING LOW UNTIL NEAR 21/12Z..."

The track was adjusted much further east at this point which would bring hurricane Michael into Placentia Bay, Newfoundland by 0000 UTC 20 October. The delay in the merger to 1200 UTC 21 October was some 36 hours later than the previous thinking, although it is speculated that this was an error.

It was not until the morning of 19 October that there were indications Michael would end up being the dominant centre. The track was adjusted back to the west in the 1800 UTC bulletin. Data from ship 3EHR6 at 1700 UTC had not yet been confirmed so the hurricane's intensity was kept at 65 knots in that issue. After discussing this report with the NHC, the CHC upgraded the storm to 80 knots in their 2100 UTC discussion, and a final adjustment to the track was made, with anticipated landfall west of the Burin Peninsula *as a hurricane* within a couple of hours. By 0000 UTC 20 October Michael was inland over south-central Newfoundland. CHC declared it post-tropical at that point with maximum sustained winds of 70 knots. The first indications of forecast rainfall amounts (near 60 mm) were made in the 0000 UTC issue. This ended up being representative for areas west of the track, where between 40 and 75 mm were recorded.

The final discussion was issued at 1200 UTC 20 October when the storm was moving slowly northeastward off the northeast coast of Newfoundland.

3. Newfoundland Weather Centre Public and Marine Forecasts

Issue sequence of key bulletins:

FPCN22:	19/1757Z	Marine Synopsis
FPCN20:	19/1800Z	Marine Forecast
FPCN11:	19/1829Z	Public Forecast
FPCN20:	19/1939Z	Marine Forecast (Amendment)
FPCN11:	19/2002Z	Public Forecast (Amendment)
FPCN20:	19/2230Z	Marine Forecast
FPCN22:	19/2250Z	Marine Synopsis
WOCN10:	20/0019Z	Special Weather Statement
FPCN11:	20/0100Z	Public Forecast
WOCN10:	20/0325Z	Special Weather Statement
WOCN10:	20/1444Z	Storm Summary

This section will focus on warnings issued by the NWC. Although there were also warnings issued by the Maritimes Weather Centre (MWC) during this event, they will not be discussed in detail here.

Two important forecasts were issued in the afternoon of 19 October. The marine forecast (FPCN20 CYQX) was issued at 3:30 p.m. local time (1800 UTC) and the public forecast (FPCN11 CYQX) was issued at 4:00 p.m. (1830 UTC). These forecasts followed the theme that Michael would weaken to tropical storm strength while passing over colder waters and evolve into a strong extratropical cyclone. The Hurricane Centres had not yet finished assessing the validity of the ship observation of 80-knot sustained winds at 1700 UTC.

3.1 Public Forecasts

Wind warnings (gusts to 110 km/h) were in effect for the Avalon Peninsula, Burin Peninsula, East Coast and Central Newfoundland forecast regions. Heavy rainfall advisories (up to 40 mm) were in effect for the East Coast, Central Newfoundland, South Coast (except the Burin Peninsula), and the West Coast forecast regions. After confirmation with the NHC on the validity of ship 3EHR6, the CHC relayed the information to the NWC and an amended public forecast was sent out at 5:30 p.m. local time (2000 UTC):

"...HURRICANE MICHAEL APPROACHING NEWFOUNDLAND FROM THE SOUTH IS NOT WEAKENING AS FAST AS EXPECTED. AS A RESULT POSSIBLE DAMAGING WINDS WITH GUSTS TO 130 KM/H ARE EXPECTED THIS EVENING OVER PARTS OF THE SOUTH COAST. AS WELL HEAVY RAIN IS EXPECTED THIS EVENING..."

The amendment was to upgrade the wind warning for the south coast, east of Burgeo including the Burin peninsula for southerly winds of 70 km/h gusting to 130 km/h for Thursday (19 October) evening. Rainfall amounts were not changed. In the 10:30 p.m. (0100 UTC 20 October) public forecast update, Michael was well inland and rainfall advisories were continued only for the south coast Burgeo and west, and the West Coast. Wind warnings remained in effect for westerlies gusting to 110 km/h on the south side of the remnant storm on Friday.

Other public warnings

Heavy rainfall warnings were issued by the MWC in Dartmouth for all of Nova Scotia and Prince Edward Island and the Magdelan Islands during this event. Wind warnings were issued for all of Cape Breton, Kings and Queens counties on Prince Edward Island, and the Magdelan Islands. No warnings were issued by the New Brunswick Weather Centre. Heavy rainfall (50 mm or more) fell over all but western Nova Scotia. These amounts were also recorded across Prince Edward Island, the Magdelan Islands and southeastern New Brunswick. High winds (gusts to 90 km/h or more) were experienced over the Cape Breton highlands and eastern Prince Edward Island. The weather conditions experienced throughout these regions were not directly related to Michael but due to the larger scale circulation encompassing Michael.

3.2 Marine Forecasts

Storm-force wind warnings were in effect for the majority of Newfoundland marine regions in the marine forecast issued at 1800 UTC 19 October. Generally these were for marginal storm force-winds of 50 kts - first in the southeasterlies ahead of Michael, then in the westerlies behind Michael. As with the public forecast, a revised marine forecast was sent out at 5:00 p.m. after verification of the hurricane's upgraded intensity. The amendment was to upgrade the Storm

Warning to a Hurricane-force Wind Warning (65 to 75 knots) for the Southwest Coast east of Ramea. For the South Coast region, Storms of 50 knots were upgraded to Storms of 60 knots.

The marine synopsis (FPCN22 CYQX) issued at 3:30 p.m. (1800 UTC) discussed the position and motion of pressure systems throughout the district, as well as a paragraph on hurricane information and a summary of warnings. This issue opened with saying "...a ridge of high pressure..." followed by the hurricane information in the last paragraph before the warning summary. This style was carried over from previous bulletins. To better emphasize the main event, it would have been best to open the synopsis with information on the hurricane, then discuss other features such as ridges and minor troughs (discussion based on level of importance). The synopsis was not updated with the regular forecast amendment, but given the severity and rarity of the event and the fact that Storm Warnings were upgraded to hurricane-force winds, updating the synopsis would have increased the warnings' effectiveness. The 8 p.m. synopsis was re-written such that the hurricane information appeared in the first paragraph, and provided a better portrayal of the severity of the storm, even though by that time the centre was inland. (The NWC also made mention of higher than normal water levels in their marine synopses from information derived at the CHC.)

Other marine warnings

A variety of marine wind warnings were issued by the MWC for their southeastern forecast waters including hurricane-force winds for Banquereau Bank, Laurentian Fan and the southeastern half of the East Scotian Slope at 1414 UTC 19 October. For the East Scotian Slope, this provided a lead-time of only a couple hours. For Laurentian Fan, the lead-time was about four hours and for Banquereau, about six hours.

3.3 Special Weather Statements

In addition to the regular bulletins issued by the NWC, three Special Weather Statements (WOCN10 CYQX header) were issued. The first of these was issued at 9:50 p.m. (0020 UTC 20 October) stating where Michael had made landfall, maximum observed winds and the extent of rainfall. Another one was sent out at 12:55 a.m. which was essentially an update to the previous issue, with a new maximum wind report of 93 knots (172 km/h) at St. Lawrence. A third and final report was sent out at 12:14 p.m. (1444 UTC 20 October) summarizing winds and rainfall amounts observed across Newfoundland.

4. Forecast Verification Statistics

4.1 National Hurricane Center / Canadian Hurricane Centre

Table 1 summarizes the track and absolute wind error statistics for the Hurricane Centres. Figure 1 presents these data in graphical format.

TABLE 1. Hurricane Michael track and absolute wind error statistics for the NHC and CHC (Track errors are in nautical miles (NM) and wind speed errors are in knots (KT))

NHC - AVERAGE TRACK FORECAST ERRORS (NM)

FCST HR	12	24	36	48	72
ERROR	63	133	202	247	299
#CASES	11	11	8	7	4

NHC - AVERAGE ABSOLUTE WIND SPEED FORECAST ERROR (KT)

FCST HR	12	24	36	48	72
ERROR	11	14	21	25	25
#CASES	11	11	8	7	4

CHC - AVERAGE TRACK FORECAST ERRORS (NM)

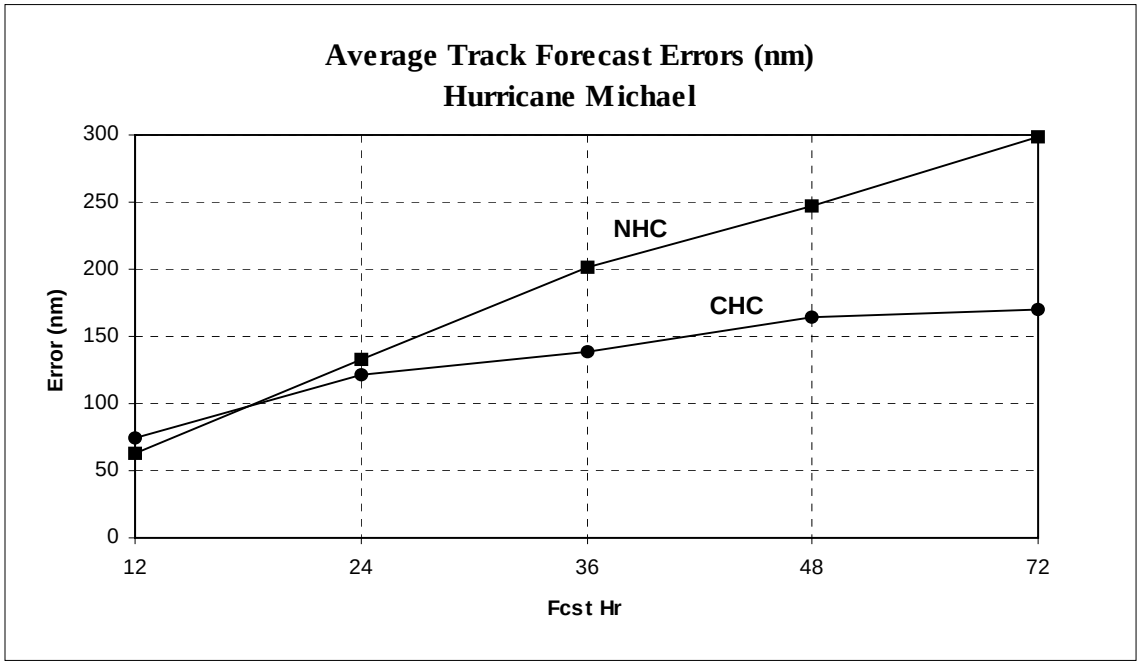
FCST HR	12	24	36	48	72
ERROR	74	122	139	165	170
#CASES	12	9	9	6	3

CHC - AVERAGE ABSOLUTE WIND SPEED FORECAST ERROR (KT)

FCST HR	12	24	36	48	72
ERROR	9	13	15	17	12
#CASES	12	9	9	6	3

Significant challenges with predicting Michael were related to intensity changes both initially and during the baroclinic transition. The storm's intensity was under-forecast by both Centres. Both track and wind speed errors were reported to have been greater than the 10-year average (1990-1999) at the NHC (Stewart 2000, section C) . Forecast track errors were large during the pre-transition phase because it was unclear which low centre would dominate - Michael or the baroclinic low off Nova Scotia.

The CHC was successful in adapting data from the NHC to provide a more accurate forecast of both the track and wind speeds, especially beyond 36 hours. In addition, the CHC was talking about the possibility of a re-intensification more than 24 hours sooner than the NHC. This earlier "jump" on the transition was reflected in the forecast accuracy.



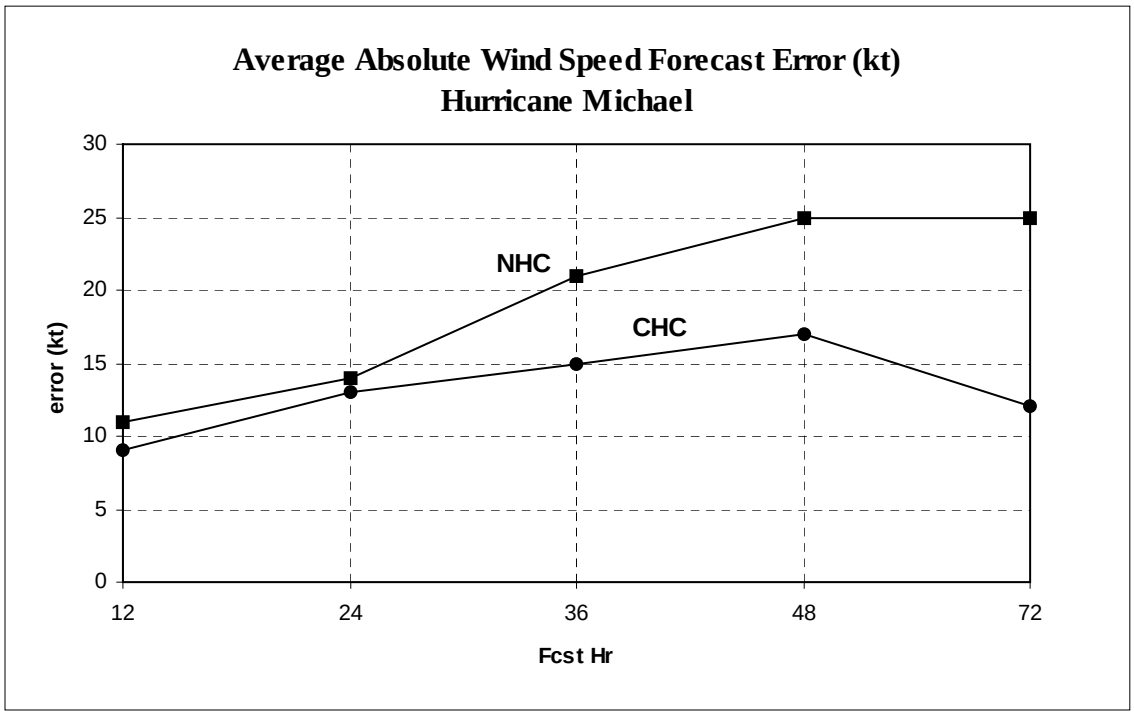


FIGURE 1. Track and absolute wind error statistics for the NHC and CHC

4.2 Newfoundland Weather Centre

Table 2 summarizes the warnings and advisories issued by the NWC and their verifications (underestimated forecast values indicated with 'U'):

TABLE 2. NWC forecast verification summary

Warning/Advisory	***Region***	***Lead Time***	***Verification***
inland regions...			
Wind Warning (60G110 km/h)	Avalon, Burin East Coast, Central NF	15 hrs	Hit (U)
Rainfall Advisory (30-40 mm)	South Coast (except Burin) West/East Coast, Central NF	12 hrs	Hit (U)
coastal marine regions...			
Gale Warning	Northeast Gulf, Gulf Port-Au Port	42 hrs	Hit (U)
Storm Warning	Belle Isle	24 hrs	Hit
Storm Warning	Southwest Coast, South Coast	39 hrs	Hit (U)
Storm Warning	East Coast, Northeast Coast	30 hrs	Hit (U)
Hurricane Warning	Southwest Coast (East of Ramea)	2 hrs	Hit

Missed events:

Wind:	South Coast (west of Burin) Northern Peninsula
Heavy Rainfall:	West Coast, East Coast (Baie Verte), Northern Peninsula (east)
Storm:	Northeast Gulf

The verifying data for rainfall and winds are shown in Figures 2 and 3, respectively. Rainfall data (Richards, 2000) comprising Figure 2 were collected from a network of 64 rain gauges across the island. A complete listing of those data appears in Table 3.

TABLE 3. Comprehensive post-landfall rainfall data - Hurricane Michael - 06 UTC 19 October - 06 UTC 21 October 2000 for Newfoundland (island)

No. of Sites 64

LAT DD	LAT MM	LON DD	LON MM	PR	mm	SITE
48	58	56	04	27.8		Badger
47	59	55	48	40.6		Bay d'Espoir Gen. Stn.
49	02	55	33	28.8		Bishop's Falls
48	34	58	22	50.9		Black Duck
47	26	54	51	35.8		Boat Harbour
48	40	53	07	20.5		Bonavista
48	02	53	07	16.9		Brownsdale
48	50	56	52	33.8		Buchans
47	37	57	37	33.9		Burgeo
47	35	53	19	33.0		Butlerville
46	39	53	04	19.1		Cape Race
49	24	54	16	20.8		Carmanville
48	23	53	40	12.8		Charleston
48	12	53	58	13.2		Clarenville
49	19	57	24	52.4		Cormack
48	56	57	55	43.1		Corner Brook
49	54	57	48	15.2		Cow Head
50	14	57	35	48.0		Daniel's Harbour
49	10	57	26	48.8		Deer Lake
50	43	56	07	77.0		Englee
48	46	56	36	47.0		Exploits Dam
49	43	54	18	35.2		Fogo
48	42	58	14	60.0		Gallants
48	57	54	23	27.8		Gander
47	14	55	21	23.9		Garnish
48	59	54	51	28.8		Glenwood
47	57	53	58	24.0		Goobies
48	56	55	40	20.0		Grand Falls
47	28	55	50	36.0		Harbour Breton
50	22	56	31	65.4		Harbour Deep
50	36	57	11	11.2		Hawke's Bay
47	52	53	23	12.0		Heart's Content
47	27	53	06	21.2		Holyrood Gen. Stn.
49	02	53	53	22.6		Indian Bay
47	35	58	58	43.2		Isles Aux Morts
48	21	53	53	16.0		Lethbridge
47	37	52	40	14.0		Logy Bay
48	39	58	59	39.0		Lourdes
51	11	56	01	56.0		Main Brook
49	04	58	07	62.8		McIvers
49	41	56	05	76.0		Middle Arm
49	27	53	59	27.8		Musgrave Harbour
47	08	53	40	38.0		North Harbour
51	04	56	53	41.2		Plum Point
49	20	55	24	29.2		Port Leamington
47	34	59	10	58.5		Port Aux Basques
48	21	54	10	20.0		Port Blandford
47	38	52	49	23.0		Portugal Cove
49	04	55	18	29.4		Rattling Brk. Norris Arm
47	18	55	01	41.0		Red Harbour
49	34	57	53	53.5		Rocky Harbour
47	22	55	48	33.0		Sagona Island
47	16	53	17	28.2		Salmonier Nature Park
47	34	52	41	28.0		Signal Hill

49 46 56 53	60.4	Sop's Arms White Bay
51 23 56 05	42.0	St. Anthony
46 55 54 10	15.2	St. Bride's
47 37 52 44	29.9	St. John's
48 32 58 33	48.2	Stephenville
47 53 54 13	29.8	Swift Current
48 33 53 58	13.8	Terra Nova Nat. Park
47 46 53 13	27.0	Victoria
47 25 53 32	29.7	Whitbourne
47 08 55 20	27.0	Winterland

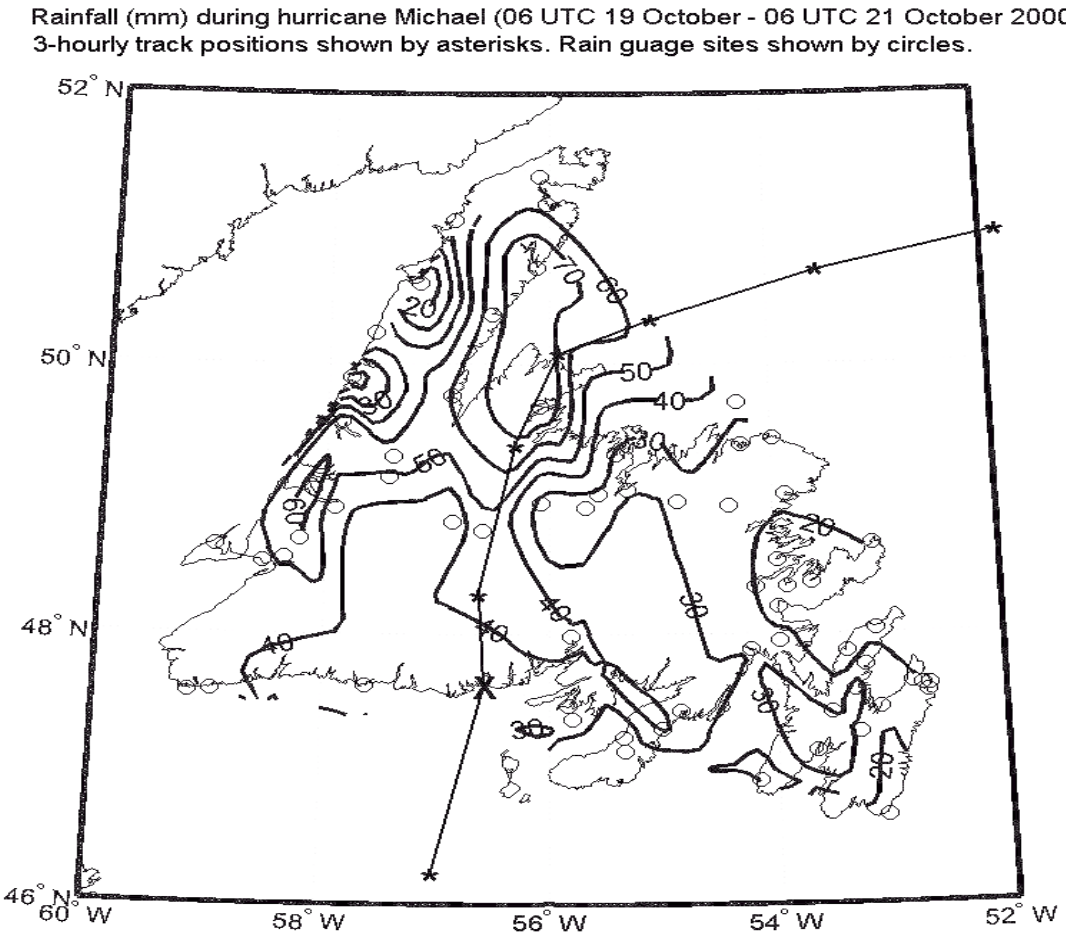


FIGURE 2. Rainfall (mm) during Hurricane Michael (06 UTC 19 October - 06 UTC 21 October 2000). 3-hourly track positions shown by asterisks. Rain gauge sites shown by circles.

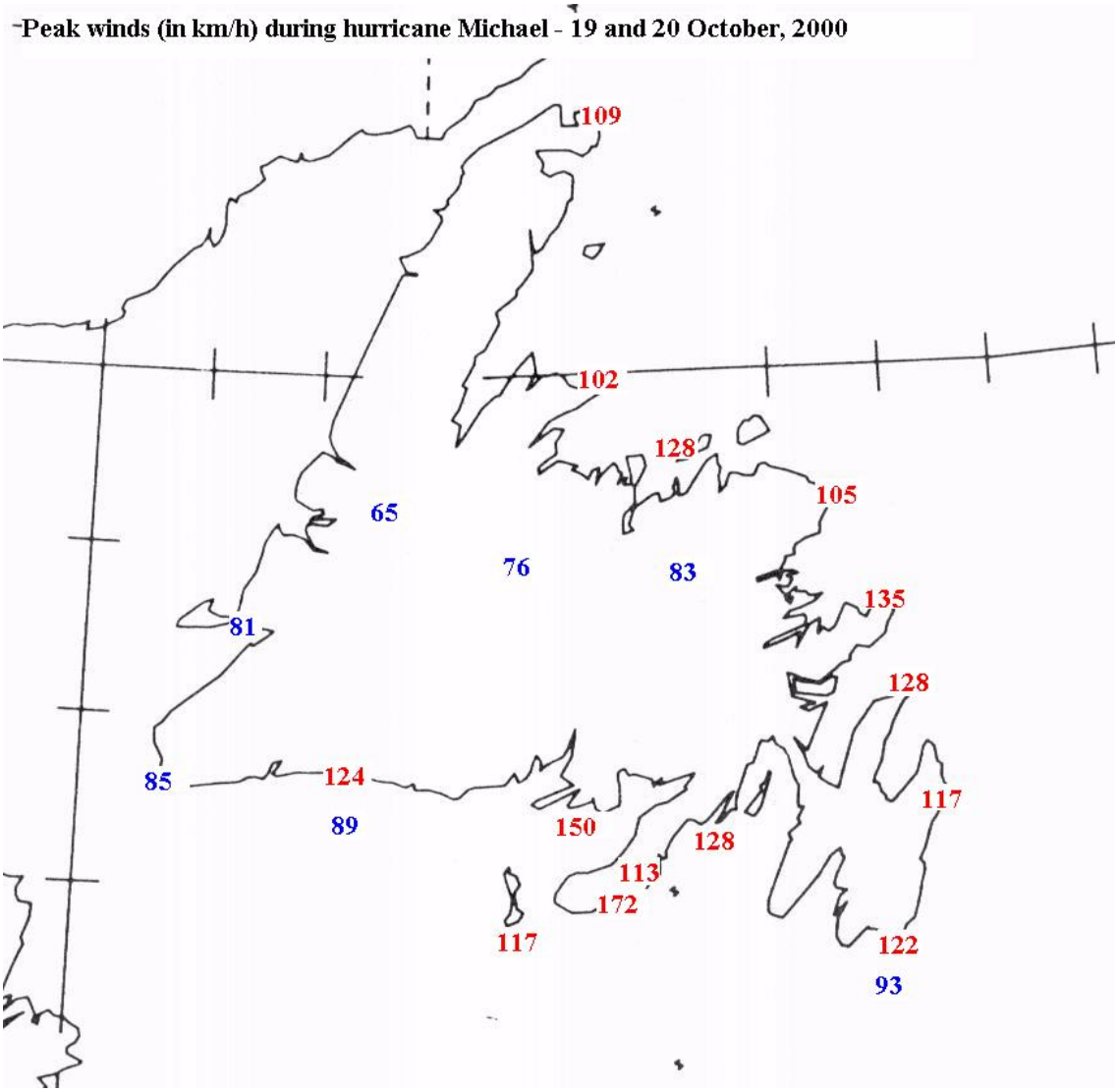


FIGURE 3. Peak winds (km/h) during Hurricane Michael - 19 and 20 October 2000.

5. Coordination between the Hurricane Centres and the Newfoundland Weather Centre

In the case of the ship report of 80-knot winds at 1700 UTC 19 October, the forecaster at the NHC phoned the duty forecaster at the CHC to discuss the credibility of the report. At the time he had not yet confirmed the 80-knot wind but indicated that he would make another phone call after consulting with the U.S. Coast Guard. The call was not received, so the forecaster at the CHC transmitted the 1800 UTC bulletin, making note of the "unconfirmed" ship report but not upgrading Michael's winds. The CHC immediately relayed this information to the NWC in Gander, and later issued an updated bulletin at 2100 UTC after calling the NHC to get final word on the ship report. Just prior to the 0000 UTC 20 October update of the FXCN05, the CHC received another call from the NHC regarding the time when Michael became extratropical. Both forecasters agreed that Michael was extratropical not long after landfall, but they were unable to resolve the time of transition. Frequent contact was made between the CHC and NWC just prior to and just after landfall with regard to forecasts, warnings and details on Michael. The NWC contacted the CHC with estimated time and location of landfall, and reported that the eyewall was detected on Holyrood radar. Also, a draft of the WOCN10 CYQX was faxed to the CHC to confirm the data before transmission. The CHC called NWC regarding the central pressure at landfall - estimated to be 965 mb based on extrapolation from buoy 44255's report of 967.7 mb. The bulletin was finalized and transmitted at 9:49 p.m. local time.

6. Conclusions

Hurricane Michael presented many forecasting challenges during its rapid deepening and extratropical transition over Newfoundland. Even during the early stages of its development from a subtropical low, forecasters were unsure how intense the storm would become. The key lesson to be learned from this event was the role of the upper-level mid-latitude trough in the deepening and extratropical transition of the hurricane. Since the trough was intensifying (or "digging") at precisely the same time as Michael was moving just ahead of it, baroclinic energy was transferred to the system in much the same way as it would be for an ordinary developing extratropical low.

The Canadian weather offices involved with the forecasting of this event (Canadian Hurricane Centre, Newfoundland Weather Centre and Maritimes Weather Centre) issued many warnings. In general the warnings were adequate, but forecast lead times were short owing to the rapid forward acceleration of the storm. Forecasters are generally aware of this rapid motion, yet Michael still caught most by surprise. Also surprising was the intensity of the storm at landfall, partly due to the fact that there was little time for it to weaken over colder waters.

It goes without saying that there is much to be learned about forecasting extratropical transition, particularly the potent combination of mid-latitude troughs with hurricanes. Detailed studies of storms like this one, along with the analysis of aircraft reconnaissance and remotely-sensed data integrated with numerical model simulations will continue to shape the future in our understanding of these dangerous storms.

References

Richards, W. 2000: Atlantic Climate Centre, Fredericton, New Brunswick, Canada. [Contact information available at http://www.ns.ec.gc.ca/climate/contacts.html]

Stewart, S. R., 2000: **Tropical Cyclone Report Hurricane Michael 17 - 19 October 2000**. 13 pp. [Available online at http://www.nhc.noaa.gov/2000michael.html.]