The Seasonal Cycle of Significant Wave Height in the Ocean: Local vs Remote Forcing

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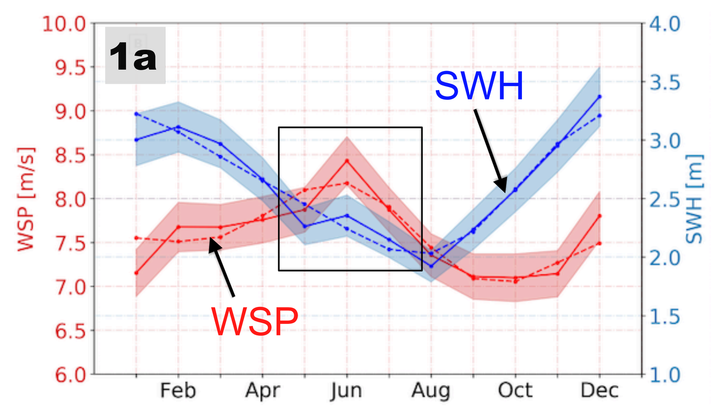
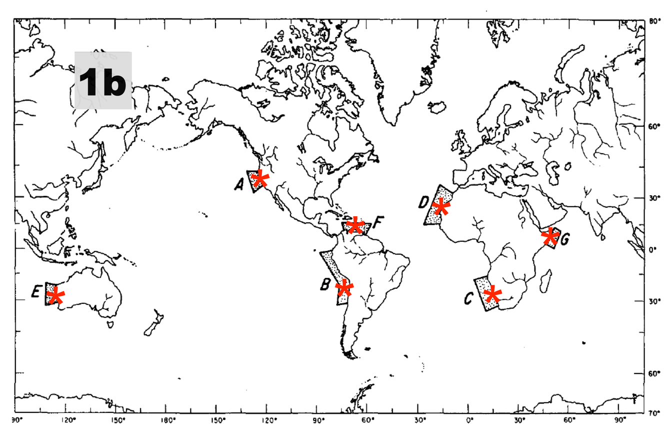
Motivation

Wind generated **surface gravity waves** are fundamental to our understanding of the **interactions** between the ocean and atmosphere. A common metric for characterizing the sea state is **significant wave height** (SWH). In most world oceans, **remotely forced** wind waves, generated by storm systems, dominate the wave field[1].

SWH undergoes a sinusoidal **annual cycle** due to large-scale seasonal patterns in storms. However, **local wind events** can cause deviations from this annual cycle. Villas Bôas et al. analyzed a particular **deviation** from SWH's annual cycle off the California coast[2] due to local wind events known as **expansion fan winds**[3]. These wind events are identified by high wind speed (WSP) along-shore winds and a distinct **increase** in SWH occurring during the late spring to early summer months (Fig 1a).



Regional Climatology of SWH (solid blue) and WSP (solid red) in 4x4 degree box off the coast of California.



Hypothesized expansion fan wind regions from Winant et al. 1988.

Similar local wind events have been hypothesized by Winant et al. to be present in other regions with similar coastal topography and atmospheric conditions as California (hereon referred as summer wind anomaly regions (SWARs)). In the present work, we **assess**:

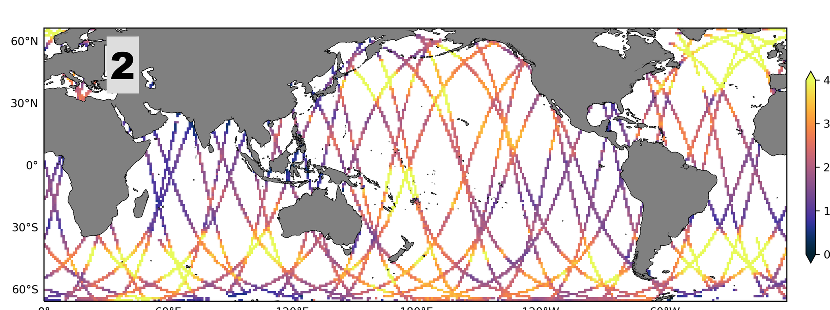
- Are deviations from the SWH annual cycle **present** in other SWARs?
- Is there a corresponding **maximum** in WSP climatology correlated with the SWH deviation?
- What does the SWH deviation imply about the **sea state** of the wave field?

Data and methods

We use global **satellite measurements** of SWH and WSP from 1 January 1993 to 31 December 2015.

IFREMER SWH Satellite Altimetry Data

IFREMER's **along track** cross calibrated SWH altimetry data collected from multiple near polar non-sun synchronous satellites binned to global 1x1 degree spatial and daily temporal **resolution.**



January 1st, 1993 IFREMER SWH along track data

Cross-Calibrated Multi-platform version 2 Wind Vector Product

CCMP2 is a **gridded** wind vector product that blends satellite remote sensed, in-situ buoy, and modeled **wind velocity** data with global 0.25x0.25 degree spatial and 6 hourly temporal resolution.

All analysis between IFREMER SWH and CCMP2 WSP is implemented with **monthly averaged** 1x1 degree spatial resolution data.

Annual and Semi-annual SWH and WSP Model

To analyze the seasonal cycle, we **least-squares fitted** SWH and WSP with annual and semi-annual sinusoidal cycles:

$$f(t) = a_0 + a_1 \times \sin\left(\frac{2\pi t}{T}\right) + a_2 \times \cos\left(\frac{2\pi t}{T}\right) + a_3 \times \sin\left(\frac{4\pi t}{T}\right) + a_4 \times \cos\left(\frac{4\pi t}{T}\right).$$

A fit is computed for each grid point across the globe, allowing us to examine **geographic variations** in the parameters.

Acknowledgements

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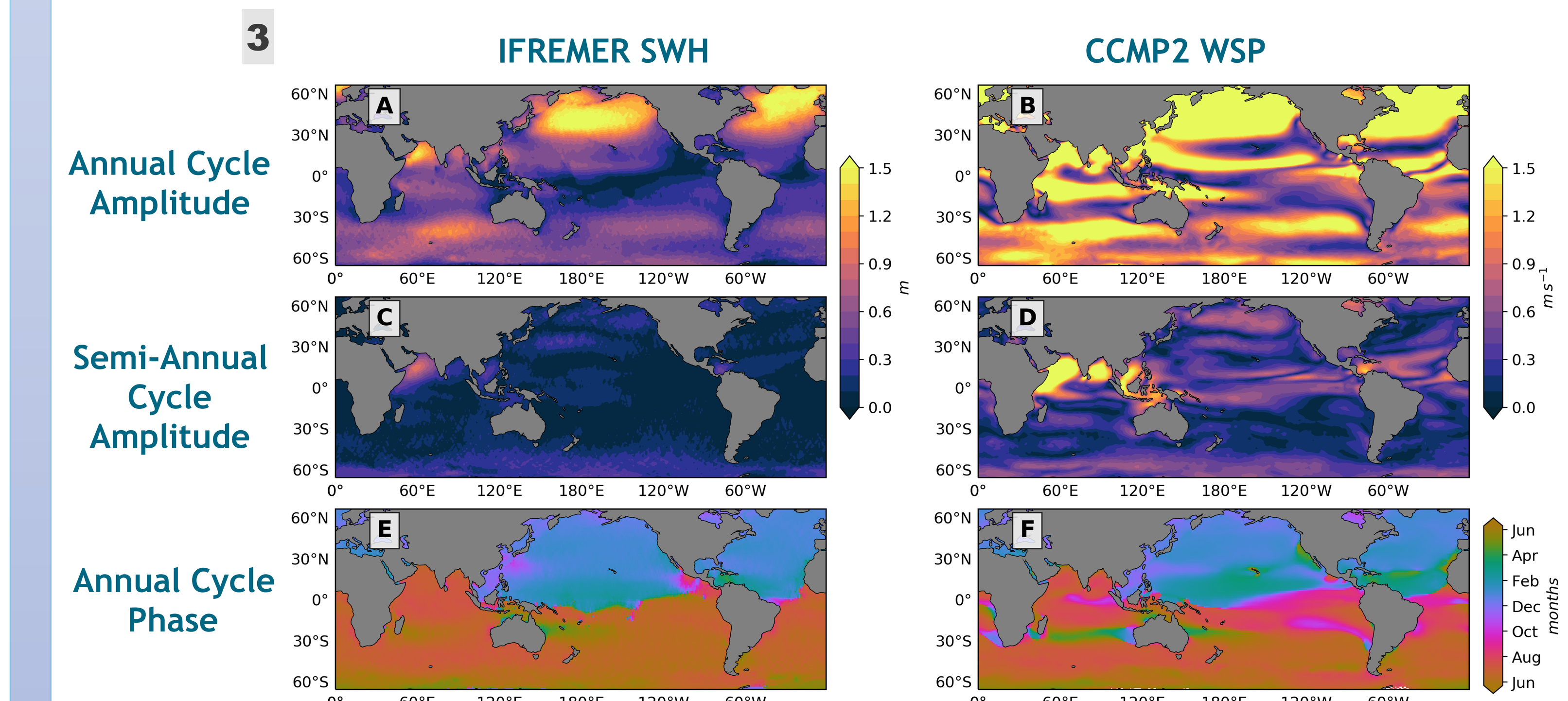
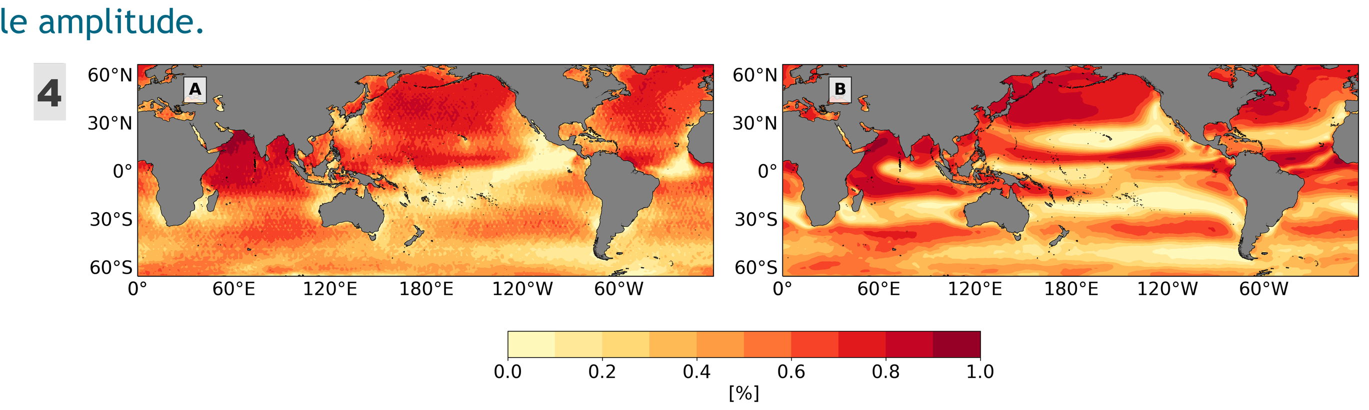
Parameters of Annual and Semi-Annual Model

The **parameters** of the annual and semi-annual model reveal:

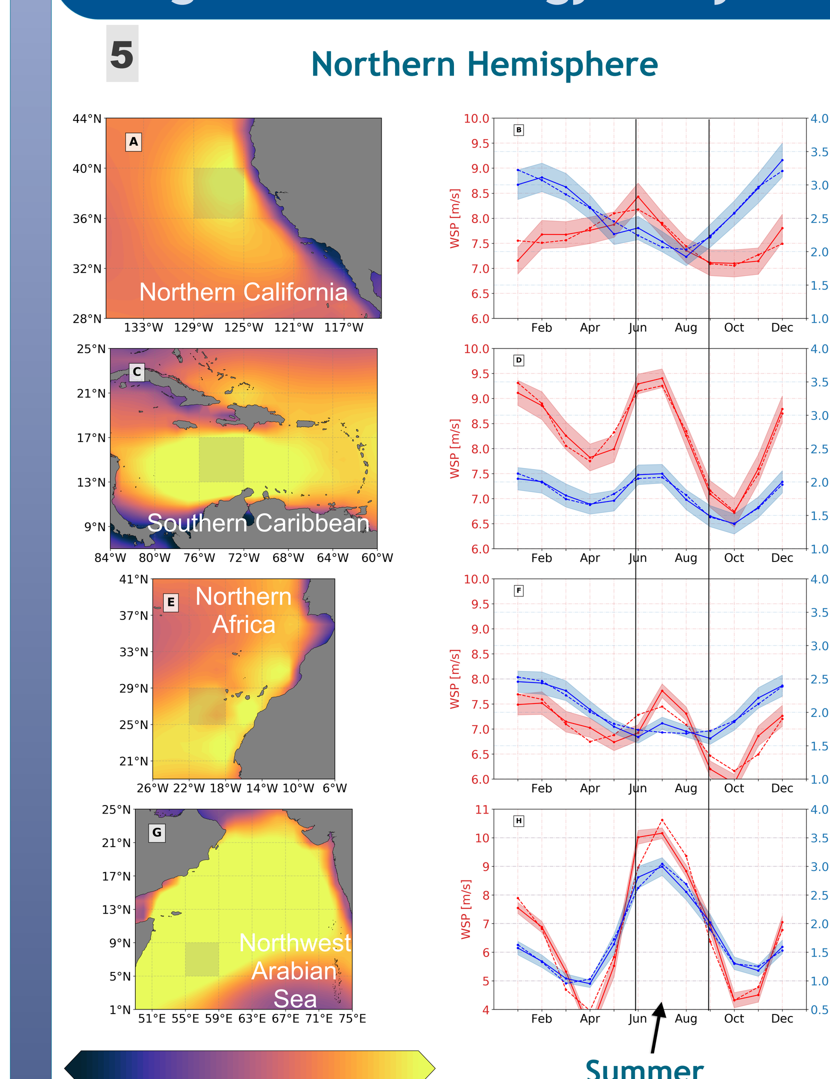
- High annual cycle **amplitude** in high latitudes of Northern Hemisphere
- High semi-annual cycle amplitude in monsoon and some SWAR regions
- Generally annual cycle is **6 months out of phase** between Northern and Southern Hemisphere for SWH and WSP and between SWARs and surrounding regions for WSP



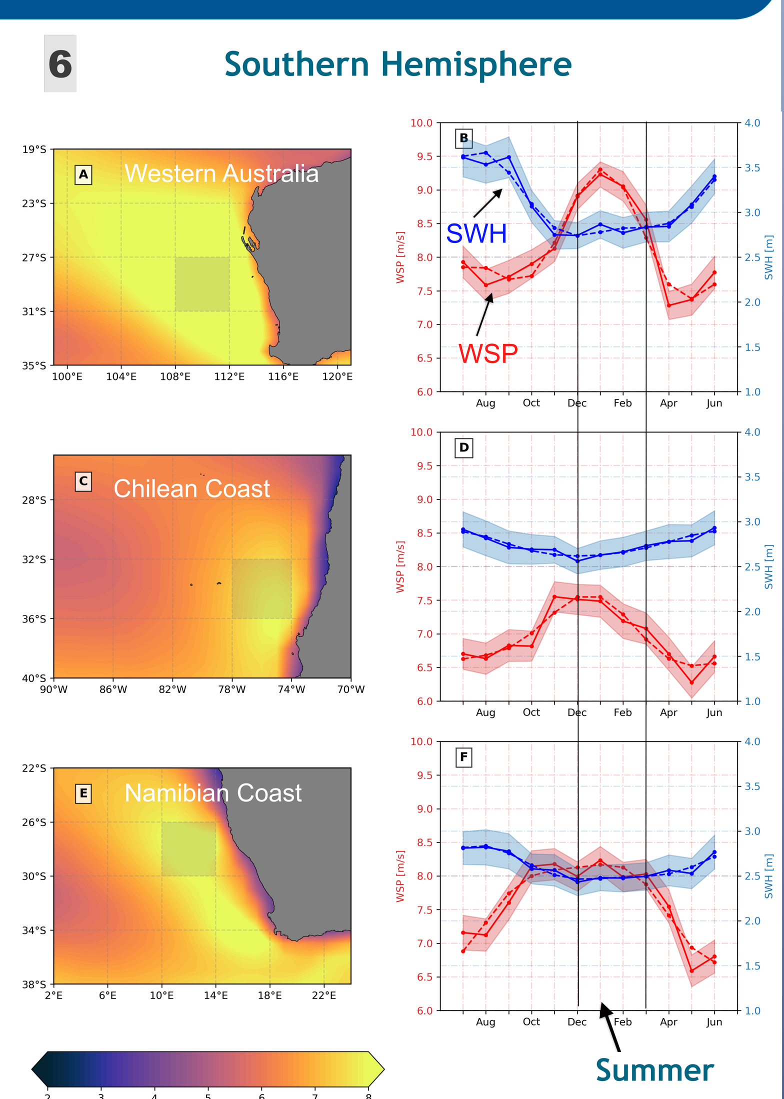
Goodness of fit of the five parameter least square fit model, quantified by the coefficient of determination, shows high **percent variance explained** in regions with high annual or semi-annual cycle amplitude.



Regional Climatology Analysis



Northern Hemisphere SWARs show **local maxima** in SWH in summer **coinciding** with local wind maxima.



Deviations from SWH annual cycle in the Southern Hemisphere SWARs are **less pronounced** or not present at all.

The magnitude of the deviation from the SWH cycle is determined by the local conditions and characteristics of the wave field within the region.

Dashed Blue: SWH model
Dashed Red: WSP model
Contour map NH: JJA mean WSP
Contour map SH: DJF mean WSP

Probability of Swell: Consistency between Metrics

Wave Age

SWH deviations are caused by the local wind events if waves in these SWARs during spring months are predominantly **locally forced**. We use wave age to **separate** growing seas from **fully developed** seas by quantifying the stage of **development** of the wave field through the ratio criterion:

$$A = \frac{c_p}{U_{10}} \quad \text{where} \quad A > 1.2 \rightarrow \text{Remotely Forced Waves (Swell)}, \quad A \leq 1.2 \rightarrow \text{Locally Forced Waves (Wind-seas)}$$

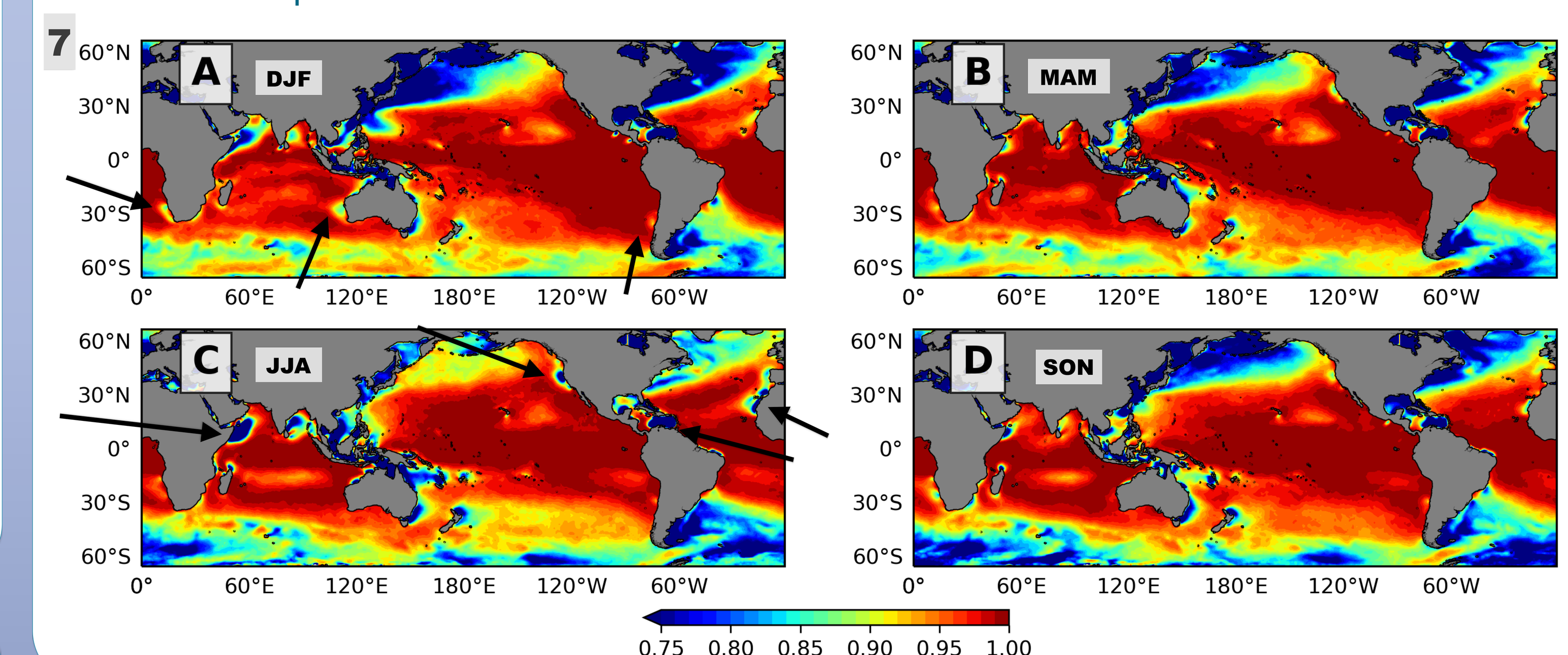
where c_p is peak phase speed and U_{10} is wind speed 10 meters above the ocean surface.

Probability of Swell

Probability of swell[4] quantifies the **number of swell events** (N_{swell}) relative to total number of wave events (N_{total}) over a time period using wave age as the **separation criterion** for wind-seas and swell events:

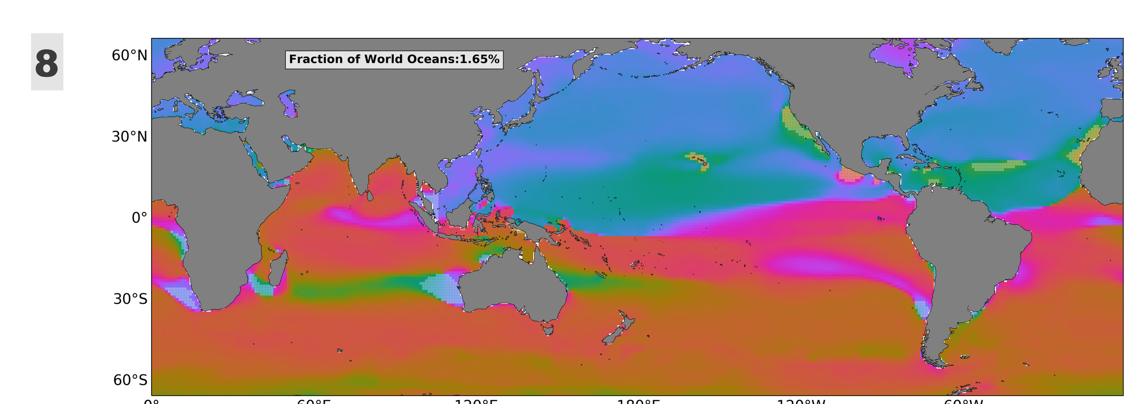
$$P_s = \frac{N_{swell}}{N_{total}} \quad \text{where} \quad N_{total} = N_{swell} + N_{wind}$$

In global **seasonal** progression maps of probability of swell below, SWARs contained waves that are mostly categorized as **locally forced** during the spring and summer months for the respective hemisphere. In the southern hemisphere, this **decrease** in probability of swell is less than the northern hemisphere.



Final Remarks

- **Deviations** from SWH seasonal cycle are larger in the Northern Hemisphere than in the Southern Hemisphere due to close **proximity** to large Southern Ocean swells that overwhelm locally forced waves.
- Using **wave age**, probability of swell **decreases** significantly in all SWARs during the spring and summer months implying an **increase** in the amount of locally forced waves in SWAR. This is consistent with our hypothesis that local forced waves **cause** the deviation from the SWH annual cycle.
- **Future** assessments will focus on using **spectral data** from WW3 to **partition** the wave field into swell and wind seas and plot regional climatologies of SWH for these partitions in order to further understand the **dynamics** between swell and wind-sea waves influencing the magnitude of the SWH deviation.
- **Modulation** of the wave field by strong wind events may lead to **enhanced wave breaking** which could have implications for **air-sea fluxes**.



WSP annual cycle phase with gridded and lighter regions indicating anomalous wind regions. Anomalous is defined as WSP reaching a maximum during boreal (austral plus April and May) winter months for the Southern (Northern) Hemisphere. Highlights nearly all SWA regions. Fraction of World Oceans that are categorized as SWARs is 1.65%.

References

[1]Semedo, Alvaro, et al. "A global view on the wind sea and swell climate and variability from ERA-40." *Journal of Climate*24.5 (2011): 1461-1479.
[2] Villas Bôas, Ana B., et al. "Characterization of the deep water surface wave variability in the California Current region." *Journal of Geophysical Research: Oceans* 122.11 (2017): 8753-8769.
[3] Winant, C. D., et al. "The marine layer off northern California: An example of supercritical channel flow." *Journal of the Atmospheric Sciences* 45.23 (1988): 3588-3605.
[4] Chen, Ge, et al. "A global view of swell and wind sea climate in the ocean by satellite altimeter and scatterometer." *Journal of Atmospheric and Oceanic Technology* 19.11 (2002): 1849-1859.