Country Report from Bermuda for the 39th Session of the WMO Regional Association IV Hurricane Committee

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1. Review of 2016 Season

Bermuda experienced a more active season than 2015. This was coincident with the official NOAA 2016 Atlantic Hurricane Season Outlook calling for a more active than average season, largely due to the AMO and a weakening El-Nino cycle transitioning into ENSO-Neutral conditions. The early part of the season was largely uneventful, with the exception of Tropical Storm Colin that brought near tropical storm force gusts to the Island as it passed to the distant west on 7th June. Towards the heart of the season, there was plenty of activity to the distant west and east of Bermuda (Hurricanes Gaston & Hermine, and Tropical Storm Ian), which generated some elevated swell for the Island from time to time, necessitating the issuance of local Small Craft Warnings.

However, it was not until Tropical Storm Karl that Bermuda experienced a direct impact from a tropical system. Karl passed by just 44 nautical miles to the southeast on the morning of 24th September, and brought sustained tropical storm force winds to parts of the Island with isolated gusts towards hurricane force in the most exposed/elevated locations. In addition, Karl generated some significant swells, up to around 18 feet, as well as plentiful tropical rainfall, amounting to 4.71 inches for the whole event. A Tropical Storm Watch, then Tropical Storm Warning was posted, as well as a temporary Hurricane Watch (which was later ended), when there was some indication from the NHC that Karl might intensify into a hurricane on final approach to Bermuda.

The main impact for the season came towards mid-October, when strengthening Hurricane Nicole set a path towards Bermuda after several days of meandering as a tropical storm to the south. This placed the Island under a Hurricane Warning as of the afternoon of Tuesday 11th October. Aided by low wind shear, and near record high sea surface temperatures, Nicole intensified to a major category 4 hurricane just 155 nautical miles south-southwest of Bermuda. Thankfully, the intensification phase transitioned into a steady weakening phase as Nicole made its final approach, due to increasing shear and gradually lowering sea temperatures. Landfall occurred around midday on Thursday 13th October as a weakening category 3 hurricane (N.B. high end category 2 winds were observed across Bermuda's AWOS network), when the Island once again experienced a rare eye passage of a major hurricane. Wind speeds and surge/swell observations were very much on par with major Hurricane Gonzalo of two years prior. However, the damage and other impacts were not as severe as those of the late 2014 season, and the Island was able to recover and get back to business as usual within a day or two. One notable fact from Nicole was the copious rainfall it produced, thanks to a very moist forward side of this particular system. This aspect was not especially well modelled, especially during the days ahead of landfall, when Nicole essentially fed very moist/tropical air into a frontal boundary that exhibited the characteristics of a wide and long lasting warm front over the area, producing towards 2 inches of rain. As for Nicole itself, this system brought near 7 inches of rain to the airport on the 13th, making this one of the wettest tropical events in history. The fact that much of the rain fell on the forward side before the hurricane force winds set in, no doubt assisted with the rainfall actually registering in the rain gauge.

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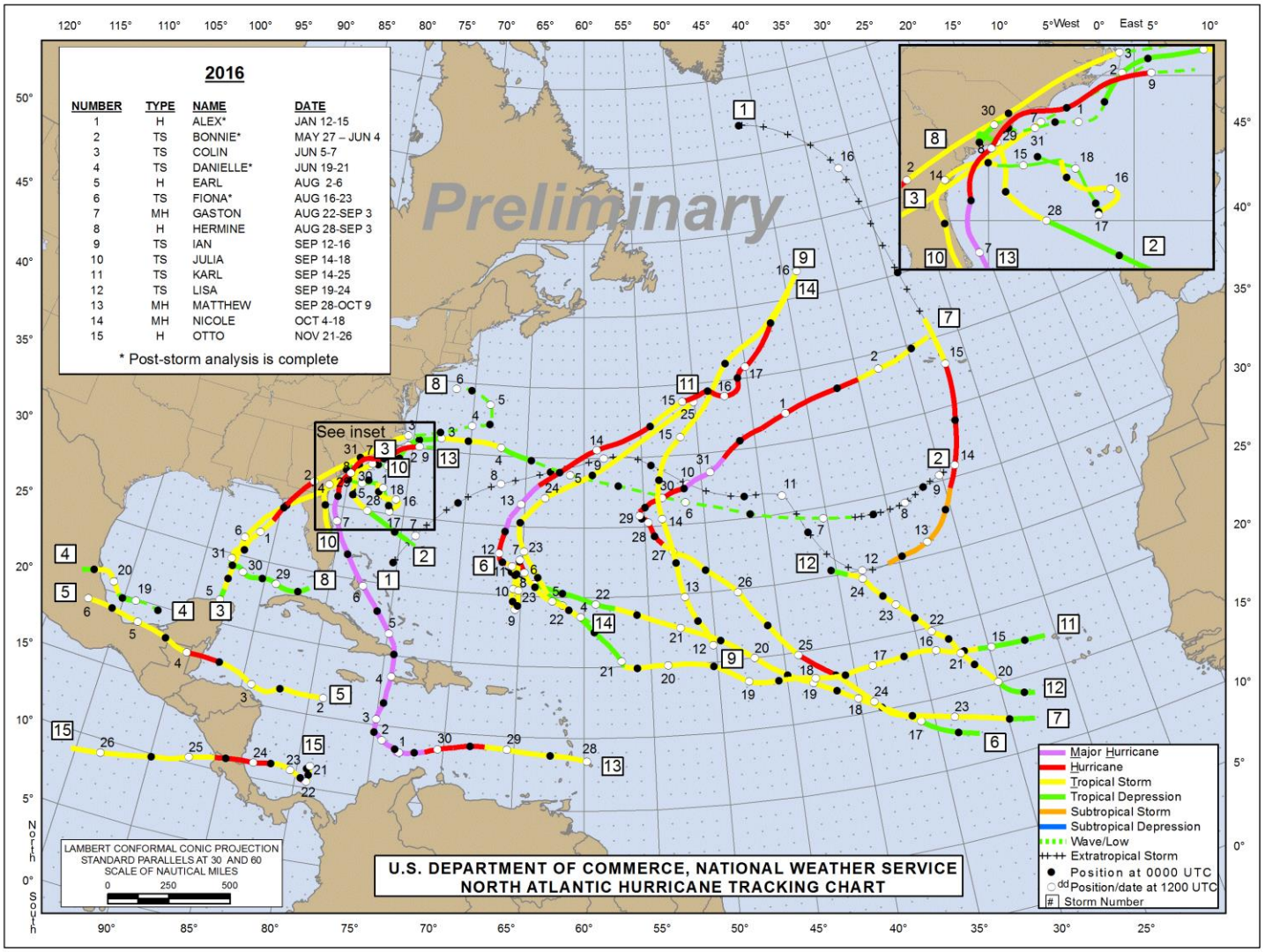
To summarise, after a slow start to the season, 2016 turned out to be another very active season for the small Island archipelago of Bermuda, with yet another unprecedented landfall of a major hurricane. This adds further weight to the fact that this part of the Atlantic is currently going through an active tropical period (c.f. Atlantic Multi-decadal Oscillation or AMO).



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2. Hurricane Nicole, October 12th-13th

Preparations –

Bermuda Weather Service (BWS) issued Threat status (system expected to come within 100 nautical miles of Bermuda within 72 hours) for this system at 6am on Monday 10th October. Forecast and model projections by this stage were relatively confident in the short to medium term track of Nicole, now beginning to make its move towards the north and Bermuda, all the while intensifying from a strong Tropical Storm into a Hurricane. With that in mind, a Hurricane Watch was issued at 6pm on Monday.

In line with further watch and warning protocols, a Tropical Storm Warning (in addition to the Hurricane Watch) was issued at 6am on Tuesday 11th. With continued model and forecast confidence of a direct impact by Hurricane Nicole on Thursday, the watch/warning was upgraded to a Hurricane Warning at 3pm on the Tuesday. BWS management briefed the Emergency Measure Organisation (EMO) on both Monday 10th and Tuesday 11th, as well as the airport (Department of Airport Operations) on Tuesday 11th, emphasising the likelihood of a hurricane impact early on Thursday 13th. With this preferred amount of lead time and the Hurricane Warning now in place, the Island was given plenty of notice to make the necessary preparations ahead of Hurricane Nicole.

As part of hurricane preparations, the local cellular networks transmitted Hurricane Warning and Preparedness texts to the community. In addition, press releases in combination with a press conference (chaired by the Minister of National Security, Jeff Baron), urged the Bermuda public to prepare for a direct hurricane impact. As such, plans were made to essentially shut down the Island for Thursday 13th, including the airport (closure notified by NOTAM, 0100UTC Thursday 13th until 1500UTC on Friday 14th), the Causeway (shut from 11pm Wednesday 12th until 10pm Thursday 13th), public transport, offices, schools and so on. In fact businesses and schools closed early on Wednesday in order to allow staff and families to prepare adequately. Further to this some businesses did not expect staff to return to work until Friday afternoon, and with regards public schools, these were scheduled to remain closed through Friday.

The timeline of the issuance of BWS watches and warnings is detailed in the table below (all times are local):

Status/Watch/Warning Type	Issuance Time	NHC Advisory #
Hurricane Watch issued	6pm Monday 10th October	27
Tropical Storm Warning & Hurricane Watch issued	6am Tuesday 11th October	29
Hurricane Warning issued	3pm Tuesday 11th October	30A
Hurricane Warning ended, Tropical Storm Warning issued	6pm Thursday 13th October	39
Tropical Storm Warning ended	9pm Thursday 13th October	39A

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Onset –

In the few days running up to Hurricane Nicole, strong winds were observed, with gusts to gale force. This was due to an isobaric squeeze that had set up between a ridge of high pressure to the north, and developing Hurricane Nicole to the south. In addition to the strong winds, some significant rainfall was recorded ahead of Nicole (towards 2 inches). A combination of these two weather phenomena no doubt hindered some people's ability to efficiently prepare for the hurricane. Conditions really started to deteriorate on the night of Wednesday 12th, when the strong winds began increasing, and tropical storm force gusts began to be routinely recorded. Sustained tropical storm force easterly winds developed later in the night with gusts to storm force. Sustained hurricane force winds finally started to impact the Island by mid-morning on Thursday 13th, as the leading eyewall of Nicole approached the Island. This onset eyewall produced the highest recorded wind gust during the event of 118knots or 136mph (around 10:30am) at the Windguru site on the Commissioner's House in Dockyard. Several other locations around the Island recorded in excess of 100mph at this time.

Towards midday, the effects of the eye (at least as wide as the Island based on radar imagery and as wide as 30nm beforehand) started to influence Bermuda, with easterly winds easing dramatically towards the west end, before progressing east towards BWS and the airport. During the eye, wind speeds dropped to as low as 5knots, and BWS were in the enviable position of being able to launch a 15Z weather balloon in the eye of Hurricane Nicole. It is worth noting that this is not unprecedented for Bermuda, as just two short years ago, BWS was able to release a weather balloon into the eye of Hurricane Gonzalo. The eye duration was approximately 1.5 hours, before the winds quickly increased once again, this time out of the northwest. Winds finally started to decrease by mid-afternoon, and the Hurricane Warning was ended at 6pm, with the subsequent issue of a Tropical Storm Warning in its place. Winds further eased into the evening, and with sustained tropical force strength winds decreasing by 9pm, the Tropical Storm Warning was ended at the 9pm NHC intermediate advisory update. Thereafter, with strong winds (20kt or more) and rough seas (9ft or more) continuing in the Bermuda area, a local Small Craft Warning was issued.

Most of the rainfall (6.77 inches) fell on the forward side of this very wet tropical system. With such copious rainfall, localised flooding was inevitable. The radar imagery very much mirrored the large amounts BWS recorded, and it is also worth mentioning that during the forward side of Nicole, specifically the forward right quadrant, the Doppler radar software identified several meso-vortices that were coincident with the classic striated radar reflectivity pattern. However, these appeared to remain off-shore and no definitive tornado touch downs were reported. The Bermuda public was nevertheless notified of this hazard by not only local BWS products, but by a hazard statement in relevant NHC advisories.

With regards to seas and storm surge, seas were rough well in advance of Nicole's final onset, with rough swells (9ft or more) affecting the area several days ahead of Nicole, thanks to southerly and sometimes confused swell from another tropical system to the southwest, Hurricane Matthew. As Nicole moved through the general Bermuda area, NOAA OPC sea state analyses suggested seas to as high as 44ft. However, based on this data and local wave model data, local seas are more likely to have peaked at around 35ft outside the reef, especially towards the southern and eastern marine area. There was some concern during the warning preparation phase that the forecast surge (as much as 6-8ft based on NHC estimates) would coincide with high tide during the morning of Thursday 13th. However, due to a change in onset timing, the maximum surge (estimated at nearer 4ft from the only tide gauge on the Island) thankfully coincided with low tide, meaning that surge inundation was relatively minimal. Having said that, there were still reports of flooding in the Mill's Creek area of Hamilton, and around Boaz Island in the West End, both fairly typical spots for

flooding/surge inundation impacts during hurricanes. Aside from flooding associated with the surge, there was also quite a lot of inland flooding from the heavy rains, which were exacerbated by the wet days ahead of Nicole.

Damage Impacts & Recovery –

With Hurricanes Fay and Gonzalo only 2 years prior, it was natural for the local community to want to compare the damage of Nicole with those previous hurricanes, and ask the question 'Why is the damage not worse, considering Nicole impacted Bermuda as a stronger hurricane than either Fay or Gonzalo?'. Indeed, it was clear to see that Bermuda did appear to weather Hurricane Nicole better than the Fay/Gonzalo double hurricane episode of mid-October 2014, which had significantly more building and vegetation damage. There were some well documented reasons for this. Ahead of Fay and Gonzalo there was a lot of old/weak vegetation growth (exacerbated by waterlogged ground and weakened root structures) and likely some poorly maintained building infrastructure, which ultimately succumbed to these hurricanes, especially Fay, due to its rapid onset and the very gusty nature (large mean wind to gust ratio), including anecdotal evidence of embedded tornadoes. Therefore, Fay/Gonzalo cleared out a lot of the 'dead wood' and weak infrastructure.

In terms of impact during Nicole, perhaps of greatest note was the local electricity provider's (BELCO) outage, which affected 27,000 customers (90% of their customer base) in the height of the hurricane. However, thanks to significant shoring up of their infrastructure post-Fay and Gonzalo (80% of electricity poles were replaced), the return to service for most customers was a lot quicker, with most outages fixed within 2-3 days. Some minor cellular and cable TV/internet outages were also experienced, but once again not as significant as during October 2014.

As for infrastructure damage during Nicole, there was some limited damage to buildings, with some roof damage. There were also several reports of general vehicle damage from projectiles (mainly window damage). Several yachts and boats succumbed to the fury of Nicole, breaking from their moorings and smashing up against rocks, docks and jetties. Two notable anemometers failed during the initial eyewall of Nicole – these were the Windguru site on Commissioner's House in Dockyard, and one of a pair of anemometers at the Harbour Radio (MAROPS – Marine Operations) site in St George's.

With respect to tree and foliage damage, a scattering of trees were felled across the Island. Of greatest visual impact was the wind- and salt spray-burn impact across the entire Island's flora. Not a *damage* impact as such, but it is also interesting to note that the sea surface temperature dropped by 5F/3C during the course of the whole Nicole event. Being as small as it is, Bermuda's temperatures are very much dictated by the temperature of the surrounding ocean. As such the highs of towards 86F/30C were no more after Nicole, and a sharp transition from summer to autumn was observed.

The general feeling across the community was that the Island avoided the worst of what could have been a very damaging hurricane impact, especially if it had maintained its category 4 status at landfall. Bermuda has now experienced several hurricane impacts in recent years, and with that wealth of experience the hurricane preparation process is now a very well-practiced one. As such, the Island was able to get back to business as usual within a day or so, and certainly by the week of 17th October. Hurricane Nicole made a lot a media coverage across the world, and the fact that the Island recovered from a major category 3 hurricane so quickly is a testament to not only the resilience of the infrastructure and building code, but also the aforementioned well-practiced hurricane preparedness process. Perhaps the most remarkable fact of all is that there was no loss of life, just a few minor injuries.

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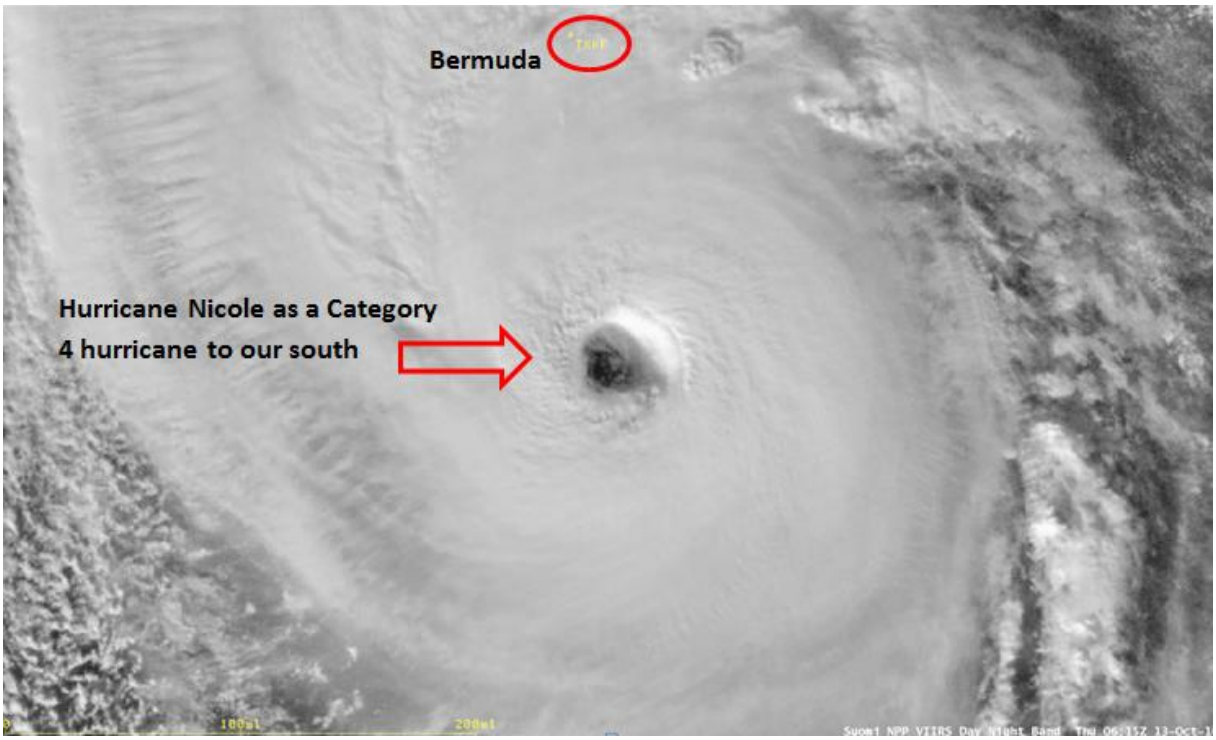
Communications –

One of the most important aspects of hurricane preparedness is communication and education to the community. BWS and the Bermuda Government run a Hurricane Preparedness Week each year at the start of the hurricane season to refresh the pubic on this important topic. In addition, during the last couple of hurricanes, BWS have been able to work with Government in order to update the community throughout the hurricane event via an emergency broadcast radio station 100.1FM. With power outages being inevitable in these situations, and likely cable TV and cellular phone outages, a battery powered radio is one the most resilient forms of media for communicating.

During Nicole, BWS management went on this radio station every hour to provide the very latest details, including not only the forecast, but also the latest observations (wind details, satellite, radar data etc.). This was very well received by the public, and helped to provide a certain level of comfort during what can be quite a stressful event, especially for the more vulnerable members of the community. As such, BWS plan to continue this standard of communication during future significant tropical events, and BWS is working hard with Government to ensure that this process remains. Another benefit of the emergency broadcast radio station, is that it also provides a communication back-up to key decision makers, such as members of the Emergency Measures Organisation (EMO), that have lost the use of their email and other communication channels.

Supporting Imagery –

Visible Satellite image with Nicole as a major category 4 hurricane to the near south –



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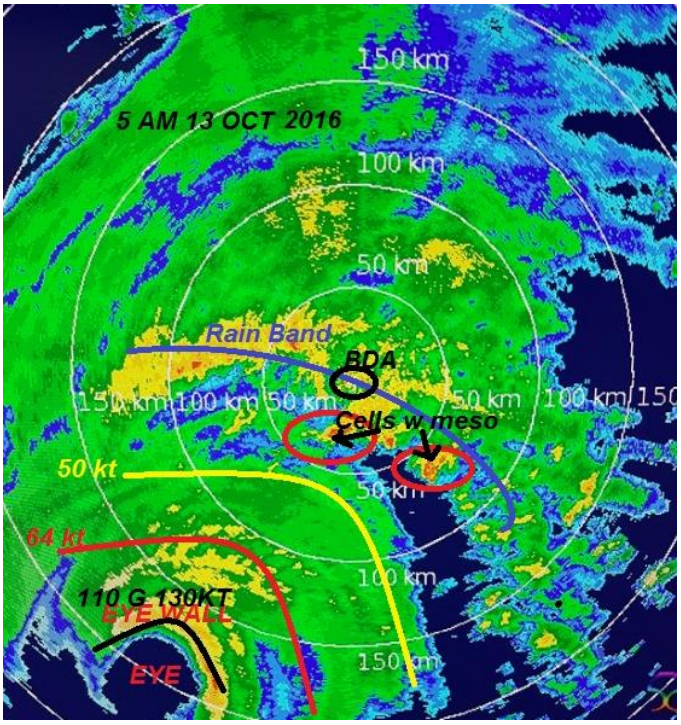
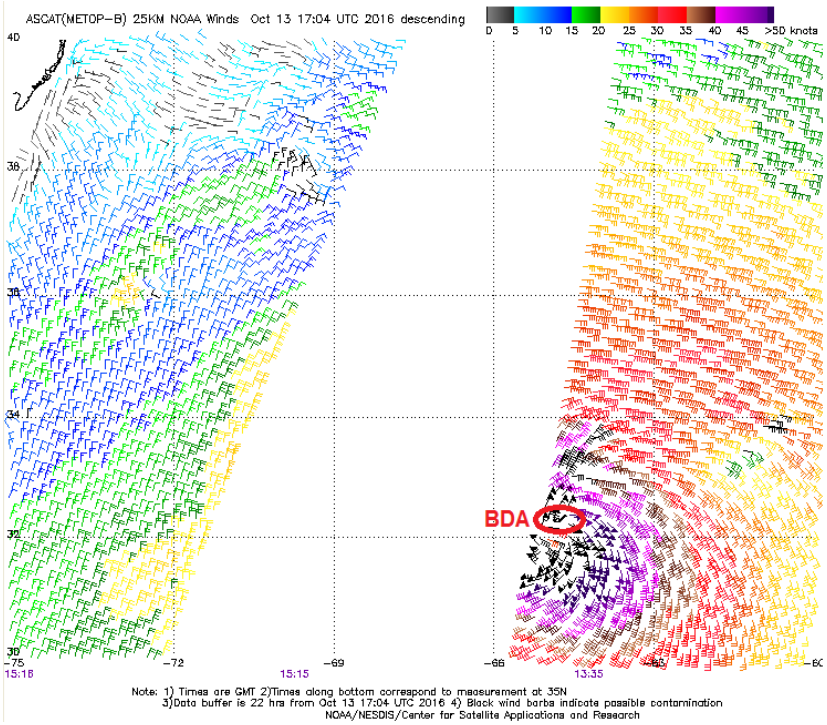
Doppler Radar image showing Nicole's approach (including reflectivity characteristics) –



Satellite derived wind data (NOAA NESDIS Ascat pass 13-15Z) –



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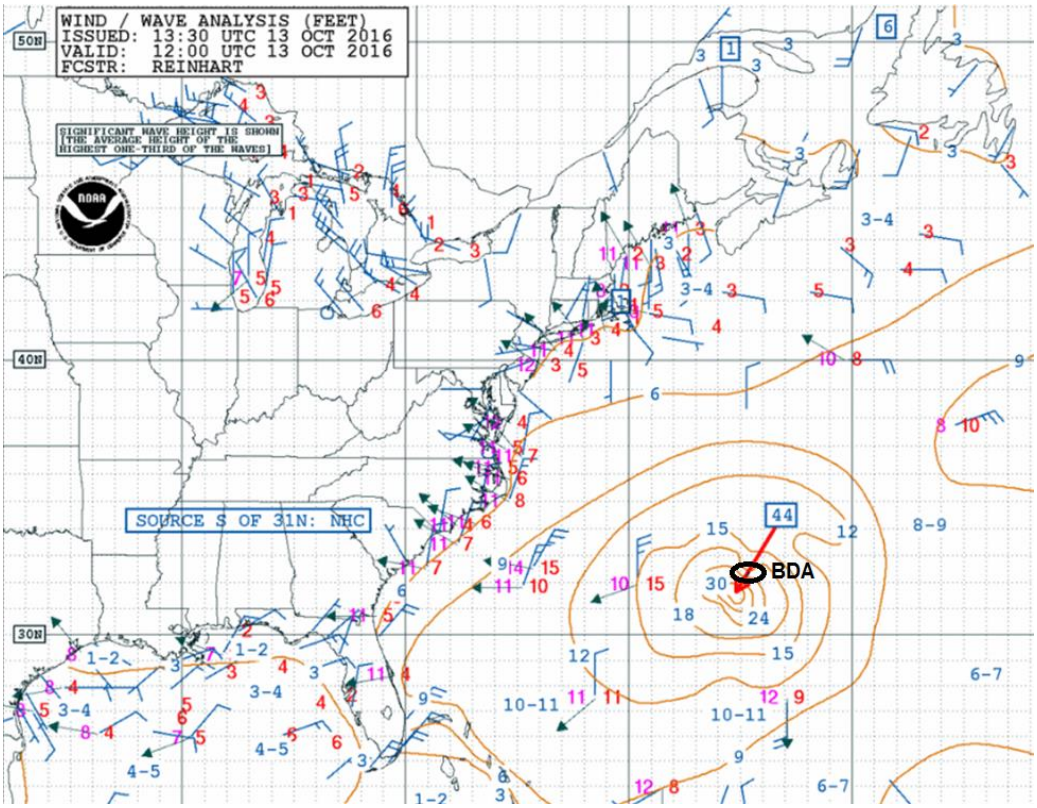
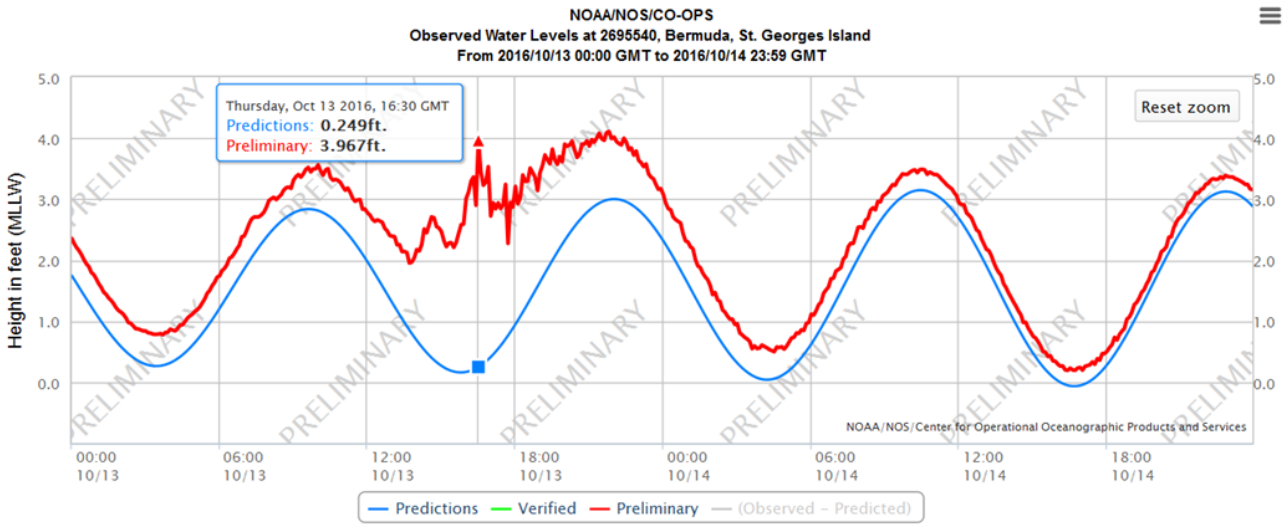
NOAA OPC Wind/Wave analysis –



NOAA Esso Pier Tide gauge data (highlighting surge on the north side of St George's) –



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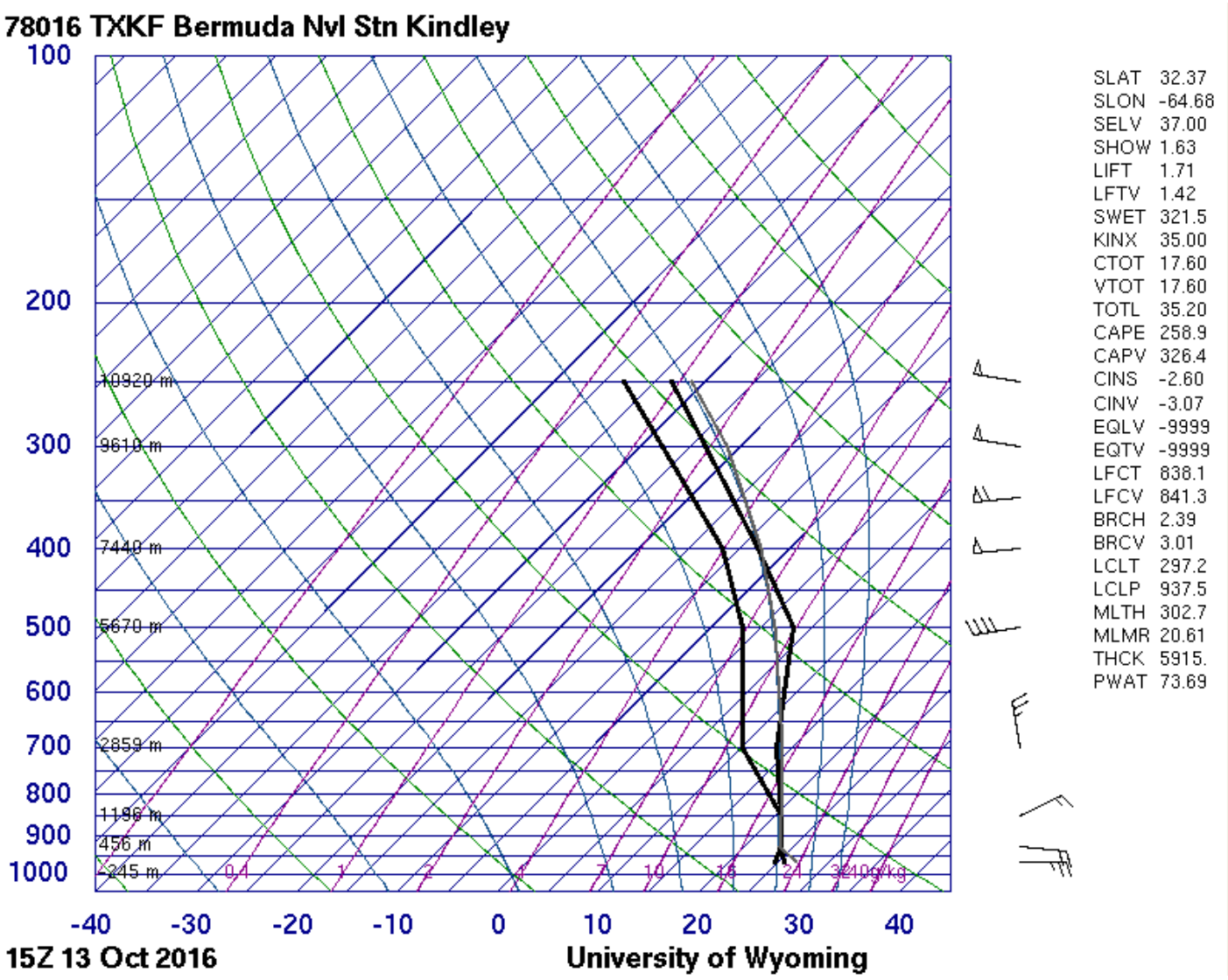
Skew-T diagram from 15Z radiosonde launch in eye of Hurricane Nicole –



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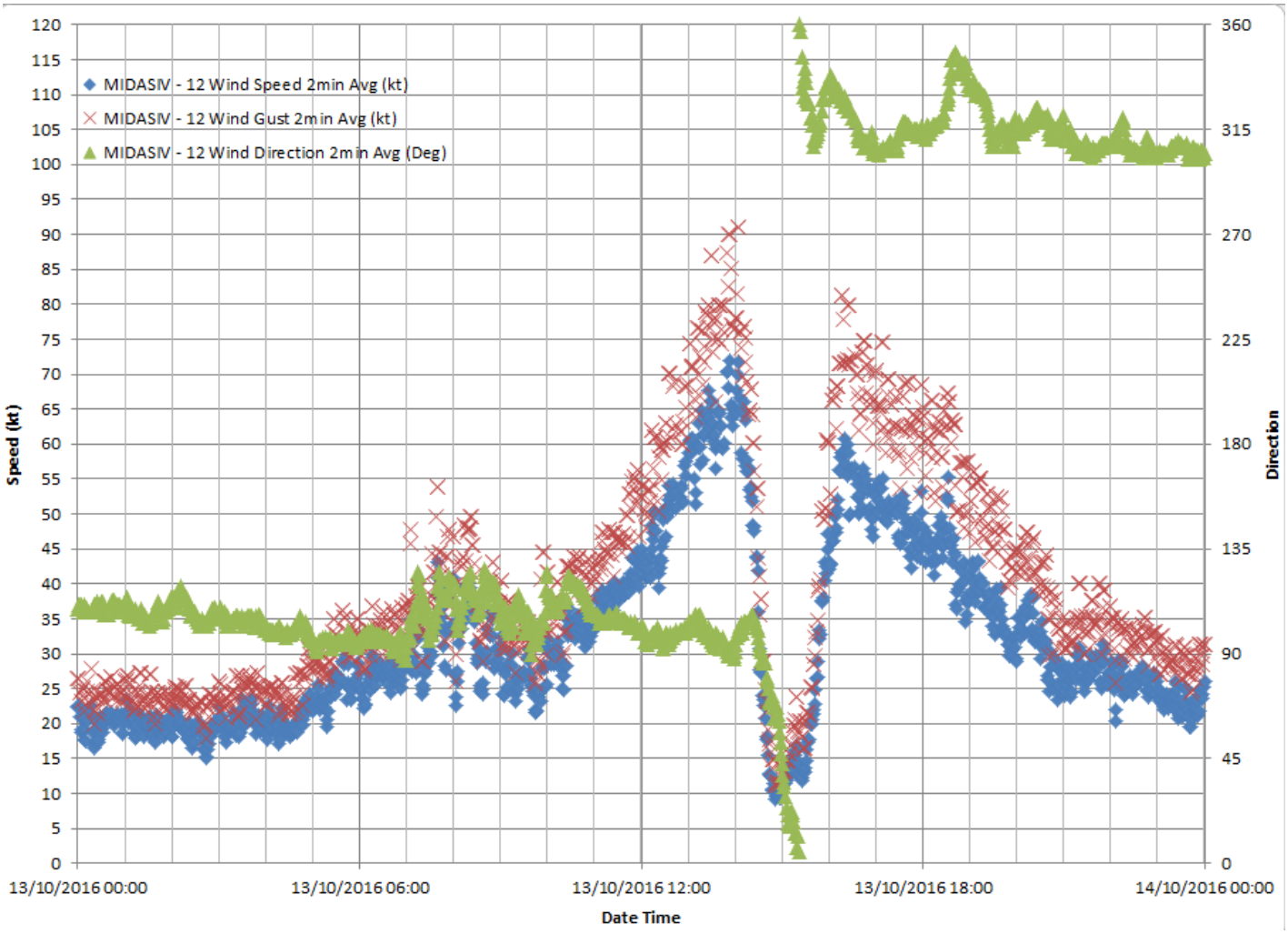
Wind trace (speed/gust/direction) from RWY12 AWOS sensor –



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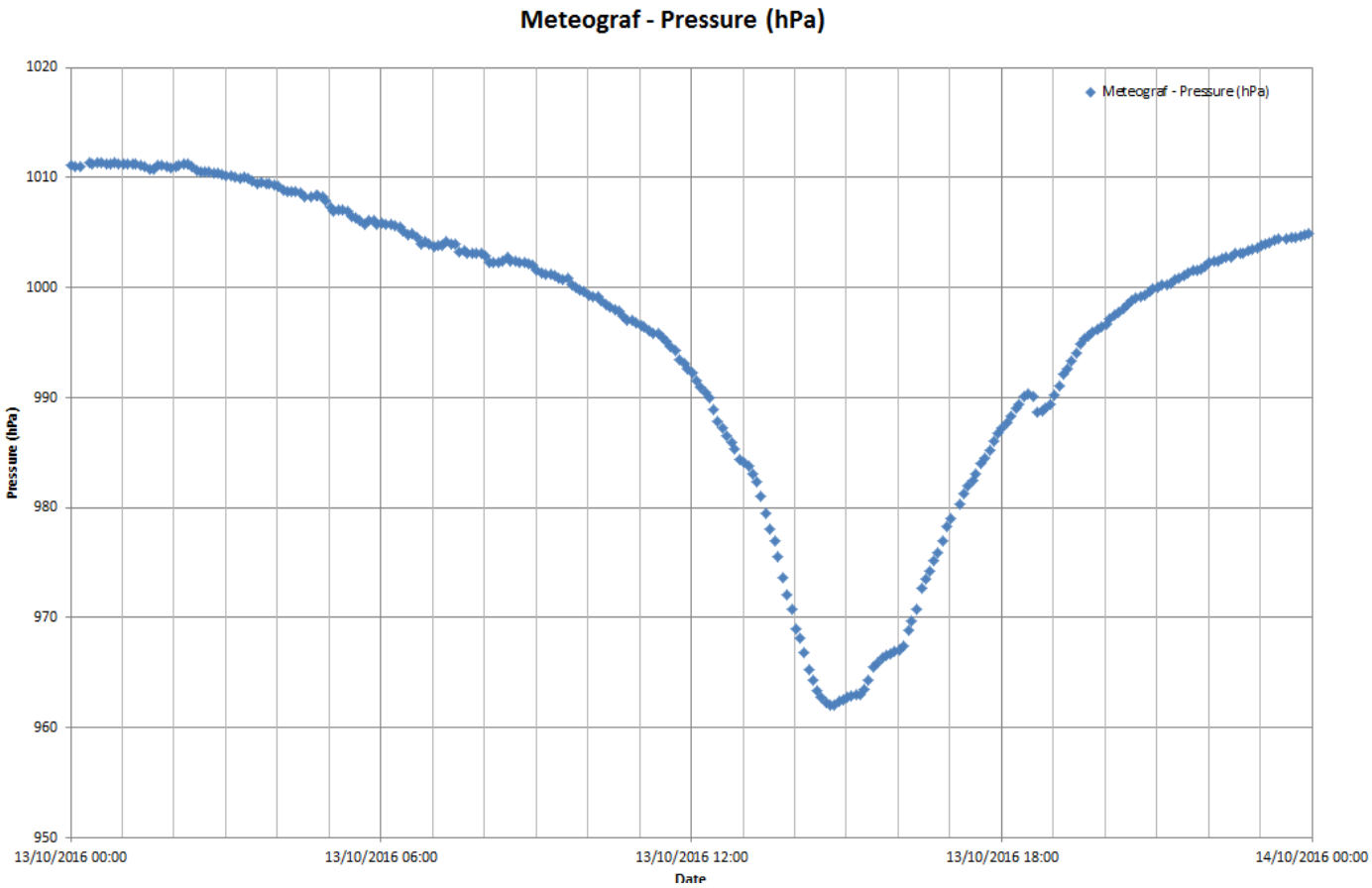
Pressure trace from Meteograf digital barometer at BWS –



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3. Summary Table – 2016 Tropical Systems that affected Bermuda

Tropical Season 2016 – Bermuda Tropical Cyclone Summary Table

Storm Name	Month	Watch/Warning Issued for Bermuda	Maximum Wind Speed at LF Wade (10min averaging)	Maximum Wind on/near Island	Significant Surge, Swell, Rainfall &/or Flooding	CPA & other notes	Verification
TS Colin	June 7th	Potential Threat Small Craft (more assoc. with merging front)	26g33kt	n/a	n/a	450nm to WNW @ 6pm	
Hurcn Gaston (Major)	Aug 26-29th	Not a Threat at this time Small Craft (in association with building swells)	n/a	n/a	Building easterly swell (9ft+) with hazardous surf	490nm to E @ 12noon Aug 29th	
Hurcn Hermine	Aug 29th- Sept 5th	Not a Threat at this time Small Craft (in association with building swells)	n/a	n/a	Building westerly swell (9ft+)	350nm to NNW @ 12 midnight Sep 4th	
TS Ian	Sept 14-15th	Not a Threat at this time	n/a	n/a	Minimal easterly swells	570nm ESE @ 6pm Sep 14th	
TS Karl	Sept 23-24th	Threat, Tropical Storm Watch/Warning, also temporary Hurcn Watch	30g41kt around 8-9am on 24th	38g59kt @ MAROPS around 8-9am on 24th 38g50kt around 9am @ Heliport (new Causeway)	Estimated surge of 1ft around 9am on 24th Very rough SE swells up to 18ft around 6am on 24th. Extensive rainfall of 4.71inches for whole event, with localised flooding – contributed to wettest September on record	44nm to SE @ 6am on 24th	Track forecast was okay with a near passage to the SE. However, intensity was uncertain – strong TS or weak Cat 1 Hurcn @ CPA time.
Hurcn Nicole (Major)	Oct 12-13th	Threat, Tropical Storm Warning, Hurricane Watch and then Hurricane Warning	72g91kt (2min averaging)	Heliport (old Causeway, 1min averaging) 61g89kt @ 1:30pm Comms Pt (Windguru, 1min averaging) 87g118kt @ 10:30am	Large swells, even days before onset of TS winds. Combined seas/swells estimated by local wave model and OPC analysis to be around 35ft. Esso pier data suggested a surge of towards 4ft, coincident with low tide on 13th though. Around 7 inches or rain, with isolated thunder. Some localised flooding in usual spots (e.g. Mills Creek) and at Boaz Island.	Overhead at noon on 13th, eye passage for all Island for approx. 1-1.5 hours	Models were generally in good agreement on track from several days out, even suggesting the landfall. However, intensity forecast was poor, initially not even suggesting a major hurcn.