FORECASTING OCEANIC CYCLONES AT THE NOAA OCEAN PREDICTION CENTER

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1. INTRODUCTION

The NOAA Ocean Prediction Center (OPC) is one of the nine service centers that make up the National Centers for Environmental Prediction (NCEP). The OPC is responsible for issuing wind warnings for the extratropical western North Atlantic and central and eastern North Pacific Oceans. The OPC wind warnings are used by mariners to aid in safe ocean transit. Warning categories are: GALE – Winds 17.2 to 24.4 ms^{-1}, STORM – Winds 24.5 to 32.6 ms^{-1}, and HURRICANE FORCE – 32.7 ms^{-1} and greater. These warnings are distributed via text bulletins and are also displayed on OPC graphical surface 48 and 96 hour forecasts and 00 hour analyses. These graphical analyses and forecasts are available at sea via U.S. Coast Guard High Frequency Radiofacsimile and the Internet at www.opc.ncep.noaa.gov/. The purpose of this paper is to assess the current skill of the OPC forecast staff in forecasting the central pressure, location, and warning category of extratropical cyclones over the North Pacific and North Atlantic at the 48 and 96 hour time steps. A brief history of forecasting ocean cyclones will be given in Section 2. Ocean cyclone forecast skill at the NOAA OPC will be discussed in Section 3. Summary and conclusions will be given in Section 4.

2. HISTORY OF FORECASTING OCEANIC CYCLONES

Accurately forecasting the intensity, central pressure, and location of oceanic cyclones twenty-five years ago or more was an illusive goal. The ocean liner *Queen Elizabeth II* was damaged by a rapidly intensifying extratropical storm in September 1978. The explosive intensification of the *QE II* storm (60 hPa in 24 hours) was nearly completely missed by operational numerical models (Anthes et al., 1983, Gyakum 1983a). Sanders and Gyakum (1980) examined the climatology of rapidly intensifying ocean cyclones over the northern hemisphere. These extreme events were called meteorological "bombs" and were found to be primarily fall and winter phenomena.

Following Sanders and Gyakum (1980) a decade ensued with an intense focus on understanding and predicting the meteorological bomb. Anthes et al., (1983) conducted numerical experiments on the *QE II* storm and concluded that improved forecasts over the operational model forecasts were made through improved initial conditions, improved horizontal and vertical resolutions, and changes in the physical parameterization of surface fluxes and latent heating. Two major field experiments took place off the mid-Atlantic coast of the United States during the 1980's. The Genesis of Atlantic Lows Experiment (GALE) was conducted during the winter and spring of 1986 (Dirks et al., 1988). The Experiment on Rapidly

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Intensifying Cyclones over the Atlantic (ERICA) followed during the winter of 1988-89 (Hadlock and Kreitzberg, 1988). Sanders, through a series of papers, examined the progress made by the operational numerical models in predicting marine cyclones (Sanders, 1986, 1987, 1992). A review of the LFM forecast skill from 1981 to 1984 lead Sanders (1986) to state, "the LFM is able to capture the essentials of the baroclinic process, and that the amount of response to baroclinic forcing remains *intractable*." Following the 1987/1988 cold-season, Sanders and Auciello (1989) found improvement in the ability to forecast explosive cyclogenesis over the previous cold season for the National Meteorological Center's AVN and NGM models. So numerical model developments were improving forecast skill for explosive deepening cyclones.

In a study of numerical model performance for the ERICA period during the 1988/89 cold season, Sanders concluded that, "…it seemed clear that the state of the art in prediction of marine cyclones has advanced substantially over the last 15 years." Use of numerical model guidance to help in the decision-making process resulted in a very successful ERICA field project.

Uccellini et al, (1999) examined the skill of forecasting North Pacific cyclones at the day 4 forecast period and concluded that, " It is clear that the goal of V. Bjerknes and his collaborators to improve the forecasts of major storm systems over the ocean through the application of mathematical principles to weather forecasting is being realized some 80 years later. This accomplishments represents one of the major intellectual achievements of the twentieth century." It was further stated that, "…if a major cyclone is forecast by the Marine Forecast Branch for the relatively data sparse North pacific at day 4, it will generally occur". These statements summarize the immense progress made in a relatively short amount of time at forecasting the range of marine cyclones.

3. FORECASTING OCEAN CYCLONES AT THE NOAA OCEAN PREDICTION CENTER

The purpose of this paper is to assess the current skill level of forecasting ocean cyclones as practiced by the NOAA Ocean Prediction Center. We are attempting to establish a baseline of the current skill level and identify possible deficiencies in the present state of forecasting ocean cyclones. Our eventual goal (beyond the scope of this paper) is to then improve upon any deficiencies. The areas of concern are the extratropical North Atlantic and North Pacific Oceans. Sanders and Gyakum (1980) documented that explosive cyclogenesis has a high frequency of occurrence across the western portions of these basins.

OPC forecasters daily produce (per ocean basin) four surface pressure and feature analyses, two 48-hour surface forecasts, and one 96-hour surface forecast. The domain for this study was the North Atlantic and North Pacific Oceans from 17°N to 65°N. In this paper, we compared 1200 UTC 48 and 96 hour forecasts with the verifying 1200 UTC surface analyses. For each cyclone observed we compared forecast position, central pressure, and wind warning category. The period of study was October 1, 2003 to March 31, 2004.

48 hour position errors (nm)

	Atlantic	Pacific
Sanders (88-89)	170	228
All (2003-04)	143	157
980 or <(2003-04)	103	136
965 or <(2003-04)	84	185
HRCN Force (2003-04)	64	123
NHC TC error (1993-03)	150	

Table 1. 48 hour forecast mean position errors (MPE) for the North Atlantic and North Pacific from Sanders (1992) study of 1988-89, and 4 classifications of observed cyclones (2003-04). The 10-year mean track error (1993-03) for Atlantic tropical cyclones is also given.

a) Position Errors

Position errors were calculated for all observed cyclones. Cyclones were then further categorized. These sub-categories included cyclones observed to have a central pressure of 980 hPa or less, 965 hPa or less, and those with Hurricane Force conditions. Tables 1 and 2 show the mean position errors for each cyclone category for 48 and 96-hour forecasts, respectively.

96 hour position errors (nm)

	Atlantic	Pacific
Sanders (88-89)	350	279
All (2003-04)	240	295
980 or <(2003-04)	208	260 (**284**)
965 or <(2003-04)	132	209 (**248**)
HRCN Force (2003-04)	242	279
NHC TC error (1993-03)	282	

Table 2. As in Table 1 except showing 96 hour forecast mean position errors. For the Pacific cyclone categories 980 or less and 965 or less the numbers in parenthesis (bold) are mean position errors from Uccellini et al., 1999 for the years 1993-94.

For the years 2003-04, 48 and 96 hour mean position errors (MPE) for all categories of cyclones were larger for the North Pacific than the North Atlantic. This is in disagreement with the results of Sanders (1992) who studied only eastern North Pacific cyclones. Also, there was significant improvement in MPE in 2003-04 over both the Sanders (1992) and Uccellini et al., (1999) studies. As in earlier studies, the lower the observed central pressure the smaller the MPE. This is excellent news and bolsters the comments earlier by Uccellini et al., (1999) concerning forecasting major oceanic cyclones. All 2003-04 MPE's are lower than the comparable Tropical Prediction Center (TPC) 10- year mean track error for Atlantic tropical cyclones for both 48 and 96-hour time steps. Considering that extratropical cyclones have significantly shorter life spans than their tropical cousins and that the TPC only makes forecasts for existing cyclones, the MPE's of the OPC are impressive and a good indication of the state of the science to this point.

However, one set of MPE's is disappointing. For the 96-hour forecasts the Hurricane Force category storms the MPE's are significantly larger than any of the categories based on central pressure. This is not the case at 48 hours where the MPE's are the lowest for this extreme cyclone.

b. Mean Pressure Errors

Mean sea-level pressure (MSLP) errors (hPa) were calculated for all categories of cyclones for 2003-04 and are shown in Fig. 1.

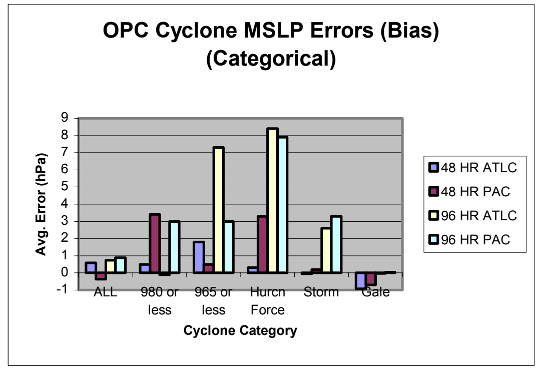

Fig. 1. OPC Cyclone Mean Sea Level Pressure Errors (MSLP, hPa) for 2003-04 for 5 categories of observed cyclones: ALL, 980 hPa or less, 965 hPa or less, Hurricane Force, Storm Force and Gale Force.

On average MSLP errors tended to be positive suggesting that there is a tendency to under forecast central pressure at both 48 and 96 hours. Only the categories ALL and Gale Force show any MSLP errors that are negative. Of the three pressure categories, the Atlantic 96-hour forecasts of cyclones observed 965 hPa or less shows the greatest tendency (+7.3 hPa) to be under forecast. Interesting we do not see such magnitude of error in the Pacific. The Warning Category of Hurricane Force for both the Atlantic and Pacific at 96-hours clearly stands out with MSLP errors 8 hPa or greater. We have seen that the track error for this category of cyclone is also greater than the other categories and points to possible inadequacies in forecast skill by numerical forecast guidance at the day 4 time step.

c. Warning Categories

Wind warning categories as described early are Hurricane Force, Storm, and Gale. OPC forecasters include a wind-warning category (when appropriate) for each forecast cyclone. The forecast categories were then compared to each verifying analysis. A percent correct for each warning category was then calculated and is shown in Fig. 2.

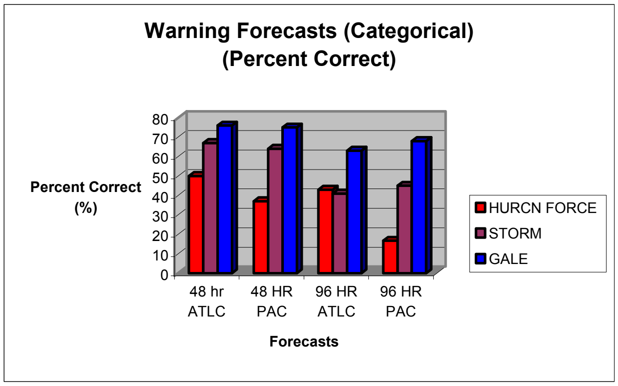

Fig. 2. Categorical warning verification shown as percent correct for both the Atlantic and Pacific 48 and 96 hour forecasts.

The Gale category of warning shows the highest likelihood of being correct with a nearly 75% success rate at 48 hours in both oceans. This rate drops to between 60 and 70% at 96 hours, again impressive. The Storm category is correct in excess of 60% of the time at 48 hours for both oceans but drops to approximately 40% correct at 96 hours. Warning category verification for Hurricane Force cyclones is substantially lower than Gale or Storm. There was a success rate of less than 50% for the 48-hour forecasts for both the Pacific and Atlantic with the Pacific at approximately 35% success. At 96 hours, the chance of a successful forecast of hurricane force conditions fell to approximately 17% for the Pacific. For the Atlantic, the percent correct for Hurricane Force was similar to Storm force at 96 hours at approximately 40%.

If the OPC forecasters are not correctly forecasting the Hurricane Force warnings nearly 83% of the time for the Pacific at 96 hours, how are they missing? Figure 3 shows the percent breakdown of correct, over forecast (by one warning category) and under forecast (again by one category). From Figure 3, it is clear that 67% of the missed Hurricane Force warnings were forecast by one category too low (Storm force). The wind speed differences between

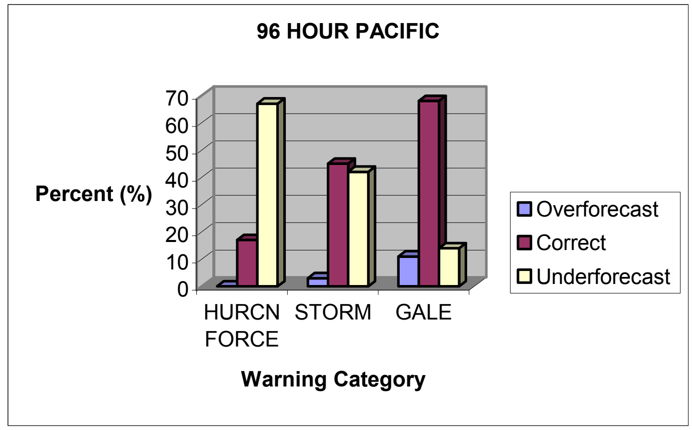

Fig. 3. Distribution of warning category forecasts for 96 hours for the North Pacific by % correct, overforecast, and underforecast by one warning category.

Warning categories could be as little as 2.5 ms^{-1}. Taking that into account these results are not as discouraging as may seem. It is clear from this graph and others not shown that there is a tendency (if incorrect) to under forecast by one warning category the stronger wind warnings.

4. CONCLUSIONS

An increasing understanding of explosive cyclone development coupled with the application of this understanding in numerical models in the 1980's has lead to the forecast skill that we now enjoy. The mean position and pressure errors for oceanic cyclones from the 2003-04 cold season across the North Pacific and North Atlantic show that there has been a continuous increase in skill from the studies of Sanders (1992) and Uccellini et al., (1999). MPE's are lower now than ever before for all cyclones at 48 and 96 hours. For stronger categories of cyclones of 980 hPa or less and 965 hPa or less mean pressure errors were significantly less than for all cyclones at both 48 and 96 hours. This is encouraging and suggests that there may indeed be higher skill for the stronger cyclones. Uccellini et al., 1999 first observed this. Position errors typically all fell below the most recent ten-year average track errors for NCEP Tropical Prediction Center Atlantic tropical cyclones. Considering that most extratropical cyclones have fairly short life cycles (on the order of 3 to 5 days) as compared to many tropical cyclones and that those forecasts verified by TPC are only those made for existing TC's at 00 hour this is a significant feat and a tribute to the skill of numerical forecast guidance.

Pressure errors on average were positive for both forecast time ranges and nearly all categories of cyclones with most falling within 3 hPa of verifying analyses. The exceptions were the 96-hour forecasts of both Hurricane Force cyclones (Atlantic and Pacific) (approximately +8.0 hPa) and those observed to reach 965 hPa or less in the North Atlantic (+7.3). Predictability may in part be a factor as we do not see similar results at the 48 hour forecast period. Perhaps ensemble techniques applied to deterministic forecasts would help reduce this error.

Warning category verification is of extreme interest to OPC forecasters and mariners. In this paper we have identified the inability to forecast Hurricane Force cyclones consistently at 96 hours. However, there is a strong tendency to under forecast the winds with these extreme cyclones by one only one warning category (Storm versus Hurricane Force). This one warning category difference may be accounted for by the +8 hPa mean pressure errors for this classification of cyclone. A second possible source for this tendency may lie in the wind guidance provided by the numerical models. This remains a topic for additional study. On the positive side, we have shown that at the 48-hour time step the OPC is able to consistently forecast the most extreme conditions nearly half the time. Reflecting on discussions by Sanders (1986) about LFM skill forecasting explosive development being intractable then this ability is a significant achievement.

We have attempted to define the current skill in forecasting oceanic cyclones as practiced at the NOAA OPC. This effort will continue for the foreseeable future. Steady improvement in Mean Position Errors for a variety of cyclone intensities have been shown. Deficiencies in forecasting location, central pressure, and strength of winds for the extreme hurricane force event at 96 hours exist and will become the focus of the OPC Ocean Applications Branch for the near future. Ensemble techniques will be explored to help in making deterministic forecasts. Probabilities (based on a suite of ensemble forecasts) of occurrence of warning criteria may prove to be a useful tool for both forecaster and mariner. There remain unanswered questions regarding the extreme cyclone. Perhaps we are seeing at 96 hours an inability of the numerical models to indeed simulate the inner core structure of the extreme cyclone. Cyclone phase diagrams may prove to be useful to determine whether to intensify a cyclone beyond numerical guidance central pressure and winds. In addition, large-scale signals may exist with preferred phases for extreme cyclone development and is a source for future study.

The progressive improvement in forecasting extratropical oceanic cyclones documented rigorously by Sanders, then followed by Uccellini et al., 1999, and discussed here cannot be understated. The achievements of the past 25 years have truly been remarkable.

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