New directional wave satellite observations : Towards improved wave forecasts and climate description in Southern Ocean

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Key Points:

- The assimilation of partitions wavenumber components induces a significant reduction of SWH bias in Southern Ocean.
- The study clearly reveals the improvement of the energy transfer of wind waves during the wave growth phase under unlimited fetch conditions such in Pacific Southern Ocean.
- The wave age and dominant wavenumber have been significantly corrected by the assimilation of directional observations of SWIM compared to the assimilation of SWH-nadir only.

Abstract

In spite of continous improvements of ocean wave models in the last decades, results still show large in certain condition, in particular in strongly forced conditions, as encountered in the Southern Ocean, where strong westerly winds generate some of the fiercest waves on Earth in almost unlimited fetch conditions. The newly launched Chinese-French Oceanography Satellite (CFOSAT) provides directional spectra of ocean waves for both wind seas and swells. Compared to Synthetic Aperture Radar (SAR), it resolves shorter wavelengths, which dominates in non-fully developed wind waves. Here we demonstrate that the assimilation of the wave number components from CFOSAT spectra produce more accurate predictions of wave growth than assimilation of significant wave height alone and results in a notable reduction of model bias in the Southern Ocean, especially in the Pacific Ocean sector. In addition results also indicate a downward shift of the wave age consistent with theoretical wave growth curves.

Plain Language Summary

This work focuses on the importance of using directional wave observations to improve model wave prediction in the Southern Ocean. The results indicate a significant impact on the transition from a wind-dependent sea to a well-developed sea. A direct consequence of this work will concern a better understanding of the wave climate in Southern Ocean and therefore an improvement of coupled ocean/waves/atmosphere systems.

1 Introduction

The accuracy of wave prediction models has increased notably over the past decade, following the improvement of atmospheric models, which provide the wind forcing. Furthermore, development of assimilation techniques has allowed the incorporation of satellite data into models to optimize performances (Lionello et al, 1992). In this respect, space-borne altimeter sensors scan the ocean surface globally and return observations of significant wave height—a measure of the overall energy content of the wavy surface—which contributes to adjusting the variance of the wave energy spectrum. Moreover, Synthetic Aperture Radar (SAR) technology provides images that can be converted into directional wave energy spectra. Assimilation of the latter enables a more comprehensive control of the energy density function, not only allowing the optimization of the variance, but also controlling wave periods and wave directions for example (Aouf et al, 2019). Nevertheless, SAR only detects swell systems, i.e. a long wave system no longer under the effect of local wind, with wavelength longer than 200 m (Collard et al. 2005), but does not resolve, and thus assimilation does not correct, the wind sea, i.e. the short-wave components directly generated by the local wind.

Generation and growth of wind sea depend on the fetch conditions (Hasselman et al, 1973, Donelan et al, 1985, Young 1999), and generate (nonlinear) energy transfer across wave scales until an equilibrium state (full development) is reached. More specifically, the transfer consists of an inverse cascade transferring energy from high to low frequencies, which downshifts the spectral peak, stretches the wavelengths and consequently accelerates the wave phase speed.

Growth stops, and wind sea becomes swell, when the ratio of the wave phase speed to the wind speed (i.e. wave age) is greater than about 1.2 (atmosphere cannot force waves that move faster than the wind, Pierson and Moskovitz 1964, Phillips 1977, Hasselmann et al. 1973, Young 1999). Concomitantly, there is a direct cascade that shifts energy towards high frequencies, forcing energy to dissipate mostly by wave breaking and counterbalancing wind input.

Energy further re-distributes across directions so that the wave spectrum broadens during growth (e.g. Hasselmann et al , 1980, Donelan et al, 1985, Fadaeiazar et al., 2020). The directional distribution and integrated values such as the mean wave direction are crucial parameters affecting wave growth through wind input, as the atmosphere forces energy into wave components that are aligned (and almost aligned) with wind. Despite their role, however, directional properties remain one of the less known properties of the ocean surface. Contemporary wave models use parametrizations to shape the directional spreading during the wave growth, which assume the directional distribution being unimodal (i.e. energy is concentrated around one dominant direction, Hasselmann et al. 1980, Mitsuyasu et al. 1975, Donelan et al. 1985) and defined by a directional spreading function of the form $\cos^{2s}()\vartheta$, where ϑ is the wave propagation direction. Nevertheless, there is no general consensus on the shape of the directional distribution. Moreover, field and laboratory observations have also suggested that the nonlinear interactions induce a bimodal directional distribution in the early state of wave growth (Young 1995, Ewans 1998, Toffoli et al. 2010, Toffoli et al. 2017), with the angle of separation among peaks depending on the wave age and wind direction (Long and Resio 2006). Peaks eventually merge into a unimodal directional function consistent with $\cos^{2s}(\vartheta)$ when approaching full development (e.g. Toffoli et al. 2017, Fadaeiazar et al., 2020).

Uncertainties on the directional properties affect the identification of those wave components that are aligned with the wind and thus translate into errors in the estimation of the wind input process in the wave prediction model. The extent of these errors is yet to be quantified. As contemporary satellite products cannot optimize wind sea, the latter remains a notable source of model errors, resulting in an overestimation of significant wave height (positive bias). This is exacerbated in the Southern Ocean (Ziegler et al. 2015)-a region covering an uninterrupted band of water around Antarctica south of the main landmasses of Africa, Australia, and South America—that is dominated by strong westerly winds, which blows all-the-year-round with almost unlimited fetches and speed in excess of 13 m/s during summer months and 18 m/s during winter months (Young et al. 2020). These intense winds generate some of the fiercest waves on the planet with high percentiles of wave height exceeding 5 m during summer and 7 m during winter (e.g. Babanin et al. 2019, Barbariol et al. 2019, Letraon et al. 2019, Vichi et al. 2019, Young et al. 2020).

The newly launched Chinese-French Oceanography Satellite (CFOSAT) uses Surface Wave Investigation Measurements (SWIM) sensor (Hauser et al. 2018) to monitor the ocean surface. Compared toSAR, SWIM resolves a broader range of wavelengths, spanning from 70 to 500 m, and returns a directional wave energy spectrum that includes both wind sea and swells. Here we discuss the effect of data assimilation on model performance in the Southern Ocean. We demonstrate that assimilating directional properties from SWIM spectra improves prediction of energy transfer during wave growth and concurrently of significant wave height. We show that

model bias is reduced more efficiently when compared with classical assimilation procedures that incorporate information on the significant wave height only.

2 CFOSAT mission and SWIM spectra

The instrument SWIM of CFOSAT is a real aperture scanning radar which provides directional wave spectra from several off-nadir beams (pointing at 6, 8 an 10°). Each spectrum is representative of an area of about ±35 km along-track by 90 km on each side of the nadir track, and is discretised over 32 wave numbers from [0.0126–0.279] rad/m, corresponding to the wavelength domain [22–500] m, with a geometric progression of 1.1, and 12 directions , i.e, every 15° with a 180° ambiguity in the propagation direction. During the calibration/validation phase of the mission a detailed analysis was carried out to evaluate the ability of SWIM to provide accurate parameters from the wave spectra (see Hauser et al. 2020) such as the dominant direction, dominant wave height and significant wave height. It was concluded that, except when waves propagate close to the along-track direction directional wave spectra can be provided with good accuracy over the wavelengths range of 70 to 500 m (see Hauser et al. 2020). In this study we use the directional wave spectra from the beam 10° which have been shown to perform better in comparison with the other beams (see Hauser et al, 2020). SWIM also provides Significant Wave Height (SWH) along its track from nadir measurements just like the classical altimeter measurement (referred to as SWIM-nadir).For the assimilation, we used observations made over a 36 days period from April 26 to 1 June 2019. During this period, 343885 wave spectra from SWIM were collected for the global ocean, and 95281 of which were from the Southern Ocean.

3 Numerical model and data assimilation technique

The MFWAM wave model describes the evolution of wave spectra in space and time through the wave action conservation equation with source terms representing the wave generation by the wind, the non-linear interactions and the wave breaking at sea surface. The wave model MFWAM of Meteo-France is based on the IFS-ECWAM computing code of the ECMWF (see IFS-38R2). The model MFWAM uses an ST4 dissipation term related to wave breaking as developed by Ardhuin et al. (2010). Also, in the MFWAM model the wind input source term takes into account a dissipation term due to the damping of the swell by the surface friction. The non-linear interactions are represented by the Discrete Interaction Approximation (DIA) which is a common approximation in numerical wave models due to its computational efficiency. The MFWAM model is used for the global wave system of the Copernicus Marine Service with a recent update which takes into account a spectra tail in the form of the Phillips' spectrum. This parameterization is important for the calculation of the total stress provided to the ocean model and the impact of waves on the atmosphere in a coupled simulation.

In the present study the model MFWAM uses a discretization of the wave spectrum in 24 directions (from 0 to 360^{o}) and 30 frequencies increasing from 0.035Hz with a geometric progression of 1.1. The MFWAM model is set for a global configuration with a grid resolution of 0.5°. The model is forced by analyzed winds and sea ice fraction provided by the IFS atmospheric system of the ECMWF. Four sets of simulations were run : (i) with assimilation of wavenumber components Kx and Ky from SWIM spectra (run A); (ii) with assimilation of SWIM SWH only (run B); (iii) with assimilation of both SWH and wave number components

(run C); and (iv) without assimilation (run D) as a control run to examine the impact (or to build a benchmark database).

Wavenumber components were assimilated into the model with the following scheme (Aouf et al., 2006 & 2019): (i) model and SWIM spectra are partitioned to separate wind sea from swell systems, following Gerling (1992); (ii) partitions of the model spectra are matched with the SWIM counterpart; (iii) an optimal interpolation between model and observations to the two components Kx and Ky of the partition wave number is applied; and (iv) analyzed partitions are superposed to reconstruct the analyzed wave spectrum, with smoothing procedure to avoid gaps between partitions. Only modes with wavelengths greater than 70 m were used for the assimilation, while the first guess wave spectrum from the model stays unchanged otherwise.

The assimilation of SWH from SWIM instrument at nadir look consists in performing only the optimal interpolation scheme for SWH (as a stand-alone procedure or in conjunction with the assimilation of wavenumber components). Note, however, that assimilation of SWH further requires a scaling of the wave spectrum in the frequency range by using the empirical power laws developed in Lionello et al. (1992). This is the classical approach as used in most operational models (see Aouf and Lefevre 2015).

The study area focuses on the Southern Ocean where a large number of storm events with strong winds are generated during the Southern winter. We should remark that during the period of study surface wind speed exceeding 20 m/s represent 30% for the Pacific Southern Ocean between the longitudes 150°E-250°E.

The Southern Ocean is well covered by altimeter missions. Therefore, the validation of the model simulations is based on significant wave heights provided by the Jason-3, Saral/Altika and Sentinel-3 altimetry missions in this region. Super-observations of SWH from altimeters have been generated on the grid size of the model, which is 0.5°x 0.5°. Thus, to evaluate the impact of assimilation, we compare SWH from the four model runs with those provided by the altimeters on this grid size.

3 Results and discussions

Biases on SWH from the model runs, with respect to the independent altimeter data, are presented in Fig.1 as maps covering the[50°S -70°S] area. For all runs, we can clearly see a dominant trend of positive bias in the Southern Ocean and the highest values are often found in the Pacific Southern Ocean. However negative bias of SWH are also observed in the Atlantic and Indian ocean near the Marginal Ice Zone (MIZ), where it is expected a strong uncertainty on local winds related to sea-ice melt-water. There is an evident reduction of bias when assimilating satellite data into the model. On average, the control run (without assimilation)leads to a mean bias for SWH of approximately 0.13 m (Fig. 1d) with maximum values reaching 1 m. The mean bias reduces to 0.10 m when assimilating the SWH (Fig. 1b). Incorporating wavenumbers in the assimilation contributes significantly to reduce the bias, the latter dropping to 0.03 m for assimilation of wavenumbers only (Fig. 1c) and 0.05 m, when assimilating both wavenumbers and SWH (Fig. 1c).

To examine the impact of the assimilation on high SWH in Southern Ocean, scatter analysis of SWH from MFWAM versus the one from altimeter sensors have been performed for SWH greater than 5 m. Overall, run A results in an excellent correlation with altimeter data, with scatter diagram laying on the slope 1:1 and intercept of 0.04m, substantiating the significant bias reduction. On the contrary, run B shows an overestimation of model results, with data point distributing along a slope of 1.05 and intercept of -0.19m and a mean positive bias of 0.13 m. In terms of Normalized Root Mean Square Error (NRMSE), the best performance for high SWH (gretaer than 5m) is obtained when assimilating wavenumber components (runs A and C) with 10.3%. While for the assimilation of SWH only and the control run, NRMSE are roughly 10.6% and 11%, respectively.

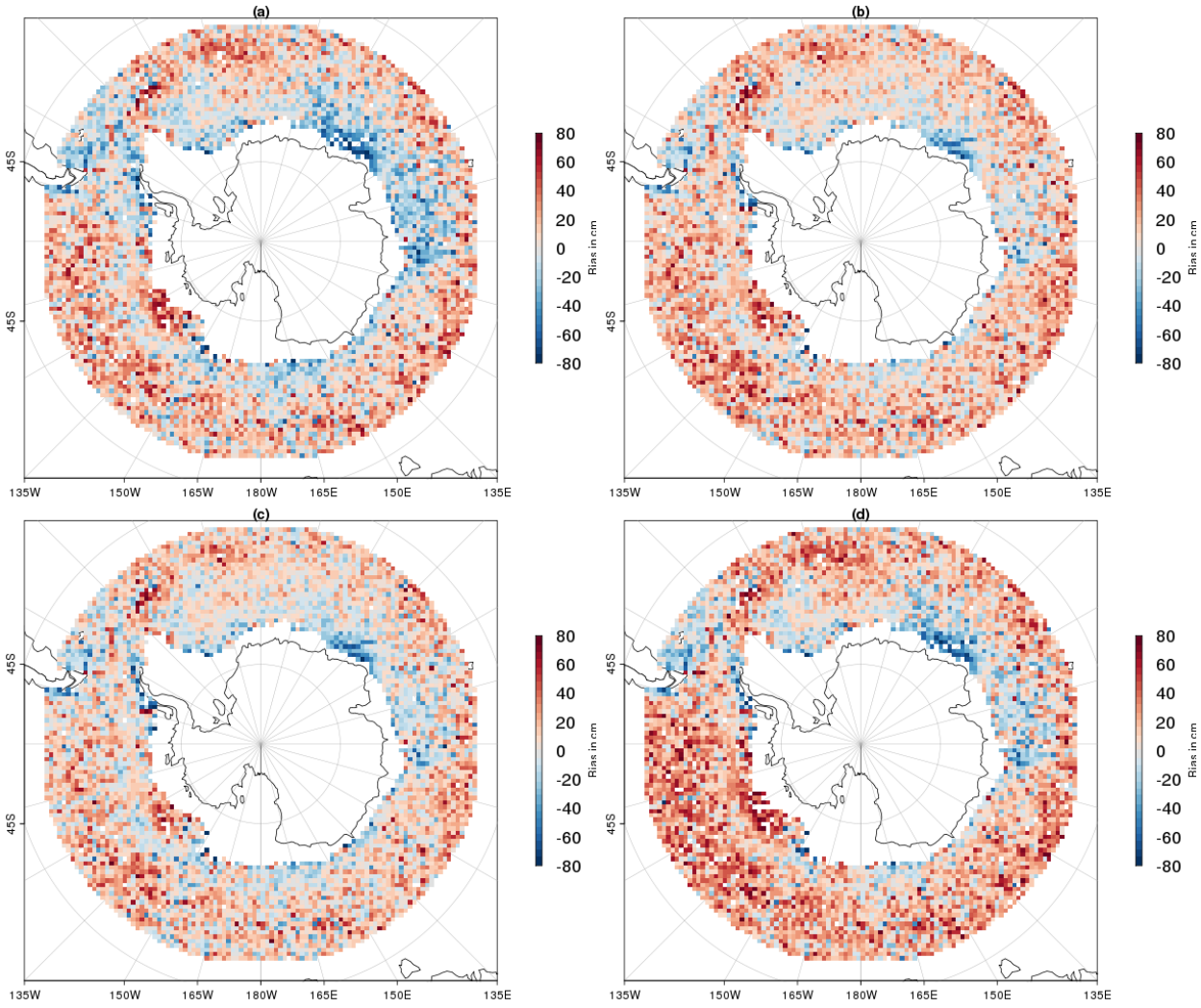

Figure 1. Bias maps of SWH (in cm) for simulations of the MFWAM model in comparison with altimeters Jason-3, Saral/Altika and Sentinel-3 during the period starting from 26 April to 1 June 2019. (a), (b), (c) and (d) indicate runs A, B, C and C, respectively.

To explain this finding, it is interesting to note that in the wind wave growth phase there is a transfer of wave energy from the high frequencies to the smaller frequencies until an equilibrium

state is reached. In general the wind input term in a wave model which describes the wave growth depends, for each frequency, upon the difference of wave and wind directions. The fact that the assimilation of wavenumber components corrects the wave direction and the dominant frequency leads directly to an improvement of the wave growth and the energy transfer for wind waves before the equilibrium state.

Recall that the wave age which is expressed as the ratio of peak wave phase speed C_p and the surface wind speed U_{10}, indicates whether the sea state is windsea or swell dominant. The windsea can therefore be identified by a wave age C_p/U_{10} lower than 1. Figure 2a shows the regional distribution of wind sea, by the probability of occurrence associated with a wave age smaller than 1 (estimated over the analyzed period). There is a general predominance of wind sea throughout the entire Atlantic Ocean and Indian Ocean sectors. This is due to the occurrence of relatively close storm systems, which limits fetch for wave growth.

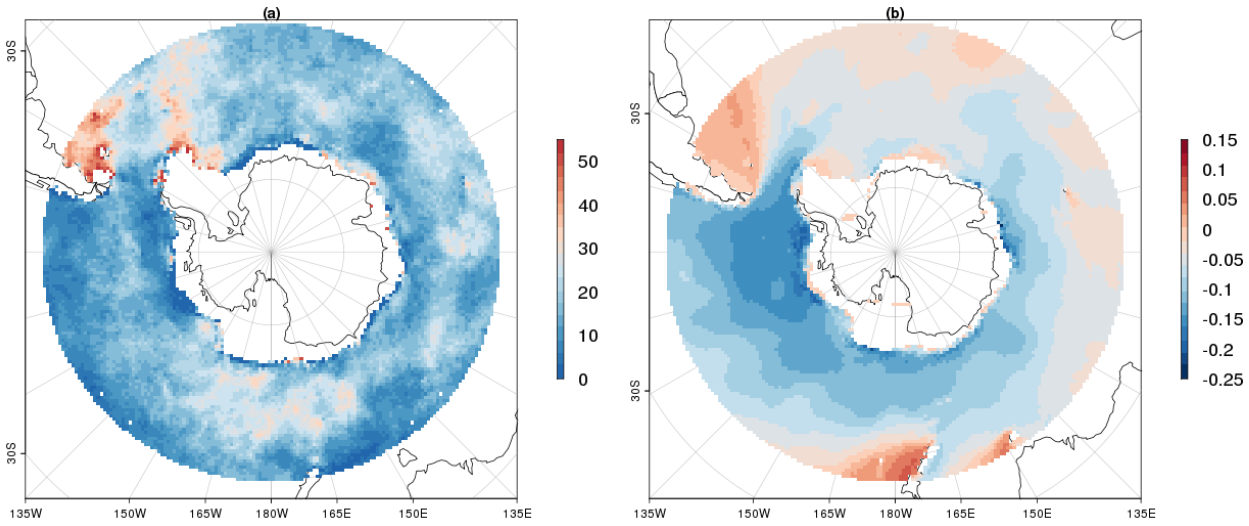

Figure 2. (a) Probability of occurrence (color code) of dominant windsea sea state ($C_p/U_{10}<1$)from the control run A. (b) mean difference of SWH between run A and run D during the period from 26 April to 1 June 2019.

The Pacific Ocean sector, on the contrary, shows two distinct occurrence zones. The first zone is an extended area between 150°E-150°W and South of New Zealand representing a strong occurrence (greater than 25%) of wind sea with uninterrupted fetch conditions. Elsewhere of this zone the low probability of wind sea (i.e. predominance of swell) indicate the presence of fully-developed waves of swell, for instance the drake passage and Chile sector. Figure 2b shows the difference between the mean SWH derived from model runs with assimilation of partition wavenumber components (run A) and benchmark simulation (run D). The assimilation results in a significant reduction of the significant wave height throughout the Southern Ocean in comparison with the control run. The extent of this difference depends on the wave age (cf. Figure 2a). Small differences are reported in the Atlantic Ocean and Indian Ocean Sector, where swell is not dominant (cf. Fig. 2a), while the largest average differences—up to -0.25 m—are found in the Pacific Ocean sector, especially in the Amundsen Sea and Bellingshausen Sea

subsectors and in the Drake passage. There are the areas where the wind sea generated South of New Zealand has transformed into a swell after a long, uninterrupted propagation.

Let's call the difference between assimilation runs and the control run the analysis increment. The impact of run A on the peak wave age indicates two trends on the analysis increment as shown in Figure 3a. The first trend concerns the Pacific Ocean sector and Drake Passage where there is a strong negative analysis increment on average which is linked to the overestimation of the wave age by the run D. The average difference in this sector reaches -0.25. The second trend is observed in the Atlantic and Indian oceans sectors where we see that the assimilation of partitions wavenumbers induces a positive increment. This latter indicates an underestimation of the wave age by the control run D with a maximum average difference of 0.15. By comparing figures 3a and 3b we see that run B mainly indicates positive increments in all sectors and enhanced in some regions the impact in comparison with run A. The negative increment caused by run B is limited and not significant correction. This can be explained by the use of empirical power laws (Lionello et al. 1992) which seems less efficient to correct peak wave age in unlimited fetch conditions in Pacific Southern Ocean.

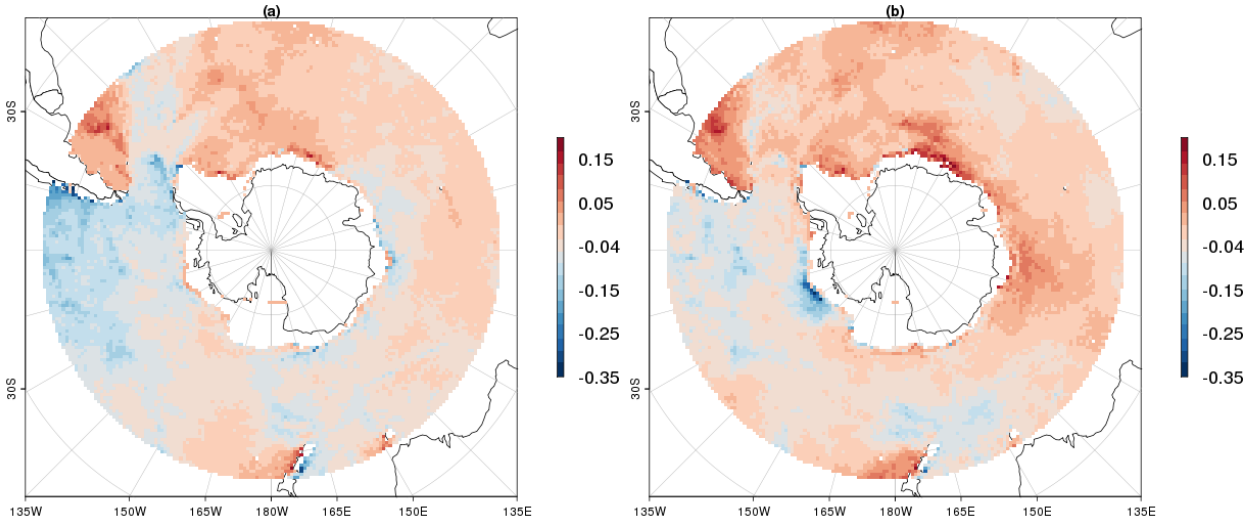

Figure 3. Average of difference of wave age (C_p/U_{10}) of runs with and without assimilation during the period between 26 April and 1 June 2019. (a) stand for the assimilation of wavenumber components (run A), while (b) indicate the assimilation of SWH only. Negative values mean overestimation of wave age and conversely positive values indicate underestimation of the control run.

To investigate the difference between run A and run B we analyzed the analysis increment of dominant wavenumbers from these two runs in comparison with the control run D. Figure 4a and 4b show respectively the analysis increment of the dominant wavenumber of runs A and B as a function of SWH located on the altimeters tracks used for the bias evaluation in the Southern Ocean. We can clearly see that the assimilation of the partition wavenumbers mainly leads to a positive correction of the dominant wavenumber k_p (Fig.4a), which indicates an underestimation of the control run D. This increase of the wave number is clearly visible for strong SWH (greater than 5 m), which shows that assimilation maintains the wave regime in the

growth phase. Figure 4c reveals that the majority of the dominant wavenumbers k_p points are between the theoretical curves of young and mature seas as given by the Elfouhaily spectrum (Elfouhaily et al., 1997). Figure 4c clearly indicates a good consistency of the variation of dominant wavenumber with SWH in comparison with theoretical curves. On the contrary for run B (Fig. 4b) , we notice that the correction of k_p is dominated by negative analysis increments for strong SWH (greater than 5 m). This explains the difficulty of run B to reduce the bias for large SWH, and also to improve the dominant wavenumbers during the growth phase. Figure 4d also indicates that the number of k_p points between the young and mature sea curves is smaller compared to Figure 4c.

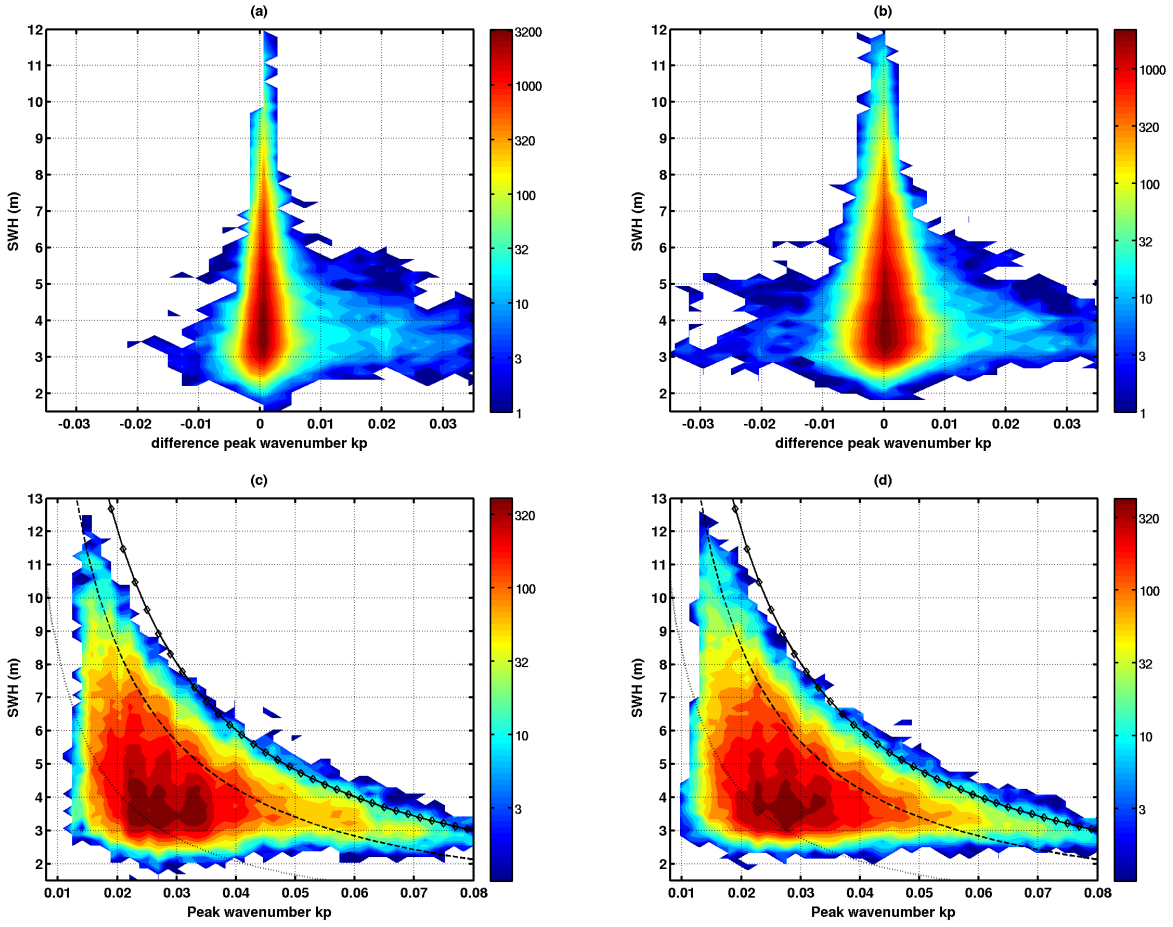

Figure 4.(a,b): variation of analysis increment of peak wavenumber with SWH, for model runs A and B, respectively. (c,d): Relation between SWH peak wavenumber with, for model runs A and B., respectively. The dotted, dashed and diamond lines indicate the theoretical variation for peak wavenumber of young (wave age=0.7), mature (wave age=1) and fully developed (wave age=1.2) seas according to the wave spectrum model of Elfouhaily et al. (1997). With equations (37) and (38) in Elfouhaily et al.(1997), we obtained the following relation $SWH=(0.17/k_p)*\Omega^{-1.7}$ where Ω is the inverse wave age. Color bars indicate the density of points by pixel.

4 Conclusions

The Southern Ocean is dominated by strong wave systems which can impact air-sea interaction and ocean and sea-ice dynamics (e.g. Humphries et al. 2016; Schamle et al. 2019, Thurnherr et al. 2020, Vichi et al. 2019, Alberello et al. 2020). Contemporary wave models provide biased estimates of the significant wave height in this region, despite assimilation of satellite observations. These, however, are limited to significant wave height or truncated directional wave energy spectra, which account for swell systems, but neglect the short wave components of the wind sea. However, with the instrument SWIM carried by the CFOSAT satellite, it is now possible to detect directional wave spectra that resolve both swell and wind-wave systems. This study has demonstrated that the assimilation of the wavenumber components from more comprehensive spectra enhance model prediction of energy transfer during the wave growth phase and concurrently improve estimation of the significant wave height in the Southern Ocean. A validation was conducted by comparing significant wave height from model runs with and without assimilation against observations from altimeter sensors. Overall, data assimilation reduces biases. Model runs, however, show that assimilation of wavenumber components (i.e. directional properties) is more efficient in optimizing the model and results in more substantial bias reduction (from 13cm bias without assimilation to 3cm with assimilation) than assimilation of significant wave height only.

Furthermore, the results show that the assimilation of the wavenumbers components corrects significantly the wave age and the dominant wavenumber in the Souther Ocean, which keeps the wind waves between young and mature seas regimes. This has been verified with the theoritical growth curves (SWH as function with k_p) as given by Elfouhaily et al. (1997). We have observed a better spread of the impact on wave age when using directional observations around the Southern Ocean in comparison with the assimilation of significant wave height only. The transition to swell regime and the propagation in northern ocean region is also well tracked as it is observed in Pacific Southern Ocean. However, the assimilation of SWH only showed a limited and localized impact on the wave age.

This research opens perspectives on the use of the directional properties of SWIM instrument of CFOSAT mission to improve wave model and also provide accurate wave spectra. We expect a promising use of the assimilation of wave number components for ocean/waves coupling in terms of momentum flux transfer in southern ocean where gas exchanges are still poorly understood in climate models.

Acknowledgments and data

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References

Alberello, A., Bennetts, L., Heil, P., Eayrs, C., Vichi, M., MacHutchon, K., Onorato, M. & Toffoli, A.: Drift of Pancake Ice Floes in the Winter Antarctic Marginal Ice Zone During Polar Cyclones, Journal of Geophysical Research: Oceans, 125, e2019JC015 418, doi.org/10.1029/2019JC015418, 2020.

Aouf L., Dalphinet, A., Hauser, D., Delaye, L., Tison, C., Chapron, B., Hermozo, L., &Tourain, C. (2019), On the Assimilation of CFOSAT Wave Data in the Wave Model MFWAM : Verification Phase, proceedings of IGARSS 2019 - IEEE International Geoscience and Remote Sensing Symposium, Yokohama, Japan, 2019, pp. 7959-7961, doi: 10.1109/IGARSS.2019.8900180.

Aouf L. & Lefèvre J-M. (2015), On the impact of the assimilation of SARAL/Altika wave data in the operational wave model MFWAM, Marine Geodesy, 38, 381-395. doi:10.1080/01490419.2014.1001050

Aouf, L., Lefèvre, J-M. & Hauser D. (2006), Assimilation of directional wave spectra in the wave modelWAM: An impact study from synthetic observations in preparation for the SWIMSAT Satellite mission. J Atmos Ocean Technol. doi: 10.1175/JTECH1861.1

Ardhuin, F., Rogers, E., Babanin, A., Filippot, J-F., Magne, R., Roland, A., Van Der Westhuysen, A.; Queffeulou, P., Lefèvre, J-M., Aouf, L. & Collard, F. (2010), Semi empirical Dissipation Source Functions for Ocean Waves. Part I: Definition, Calibration, and Validation. *J. Phys. Oceanogr.*, **40**, 1917–1941, doi:10.1175/2010JPO4324.1.

Babanin A. V., Rogers, E. W., de Camargo, R., Doble, M., Durrant, T., Filchuk, K., Ewans, K., Hemer, M., Janssen, T., Kelly-Gerreyn, B., Machutchon, K., McComb, P., Qiao, F., Schulz, E., Skvortsov, A., Thomson, J., Vichi, M., Violante-Carvalho, N., Wang, D., Waseda, T., Williams, G. &Young, I. R. (2019) Waves and swells in high wind and extreme fetches, measurements in the Southern Ocean, Frontiers in Marine Science, 6, 361, DOI:10.3389/fmars.2019.00361

Barbariol, F., Benetazzo, A., Bertotti, L., Cavaleri, L., Durrant, T., McComb, P., & Sclavo, M.: Large waves and drifting buoys in theSouthern Ocean, *Ocean Engineering*, 172, 817–828, 2019

Csanady, G. T.: Air-sea interaction: laws and mechanisms, Cambridge University Press, 2001.

Collard F., Ardhuin, F. &Chapron, B. :Monitoring and analysis of ocean swell fields from space : New methods for routines observations, Journal of Geophysical Research, 10.1029/2008JC005215, 14, issue C7, 2005

ECMWF (2013) Part VII : IFS Documentation CY38R1, Part VII ECMWF Wave Model. https://www.ecmwf.int/node/9248

Ewans K., 1998, Observations of the directional wave spectrum of fetch-limited waves, *J. Phys. Oceanogr.*, **28,** 498–512.

Donelan, M. A., Hamilton, J. &Hui, W. H. (1985) : Directional spectra of wind-generated waves. *Philos. Trans. Roy. Soc. London.*, **A315,** 509–562.

Elfouhaily, T., Chapron, B., Katsaros, C. &Vandemark, D. :A unified directional spectrum for long and short wind-driven waves. Journal of Geophysical Research, Volume 102, C7, https://doi.org/10.1029/97JC00467.

Fadaeiazar, E., Leontini, J., Onorato, M., Waseda, T., Alberello, A.& Toffoli, A.: Fourier amplitude distribution and intermittency in mechanically generated surface gravity waves, *Phys. Rev. E*, 102, 013 106, doi.org/10.1103/PhysRevE.102.013106, 2020

Humphries, R. S., Klekociuk, A. R., Schofield, R., Keywood, M., Ward, J.& Wilson, S. R.: Unexpectedly high ultrafine aerosol concen-385trations above East Antarctic sea ice, *Atmos. Chem. Phys.*, 16, 2185–2206, doi.org/10.5194/acp-16-2185-2016, 2016.

Gerling, T. W., Partitioning sequences and arrays of directional ocean wave spectra into component wave systems, *J. Atmos. Oceanic Technol.*, 9, 444– 458, 1992.

Hasselmann K., P. T. Barnett, E. Bouws, H. Carlson, E. D. Cartwright, K. Enke, A. J. Ewing, H. Gienapp,E. D. Hasselmann, P. Kruseman, A. Meerburg, P. Muller, D. Olbers, K. Richter, W. Sell, & H.Walden. Measurements of wind-wave growth and swell decay during the joint north sea wave project (jonswap). Deut. Hydrogr. Z. , 8 :1–95, 01 1973.

Hasselmann, D. E. & Dunckel, M. & Ewing, J. A. (1980) : Directional wave spectra observed during JONSWAP 1973. *J. Phys. Oceanogr.,* **10,** 1264–1280.

Hasselmann K., Chapron B., Aouf L., Ardhuin F., Collard F., Engen G., Heimbach P., Janssen P., Krogstad H., Lehner S., Li J-G., Li Xiaoming, Rosenthal W. & Schulz-Stellenfleth J. (2012) : TheERS SAR Wave Mode – A Breakthrough in global ocean wave observations. European SpaceAgency, (Special Publication) ESA SP. 1326.

Hauser D., et al., "New Observations From the SWIM Radar On-Board CFOSAT: Instrument Validation and Ocean Wave Measurement Assessment," in IEEE Transactions on Geoscience and Remote Sensing, doi: 10.1109/TGRS.2020.2994372.

Kuik, A. J., van Vledder, G. Ph. &L. H. Holthuisen, (1988): A method for the routine analysis of pitch-and-roll buoy wave data. *J. Phys.Oceanogr.,* **18,** 1020–1034.

Le Traon P. Y., Reppucci A. & Alvarez Fanjul E. et al (2019) From Observation to Information and Users: The Copernicus Marine Service Perspective. Front Mar Sci. doi: 10.3389/fmars.2019.00234

Lionello, P., Gunther, H. & Janssen, P. A. E. M. (1992). Assimilation of altimeter data in a globalthird generation wave model. J. Geophys. Res., C97, 14453–14474.

Long,C.E.& Resio, D. (2007). Wind wave spectral observations in Currituck Sound, North Carolina. J.Geophys.Res. 112, CO5001.

Mitsuyasu,H., Tasai,F., Suhara,T., Mizuno,S., Ohkusu,M., Honda,T.& Rikiishi,K. &(1975). Observations of the directional spectrum of ocean waves using a clover leaf buoy. J. Phys. Oceanogr. 5, 750–760.

Pierson, W. J., & Moskowitz, L., A proposed spectral form for fully developed wind sea based on the similarity theory of S. A. Kitaigorodskii, J . GeophysR. es., 69, 5181-5190, 1964.

Phillips, O. M., The Dynamics of the Upper Ocean, 2nd ed., Cambridge Univ. Press, New York, 1977.

Resio D. T., Linwood V.& Ardag D., Characteristics of directional wave spectra and implications for detailed-balance wave modeling, Ocean Modelling, doi:10.1016/j.ocemod. 2015. 09.009

Schmale, J., Baccarini, A., Thurnherr, I., Henning, S., Efraim, A., Regayre, L., Bolas, C., Hartmann, M., Welti, A., Lehtipalo, K., Aemisegger,F., Tatzelt, C., Landwehr, S., Modini, R. L., Tummon, F., Johnson, J. S., Harris, N., Schnaiter, M., Toffoli, A., Derkani, M., Bukowiecki, N., Stratmann, F., Dommen, J., Baltensperger, U., Wernli, H., Rosenfeld, D., Gysel-Beer, M.& Carslaw, K. S.: Overview of the AntarcticCircumnavigation Expedition: Study of Preindustrial-like Aerosols and Their Climate Effects (ACE-SPACE), *Bull. Am. Meteorol. Soc.*,100, 2260–2283, doi.org/10.1175/BAMS-D-18-0187.1, 2019.

Thurnherr, I., Kozachek, A., Graf, P., Weng, Y., Bolshiyanov, D., Landwehr, S., Pfahl, S., Schmale, J., Sodemann, H., Steen-Larsen, H. C.,Toffoli, A., Wernli, H. & Aemisegger, F.:

Meridional and vertical variations of the water vapour isotopic composition in the marine boundary layer over the Atlantic and Southern Ocean, *Atmos. Chem. Phys.*, 20, 5811–5835, doi.org/10.5194/acp-20-5811-2020, 2020

Toffoli, A., Proment, D., Salman, H., Monbaliu, J., Frascoli, F., Dafilis, M., Stramignoni, E., Forza, R., Manfrin, M. & Onorato, M., 2017, Wind Generated Rogue Waves in an Annular Wave Flume, Phys. Rev. Letters, 118, issue 14, 10.1103/PhysRevLett.118.144503.

Toffoli,A., Onorato, M., Bitner-Gregersen, E.M.& Monbaliu, J. (2010). Development of a bimodal structure in ocean wave spectra.J.Geophys.Res.115.

Vichi, M., Eayrs, C., Alberello, A., Bekker, A., Bennetts, L., Holland, D., de Jong, E., Joubert, W., MacHutchon, K., Messori, G., Mojica,J. F., Onorato, M., Saunders, C., Skatulla, S.& Toffoli, A.: Effects of an explosive polar cyclone crossing the Antarctic marginal ice zone, *Geophys. Res. Lett.*, 46, 5948–5958, 2019.

Young, I. R. 1999: Seasonal variability of the global ocean wind and wave climate, Int. J. Climatol., 19, 931-950, doi:10.1002/(SICI)1097-0088(199907)19:9,931

Young, I. R., Fontaine, E., Liu, Q., & Babanin, A. V.: The Wave Climate of the Southern Ocean, *J. Phys. Oceanogr.*, 50,1417–1433, 2020.

Young I. R., Verhagen, L. A. &Banner, M. L. (1995) : A note on the bimodal directional spreading of fetch-limited wind waves. *J. Geophys. Res.*, 100 (C1), 773–778.

Zieger, S., Babanin, A. V., Rogers, W. E.& Young, I. R.: Observation-based source terms in the third-generation wave model WAVE-WATCH, *Ocean Modelling*, 96, 2–25, 2015.