Ensemble wave forecasting in Southeastern Australia

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1 Research proposal

The work presented here focuses on starting a new investigation in ocean wave ensemble forecast for the southeast coastal of Australia. The buoy data used and the model setup are described in sections 2 and 3, respectively. For validating the SWAN model on the study area, we performed deterministic runs of the SWAN model hindcast mode, with boundary conditions from ERA5 and also from NOOA/WW3, with the results presented in section 4. In forecast mode, we executed SWAN with ensemble boundary conditions from the Global Ensemble Forecast System, (GWES). An additional wave ensemble forecast system is executed where we have generated the wave boundary data by a perturbation technique. The two wave ensemble forecasts systems are described in section 5.

2 Buoy data

The buoy data used is obtained from the Australian Ocean Data Network (AODN) and can be retrieved as follows.

- Access https://portal.aodn.org.au/ ;
- Click on "Get Ocean Data Now" in the middle of the page;
- On the left side of the page, scroll down to the bottom, where you will see a search box;
- Type in "Wave buoy data" ;
- The search results will be shown on the right of the screen. About 4 down you will see: Waverider buoys Observations - Australia - delayed (National Wave Archive);
- Click on this and the map will allow you to download any of the buoys data.

No Waverider buoys from Australia are update daily; the most resent are for the year of 2018.

3 The SWAN wave model setup

The SWAN wave model setup will follow the work by Rogers et al. [2]. The physical parameters were selected from the SWAN manual version 41.31, as described on its page 58. Table 1 present the SWAN model configuration used here.

- GEN3 ST6 4.7E-7 6.6E-6 4.0 4.0 UP FAN VECTAU U10 PROXY 28.0 AGROW

The complex bathymetric and nearshore morphological features at the Southeastern coast of Australia are characterised with an unstructured grid (Figure 1). This grid can represent rapidly changes in bathymetry since the nearshore region has a resolution of 0.2 km, while in deep water a resolution of 10 km is employed. Then, the wave propagation from deep to shallow water are better represented. The bathymetric data were obtained from GEBCO web site (GEBCO: https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search♯/metadata/67703)

Table 1: SWAN physics, numerical configuration, and the computational grid information.

Run Model	NonStationary	
Time Step	15 min	
Frequency bins	24	0.05-1.0 hertz
Directional space	36	10^o-360^o
Number of experiments	10	
Spin up period	5 day previous	
Physical parameters		
	Gen3	ST6
	WindGrowth	Activated
	Quadrupled wave-wave interaction	Full explicit peer sweep
	Triad wava-wave interaction	Activated
	Friction	JONSWAP
	WhiteCapping	Komen
	Depth induced breaking	Constant 1.0 0.73
	Propagation scheme	BSBT
	Number of interaction	15
Numerical Grid		
	Class	Unstructured grid
	Spacing	100 m - 5 km
	Wind forcing	GFS-control
	Wave boundary	WW3-Ensemble
	Bathymetric	GEBCO

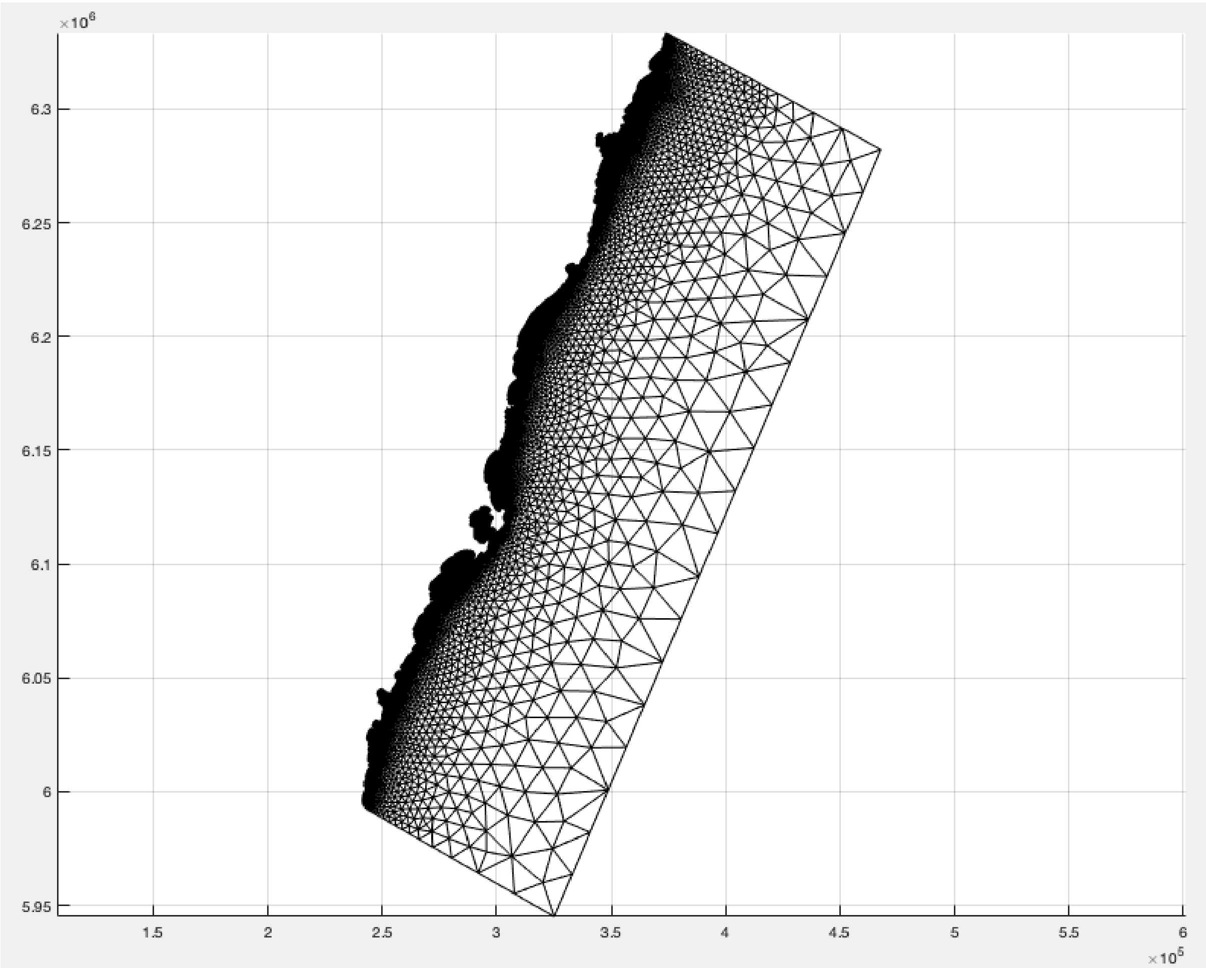

Figure 1: Unstructured Grid

4 SWAN validation

Two experiments are carried out to investigate the sensibility of the SWAN wave model in representing wave fields for Australia southern east coast. The first experiment uses wind and wave hindcast from ECMWF-ERA5 (Fig.3). The second one is done using wind from ERA5

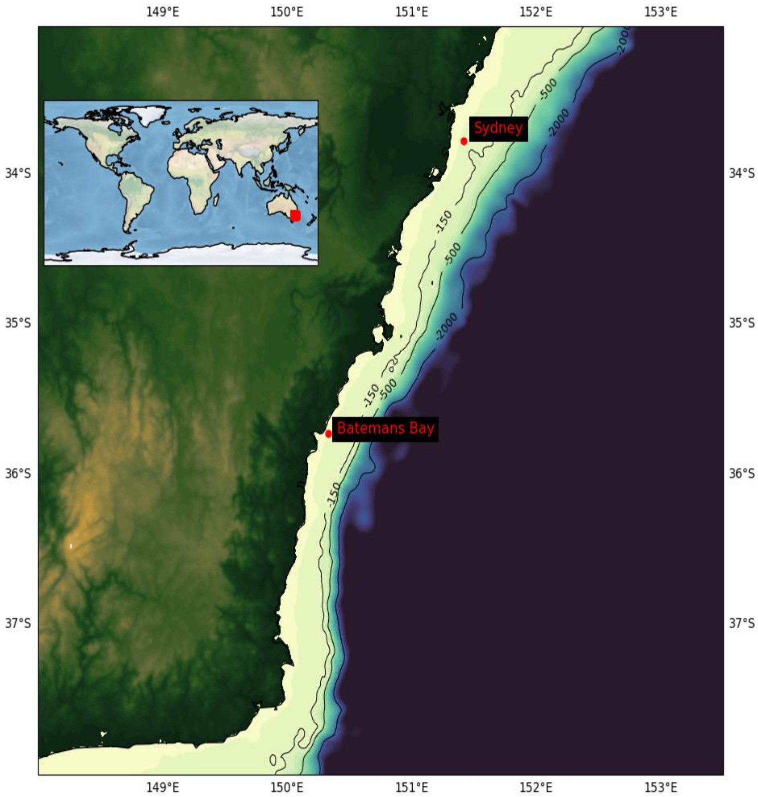

Figure 2: Study area

reanalysis and wave boundary condition from NOAA/WW3 (Fig.4). The hindcast outputs are verified against delayed ocean wave buoy for June and July of 2014.

The results show that the significant wave height computed by the model is well correlated with the measured values by the three buoys at Batemans, Sydney and Port Kembla.

Statistical analysis for both plots show an RMSE between 0.33 and 0.46 andPearson Correlation values between 0.73 and 0.89.

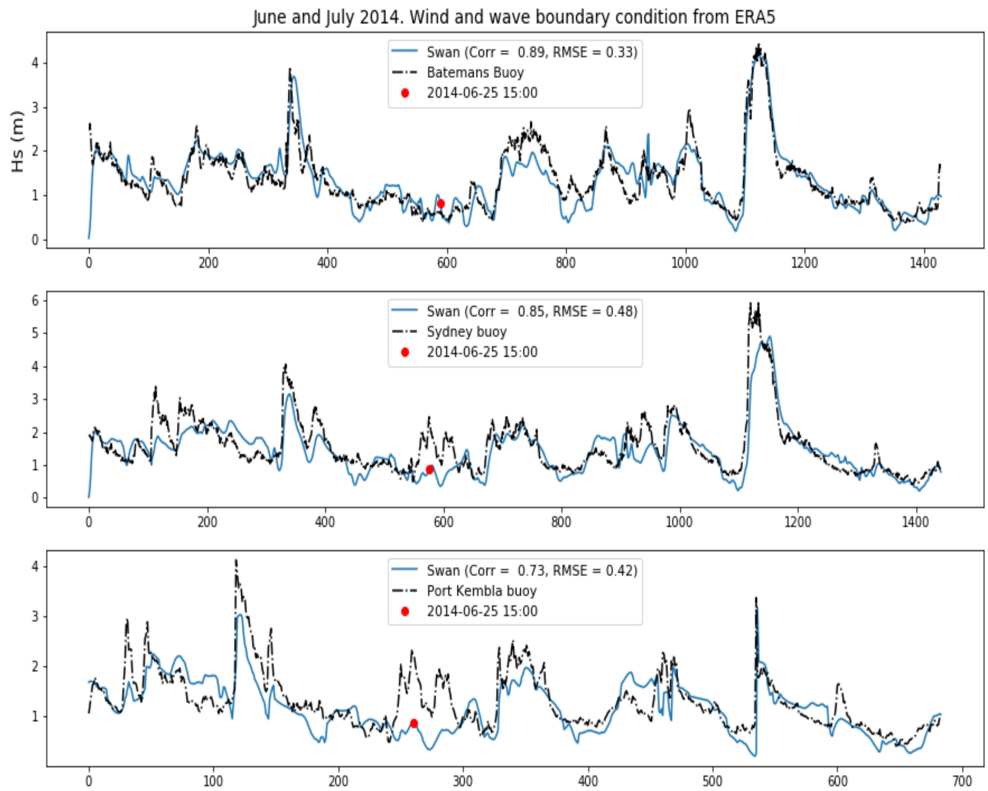

Figure 3: SWAN wave model forced with atmospheric data and with wave boundary condition from ECMWF-ERA5. The solid blue line represent SWAN model and the doted black line the buoy. The horizontal axes represent time in hours, for June and July 2014.

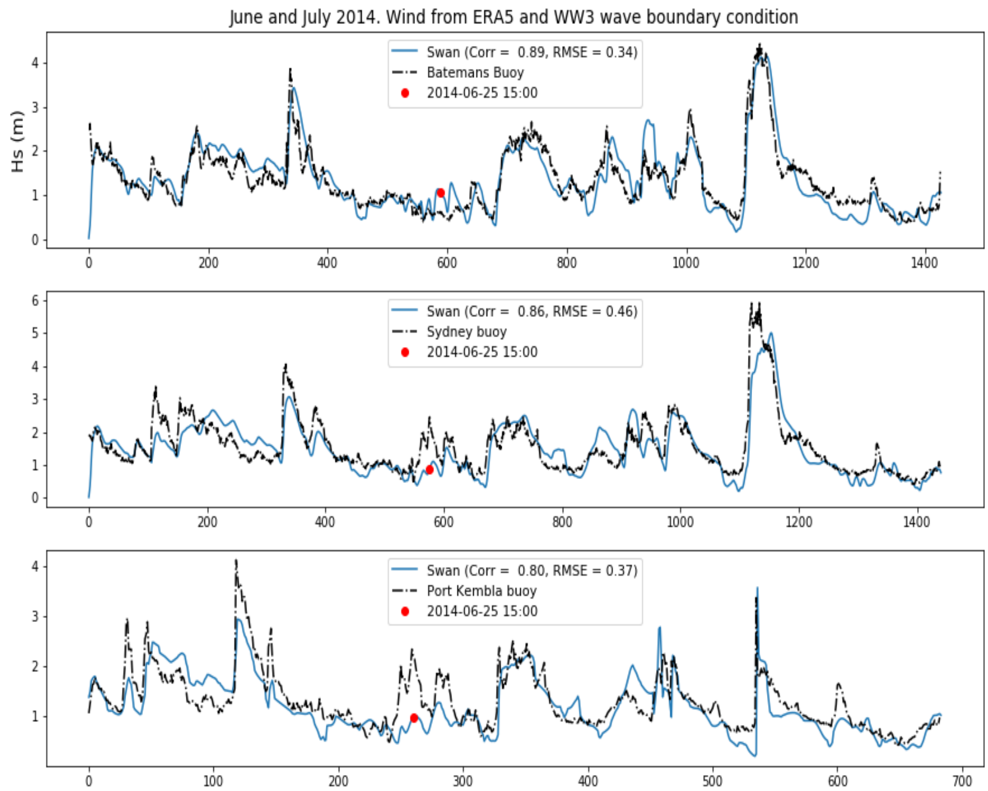

Figure 4: SWAN wave model forced with atmospheric data from ECMWF-ERA5 and with wave boundary condition from NOAA/WW3. The solid blue line represent SWAN model and the doted black line the buoy. The horizontal axes represent time in hours, for June and July 2014.

5 Ensemble forecast systems

With the purpose to investigate the state-of-art of wave ensemble forecast, we analysed 6 forecast cases and highlight the main findings. Each forecast case has 10 days lead time and were compared with coastal buoys around Sydney and Batmen Bay in Southeast Australia. Rather than analysing each individually forecast case, we will investigate the combination of them aiming to establish a general behaviour. For the individual resutls of each forecast case, see the appendix. Two experiment where conducted, and are described as follows.

- 1) SWAN-GWES ensemble forecast system. SWAN is run with an ensemble of wave boundary conditions from 30 members provided by the NCEP Global Wave Ensemble System. The NCEP global wave ensemble system is based on the third-generation wave model WAVEWATCH III. The actual GWES version used in this paper, forecasts with 10 day lead time, generating 31 forecasts (the members plus one control member) from perturbed atmospheric conditions. Currently the GWES presents a space-time resolution of 0.25^0 and 3 hours.
- 2) SWAN-PER ensemble forecast system. SWAN is run with boundary wave condition generated using the standard-deviation (STD) from historical wave buoy data. In brief, the Latin Hypercube Sampling (LHS) used STD values for each wave parameters ($H_s^{std} = \pm 0.70$, $T_p^{std} = \pm 1.42$ and $D_p^{std} = \pm 38.9$) to perturb the GWES control member alongside the forecast lead-time, therefore generating 30 perturbed members.

Both systems above use the same wind fields as forcing, namely the 10 days forecast 10 m wind by NOAA. In fact, for each SWAN run we are only varying the wave boundary condition to perform the forecasts.

The near-real time wave buoy data obtained from Australia Ocean data network (AODN) are used as quality-control for all the forecast cases. Statistics parameters, such as NBIAS, NRMSE, SI, Pierson correlation and Skills, are used to verify the results. Furthermore, the arithmetic ensemble mean (EM-AR) and the weighted ensemble mean (EM-WE) are computed from the ensemble members. In brief, the weights in EM-WE are determined based on the residual between model and buoy values at the forecast start time.

6 Results and discussion

6.1 SWAN-GWES

The analysis is divided in two main region, the southern portion represented by Batemans bay and the northern portion by Sydney.

In Figure 5 and 6, the statistics are presented for each region. The evaluation is assessed as a function of forecast lead time. As a result, it is clear to identify the trend in the forecast lead time; indeed the forecasts tend to deteriorate over the forecast lead time. Such as, that SI, NRMSE , CC and Skill plot, we observe an increase in error, and this is systematic after 5 days. Similar findings were reported by Campos et al. [1].

In Figure 7, the bias in H_s for each ensemble member, as function of lead time, is presented for each of the two locations. For Sydney we observe a slightly overconfidence in the forecast up to day 4 and after day 8, while underestimation in H_s between day 4 and 8. Further, in Batemans bay, the SWAN-GWES forecast system slightly underestimates in the first 6 days, with a peak in day 4, and after day 7, a increase in overconfidence. However, no trend is clear, as opposed to the results in Campos et al. [1, Fig. 5], which points out a trend in GWES to overconfidence until day 5, and afterwards the GWES tends to underestimate the forecast. This difference in behavior could be related to the fact that we are using the GWES as wave boundary condition in SWAN. In addition, we are analysing a combination of 6 forecast events and Campos et al. used only one event.

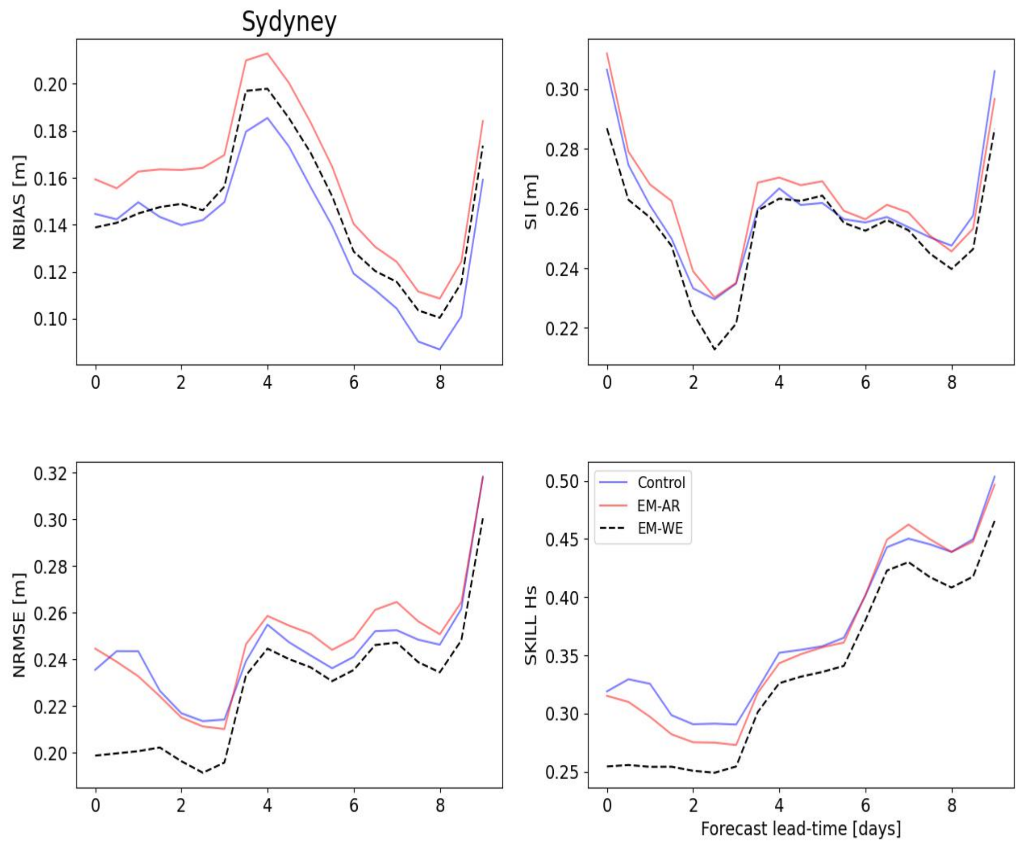

Figure 5: Statistical analysis for Sydney buoy is presented WW3.

In ensemble forecast analysis, the spread is commonly used to identify how members deviate from the ensemble mean. In Figure 8 the spread for lead times +0, +3, +6 and +10 are presented. We notice an increase in the spread over the forecast lead-time, as expected.

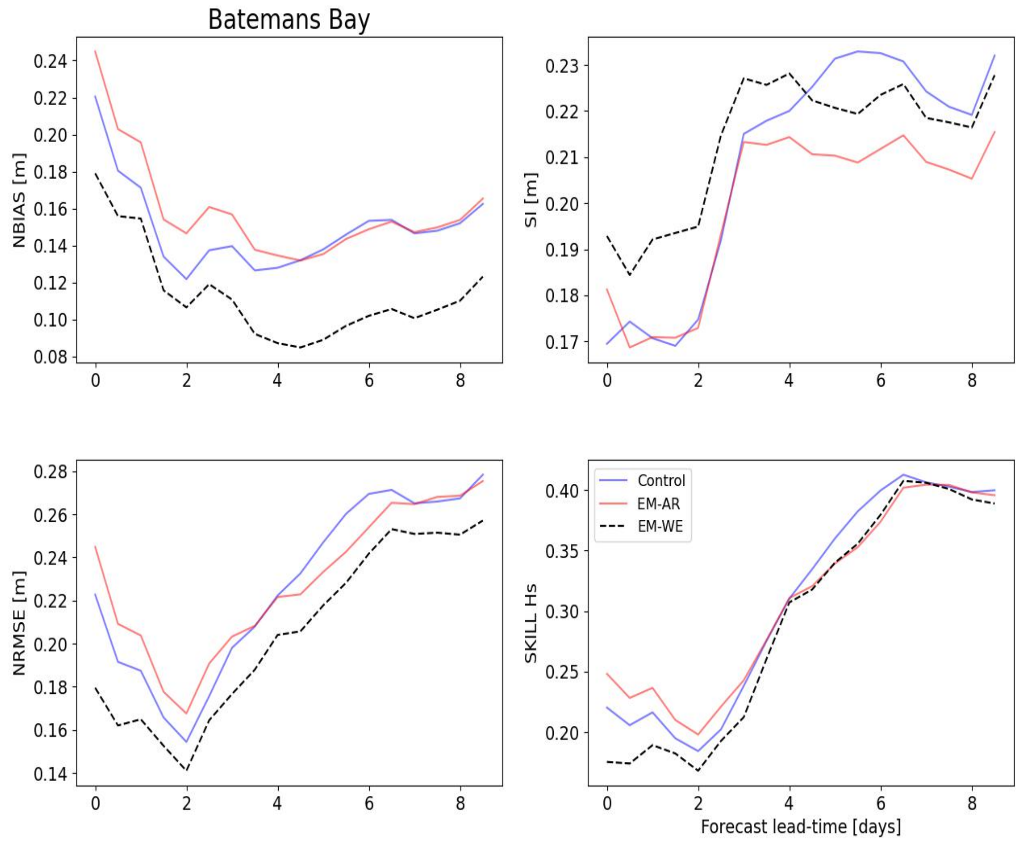

Figure 6: Statistical analysis for Batemans bay buoy is presented.

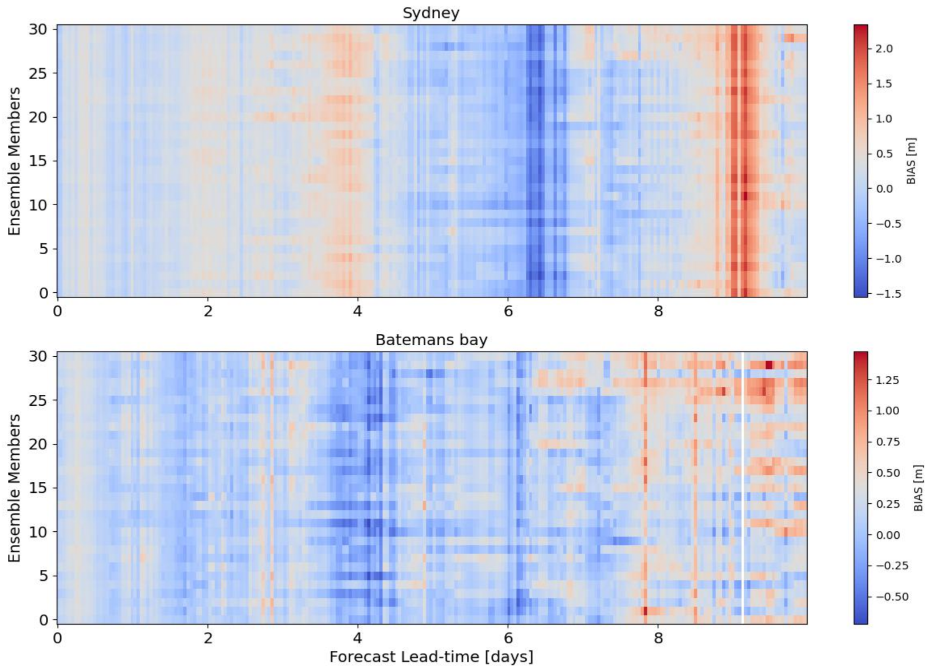

Figure 7: Bias in H_s for the SWAN-GWES ensemble system, for Sydney and Batemans bay buoy related to overall analysis of the 6 events. The bias is calculated and the difference between observation and model; the light blue indicates underestimation while red indicates overestimation.

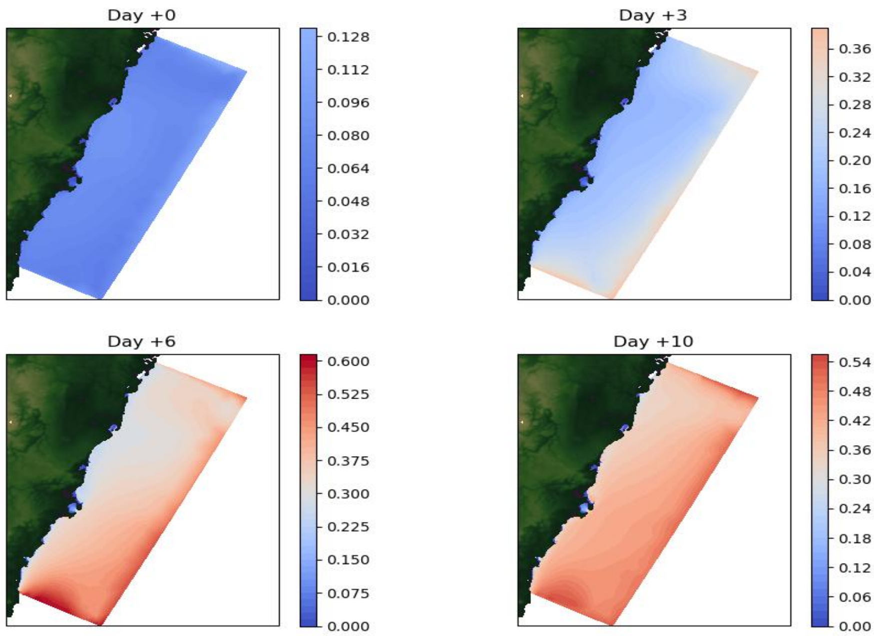

Figure 8: Spread map for the SWAN-GWES forecast system in Southeast Australia, for +0, +3, +6 and +10 lead times.

6.2 SWAN-PER

This analysis is related to the SWAN runs with the perturbed wave boundary generated using standard deviation model/buoy (section 5, item 2). Figures 9 and 10 present the statistics for Sydney and Batemans bay, respectively.

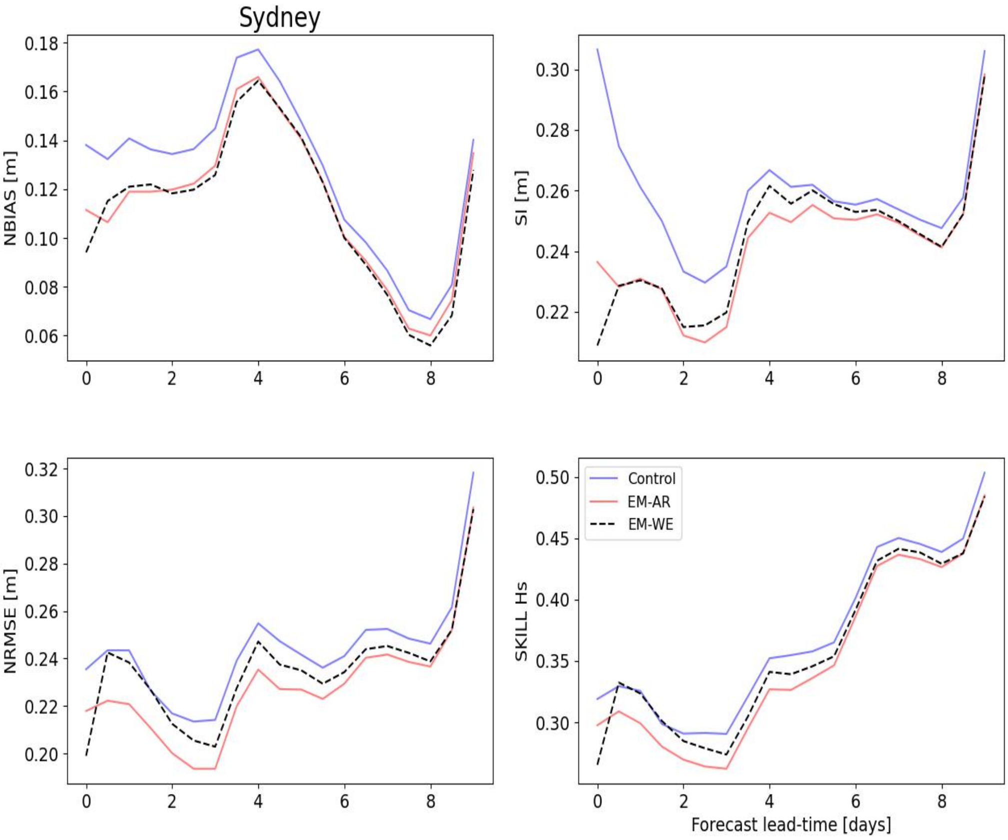

Figure 9: Statistical analysis for Sydney buoy is presented.

In Figure 11 the bias matrix, with the 31 members as function of forecast lead time, as in Figure 7. Similarly to the SWAN-GWES forecast system, the bias for Sydney oscillates between underestimation and overestimation in the first days, which a strong peak of overconfidence at lead time 4. Further, a strong negative bias is observed between day 6 and 7 until day 8, which presents a strong overconfidence. However, for Batemans bay, in general the model underestimates with a strong peak in lead time 4. After day 8, there are some patterns of overconfidence, similarly finding to SWAN-GWES.

The spread map for SWAN-PER is presented in Figure 12. Differently from SWAN-GWES, the spread values do not increase everywhere with forecast lead time and the higher values slightly more concentrated at the borders than for the SWAN-GWES.

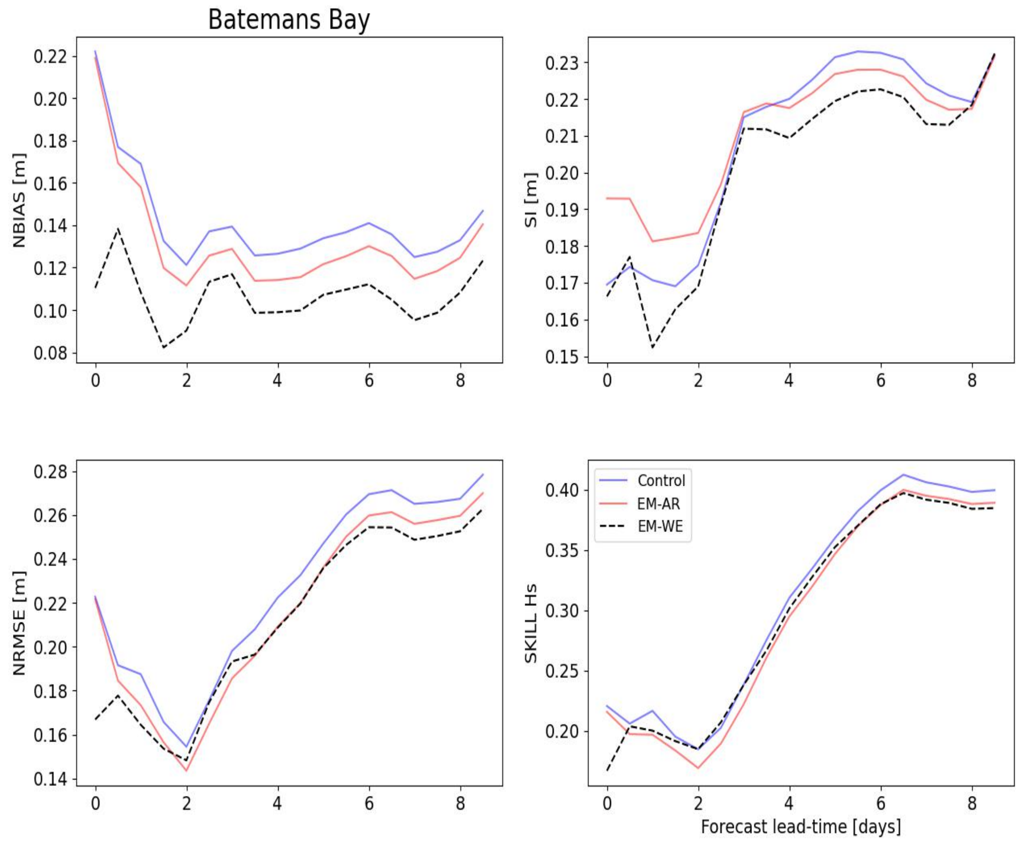

Figure 10: Statistical analysis for Batemans bay buoy is presented.

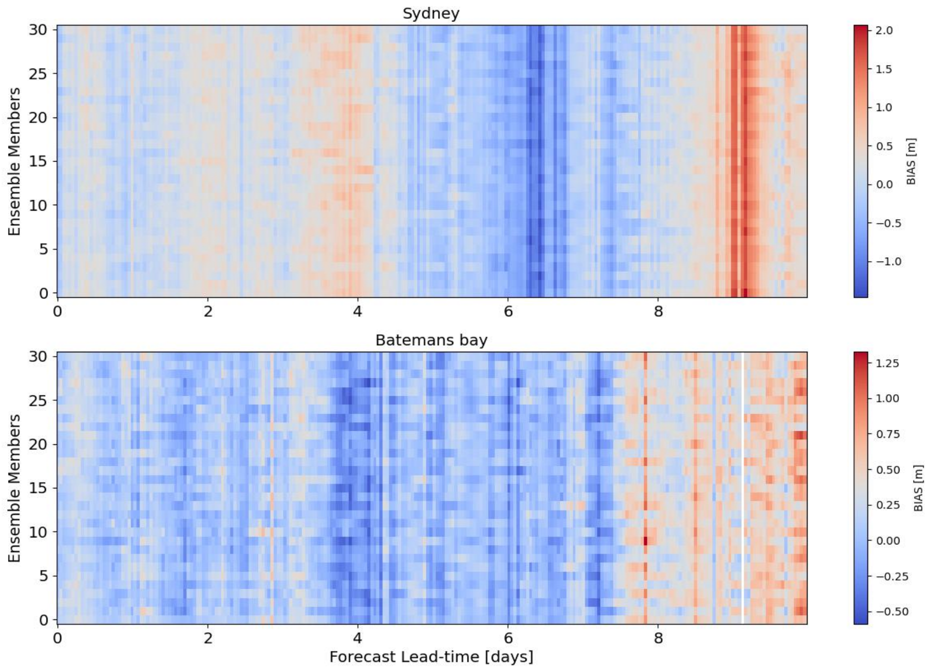

Figure 11: Bias in H_s for the SWAN-PER ensemble system, for Sydney and Batemans bay buoy related to overall analysis of the 6 events. The bias is calculated as the difference between observation and model; the light blue indicates underestimation while red indicates overestimation.

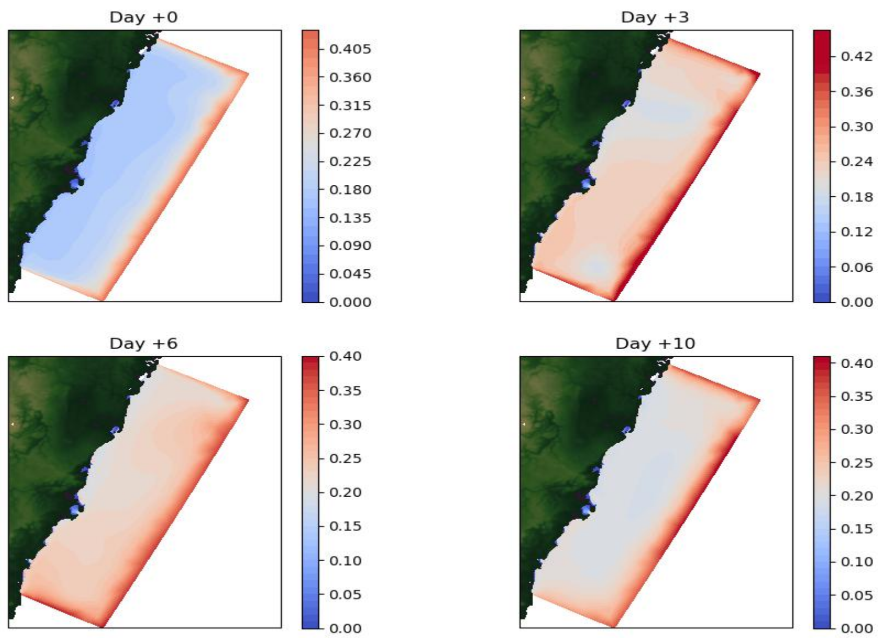

Figure 12: Spread map fro SWAN-PER for Southeast Australia from day +0, +3, +6 and +10 forecast time.

References

[1] Ricardo Martins Campos, Vladimir Krasnopolsky, Jose-Henrique Alves, and Stephen G Penny. Improving NCEP's global-scale wave ensemble averages using neural networks. *Ocean Modelling*, page 101617, 2020.

[2] W Erick Rogers, Alexander V Babanin, and David W Wang. Observation-consistent input and whitecapping dissipation in a model for wind-generated surface waves: Description and simple calculations. *Journal of Atmospheric and Oceanic Technology*, 29(9):1329–1346, 2012.

A Appendix

Here we present the analysis for each of the 6 forecast cases, separately.

A.1 Forecast 29/08/2021

Figure 13 shows that all wave initial condition start with a small spread which increase over forecast time. Since the storm event period is at the end of the forecast, therefore is high uncertainty involved. In fact, It is clear that after 72 hours of forecast lead-time, the GWES turns chaotic, reaching H_s peak of 6 m for Sydney and 5 m at Batemans Bay. While observed H_s reachs 3.8 m and 4 m at wave buoy. At the bottom plot, the forecast for Batemans Bay hardly matches the near-real time Waverider buoy observation. The chaotic state of storm generated great uncertainty in GWES.

Figure 14 the statistical analysis show that a systematic deterioration of forecast lead-time. From day 5 the uncertainty increase, as show is SI, NRMSE and CC.

SWAN model present a overconfidence in predicting extreme events when run with GWEFS (Fig. 15). However, we point out that EM can slightly enhance the accuracy of the forecast, in fact both EM-AR and EM-PO better represent wave forecast condition when compare to the control member, such as, that RMSE and SI are lowest for each EM-AR (0.49 and 0.35) and EM-PO (0.44 and 0.34).

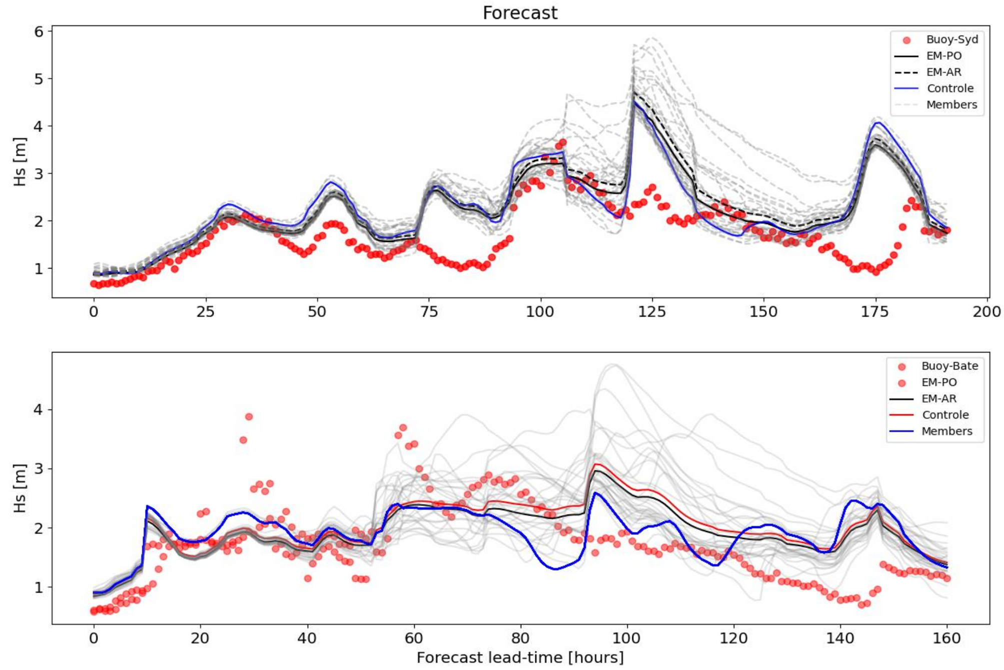

Figure 13: Hs from GFS/WW3

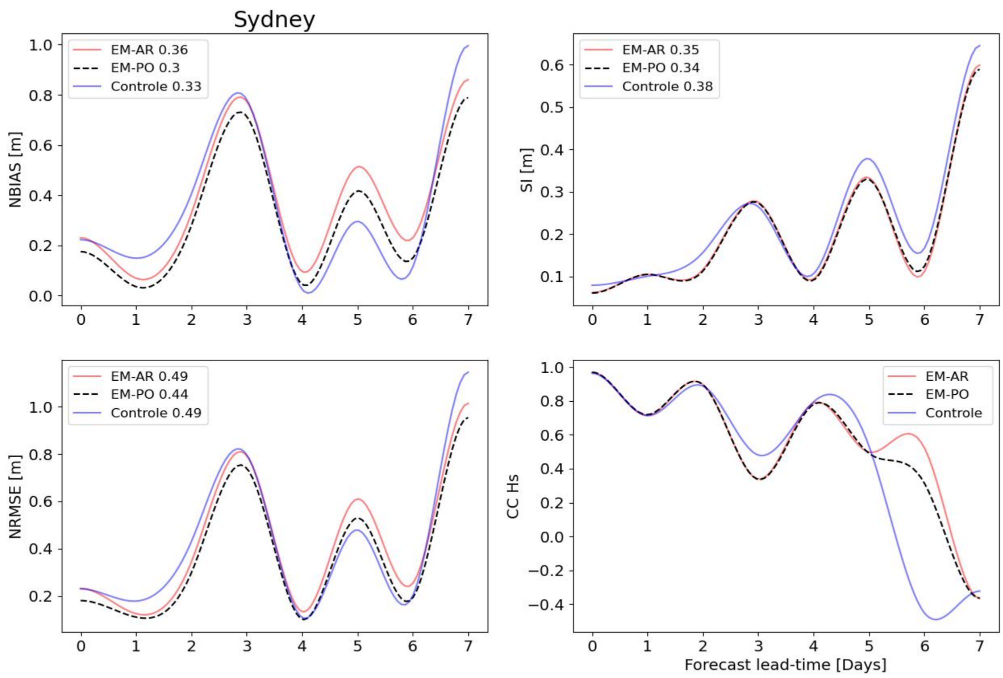

Figure 14: Statistical analysis for Sydney buoy is presented. NBIAS (top left), SI (top right), NRMSE (bottom left) and CC (bottom right) of Hs from GWEFS lead-time versus buoy observation. Red line is ensemble arithmetic mean (EM-AR), black dot-line represent ensemble weighted arithmetic mean (EM-PO) and the blue line the control member. Also in each plot legend the statistical analysis for all forecast time-series

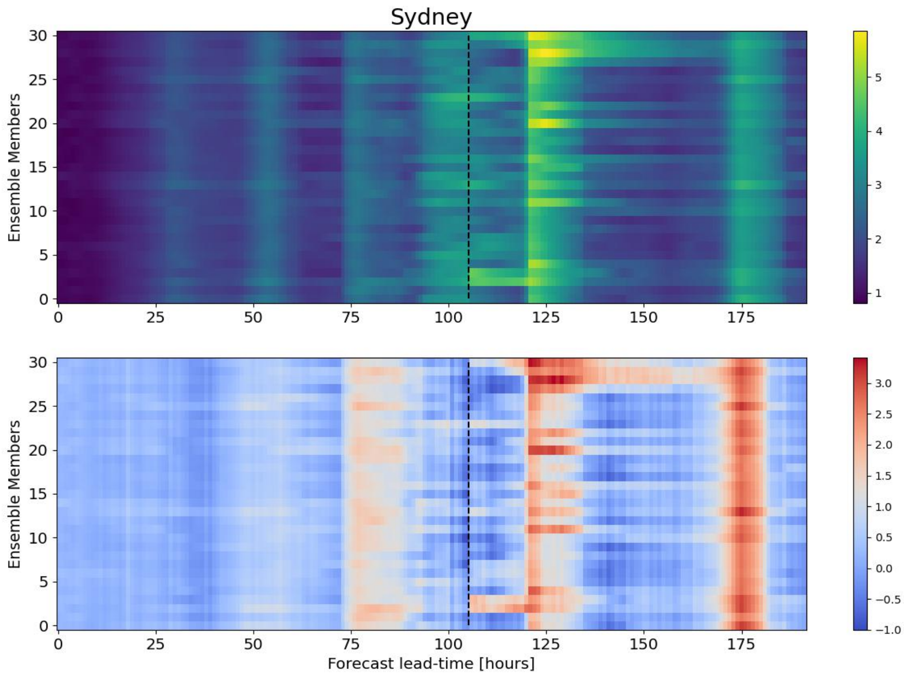

Figure 15: Matrix of GWEFS for Sydney buoy related to nowcast on 2021/29/08, 0Z, and up to 7-day forecast. The top plot show the Hs of 31 GEFS, and the dot line show the period of register of the max Hs in wave rider buoy, which is 3.8 m. The bottom plot show the difference in meters of observed minus GWEFS, where light blue indicate underestimation, while red indicate overestimation, and the white color the perfect agreement.

A.2 Forecast 03/09/2021

Figure 16 shows a storm event that occur in first 72 hours forecast lead-time. Therefore, the forecast accuracy is rather correct than chaotic. Since, wave forecast tend to predict with fine accuracy the first day forecast lead-time. In turns after day 4 the forecast spread increase as expected, even though the there is no storm events.

In Figure 17 the statistical analysis show that a systematic deterioration of forecast lead-time. From day 4 the uncertainty increase, as show is SI, NRMSE and CC.

SWAN model presents a overconfidence in predicting extreme events when run with GWEFS (Fig. 18). However, we point out that EM can slightly enhance the accuracy of the forecast, in fact both EM-AR and EM-PO better represent wave forecast condition when compared to the control member, such as, that RMSE and SI are lowest for each EM-AR (0.49 and 0.35) and EM-PO (0.44 and 0.34).

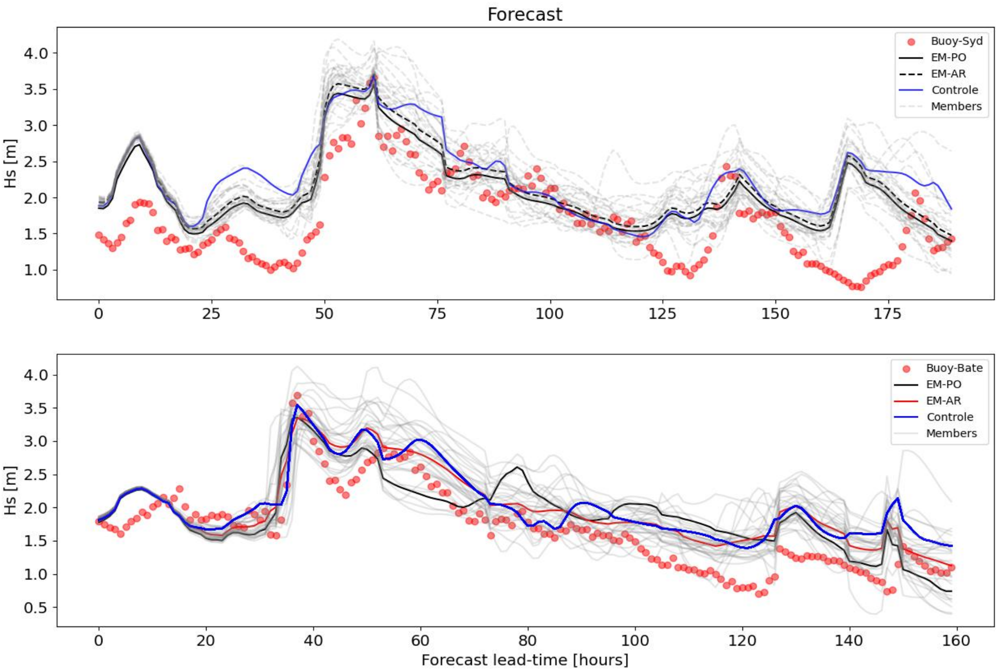

Figure 16: Hs from GFS/WW3

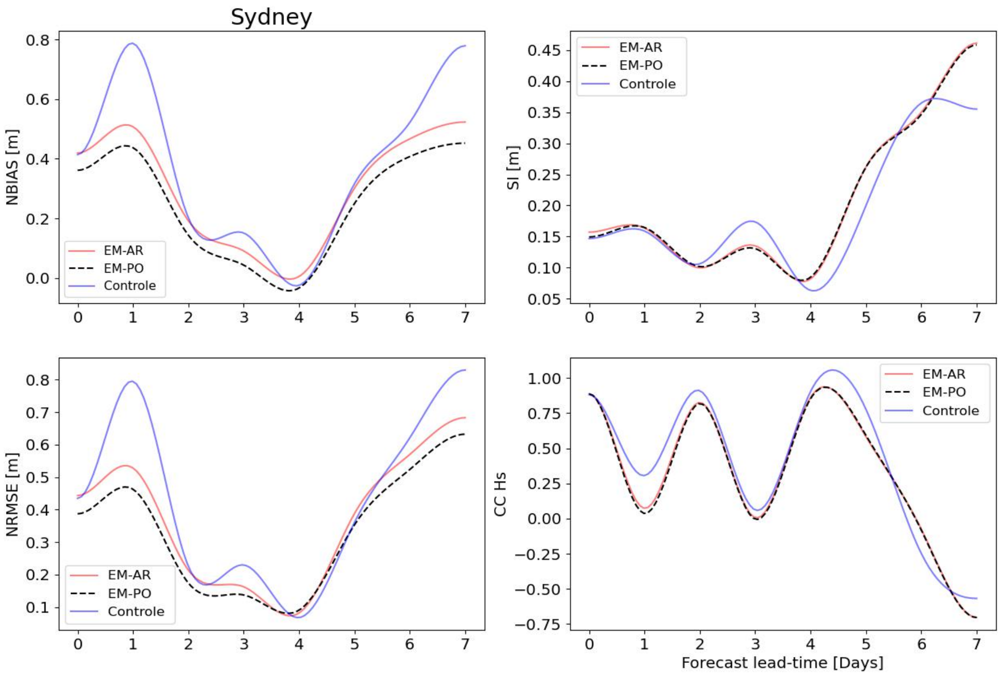

Figure 17: Statistical analysis for Sydney buoy is presented. NBIAS (top left), SI (top right), NRMSE (bottom left) and CC (bottom right) of Hs from GWEFS lead-time versus buoy observation. Red line is ensemble arithmetic mean (EM-AR), black dot-line represent ensemble weighted arithmetic mean (EM-PO) and the blue line the control member. Also in each plot legend the statistical analysis for all forecast time-series

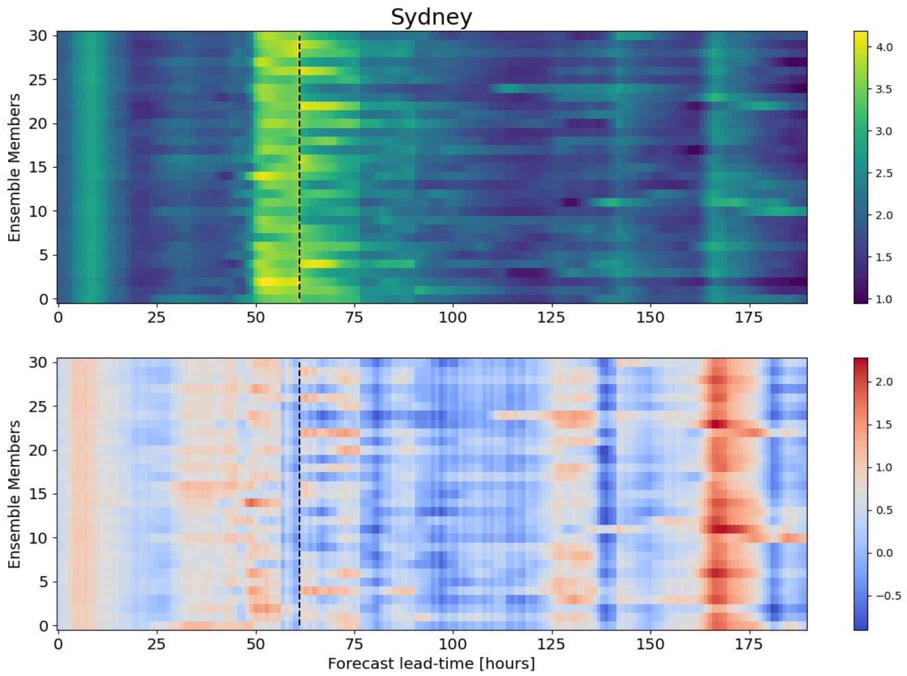

Figure 18: Matrix of GWEFS for Sydney buoy related to nowcast on 2021/03/09, 0Z, and up to 7-day forecast. The top plot show the Hs of 31 GEFS, and the dot line show the period of register of the max Hs in wave rider buoy, which is 3.7 m. The bottom plot show the difference in meters of observed minus GWEFS, where light blue indicate underestimation, while red indicate overestimation, and the white color the perfect agreement.

A.3 Forecast 15/09/2021

The Figure 19 show a storm event that occur in at the end of the forecast lead-time. Therefore, the forecast accuracy is chaotic. Since, the uncertainty wave forecast evolve whit the time. However, for Batemen Bay the SWAN forecast overestimate the Hs of the storm, and the EM-AR and EM-PO best agree with wave condition.

In Figure 20 the statistical analysis show that a systematic deterioration of forecast lead-time. From day 4 the uncertainty increase, as show is SI, NRMSE and CC.

In this case SWAN model present a underconfidence in predicting extreme events when run with GWEFS (Fig. 21). Although, we points out that EM can slightly enhance the accuracy of the forecast, in fact both EM-AR and EM-PO better represent wave forecast condition when compare to the control member, such as, that RMSE and SI are lowest for each EM-AR (0.49 and 0.35) and EM-PO (0.44 and 0.34), nan of the EM reach the peak of the storm.

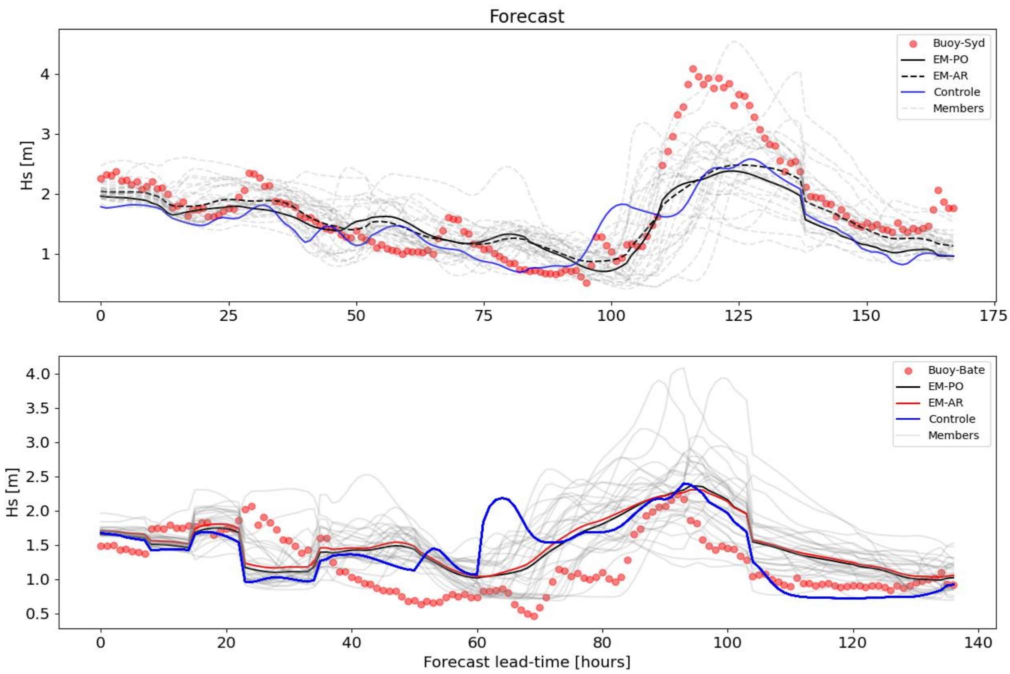

Figure 19: Hs from GFS/WW3

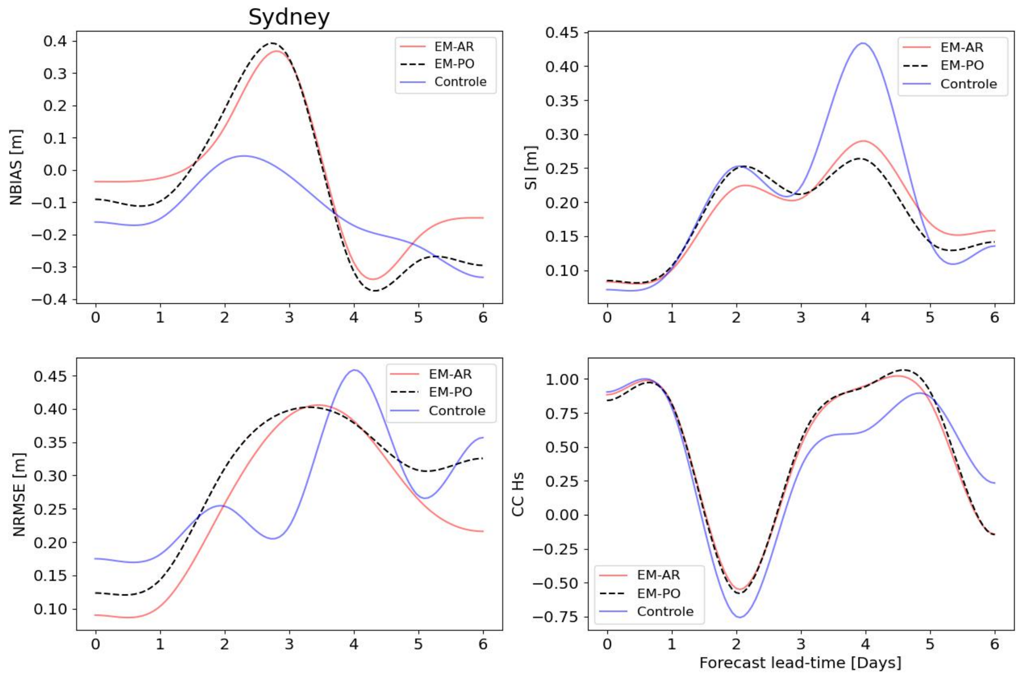

Figure 20: Statistical analysis for Sydney buoy is presented. NBIAS (top left), SI (top right), NRMSE (bottom left) and CC (bottom right) of Hs from GWEFS lead-time versus buoy observation. Red line is ensemble arithmetic mean (EM-AR), black dot-line represent ensemble weighted arithmetic mean (EM-PO) and the blue line the control member. Also in each plot legend the statistical analysis for all forecast time-series

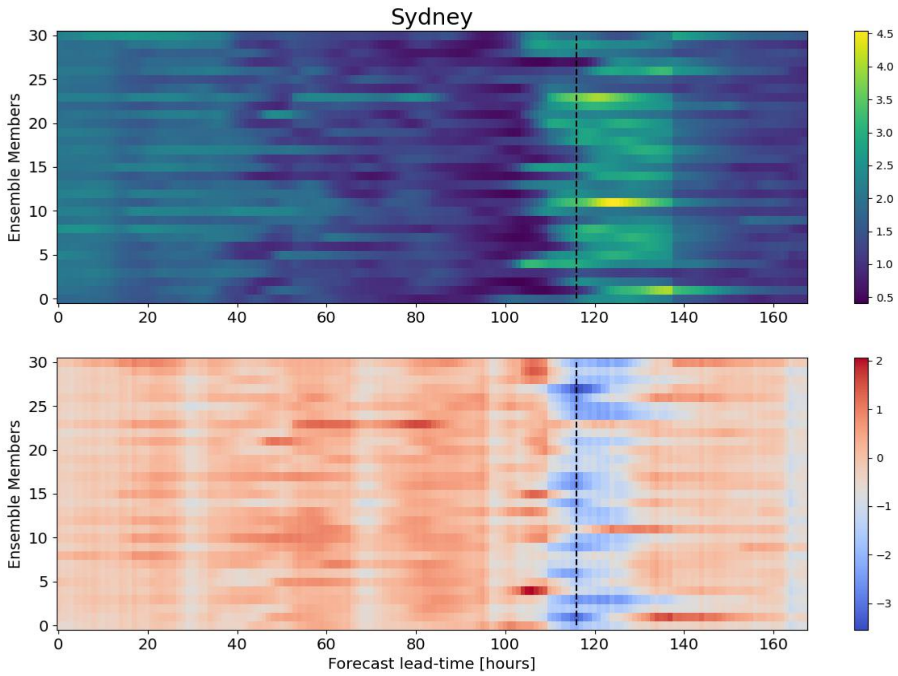

Figure 21: Matrix of GWEFS for Sydney buoy related to nowcast on 2021/15/09, 0Z, and up to 6-day forecast. The top plot show the Hs of 31 GEFS, and the dot line show the period of register of the max Hs in wave rider buoy, which is 4.2 m. The bottom plot show the difference in meters of observed minus GWEFS, where light blue indicate underestimation, while red indicate overestimation, and the white color the perfect agreement.

A.4 Forecast 22/11/2021

The Figure 22 show a storm event that occur at day 4 of the forecast. Therefore, in this cases the forecast accuracy rather correct that chaotic.

In Figure 23 the statistical analysis show a great agreement whit of forecast lead-time and buoy. From day 4 the uncertainty does not increase, as show is SI, NRMSE and CC.

In this case SWAN model present a overconfidence in predicting extreme events when run with GWEFS (Fig. 24). In fact, we points out that EM can slightly enhance the accuracy of the forecast, in fact both EM-AR and EM-PO better represent wave forecast condition when compare to the control member, such as, that RMSE and SI are lowest for each EM-AR (0.21 and 0.21) and EM-PO (0.19 and 0.19), none of the EM reach the peak of the storm.

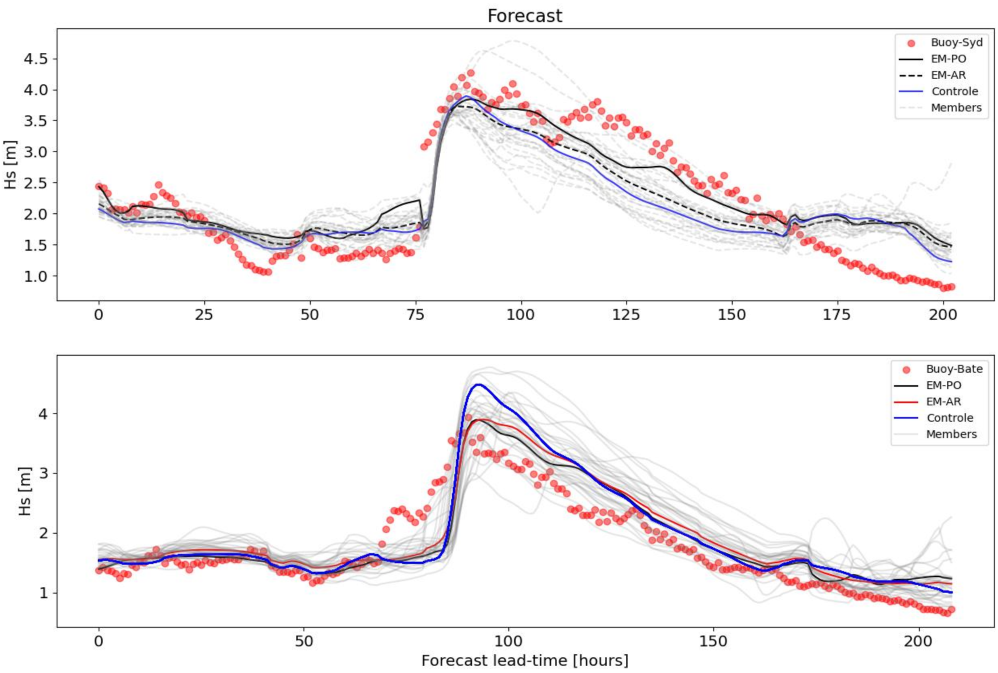

Figure 22: Hs from GFS/WW3

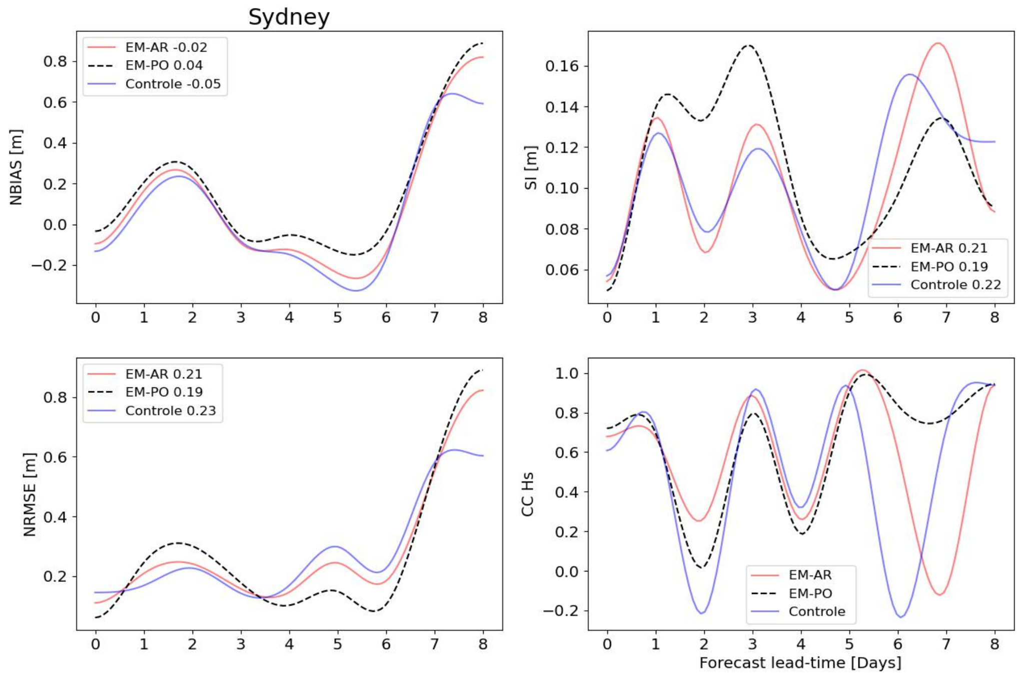

Figure 23: Statistical analysis for Sydney buoy is presented. NBIAS (top left), SI (top right), NRMSE (bottom left) and CC (bottom right) of Hs from GWEFS lead-time versus buoy observation. Red line is ensemble arithmetic mean (EM-AR), black dot-line represent ensemble weighted arithmetic mean (EM-PO) and the blue line the control member. Also in each plot legend the statistical analysis for all forecast time-series

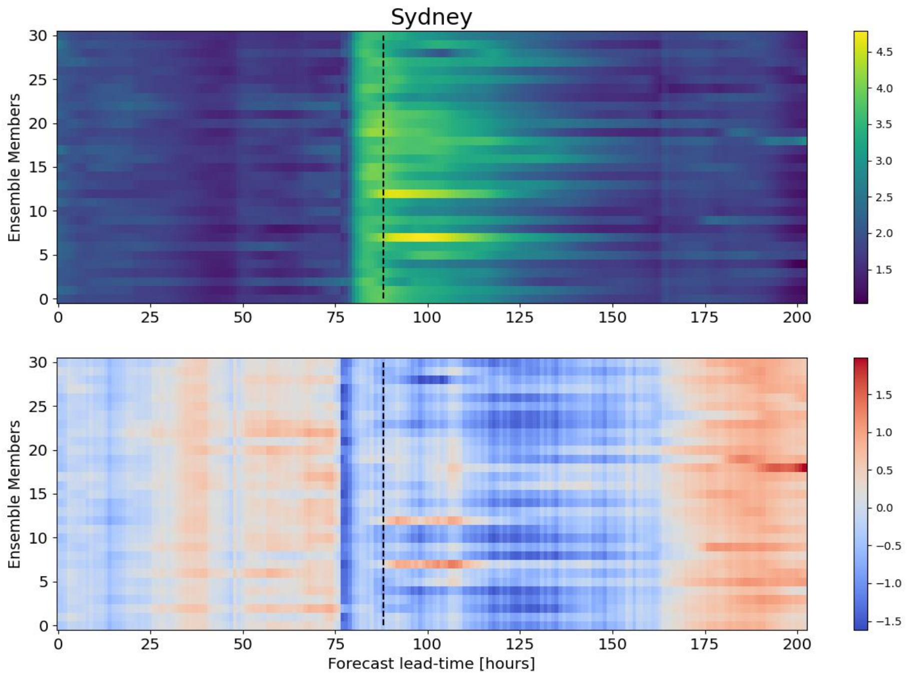

Figure 24: Matrix of GWEFS for Sydney buoy related to nowcast on 2021/22/11, 0Z, and up to 7-day forecast. The top plot show the Hs of 31 GEFS, and the dot line show the period of register of the max Hs in wave rider buoy, which is 4.5 m. The bottom plot show the difference in meters of observed minus GWEFS, where light blue indicate underestimation, while red indicate overestimation, and the white color the perfect agreement.

A.5 Forecast 06/12/2021

The Figure 25 show a storm event that occur at day 5 of the forecast. Therefore, in this cases the forecast anticipated the storm event in few hours nad miss the Hs peak for Sydney. However, for Batemen Bay the SWAN forecast accurately predict the peak of the storm

In Figure 26 the statistical analysis show a great agreement whit of forecast lead-time and buoy. From day 4 the uncertainty does not increase significant, as show is SI, NRMSE and CC.

In this case SWAN model present a underconfidence in predicting extreme events when run with GWEFS (Fig. 27). In fact, we points out that EM can slightly enhance the accuracy of the forecast, in fact both EM-AR and EM-PO better represent wave forecast condition when compare to the control member, such as, that RMSE and SI are lowest for each EM-AR (0.34 and 0.33) and EM-PO (0.35 and 0.34), none of the EM reach the peak of the storm.

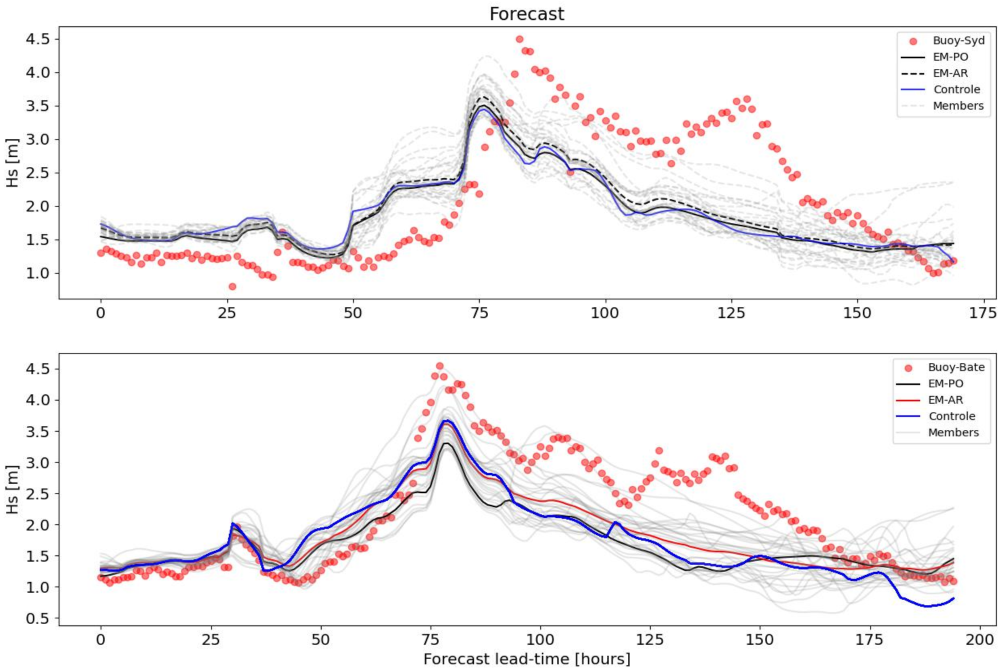

Figure 25: Hs from GFS/WW3

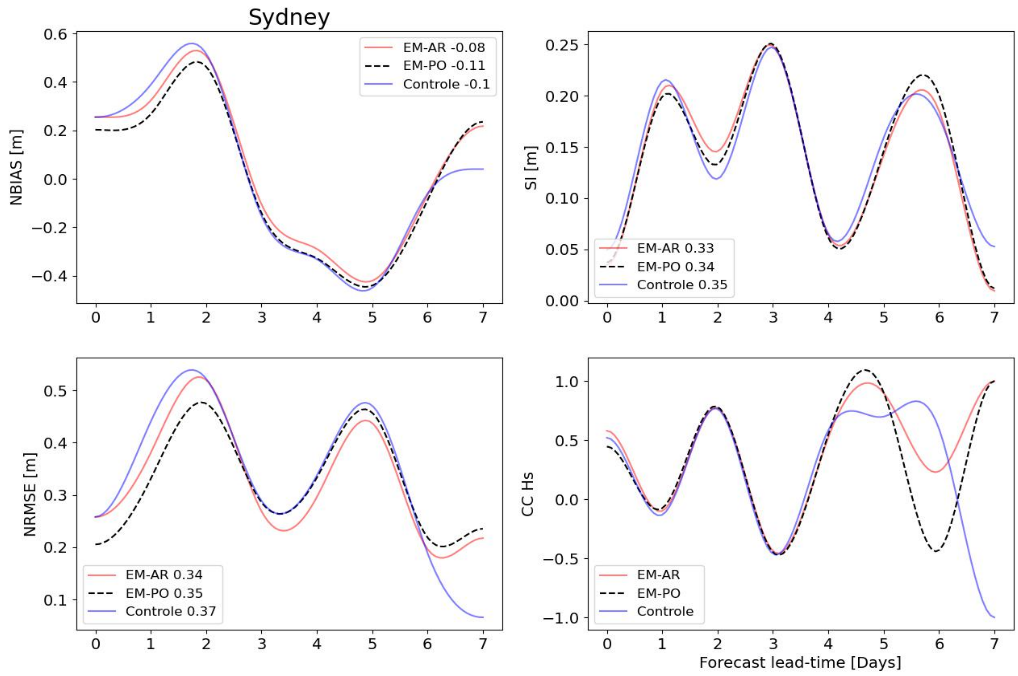

Figure 26: Statistical analysis for Sydney buoy is presented. NBIAS (top left), SI (top right), NRMSE (bottom left) and CC (bottom right) of Hs from GWEFS lead-time versus buoy observation. Red line is ensemble arithmetic mean (EM-AR), black dot-line represent ensemble weighted arithmetic mean (EM-PO) and the blue line the control member. Also in each plot legend the statistical analysis for all forecast time-series

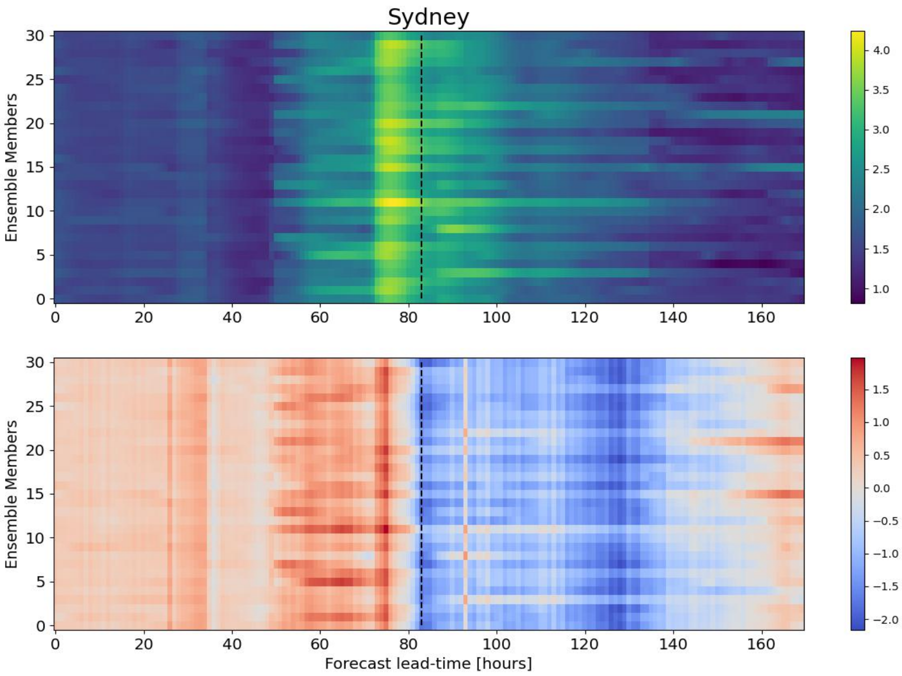

Figure 27: Matrix of GWEFS for Sydney buoy related to nowcast on 2021/06/12, 0Z, and up to 7-day forecast. The top plot show the Hs of 31 GEFS, and the dot line show the period of register of the max Hs in wave rider buoy, which is 4.5 m. The bottom plot show the difference in meters of observed minus GWEFS, where light blue indicate underestimation, while red indicate overestimation, and the white color the perfect agreement.

A.6 Forecast 19/12/2021

The Figure 28 show a storm event that occur at day end of the forecast. This case represente a low energy wave condition during most of ther forecast time. Therefore, the forecast represent with great accuracy the wave condition for all forecast lead-time (same for Batemen Bay). However, close to day 7 there is a increase in forecast uncertainty.

In Figure 29 the statistical analysis show a great agreement whit of forecast lead-time and buoy. From day 4 the uncertainty does not increase significant, as show is SI, NRMSE and CC.

In this case SWAN model present a overconfidence in predicting extreme events when run with GWEFS (Fig. 30). In fact, we points out that EM can slightly enhance the accuracy of the forecast, in fact both EM-AR and EM-PO better represent wave forecast condition when compare to the control member, such as, that RMSE and SI are lowest for each EM-AR (0.28 and 0.23) and EM-PO (0.26 and 0.22), none of the EM reach the peak of the storm.

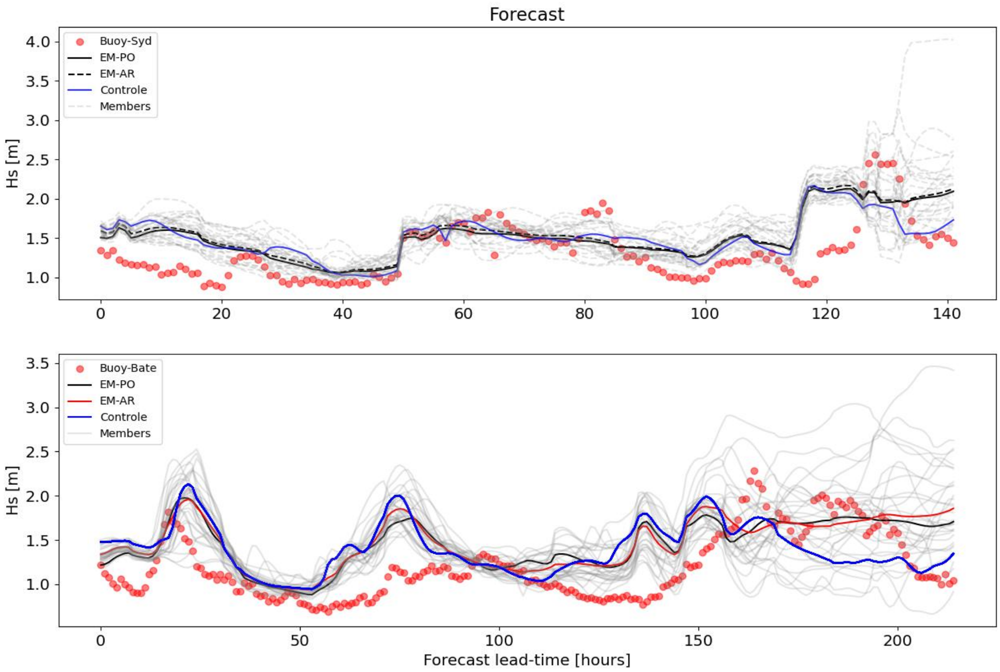

Figure 28: Hs from GFS/WW3

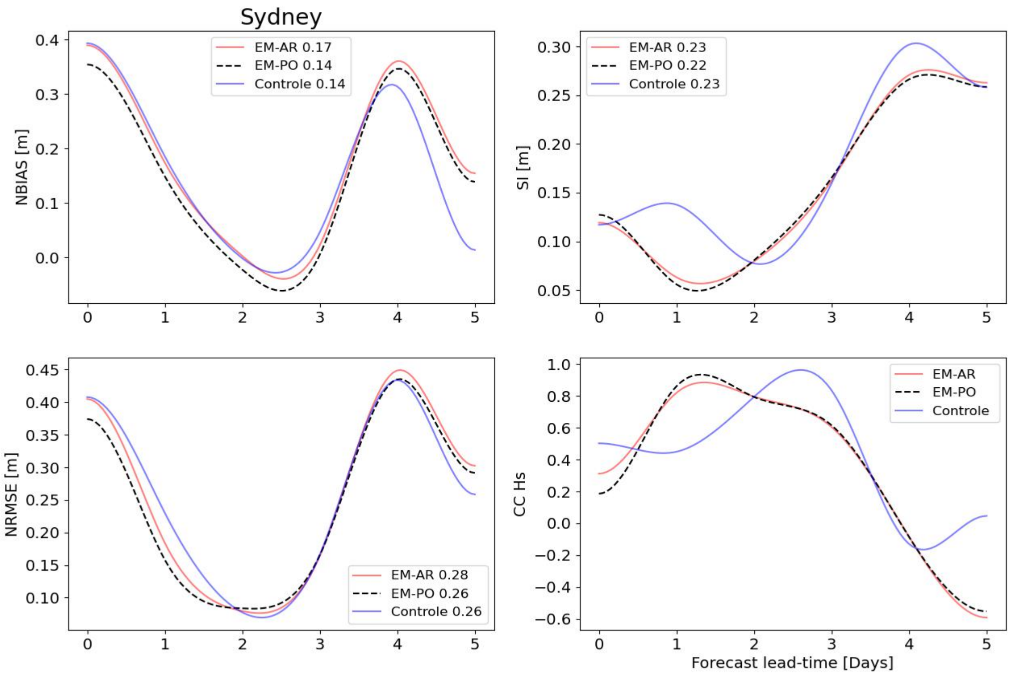

Figure 29: Statistical analysis for Sydney buoy is presented. NBIAS (top left), SI (top right), NRMSE (bottom left) and CC (bottom right) of Hs from GWEFS lead-time versus buoy observation. Red line is ensemble arithmetic mean (EM-AR), black dot-line represent ensemble weighted arithmetic mean (EM-PO) and the blue line the control member. Also in each plot legend the statistical analysis for all forecast time-series

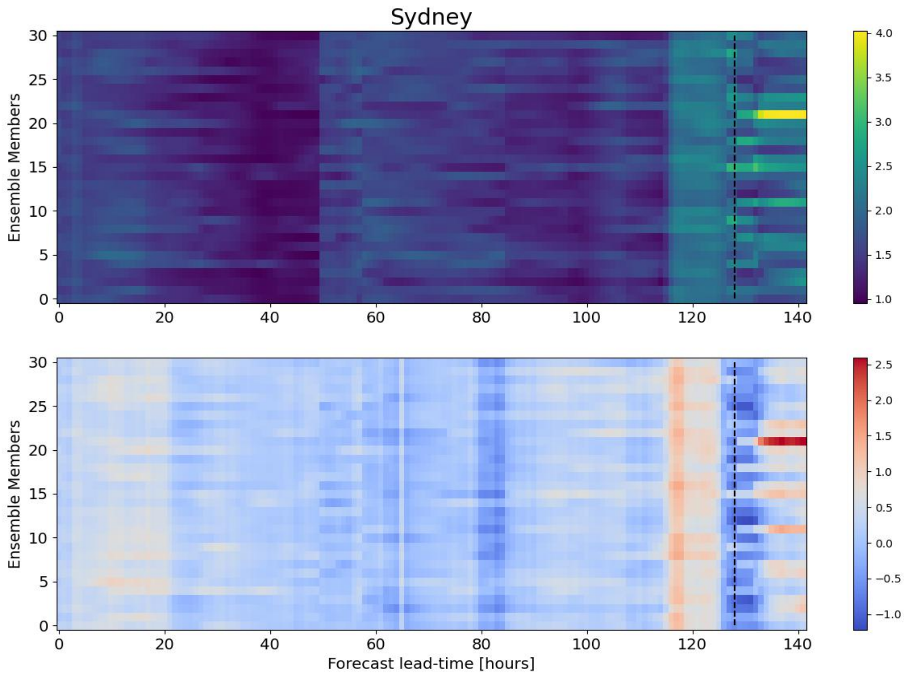

Figure 30: Matrix of GWEFS for Sydney buoy related to nowcast on 2021/19/12, 0Z, and up to 7-day forecast. The top plot show the Hs of 31 GEFS, and the dot line show the period of register of the max Hs in wave rider buoy, which is 2.5 m. The bottom plot show the difference in meters of observed minus GWEFS, where light blue indicate underestimation, while red indicate overestimation, and the white color the perfect agreement.