TROPICAL CYCLONE AMOS (2016)
FORECASTING CHALLENGES: A MODEL'S PERSPECTIVE

TRACEY DORIAN

I.M. Systems Group at NOAA/NCEP/EMC, College Park, USA

BILL WARD

NWS Pacific Region Headquarters, Honolulu, USA

YI-LENG CHEN

University of Hawai'i at Mānoa, Honolulu, USA

ABSTRACT

The tropical cyclone (TC) named Amos (2016) that impacted the Samoan Islands on 23 April 2016 was a particularly difficult storm to forecast. Both the intensity changes and the track of Amos represent a significant challenge for forecasters and this is briefly summarized in this report.

Model forecasts initially indicated that the cyclone would track south of the Samoan Islands. However, the forecasts generally changed to a direct hit over Samoa as a Category 4 storm at approximately 0000 UTC 24 April based on model cycles initialized at 0000 UTC 23 April.

TC Amos' central pressure dropped from 983 hPa to 957 hPa between 0000 UTC 21 April and 0000 UTC 23 April. The models did not pick up on this rapid intensification until the intensification had already begun around 0000 UTC 21 April. The models also struggled to capture the rapid weakening of TC Amos due to vertical wind shear that began 0000 UTC 24 April as the cyclone continued to move north of the islands.

Because of the initially ominous track forecasts for TC Amos to hit land, preparations for a Category 3 or Category 4 cyclone were underway in the Samoan islands and the population prepared for the worst. After the center of the storm moved north of the islands as a weaker storm than anticipated, the residents of the Samoan Islands were both surprised and relieved that the cyclone only gave a "glancing blow" to the islands and that the impacts were not as bad as originally feared. An in-depth evaluation of this particular tropical cyclone helps to shed some light on model deficiencies and can be used to help determine future model changes.

Keywords: evaluation of TC forecasts, TC Amos, Samoan Islands

1. Introduction

Tropical cyclone forecasting has advanced significantly during the past few decades; this is especially true with regards to cyclone tracks (Franklin et al., 2003). Hurricane models today can predict with much better accuracy both the track and intensity than they have been able to in the past (Alaka et al., 2017). Despite the advances, there are still many challenges with hurricane forecasting today and the numerical weather prediction models do not always forecast the correct track or intensity. Both satellite data and conventional observations are used to initialize the models in an attempt to represent the current state of the atmosphere. Assuming that the model depicts a near-perfect representation of the initial state of the atmosphere, the model also needs to predict the evolution of the cyclone track and intensity based on complex dynamical equations. Many factors can influence a tropical cyclone's intensity such as vertical wind shear, proximity to land, sea surface temperature changes, and changes in atmospheric water vapor content. Other factors can also influence tracks, such as minor intensity or position changes in synoptic ridges or troughs; this can be explained by the fact that the atmosphere is a fluid in constant motion and that any deviations in the atmospheric steering mechanisms can quickly change a cyclone's projected path. Even small changes in the atmospheric conditions can change the forecasts from being a disaster to a mere inconvenience for any particular region.

TC Amos (https://en.wikipedia.org/wiki/Cyclone_Amos) was a particularly challenging storm to forecast. It was

Corresponding author: Tracey Dorian, tracey.dorian@noaa.gov

DOI: 10.6057/2018TCRR03.03

one of the most interesting and difficult tropical cyclones Pacific Region has had to work with in a very long time. Models and forecasters predicted that TC Amos' track would remain south of the Samoan islands, but instead of a path southeast, TC Amos tracked east and remained just north of the islands (Fig. 1). The intensity of TC Amos was also difficult to forecast, and the cyclone was not as strong after peak when approaching the Samoan islands as earlier feared. One of the mechanisms that appeared to cause TC Amos to suddenly weaken was the vertical wind shear between 850 hPa and 200 hPa. TC Amos was sheared off just prior to going over all of the Samoan Islands, and unfortunately the models didn't pick up on this. The low-level easterlies combined with the mid-latitude westerlies created the vertical wind shear that eventually led to Amos' rapid dissipation. Vertical wind shear is detrimental to tropical cyclones since it essentially tears apart the cyclone, destroying the circulation and disrupting any thunderstorm organization. The timing of the potential landfall of the storm was also a challenge to forecast correctly, as the forecasts for the cyclone's arrival were nearly a full day after it actually swung by the islands giving the islands a glancing blow.

2. Overview

After impacting Fiji with strong winds and heavy rainfall as a tropical depression, TC Amos was officially named on 20 April 2016 after reaching Category 1 intensity based on the Australian Cyclone Intensity Scale. Between 1200 UTC 19 April and 1200 UTC 20 April, TC Amos was nearly stationary before the primary atmospheric steering mechanism changed to a near-equatorial ridge of high pressure to the north. The tropical cyclone intensified and peaked between 1200 UTC 22 April and 1200 UTC 23 April to Category 3 intensity, with Joint Typhoon Warning Center (JTWC) estimating sustained 1-minute winds of 105 mph (~47 ms^{-1}) on 22 April 2016 ("Cyclone Amos"). The storm then maintained the same intensity for another 24 hours as it moved southeast towards the Samoan islands (see Fig. 1). Based on historical records (https://en.wikipedia.org/wiki/) since 1990, only five severe tropical cyclones have impacted the Samoan Islands: those are Ofa (Cat 5), 2/3-5/90; Val (Cat 5) 12/4/91; Heta (Cat 5) 12/25/03; Olaf (Cat 5), 2/16/05 and Wilma (Cat 4) 1/23/11. TC Amos was the strongest tropical cyclone to track near Samoa and American Samoa in over three years. Fortunately, the worst of the cyclone remained to the north of the small southwest Pacific islands.

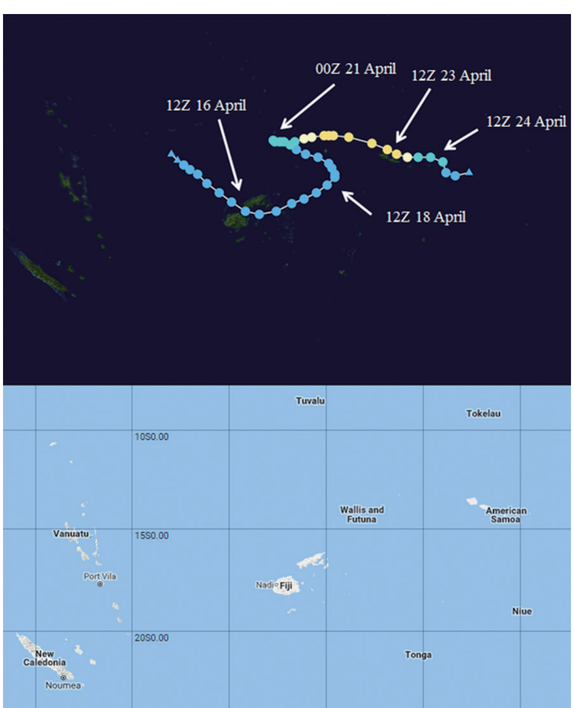


FIG. 1. Timeline TC Amos' track (top) with intensity depicted by a color scheme (warmer colors represent higher intensities) and a map of Fiji and the Samoan islands (bottom). Each dot in the track is spaced out by 6-hourly intervals.

3. Cyclone track

Two National Centers for Environmental Prediction (NCEP) models, the Hurricane-WRF (HWRF) (Tallapragada et al., 2012) and the Global Forecast System (GFS) (Yang et al., 2016), had impressively accurate track forecasts moving southeast just north of the Samoan Islands from one specific cycle, the 1200 UTC 18 April cycle (not shown), before TC Amos had even been named. However, by the 1200 UTC 19 April cycle, the HWRF and GFS forecasts no longer showed any approach towards the Samoan Islands; the HWRF model forecasted the storm to circle around and meander west of the islands, while the GFS forecasted the cyclone to trek south of the islands. On 20 April, the day TC Amos was named, the HWRF model forecast initialized at 1200 UTC showed a direct hit around 1200 UTC 22 April, while the GFS and the Geophysical Fluid Dynamic Laboratory (GFDL) (Bender et al., 2007) track forecasts were far south of the islands. By the 1200 UTC 21 April cycle, there was more agreement and less spread in track forecasts between models, but the tracks were incorrect and still to the south of the islands (Fig. 2a). The models on 1200 UTC 22 April continued to forecast a track south of the islands. On 23 April 2016, forecasters predicted TC Amos to make a direct landfall over the island of Samoa as a Category 4 storm in the following 24 hours based on the 1200 UTC 20 April, 1200 UTC 21 April, and 0000 UTC 23 April (Fig. 2b) cycles of the Hurricane-WRF (HWRF) model. The GFDL model was the only model that correctly forecasted the cyclone to move north of the islands after the 0000 UTC 23 April run (Fig. 2b). The models continued to show a direct hit over American Samoa in the following cycle from 0000 UTC

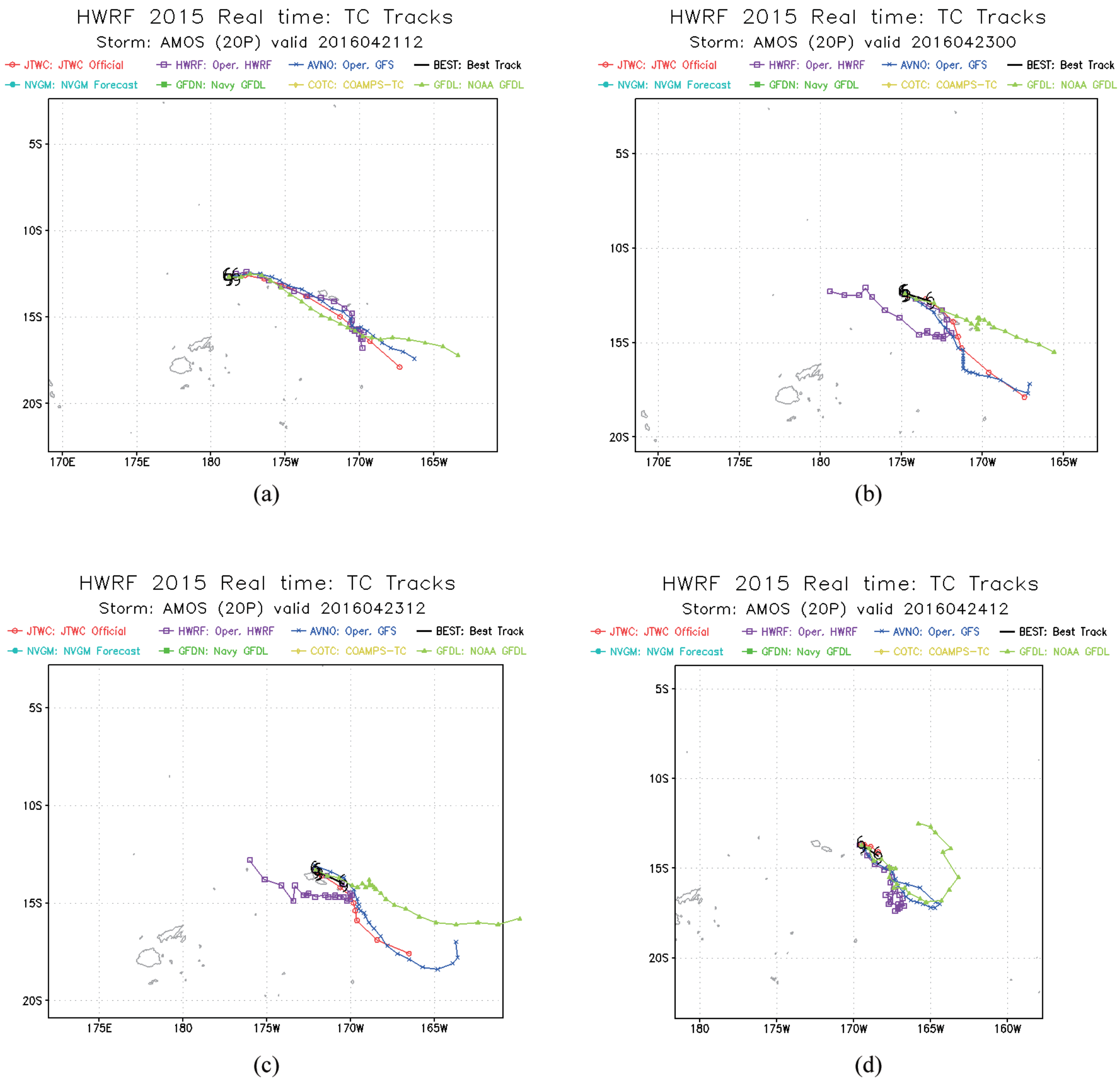


FIG. 2. Forecasted tracks of TC Amos from the 1200 UTC 21 April 2016 cycle (a), the 0000 UTC 23 April cycle (b), the 1200 UTC 23 April cycle (c), and the 0000 UTC 24 April cycle (d) out to the 5-day forecast (or 120-hour forecast). The actual track of TC Amos was north of the islands and not south of the islands as the models predicted. The colored markers are spaced out by 6-hourly time intervals (Source: http://www.emc.ncep.noaa.gov/gc_wmb/vxt/HWRF/index.php).

24 April, while the GFDL kept it north of the islands (not shown). It was not until 1200 UTC 24 April when observations made it clear that the system would continue east and not make a direct hit over American Samoa. It was during this cycle (1200 UTC 24 April) when the models correctly predicted the system to move eastward just to the north of the island of American Samoa (Fig. 2d). Unfortunately, most of the models did not predict the correct track north of the Samoan islands until the system was already north of the islands. This implies that something was inaccurate in the model, whether it was the initial state or the forecast.

Despite some damage to roads in Savai'i in central Samoa due to flooding and an extensive loss of electricity, the Samoan islands were largely spared of the severe conditions that were initially forecasted by the models. TC Amos ended up missing the American Samoa capital of Pago Pago (Fig. 1), but the cyclone still dumped about 3 inches of rainfall on the city. American Samoa was originally under a hurricane warning, but the warning was removed once TC Amos weakened. JTWC forecasted TC Amos to miss the Samoan islands to the south about four days before TC Amos skirted the islands on the north side (Fig. 3a). By 0900 UTC 23 April, the JTWC forecasted track had changed to a track just north of the islands before curving southward towards American Samoa (Fig. 3b). It was not until 1200 UTC 24 April when the JTWC forecasters forecasted a track that would not make landfall over any of the Samoan islands (Fig. 3c).

4. Cyclone intensity

The intensity forecasts by a handful of numerical weather prediction models, including the HWRF, U.S. Navy COAMPS-TC Model Forecast (COTC) (Hendricks et al., 2011), GFDL, and the Navy-Initialized Version of the GFDL Hurricane Model (GFDN) are examined. Before TC Amos was officially named on 20 April, the models underestimated its intensification before its close approach to the Samoan islands. TC Amos intensified into a storm with central pressure of 957 hPa between 1200 UTC 22 April and 1200 UTC 23 April. As seen in Figure 4b, all of the models underestimated the intensity from the 1200 UTC 19 April cycle for the 72-96 hour forecasts. The model with the best intensity forecast for this particular cycle was the GFDN, but even this model underestimated the rapid deepening in central pressure. All models generally began forecasting a pressure drop down to 957 hPa starting with the 0000 UTC 21 April cycle. By the 1200 UTC 21 April cycle, the HWRF and GFDL actually overestimated the intensification and forecasted a drop down to 945 hPa during TC Amos' peak (not shown).

After TC Amos' peak intensity, the cyclone unexpectedly began to rapidly weaken. The HWRF correctly forecasted Amos to weaken shortly after its peak starting with the 1200 UTC 20 April cycle, but this weakening was due to landfall in an erroneous track forecast. In 0000 UTC 21 April cycle, the HWRF similarly forecasted TC Amos to weaken, but had poor track forecasts predicting TC Amos to move south of the islands.

In the 0000 UTC 24 April cycle, the HWRF continued to correctly forecast a weakening trend, but incorrectly predicted landfall over American Samoa. TC Amos was close in proximity to an area of very strong vertical wind shear to its south around the time it began to weaken around 1200 UTC on 23 April 2016 while the storm was just north of Samoa (Fig. 5). The HWRF was often too weak in its forecasts before TC Amos peaked, but then overestimated peak intensity (not shown). After peak, the HWRF was the only model to capture the potential for rapid weakening, but the forecasts for weakening were initially due to landfall and not due to vertical wind shear.

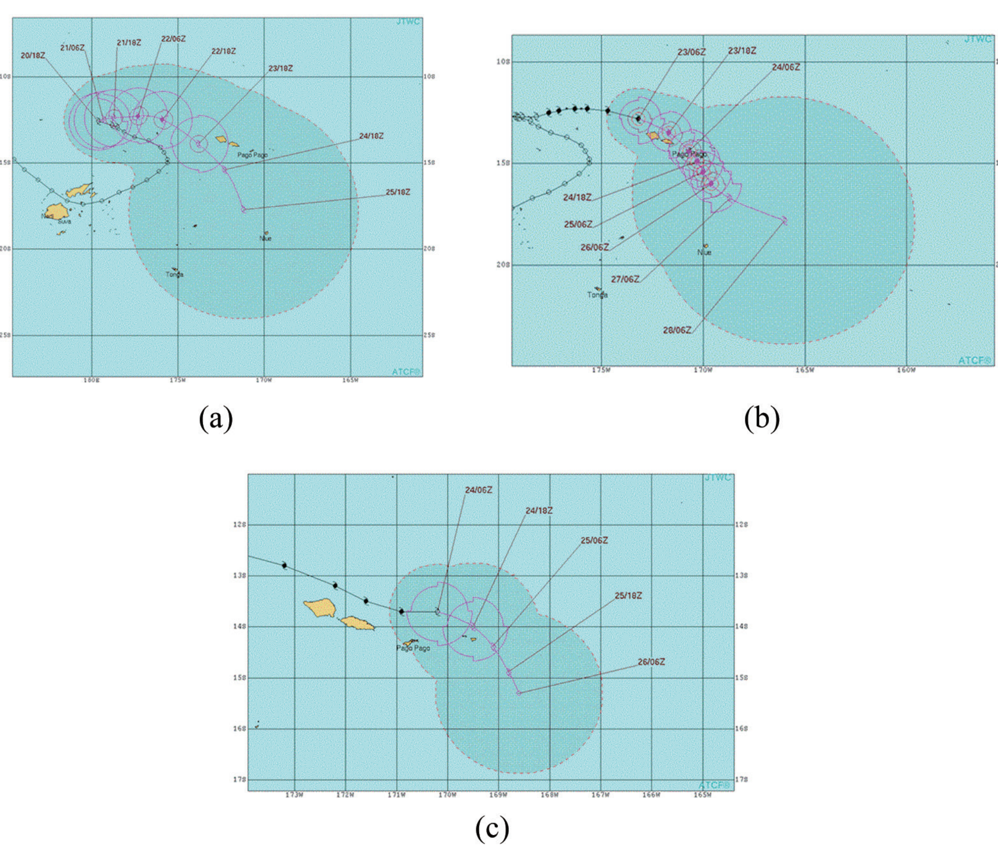
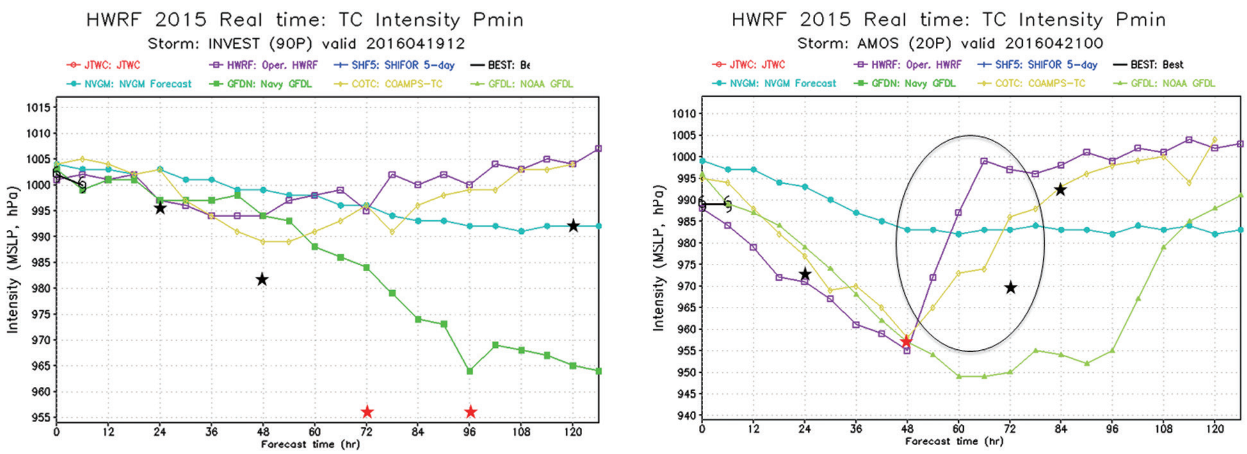


Fig. 3. Forecasted tracks of TC Amos by the Joint Typhoon Warning Center issued on 0800 UTC 20 April 2016 (a), 0600 UTC 23 April 2016 (b), and on 0600 UTC 24 April 2016 (c). (Source: http://www.usno.navy.mil/JTWC/).



(a) (b)

FIG. 4. Forecasts of storm intensity from the 1200 UTC 19 April 2016 cycle (a) and from the 0000 UTC 21 April cycle (b) for Invest 90P (shortly thereafter named TC Amos) out to the 120-hour forecast. The black and red stars depict the observed intensities. The red stars correspond to timing of observed peak intensity (Source: http://www.emc.ncep.noaa.gov/gc_wmb/vxt/HWRF/index.php).

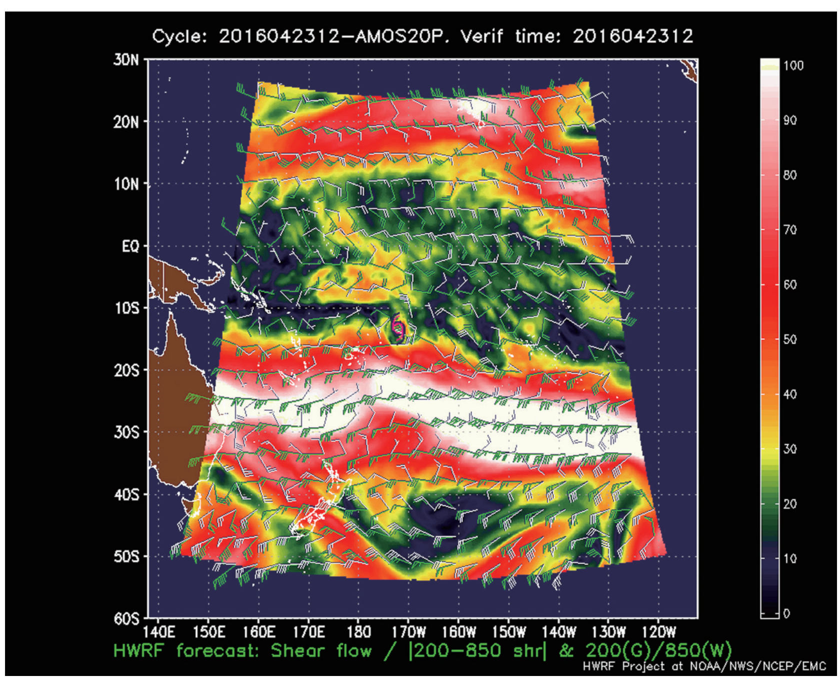
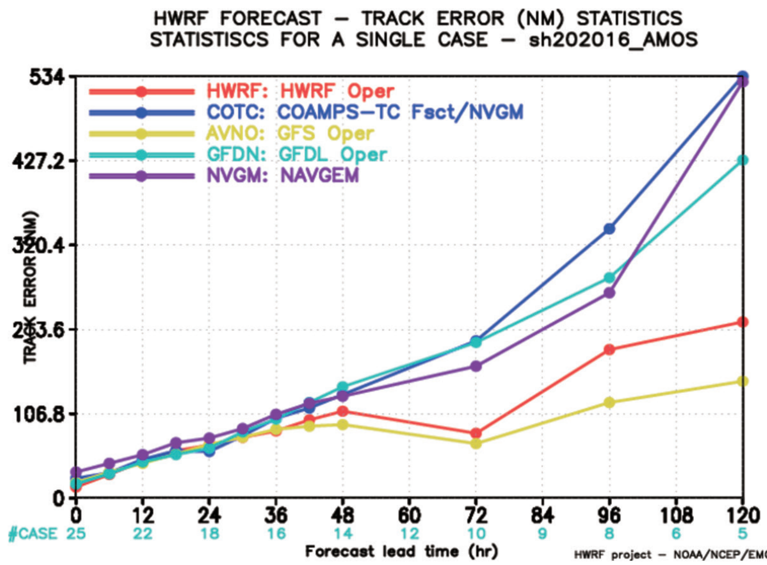


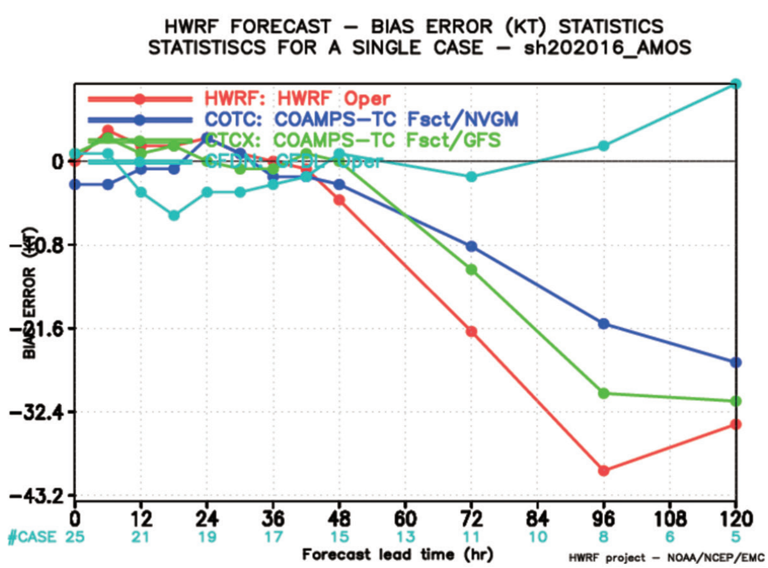
FIG. 5. HWRF analyzed vertical wind shear from 850 hPa to 200 hPa valid 1200 UTC 23 April 2016 (Alaka et al 2017). The storm began to rapidly weaken by 1200 UTC 23 April.

5. Model evaluations

Important metrics for measuring the overall performance of numerical weather prediction models regarding tropical cyclones include track, intensity, and bias errors. As seen in Figure 6, the models with the lowest track errors are the GFS (AVNO) and HWRF between the 36-hour and the 120-hour forecast. Also shown in Figure 6 is the bias error for the computer forecast models. Notice in this figure that nearly all of the models have negative bias errors, implying that their intensity forecasts were too weak. The HWRF



(a)



(b)

Fig. 6. Track errors (nautical miles) (a) and bias errors (knots) (b) for specific models [HWRF, COTC, AVNO, and Navy Global Environmental Model (NVGM) (Hogan 2014)] based on all cycles between 1800 UTC 15 April and 1200 UTC 24 April for TC Amos. Units are nautical miles for track errors and knots for intensity bias errors. (1 nautical mile is approximately 1.85 km) (Source: http://www.emc.ncep.noaa.gov/gc_wmb/vxt/HWRF/index.php).

had the largest negative intensity errors in the longer-range forecasts beyond the 84-hour forecast, but actually had positive intensity errors in the short-range, implying too strong of forecasts. The GFDN had the smallest intensity errors for almost all forecast hours. A list is presented in Figure 7 that shows the "best" model based on the author's subjective evaluation for several individual model runs in terms of intensity and track forecasts. As can be seen, the "best" model for every cycle was not always the same.

6. Summary and conclusions

The inability of the models to correctly forecast the track and intensity for this particular case could have been due to a number of reasons, and it is difficult to know exactly what

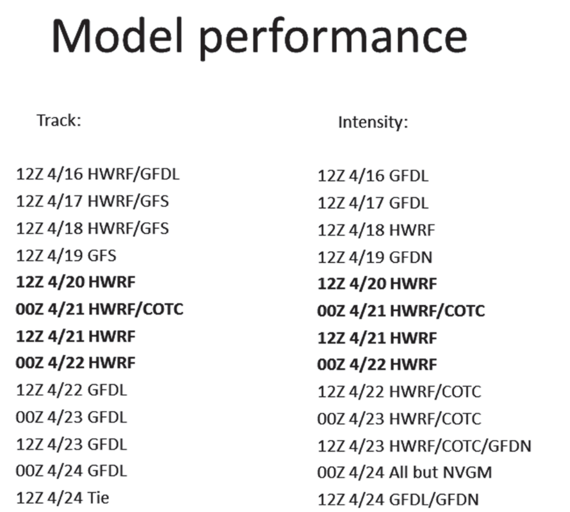


FIG. 7. Models with "best" track and intensity forecasts for individual cycles based on subjective evaluation.

the causes were. There are a lot of things that can impact model forecasts, including initial conditions, microphysics schemes, planetary boundary layer schemes, convection schemes, horizontal resolution, vertical levels, whether the model is coupled or non-coupled, and more. One of the most important parts of hurricane development is convection, and if the model doesn't correctly depict the convection, this will influence whether or not the storm will intensify or weaken. The data assimilation and initialization of the state of the atmosphere could have also led to errors due to lack of radiosonde, aircraft, and ship observations in the western Pacific that help supplement satellite observations. For example, aircraft observations in the western Atlantic during the Atlantic hurricane seasons have been shown to help improve model forecasts of a storm's path (Langford 1993). The complex interaction between Cyclone Amos and the ridging to its north along with the upper level westerlies to its south and subsequent entrainment of stronger winds may have also contributed to this challenging forecast. It is necessary for the model to correctly forecast the intensity of the lower and upper-level winds, the magnitude and position of surface highs and lows, in addition to the correct size and intensity of the cyclone itself, in order to accurately predict a cyclone's track and intensity evolution. Additionally the models need to accurately portray the sea-surface temperatures and air-sea interactions. The intensity of a tropical cyclone itself also determines how much it will be influenced by upper-level winds, namely the stronger the cyclone is, the more it is steered by the upper-level winds.

An in-depth evaluation into this particular case demonstrates the deficiencies of current state-of-the-art models in handling this type of event and the need for continued modeling efforts and research to provide better numerical guidance to forecasters in operational settings.

References

Alaka, G.J. Jr., X. Zhang, S.G. Gopalakrishnan, S.B. Goldenberg, and F.D. Marks, 2017: Performance of Basin-Scale HWRF Tropical Cyclone Track Forecasts. *Wea. Forecasting,* **32**, 1253–1271, https://doi.org/10.1175/WAF-D-16-0150.1

Alaka G.J. Jr., X. Zhang, S. Gopalakrishnan, and F. D. Marks Jr., 2017: Investigation of Tropical Cyclone Forecasts in the Basin-Scale HWRF Ensemble System. WAF/NWP Posters: Forecasting Tools, Numerical Weather Prediction, and Tropical Cyclones. *28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction.* 23-26 January, Seattle, WA.

Bender, M.A., I. Ginis, R. Tuleya, B. Thomas, and T. Marchok, 2007: The Operational GFDL Coupled Hurricane–Ocean Prediction System and a Summary of Its Performance. *Mon. Wea. Rev.,* **135**, 3965–3989, https://doi.org/10.1175/2007MWR2032.1

Franklin, J.L., C.J. McAdie, and M.B. Lawrence, 2003: Trends in Track Forecasting for Tropical Cyclones Threatening the United States, 1970–2001. *Bull. Amer. Meteor. Soc.,* **84**, 1197–1203, https://doi.org/10.1175/BAMS-84-9-1197

Hendricks, E.A., M.S. Peng, X. Ge, and T. Li, 2011: Performance of a Dynamic Initialization Scheme in the Coupled Ocean–Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC). *Wea. Forecasting,* **26**, 650–663, https://doi.org/10.1175/WAF-D-10-05051.1

Hogan, T.F. 2014. The Navy Global Environmental Model. *Oceanography*, **27(3)**, 116–125, http://dx.doi.org/10.5670/oceanog.2014.73.

Langford, J.S. and K.A. Emanuel, 1993: An Unmanned Aircraft for Dropwindsonde Deployment and Hurricane Reconnaissance. *Bull. Amer. Meteor. Soc.,* **74**, 367–375, https://doi.org/10.1175/1520-0477(1993)074<0367:AUAFDD>2.0.CO;2

Paterson, L.A., B.N. Hanstrum, N.E. Davidson, and H.C. Weber, 2005: Influence of Environmental Vertical Wind Shear on the Intensity of Hurricane-Strength Tropical Cyclones in the Australian Region. *Mon. Wea. Rev.,* **133**, 3644–3660, https://doi.org/10.1175/MWR3041.1

Rennick, M.A., 1999: Performance of the Navy's Tropical Cyclone Prediction Model in the Western North Pacific Basin during 1996. *Wea. Forecasting,* **14**, 297–305, https://doi.org/10.1175/1520-0434(1999)014<0297:POTNST>2.0.CO;2

Tallapragada, V., C. Kieu, S. Trahan, Z. Zhang, Q. Liu, W. Wang, M. Tong, B. Zhang, and B. Strahl, 2015: Forecasting Tropical Cyclones in the Western North Pacific Basin Using the NCEP Operational HWRF: Real-Time Implementation in 2012. *Wea. Forecasting,* **30**, 1355–1373, https://doi.org/10.1175/WAF-D-14-00138.1

Yang. F., 2016: Evaluation of Hurricane Forecast Skills of NCEP GFS Retrospective Experiments for the FY2016 Implementation. *32nd Conference on Hurricanes and Tropical Meteorology.* 17-22 April, San Juan, PR.