GODAE OceanView Symposium 2019 - OceanPredict '19

ASSESSMENTS OF AN OPERATIONAL WAVE FORECAST FOR THE BRAZILIAN COAST

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INTRODUCTION

The **Brazilian Navy Hydrographic Center (CHM)** operates the Marine Meteorological Service (SMM), which generates daily weather forecast products for the sake of the Safety of Navigation and in compliance with the responsibilities of Brazil according to the Convention for the Safety of Life at Sea (SOLAS). In partnership with CHM operates the Oceanographic Modeling and Observation Network (REMO), which is a Brazilian effort towards operational oceanography that is in permanent improvement by researchers from different institutions in Brazil. In order to analyse and improve our wave prediction system a detailed multivariate assessment was developed by CHM-REMO.

METODOLOGY

Wave forecast: 2 cycles per day, at 00Z and 12Z, using WAVEWATCH III with multi-grid and source terms ST4 (Ardhuin et al., 2010):

$$S_{in}(k,\theta) = \frac{\rho_a}{\rho_w}\frac{\beta_{max}}{\kappa^2} e^Z Z^4 \left(\frac{u_*}{C}\right)^2 \times max[cos(\theta-\theta_u),0]^2 \sigma F(k,\theta)$$

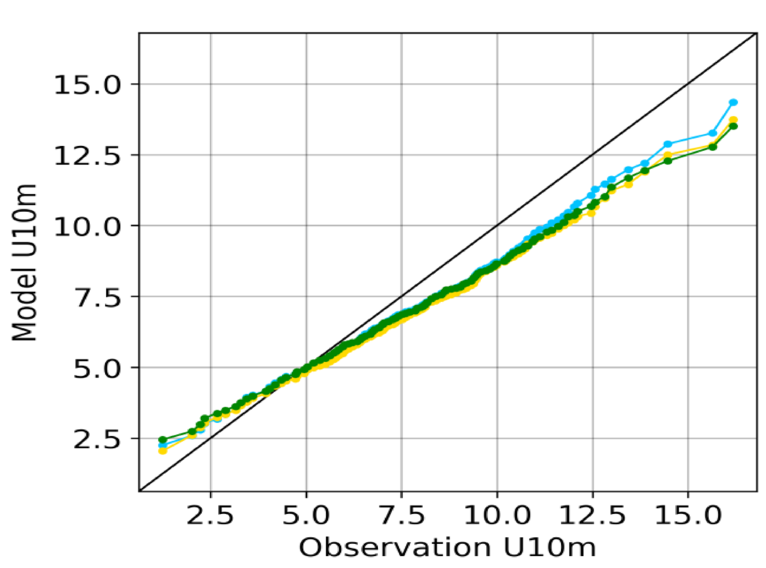
Resolution of Brazilian grid: 0,1°X0,1° and 1 hour (being currently upgraded). Input winds: NCEP Global Forecast System (NCEP/GFS); ICON (Icosahedral Nonhydrostatic Model); and a downscaling simulation using COSMO (Consortium for Small-scale Modeling).

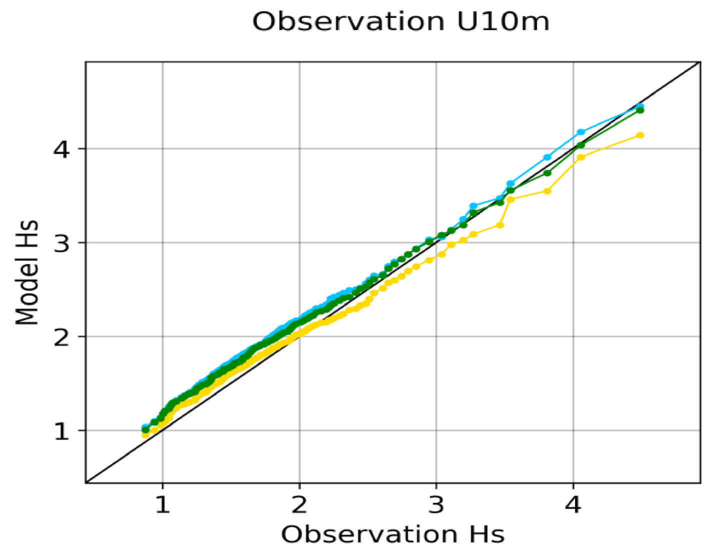
Forecast accuracy and precision of surface winds and wave heights: function of: i) the forecast range (up to 5 days), ii) the percentiles (severity), iii) the location, and iv) the input winds. One year (2017) of analyses and assessments: six buoys from National Buoy Program (PNBOIA), and four satellite missions: JASON2, JASON3, CRYOSAT, and SARAL. Eight error metrics based on Mentaschi et al. (2013) and Campos et al (2018), including:

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i) \qquad RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \qquad SI = \sqrt{\frac{\sum_{i=1}^{n}\left[(y_i-\bar{y})-(x_i-\bar{x})\right]^2}{\sum_{i=1}^{n}x_i^2}} \qquad CC = \frac{\sum_{i=1}^{n}(y_i-\bar{y})(x_i-\bar{x})}{\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2\sum_{i=1}^{n}(x_i-\bar{x})^2}}$$

1228 model/measurement data pairs for the evaluation with buoy data and 4,477,863 pairs with satellite data.

RESULTS AND DISCUSSION

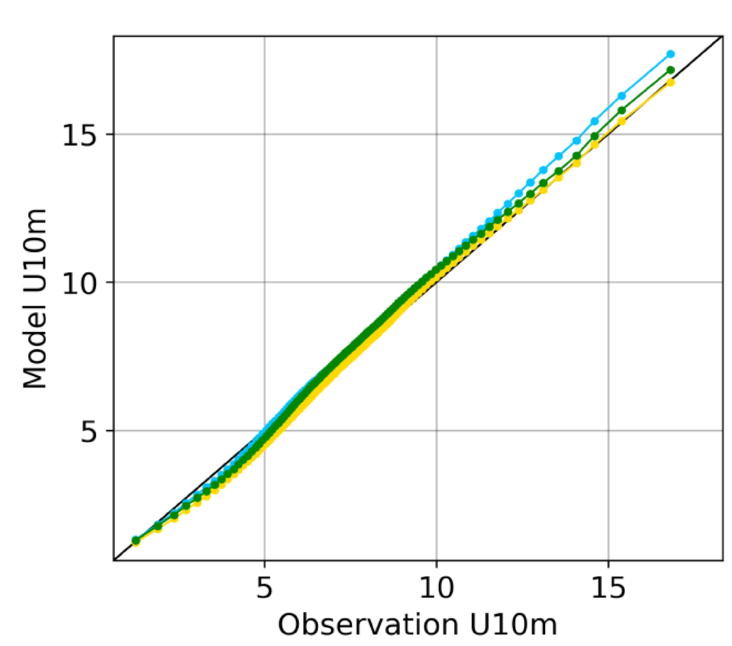




WW3 Assessments using Buoy data. From Figure 1 (top): small overestimation of the wind intensity for calm conditions, evolving to a great underestimation for intense winds. The uncertainties of buoy observations and wind speed profile approximations must be considered. Results for the significant wave height (Hs, Figure 1, bottom): agreement between the three wave models and buoy measurements. For calm conditions there is a small overestimation of the models whereas for extreme quantiles WW3/GFS overestimates and WW3/ICON slightly underestimates the observation.

Fig.1: Wind QQ-plots (top, in m/s) and wave QQ-plots (bottom, in m) for the GFS (blue), ICON (yellow) and COSMO (green) models in comparison with observations from buoy data.

WW3 Assessments using Altimeter data. From Figure 2 (top): Better agreement of wind forecasts with altimeters (small overestimation of GFS) and very good results of ICON. On the bottom: direct impact of wind inputs on the wave fields, with overestimation of Hs from WW3/GFS. The small underestimation of WW3/ICON suggests a slight modification of the wave model parameters (equation 1), which is a currently effort of CHM and the next generation of calibrated high-resolution multi-grid operational forecast.



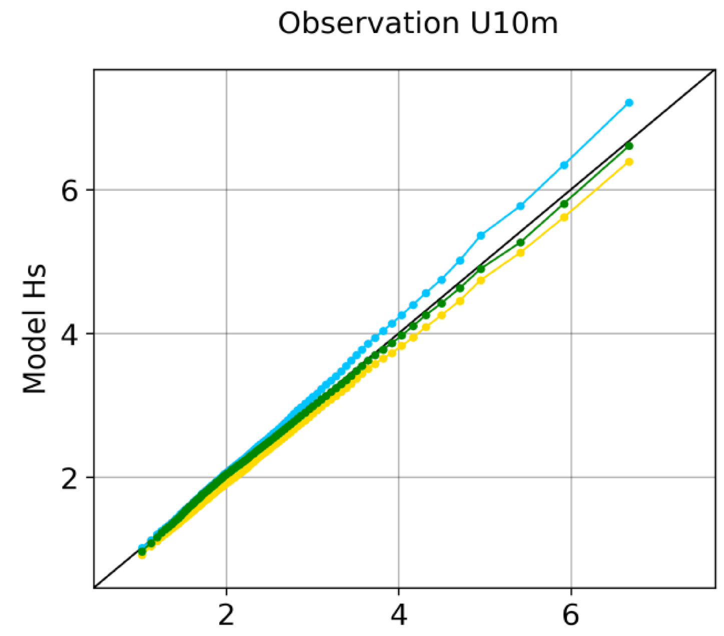


Fig.2: Wind QQ-plots (top, in m/s) and wave QQ-plots (bottom, in m) for the GFS (blue), ICON (yellow) and COSMO (green) models in comparison with observations from altimeter data.

Multivariate aspect of the *residue* (signal of the forecast error)

$$\mathcal{E}_M(F_t, T, P_v, L_{xy}, V, \ldots)$$

Skill of wind intensify and significant wave height as a **function of forecast range** in Table 1:

- Very low bias and high correlation coefficient (between 0.7 and 0.9), in general. Results involving the 3 groups of simulations are similar.
- The lowest scatter errors come from simulations forced with ICON winds.
- Expected deterioration of predictability after the 3rd day due to the chaotic behaviour of the atmosphere.

Bi-variate analysis in Figure 3, looking at the **forecast range and severity** (percentiles):

- All models underestimate the waves and extreme winds for longer forecast ranges.
- Corroborates the assessments using buoys, where ICON and WW3/ICON present low errors and excellent predictability.
- Waves above 4 m and beyond the 3rd forecast day present the largest errors (RMSE>1m).

Table 1: Error metrics versus forecast range for the first five days. One year of assessment using altimeter data.

Forecast leads (h)	Model	Wind				Wave			
		Bias	RMSE	SI	CC	Bias	RMSE	SI	CC
0	GFS	0.13	1.27	0.15	0.92	0.09	0.35	0.12	0.96
	ICON	0.00	1.12	0.14	0.93	-0.10	0.31	0.11	0.97
	COSMO	0.00	1.16	0.14	0.93	-0.05	0.33	0.12	0.96
48	GFS	0.24	1.77	0.21	0.85	0.10	0.41	0.14	0.95
	ICON	-0.16	1.75	0.21	0.85	-0.12	0.37	0.13	0.95
	COSMO	0.22	1.96	0.23	0.82	0.00	0.40	0.15	0.94
96	GFS	0.23	2.49	0.30	0.71	0.10	0.58	0.21	0.89
	ICON	-0.17	2.37	0.28	0.73	-0.13	0.55	0.19	0.89
	COSMO	0.18	2.58	0.31	0.68	0.04	0.58	0.21	0.88

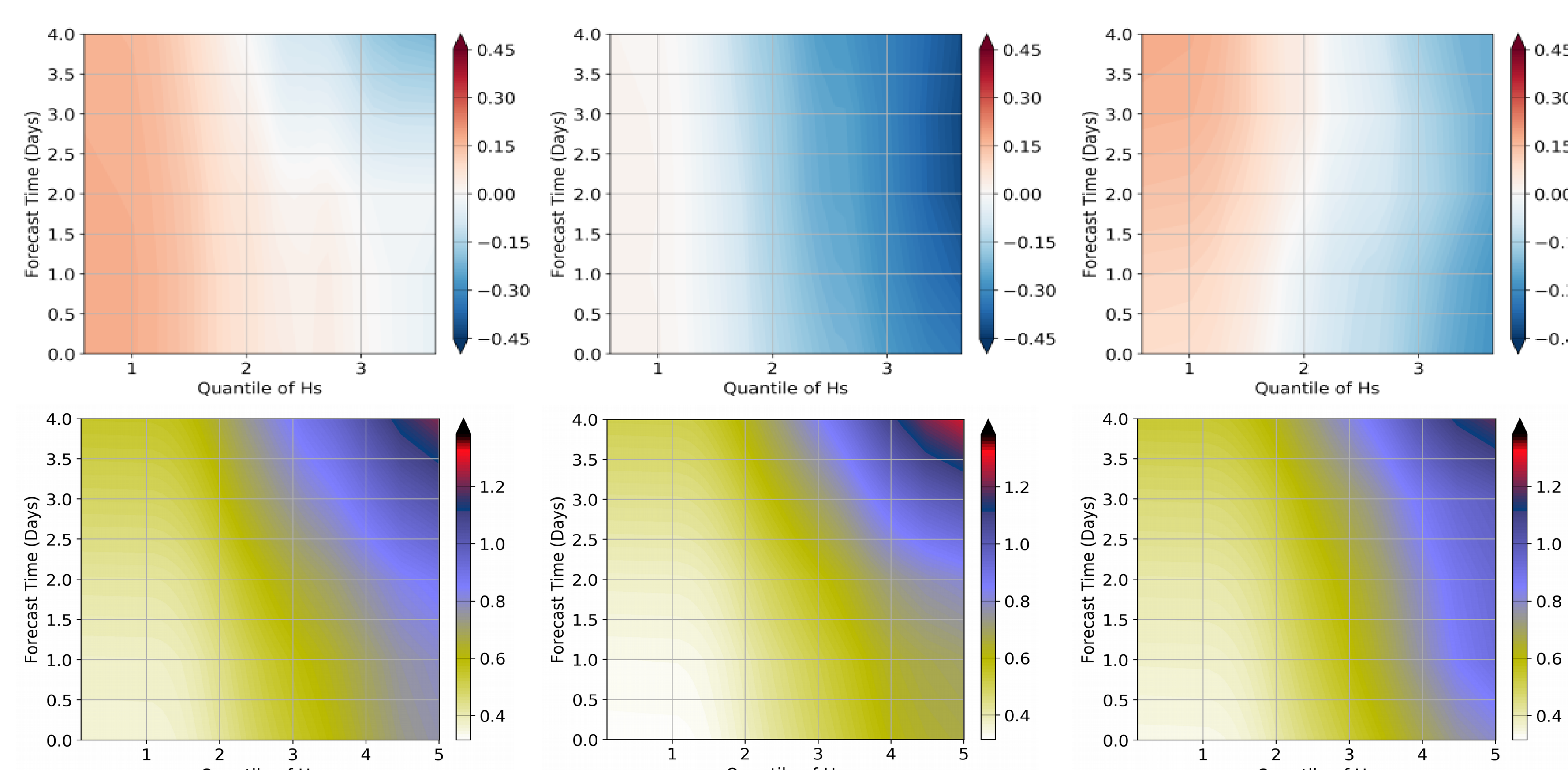


Fig.3: Combination of the error of Hs as a function of forecast time and severity comparing model and altimeter data. Bias on the top (hot colors: forecast overestimation / cold colors: forecast underestimation) and RMSE at the bottom. Left column (GFS), on the middle (ICON), and on the right (COSMO).

Spatial Distribution of forecast errors:

- WW3/GFS: Overestimation and poorer results at southermost (extratropical) latitudes, and the lowest RMSE at tropical areas.
- COSMO tends to overestimate the winds (propagate to the waves) at latitudes from 20°S to 0°.
- WW3/ICON tends to underestimate the results; however it has low errors at subtropical areas and the lowest RMSE for extratropical latitudes.

These pattern indicates that the Betamax parameter of the WAVEWATCH III source terms ST4 (equation 1) can be sligtly reduced for simulations forced with GFS and increased for simulations with ICON (currently ongoing calibration process).

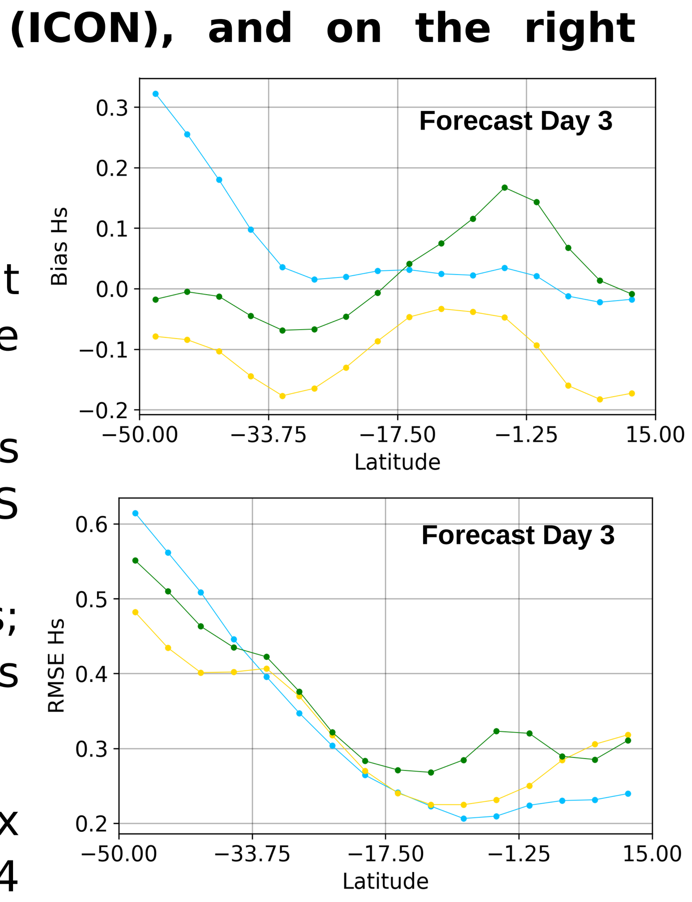


Fig.4: RMSE of Hs as a function of Latitude. Input winds: GFS (blue), ICON (yellow), COSMO (green).

CONCLUSIONS

- Performance analyses of wave forecast system present good wave predictions, even at longer forecast ranges the CC remains around 0.7 (winds) and 0.9 (waves).
- Larger errors are found above the 90th percentile beyond the third forecast day.
- Considering the whole multivariate assessment, WW3/ICON presents the best predictability (systematic errors up to 0.1 m and scatter errors between 10% and 20%).

The operational wave forecast addressed is made publicly available by the Brazilian Navy at **https://www.marinha.mil.br/chm/**