

Assessment of Global Wave Products Against Lagrangian Drifting Buoys in the Southern Ocean

Carla S. Leite

caarlaleite9@gmail.com

Universidade Federal de Santa Catarina (UFSC)

Pedro V. Guimarães

Universidade Federal de Santa Catarina (UFSC)

Ricardo M. Campos

National Oceanic and Atmospheric Administration

Luciano Ponzi Pezzi

Instituto Nacional de Pesquisas Espaciais (INPE)

Marcelo Santini

Instituto Nacional de Pesquisas Espaciais (INPE)

Research Article

Keywords: Southern Ocean, Wave modeling, Extreme events, Drifting buoys, WAVEWATCH III, ERA5

Posted Date: September 9th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10744635/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Assessment of Global Wave Products Against Lagrangian Drifting Buoys in the Southern Ocean

Carla S. Leite^{1*}, Pedro V. Guimarães¹, Ricardo M. Campos²,
Luciano Ponzi Pezzi³, Marcelo Santini³

^{1*}Programa de Pós-Graduação em Oceanografia, Universidade Federal de Santa Catarina (UFSC), Florianópolis, Brazil.

²National Oceanic and Atmospheric Administration (NOAA), National Weather Service (NWS), USA.

³Instituto Nacional de Pesquisas Espaciais (INPE), São José dos Campos, Brazil.

*Corresponding author(s). E-mail(s): caarlaleite9@gmail.com;

Abstract

This study evaluates the accuracy of five global wave products (ERA5, GDAS, GFS, IFS, and the LOPS-WW3 hindcast) across the Southern Ocean. The evaluation is based on space-time collocation with in situ data from 50 Spotter Lagrangian drifting buoys deployed around the South Pole. Results reveal systematic discrepancies among modeling architectures. ERA5 and uncoupled forecasts (GFS, GDAS) exhibit negative biases of up to -0.18 m, with underestimation increasing non-linearly during severe storm events from the 95th ($Hs \geq 6.51$ m) to the 99th ($Hs \geq 8.30$ m) percentile. This behavior is physically associated with wind forcing resolution limits under polar lows and aerodynamic drag coefficient saturation under extreme winds. In contrast, the LOPS-WW3 hindcast mitigates wave height underestimation in extreme regimes ($RMSE_{P95} = 0.67$ m; $RMSE_{P99} = 0.77$ m) through its specialized T475 parameterization; however, this configuration overestimates modal conditions (Bias = +0.33 m) and reduces Peak Period (Tp) accuracy ($CC = 0.47$; $RMSE = 2.66$ s). Operational IFS forecast (ECMWF) exhibited the lowest overall error ($RMSE = 0.32$ m; $CC = 0.98$ for Hs) and maintained lower errors in extreme regimes ($RMSE_{P95} = 0.61$ m; $RMSE_{P99} = 0.92$ m) due to its two-way wave-atmosphere coupling, fine spatial grid, and updated dissipation physics. Peak Direction (Dp) was represented with circular correlation above 0.56, indicating that discrepancies stem from wave-growth physics rather

than storm-track representation. These findings provide guidelines for model calibration, Extreme Value Analysis (EVA) for ocean engineering, and maritime navigation safety in Antarctic waters.

Keywords: Southern Ocean, Wave modeling, Extreme events, Drifting buoys, WAVEWATCH III, ERA5

1 Introduction

The Southern Ocean acts as an oceanographic gateway that connects the world’s major basins and regulates global transfers of heat, momentum, and carbon dioxide on a planetary scale (Cai et al., 2023; de Carvalho et al., 2025). The wave climate dynamics across these high-latitude waters (50°S to $\sim 75^\circ\text{S}$) are characterized by high-energy conditions; the complete absence of continental barriers combined with the continuous forcing of the westerly winds (*westerlies*) provides an infinite circum-polar fetch that generates some of the most intense sea states on Earth (Lemos et al., 2023; Salimbeni et al., 2024). This wave energy regime is subject to significant inter-annual variability modulated by large-scale atmospheric modes, such as the Southern Annular Mode (SAM) and the El Niño–Southern Oscillation (ENSO), which control the positioning and intensity of polar storm tracks (Shimura et al., 2026; Meucci et al., 2023). Specifically, positive SAM phases strengthen the meridional pressure gradient between mid-latitudes and Antarctica, shifting westerly winds and storm tracks poleward to directly enhance wave heights in high latitudes (Shimura et al., 2026; Meucci et al., 2023). Conversely, ENSO modulates wave conditions through atmospheric teleconnections, propagating Rossby wave trains from tropical convective anomalies to polar latitudes, which reorganizes regional pressure systems such as the Amundsen Sea Low (Shimura et al., 2026; Meucci et al., 2023). However, due to prohibitive logistical costs and hostile operational conditions, the Antarctic polar seas remain chronically undersampled in terms of continuous *in situ* wave measurements (Sharmar et al., 2021; Bessonova et al., 2025). To address this observational limitation, the present study conducts a multivariate accuracy assessment of five global wave products, proposing a validation framework under both modal and extreme storm conditions. By validating contemporary grid predictions against high-resolution, independent Lagrangian observations, this research aims to characterize systematic numerical biases, quantify predictability degradation, and guide polar navigation safety and future global model calibrations in the Southern Ocean.

To achieve a consistent evaluation, this paper assesses five numerical datasets categorized into three distinct operational architectures: retrospective products (reanalysis and hindcast), operational analysis, and operational forecasts. The retrospective datasets comprise the fifth-generation atmospheric reanalysis (ERA5) (Hersbach et al., 2020) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the specialized global wave hindcast (LOPS-WW3) (Alday et al., 2021) developed by the Laboratoire d’Océanographie Physique et Spatiale (LOPS/IFREMER) with physics tuned for extreme events. Operational analysis is represented

by the National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) (Kleist et al., 2009). Operational forecast systems include NCEP’s Global Forecast System (GFS) (Saha et al., 2010) and ECMWF’s Integrated Forecasting System (IFS) (ECMWF, 2023). While retrospective products (ERA5 and LOPS-WW3) and uncoupled analysis/forecast frameworks (GDAS and GFS) are widely utilized for climate reconstructions and maritime planning, they are prone to systematic energy deficits under severe regimes, which contrast with the dynamic, two-way coupled wave-atmosphere architecture of the operational IFS (ECMWF, 2023; Campos et al., 2020a).

The systematic underestimation of high-energy wave peaks by uncoupled configurations—historically described as the “missing the peaks” phenomenon—is driven by two primary physical limitations (Cavaleri, 2009; Bessonova et al., 2025). First, the spatial grid resolution of global atmospheric models limits the representation of sub-mesoscale pressure gradients within rapidly intensifying polar lows, yielding simulated surface wind forcings that are systematically weaker than observed (Campos et al., 2022b; Sharmar et al., 2021). Second, wave model parameterizations of the aerodynamic drag coefficient (C_d) often reach a saturation limit (*capping*) under high-wind conditions ($U_{10} > 20\text{--}25$ m/s), restricting further wind-to-wave momentum transfer (Elshinnawy et al., 2024). Furthermore, circumpolar waves are modulated by wave-current interactions induced by the Antarctic Circumpolar Current (ACC) (Guimarães et al., 2022). Surface current jet velocities in the ACC, ranging between 0.5 and 1.5 m/s, alter the relative wind speed experienced by waves ($U_{\text{rel}} = U_{10} - U_c$), while current gradients trigger wave refraction and steepening (Ardhuin et al., 2012; Guimarães et al., 2022). In ice-covered waters, wave propagation is further modulated by viscoelastic filtering, floe scattering, and frictional dissipation within the sea-ice Marginal Ice Zone (MIZ) (Voermans et al., 2020; Montiel et al., 2025). Although specialized hindcasts like LOPS-WW3 incorporate surface currents and extreme-wind-calibrated source term physics (T475) to mitigate the wave height deficit, this specific configuration introduces spectral trade-offs that degrade period predictions (Alday et al., 2021; Montiel et al., 2025).

Quantifying these numerical biases requires independent observational benchmarks. To address this, the ATMOS 1.0 and 2.0 projects deployed a network of approximately 50 Spotter Lagrangian drifting buoys in the Southern Ocean (Voermans et al., 2021; Hlophe et al., 2025). Initially launched in the Drake Passage, these sensors operated as Lagrangian drifting platforms, moving southward and eastward into high-latitude polar waters and the Marginal Ice Zone (MIZ) while providing continuous measurements of directional wave spectra. This observational effort yielded a synchronized database of $N = 26,014$ quality-controlled matchups, which serves as the independent *in situ* benchmark for validating simulated wave height, period, and direction (Campos, 2023; Voermans et al., 2021).

Using this observational dataset, we analyze model skill across modal conditions and high-energy regimes stratified by the 95th ($H_s \geq 6.51$ m) and 99th ($H_s \geq 8.30$ m) wave height percentiles (Campos, 2023). We hypothesize that: (1) uncoupled configurations (GFS and GDAS) and reanalyses (ERA5) exhibit non-linear underestimations

of Hs linked to grid-resolution constraints and drag coefficient saturation; (2) coupled systems (IFS) and extreme-tuned hindcasts (LOPS-WW3) partially mitigate this energy deficit, though the latter introduces spectral trade-offs that degrade period accuracy; and (3) all evaluated products systematically underestimate Peak Period (Tp) within ice-covered waters, reflecting physical constraints in wave-ice dissipation parameterizations within the MIZ (Montiel et al., 2025).

2 Data and Methods

2.1 Experimental setup and the ATMOS wave buoy experiments

The study area comprises the Southern Ocean and Antarctic polar waters, delimited between the latitudes of 50°S and approximately 75°S (the practical empirical limit defined by the seasonal sea-ice extent and the Antarctic coastline), as illustrated in Fig. 1. To overcome the persistent scarcity of continuous *in situ* measurements in this remote environment, the observational core of this study relies on a detailed dataset acquired during the ATMOS (Antarctic Modeling and Observation System) 1.0 and 2.0 projects.

During these projects, a network of approximately 50 Spotter (Sofar Ocean Technologies) wave buoys was deployed. These sensors were initially launched in the Drake Passage during the Antarctic Operations (OPERANTAR) campaigns: OP39 (austral summer 2020/2021), OP40 (2021/2022), OP41 (2022/2023), and OP42 (2023/2024 and 2024/2025), aboard the Polar Vessel *Almirante Maximiano* (H-41) or through opportunity launches performed by the Brazilian Navy crew. Following deployment, the buoys operated as Lagrangian drifting sensors, drifting southward and eastward into the sampled high-latitude regions of the Southern Ocean and the Marginal Ice Zone (MIZ) (Voermans et al., 2021; Hlophe et al., 2025).

Operating as water-following platforms, these buoys utilize highly accurate GPS-based (GNSS) displacement receivers to provide high-resolution, half-hourly spectral wave data (Voermans et al., 2021). This extensive Lagrangian dataset serves as the independent *in situ* reference for validating modeled Significant Wave Height (Hs), Peak Period (Tp), and Peak Direction (Dp) under both open-water and ice-covered polar conditions.

2.2 Wave products description

To perform a systematic intercomparison, five open-access global wave products were selected, encompassing different numerical architectures, spatial and temporal resolutions, and physical parameterizations (Campos et al., 2022a). The main technical specifications, including atmospheric forcings, resolutions, and output frequencies, are summarized in Table 1.

- **ERA5 (ECMWF):** The fifth-generation global reanalysis, utilizing the ECWAM model coupled to the IFS (Cycle 41r2) atmospheric system (Hersbach et al., 2020; Copernicus Climate Change Service, 2023). It operates at a global spatial grid of ~ 40 km (0.36°) with 1-hourly temporal outputs. The wave physics are based on the

Oceanographic Buoy Trajectories — Antarctic Region

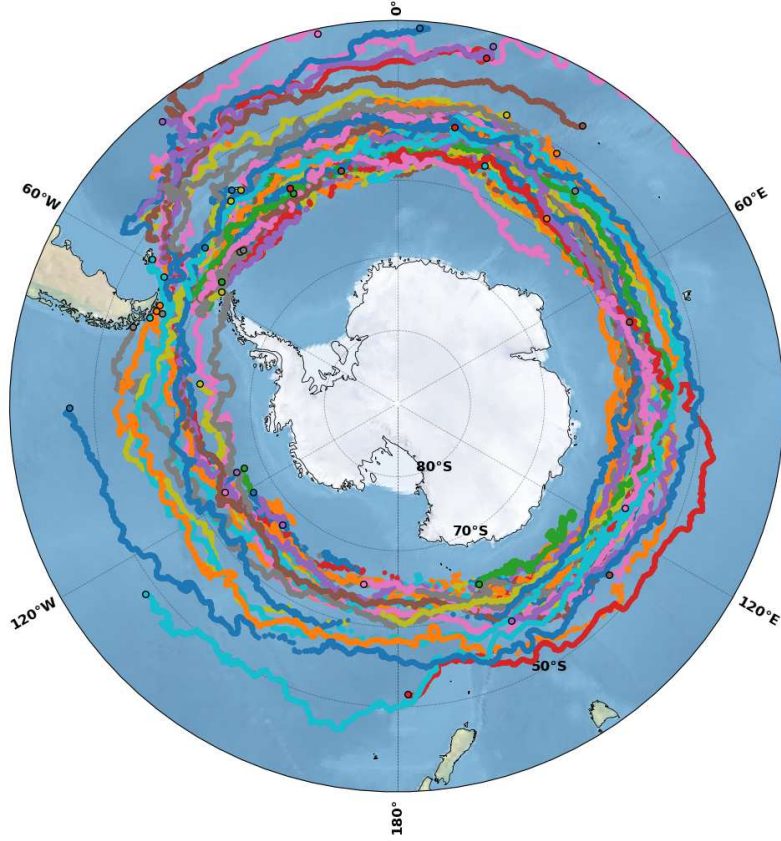


Fig. 1 Study area encompassing the Southern Ocean and Antarctic polar waters projected in a polar stereographic coordinate system. Individual colored lines represent the Lagrangian trajectories of the 50 Spotter drifting buoys deployed during the ATMOS 1.0 and 2.0 projects, serving as the independent *in situ* benchmark for model validation.

formulations of [Janssen \(1991\)](#)), with whitecapping and swell dissipation parameterizations updated by [Bidlot et al. \(2007\)](#); [Bidlot \(2012\)](#). While atmospheric fields assimilate multi-source observations via a 4D-Var scheme, wave data assimilation relies on 2D Optimal Interpolation (OI) of satellite altimetry ([Hersbach et al., 2020](#)). Sea ice is treated using a standard binary threshold mask ([Hersbach et al., 2020](#)).

- **LOPS-WW3 (IFREMER):** A specialized global hindcast based on the WAVEWATCH III (WW3 version 6.07) model ([Alday et al., 2021](#); [The WAVEWATCH III Development Group \(WW3DG\), 2019](#)). Forced by 10-m ERA5 winds, it operates on a 0.5° global spatial grid with 3-hourly outputs. The T475 parameterization applies a non-linear correction to the momentum transfer coefficient for wind speeds exceeding 21 m/s, enhancing the wave growth parameter (β_{max}) to compensate for known negative wind biases in the ERA5 forcing ([Alday et al., 2021](#)). Uniquely, it integrates ocean surface currents (GLOBCURRENT) and advanced mechanical wave

attenuation masks derived from sea-ice concentration and icebergs (ALTIBERG) (Alday et al., 2021).

- **GFS and GDAS (NCEP/NOAA):** The Global Forecast System (GFS) and the Global Data Assimilation System (GDAS) utilize the WW3 model (The WAVE-WATCH III Development Group (WW3DG), 2019) forced by NCEP atmospheric fields on a 0.25° global spatial grid (Kleist et al., 2009; Saha et al., 2010). GDAS provides the initial sea-state analysis through atmospheric data assimilation (note that wave parameters are not directly assimilated into GDAS wave fields), whereas GFS represents the operational real-time forecast (Kleist et al., 2009; Campos et al., 2020b). Both rely on the ST4 parameterization scheme for wind-wave growth and dissipation (Ardhuin et al., 2010; Stopa et al., 2016) and apply a binary sea-ice mask, providing output fields at 3 to 6-hourly intervals.
- **IFS (ECMWF):** The high-resolution operational forecast system (ECMWF, 2023). Operating on a 0.25° global spatial grid, it features a dynamic two-way coupling between the atmosphere and the ECWAM wave model, continuously adjusting the aerodynamic surface roughness (ECMWF, 2023). Modern operational cycles (e.g., CY46R1 and CY48R1) utilize the updated by Ardhuin et al. (2010) parameterizations for whitecapping dissipation (ECMWF, 2023; Ardhuin et al., 2010).

Table 1 Technical specifications, spatiotemporal resolutions, and atmospheric forcings of the evaluated global wave products. Spatial resolutions refer to global grid configurations. Output update cycles indicate file availability; for operational forecasts and analyses, continuous time series were constructed using earliest lead times.

Product	Type	Wave Model	Spatial Grid	Temporal Resolution	Wind Forcing
ERA5	Reanalysis	ECWAM	0.36° (~ 40 km)	1-hourly	IFS (Cy41r2)
LOPS-WW3	Hindcast	WW3	0.50° (~ 55 km)	3-hourly	ERA5 (SSM/I)
GDAS	Analysis	WW3	0.25° (~ 28 km)	6-hourly	GDAS (Data Assim.)
GFS	Forecast	WW3	0.25° (~ 28 km)	6-hourly	GFS (Operational)
IFS	Forecast	ECWAM	0.25° (~ 28 km)	3-hourly	IFS (Operational)

2.3 Data quality control and collocation

Prior to space-time collocation with the numerical grids, an automated Quality Control (QC) protocol was applied to the raw observational data to ensure the reliability of the *in situ* reference dataset (Voermans et al., 2021). Telemetry gaps longer than 3 days were treated as independent time-series segments. Anomalous displacement spikes caused by transient GNSS loss during wave overtopping were removed using physical threshold bounds ($0.25 \leq Hs \leq 20.0$ m; $3.0 \leq Tp \leq 30.0$ s) (Hlophe et al., 2025; Voermans et al., 2021).

To mitigate shallow-water physical processes unresolved by coarse global grids (e.g., shoaling and refraction), a geographical filter utilizing water depth and distance-to-coast fields extracted from the ETOPO 2022 global dataset (MacFerrin et al., 2025; NOAA National Centers for Environmental Information, 2022) discarded measurements recorded at depths shallower than 80 m or closer than 25 km to the coastline (Campos et al., 2022b; Fanti et al., 2023). Finally, a GFS-based land and ice contour mask was applied to guarantee that only open-ocean drifting records were evaluated (The WAVEWATCH III Development Group (WW3DG), 2019).

Following QC, a space-time collocation protocol matched the Eulerian model grids with the Lagrangian buoy trajectories (Campos, 2023). Given the heterogeneity of output frequencies, the temporal resolution was standardized to 3-hourly synoptic intervals. For operational forecasts (GFS, IFS) and the GDAS analysis, continuous time series were constructed by concatenating only the earliest lead times (e.g., f000 to f003) of each operational cycle, preventing lead-time predictability degradation (Campos et al., 2022a). A representative visualization of this dynamic collocation procedure along a single trajectory is illustrated in Fig. 2 for Spotter buoy 30163D under the ERA5 H_s field.

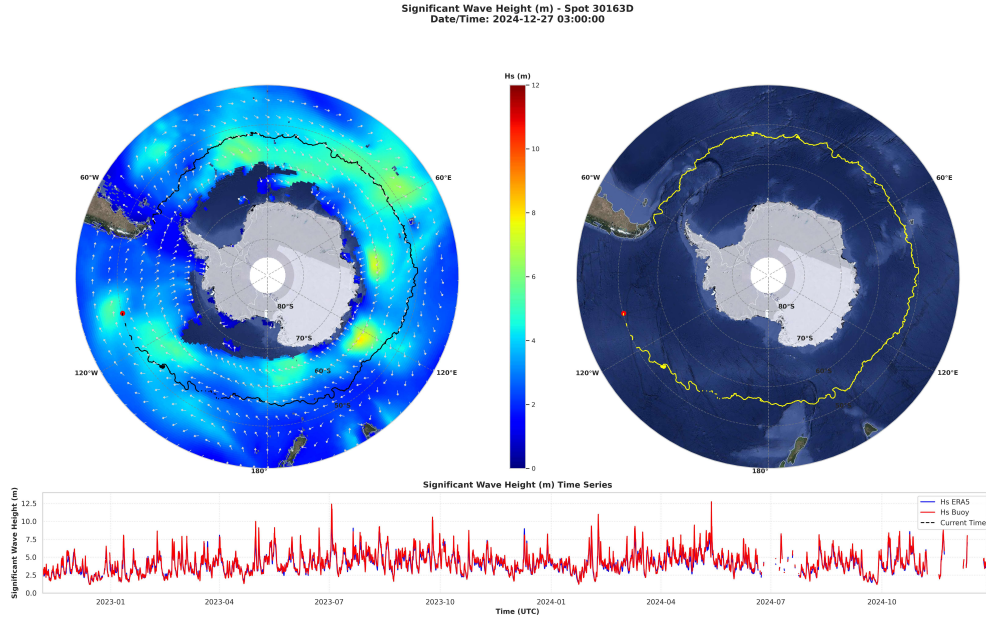


Fig. 2 Representative example of the Lagrangian-Eulerian space-time collocation. The figure displays the final frame of the spatial trajectory for Spotter buoy 30163D drifting across the Southern Ocean, overlaid on the corresponding ERA5 hourly Significant Wave Height (H_s) field. The complete high-resolution MP4 animation is available on YouTube at <https://youtu.be/GpHstOPDWLA>.

Temporal collocation was restricted to a strict ± 30 -minute tolerance window between buoy measurements and model output timestamps (Campos, 2023). For

spatial collocation, bilinear interpolation extracted wave parameters at exact buoy coordinates (Campos, 2023). A nearest-neighbor fallback mechanism was implemented to prevent data loss near coastal boundaries or marginal ice edges where numerical masks might output unmapped (NaN) values (Campos, 2023).

To evaluate model skill across both modal and extreme conditions, statistical assessments were stratified into three regime levels based on empirical buoy distributions: total sample, 95th percentile ($P95\%$), and 99th percentile ($P99\%$). The extreme thresholds derived directly from buoy measurements were set at $Hs \geq 6.51$ m ($P95\%$) and $Hs \geq 8.30$ m ($P99\%$) for wave height, and $Tp \geq 14.63$ s ($P95\%$) and $Tp \geq 17.07$ s ($P99\%$) for period. For multivariate normalized Taylor Diagrams, a strictly synchronized dataset across all five products was established, yielding $N = 26,014$ common co-locations.

2.4 Statistical validation and comparison metrics

Model accuracy was quantified through a standard set of statistical metrics: Mean Absolute Error (MAE), Root Mean Square Error (RMSE), systematic error or Bias, Scatter Index (SI), Pearson Correlation Coefficient (CC or r), and linear Regression Slope (Mentaschi et al., 2013; Fanti et al., 2023; Lemos et al., 2023). Considering S_i as simulated values, O_i as *in situ* drifting buoy observations, N as the total number of collocated data pairs, and $\bar{S}$ and $\bar{O}$ as sample arithmetic means, these metrics are defined as follows:

$$Bias = \frac{1}{N} \sum_{i=1}^N (S_i - O_i) \quad (1)$$

$$MAE = \frac{1}{N} \sum_{i=1}^N |S_i - O_i| \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (S_i - O_i)^2} \quad (3)$$

$$SI = \sqrt{\frac{\sum_{i=1}^N [(S_i - \bar{S}) - (O_i - \bar{O})]^2}{\sum_{i=1}^N O_i^2}} \quad (4)$$

$$CC = \frac{\sum_{i=1}^N (S_i - \bar{S})(O_i - \bar{O})}{\sqrt{\sum_{i=1}^N (S_i - \bar{S})^2 \sum_{i=1}^N (O_i - \bar{O})^2}} \quad (5)$$

$$Slope = \frac{\sum_{i=1}^N (O_i - \bar{O})(S_i - \bar{S})}{\sum_{i=1}^N (O_i - \bar{O})^2} \quad (6)$$

The formulation of SI in Eq. (4) subtracts sample mean errors prior to scatter calculation, acting as a centered/unbiased scatter index as demonstrated by Mentaschi et al. (2013). For Peak Direction (Dp), standard arithmetic was replaced by circular statistics to account for the 360° directional discontinuity, evaluating the shortest angular arc (Fanti et al., 2023; Lemos et al., 2023).

As demonstrated by Mentaschi et al. (2013), relying solely on quadratic error metrics like RMSE can be misleading, as models exhibiting negative biases during severe storms may yield lower quadratic overall values. To address this limitation, quantitative error metrics were complemented with distribution assessment tools, including Kernel Density Estimation (KDE) and Quantile-Quantile (Q-Q) plots, which evaluate skill across extreme upper tails (Cavaleri, 2009). Additionally, normalized Taylor Diagrams synthesized the Correlation Coefficient, Centered RMSE (RMSEc), and Standard Deviation (σ) into a single 2D space to evaluate model variance representation across parameters (Bessonova et al., 2025; Salimbeni et al., 2024).

3 Results and Discussion

3.1 Overall evaluation of significant wave height (H_s)

The statistical evaluation of the global wave products revealed distinct behaviors in their ability to represent the Southern Ocean wave climate. As summarized in Table 2 and illustrated by the scatter density plots in Fig. 3, the performance is closely linked to the underlying modeling architectures.

Table 2 Statistical performance metrics for Significant Wave Height (H_s) across total sample, 95th percentile ($P_{95\%} \geq 6.51$ m), and 99th percentile ($P_{99\%} \geq 8.30$ m) regimes.

Product	RMSE (m)			CC			Bias (m)	SI	Slope
	Total	$> P_{95\%}$	$> P_{99\%}$	Total	$> P_{95\%}$	$> P_{99\%}$			
IFS	0.32	0.61	0.92	0.98	0.86	0.79	+0.07	0.08	0.94
GFS	0.65	1.28	1.60	0.91	0.62	0.53	-0.17	0.17	0.92
GDAS	0.65	1.28	1.61	0.91	0.63	0.54	-0.18	0.17	0.92
ERA5	0.41	0.86	1.14	0.97	0.85	0.79	-0.14	0.11	0.88
LOPS-WW3	0.54	0.67	0.77	0.96	0.83	0.78	+0.33	0.14	0.97

Operational Forecasts (IFS vs. GFS): When comparing the real-time operational models, the IFS (ECMWF) demonstrated superior performance over the GFS (NCEP/NOAA). The IFS registered the lowest absolute error among all evaluated products (RMSE = 0.32 m), the highest linear correlation (CC = 0.98), and a minor positive bias of +0.07 m (Fig. 3a). In contrast, the uncoupled GFS forecast (Fig. 3b) presented a pronounced negative bias (−0.17 m) and nearly doubled the quadratic errors (RMSE = 0.62 m), indicating a notable limitation in sustaining wave energy during storm developments.

Hindcast and Analysis Products (GDAS vs. ERA5 vs. LOPS-WW3): Among the retrospective and analysis datasets, distinct physical behaviors emerge. The GDAS operational analysis (Fig. 3c) exhibited high scatter indices (SI = 0.17) and a pronounced systematic underestimation (Bias = −0.18 m), sharing the structural energy deficit seen in the GFS. The ERA5 reanalysis (Fig. 3d), while showing excellent phase correlation (CC = 0.97) and low scatter (SI = 0.11), exhibited a systematic

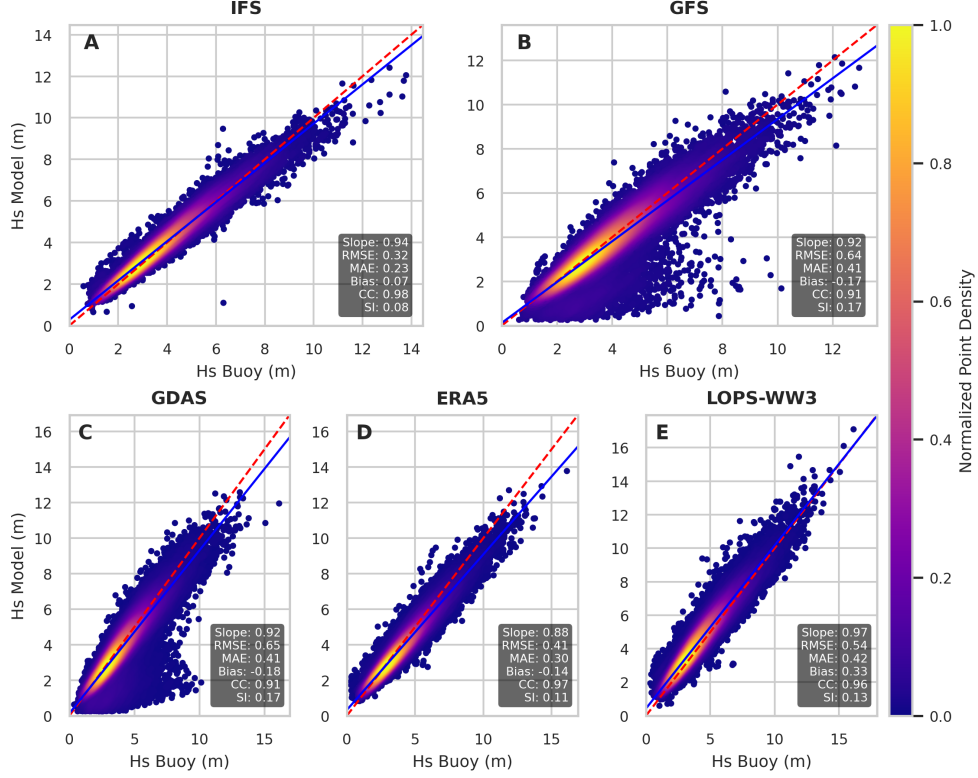


Fig. 3 Bivariate scatter density plots of Significant Wave Height (H_s , in meters) comparing *in situ* buoy observations with the evaluated global products: (a) IFS, (b) GFS, (c) GDAS, (d) ERA5, and (e) LOPS-WW3.

negative bias (-0.14 m). This corroborates recent global evaluations indicating its tendency to underestimate severe wave magnitudes (Sharma et al., 2021; Wang and Wang, 2022).

Furthermore, wave generation and growth in these high southern latitudes are continuously modulated by background ocean circulation, particularly the Antarctic Circumpolar Current (ACC). The ACC core features surface velocities typically ranging from 0.5 to 1.5 m/s. In a co-flowing wind-current regime, the surface current velocity ($\vec{U}_{\text{current}}$) reduces the relative wind speed experienced by developing short waves, defined as $\vec{U}_{\text{rel}} = \vec{U}_{10} - \vec{U}_{\text{current}}$, effectively dampening wind-sea energy transfer (Ardhuin et al., 2012). As demonstrated by Ardhuin et al. (2012) and Ardhuin et al. (2017), omitting surface current forcing in wave modeling alters relative wind forcing and wave refraction gradients. In this evaluation, current forcing represents a key controlled variable: while LOPS-WW3 explicitly incorporates surface current fields via GLOBCURRENT assimilation (Alday et al., 2021), and IFS/ERA5 include currents through the coupled ocean-atmosphere IFS framework, the NCEP products

(GDAS and GFS) lack dynamic surface current inputs. Despite this relative wind damping effect, the LOPS-WW3 hindcast (Fig. 3e) displayed a marked overestimation of mean modal conditions (Bias = +0.33 m). This behavior occurs because the non-linear multiplier in its T475 source-term package significantly boosts wind energy input under strong winds to overcome ERA5 atmospheric deficits, overriding relative wind damping across moderate sea states (Alday et al., 2021).

The favorable skill exhibited by the IFS model can be attributed to its integrated configuration, which combines a dynamic two-way atmospheric-wave coupling architecture, high spatial resolution ($\sim 0.25^\circ$), and updated saturation-based whitecapping dissipation physics (Ardhuin et al., 2010; ECMWF, 2023). In this coupled framework, the evolving sea state continuously modulates atmospheric boundary layer roughness (Charnock parameter) in real-time. However, disentangling the isolated contribution of two-way wave-atmosphere coupling from higher spatial resolution and updated dissipation physics would require controlled numerical experiments holding resolution and physics constant (Janssen, 1991).

3.2 Representation of peak period (T_p) and peak direction (D_p)

Predicting the Peak Period (T_p) remains a challenge for global spectral models (Fig. 4). Consistent with recent evaluations (Salimbeni et al., 2024), correlation coefficients for T_p across all products were systematically lower than those found for H_s , with all models exhibiting a persistent tendency to underestimate the wave period.

Table 3 Statistical performance metrics for Peak Period (T_p , in seconds) across total sample, $P_{95\%} \geq 14.63$ s, and $P_{99\%} \geq 17.07$ s regimes.

Product	RMSE (s)			CC			Bias (s)	SI	Slope
	Total	$> P_{95\%}$	$> P_{99\%}$	Total	$> P_{95\%}$	$> P_{99\%}$			
IFS	1.24	1.66	2.60	0.81	0.39	-0.05	-0.10	0.11	0.75
GFS	1.73	2.04	3.25	0.65	0.27	-0.05	-0.06	0.16	0.67
GDAS	1.74	2.03	3.22	0.65	0.28	-0.06	-0.06	0.16	0.67
ERA5	1.34	2.10	3.67	0.78	0.22	-0.32	-0.28	0.12	0.71
LOPS-WW3	2.66	4.59	7.04	0.47	-0.02	-0.12	-1.10	0.24	0.57

Operational Forecasts (IFS vs. GFS): The IFS model achieved higher period skill (RMSE = 1.24 s; CC = 0.81; Bias = -0.10 s) compared to other operational products (Fig. 4a). The uncoupled GFS (Fig. 4b) exhibited reduced skill in capturing long, mature swell arrivals, resulting in larger error scatter (RMSE = 1.73 s; CC = 0.65).

Retrospective and Analysis Products (GDAS vs. ERA5 vs. LOPS-WW3): Among retrospective products, ERA5 presented the highest phase correlation (CC = 0.78), despite a negative bias (-0.28 s) (Fig. 4d). GDAS analysis (Fig. 4c)

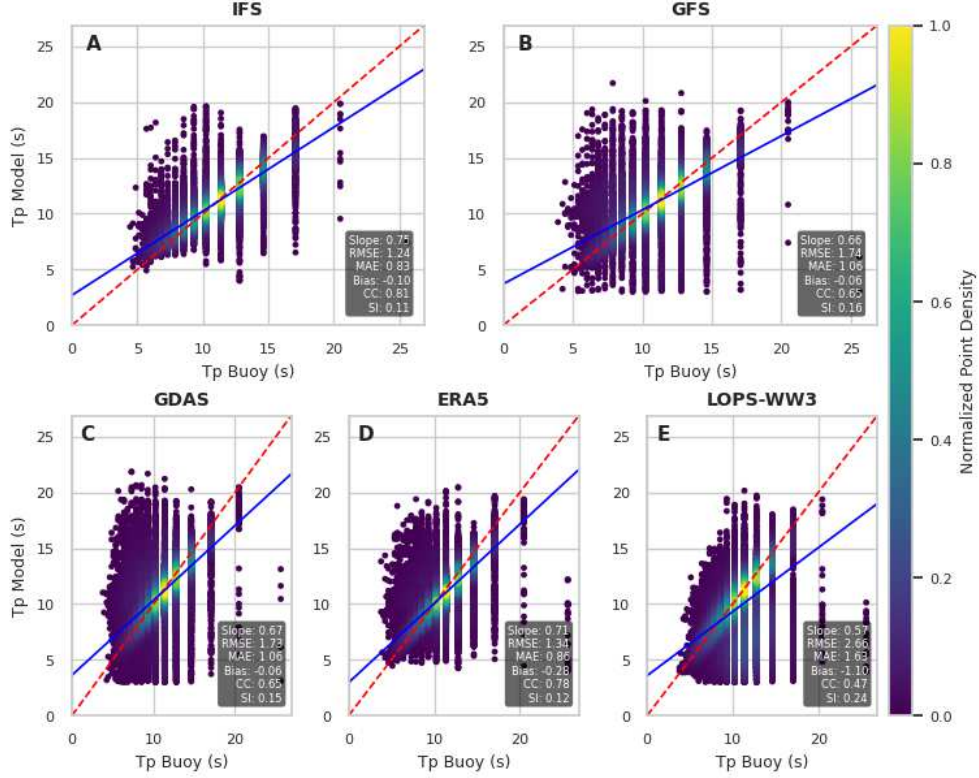


Fig. 4 Bivariate scatter density plots of Peak Period (T_p , in seconds) comparing *in situ* buoy observations with global products: (a) IFS, (b) GFS, (c) GDAS, (d) ERA5, and (e) LOPS-WW3.

propagated larger scatter. Notably, the LOPS-WW3 hindcast (Fig. 4e), despite mitigating extreme H_s underestimation, yielded lower period accuracy ($CC = 0.47$; $RMSE = 2.66$ s; $Bias = -1.10$ s).

This degradation in peak period accuracy within LOPS-WW3 represents a direct consequence of the T475 source-term design (Alday et al., 2021). By enhancing momentum transfer under strong wind forcing, T475 shifts spectral energy density toward higher frequencies, resulting in shorter simulated wave periods compared to the low-frequency swells observed *in situ*.

Regarding Peak Direction (D_p), as illustrated by the KDE distributions in Fig. 5, all products demonstrated consistent performance (Salimbeni et al., 2024). The IFS and LOPS-WW3 achieved circular correlation coefficients of $CC = 0.62$ and $CC = 0.64$, respectively (Table 4). Absolute angular errors (RMSE between 25.3° and 32.2°) fall within the expected range for high-latitude directional variability, indicating that major meteorological centers accurately resolve the synoptic-scale kinematics of polar frontal systems and storm tracks.

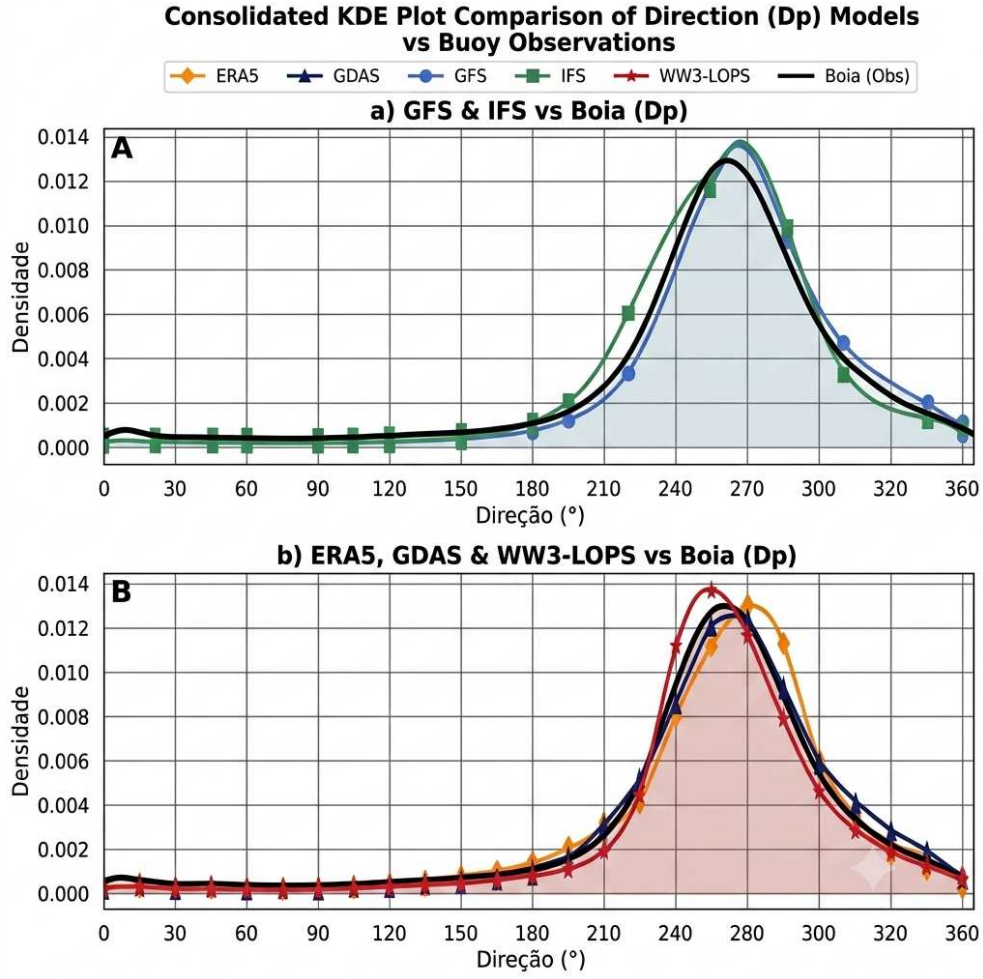


Fig. 5 Evaluation of Peak Direction (D_p , in degrees) comparing *in situ* buoy observations with evaluated global products, including Kernel Density Estimation (KDE).

Table 4 Circular statistical metrics for Peak Direction (D_p , in degrees) conditioned upon H_s energy regimes ($P_{95\%} \geq 6.51$ m and $P_{99\%} \geq 8.30$ m).

Product	RMSE (°)			CC			Bias (°)
	Total	$> P_{95\%}$	$> P_{99\%}$	Total	$> P_{95\%}$	$> P_{99\%}$	
IFS	25.3	10.0	7.0	0.62	0.94	0.95	+3.8
GFS	32.1	12.7	9.4	0.56	0.75	0.80	+3.2
GDAS	32.2	12.6	9.4	0.56	0.74	0.73	+3.1
ERA5	26.3	10.8	8.4	0.65	0.85	0.86	+3.8
LOPS-WW3	28.8	8.5	5.8	0.64	0.91	0.92	-2.5

3.3 Performance in extreme events and the “missing the peaks” problem

Evaluating the upper tail of the distribution ($H_s \geq P_{95\%} \geq 6.51$ m) using Probability Density Functions (PDF) and Quantile-Quantile (Q-Q) plots (Fig. 6) highlights a documented limitation in spectral wave modeling: the “missing the peaks” phenomenon (Cavaleri, 2009).

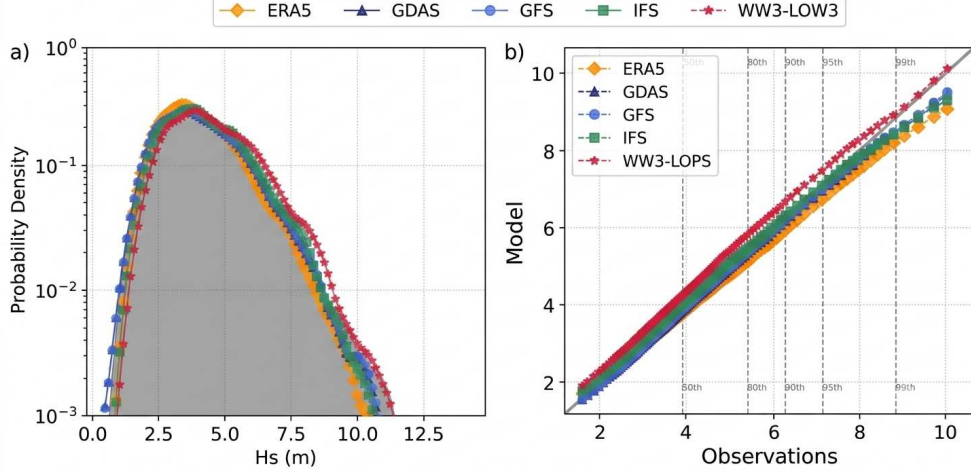


Fig. 6 Probability Density Functions (PDF) and Quantile-Quantile (Q-Q) plots for Significant Wave Height (H_s , in meters), highlighting model behavior in extreme upper percentiles.

As extratropical cyclones deepen and wave heights exceed 6.51 m, quantile curves for ERA5, GDAS, and GFS deviate below the 1:1 reference line. This underestimation is physically rooted in two primary mechanisms:

1. **Atmospheric forcing resolution:** Coarse spatial grids in global atmospheric models smooth sub-mesoscale pressure gradients within rapidly intensifying polar cyclones, yielding negative surface wind biases for wind speeds exceeding 20 m/s (Campos et al., 2022b; Sharmar et al., 2021).
2. **Aerodynamic drag saturation:** Spectral wave growth depends non-linearly on friction velocity (u_*). Atmospheric and wave models apply a capping threshold to the drag coefficient (C_d) under strong winds ($U_{10} > 20$ –25 m/s) (Elshinnawy et al., 2024). In ST4 and ECWAM parameterizations, this C_d saturation limits additional momentum transfer, compounding atmospheric wind deficits during severe storms.

In contrast, LOPS-WW3 maintains growth rates across extreme quantiles ($RMSE_{P95} = 0.8$ m) due to its T475 package, which applies a non-linear multiplier to momentum transfer above 21 m/s (Alday et al., 2021).

These behaviors are synthesized in the normalized Taylor Diagram (Fig. 7), constructed from $N = 26,014$ synchronized observation-model pairs. Models affected by

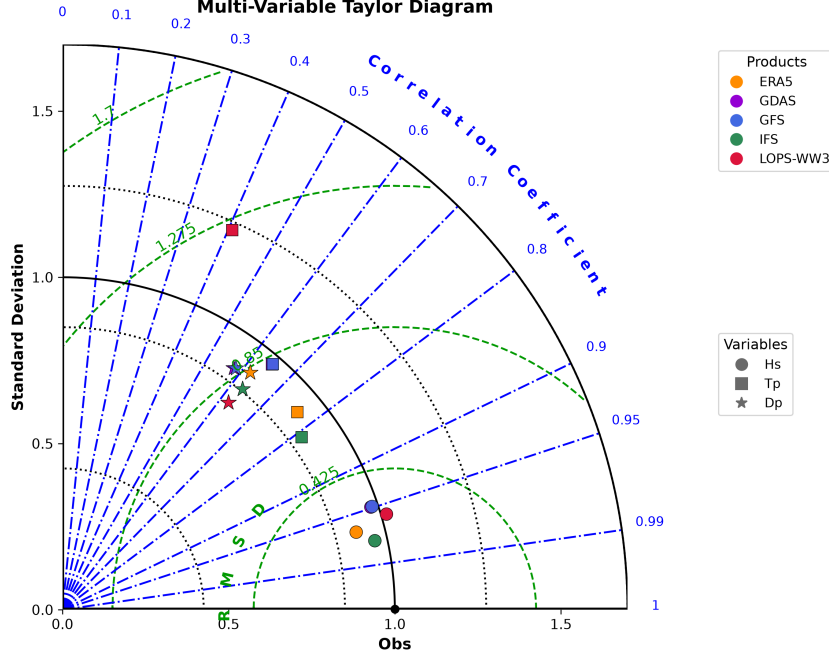


Fig. 7 Normalized Taylor Diagram synthesizing multivariate performance (Correlation Coefficient, Centered RMSE, and Standard Deviation) across a synchronized dataset ($N = 26,014$).

peak underestimation (ERA5, GDAS, GFS) exhibit normalized standard deviations lower than 1.0 due to storm-peak smoothing. Conversely, LOPS-WW3 exhibits inflated variance ($\sigma > 1.0$) driven by modal overestimation. The coupled IFS forecast displays balanced variance representation ($\sigma \approx 1.0$) alongside low centered quadratic error.

3.4 Practical implications and limitations

The diagnostic assessments presented above carry relevant implications for oceanographic modeling and engineering applications. For operational nowcasting, Antarctic logistical planning, and short-term navigation safety, the operational IFS forecast demonstrates distinct performance advantages, owing to its dynamic two-way wave-atmosphere coupling and updated whitecapping dissipation physics, which maintain a balanced representation of both modal and high-energy sea states.

Conversely, for applications such as Extreme Value Analysis (EVA), offshore structure design, and long-term climate risk assessments, the direct uncorrected use of atmospheric reanalyses (ERA5) or uncoupled forecasts (GFS and GDAS) warrants careful consideration. In energetic regimes ($Hs \geq 6.51$ m; $P95$), ERA5 underestimation increases non-linearly, with $RMSE$ elevating from 0.40 m in the total sample to 0.86 m at $P95$ and 1.14 m at $P99$. Utilizing uncalibrated reanalyses in EVA without addressing this upper-tail energy deficit may yield non-conservative design wave parameters. In such scenarios, implementing statistical post-processing

techniques—such as the Quantile Mapping Method applied to severe wind fields (Campos et al., 2022b)—or employing extreme-oriented hindcasts (such as LOPS-WW3) provides an effective pathway to recover missing extreme wave energy.

These findings from the Southern Ocean—a quintessential high-energy, unlimited-fetch basin—offer valuable insights for other storm-dominated regions globally, such as the North Atlantic and North Pacific. However, regional extrapolations must account for local dynamics, including coastal bathymetric transformations and sea-ice interactions in polar Marginal Ice Zones (MIZ).

Finally, methodological limitations of the present framework must be acknowledged:

1. **Grid resolution and drag physics:** While global model resolutions (0.25° to 0.50°) smooth sub-mesoscale pressure gradients in deep cyclones, extreme wave underestimation is also intrinsically constrained by the physical saturation (capping) of the surface drag coefficient (C_d) under high wind speeds.
2. **Lagrangian buoy dynamics:** The continuous mobility of drifting Spotter buoys means sensors sample spatially heterogeneous wave and bathymetric fields over time, rather than fixed Eulerian points. Consequently, these Lagrangian records represent space-time trajectory tracks rather than stationary univariate time series.

4 Conclusions and Recommendations

The systematic evaluation of five global wave products (ERA5, GDAS, GFS, IFS, and the LOPS-WW3 hindcast) against Quality-Controlled Spotter drifting buoy measurements in the Southern Ocean highlights important distinctions in contemporary wave modeling. By applying the spatial and temporal collocation criteria proposed by Campos (2023), interpolation-related noise was minimized, allowing metrics such as the Scatter Index (SI) and the centered $RMSE$ to reflect the physical discrepancies of the models rather than collocation artifacts (Campos et al., 2020b; Campos, 2023). Furthermore, stratifying the validation into modal, 95th percentile ($P95 \geq 6.51$ m for H_s), and 99th percentile ($P99 \geq 8.30$ m for H_s) regimes provided a clear diagnosis of model predictability degradation during high-energy events.

Based on these findings, the following conclusions and practical recommendations are presented to guide users in selecting the most appropriate dataset for specific applications:

1. **Short-term operations and maritime safety (IFS):** The operational IFS model (ECMWF) exhibited the most consistent integrated performance across all sea-state regimes, yielding the lowest overall $RMSE$ (0.32 m), SI (0.08), and a near-zero mean bias (+0.07 m). In extreme regimes, IFS maintained superior skill, with $RMSE$ increasing moderately to 0.61 m at $P95$ and 0.92 m at $P99$. Its dynamic two-way wave-atmosphere coupling, combined with fine grid resolution and updated whitecapping physics, effectively regulates momentum transfer (Ardhuin et al., 2010; ECMWF, 2023).

Recommendation: For applications requiring high-precision short-term predictability, such as maritime navigation, search and rescue (SAR) operations, and logistical

planning for Antarctic expeditions, the operational IFS forecast represents a highly reliable choice among global products.

2. **Long-term climate studies and Extreme Value Analysis (ERA5):** The ERA5 reanalysis demonstrated excellent phase correlation ($CC = 0.97$) and low error dispersion in modal conditions ($RMSE = 0.40$ m). However, it exhibited a non-linear loss of skill during severe storms, with $RMSE$ elevating to 0.86 m at $P95$ ($Hs \geq 6.51$ m) and 1.14 m at $P99$ ($Hs \geq 8.30$ m), characteristic of the “missing the peaks” phenomenon (Cavaleri, 2009; Bessonova et al., 2025).

Recommendation: While ERA5 provides long-term historical consistency ideal for general climate variability studies (Hersbach et al., 2020), its direct uncorrected use in Extreme Value Analysis (EVA), return-period estimation, or offshore engineering design warrants caution. Implementing statistical post-processing or bias-correction algorithms—such as the Quantile Mapping Method applied to wind or wave fields (Campos et al., 2022b; Fanti et al., 2023)—is recommended to recover missing extreme energy before establishing design criteria.

3. **Extreme wave height representation (LOPS-WW3):** The specialized LOPS-WW3 hindcast persistent mitigated upper-tail underestimation, maintaining low errors in extreme quantiles ($RMSE_{P95} = 0.67$ m; $RMSE_{P99} = 0.77$ m). This capability stems from its T475 source-term package, which enhances the wave growth parameter (β_{max}) under strong winds (Alday et al., 2021; Elshinnawy et al., 2024). However, this calibration introduces a spectral trade-off, overestimating mean modal wave heights ($Bias = +0.33$ m) and systematically underestimating Peak Period ($RMSE_{Tp} = 2.66$ s; $CC_{Tp} = 0.47$).

Recommendation: This hindcast is best suited for studies focusing specifically on extreme wave height thresholds and storm peak duration, provided users account for its positive modal bias and lower accuracy in peak wave periods.

4. **Uncoupled forecasts and analysis systems (GFS and GDAS):** The GFS operational forecast and GDAS analysis system (NCEP/NOAA) exhibited higher error dispersion ($SI = 0.17$) and a pronounced negative bias during severe storms ($RMSE_{P99} = 1.60$ m for GFS and 1.61 m for GDAS). The absence of dynamic two-way wave-ocean coupling and coarse pressure-gradient resolution in deep polar cyclones limit these systems’ ability to sustain extreme wave growth (Campos et al., 2020b; Salimbeni et al., 2024).

Recommendation: Direct deterministic outputs from GFS and GDAS in high southern latitudes should be interpreted with caution for structural engineering applications. For operational safety under severe weather, deterministic predictions benefit from ensemble-based approaches or post-processing adjustments to mitigate scatter errors.

5. **Multivariate period (Tp) and directional (Dp) predictability:** A persistent limitation across all evaluated products was the systematic underestimation of Peak Period (Tp), with correlation coefficients degrading under extreme regimes ($CC_{P95\%}$ ranging from -0.02 to 0.39). This reflects the challenge of resolving wind-sea to swell transitions and wave-ice dissipation in Marginal Ice Zones (MIZ) (Montiel et al., 2025). Conversely, Peak Direction (Dp) was consistently captured by all products ($CC > 0.56$; $RMSE \approx 25^\circ\text{--}32^\circ$), confirming that synoptic storm

tracks are accurately resolved.

Recommendation: Researchers investigating wave kinematics in the Southern Ocean should anticipate that global wave products tend to output systematically shorter wave periods than observed *in situ*, whereas directional fields provide reliable forcing for regional nested grids.

In summary, no single global wave product serves as an optimal solution for all oceanographic applications in the Southern Ocean; rather, selection must be carefully aligned with specific user requirements. Future advances in physical oceanography will benefit from addressing the root causes of model discrepancies—namely, reducing severe wind biases in global atmospheric reanalyses, refining drag coefficient (C_d) saturation physics under high winds, and improving wave dissipation parameterizations in sea-ice environments.

Acknowledgements. This work was supported by the Brazilian Antarctic Program (PROANTAR/CNPq) under grant No. 443013/2018-7 (ATMOS 1.0) and No. 440848/2023-7 (ATMOS 2.0). The authors would like to express their sincere gratitude to the Brazilian Navy (Marinha do Brasil) and especially to the officers and crew of the Polar Vessel *Almirante Maximiano* (H-41) for their essential logistical support and dedication during buoy deployment operations. Carla S. Leite acknowledges the financial support and master’s scholarships provided by the Fundação de Amparo à Pesquisa e Inovação do Estado de Santa Catarina (FAPESC) under Public Notice No. 48/2021, and the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) - Finance Code 001.

Declarations

- **Funding:** ATMOS 1.0 and 2.0 projects (CNPq/PROANTAR grant Nos. 443013/2018-7 and 440848/2023-7). C.S.L. was supported by master’s scholarships from FAPESC (Public Notice No. 48/2021) and CAPES (Finance Code 001).
- **Conflict of interest/Competing interests:** The authors declare no competing interests.
- **Data availability:** The observational buoy dataset and model extraction scripts are available upon reasonable request.

References

- Alday, M., Accensi, M., Ardhuin, F., Dodet, G., 2021. A global wave parameter database for geophysical applications. Part 3: Improved forcing and spectral resolution. *Ocean Modelling* 166. doi:[10.1016/j.ocemod.2021.101848](https://doi.org/10.1016/j.ocemod.2021.101848).
- Ardhuin, F., Gille, S.T., Menemenlis, D., Rocha, C.B., Rascle, N., Chapron, B., Gula, J., Molemaker, J., 2017. Small-scale open ocean currents have large effects on wind wave heights. *Journal of Geophysical Research: Oceans* 122, 4500–4517. URL: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2016JC012413>, doi:<https://doi.org/10.1002/2016JC012413>.

- Ardhuin, F., Rogers, E., Babanin, A.V., Filipot, J.F., Magne, R., Roland, A., van der Westhuysen, A., Queffelec, P., Lefevre, J.M., Aouf, L., Collard, F., 2010. Semiempirical dissipation source functions for ocean waves. part i: Definition, calibration, and validation. *Journal of Physical Oceanography* 40, 1917–1941. doi:[10.1175/2010JP04324.1](https://doi.org/10.1175/2010JP04324.1).
- Ardhuin, F., Roland, A., Dumas, F., Bennis, A.C., Sentchev, A., Forget, P., Wolf, J., Girard, F., Osuna, P., Benoit, M., 2012. Numerical wave modeling in conditions with strong currents: Dissipation, refraction, and relative wind. *Journal of Physical Oceanography* 42, 2101 – 2120. URL: <https://journals.ametsoc.org/view/journals/phoc/42/12/jpo-d-11-0220.1.xml>, doi:[10.1175/JPO-D-11-0220.1](https://doi.org/10.1175/JPO-D-11-0220.1).
- Bessonova, V., Tapoglou, E., Dorrell, R., Dethlefs, N., York, K., 2025. Global evaluation of wave data reanalysis: Comparison of the era5 dataset to buoy observations. *Applied Ocean Research* 157. doi:[10.1016/j.apor.2025.104490](https://doi.org/10.1016/j.apor.2025.104490).
- Bidlot, J.R., 2012. Present status of wave forecasting at ecmwf, in: *Proceedings of the ECMWF Workshop on Ocean Waves*, ECMWF, Reading, UK. pp. 25–27.
- Bidlot, J.R., Janssen, P., Abdalla, S., 2007. A revised formulation of ocean wave dissipation and its model impact. Technical Memorandum 509. European Centre for Medium-Range Weather Forecasts. Reading, UK. URL: <https://www.ecmwf.int/en/elibrary/11029-revised-formulation-ocean-wave-dissipation-and-its-model-impact>.
- Cai, W., Gao, L., Luo, Y., Li, X., Zheng, X., Zhang, X., Cheng, X., Jia, F., Purich, A., Santoso, A., Du, Y., Holland, D.M., Shi, J.R., Xiang, B., Xie, S.P., 2023. Southern ocean warming and its climatic impacts. doi:[10.1016/j.scib.2023.03.049](https://doi.org/10.1016/j.scib.2023.03.049).
- Campos, R.M., 2023. Analysis of spatial and temporal criteria for altimeter collocation of significant wave height and wind speed data in deep waters. *Remote Sensing* 15. doi:[10.3390/rs15082203](https://doi.org/10.3390/rs15082203).
- Campos, R.M., Alves, J.H.G.M., Penny, S.G., Krasnopolsky, V., 2020a. Global assessments of the ncep ensemble forecast system using altimeter data. *Ocean Dynamics* 70, 405–419. URL: <https://doi.org/10.1007/s10236-019-01329-4>, doi:[10.1007/s10236-019-01329-4](https://doi.org/10.1007/s10236-019-01329-4).
- Campos, R.M., D’Agostini, A., França, B.R., Damião, A.L., Soares, C.G., 2022a. Implementation of a multi-grid operational wave forecast in the south atlantic ocean. *Ocean Engineering* 243. doi:[10.1016/j.oceaneng.2021.110173](https://doi.org/10.1016/j.oceaneng.2021.110173).
- Campos, R.M., D’Agostini, A., França, B.R.L., Cruz, L.M., Soares, C.G., 2020b. Extreme wind and wave predictability from operational forecasts at the drake passage. *Journal of Offshore Mechanics and Arctic Engineering* 143, 021703. URL: <https://doi.org/10.1115/1.4048151>, doi:[10.1115/1.4048151](https://doi.org/10.1115/1.4048151).
- Campos, R.M., Gramscianinov, C.B., de Camargo, R., da Silva Dias, P.L., 2022b. Assessment and calibration of era5 severe winds in the atlantic ocean using satellite data. *Remote Sensing* 14. URL: <https://www.mdpi.com/2072-4292/14/19/4918>, doi:[10.3390/rs14194918](https://doi.org/10.3390/rs14194918).
- de Carvalho, G.T., Pezzi, L.P., Lefèvre, N., Rodrigues, C.C.F., Santini, M.F., Mejia, C., 2025. Spatio-temporal variability in co2 fluxes in the atlantic sector of the southern ocean. *Atmosphere* 16. URL: <https://www.mdpi.com/2073-4433/16/3/319>, doi:[10.3390/atmos16030319](https://doi.org/10.3390/atmos16030319).

- Cavaleri, L., 2009. Wave modeling—missing the peaks. *Journal of Physical Oceanography* 39, 2757–2778. doi:[10.1175/2009JP04067.1](https://doi.org/10.1175/2009JP04067.1).
- Copernicus Climate Change Service, 2023. ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). doi:[10.24381/cds.adbb2d47](https://doi.org/10.24381/cds.adbb2d47). accessed on: [Insira a data que baixou os dados, ex: 10 Aug. 2026].
- ECMWF, 2023. IFS Documentation – Cy48r1. Part VII: ECMWF Wave Model. Technical Report. European Centre for Medium-Range Weather Forecasts. Reading, UK. URL: <https://www.ecmwf.int/en/publications/ifs-documentation>.
- Elshinnawy, A.I., Menéndez, M., Medina, R., 2024. A parameterization for the correction of era5 severe winds for extreme ocean wave modelling. *Ocean Engineering* 312. doi:[10.1016/j.oceaneng.2024.119048](https://doi.org/10.1016/j.oceaneng.2024.119048).
- Fanti, V., Óscar Ferreira, Kümmerer, V., Loureiro, C., 2023. Improved estimates of extreme wave conditions in coastal areas from calibrated global reanalyses. *Communications Earth and Environment* 4. doi:[10.1038/s43247-023-00819-0](https://doi.org/10.1038/s43247-023-00819-0).
- Guimarães, P.V., Ardhuin, F., Perignon, Y., Benetazzo, A., Bouin, M.N., Accensi, M., Garnier, V., Redelsperger, J.L., Thomson, J., 2022. Relative current effect on short wave growth. *Ocean Dynamics* 72, 621–639. doi:[10.1007/s10236-022-01520-0](https://doi.org/10.1007/s10236-022-01520-0).
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G.D., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., Thépaut, J.N., 2020. The era5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* 146, 1999–2049. doi:[10.1002/qj.3803](https://doi.org/10.1002/qj.3803).
- Hlophe, T., Taylor, P.H., Hansen, J.E., Wolgamot, H., Cuttler, M.V., 2025. Comparison of vector wave displacements from a moored and a drifting spotter buoy—from an accidental indian ocean voyage. *Ocean Engineering* 328. doi:[10.1016/j.oceaneng.2025.120967](https://doi.org/10.1016/j.oceaneng.2025.120967).
- Janssen, P.A.E.M., 1991. Quasi-linear theory of wind-wave generation applied to wave forecasting. *Journal of Physical Oceanography* 21, 1631–1642. doi:[10.1175/1520-0485\(1991\)021<1631:QLTOWW>2.0.CO;2](https://doi.org/10.1175/1520-0485(1991)021<1631:QLTOWW>2.0.CO;2).
- Kleist, D.T., Parrish, D.F., Derber, J.C., Treadon, R., Wu, W.S., Lord, S., 2009. Introduction of the gsi into the ncep global data assimilation system. *Weather and Forecasting* 24, 1691–1705. doi:[10.1175/2009WAF2222201.1](https://doi.org/10.1175/2009WAF2222201.1).
- Lemos, G., Semedo, A., Kumar, R., Dobrynin, M., Akpınar, A., Kamranzad, B., Bidlot, J., Lobeto, H., 2023. Performance evaluation of a global cmip6 single forcing, multi wave model ensemble of wave climate simulations. *Ocean Modelling* 184. doi:[10.1016/j.ocemod.2023.102237](https://doi.org/10.1016/j.ocemod.2023.102237).
- MacFerrin, M., Amante, C., Carignan, K., Love, M., Lim, E., 2025. The earth topography 2022 (etopo 2022) global dem dataset. *Earth System Science Data* 17, 1835–1849. URL: <https://essd.copernicus.org/articles/17/1835/2025/>, doi:[10.5194/essd-17-1835-2025](https://doi.org/10.5194/essd-17-1835-2025).

- Mentaschi, L., Besio, G., Cassola, F., Mazzino, A., 2013. Problems in rmse-based wave model validations. *Ocean Modelling* 72, 53–58. doi:[10.1016/j.ocemod.2013.08.003](https://doi.org/10.1016/j.ocemod.2013.08.003).
- Meucci, A., Young, I.R., Hemer, M., Trenham, C., Watterson, I.G., 2023. 140 years of global ocean wind-wave climate derived from cmip6 access-cm2 and ec-earth3 gcms: Global trends, regional changes, and future projections. *Journal of Climate* 36, 1605 – 1631. URL: <https://journals.ametsoc.org/view/journals/clim/36/6/JCLI-D-21-0929.1.xml>, doi:[10.1175/JCLI-D-21-0929.1](https://doi.org/10.1175/JCLI-D-21-0929.1).
- Montiel, F., Forbes, M., Echevarria, E., Rapizo, H., Gamble, C., 2025. Evaluation of ice dissipation parameterizations in spectral ocean wave model wavewatch iii: An intercomparison analysis. *Journal of Geophysical Research: Oceans* 130. doi:[10.1029/2024JC022113](https://doi.org/10.1029/2024JC022113).
- NOAA National Centers for Environmental Information, 2022. ETOPO 2022 15 Arc-Second Global Relief Model. doi:[10.25921/fd45-gt74](https://doi.org/10.25921/fd45-gt74). accessed: [Insira a data de acesso aqui, ex: 10 Aug. 2026].
- Saha, S., Moorthi, S., Pan, H.L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., et al., 2010. The ncep climate forecast system reanalysis. *Bulletin of the American Meteorological Society* 91, 1015–1058. doi:[10.1175/2010BAMS3001.1](https://doi.org/10.1175/2010BAMS3001.1).
- Salimbeni, A., Dragani, W., Alonso, G., 2024. Ocean waves in the southwestern atlantic ocean: An evaluation of global wave models. *International Journal of Climatology* 44, 2725–2738. doi:[10.1002/joc.8477](https://doi.org/10.1002/joc.8477).
- Sharmar, V.D., Markina, M.Y., Gulev, S.K., 2021. Global ocean wind-wave model hindcasts forced by different reanalyzes: A comparative assessment. *Journal of Geophysical Research: Oceans* 126. doi:[10.1029/2020JC016710](https://doi.org/10.1029/2020JC016710).
- Shimura, T., Mori, N., Miyashita, T., 2026. Multidecadal oscillation masks ocean wave climate trends in 75-year global wave hindcast. *Journal of Geophysical Research: Oceans* 131, e2025JC022340. URL: <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2025JC022340>, doi:<https://doi.org/10.1029/2025JC022340>. e2025JC022340 2025JC022340.
- Stopa, J.E., Ardhuin, F., Babanin, A., Zieger, S., 2016. Comparison and validation of physical wave parameterizations in spectral wave models. *Ocean Modelling* 103, 2–17.
- The WAVEWATCH III Development Group (WW3DG), 2019. User manual and system documentation of WAVEWATCH III version 6.07. Technical Note 333. NOAA/NWS/NCEP/MMAB. College Park, MD, USA. URL: <https://github.com/NOAA-EMC/WW3/wiki>. 465 pp. + Appendices.
- Voermans, J.J., Babanin, A.V., Kirezci, C., Carvalho, J.T., Santini, M.F., Pavani, B.F., Pezzi, L.P., 2021. Wave anomaly detection in wave measurements. *Journal of Atmospheric and Oceanic Technology* 38, 525–536. doi:[10.1175/JTECH-D-20-0090.1](https://doi.org/10.1175/JTECH-D-20-0090.1).
- Voermans, J.J., Rabault, J., Filchuk, K., Ryzhov, I., Heil, P., Marchenko, A., Collins III, C.O., Dabboor, M., Sutherland, G., Babanin, A.V., 2020. Experimental evidence for a universal threshold characterizing wave-induced sea ice break-up. *The Cryosphere* 14, 4265–4278. doi:[10.5194/tc-14-4265-2020](https://doi.org/10.5194/tc-14-4265-2020).

Wang, J., Wang, Y., 2022. Evaluation of the era5 significant wave height against ndbc buoy data from 1979 to 2019. *Marine Geodesy* 45, 151–165. doi:[10.1080/01490419.2021.2011502](https://doi.org/10.1080/01490419.2021.2011502).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [30163DERA5Hs.mp4](#)