Directional and frequency spread of surface ocean waves from CFOSAT/SWIM satellite measurements

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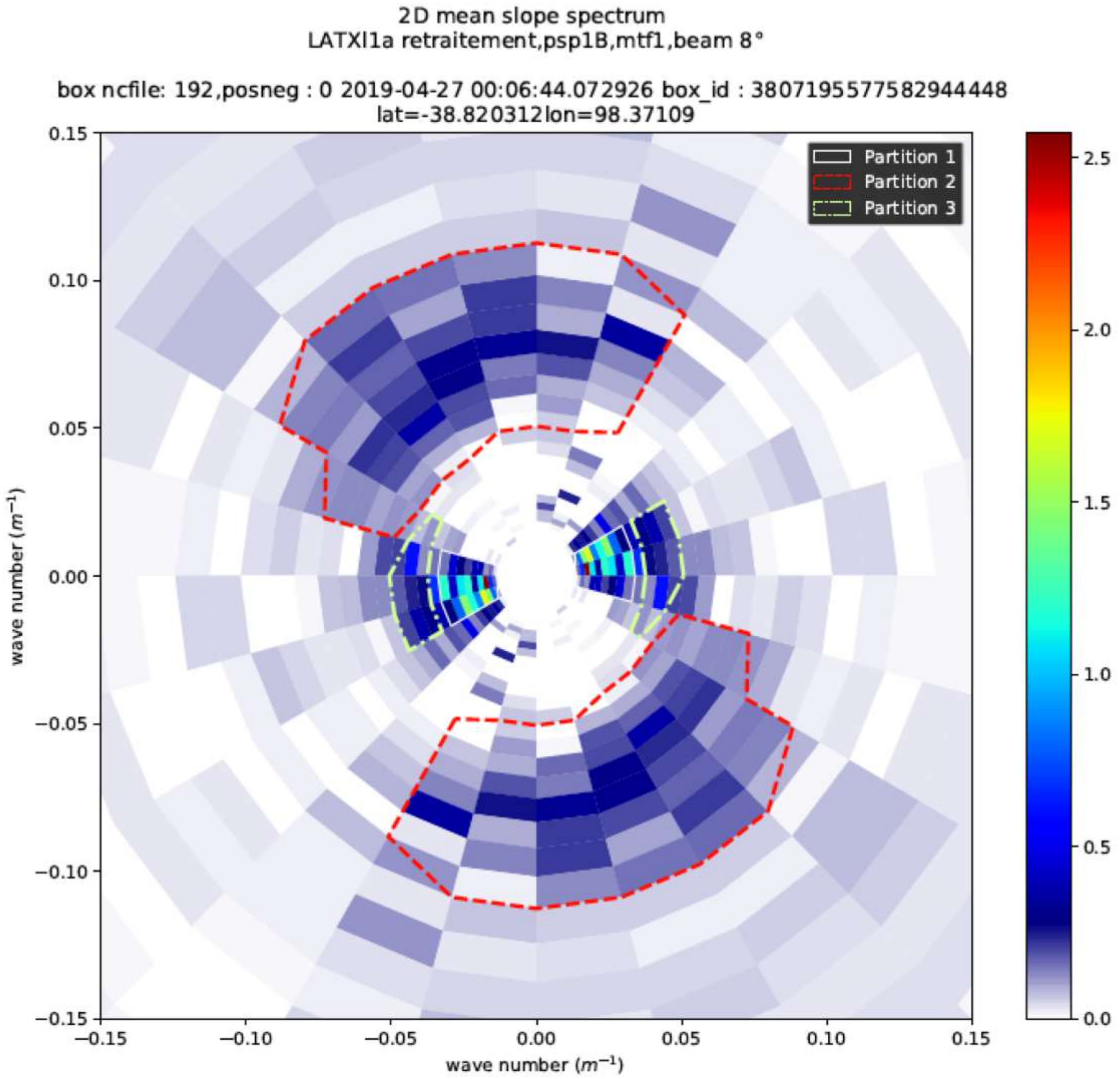
Outlines

- Presentation of SWIM ocean wave spectra and spectral shape parameters
- Analysis of spectral shape parameters
- Study about the Benjamin Feir Index
- Focus on the Southern Ocean
- Study of the directional spread as a function of frequency
- Conclusions and perspectives

Ocean wave spectrum from SWIM



Ocean wave spectra:

- provide **detailed information about the wave field**,
- are **useful for**:
  - operational needs,
  - model refinement,
  - better understanding of waves properties and processes at the air/sea interface.

Ground segment products:

- 2D wave spectra
- 1D wave spectra
- Main parameters:
  - SWH
  - dominant wavelength
  - dominant direction

Wavelength domain: 22 to 500 m
Frequency domain: 0.056 to 0.26 Hz
→ 32 bins

Angular discretization = 15°
180° ambiguity

Parameters computed from wave spectra

Frequency spread

- Half-width estimation:

$$\sigma_f = \frac{\left[\sum_{f_{\min}}^{f_{\max}} F(f)\, df\right]^2}{\sum_{f_{\min}}^{f_{\max}} F^2(f)\, df}$$

Blackman & Tukey (1959)

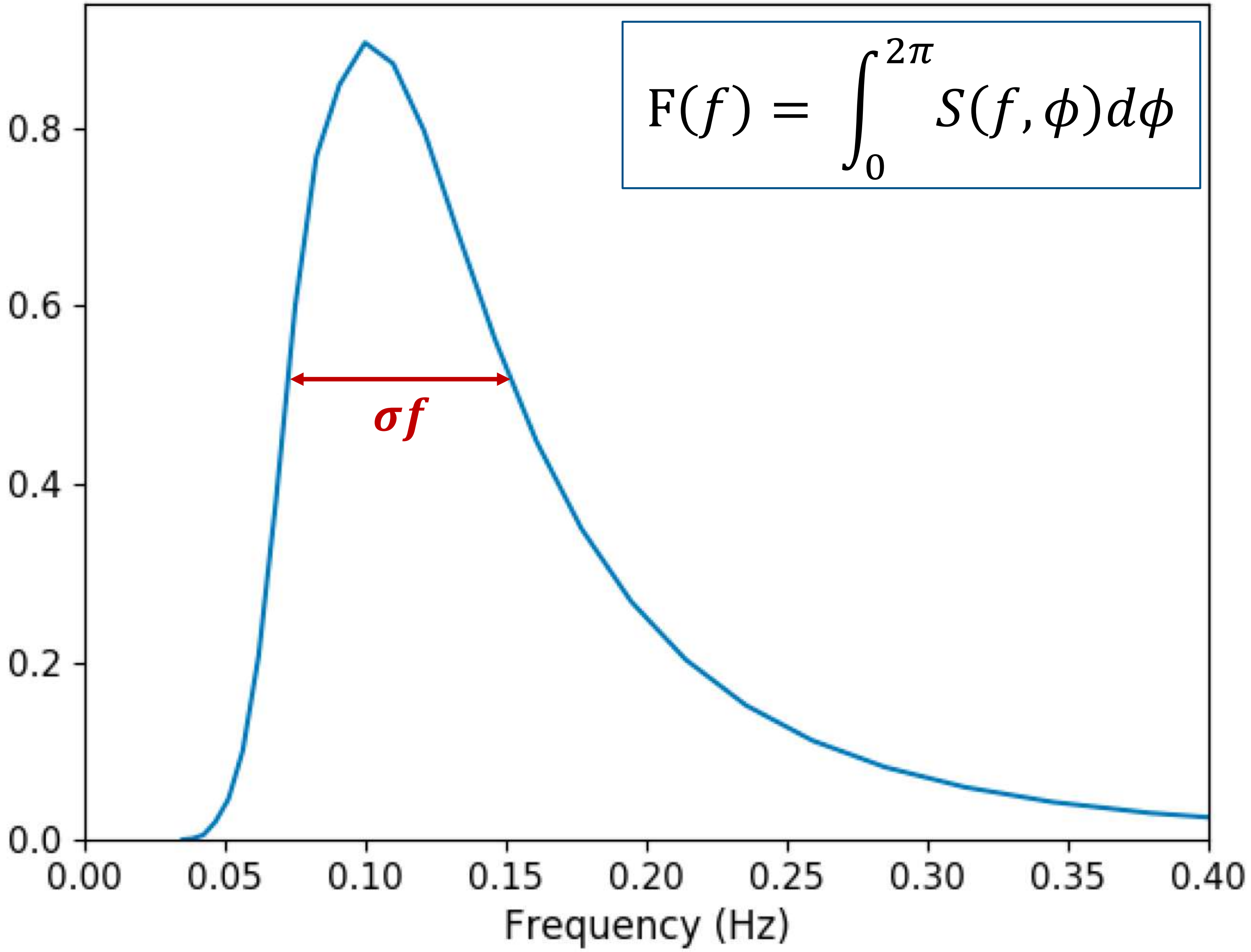
Goda parameter («*Peakedness parameter*»)

- How sharp is the spectrum:

$$Qp = \frac{2\sum_{f_{\min}}^{f_{\max}} f\ F^2(f)\, df}{\left[\sum_{f_{\min}}^{f_{\max}} F(f)\, df\right]^2}$$

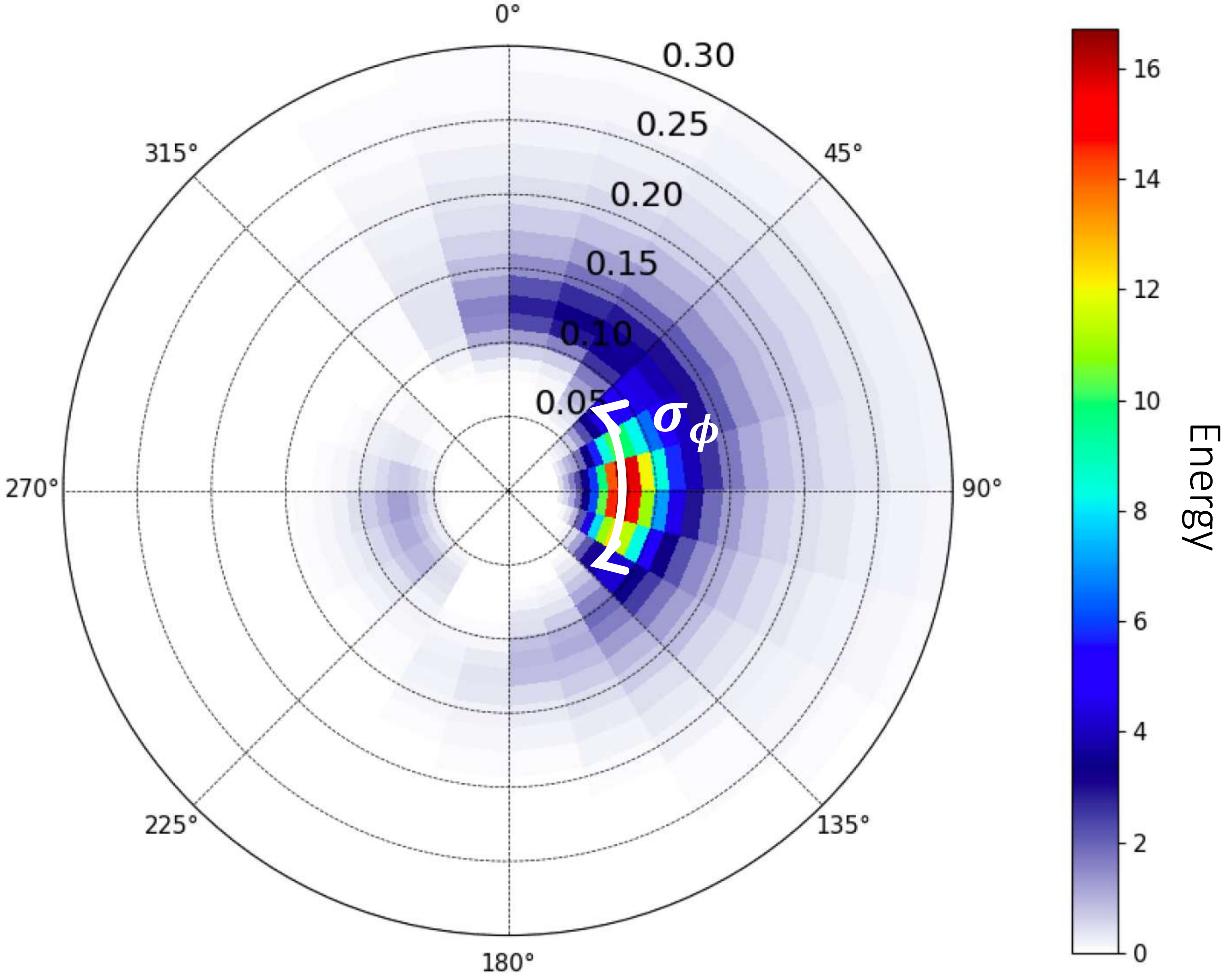
Goda (1970)

Example of an omni-directional spectrum



Parameters computed from wave spectra

Example of directional wave spectrum



Longuet-Higgins et al., (1963)

Directional spread

- Using buoy computation:

$$\sigma_\phi(f) = \sqrt{2 \times \left(1 - \sqrt{a_1(f)^2 + b_1(f)^2}\right)}$$

With the first pair of Fourier coefficients:

$$a_1(f) = Q_{12}(f) \Big/ \sqrt{(C_{22}(f) + C_{33}(f)) \times C_{11}(f)}$$

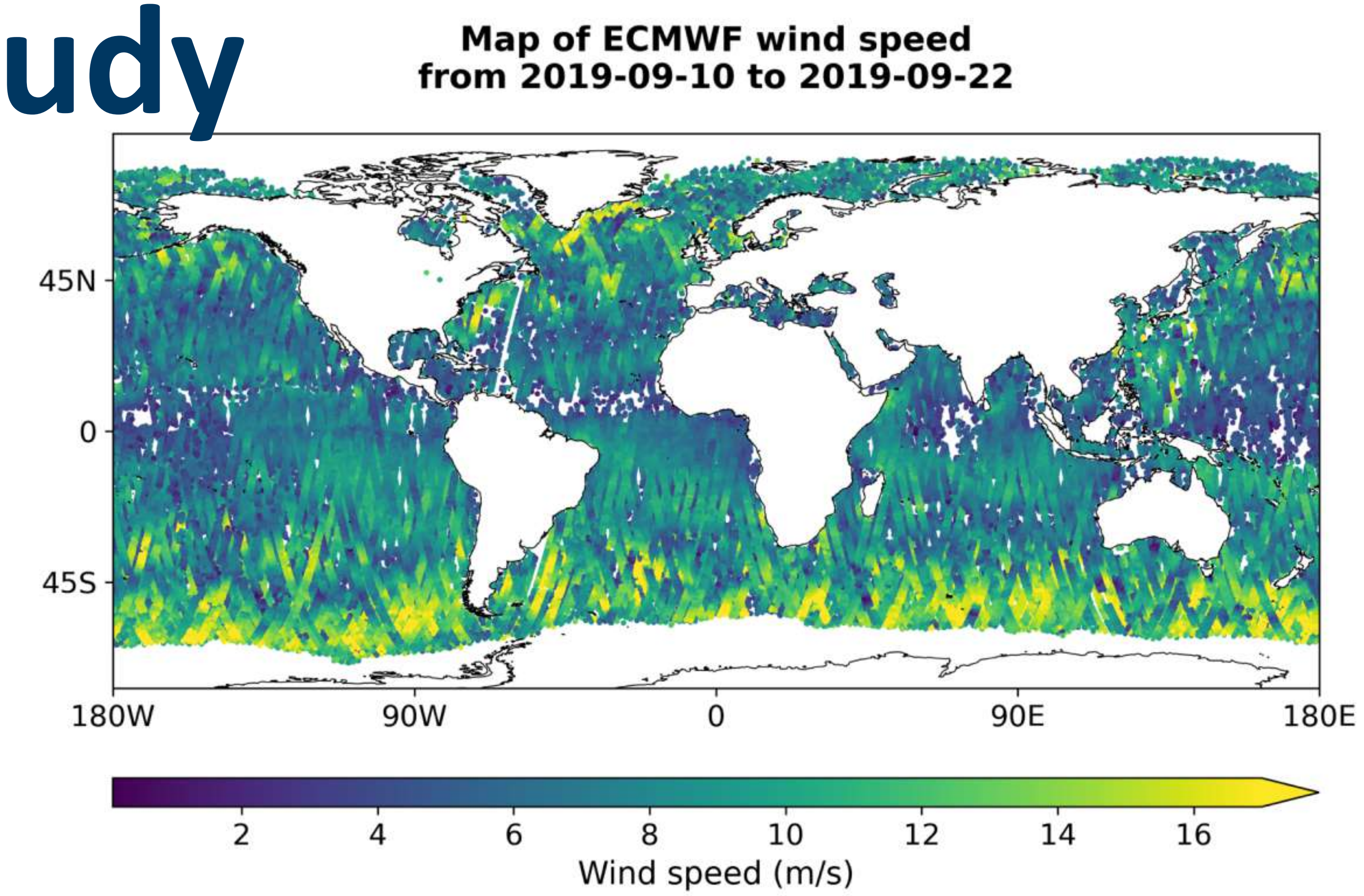
$$b_1(f) = Q_{13}(f) \Big/ \sqrt{(C_{22}(f) + C_{33}(f)) \times C_{11}(f)}$$

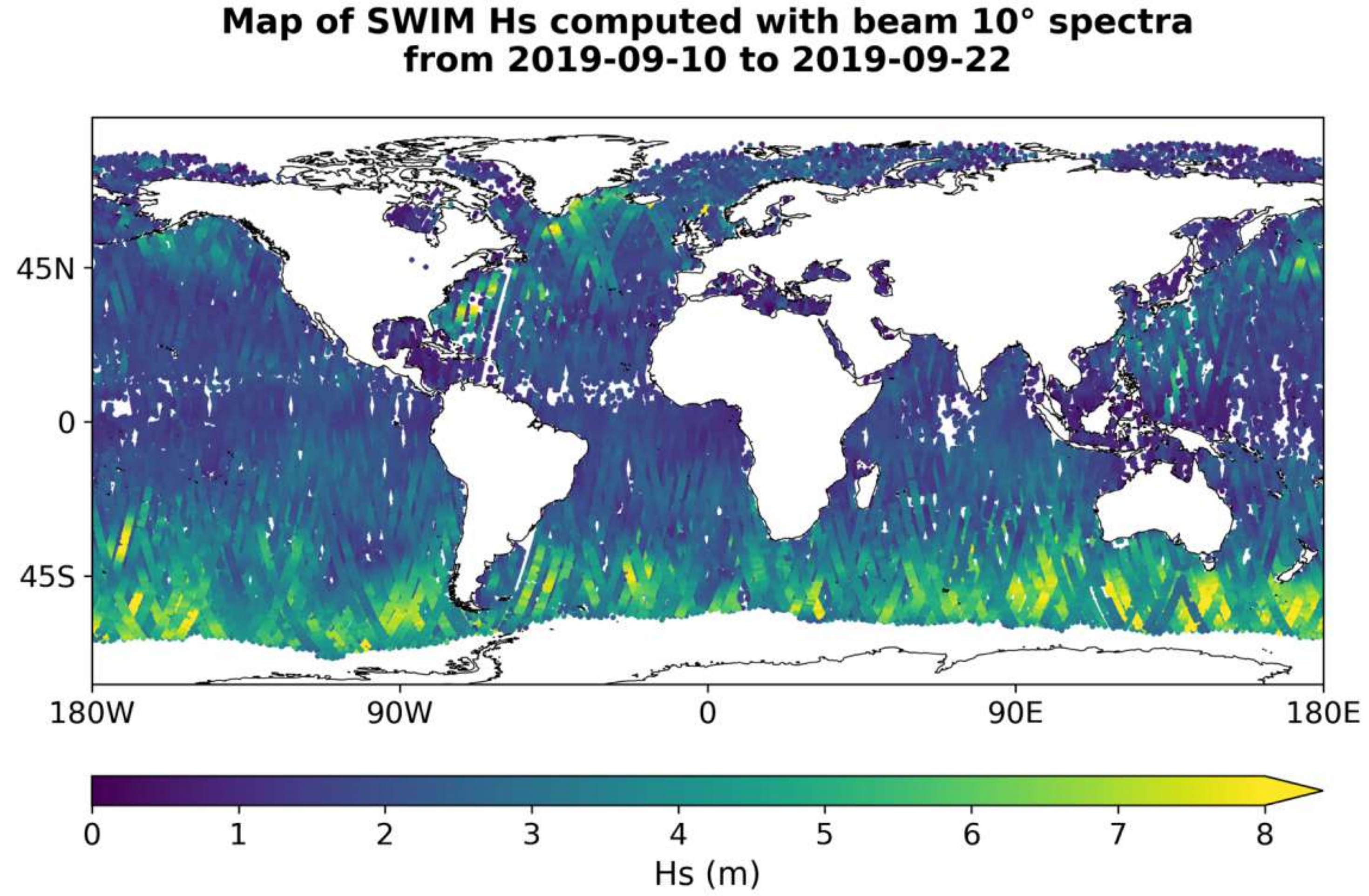
→ Cross spectra are computed using the directional SWIM spectra

Directional spread calculated at the peak of the spectra

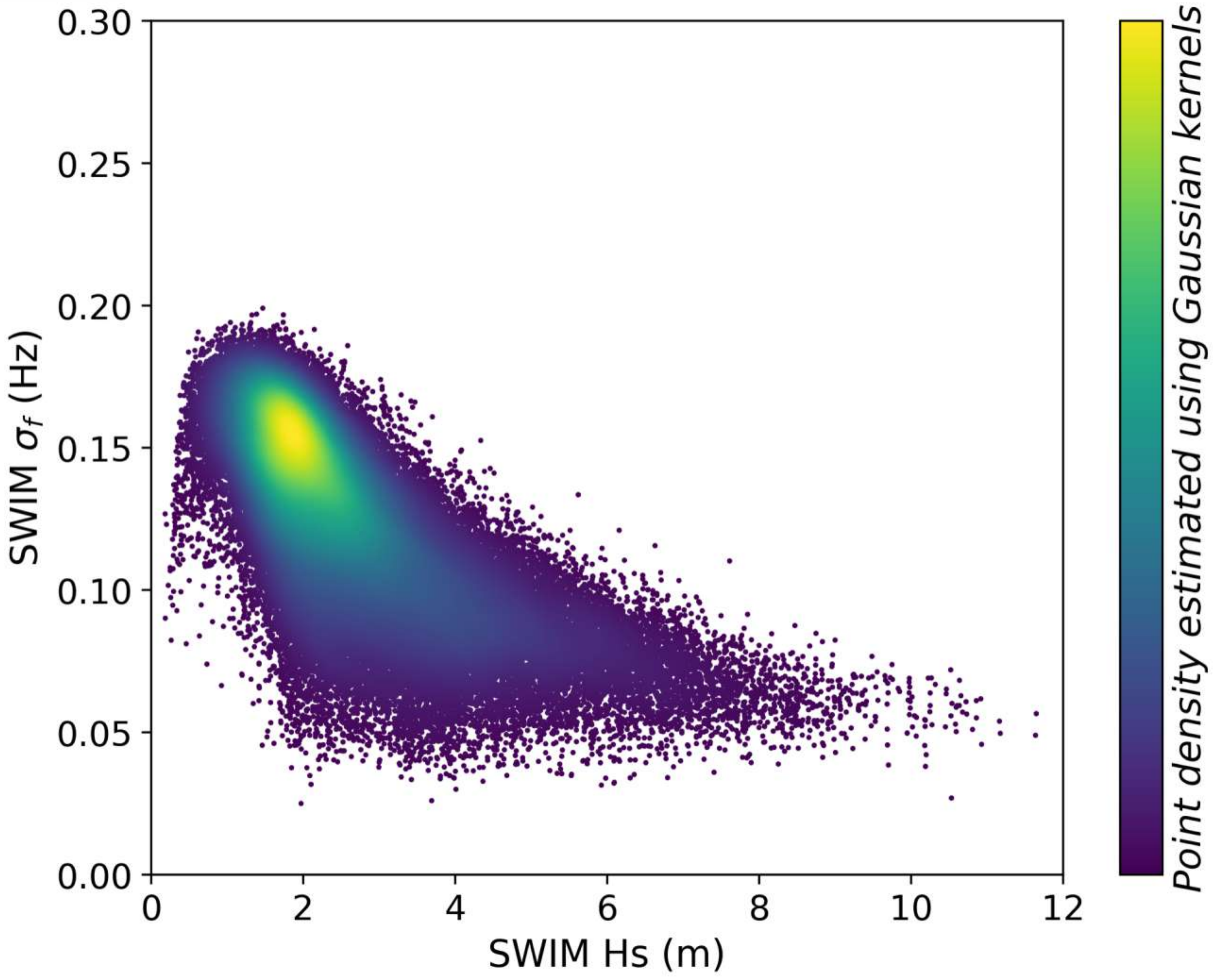
SWIM data used for the study

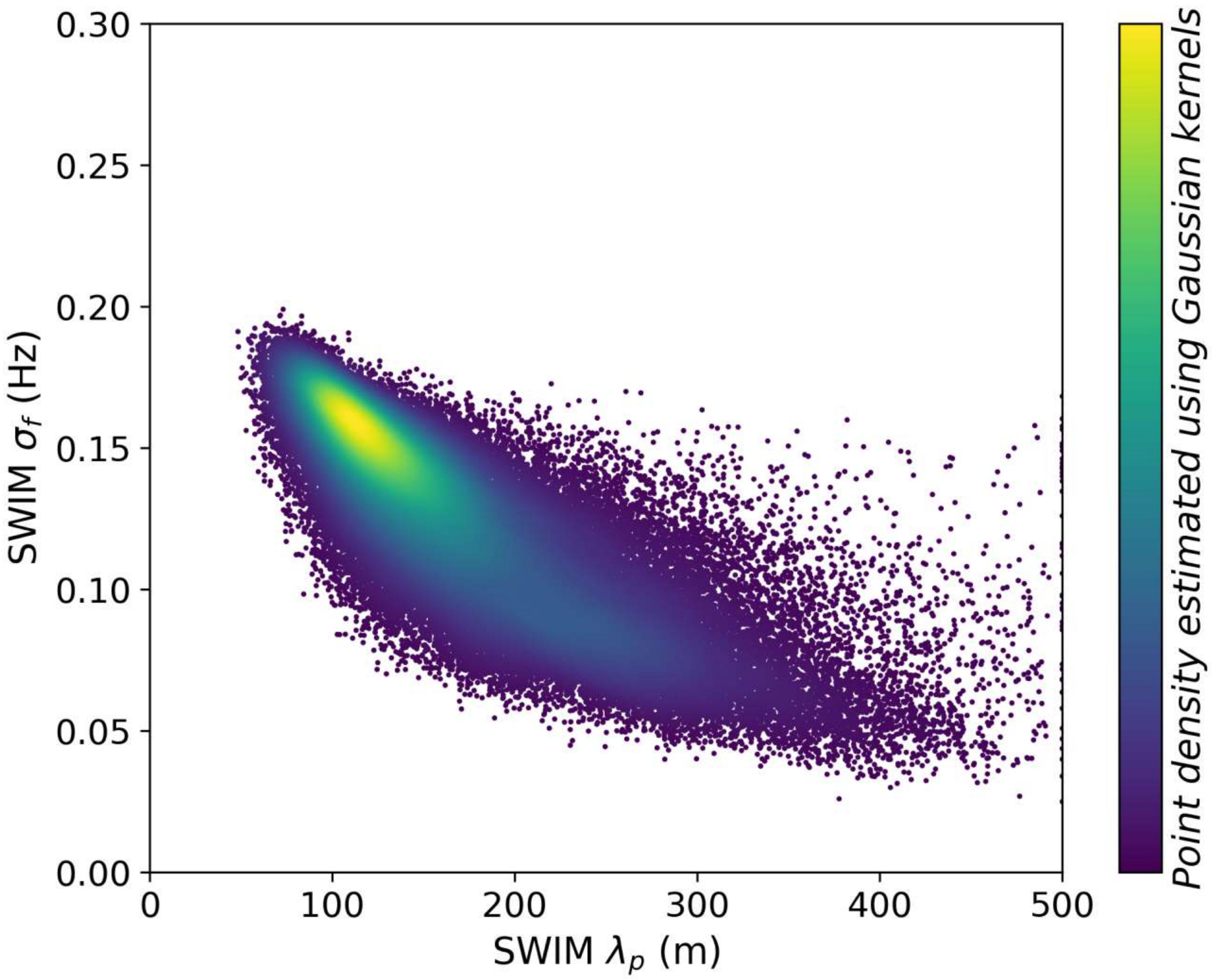
- 10 - 22 of September 2019.
- High sea state situations in the Southern Ocean and near the coasts of Greenland and North America.
- SWIM resolution:
  - 1 spectrum covers a surface of 90x70 km^2,
  - global coverage in 13 days.
- Comparisons with the wave model MFWAM.





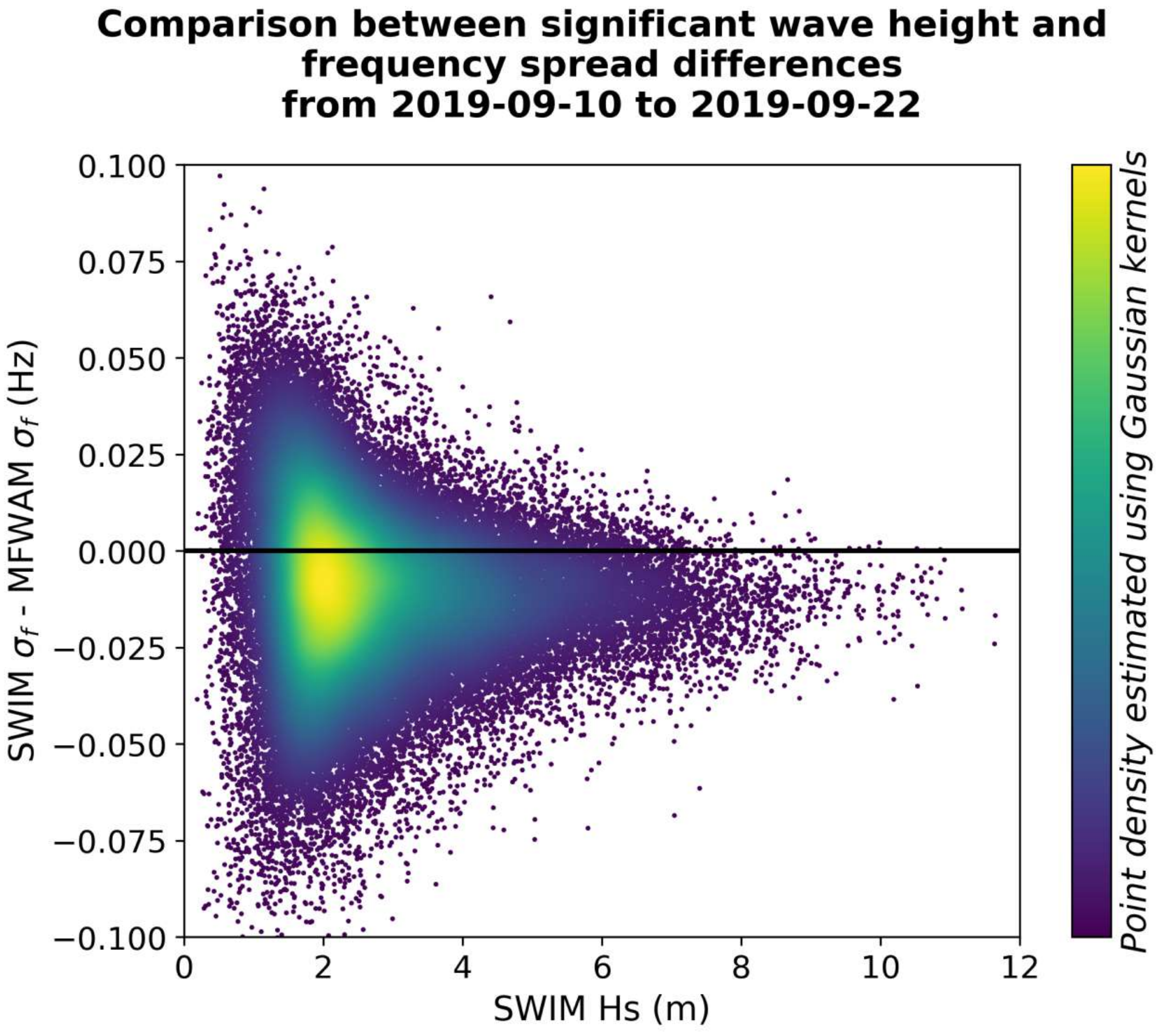
Frequency spread as a function of Hs and λ_p





- High values of frequency spread → low **Hs** and $\boldsymbol{\lambda_p}$,
- the frequency spread **decreases** as the sea state **develops**,

Frequency spread

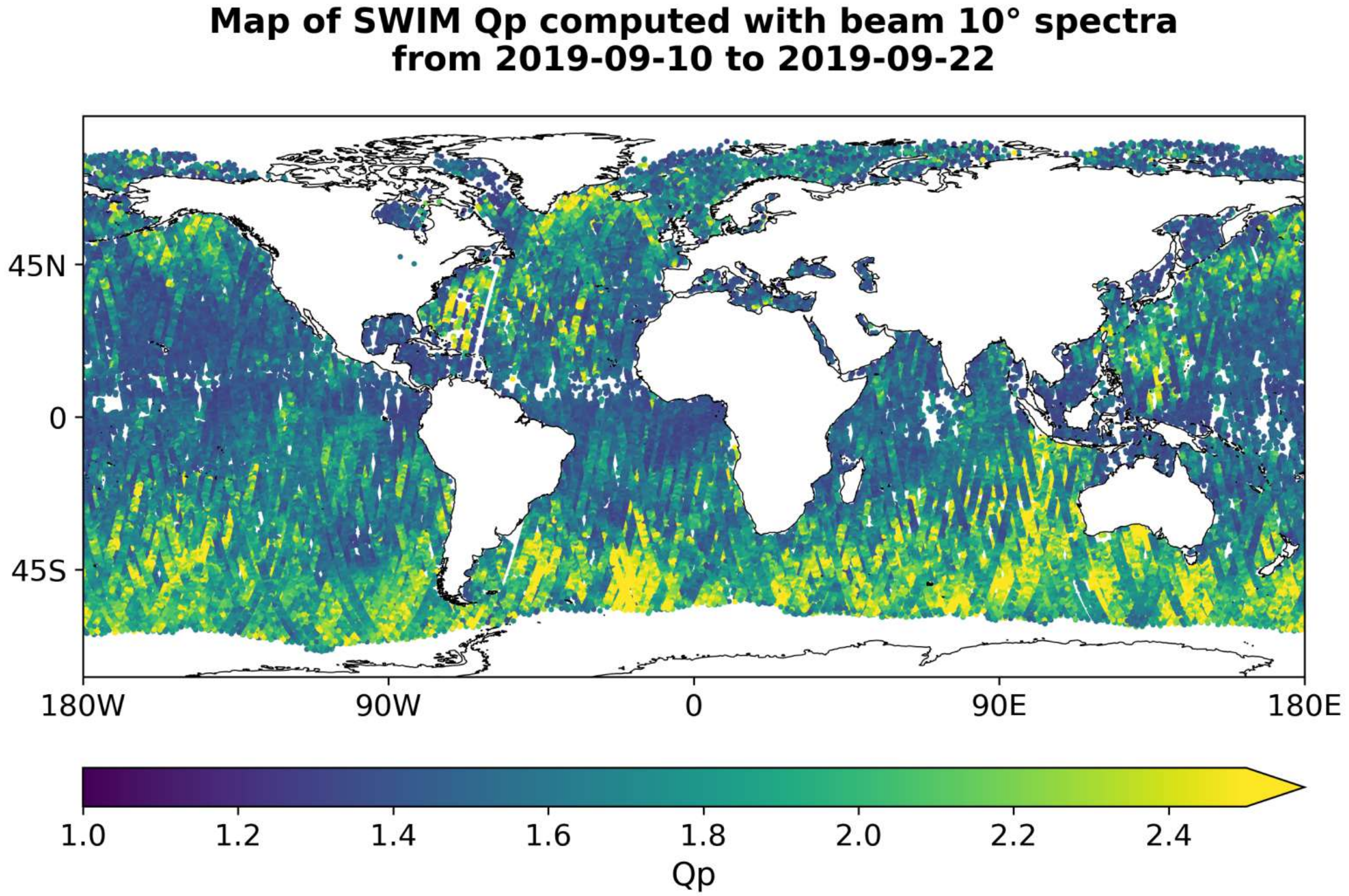


- **Important dispersion** for situations with low Hs:
  → **young sea states** or **mixed seas**.

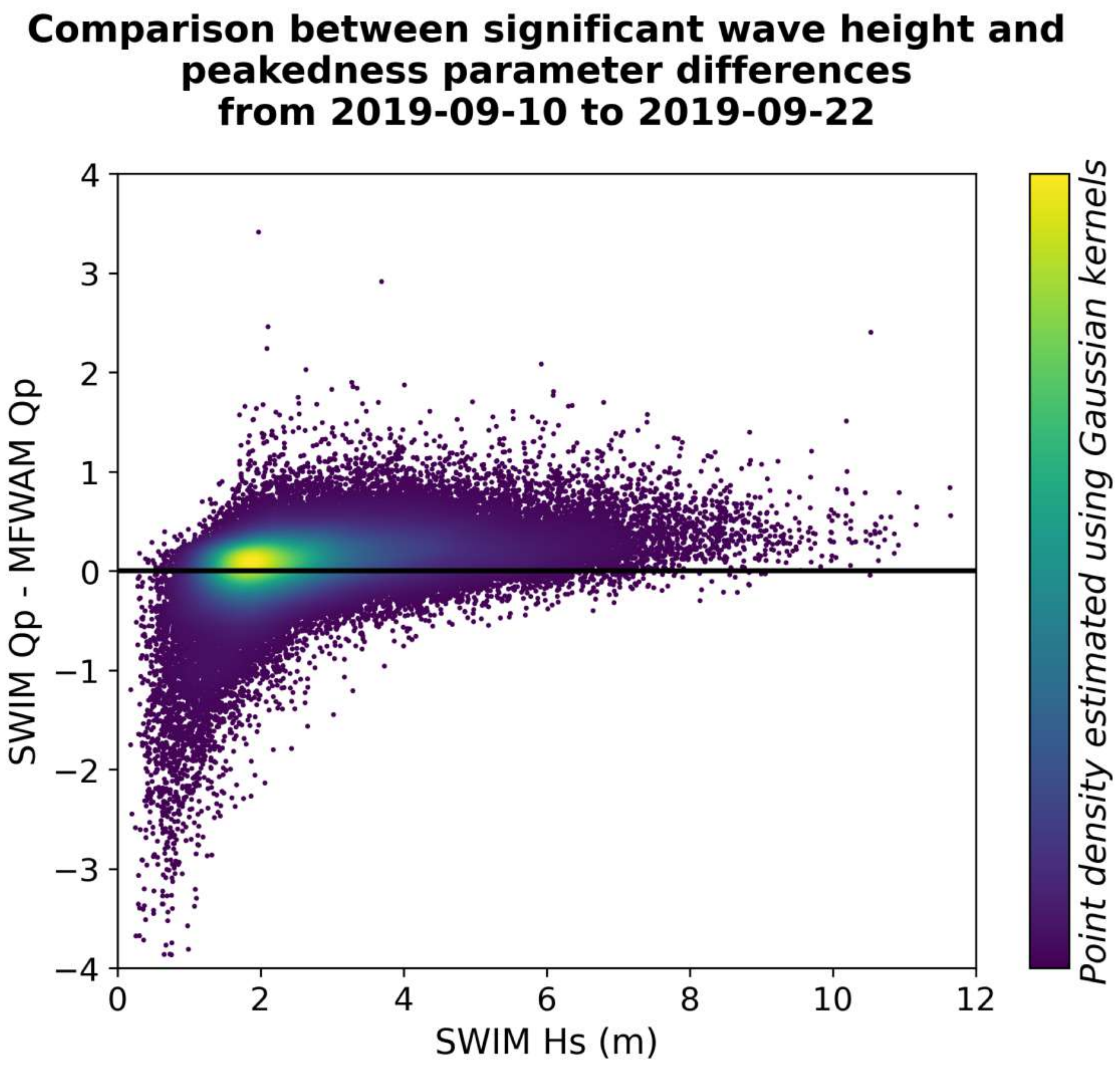
- Systematic negative bias especially for situations with Hs > 4 m.

Same conclusions with the data of the real aperture airborne radar KuROS (Le Merle et al., 2019):
→ difficulties of the model to correctly represent the shape of the spectrum during the wave growth processes.

Peakedness parameter

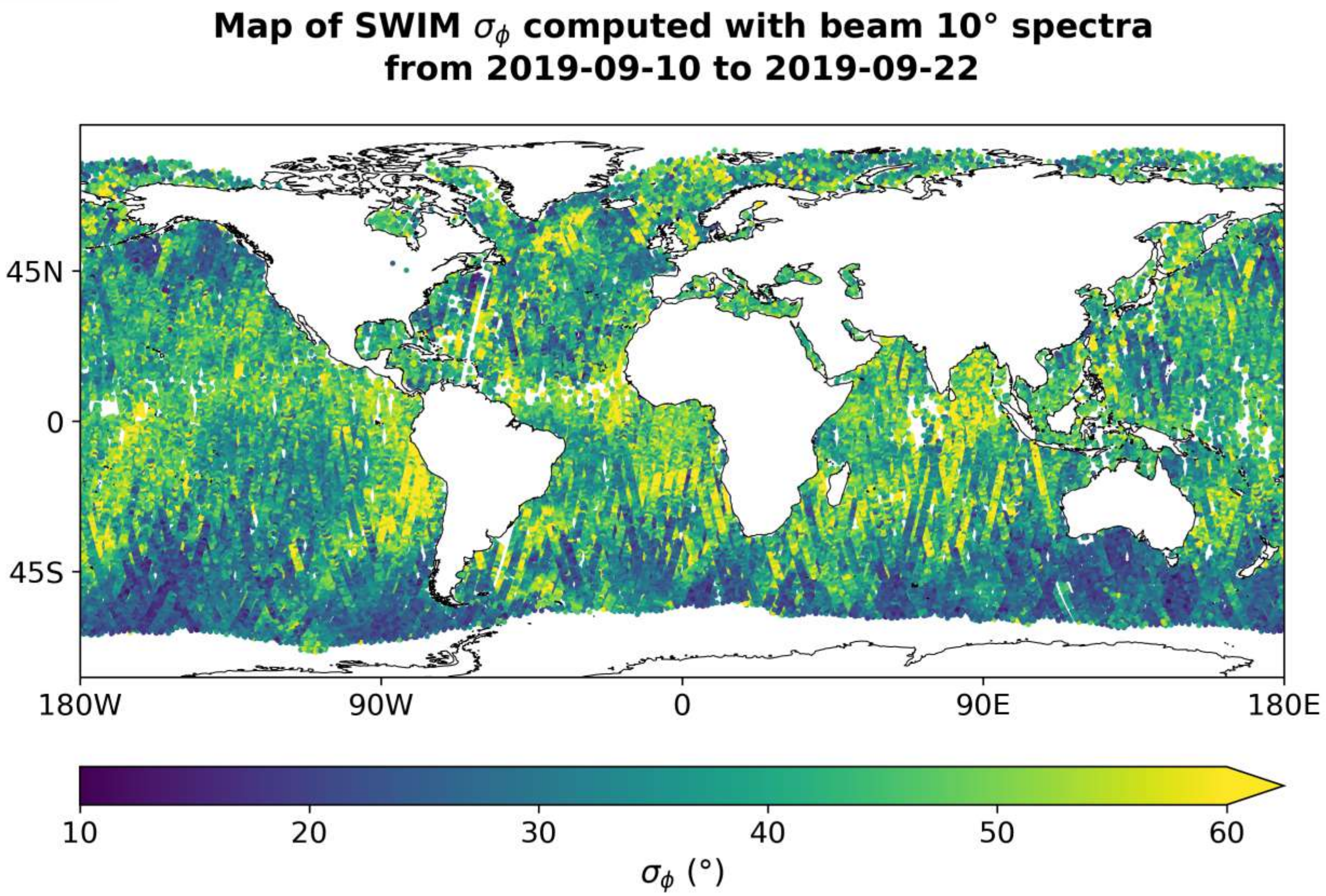


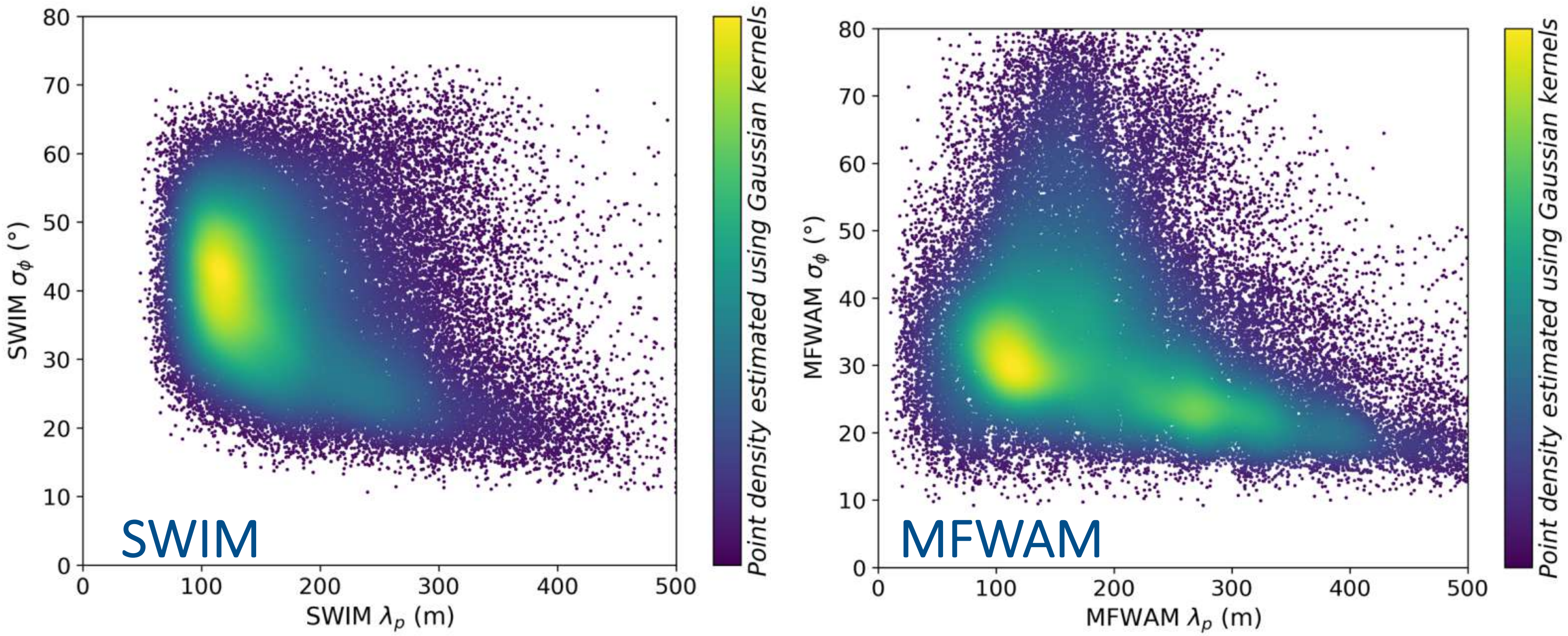
High values of Qp correspond to situations with high sea state → strong wind and high Hs



Mean positive bias. More obvious for situations with Hs > 4 m.

Directional spread





Directional spread calculated at the peak of the spectra

- Situations with short dominant wavelengths (< 200m):
  - → SWIM: $\overline{\sigma_\phi} \approx 45°$,
  - → MFWAM: $\overline{\sigma_\phi} \approx 30°$.
- Situations with long dominant wavelengths (> 200 m):
  - → good agreement SWIM - MFWAM,
  - → $\overline{\sigma_\phi} \approx 25°$.

Directional Benjamin Feir Index (BFI_{2D})

- Appropriate indicator of **non-linear interactions** between waves and of **probability of occurrence of extreme waves** (Janssen & Bidlot, 2009 ; Mori et al., 2011).

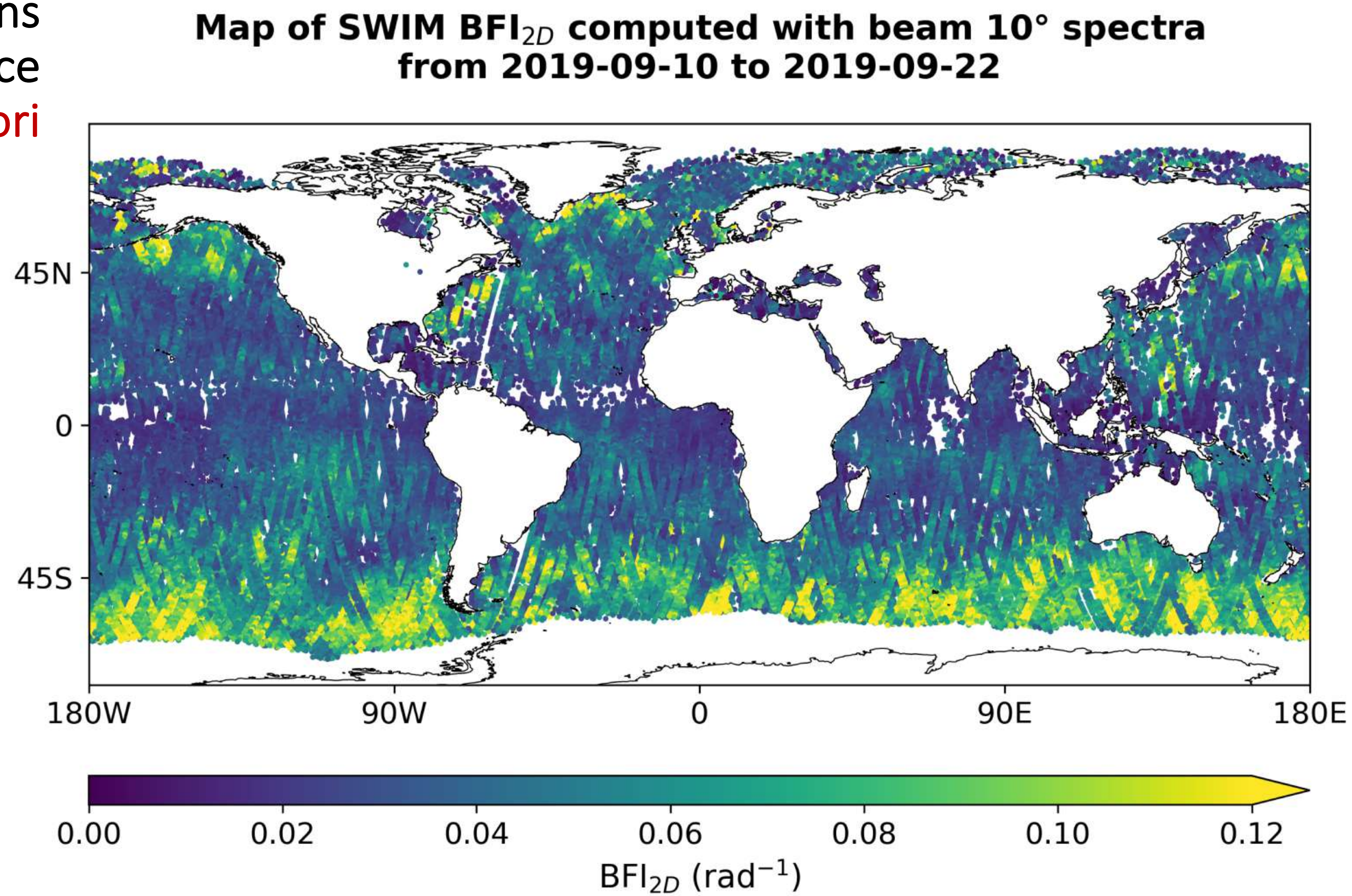
Significant slope

« Peakedness » parameter

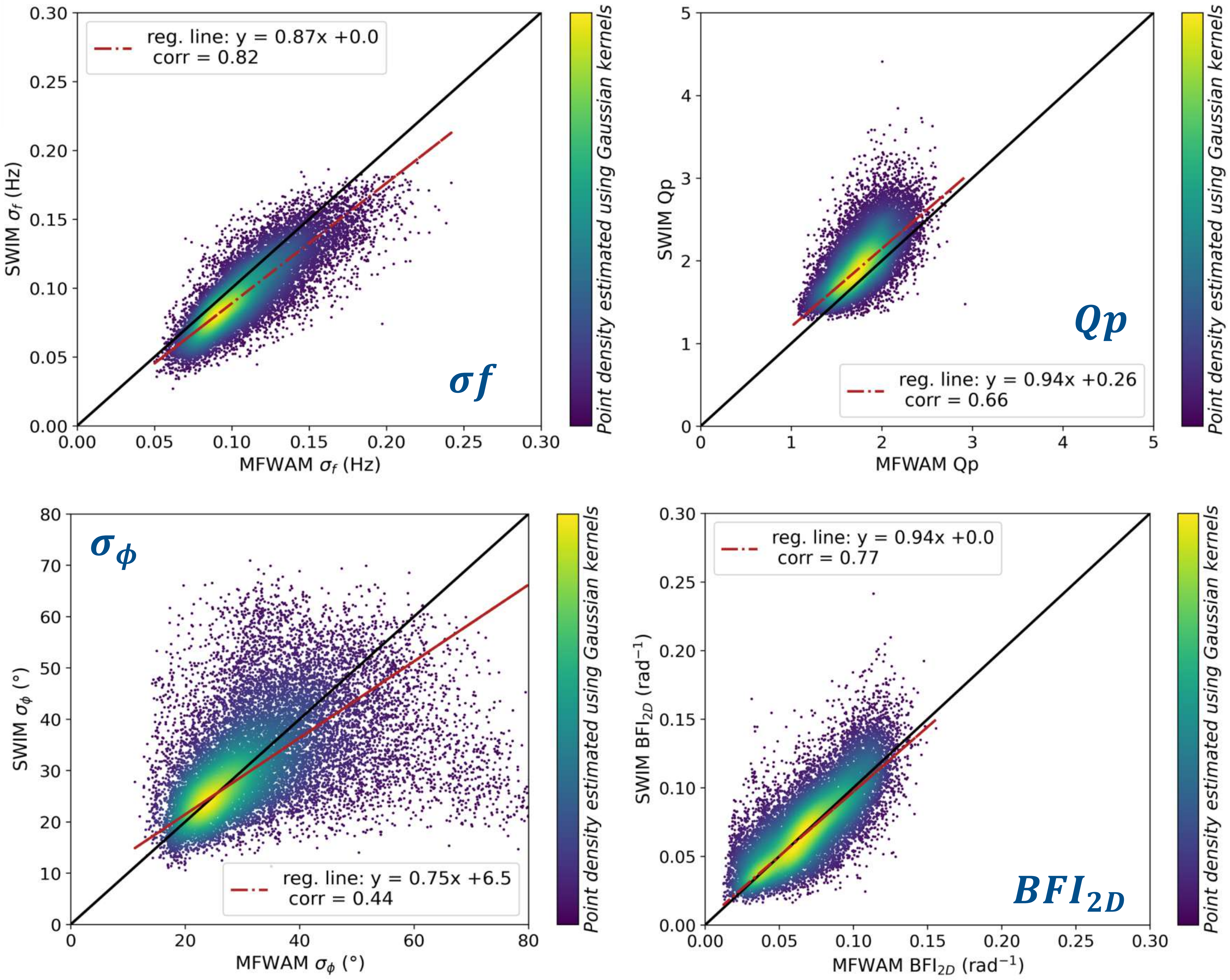
$$BFI_{2D} = \frac{k_0\sqrt{m_0}\,Qp\sqrt{2\pi}}{\sqrt{1 + 3.55 * \sigma_\phi^2 \pi Qp^2}}$$

Directional spread

First map of BFI at the global scale obtained exclusively with observations.



Focus on the Southern Ocean (40°S - 70° S)



- Extreme sea state situation : $\overline{Hs}$ = 4 m.
- Systematic bias between SWIM and MFWAM for Qp and σf.
- Small bias but important dispersion for $\sigma\phi$.
- Good agreement for BFI_{2D} due to a compensating effect.

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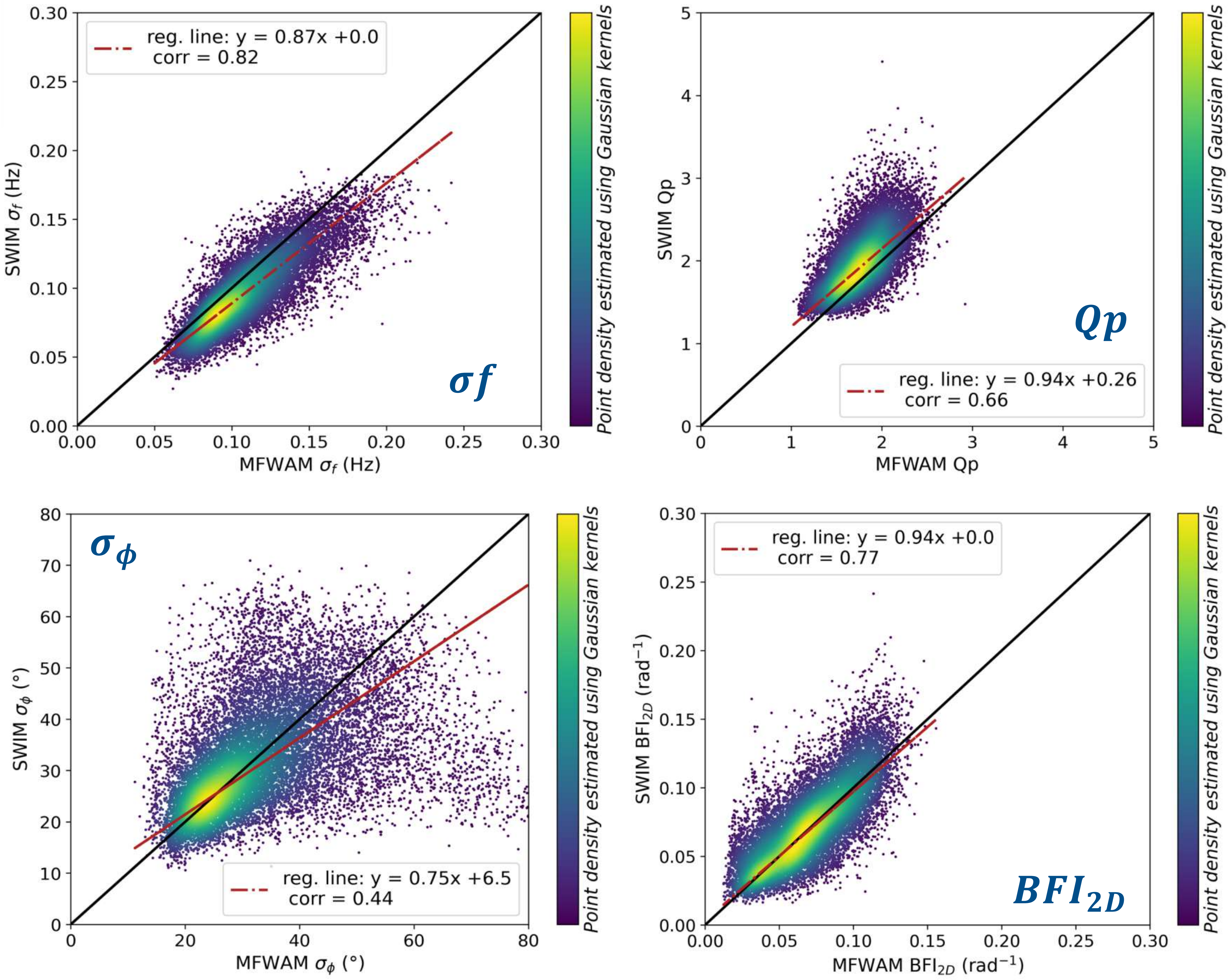

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Directional spread

Evolution of the directional spread as a function of frequency

→ Study the evolution of the directional spread as a function of frequency for different sea states

- Data from the Southern Ocean (40°S-70°S)
- Sea state categories with the wave age ($1/\Omega$)

$$^{1}/_{\Omega} = \frac{c_p}{U_{10}\ \cos(\theta_{wind} - \theta_{waves})}$$

Three categories:

- Young wind sea $1/\Omega < 1$
- Mature wind sea $1 < 1/\Omega < 1.2$
- Swell $1.2 < 1/\Omega$

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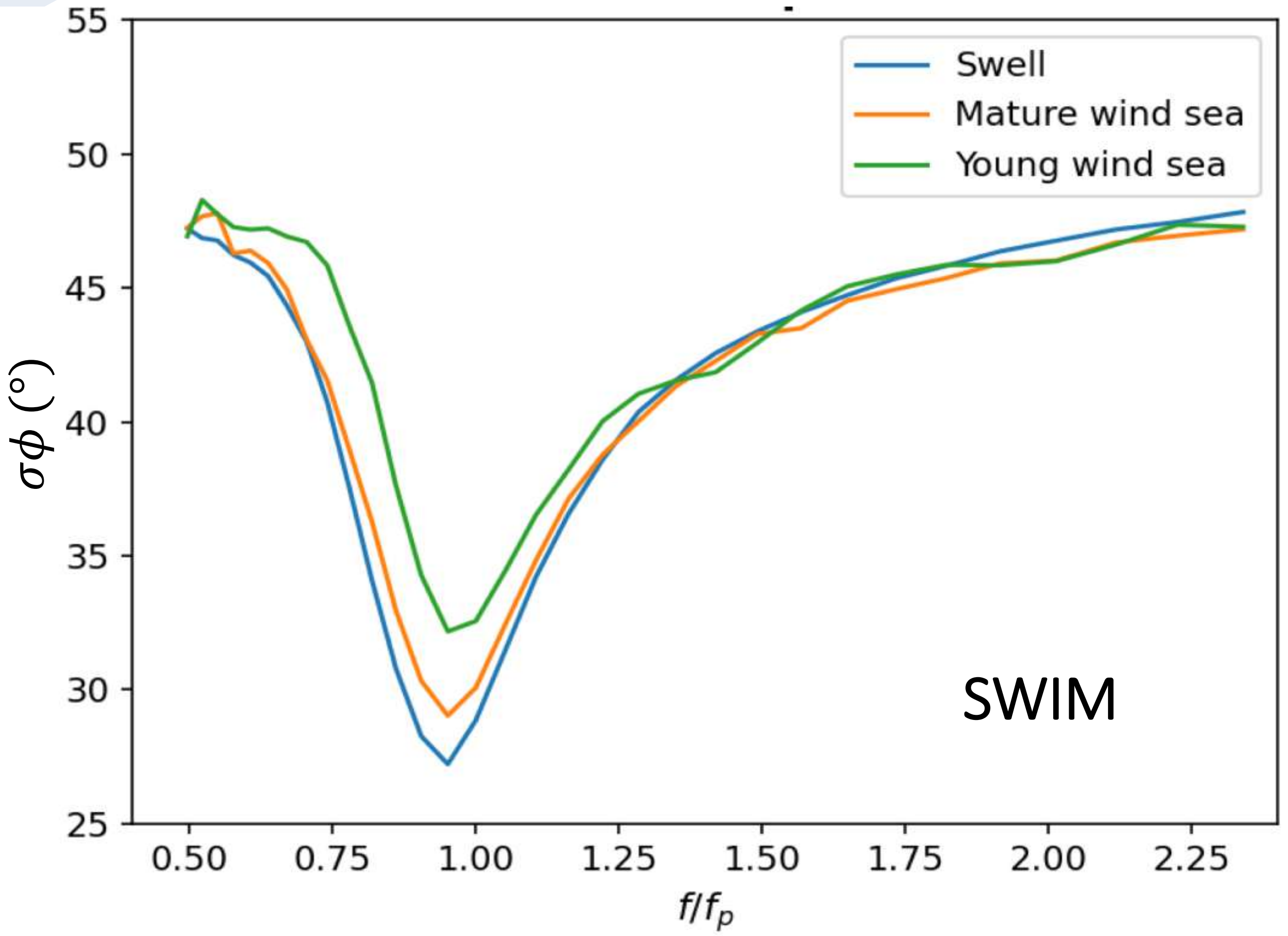
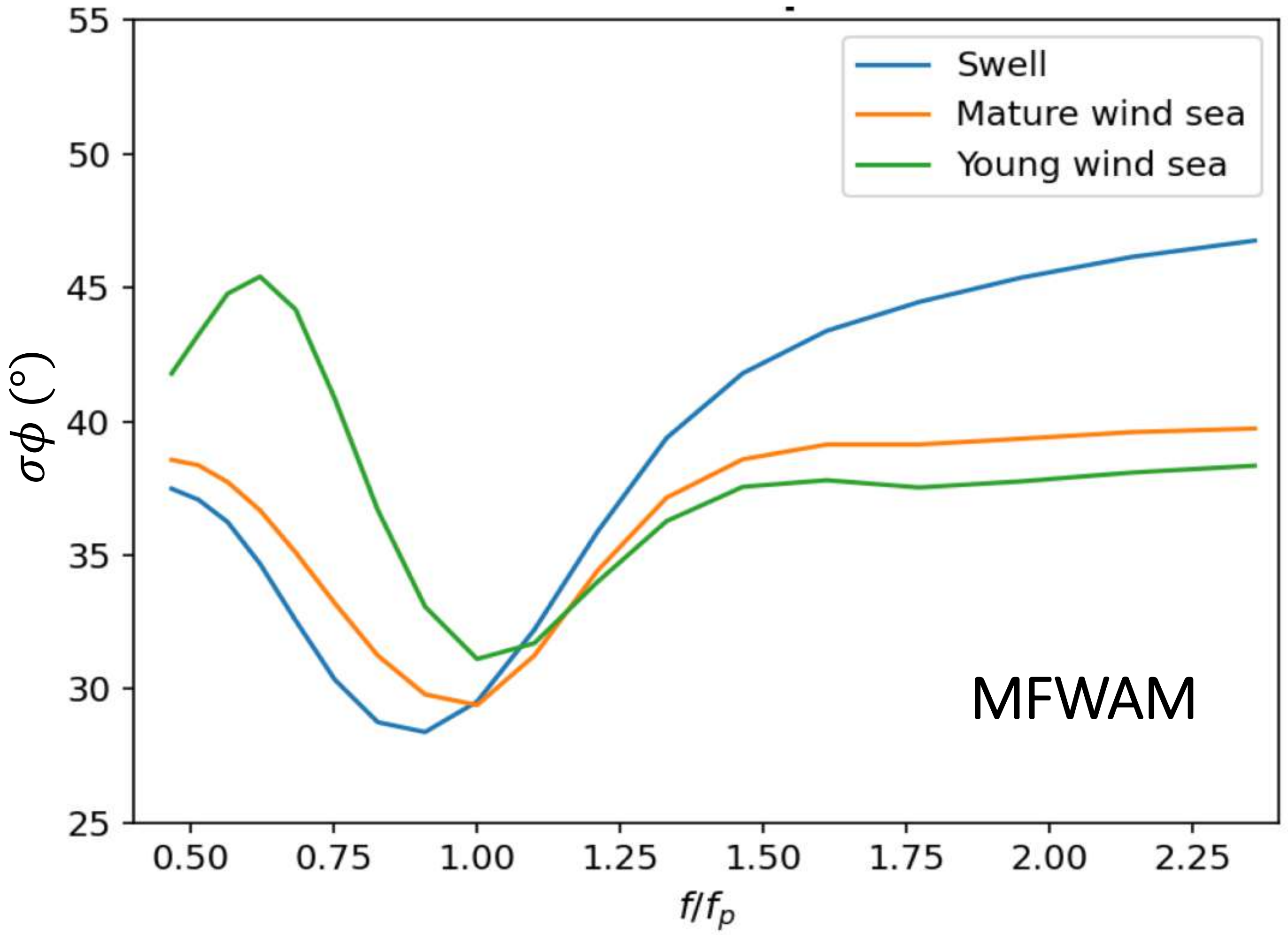
One category → one average spectrum:

- Spectra are expressed as a function of f/fp
- Spectra are rotated in direction
  → mean wave propagation direction = North
- Spectra of a same category are averaged

Evolution of the directional spread as a function of frequency



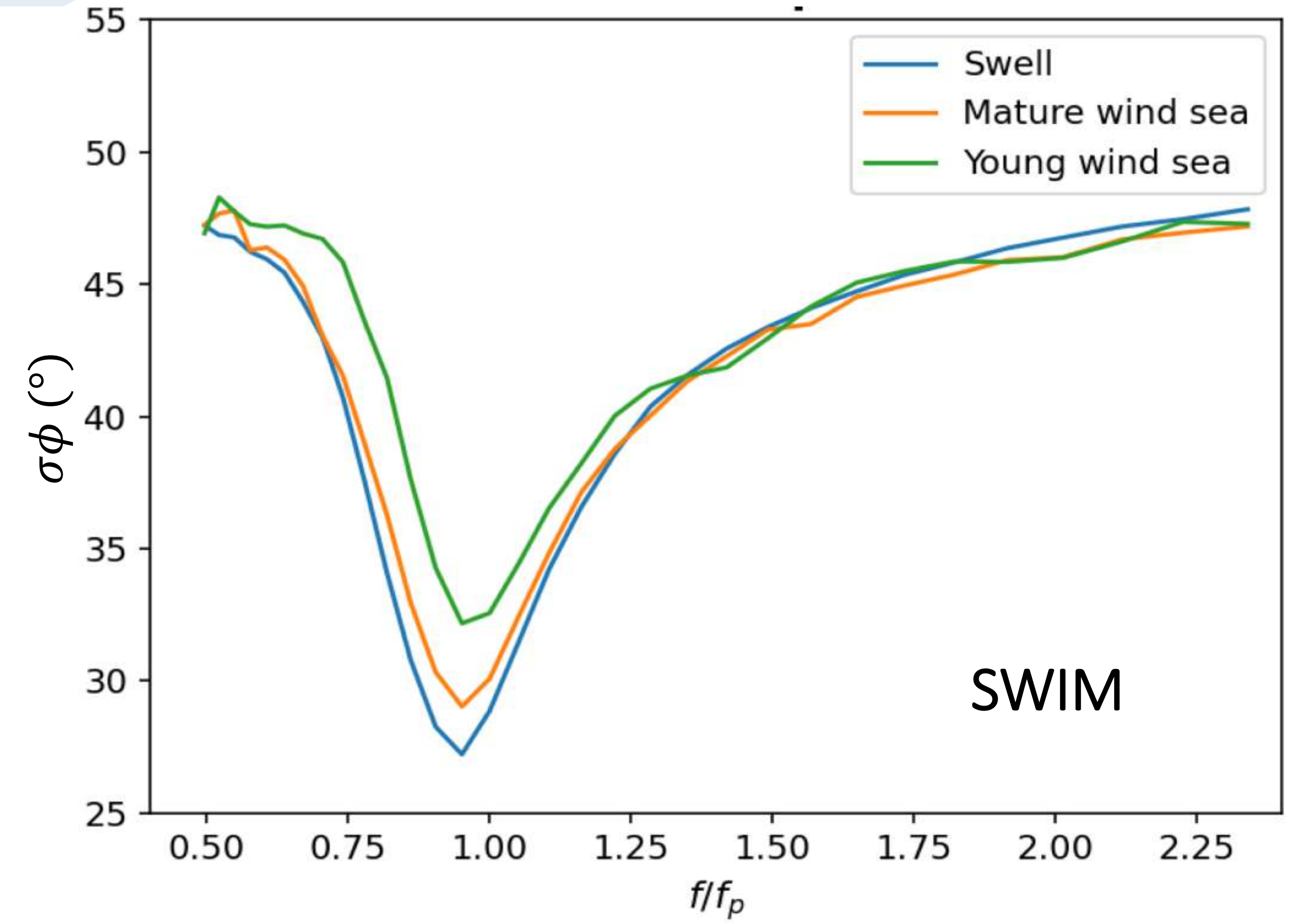


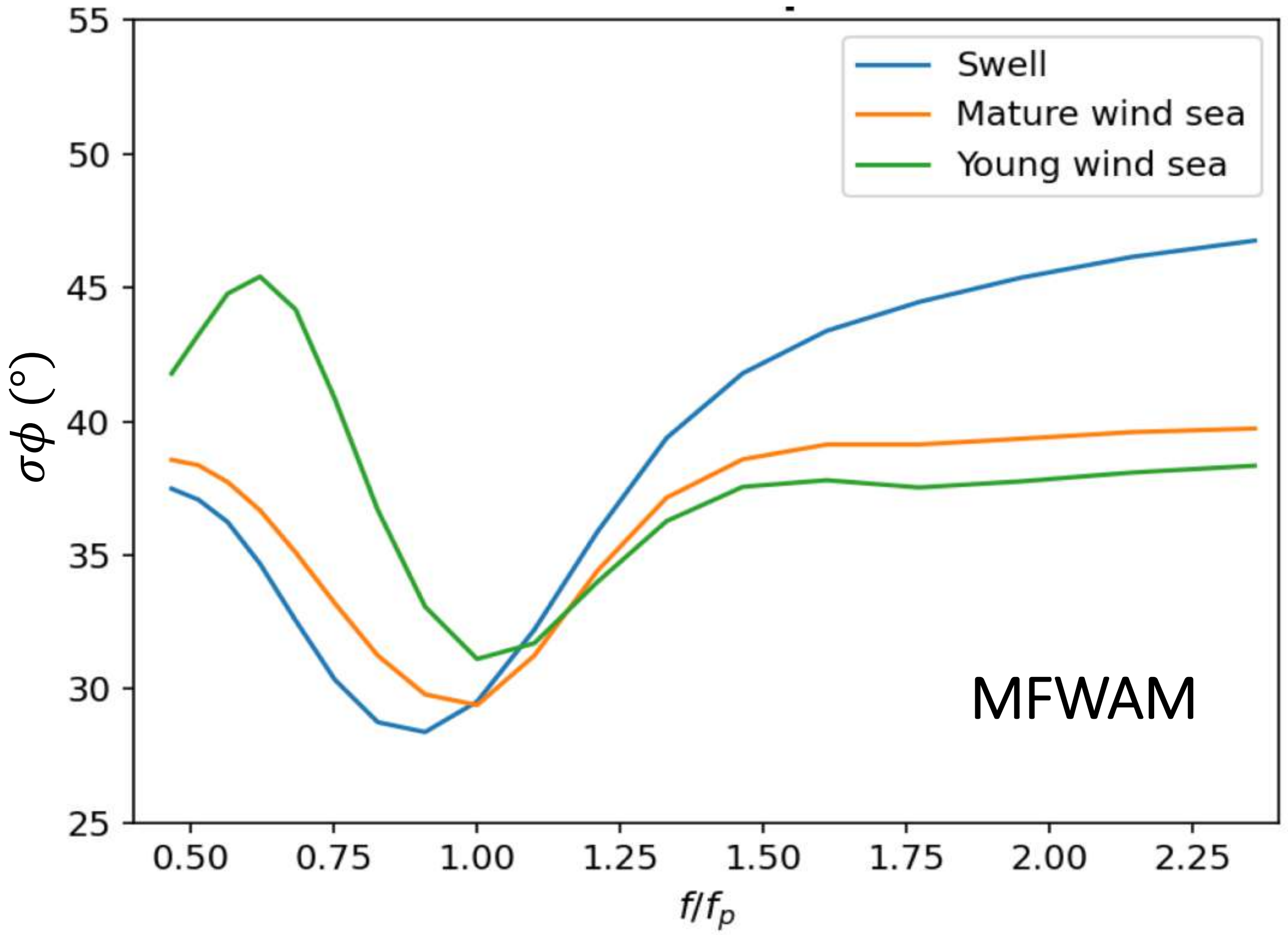
Directional spread:

$$\sigma_\phi(f) = \sqrt{2 \times \left(1 - \sqrt{a_1(f)^2 + b_1(f)^2}\right)}$$

Using the first pair of Fourier coefficients (expressed as a function of directional spectra).

Evolution of the directional spread as a function of frequency





	SWIM	MFWAM	Literature
Minimum at f/f_p=1	Yes	No	More yes (Mitsuyasu et al., 1975; Ewans, 1998; Babanin and Soloviev, 1998; Hwang et al., 2000; Pettersson et al., 2003; Romero and Melville, 2010)
Dependence w/ sea state at f/f_p=1	Yes	Yes	No except in Romero and Melville (2010)
Dependence w/ sea state at f/f_p=1.2	No	Yes	More no (Mitsuyasu et al., 1975; Hasselmann et al., 1980; Ewans, 1998; Babanin & Soloviev, 1998.)

Conclusions (1/2)

- **SWIM brings new and original information** about the wave field:
  - shape spectrum parameter and BFI,
  - useful for prediction purposes, climatological surveys and to better understand wave processes.

- **Differences** between SWIM and MFWAM are **more obvious in extreme sea state conditions** (Southern Ocean).

- Shape parameters seem to be good indicators of the wave evolution stages.

Conclusions (2/2)

- The behavior of the **angular spread** with the normalized frequency and with the wave development is in **good agreement with the literature**.

- SWIM limitations are in **enclosed seas** for the **spectrum frequency shape** and when the **waves propagate in the satellite direction** for the **spectrum directional shape**.

- Promising → **SWIM** data has already been **assimilated** in a wave model and its measurements **improve** the model **results** especially in extreme sea state areas (Aouf et al., 2021).

Perspectives

- Compare SWIM data to buoy data.
- Analyse the impact of mixed sea systems on these shape parameters.
- Study wave characteristics in the current areas.
- Measurement campaign SUMOS (Feb-Mar 2021)
  - Co-localised data with the KuROS airborne radar, buoys and the instrumented boat "*Atalante*"
  - Diverse sea state situations with long swells superimposed with wind seas