



20 ANOS DA REDE DE MODELAGEM E OBSERVAÇÃO OCEANOGRÁFICA (REMO) E VISÃO DE FUTURO DA PREVISÃO OCEÂNICA OPERACIONAL NO BRASIL

VISÃO DE FUTURO DA PREVISÃO DE ONDAS

Ricardo Martins Campos

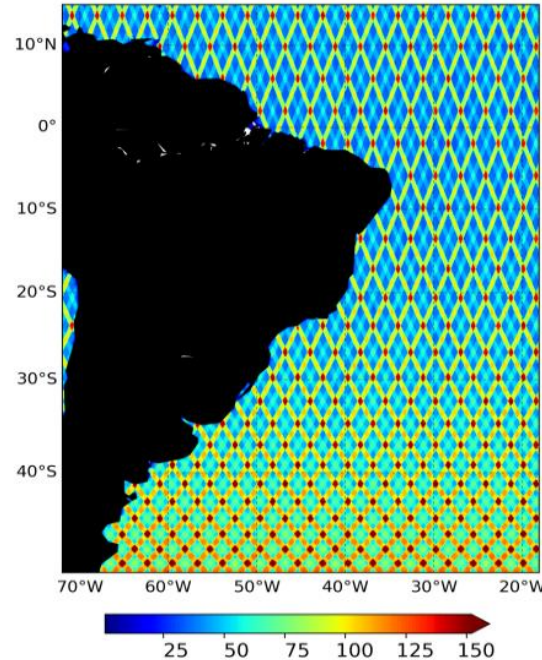
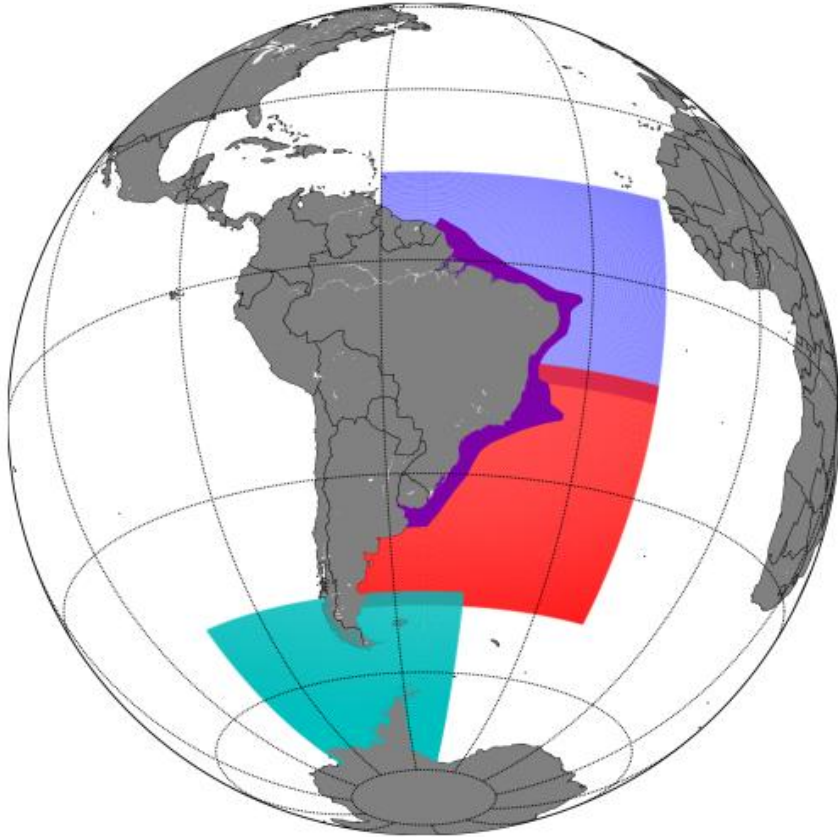
ricardo.campos@noaa.gov

Sumário

- **Novo contexto da componente de ondas em sistemas de previsão e ganho de relevância da previsão de ondas**
- **Resumo do desenvolvimento nos últimos anos na área de previsão de ondas da REMO**
- **Trabalho em andamento com o grupo de ondas da REMO**
 - WAVEWATCH III: avaliação e calibração do mosaico multi-grid e possíveis ajustes
 - Rodadas WW3-GFS, WW3-ICON-ICOMLAM e WW3-ECMWF
 - Revisão da modelagem em regiões costeiras
 - Bias-correction utilizando modelos de Machine Learning
 - Previsão por ensemble e multi-model ensemble utilizando modelos estatísticos de pós-processamento
 - Previsão probabilística de médio prazo até 16 dias
 - Machine learning no domínio da probabilidade
- **Visão do futuro na melhoria da previsão de ondas**
 - Mais observações, com informação espectral, e ampla cobertura espaço-temporal
 - Medições e modelagem para sistemas meteorológicos específicos e relevantes
 - Super ensemble em modelagem híbrida acoplada
 - Rapid refresh system (HRRR) e Assimilação de dados

Resumo do desenvolvimento nos últimos anos na área de previsão de ondas

- WAVEWATCH III multi-grid: Global 20', Meta-Sul 6', Meta-Norte 9', Ant 5X10', Costeira 2'



WW3 Spectrum at ST8 , 2019/08/17 10Z

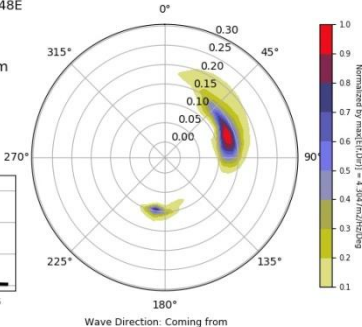
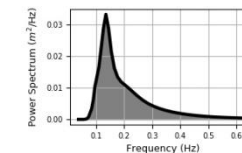
Latitude: 25.8S Longitude: 314.48E

Water Depth: 230.8 m

Significant Wave Height: 2.19 m

Wind Speed: 9.07 m/s

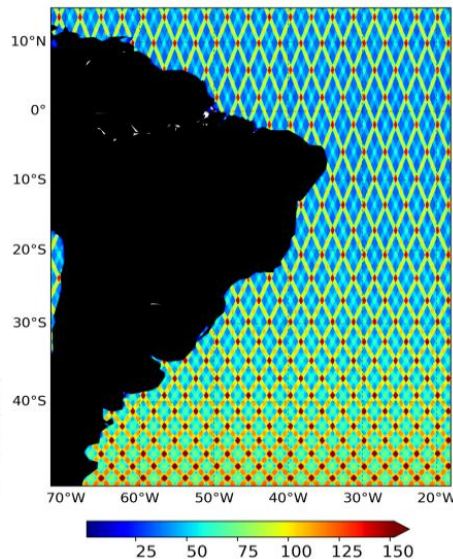
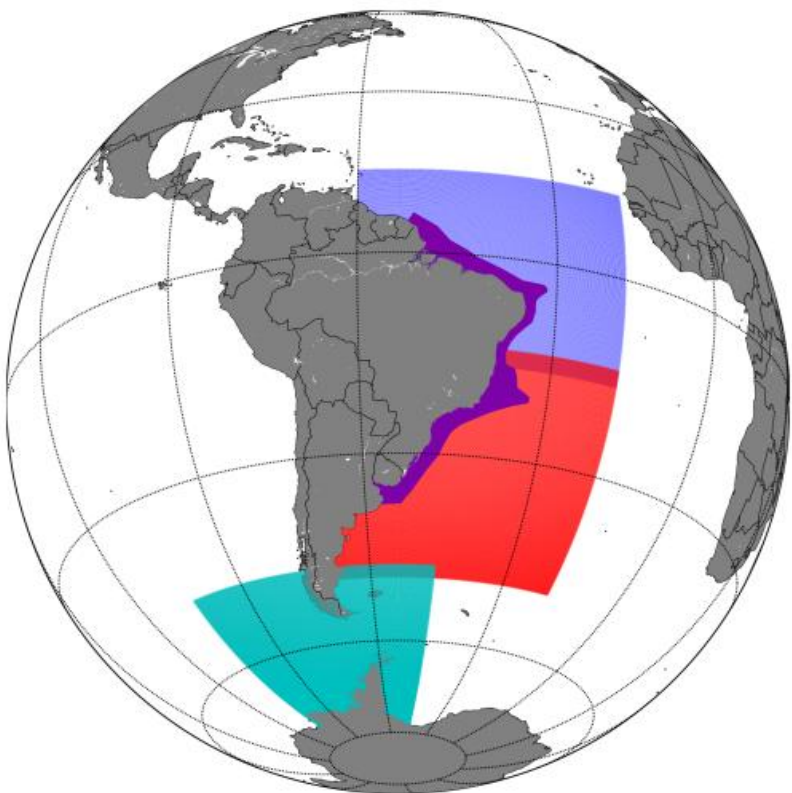
Wind Direc: 35.0°



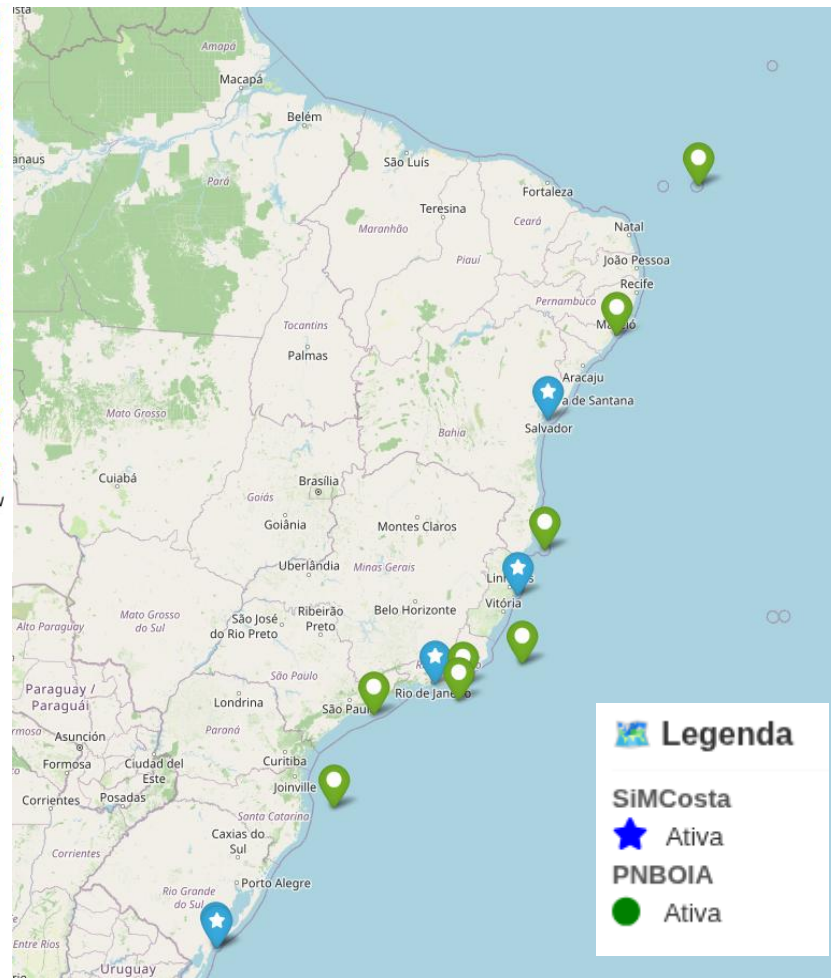
Dados de boia (PNBOIA e SIMCOSTA)
Altímetro (base AODN)

Resumo do desenvolvimento nos últimos anos na área de previsão de ondas

- WAVEWATCH III multi-grid: Global 20', Meta-Sul 6', Meta-Norte 9', Ant 5X10', Costeira 2'



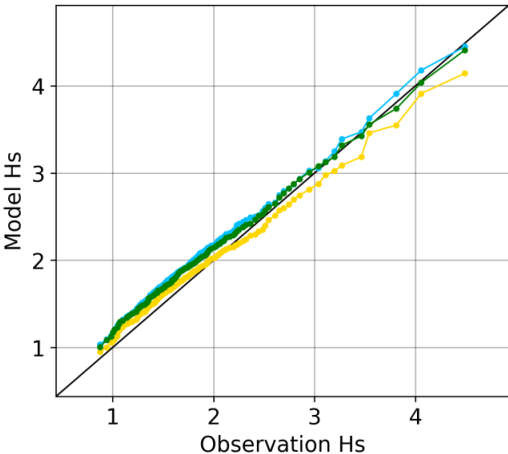
Avaliação e re-calibração atual



Resumo do desenvolvimento nos últimos anos na área de previsão de ondas

- Otimização da resolução espacial e espectral + parâmetros e termos fonte do modelo.

met6s		bias	RMSE	SI	CC	biasPct95	RMSEpct95
U10	GFS	-0.538	1.484	0.145	0.927	-1.010	1.935
	ICON	-0.669	1.484	0.139	0.931	-1.767	2.314
	COSMO	-0.677	1.556	0.147	0.923	-1.602	2.269
Hs	t1_GFS	-0.080	0.339	0.112	0.963	-0.246	0.755
	t2_GFS	-0.026	0.334	0.113	0.963	-0.108	0.743
	t3_ICON	-0.103	0.342	0.111	0.967	-0.611	0.887
	t4_ICON	-0.057	0.324	0.108	0.967	-0.498	0.818
	t5_COSMO	-0.045	0.337	0.113	0.963	-0.372	0.764
	t6_GFS	0.007	0.337	0.114	0.962	-0.028	0.747
	t7_ICON	-0.012	0.315	0.106	0.967	-0.387	0.761
	t8_GFS	0.002	0.335	0.114	0.962	-0.044	0.745



Análise multi-variada do erro (SCrmse)

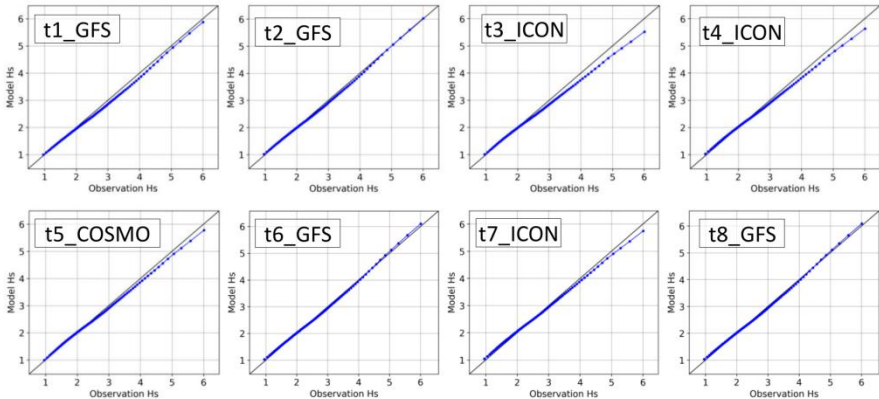
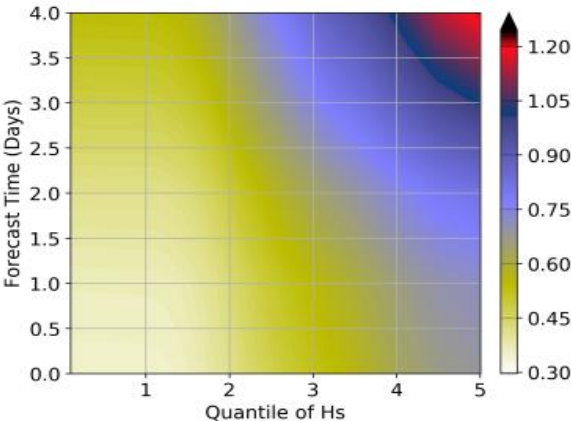
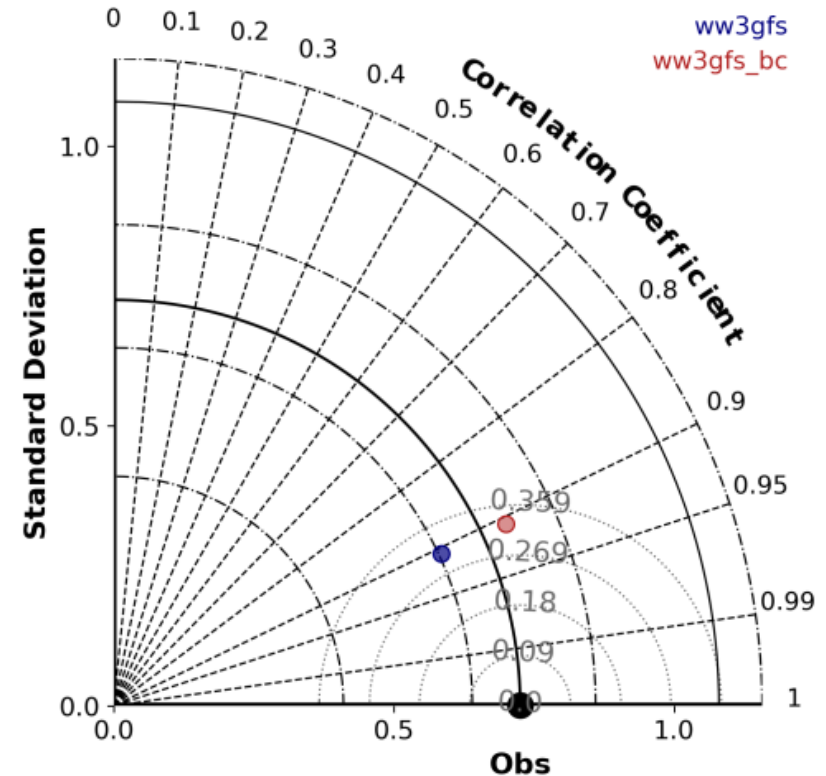
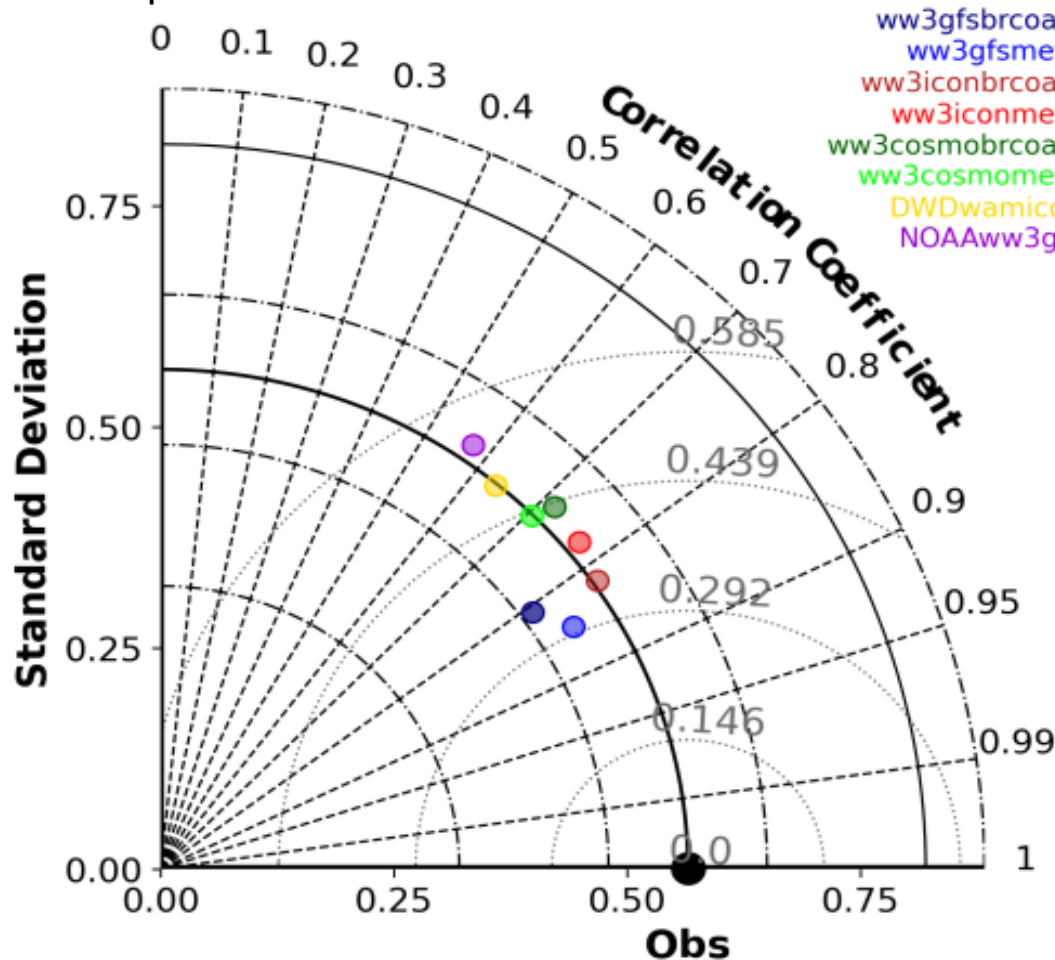


Figura 2 - QQ-plots de avaliação da altura significativa (Hs) em metros.

Resumo do desenvolvimento nos últimos anos na área de previsão de ondas

- Resultados calibrados e comparados com previsões externas

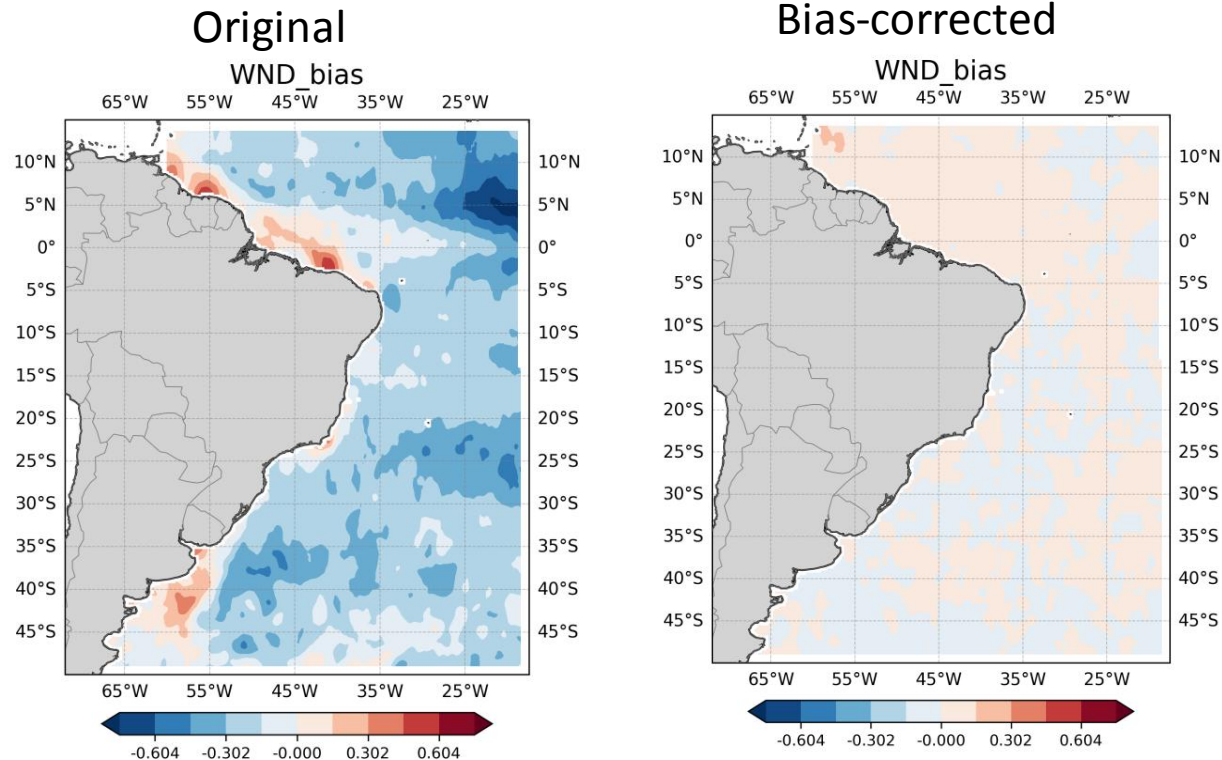
Exemplo: Imbituba



Bias correction

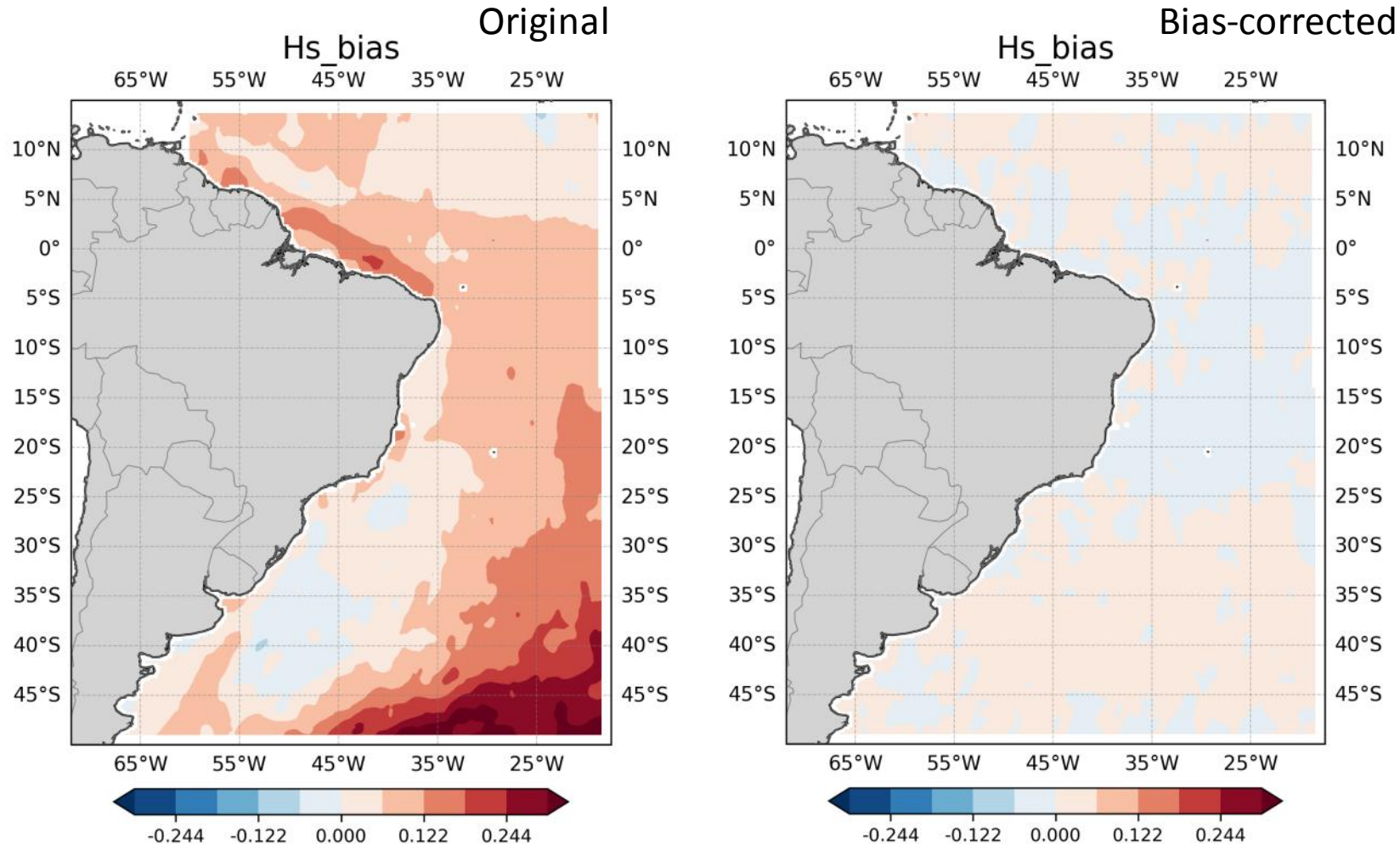
Resumo do desenvolvimento nos últimos anos na área de previsão de ondas

- Bias-correction utilizando dados de altímetro

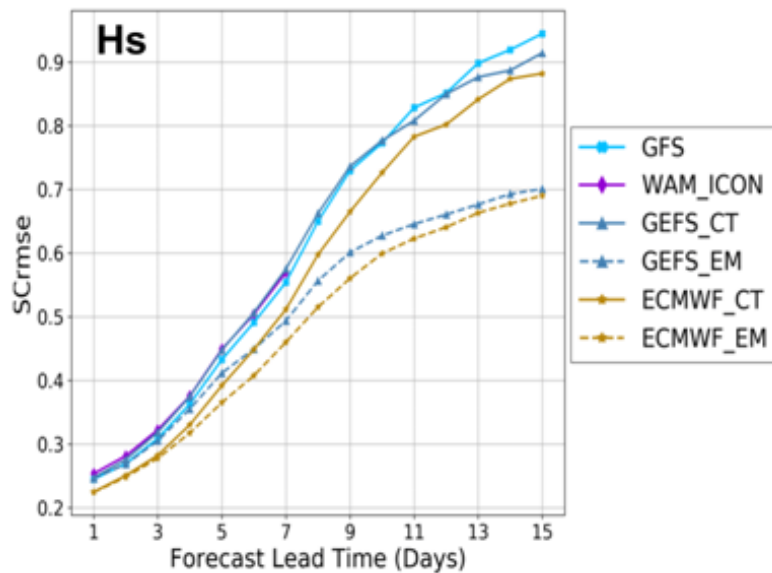
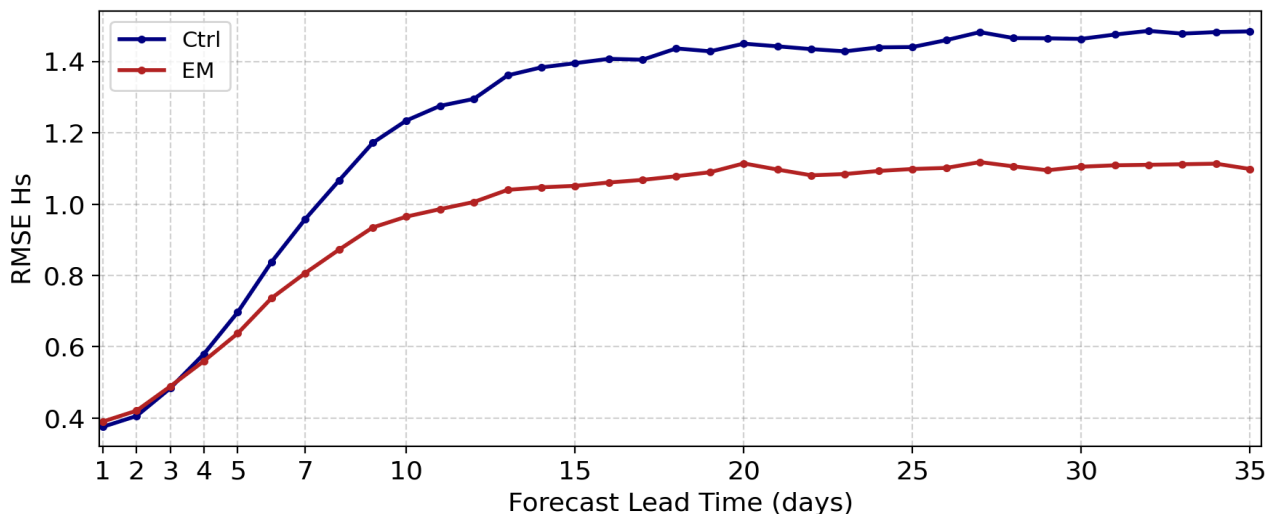
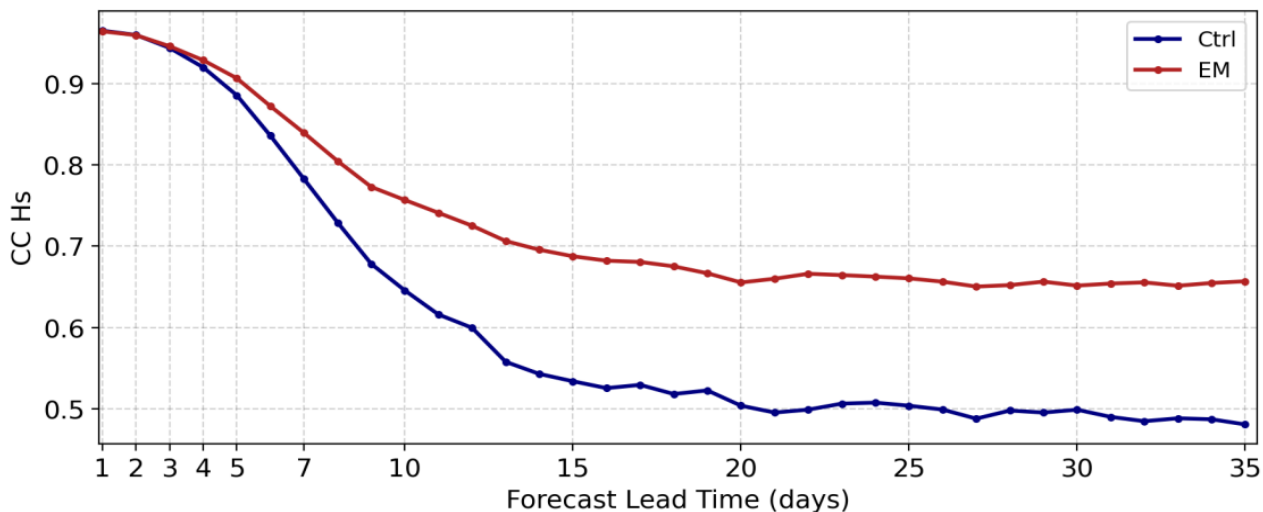


Resumo do desenvolvimento nos últimos anos na área de previsão de ondas

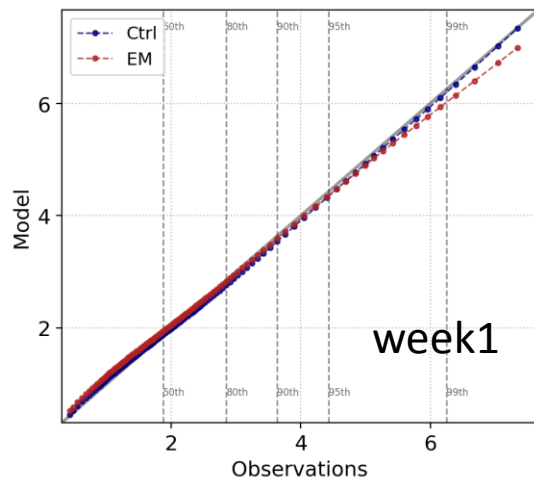
- Bias-correction utilizando dados de altímetro



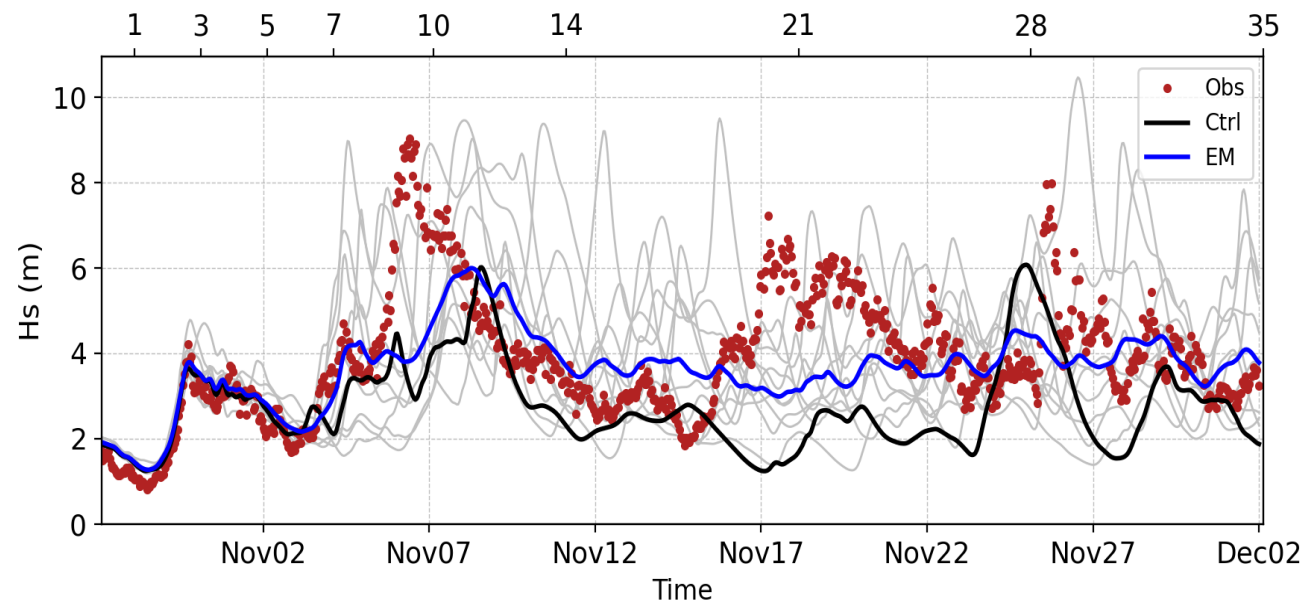
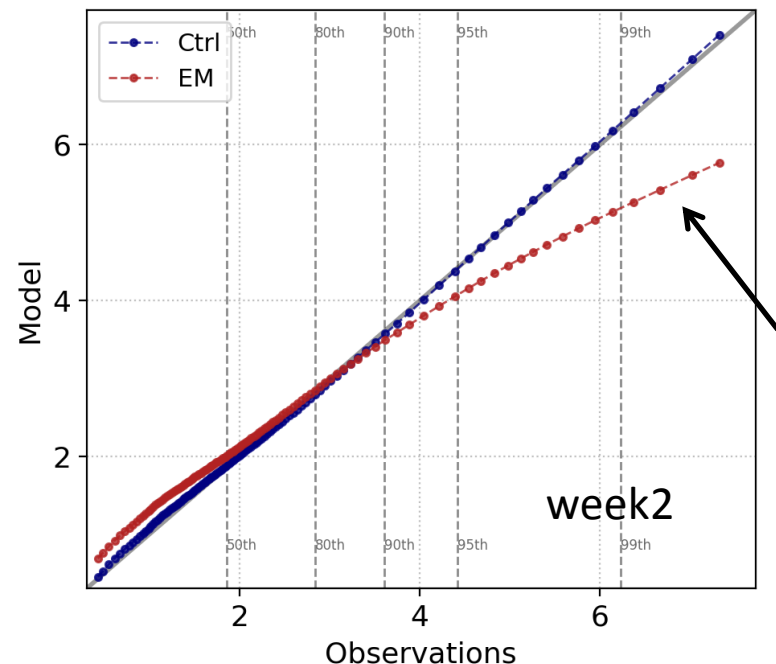
Previsão por conjunto (ensemble)



Previsão por conjunto (ensemble)



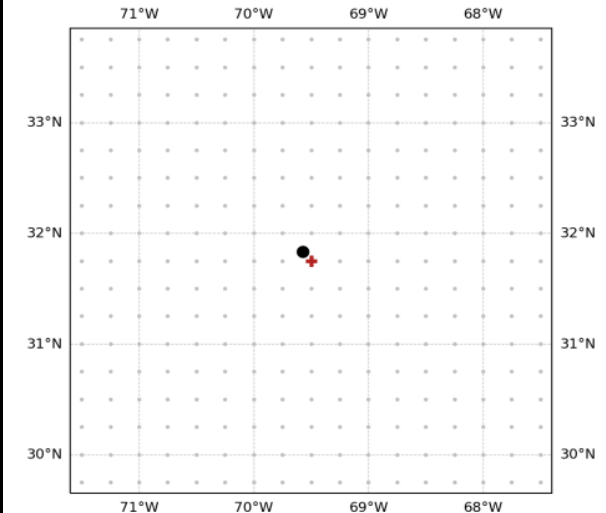
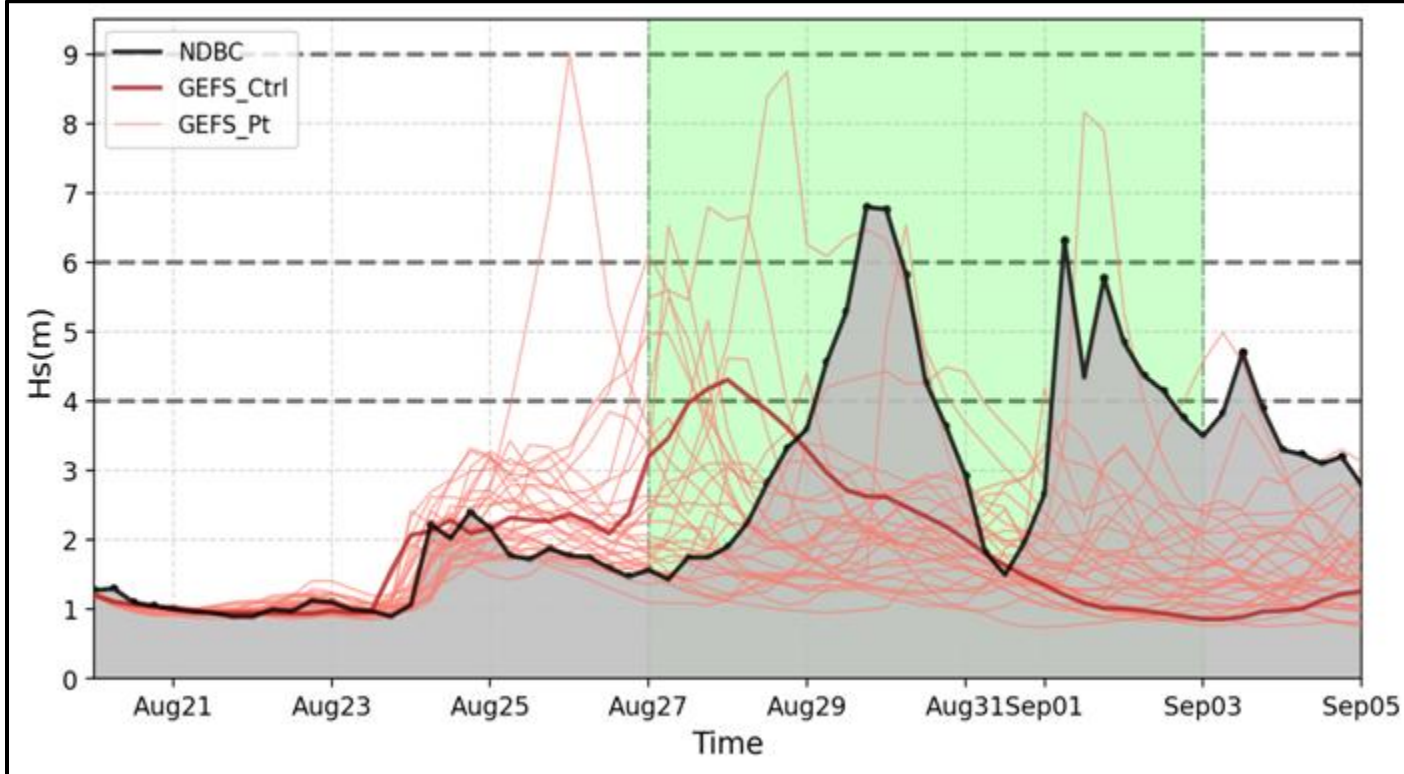
Suavização da média dos membros



Problema grave ao utilizar somente o controle e a média do ensemble.

Modelagem estatística e previsão probabilística

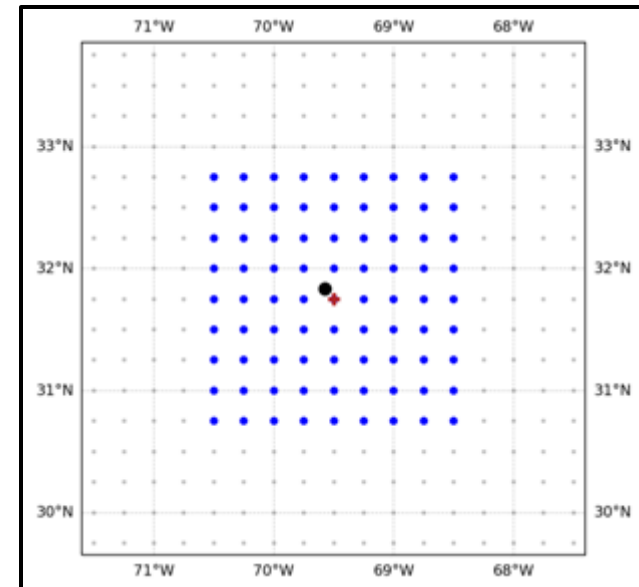
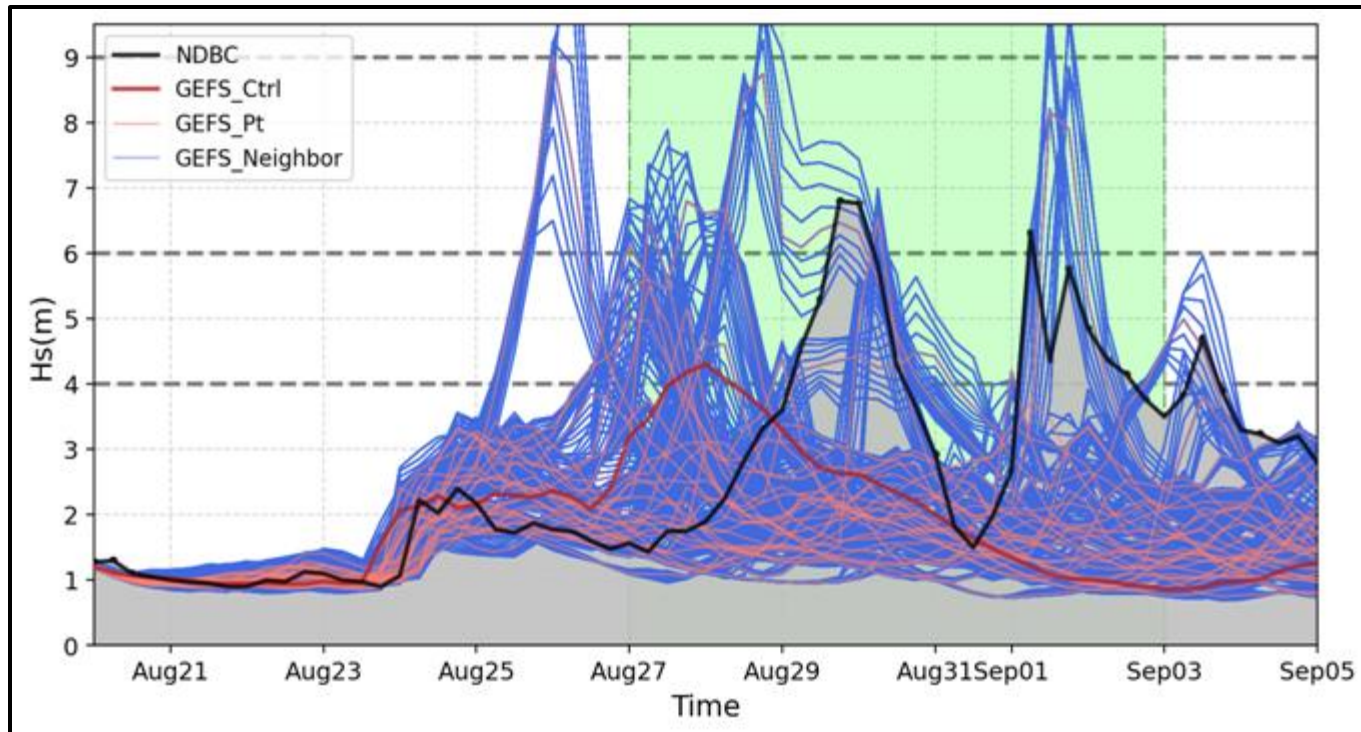
- Spatio-temporal analysis: Time (**week 2**) and Window (**2°X2°**);
- N-max selection (=2): use not only the single max value of the time-series for each member but the n-max ones;
- Distribution threshold (= 87th percentile): focus on members and locations with the most severe conditions.



Example 20-Aug-2023 (Atlantic)

Modelagem estatística e previsão probabilística

- Maximum values (6h-resolution) are selected for each 7-day segment;
- 30+1 members, $2^\circ \times 2^\circ$ neighbors (81 points for a 0.25° resolution grid);
- The resulting array has dimensions of $2 \times 31 \times 81$;
- A threshold is applied to select the tail of the ECDF (> 87 th percentile);
- Probabilities are computed for each level of H_s and U_{10} at the grid points.

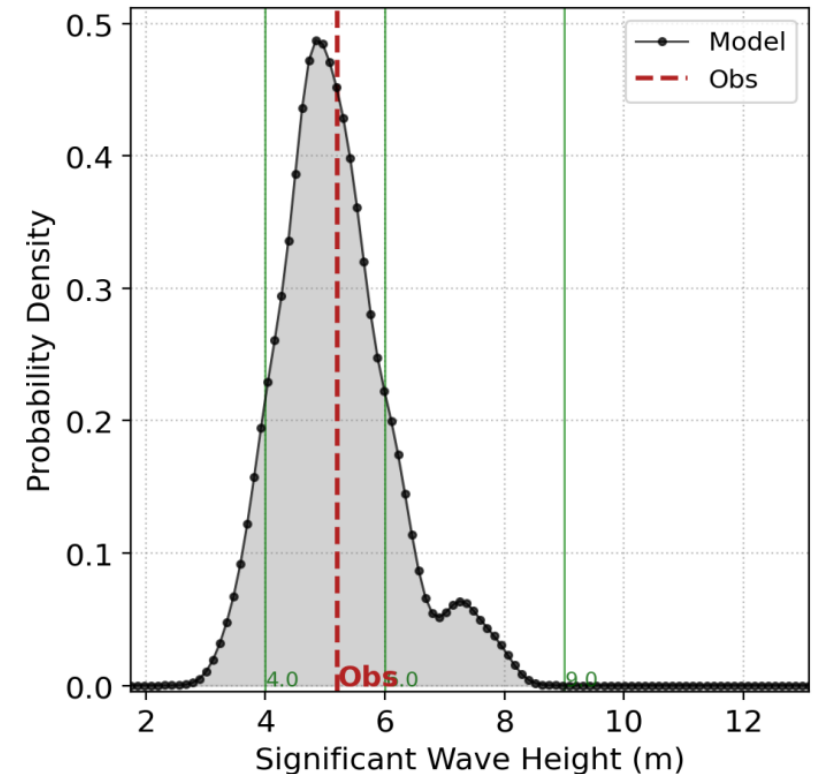
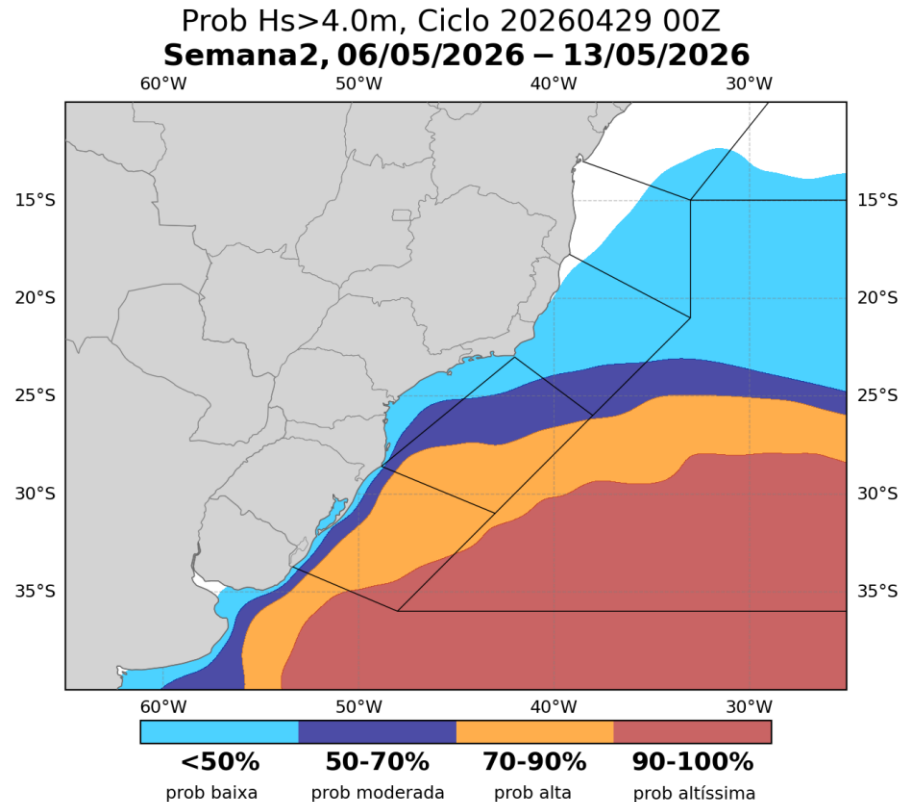


Example 20-Aug-2023 (Atlantic)

Previsão probabilística – Mapas de probabilidade

Mapas de probabilidade:

- Vento a 10-m (knots): **20, 28, 34, 41, 48;**
- Altura significativa de onda (metros): **2.5, 3, 4, 5, 6;**



Avaliação do modelo probabilístico

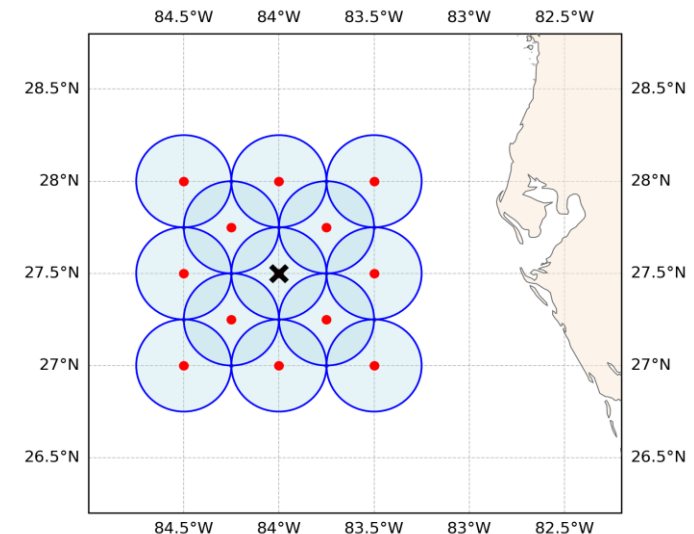
- ROC curve
- Reliability Diagram
- Ebert, E.E., 2008. Fuzzy verification of high-resolution gridded forecasts: a review and proposed framework. Meteorol. Appl. 15: 51–64, DOI: 10.1002/met.25

$$PO^D = \frac{TP}{TP + FN} \quad FA^R = \frac{FP}{FP + TP}$$

$$CS^I = \frac{TP}{TP + FN + FP}$$

$$BS = \frac{1}{N} \sum_{i=1}^N (p_i - o_i)^2$$

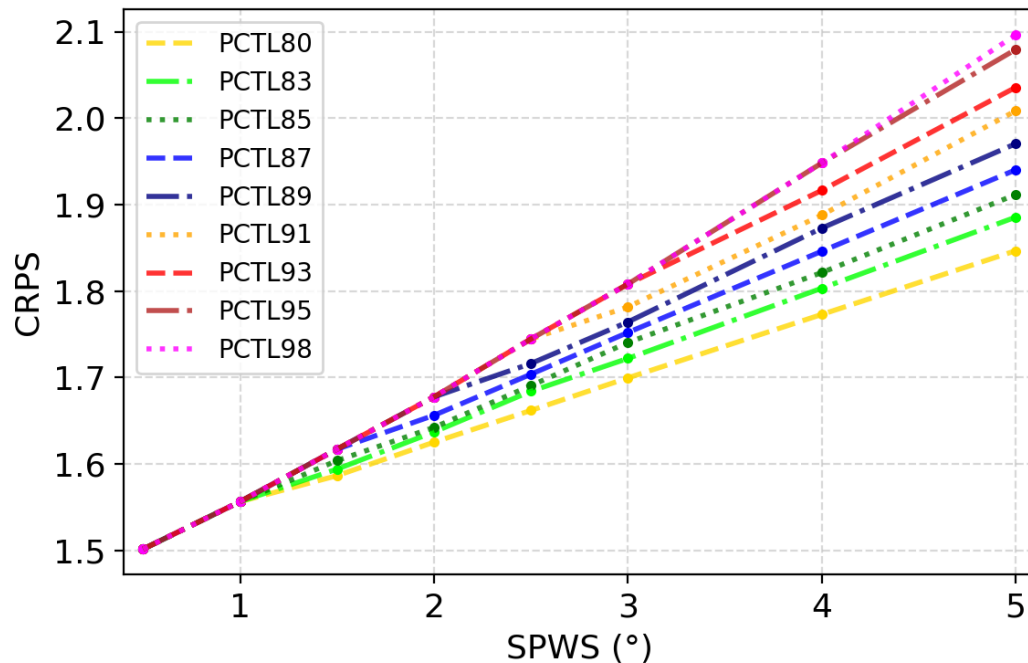
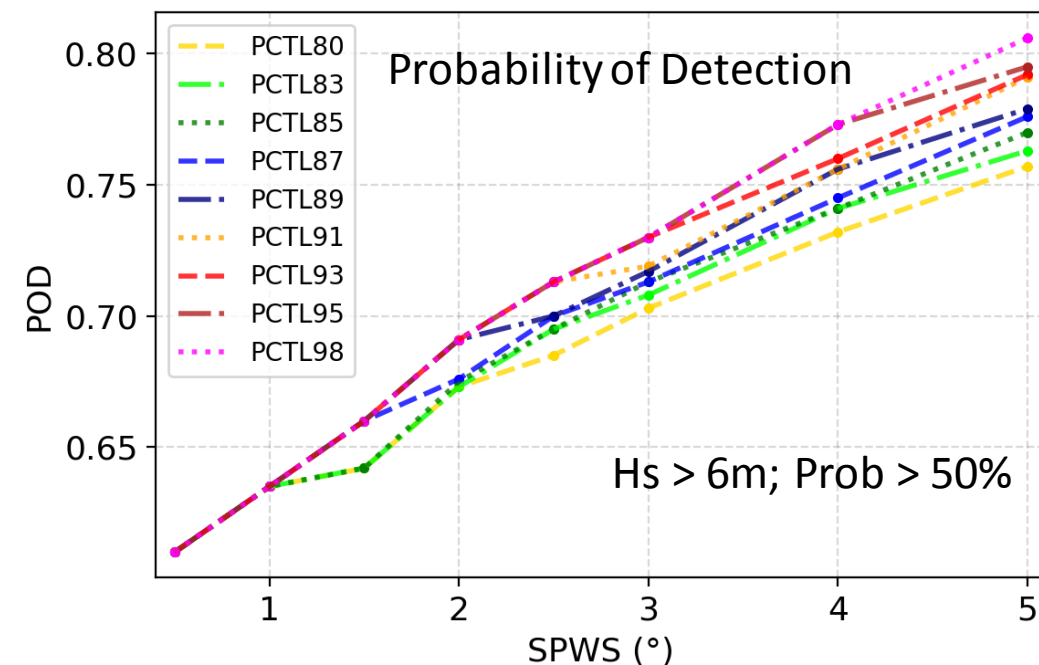
$$CRP \leq \frac{1}{N} \sum_{i=1}^N \int_{x=-\infty}^{x=\infty} (F(y) - 1\{y \geq o_i\})$$



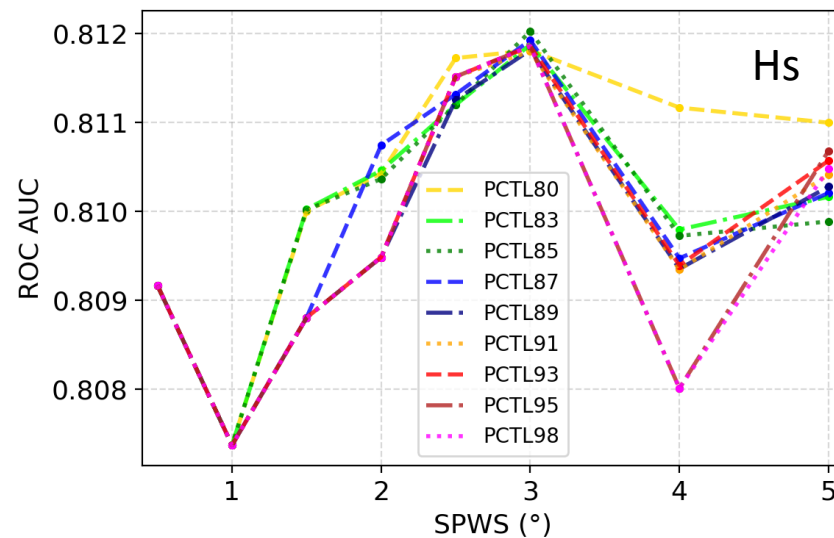
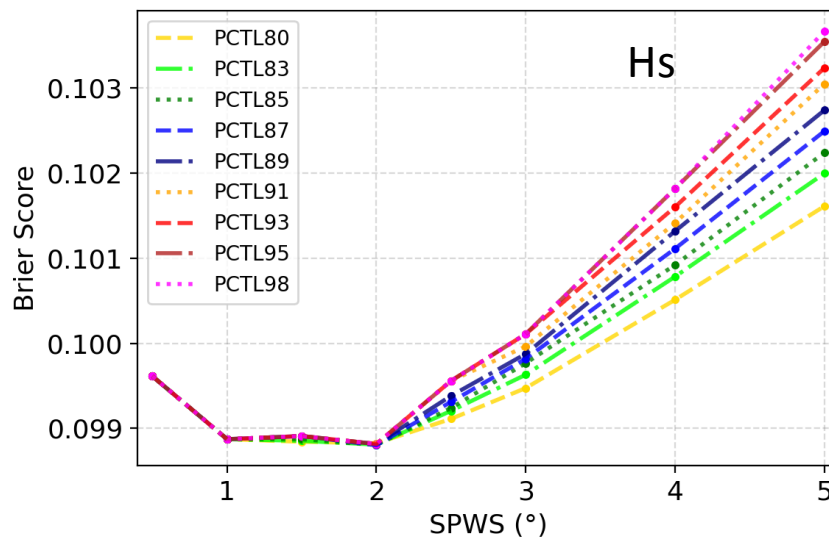
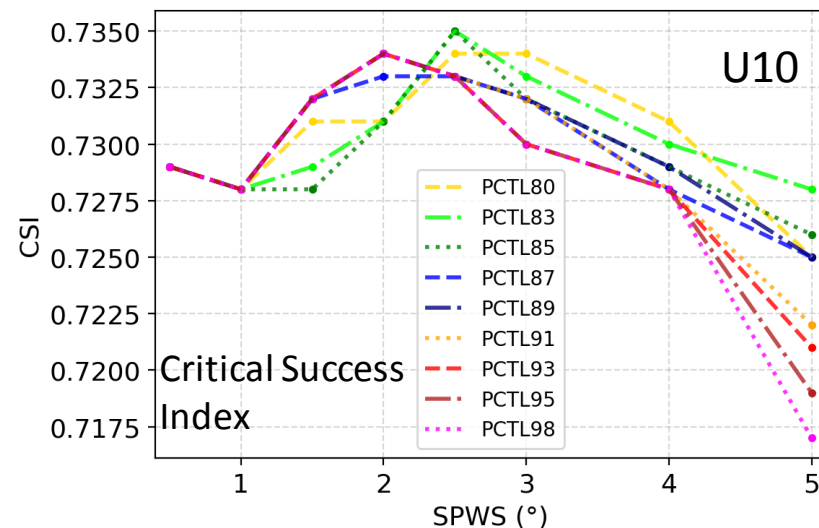
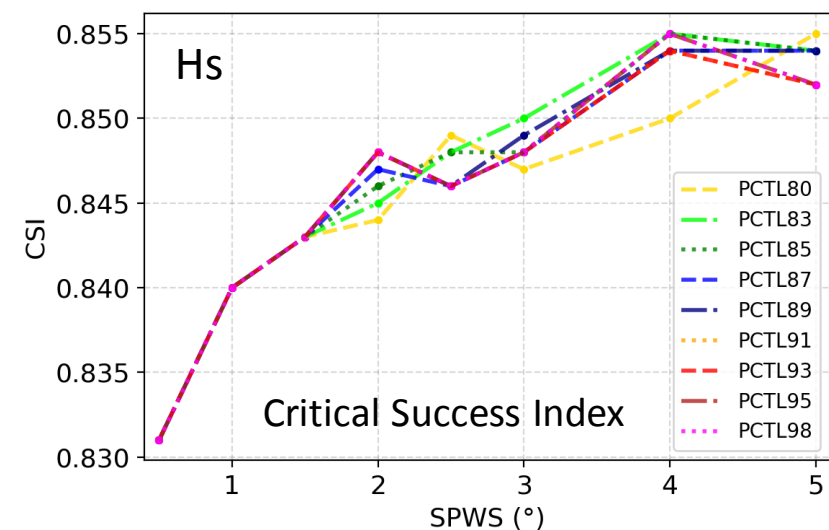
Otimização dos parâmetros do modelo probabilístico

1. *Spatial window ($2^{\circ} \times 2^{\circ}$) SWPS*
2. *Nmax (duration of top selected data) for the time-series within week 2 of each ensemble member.*
3. Threshold (percentile, *PCTL*) to subsample the most extreme values in the EPDF

Analyzed in terms of Hs and U10

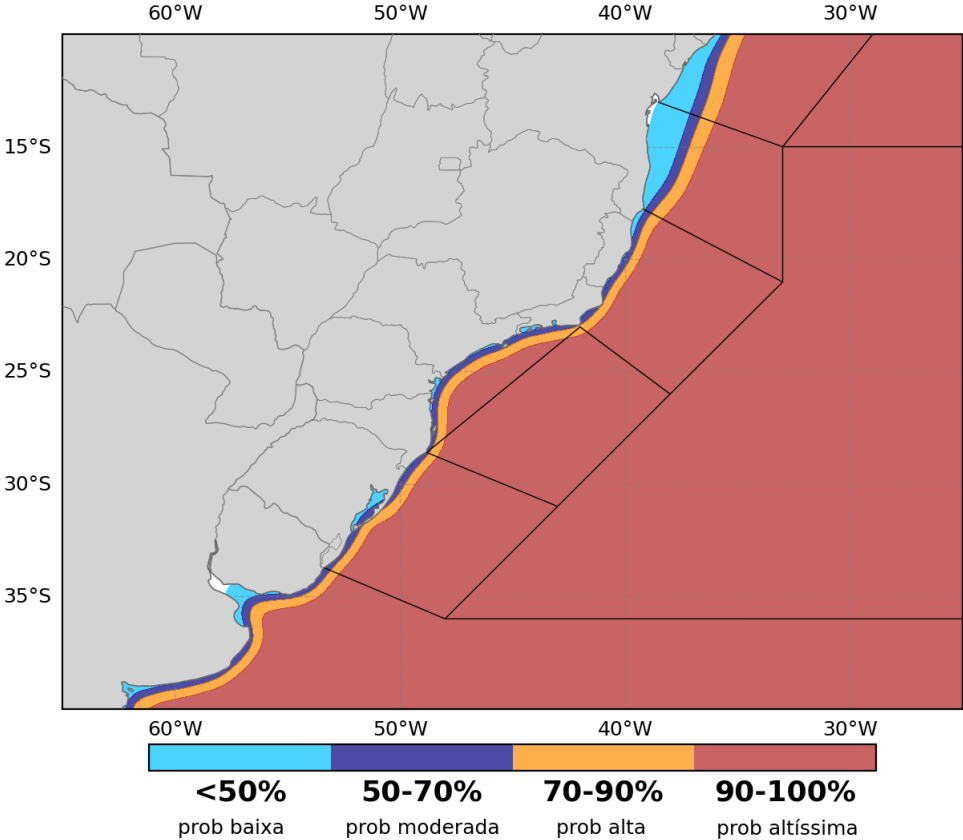


Otimização dos parâmetros do modelo probabilístico

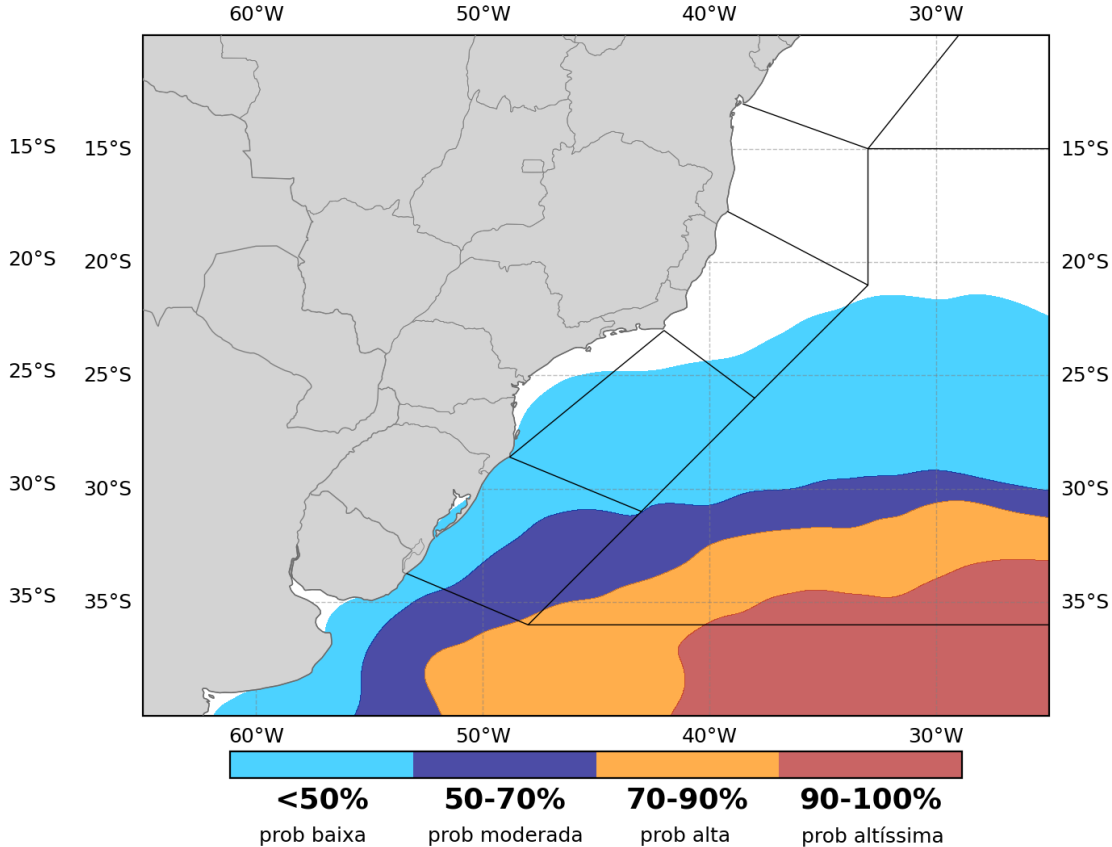


Previsão probabilística – Mapas de probabilidade

Prob Hs>2.5m, Ciclo 20260429 00Z
Semana2, 06/05/2026 – 13/05/2026

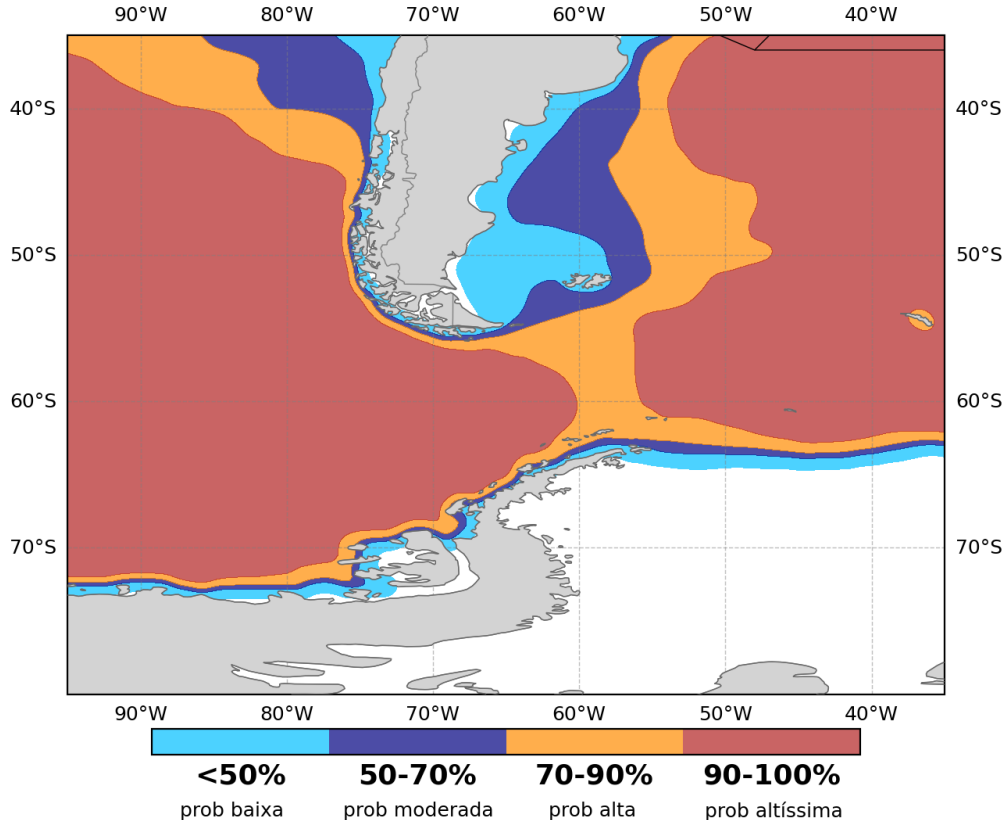


Prob Hs>5.0m, Ciclo 20260429 00Z
Semana2, 06/05/2026 – 13/05/2026

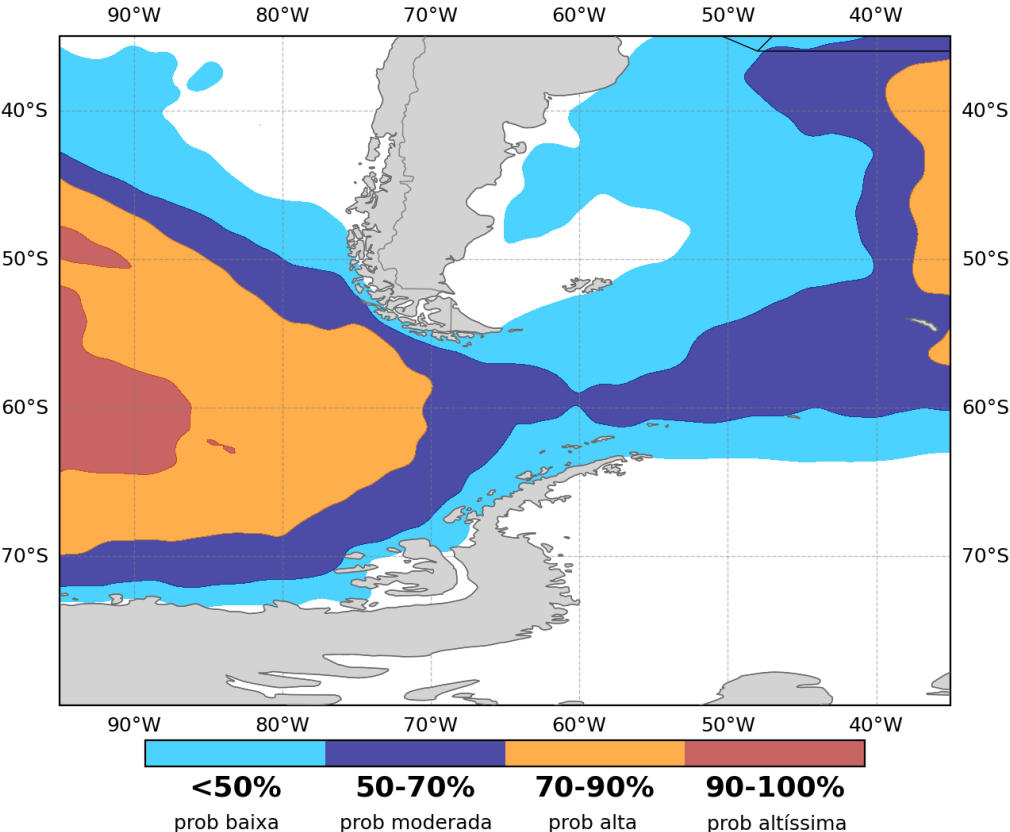


Previsão probabilística – Mapas de probabilidade

Prob Hs>4.0m, Ciclo 20260429 00Z
Semana2, 06/05/2026 – 13/05/2026



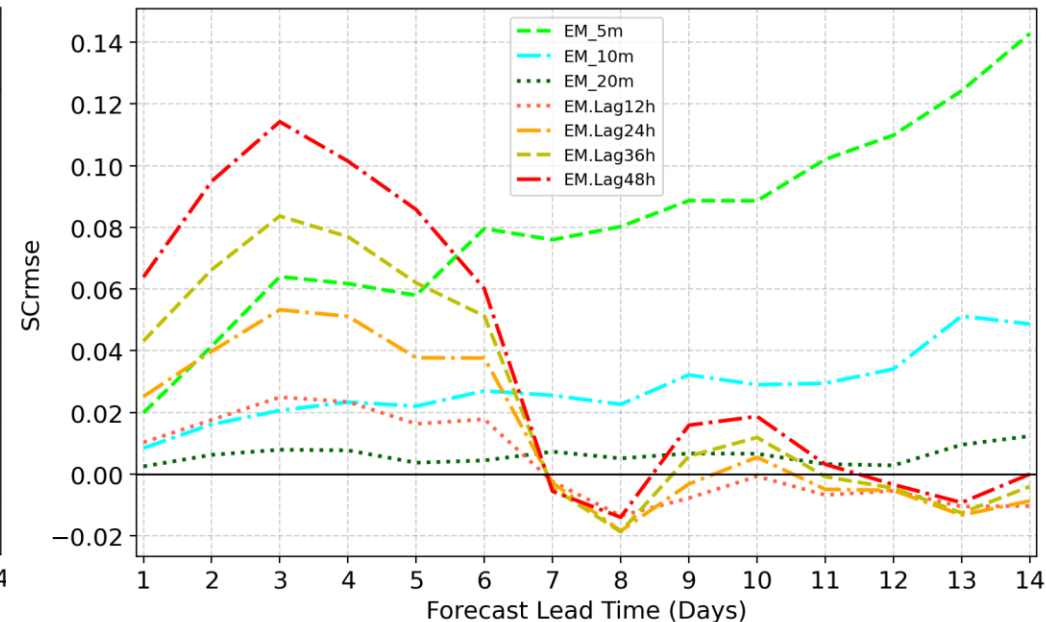
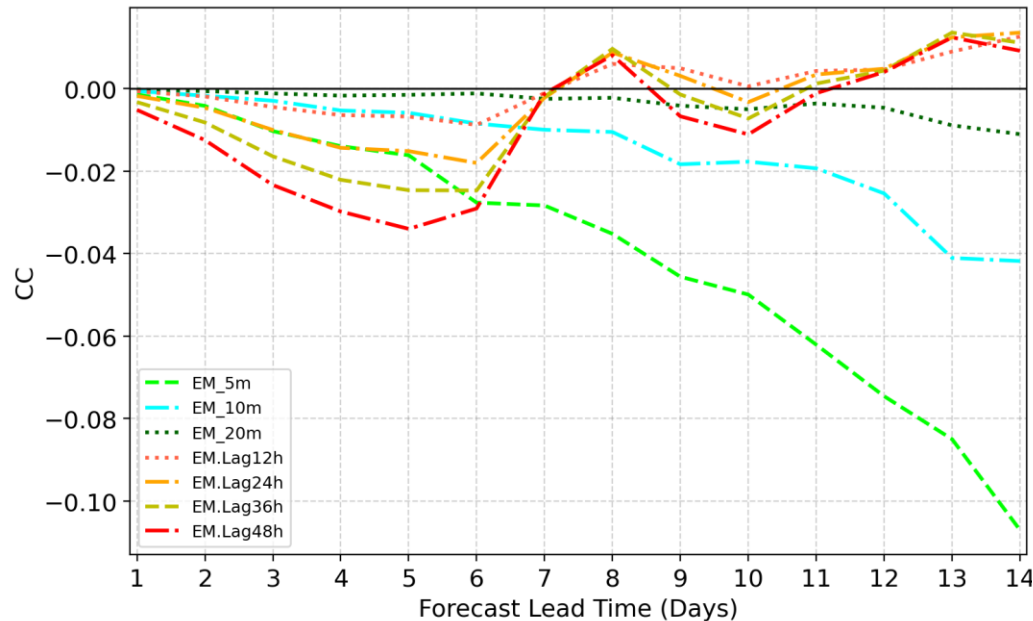
Prob Hs>6.0m, Ciclo 20260429 00Z
Semana2, 06/05/2026 – 13/05/2026



Previsão probabilística

Em andamento e desenvolvimentos futuros

- Ensemble lag
- Multi-model ensemble
- Bias correction e IA no domínio da probabilidade

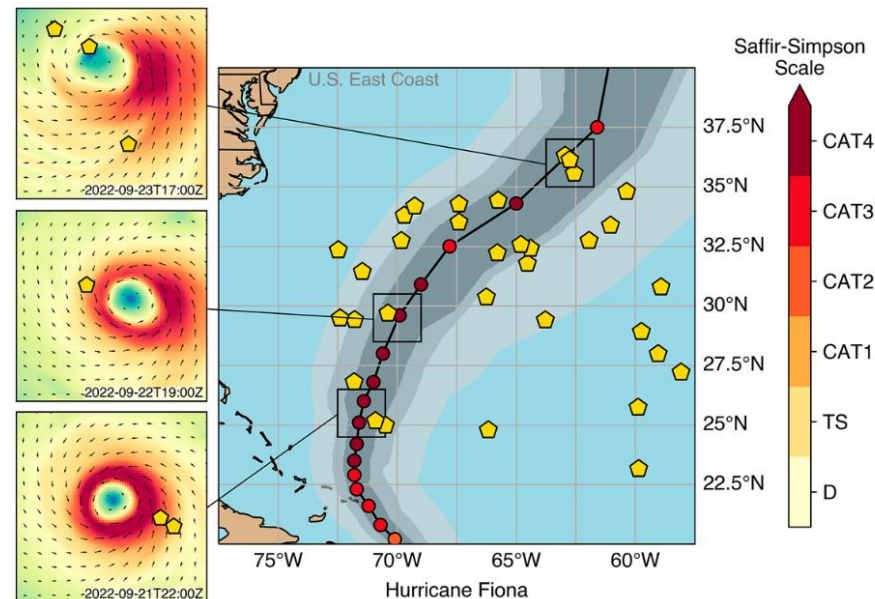
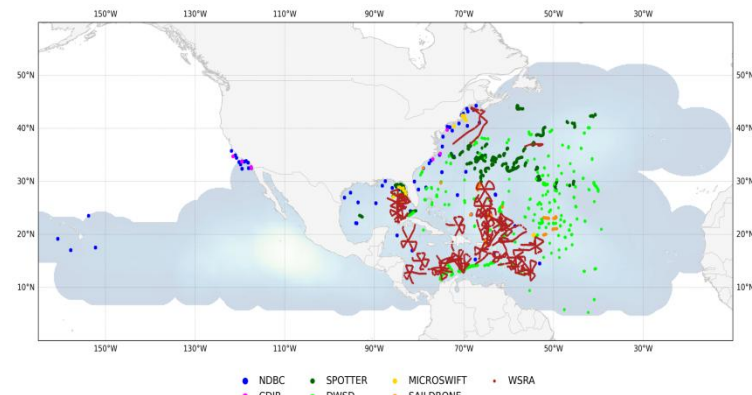
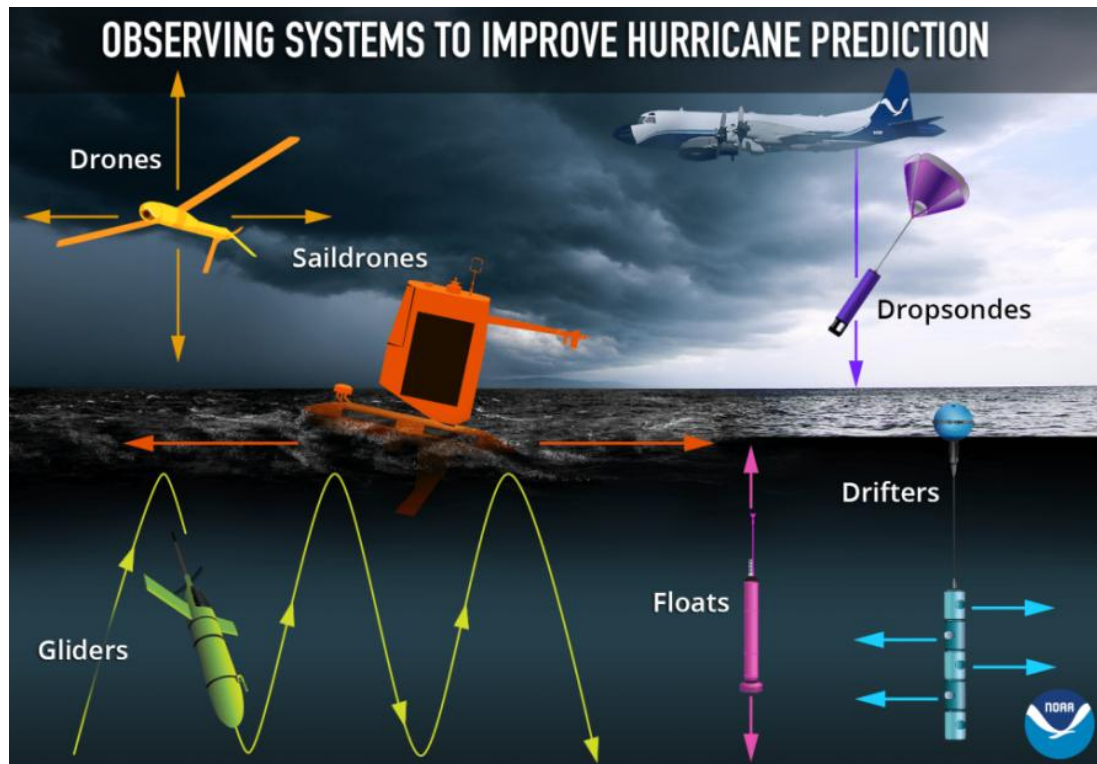


Visão do futuro na melhoria da previsão de ondas

Medições in-situ e por satélite

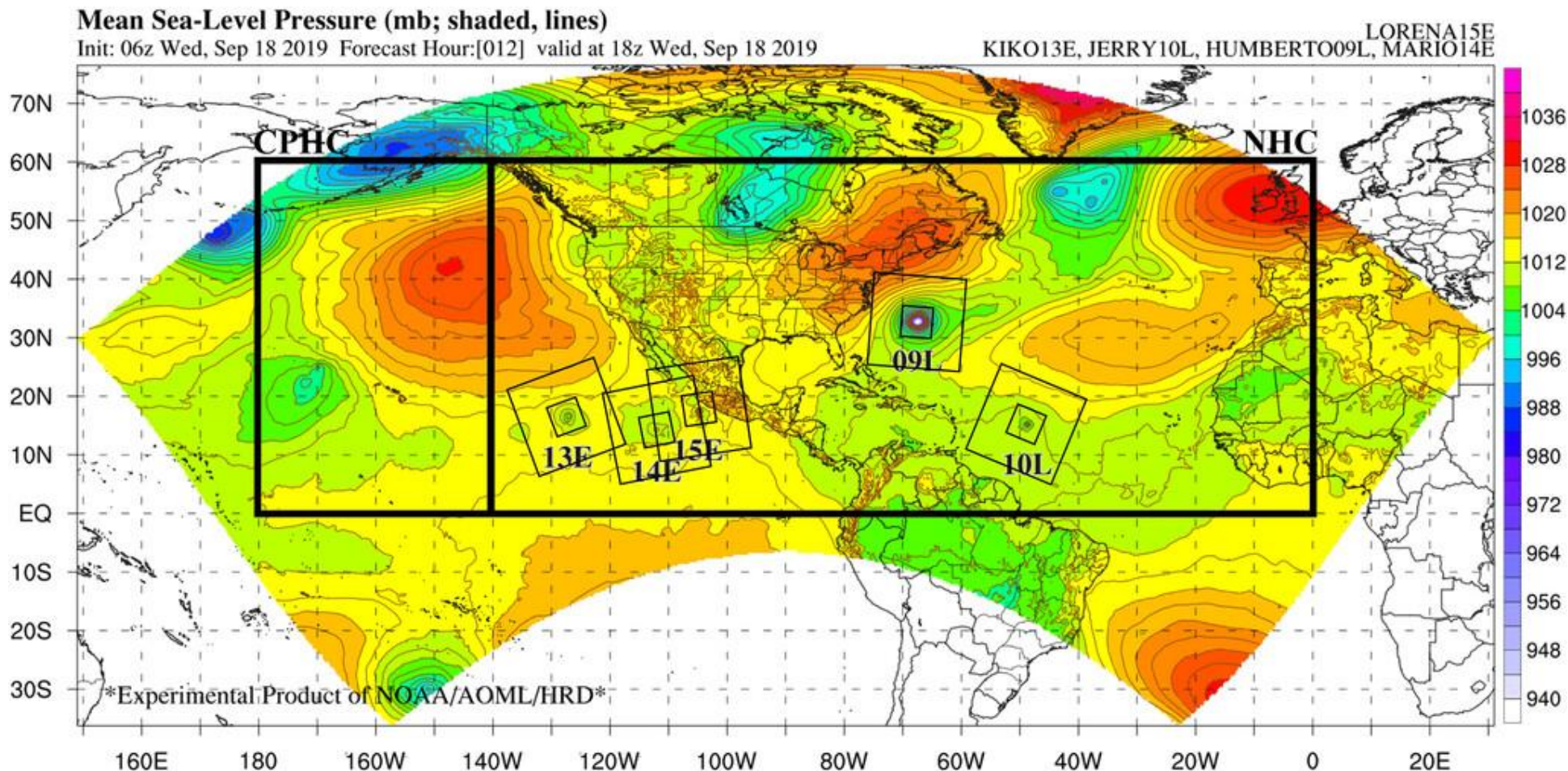
Informação do espectro de ondas em tempo real

Estratégia de coleta de dados em eventos extremos



Visão do futuro na melhoria da previsão de ondas

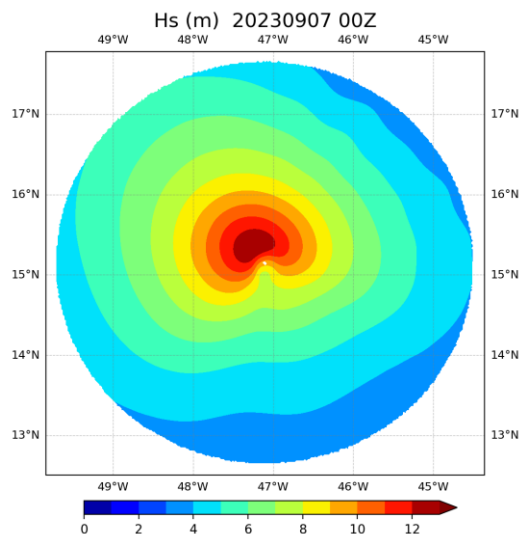
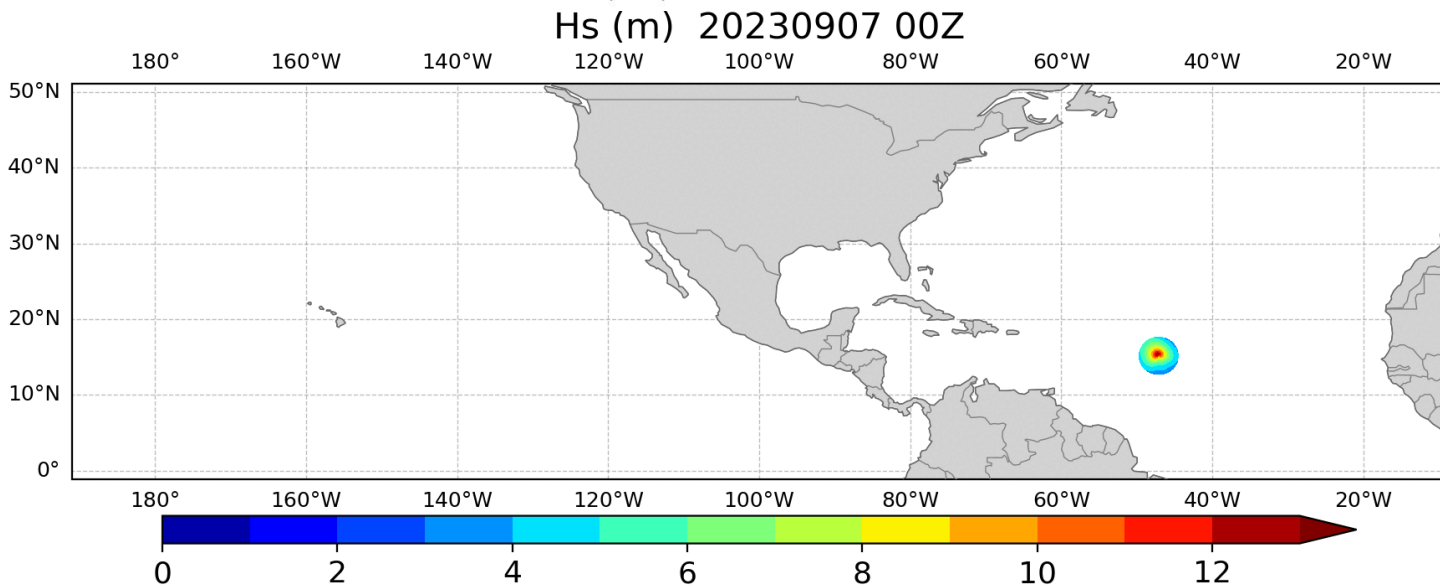
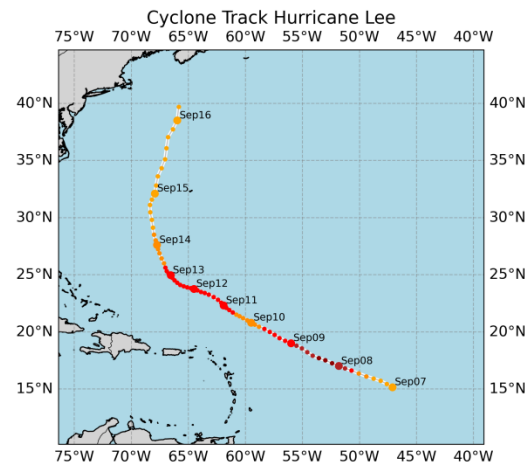
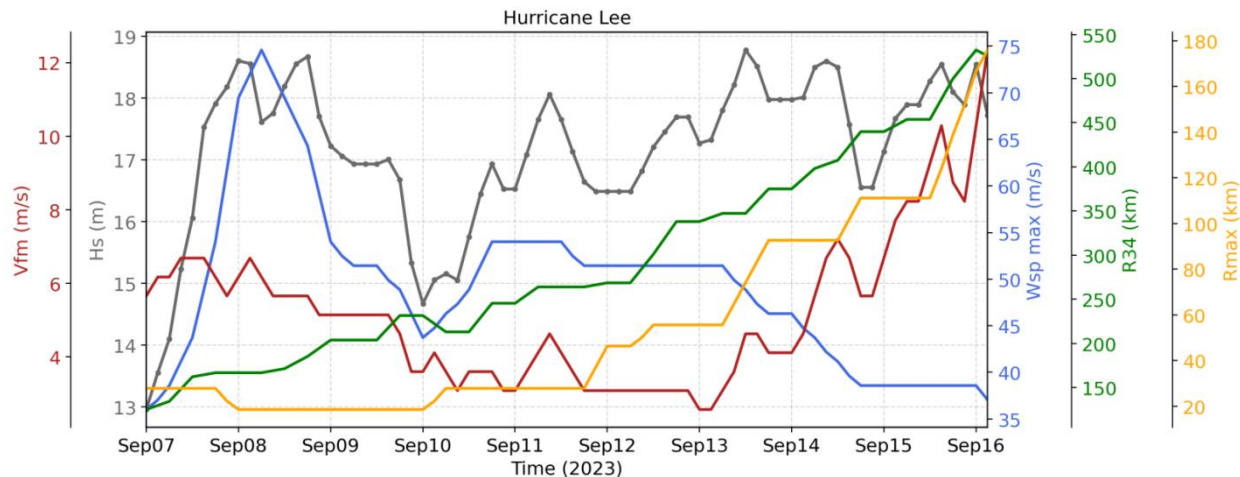
Modelagem para sistemas meteorológicos específicos e relevantes



NOAA Hurricane Analysis and Forecast System (HAFS)

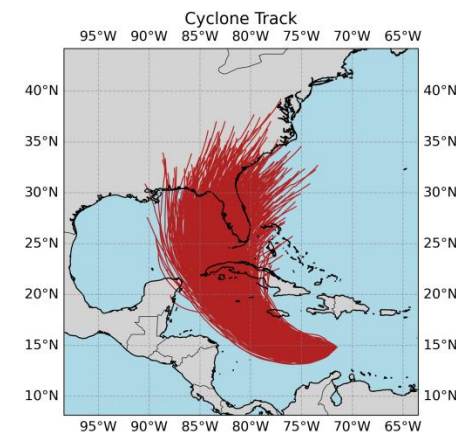
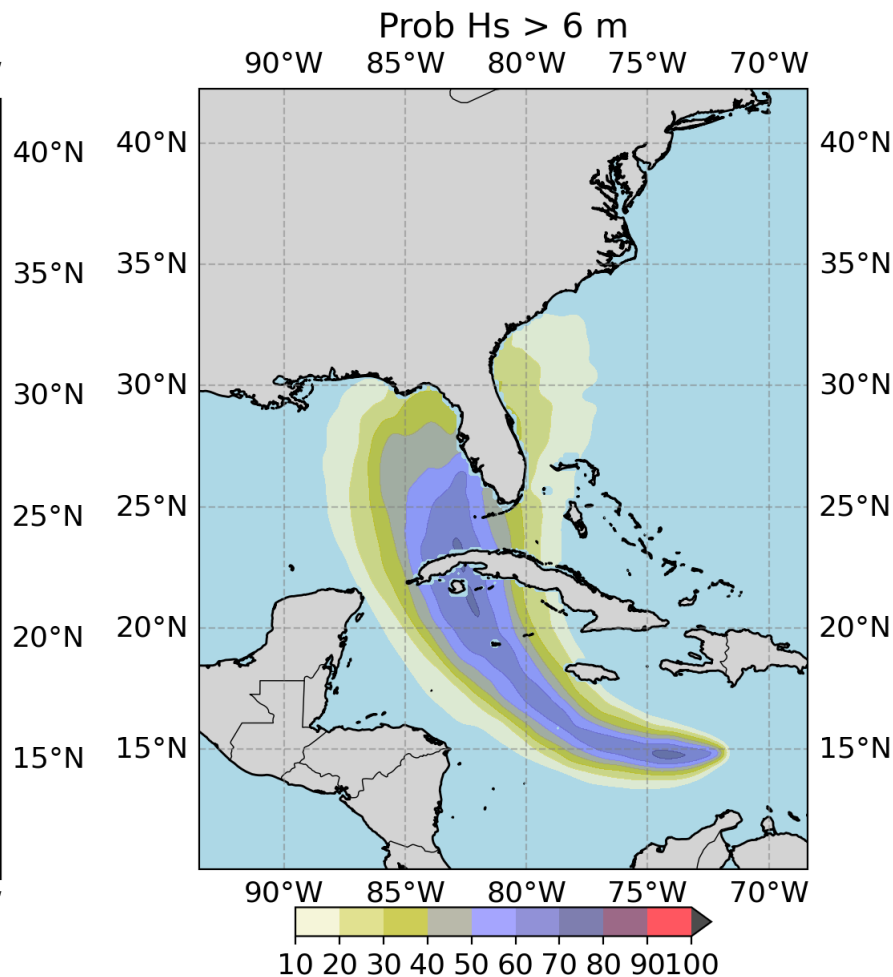
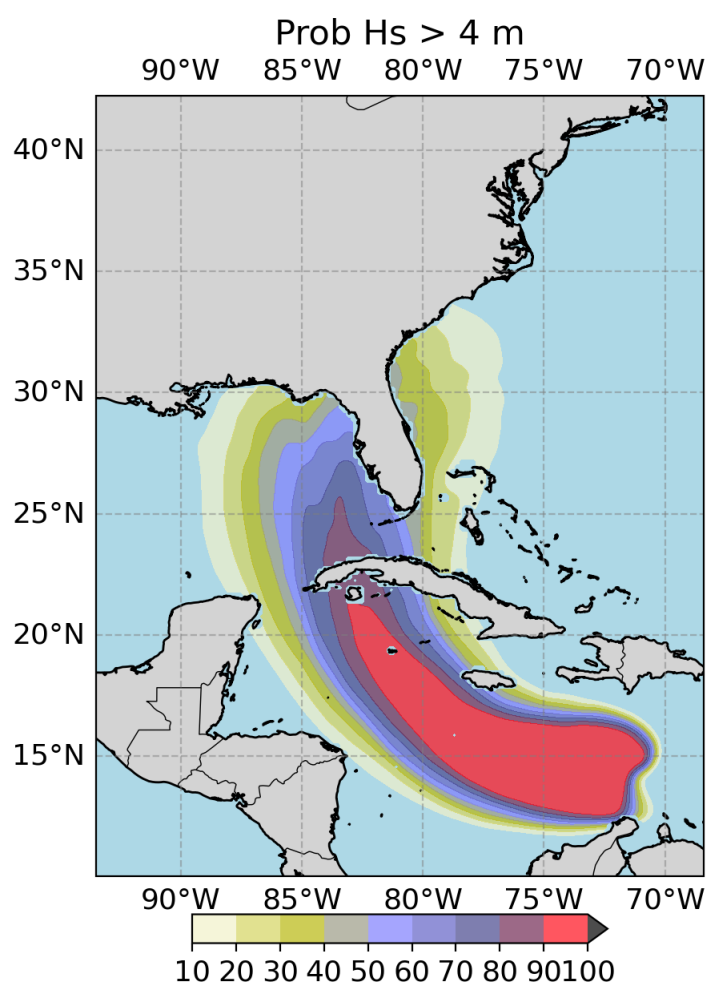
Visão do futuro na melhoria da previsão de ondas

Modelagem para sistemas meteorológicos específicos e relevantes



Visão do futuro na melhoria da previsão de ondas

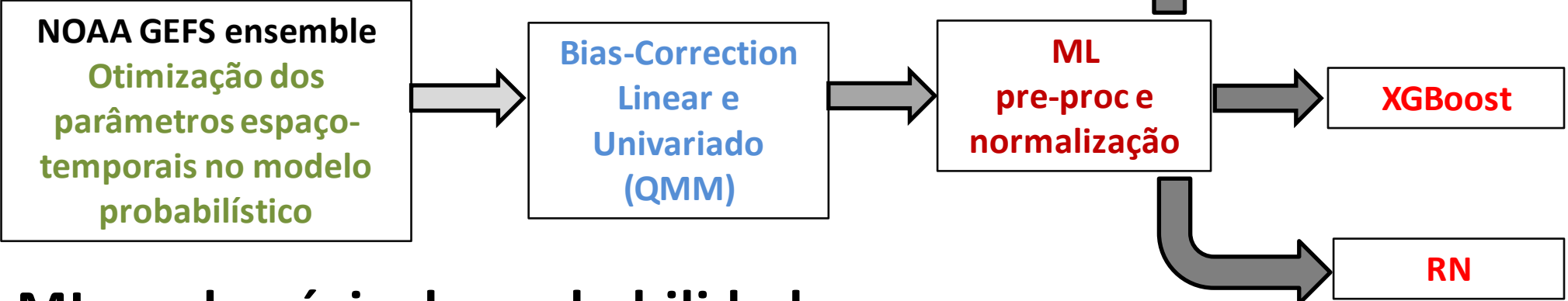
Modelagem para sistemas meteorológicos específicos e relevantes



Furacão Ian (2022)

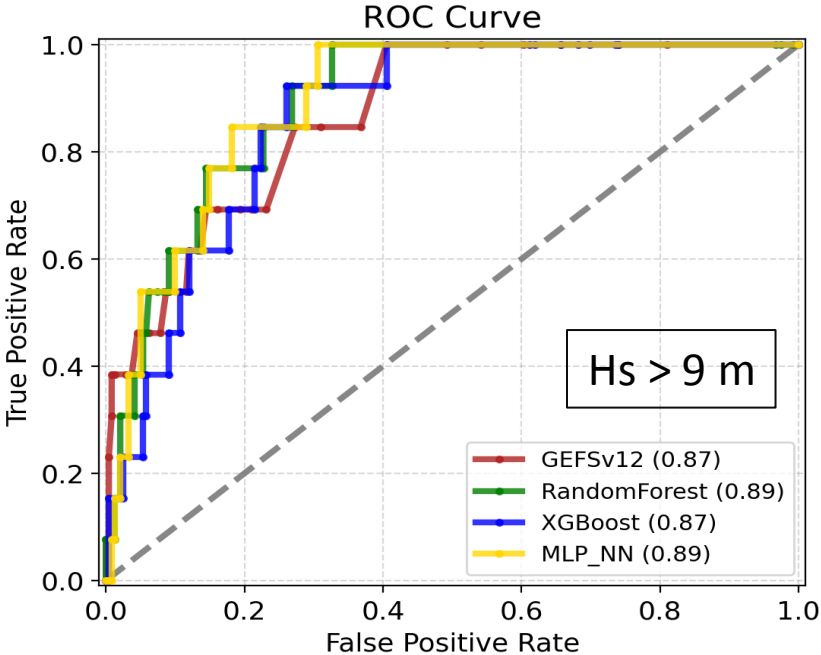
Primeira previsão probabilística de onda para furacão (ainda experimental):

Visão do futuro na melhoria da previsão

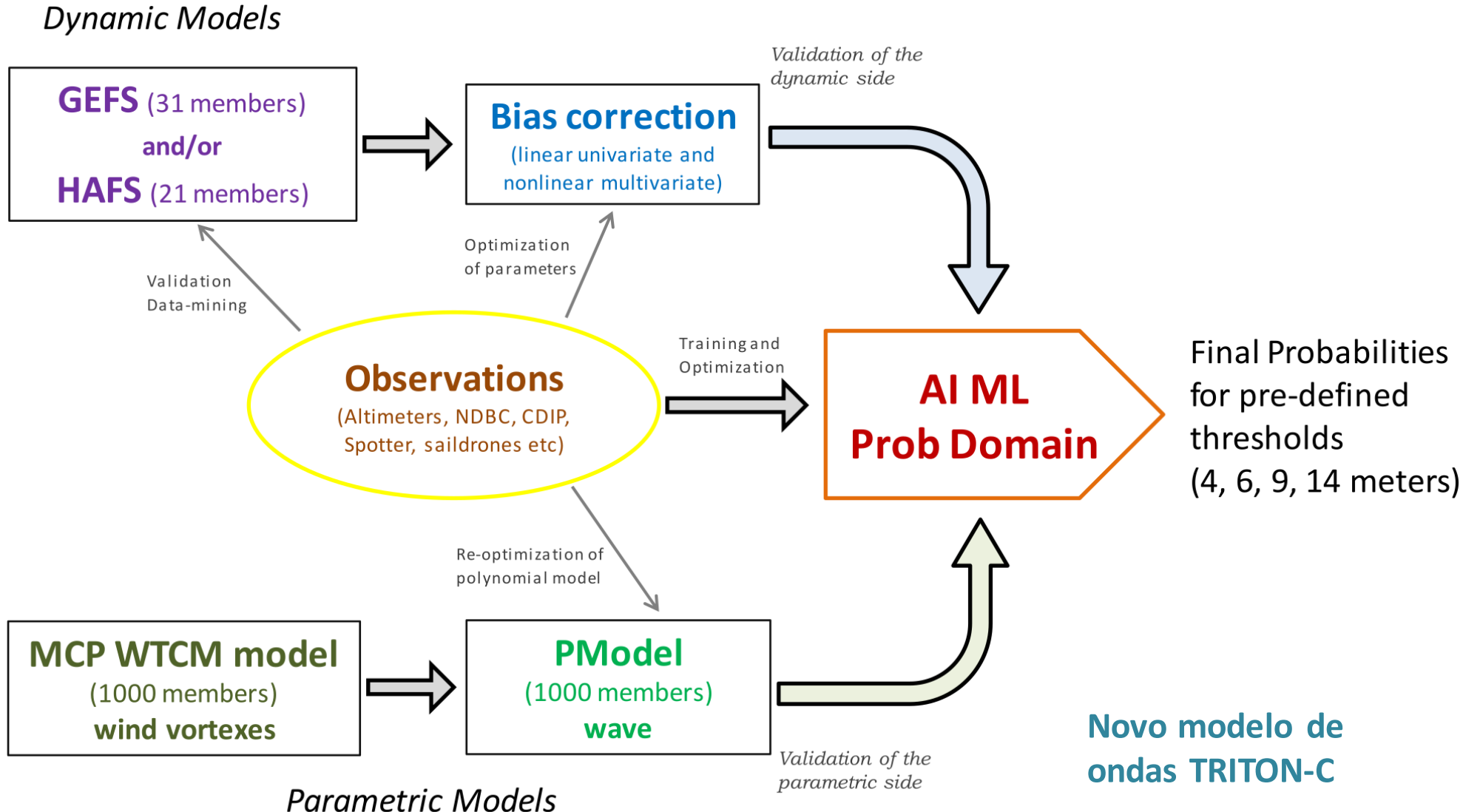


ML no domínio da probabilidade

POD		Hs>4.0	Hs>6.0	Hs>9.0
P>15%	GEFSv12	1.00	0.96	0.64
	GEFSv12 BC(QMM)	1.00	0.98	0.71
P>50%	GEFSv12	0.97	0.69	0.08
	GEFSv12 BC(QMM)	0.98	0.77	0.13
P>65%	GEFSv12	0.92	0.48	0.00
	GEFSv12 BC(QMM)	0.95	0.57	0.02
P>80%	GEFSv12	0.83	0.28	0.00
	GEFSv12 BC(QMM)	0.87	0.35	0.00



Previsão híbrida e ML do domínio da probabilidade



Visão do futuro na melhoria da previsão de ondas

Assimilação de dados de onda e rapid refresh systems:

NOAA High-Resolution Rapid Refresh (HRRR)

<https://rapidrefresh.noaa.gov/hrrr/>

Com o aumento da capacidade computacional e observações:

- Maior frequência de ciclos de assimilação+rodada, HRRR 1 hora.
- Grande melhoria na previsão, principalmente no curto prazo.
- Futuro: 10 min?

Obrigado

ricardo.campos@noaa.gov