Title: Development of a Wave Forecasting System for the Southwest Pacific and Fiji region.

Aim: Designing a Deterministic Wave Model using GFS Grib2 data for the Pacific(1.0°× 1.0°), Southwest Pacific(0.25° * 0.25°) and Fiji region(0.05° * 0.05°)

March 2022

Summary

This study to develop a wave forecasting system is based on the Japanese Meteorological Agency (JMA) wave model MRI-III using the National Centre for Environment Prediction (NCEP) Global Forecast System (GFS) wind input. The aim is to show that this new Wave forecasting System developed for the South Pacific using the GFS wind input into the optimised JMA Wave model gives very reasonable wave information.
Three domains were decided in the broader Pacific area. Pacific area(60°S to 60°N, 135°W to 255°E) with 1° x 1° resolution, South Pacific(25°S to 0°N, 160°W to 205°E) with 0.25° x 0.25° resolution and Fiji(21°S to -15.25°N, 176.5°W to 182.5°E) 0.05° x 0.05° high resolution. Wider Pacific area was chosen because large swells often develop further south and north and travel towards the Pacific Island countries. To optimise the model settings, many calculations with different cb (Coefficient of wave energy dissipation) settings were done especially for the four Tropical Cyclones (2019-2020 and 2020 -2021 season) and some high wave events (2021) which affected the Pacific Island countries. The model results were verified against the Satellite observed data (Jason 3, Saral, Sentinel a and b) and wave buoy at Komave in Fiji.

This model will be the first high resolution model for Fiji Meteorological Service which covers the whole of Fiji area. The model output will provide guidance to Fiji Meteorological Service in preparing marine alerts and warning better and in achieving its vision of "Safe and secure communities through the provision of dynamic and quality weather, climate, and hydrological services". This system will indeed provide more confidence in providing the marine forecast accurately and will be important for disaster prevention over the Southwest Pacific.

1.0 Introduction

Fiji Meteorological Service currently uses the Global (ECMWF and GFS) not so high resolution Models for wave forecasting. High resolution wave model was developed under the CIFDP (Coastal Inundation Forecast Demonstration Project) (WMO)(JCOMM Technical Report No.64) but it covers only part of Fiji(Southern coast of Viti Levu). Another high-resolution model was developed by Tonkin and Taylor covering the whole of Fiji, but it operates only during Tropical Cyclones. FMS does not have a wave forecasting system for the south Pacific. Hence, there is a need to develop a high-resolution Model for the area FMS serves.
JMA MRI III was studied in detail and the Coefficient (cb) of wave energy dissipation was optimized. The study aims to show how the Significant Wave Heights are resolved in GFS (Global Forecast System) grib2 wind input into the optimised JMA MRI-III third generation wave model. Comparing and verifying the Wave model calculation results with the observations from satellites Jason 3, Saral, Sentinel 3a/b for both the Significant Wave Heights and GFS wind speed is the main part of this study.
The goal of this study is to show that this new Wave forecasting System developed for the South Pacific using the GFS wind input into the optimised JMA Wave model gives very reasonable wave information. This newly developed wave forecasting system would be a guidance to be used by the Meteorological Officers in the south Pacific to minimise the loss of lives and reduce the extend of damages by providing the marine forecast more accurately.
There are not so much previous research for waves by tropical cyclones in the south Pacific, and many things are unknown. Therefore, this research is meaningful.

2.0 Model and Simulation settings

Wave model design: Pacific (coarse) → Fiji (regional) nested system			
model type	MRI-III (Third generation wave model)		
calculation area	Pacific area 60°S～60°N 135°W～255°E	Southwest Pacific 25°S～0°N 160°W～205°E	Fiji area 21°S～-15.25°N 176.5°W～182.5°E
grids	121 × 121	181 × 101	121 × 116
grid interval	1.0° × 1.0°	0.25° × 0.25°	0.05° × 0.05°
Bathymetry data: ETOPO1 data Wind input: NCEP GFS (0.25 resolution data) (u10, v10)			
forecast time (00 and 12UTC)	120 hours (5 days) – Hourly time step		

Table 1 JMA MRI-III Model setting for the South Pacific Area.

Three domains were decided in the broader Pacific area. Pacific area(60°S to 60°N, 135°W to 255°E) with 1° x 1° resolution, South Pacific(25°S to 0°N, 160°W to 205°E) with 0.25° x 0.25° resolution and Fiji(21°S to -15.25°N, 176.5°W to 182.5°E) 0.05° x 0.05° high resolution. Wider Pacific area was chosen because large swells often develop further south and north and travel towards the Pacific Island countries.

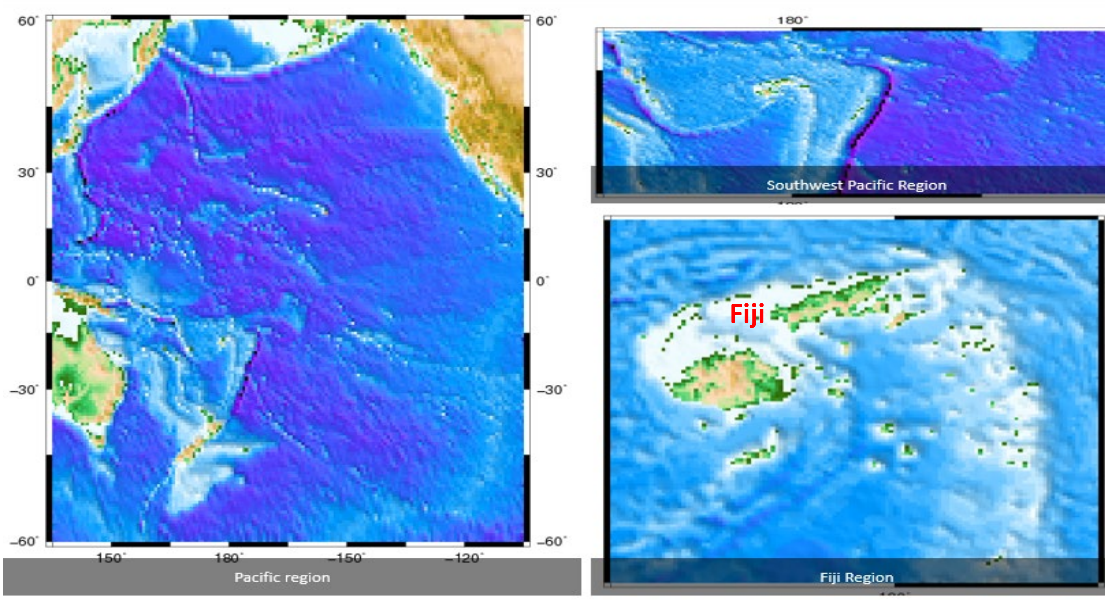


Figure 1 Different Domains

The JMA MRI-III wave model is optimsed with the GSM(Global Spectral Model) wind input. To optimise the JMA MRI-III Wave model settings for the South Pacific area to use the National Centre for Environment Prediction (NCEP) Global Forecast System (GFS) Grib2 wind input, many calculations with different cb (Coefficient of wave energy dissipation) settings were done for Tropical Cyclones (2019-2020 and 2020 -2021 season) and some high wave events in 2020 and 2021 which affected the Pacific Island countries. The model forecasts were verified against the Satellite altimetry data (Jason 3, Saral, Sentinel a and b). After many calculations and thousands of verifications, the following were tuned up in the JMA MRI Wave model.

It was observed that GFS calculates very strong winds for tropical cyclones which was the reason for overestimation of wave heights. Therefore, the formula of drag coefficient(Cd) was reconsidered. Initially, we used the Taylor and Yelland formula (2000), where Cd monotonously becomes large. It was changed to the Hwang formula (2004), which takes the maximum values around middle range wind speed but small in stormy wind.
Coefficient (cb) of wave energy dissipation was optimized to 2.35.

The Results for one of the cases TC Harold are shown in the following sections.

Results

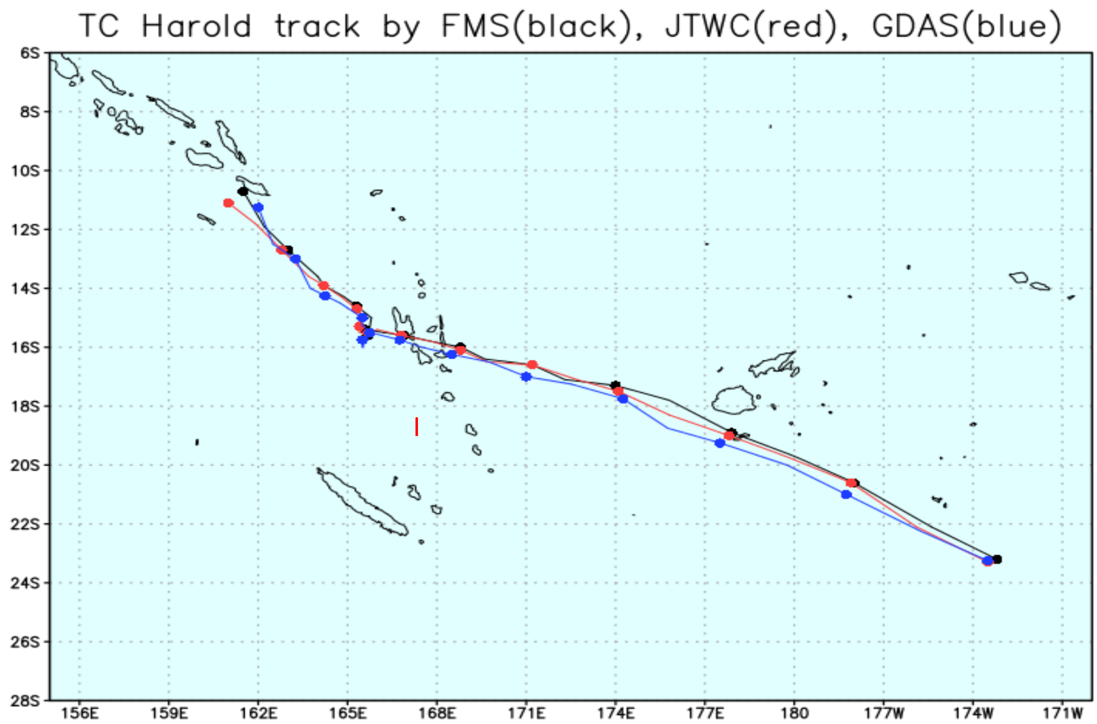


Figure 2 Best track for TC Harold from Fiji(black), GFS(blue) and JTWC(red). The best track analysis from all three centres(Fiji, JTWC and GFS) differs slightly especially after passing Vanuatu or south of 17S.

2.1 Modelled Wave

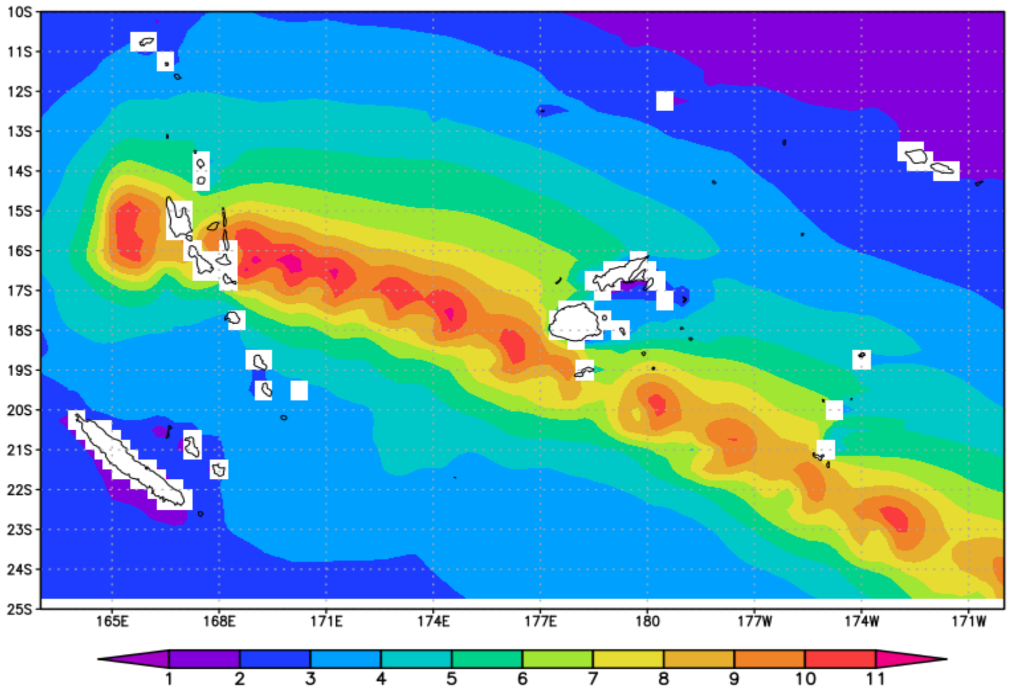


Figure 3 Map showing the Maximum Significant Wave Heights predicted by the Wave Model at hourly intervals during the passage of Harold. Heights in meters.

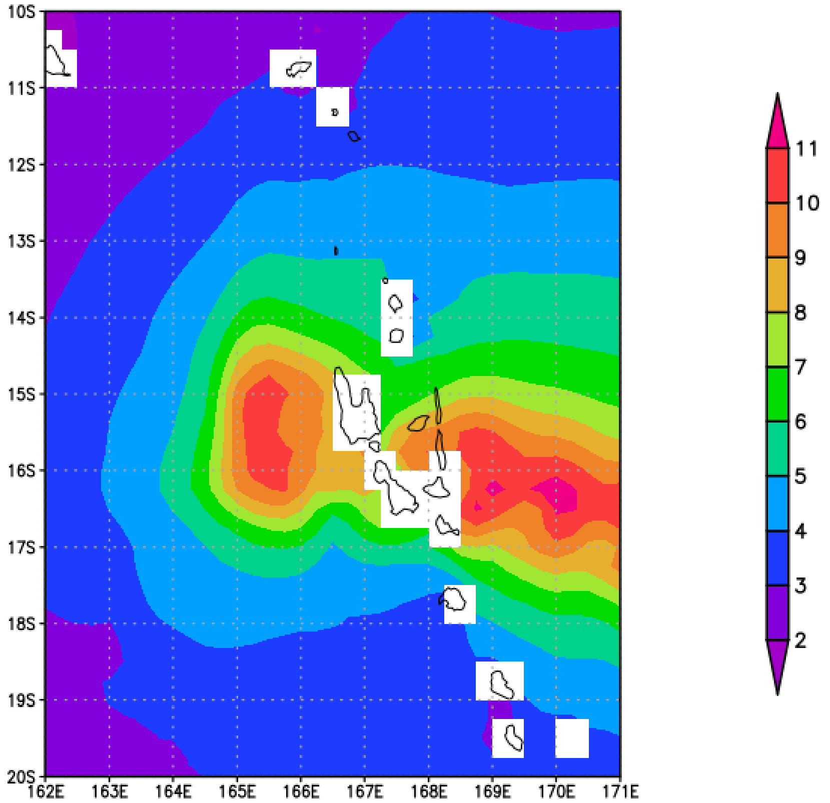


Figure 4 Map showing the Maximum Significant Wave Heights predicted by the Wave Model at hourly intervals during the passage of Harold over Vanuatu. Heights in meters.

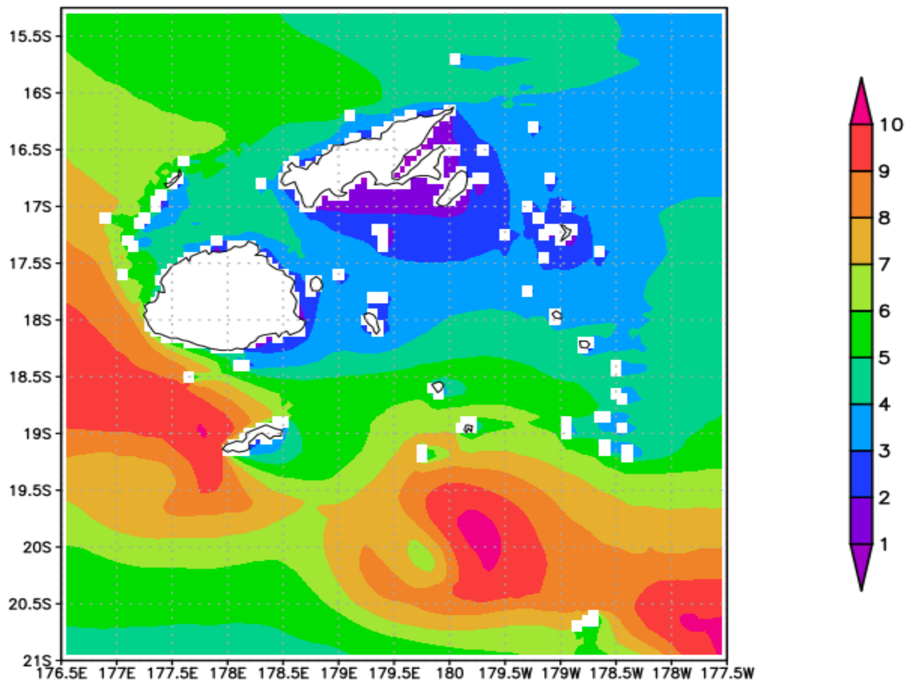


Figure 5 Map showing the Maximum Significant Wave Heights predicted by the Wave Model at hourly intervals during the passage of Harold over Fiji. Heights in meters.

Satellite	Sample #	RSME WV	RSME WS	SI WV	SI WS	Bias WV	Bias WS	R^2 WV	R^2WS
Jason 3	1651	0.52	1.51	25.37	28.90	-0.31	0.44	$R^2 = 0.8382$	$R^2 = 0.8195$

S3a	**1582**	**0.52**	**1.43**	**22.69**	**25.97**	**-0.33**	**-0.15**	**R^2 = 0.8964**	**R^2 = 0.8075**
S3b	**1586**	**0.52**	**1.04**	**29.24**	**20.52**	**0.40**	**0.05**	**R^2 = 0.3396**	**R^2 = 0.6544**
Saral	**1492**	**0.52**	**1.00**	**27.37**	**22.70**	**-0.43**	**0.23**	**R^2 = 0.6249**	**R^2 = 0.7463**

Table2 Statistical Verification Analysis summary for TC Harold- Satellite Observed vs Wave Model Forecast Significant Wave Height together with Satellite Observed Wind Speed vs GFS analysed Winds.

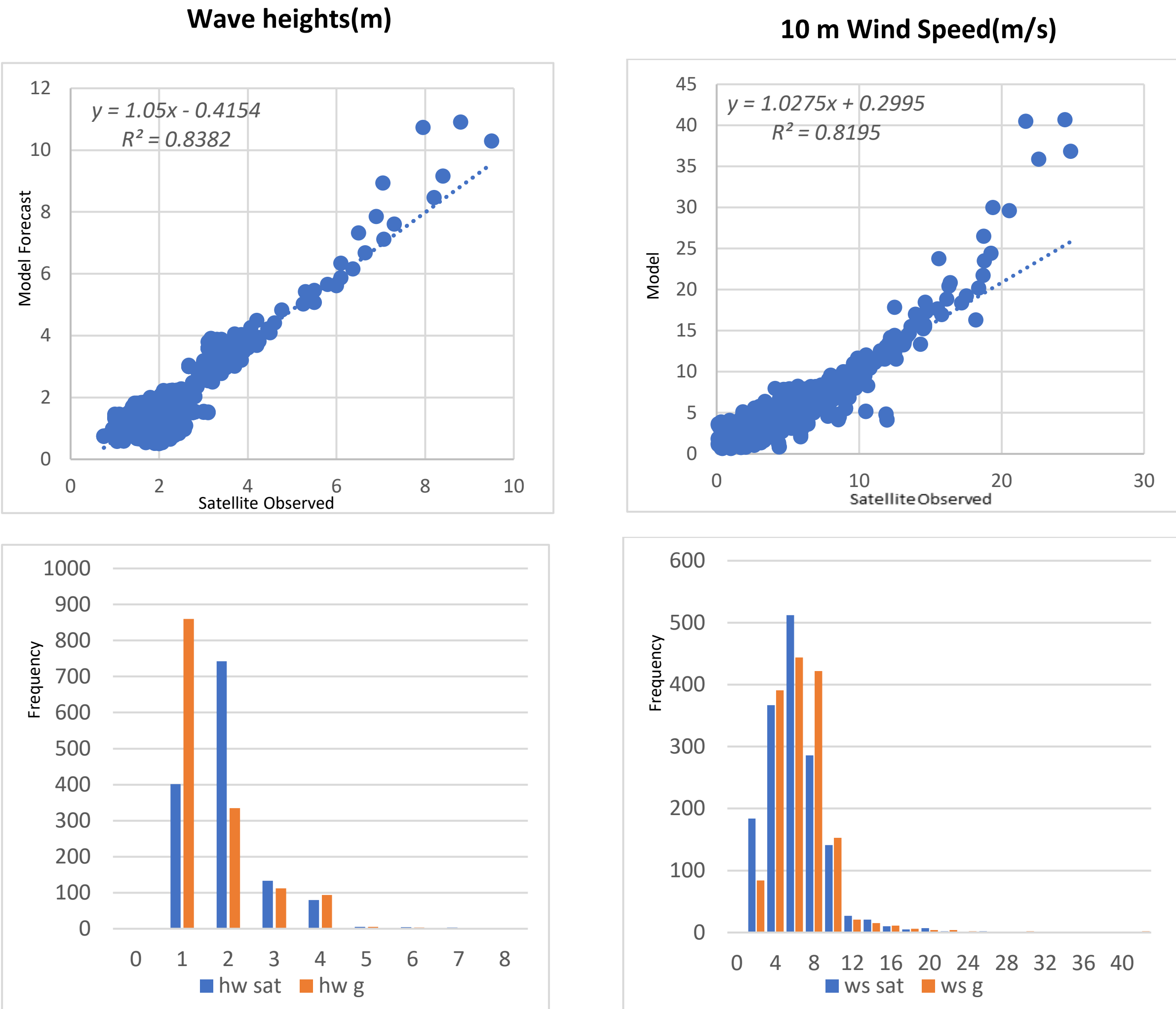


Figure 6. Scatter and histogram plots of wave heights (left) and 10m wind speeds (rights) for TC Harold. Calculated data were compared with Jason 3. hw sat = Observed Significant Wave Height. hw g = Model Forecast Significant Wave Height. ws sat= Observed Wind Speed. ws g = Model Forecast Wind Speed.

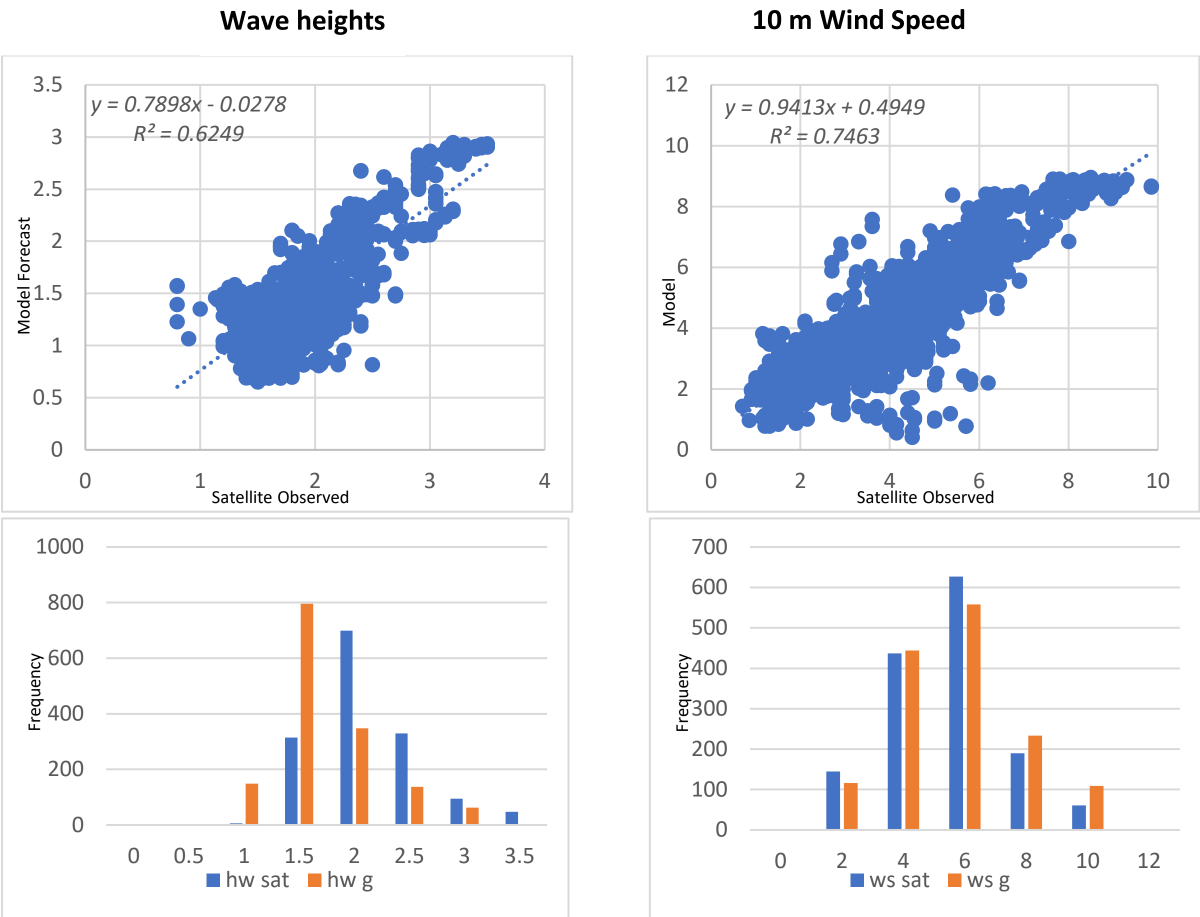
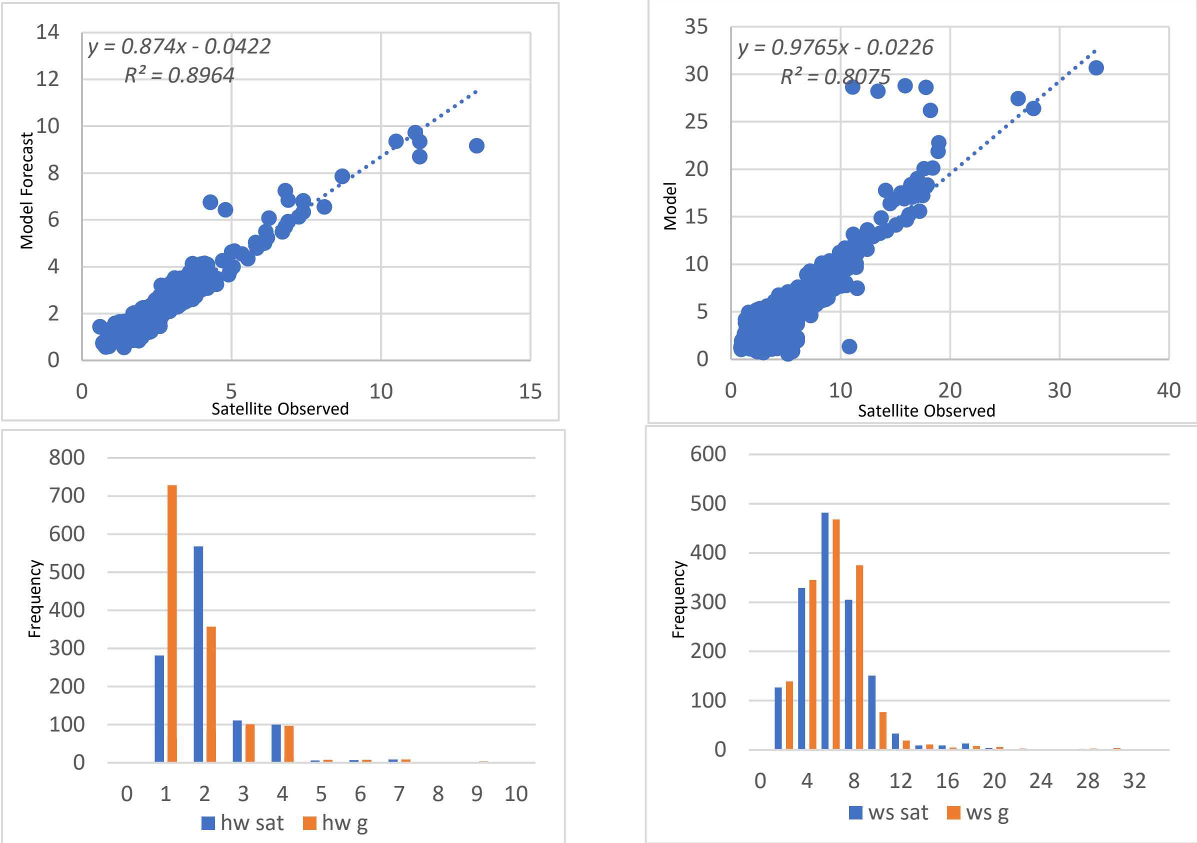


Figure 7. Scatter and histogram plots of wave heights (left) and 10m wind speeds (rights) for TC Harold. Calculated data were compared with Saral. hw sat = Observed Significant Wave Height. hw g = Model Forecast Significant Wave Height. ws sat= Observed Wind Speed. ws g = Model Forecast Wind Speed.

Wave heights

10 m Wind Speed



Wave heights(m)

10 m Wind Speed(m/s)

Figure 8. Scatter and h... ...ts (left) and 10m wind speeds (rights) for ... compared with Sentine... ...ificant Wave Height. hw g = Model Forec... Observed Wind Speed. ws g = Model Forecast Wind Speed.

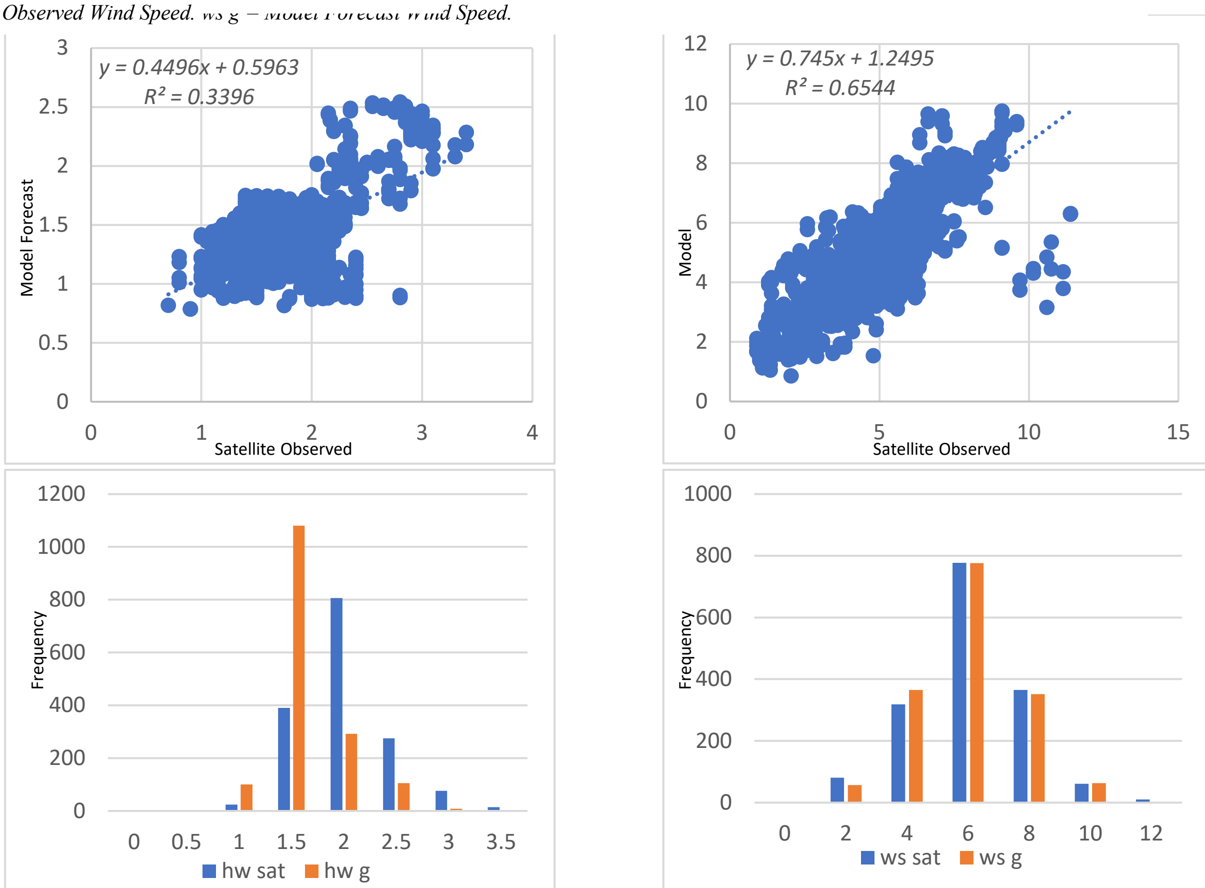


Figure 9. Scatter and histogram plots of wave heights (left) and 10m wind speeds (rights) for TC Harold. Calculated data were compared with Sentinel 3b. hw sat = Observed Significant Wave Height. hw g = Model Forecast Significant Wave Height. ws sat= Observed Wind Speed. ws g = Model Forecast Wind Speed.

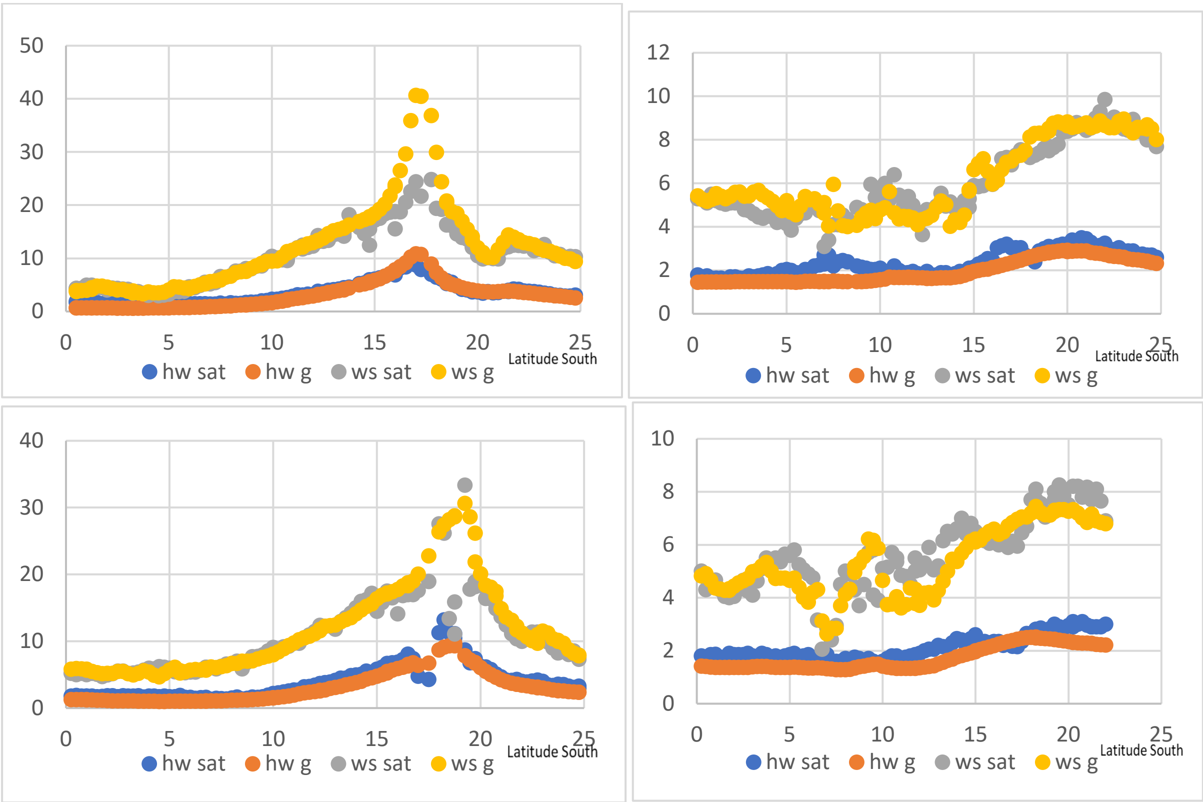


Figure 10. Satellite Observed together with the Model forecast Significant wave height and wind speed at different Latitudes. hw sat = Satellite Observed Significant Wave Height, hw g = Wave Model forecast Significant Wave Height, ws sat = Satellite Observed wind speed, ws g = GFS Model forecast wind speed. Top left Jason 3, Top right Saral, Bottom left Sentinel 3a, Bottom right Sentinel 3b.

FMS best track analysis(Fig. 2) and meteorological history shows that severe TC Harold can be considered to be a slow moving system moving at around 5m/s or less(10 knots or less) when it was near the land areas of Vanuatu and Fiji. The approximate maximum extend of Hurricane force winds were 40 nautical miles(nm), storm 80nm and gales 140nm respectively indicating Harold was not a small cyclone. The best track chart also shows that Fiji, Tonga and most of Vanuatu were on the forward left side of TC Harold's path that is where the highest significant wave heights are expected.

All the factors, high winds, duration of winds(long), large area(fetch) were present for large waves to develop. These conditions are favourable for both wind sea and swells. TC Harold coincided with king high tides in some locations along its track, resulting in catastrophic damage in Vanuatu, Fiji and Tonga.

Fig.7,8,9 shows that the predicted high wave heights extends further than the Gale, storm and hurricane wind extend from the centre due to the slow movement of Harold indicating that swells were also generated. The extend of high waves to the left of track is more in comparison to the right of the track.

After running the wave model with the optimised settings, the results were verified using the standard verification method. The statistical verification analysis and the observed data were carefully examined. The RSME, SI, Bias, R^2 together with the histogram frequency analysis and observation analysis are all showing very reasonable results. Overall, the results for both the Significant Wave Heights and Winds shows good positive correlation.

Comparing the satellites, Sentinel 3b(S3b) shows in some cases large scatter and correlation is not so good. Jason 3 shows good correlation and so does Saral and Sentinel 3a(S3a).
S3b also shows higher values when compared to S3a even though they are both using the same sensors. This results in Model forecast appearing to under forecast.
As mentioned above, wind speed, wind duration and fetch are important factors in determining the wave heights. The GFS model used for wind input has a resolution of $0.25^0 * 0.25$. The speed of movement of Harold, the extend and intensity of wind speeds by GFS would have caused discrepancy between the wave model forecast and satellite observed wave heights. This is also evident in the wind speed verification.

As evident in Figure 6 , the best track analysis from all three centres(Fiji, JTWC and GFS) differs slightly especially after passing Vanuatu or south of 17S. This Cyclone position differences is a contributing factor to the wave forecast errors. This is also evident in Figure 10 where the Satellite observed significant wave height is compared with the Wave model forecast.

Conclusion:

The purpose of this research was to develop a new wave forecasting system for the South Pacific and Fiji Region based on the JMA wave model MRI-III using the GFS NCEP wind input as there are no high-resolution wave model which covers the whole of Fiji area.

Detailed verification analysis shows very reasonable model outputs are observed after optimising the cb setting to 2.35 and changing the Taylor and Yelland formula to Hwang formula. The good agreement between model forecast and observations would provide forecasters, stakeholders and community members with the confidence that this new system could strengthen Tropical Cyclone driven risk and high wave forecast information.

The goal of this study to show that this new Wave forecasting System developed for the South Pacific using the GFS wind input into the optimised JMA Wave model gives very reasonable wave information has been successfully achieved.

This model will be the first high resolution model for Fiji Meteorological Service which covers the whole of Fiji area. The model output will provide guidance to Fiji Meteorological Service in preparing marine alerts and warning better and in achieving its vision of “Safe and secure communities through the provision of dynamic and quality weather, climate, and hydrological services”

This system will indeed provide more confidence in providing the marine forecast accurately and will be important for disaster prevention over the Southwest Pacific.