User Requirements Document (URD)

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1. Introduction

1.1 Purpose

The purpose of the *User Requirements Document* is to provide a complete set of individual requirements and constraints to meet the needs of the Climate Research Community for ECV data products related to sea state. We also note that the definition of the present wave climate may be just as important at the detection of its evolution. More generally, there are many users of the same wave data that do not belong to the climate research community, and their needs are considered here too.

As stated by GCOS (http://tiny.cc/GCOS_seastate) *"Sea state is best known for its impacts on marine safety, marine transport and damage to structures. However, waves also affect the growth or decay of sea ice, beach erosion, surface albedo, gas transfer, transport of larvae and contaminants such as oil, and air–sea exchange of energy, moisture and momentum. They thereby play large roles in the global cycles of energy, water and carbon."*
Routine observation of sea states by satellites go back 25 years, and satellite data has been key in defining and adjusting parameterizations in numerical wave models. Altimeters, SARs, high resolution optical imagery and the new SWIM wave scatterometer on CFOSAT have been developed and successfully utilized to measure significant wave height (hereinafter Hs), mean square slope (mss), and swell partitions information (height, period and direction). In climate change studies based on satellite data, it is a major challenge to construct homogeneous time series from a series of consecutive satellite sensors needed for detection of changes over several decades.

At the same time there is an evolution in sensors and observation technology, which makes it possible to measure new sea state parameters for future monitoring, for example foam properties using passive radiometers such as SMOS. Also number of other sea state parameters are also important for climate research, such as the sea state bias in altimeter data or the directional slope variance tensor for sunglint in ocean color images. There is thus a general need for a consistent estimate of all these variables.

The present document, guided by user input, is strongly focused on usual sea state variables and their long term variability and evolution, still keeping an eye on the other uses of wave data. The biggest headlines about sea states have been associated with publications on trends (Young et al. 2011) that do not always agree with modeled trends with more regions experiencing a reduction in Hs (e.g. Hemer et al. 2013), although this is particularly complex where tropical storms dominate the extremes. One of the goals in wave climate research is to better understand the natural variability of sea states and better define the statistics of the extremes (which are so important for engineering design application and natural hazard mitigation) in a context of global change with positive and negative drifts. And even where the wave height trends may be negative, defining uncertainties is critical for the understanding of total sea level changes.

1.2 Scope

The scope of this URD is to identify, analyze and assess the requirements for sea state data specified by the sea state user community, with focus on the modelling and climate research community. This URD is based on literature review, a dedicated user survey, and the analysis of the requirements by the Climate Research Group within the consortium and representatives from the Climate Modelling User Group (CMUG).

The requirements will incorporate the relevant sea state parameters needed by the research community, with focus on product, accuracy, coverage, resolution and stability of the measurements, error characterisation, quality flags, metadata (including processing algorithms), product formats, grid. The requirements for validation data from non-space platforms are also addressed. The requirements for sea state ECV data include several sea state parameters in addition to the Hs and spectral partition products.

The requirements are defined for a number of applications in particular climate modelling including model development, model validation, model initialisation, boundary layer definition and data assimilation and climate research based on time series analysis. User requirements from other application areas such as operational marine weather forecasting, ocean engineering, marine transportation and offshore operations, remote sensing and seismology are also included. The requirements are divided in two categories: (1) minimum requirements to sea ice data in order to be useful for the different applications (“must have”), and (2) target requirements, which are expected to be obtained by EO data after careful validation and/or merging with non-EO data (“nice to have”). The requirements will also account for foreseen needs as sea state and climate models become further developed.

1.3 Description of the main sea state variables

Significant wave height (Hs) is the most common sea state parameter and is defined as 4 times the standard deviation of the surface elevation in a record that is typically 20 minutes long. Hs is used in all applications, from navigation safety to coastal engineering.

Besides Hs, the time and/or spatial scales of the waves are of interest because they determine the energy flux associated to the wave field (proportional to the wave period for linear waves), forces on structures, the extent of the coastal run-up, among others. Also, the direction of wave propagation are relevant for many aspects including the impact on shorelines and navigation hazards. More details can be found in [13,14].

Hence the sea state is generally described by the **directional wave spectrum E(k,θ)**. Most sea state variables of interest can be derived from the spectrum. These include,

- The wavenumber spectrum $E(k) = \int_0^{2\pi} E(k,\theta)\, d\theta$
- frequency spectrum $E(f) = \int_0^{2\pi} E(k,\theta)\, dk/df\, d\theta$, in which dk/df is uniquely defined for linear waves by the dispersion relation.

In general this dispersion relation requires a knowledge of the wave direction and the effective current[1] velocity vector **U**

$$(2 \pi f)=[g k \tanh(kD)]^{½} + \mathbf{k} . \mathbf{U}$$

Hence, when currents cannot be neglected, it is not straightforward to transform a frequency spectrum E(f) as measured by a moored buoy, to a wavenumber spectrum E(k) as measured by a space-borne radar.

Other moments of interest include

- directional moments $a_n(f) = \int_0^{2\pi} cos(n\theta)\, E(k,\theta)\, dk/df\, d\theta \,/\, E(f)$ and $b_n(f) = \int_0^{2\pi} sin(n\theta)\, E(k,\theta)\, dk/df\, d\theta \,/\, E(f)$
- Moment periods $T_{mp,q}$, in particular the mean period $T_{m0,2}$ and the energy period $T_e=T_{m0,-1}$ defined as $T_{mp,q} = \left[\int_0^{fmax} E(f)\, f^p\, df \,/\, \int_0^{fmax} E(f)\, f^q\, df\right]^{1/q}$ that can be sensitive to the maximum frequency used in the integration
- the mean square slope $mss = \int_0^{\infty} k^2 E(k)\, dk$
- partitions and their moments (Gerling 1992, Hanson and Phillips 2001)

Relevant directional parameters are computed from the directional moments for a particular range of frequencies or spectral partition, e.g., the mean direction and spread from the first moments at each frequency (Kuik et al. 1988)

- $[\cos(\theta_1(f)),\sin(\theta_1(f))] = [a_1(f),b_1(f)]$ and $\sigma_1 =[2-(a_1^2(f) + b_1^2(f))^{½}]$

Besides **Hs**, all other parameters are estimated indirectly from remote sensing data, and the full spectrum **E(k,θ)** is generally not accessible in routine in situ measurements.

1.4 Document structure

This User Requirements Document is organised into the following sections:

Section 2. Previous requirements
Section 3. Application areas for sea state climate data
Section 4. User survey
Section 5. Consolidated requirements list
Section 6. References

[1] "Effective" in the sense that it is the velocity that advects the phase of the wave train, and is generally a function of the current profile and the wavenumber (e.g. Stewart and Joy 1974, Andrews and McIntyre 1978, Kirby and Chen 1989).

2. Review of previous user requirements

2.1 Sea states as part of the Earth system

Sea state indeed affects all activities at sea (shipping, oil & gas exploration and exploitation, fish farming) on the coast (harbours, coastal defence, marine renewable energy systems, recreational uses). Many activities require more and more accurate information from extremes (design criteria for structural failure) through to calm windows (for maintenance of offshore wind farms). Beyond activities directly linked to the ocean, sea states are of general interest in the Earth system. For example, ocean waves largely define air-sea fluxes and upper ocean mixing (Jähne and Haußecker 1998, Veron 2015, d'Asaro 2016), sediment resuspension, transport and coastal geomorphology. Waves are also the source of most of the recorded seismic noise that can be used for solid Earth monitoring (e.g. Shapiro et al. 2005) and wave climate analysis (Bernard 1991, Grevemeyer et al. 2000).

In return, extreme waves and their trace in the geological record are used as evidence for past storminess using paleo-shorelines (Bouchette et al. 2010), ripple marks (Allen & Hoffman 2005) or wave-transported boulders (Hansen & al. 2016). It is thus very important to link extreme sea states to these geological marks under present climate conditions from shoreline features (Ashton & al. 2001) to ripples (e.g. Ardhuin & al. 2002), and boulders (Kennedy & al. 2016, Autret & al. 2016, Cox 2018), in order to better understand the geological record and past climates.

Monitoring and forecasting of sea states is closely integrated with ocean and atmospheric observations and modelling. Satellite EO data play an essential role in observing atmospheric and ocean variables, including sea states.

Observations of the ocean are required for monitoring of climate and the environment on seasonal-to-interannual-to-decadal time scale. In particular, the availability of operational ocean observations is prerequisite for quality weather and ocean state forecasts. Already today, global and regional numerical weather prediction models, seasonal to inter-annual forecasts and climate models assimilate ocean observations to generate initial conditions or boundary conditions.

Requirements for sea ice data are therefore closely linked to requirements for ocean and atmospheric observations and modelling in the polar regions. Several user requirement documents have been prepared for ocean and sea ice observation from satellites. The following sections give an overview of some of these documents.

2.2 EUMETSAT Observation Requirements for Nowcasting in 2015-2025

As listed in [1] the impact of improvements to observations has been assessed for the forecast service requirements using appropriate nowcasting and very short range forecasting techniques and have then been analysed to identify the key breakthroughs. The dominant forecasting method in 2015-2025 is expected to be Numerical Weather Prediction (NWP) which by then will be able to resolve the scales of interest in very short range forecasting.

The respective main observational requirements for applications of the above user groups are summarised in this table:

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V
1	Title	Sub-Title	Required variable	Conditions (1)	Applications	Nearest WMO/CEOS parameter	WMO/ CEOS code	Required Altitude Range (2)	Accuracy threshold (3)	Accuracy optimum (3)	dx threshold	dx optimum	dz threshold	dz optimum	dt threshold	dt optimum	delay threshold	delay optimum	Priority level	Breakthrough level (if any)	Current Observing Techniques	Level met
52			**Ocean**																			
53	Observation & Extrapolation	Ocean	Sig wave ht		Marine transport	Significant wave height	72	surface	0.5m	0.1m	50km	1km	-	-	6hr	1hr	2hr	30min	VH	0.5m / 10km / 1hr	Surface in situ or HF radar	N
54	Observation & Extrapolation	Ocean	Sig wave ht	near shore	Marine construction	Significant wave height	72	surface	0.2m	0.1m	10km	1km	-	-	3hr	1hr	1hr	5min	H	0.2m / 10km / 1hr	Surface in situ or HF radar	N
55	Observation & Extrapolation	Ocean	Wave period		Marine transport	Dominant wave period	73	surface	1s	0.5s	50km	1km	-	-	6hr	1hr	2hr	30min	H	1s / 10km / 1hr	Surface in situ or HF radar	N
56	Observation & Extrapolation	Ocean	Wave direction		Marine transport	Dominant wave direction	74	surface	20°	10°	50km	1km	-	-	6hr	1hr	2hr	30min	M	20° / 10km / 1hr	Surface in situ or HF radar	N
57	Observation & Extrapolation	Ocean	Surge height	near shore	Life - Coastal flooding	Sea level	75	surface	20cm	10cm	50km	1km	-	-	6hr	1hr	2hr	30min	VH	0.2m / 10km / 1hr	Surface in situ	[U]

Table 2.1: requirements as defined by [1]

Those requirements were extensively documented before and examples of respective discussions can be found in the position papers produced by the EUMETSAT Application Expert Groups during the Meteosat Third Generation (MTG) definition process [1,2,3]. Further input has been retrieved from the IGOS (Integrated Global Observing Strategy) Ocean Theme Paper [4] and the report of the Intergovernmental Oceanographic Commission (IOC/UNESCO) on Observing the Oceans in the 21st Century [5] and the WMO and GOOS [6,7] requirements published online.

Furthermore, our requirements consider and where necessary, build upon, those contained in the following documents:

- GMES, Sentinel 3 [8]
- NPOESS IORD/II [9]
- GCOS and WCRP (via the WMO on-line requirements) [6]
- EUMETSAT OSISAF [10]

All user groups continue to require comprehensive, accurate and higher resolution oceanographic satellite observations, driven by the increase in model resolution and the number of assimilated variables.

2.2.1 Observational performance level

Three performance levels are defined as follows:

1) **Threshold** is the limit below which the observation becomes ineffectual and is of no use for the targeted application

2) **Breakthrough** level represents the level beyond which a significant improvement in the target application is achieved.

3) **Objective** is the maximum performance limit for the observation, beyond which no significant improvement in the targeted application is achieved.

Accuracy: For operational meteorological applications, the accuracy is the root mean square (r.m.s.) difference between the actual measurement and the truth, inclusive of random errors and bias. This assumes that the main source of error relevant to the 'single level 2' measurement is the random component, the bias error being small enough to not significantly influence subsequent mission definition.

Spatial resolution : Horizontal resolution, Δx - The horizontal resolution is the minimum horizontal spatial scale that must be resolved by the observing system. In most cases, the horizontal resolution is more or less transferable to the resolution of a potential instrument assuming some appropriate sampling which will be finalised during the instrument design phase.

Observation Cycle, Δt : 'Observation cycle' or 'revisit time' is the time elapsed between measurements over a given location. By default, the observation cycle is applicable to the whole Earth surface including the equatorial and polar regions, so that Δt is the time needed to cover the whole Earth surface with at least one measurement. The exception is for high latitude requirements, where the observation cycle is specific for the particular latitude and is not applicable to equatorial regions.

Delay , δ
The 'delay' is the time elapsed between observation by the satellite and the availability the product to user interface, including the nominal dissemination time.

Additional Notes for Climate Requirements
Some climate requirements are given as a 'level 3' product, which is the average of a series of 'level 2' measurements taken over a time period, Δt, (or sometimes distance, Δx) in order to reduce the uncertainty and sampling variability to a sufficiently low level. The spatial and temporal resolutions then refer to the integration periods. However, despite this, the r.m.s. accuracy for each single 'level 2' measurement is given in the accuracy requirement and not the corresponding averaged product accuracy.

2.2.2 Priority of the requirements

The following codes are used to prioritise the requirements listed in Table 2.1:

Priority 1 (Very High): Mandatory requirements that drive the mission, these requirements are of utmost importance for the success of the mission and must be implemented.

Priority 2 (High): Important requirements that substantially contribute to the success of the mission. Reasonable effort shall be made to implement them.

Priority 3 (Medium): Beneficial requirement that has certain value to the success of the mission, it shall be implemented with minimum effort.

Priority 4 (Low): Requirements which are marginally contributing to the success of the mission. It shall only be implemented on an opportunistic basis. No dedicated effort will be made to implement them.

The priorities assigned in the user requirements table 2.1 are technology free and are thus independent of the availability of appropriate reliable and affordable measurement techniques.

2.3 Requirement defined by GCOS-200 (2016)

After earlier versions with much higher resolution goals, the sea state observation requirements have been defined in the most recent GCOS document (GCOS report no. 200: The Global Observing System for Climate: Implementation Needs).

These requirements are reproduced in Table 2.2.

Ocean ECV product requirements								
ECV	Products	Frequency	Resolution	Required measurement uncertainty	Stability (per decade unless otherwise specified)	Standards/ References	Entity (see Part II, section 2.2)[100]	
							Satellite	In situ
Sea-surface temperature	Sea-surface temperature	Hourly to weekly	1–100 km	0.1 K over 100-km scales	< 0.03 K over 100-km scales	See EOV Specification sheets www.goosocean.org/eov	WGClimate	JCOMM
Subsurface temperature	Interior temperature	Hourly to monthly	1–10 km	0.01 K	Not specified			JCOMM
Sea-surface sSalinity	Sea-surface salinity	Hourly to monthly	1–100 km	0.01 psu	0.001 psu		WGClimate	JCOMM
Subsurface salinity	Interior salinity	Hourly to monthly	1–10 km	0.01 psu	Not specified			JCOMM
Surface currents	Surface geostrophic current	Hourly to weekly	30 km	5 cm/s	Not specified		WGClimate	JCOMM
Subsurface curents	Interior currents	Hourly to weekly	1–10 km	0.02 m/s	Not specified			JCOMM
Sea level	Global mean sea level	Weekly to monthly	10–100 km	2–4 mm (global mean); 1 cm over a grid mesh	< 0.3 mm/yr (global mean)		WGClimate	JCOMM
	Regional sea level	Hourly to weekly	10 km	1 cm (over grid mesh of 50–100 km)	< 1 mm/yr (for grid mesh of 50–100 km)		WGClimate	JCOMM
Sea state	Wave height	3-hourly	25 km	10 cm	5 cm		WGClimate	JCOMM
Surface stress	Surface stress	Hourly-monthly	10–100 km	0.001–4 Nm^{2}	Not specified			JCOMM

Table 2.2. Requirements for horizontal resolution, temporal resolution, measurement accuracy and stability over a decade for the ocean ECVs as defined by GCOS.

As stated by GCOS (http://tiny.cc/GCOS_seastate) *"Sea state is best known for its impacts on marine safety, marine transport and damage to structures. However, waves also affect the growth or decay of sea ice, beach erosion, surface albedo, gas transfer, transport of larvae and contaminants such as oil, and air–sea exchange of energy, moisture and momentum. They thereby play large roles in the global cycles of energy, water and carbon."*

Product	Frequency	Resolution	Required uncertainty	Required stability (per decade)
Hs	3-hourly	25 km	10 cm	5 cm

Given that Hs is mostly provided by satellite altimeters and that there are at most 6 altimeters flying at any given time, these requirements cannot be attained by existing satellite data for the period 2003-2020. Further, coastal applications generally require even finer resolution, of the order of 100 m in space (Camus et al. 2013, Boudière et al. 2014). Likewise, a higher temporal resolution of the order of 1 hour is necessary where modulation by tides are important. This is particularly relevant for extreme water levels that combine wave run up and storm surges. Today numerical models and/or statistical methods are used to arrive at these resolutions.

However, these requirements are not mutually consistent. The urgency of understanding total sea level at the coast (e.g. Melet et al., 2018) is clearly calling for a stability that matches that of the offshore sea level. Typically, 1 cm increase in offshore Hs gives 0.5 to 1 cm increase in maximum sea level at the coast (Poate et al. 2016, Dodet et al. 2018). It is not unreasonable to ask for 2 mm/year accuracy for Hs when the requirement for regional sea level is at 1 mm/year. This is particularly important in today's transition where the total ice-shelf melt contribution to sea level rise is still limited to a few centimeters. In the long term, with sea level rise of several meters, the few centimeters to decimeters due to waves will probably be less important, except where changes are dramatic, as is the case in the Arctic (e.g. Stopa et al., 2016) and possibly in tropical cyclones (Shimura et al., 2016).

2.4 Proposition for updating requirements (see [15])

Based on the analysis of all previous requirements, the evolution of user needs, as further discussed in the next sections, and the need for consistency with other ECVs we propose to update the GCOS-200 numbers for Hs and define requirements for other variables.

	Variable	Frequency	Resolution	Uncertainty	Stability
GCOS-200	H_s	3-hourly	25 km	10 cm	5 cm/decade
GCOS-200	regional sea level	hourly	10 km	1 cm	$<$ 1 mm/year
WMO	H_s	??	??	5-10% or 10 to 25 cm	??
WMO (2017)	$T_{m0,2}$	??	??	0.1 to 1 s	??
WMO (2017)	θ_m	??	??	10 deg	??
this paper	global to regional H_s	3-hourly	25 km	10 cm or 5%	5 cm/decade
this paper	coastal H_s	1-hourly	1 km	10 cm or 5%	$<$ 1 mm/year
this paper	regional $T_{m0,-1}$	3-hourly	25 km	0.2 s	$<$ 0.1 s/decade
this paper	regional $T_{m0,2}$	3-hourly	25 km	0.2 s	$<$ 0.1 s/decade

Table 2.3 : proposed updates to sea state requirements [15]. "Coastal" can be understood as regions where proximity to land and/or shallow water has a particular impact on the sea state. This thus includes all waters shallower than 100 m, and distances to coast shorter than 200 km.

These should be understood as objectives. In particular the objective for trends on Hs should apply to both the mean value and extreme values (up to percentile 99 and 100 year return period).

3. Application areas for sea state climate data

Sea state climate data are used in a wide range of application areas, ranging from climate research activities to marine biology and ecosystems research, management of marine resources, sea transportation, offshore exploration, design and construction of vessels and platforms, impact on indigenous people, insurance, governance and policy making. In this project focus is on climate research and modelling activities, but also requirements to other user groups are considered.

3.1 Climate research and engineering applications

Even though remote sensing data alone cannot reach these resolutions needed in coastal applications, remote sensing is critical for:

- validating and calibrating numerical models offshore (spatially coarse data is generally enough, see e.g. Stopa et al. 2016)

- validating patterns and gradients (in coastal regions, near the ice edge, over current gradients, at the peak of storms...): this has not been applied much so far because:
    - routine altimeter processes are dominated by noise for along-track wavelengths under 80 km or so (Ardhuin et al. 2017b). As new processing techniques have been proposed (e.g. Passaro et al. 2014, Halimi et al. 2016), there are great opportunities to better resolve these variations.

    - few images of wave parameters were available so far. This can change with more widely available SAR (e.g. Gemmrich et al. 2016, Ardhuin et al. 2017a) or sun glitter imagery (Kudryavtsev et al. 2017).

Finally, without even mentioning its evolution with global change, the wave climate, including extremes often defined through Hs statistics associated to low recurrence intervals (i.e. 20, 50, 100yr return period) is a key element in the design and operation of ocean and coastal infrastructures.

The impact of climate change on the wave climate and its applications is a topic of active research and is mostly limited by the poor knowledge on trends and variability of extreme sea states (e.g. Bitner-Gregersen et al. 2013).

As a result, a clear requirement is a validation of the highest values of Hs for all regions of the world ocean. Hanafin et al. (2012) used wind speeds the periods of radiated swells as a consistency check on the 20.1 m Hs found in the North Atlantic storm Quirin. Cardone et al. (2015) chose to filter the data without any discussion on the filter properties.

Due to the non continuous time resolution of waves measured by altimeters, the statistical distribution must be corrected for sampling biases (Izaguirre et al, 2011). Figure 1 shows an example with the 10-year Hs return values as derived from the altimeter record, which is within 1 m of the same parameter derived from a model hindcast, but differs by up to 20% from a full model time series.

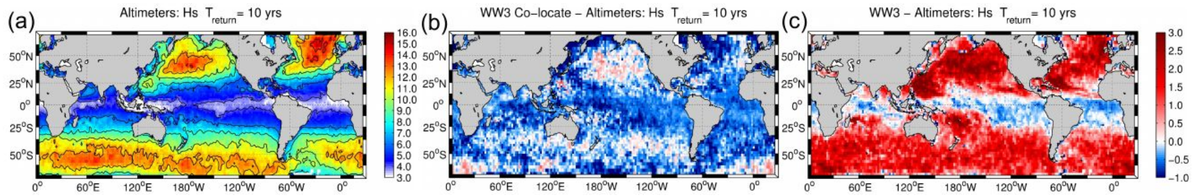

Figure 1: (a) Estimation of a 10-year return period value of Hs using the GEV distribution from the altimeters, (b) difference between the altimeters and colocated WW3 data, (c) difference for full time series of modeled data (taken from Stopa et al. presentation at 2016 OSTST Meeting, La Rochelle).

3.2 Modelling activities

Wave model development and the assessment of the suitability of the necessary wind forcing is generally done by comparing model output to in-situ observations, if available. However, it is seldom the case that one has enough in-situ observations to cover the full extend of the model domain. For this reason, the wave modelling community relies extensively on the comparison of the model output with all available altimeter observations. Provided that the area covered by the model domain is large enough and that the period covered by the model simulation includes enough interesting weather, the statistical analysis of the model-altimeter along track collocations is a useful tool in development phase of the model as well as for assessment of the global characteristics of the modelling system.(Wiese et al. 2018).

3.3 Remote sensing

Because ocean waves have clear signature in most ocean remote sensing techniques, either adding noise or biases, stable corrections and detection is very important for:

- sea level estimates from altimetry (e.g. Tran et al. 2010, Passaro et al. 2018) and tide gauges (e.g. Aucan et al. 2012)
- glitter and foam contaminate ocean color imagery
- the surface mean square slope and foam cover and thickness are major sources of uncertainty in surface salinity retrieval (e.g. Reul and Chapron 2003).
- waves have an impact of retrieved wind speeds from all sensors (altimeters, scatterometers, radiometers), that is not fully understood despite recent attempts to reconcile these different records (Young and Donelan 2018).

3.4 Air-sea fluxes

Properties of the ocean and atmospheric mixed layers in which most human activity takes place, is largely driven by the air-sea exchanges of heat, water, momentum, gasses. These fluxes have been parameterized with resistance laws in which coefficients that are often a function of wind speed alone. Additional dependencies on sea state properties have been strongly debated for the momentum flux (Drennan et al. 2005), while more recent analyses show a moderate impact for intermediate wind speeds (Edson et al. 2013), even though it is expect that the surface roughness caused by waves should play a role (Donelan 2018) although one that is often correlated with the wind speed.

The impact of waves on upper ocean mixing and sea surface temperature, in particular in cases of shallow mixed layers, is more clear (e.g. Noh et al. 2011, Janssen 2012).

Particular uncertainties in the climate systems are associated with cloud nucleation, which relies on marine aerosol production (e.g. Veron 2015) accounting for up to 30% of cloud nucleation (Quinn et al. 2018). The source functions for marine aerosols is expected to depend on sea state parameters, such as the height of breaking waves for which the significant wave height may be a good proxy away from the swell-dominated regions (de Leeuw et al. 2011).

3.5 Other wave-related effects in the Earth System

The interactions of waves and sea ice certainly influence ice edge dynamics (Squire et al. 1995, Stopa et al. 2018) and ice properties near the edge. In particular, waves are associated with the formation of pancake ice (e.g. Doble et al. 2003) that is the most common type of ice formation in the Southern ocean, and is becoming increasingly important in the Arctic too (Thomson et al. 2018). Wave action over fragmented ice can have an important influence on the ice thickness (Sutherland and Dumont 2018).

4. User survey

4.1 Introduction to the user survey

In order to develop the Essential Climate Variables (ECVs) for sea state, it is necessary to perform a user survey and analyse the requirements extracted from this survey. The questionnaire was implemented in order to collect information on the user's experience with satellite wave data, the wave parameters they are mostly interested in, their requirements in terms of spatial resolution and time coverage, their intention to use the data in relation with other ECVs, and their interest in participating in a User Consultation Meeting and training sessions. The main results of the survey are described in the following sections and open comments from participants are listed in Appendix 1.

4.2 Users involved in the survey

The user survey was conducted from 11 December 2018 to 25 January 2019. This survey was developed using an online Google form (https://goo.gl/forms/1GGPGc4APA1PXCaX2) and was broadcasted on several mailing lists (including globwave users, IOWAGA users and the "coastal list"), as well as via Twitter. **As of January 25, a total of 184 participants** had replied to the questionnaire. From this survey we see that the participants are mostly working in academic and research institutions (75%) spread all over the world (Figure 4.2.1, 4.2.2 and 4.2.3). The six most represented countries are France (18%), the United States (13%), Italy (8%), the United Kingdom (6%) and Australia (4%) ex-aequo with Spain (4%). The 43% remaining participants are based on the American (Canada, Mexico, Costa Rica, Colombia, Brasil, Uruguay, Chile), European (Belgium, Denmark, Germany, Norway, Ireland), Asian (China and India) and African continents (Tunisia, Egypt, Benin, Ghana, South Africa).

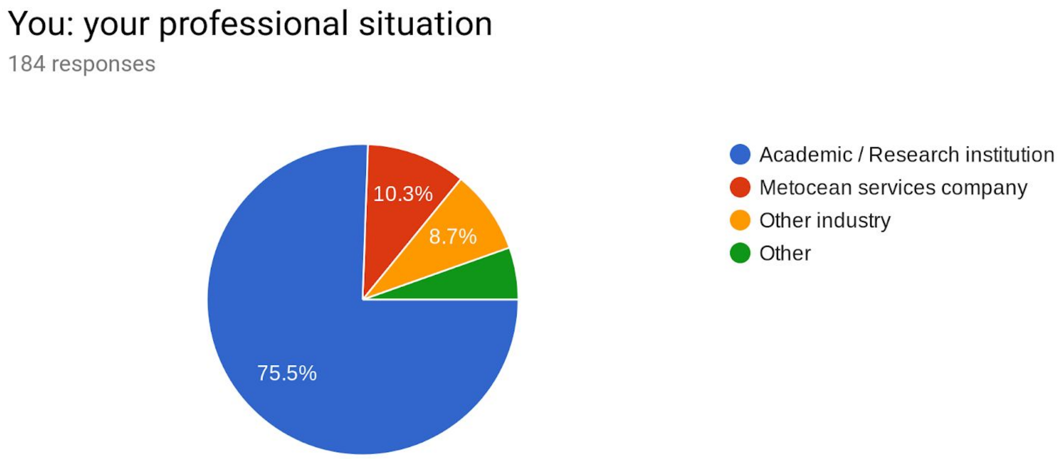

Figure 4.2.1. Professional situation of the participants

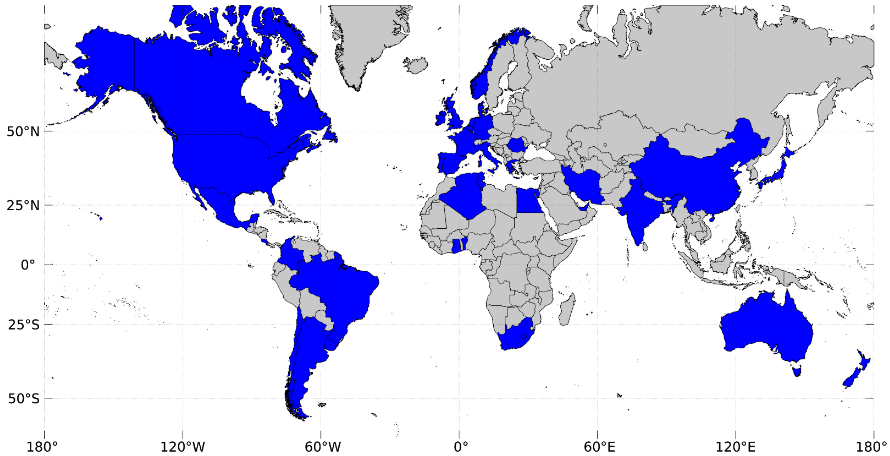

Figure 4.2.2. Countries where participants currently do most of their work (in blue)

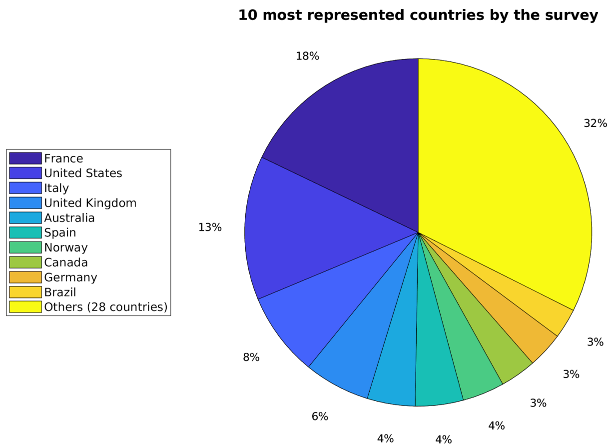

Figure 4.2.3. The 10 most represented countries in the survey

This spatial distribution of the participants highlights the worldwide interest for high quality sea state information.

4.3 Summary of survey results

4.3.1 Field of applications

The participants had to choose between eight fields of applications. The results show that the majority (66.3%) of the participants are working in the field of oceanography (38.6%) and coastal engineering (27.7%). A significant fraction of participants working in the fields of climate (8.7%) and marine meteorology (8.7%) also took part in the survey (Figure 4.3.1).

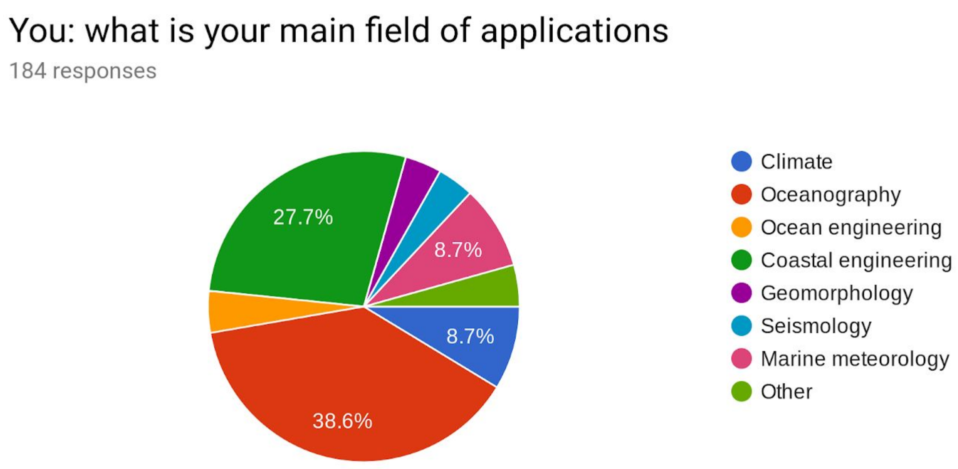

Figure 4.3.1. Distribution among the field of applications

4.3.2 The importance of various sea state parameters

The most important parameter for the quasi totality of the participants is the significant wave height, followed by the wave period (peak period Tp and mean period Tm02 rather than the mean period Tm01, not shown here) and the wave direction. The 2-D wave spectrum E(f,θ) or E(k,θ) is also of interest for the majority of the participants, and overtakes the swell partition and the heave spectrum. Among the other altimetry-derived parameters, the mean square slope of the sea surface and the microseism sources are also relevant.

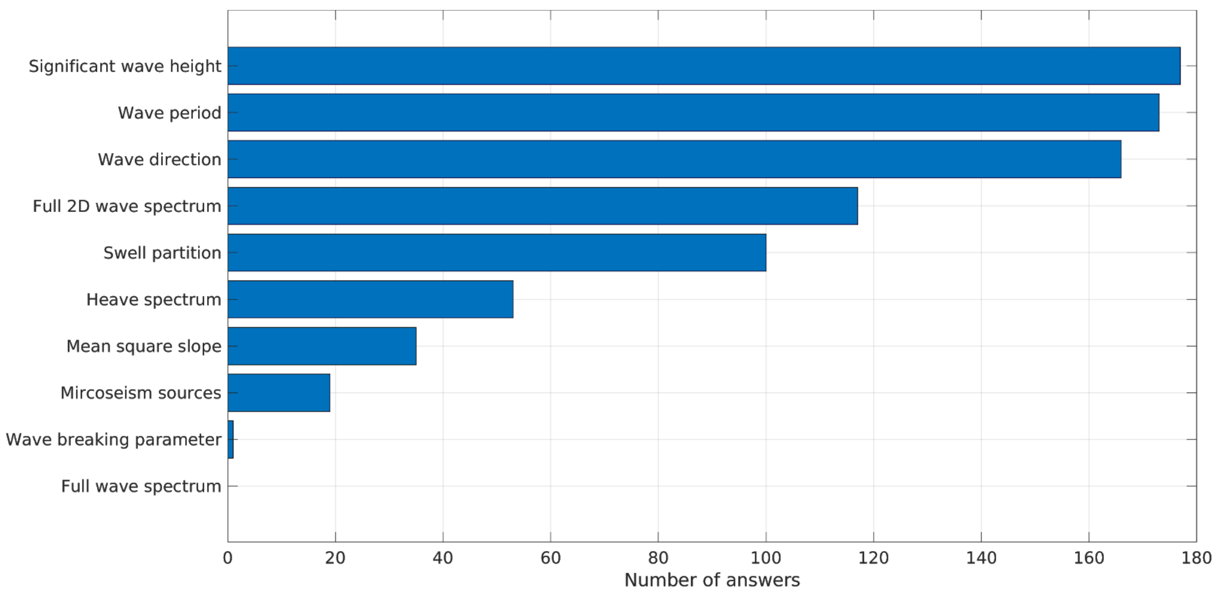

Figure 4.3.2 Sea state parameters that participants would like to use

4.3.3 Temporal coverage and spatial resolution

Figures 4.3.3.1 shows that most participants are interested in multiple years and long term statistics, although a significant fraction of the participants are also interested in less-than-a-year time-series (24%) and single event data (43.5%).

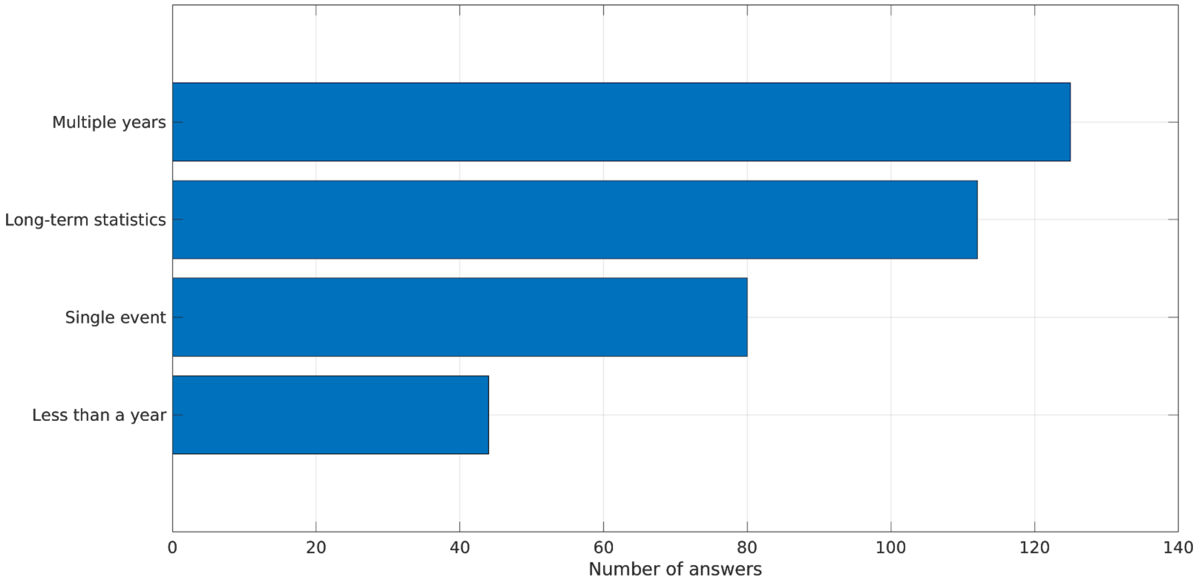

Figure 4.3.3.1 Period of time participants are interested in

For what regard the spatial resolution at which the participants expect to use the data (Figure 4.3.3.2) it clearly appears that high resolution (<10km) sea state data are of greater interest, compared to low resolution and single point measurements.

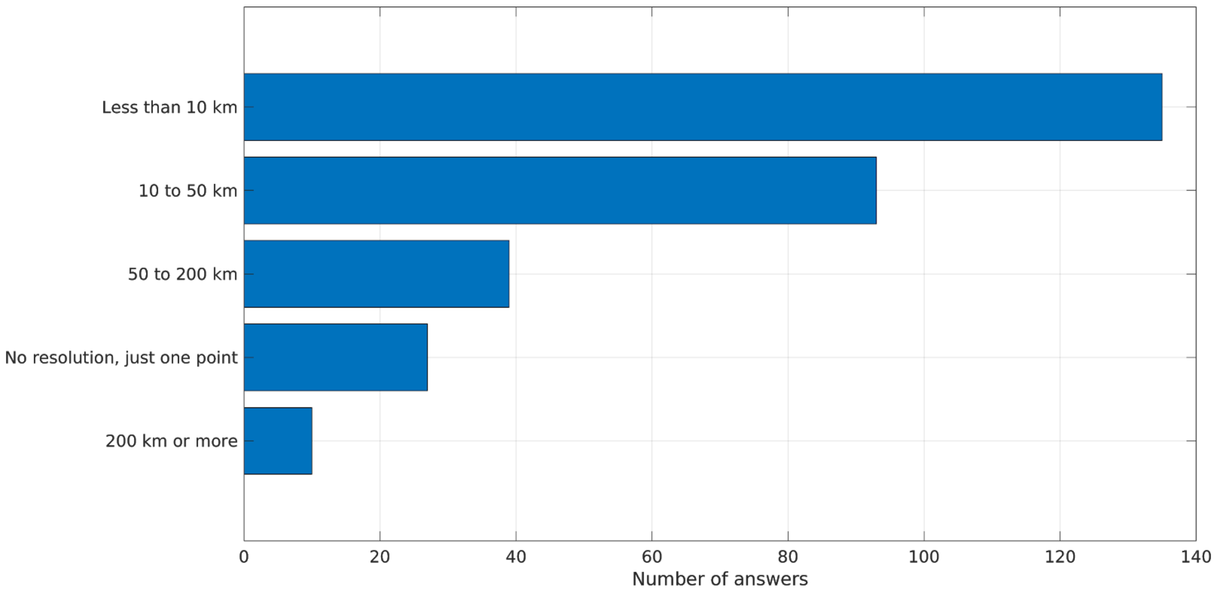

Figure 4.3.3.2 Spatial resolution at which participants expect to use the data

4.3.4 Interest in sea state data

Figure 4.3.4 reveals that the major interest for satellite wave data concerns the study of *extreme events*, the *validation of wave models* and the study of *coastal processes*. These three topics are followed by the study of *wave climate variability*, the study of *wave-current interactions*, the study of *air-sea interactions*, the study of *wave-ice interactions*, *data assimilation* and applications for *Marine Renewable Energy*. Other field of interest were also proposed (not shown), such as: *statistical downscaling*, *machine learning*, *ship hydrodynamics*, *offshore engineering*, and *seismic ambient noise characterization*.

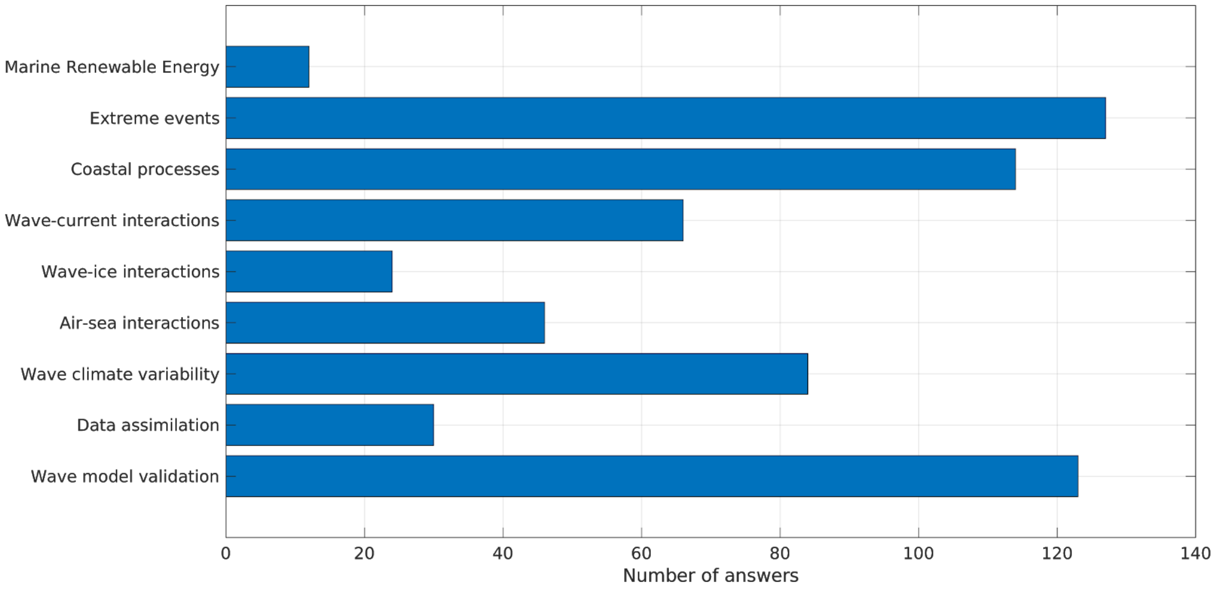

Figure 4.3.4 Answers to the question "your interest in satellite wave data concerns?"

4.3.5 Interest in other Essential Climate Variables

To the question "have you used or are you planning to use other CCI variables?", 101 participants answered *Sea Level*, 33 participants answered *Ocean Color*, 54 participants answered *Salinity*, 69 participants answered *Sea Surface Temperature*, and 42 participants answered *Sea Ice*.

4.3.6 Participation to the User Consultation Meeting and training session

To the question "do you plan to attend the User Consultation Meeting (UCM) in Brest, France (October 8th to 10th, 2019)", 35% of the participants answered "Definitely yes" or "Probably" (Figure 4.3.6). In addition, many participants are interested in training sessions on *combining model and satellite data* (62%), *SAR data* (58%), *coastal altimetry* (56%), and *CFOSAT data* (29.5%). Hence, including a training session on one or several of the above-mentioned subjects to the User Consultation Meeting will likely attract more participants.

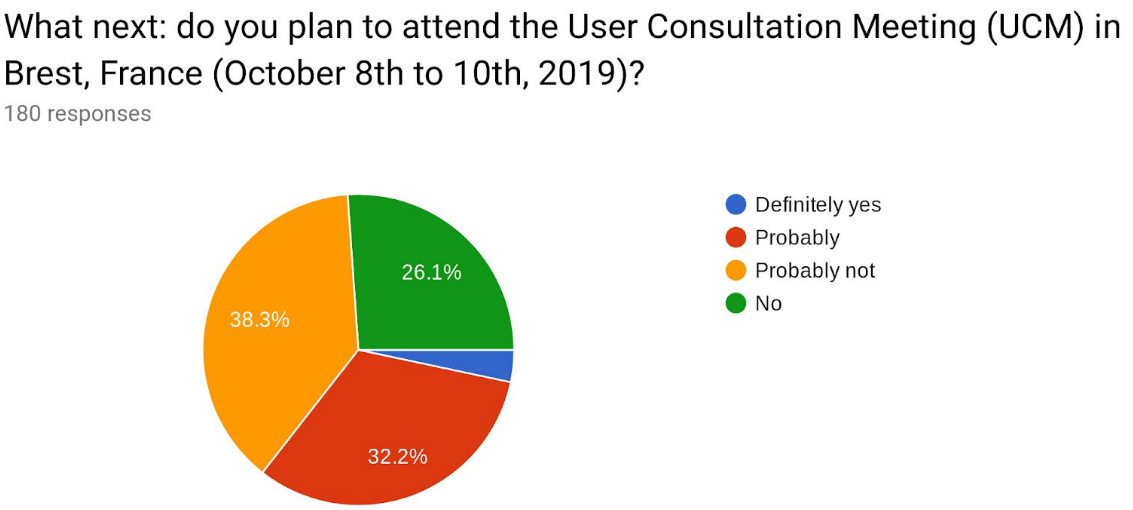

Figure 4.3.6 Interest of the participants in the User Consultation Meeting to be held in Brest in October 2019.

5. Consolidated list of User Requirements

Based on the above material, we can highlight the relevant aspects of the user requirements for the CCI Sea State project. The specific data requirements as defined in the ESA Statement of Work are recalled in section 5.2, and are linked to the user requirements when appropriate.

5.1 Top level requirements

- **resolution**: There is a clear need for data at a resolution finer than the 25 km mentioned in GCOS, in particular in the coastal regions (here defined as the combination of depths under 100 m and distances to shore under 300 km). Most of the surveyed users would like to have **10 km or less**. Given the resolution of standard satellite processing, this is really calling for improved tracking and/or denoising algorithms, and by itself it justifies the effort made on the Sea State CCI.

- **coverage in space and time:** Given that a large fraction of users (80 out of 184) are interested into **single events**, this clearly highlights the sampling issue of satellite data sets. Most events are missed, except through their associated swell fields. There is thus a need that will not be fully addressed in the Phase 1 of Sea State CCI for combining wave models and data or expanding on level 3 and 4 products such as fireworks, storm catalogs (associated with storm tracks …). We have not asked specific questions about ice-covered regions given the limitation of the version 1 of the CCI dataset, but that should be considered in future surveys.

- **Stability:** not surprisingly most users identified here are interested into long-term statistics of sea state variable, with or without a climate change aspect. Given that 101 answers out of 184 mentioned their intent to combine sea level with sea state, it is logical to reframe the requirements on sea state stability in terms of total sea level (e.g. Dodet et al., in review, see also [15] , Marcos et al. 2019). The **need** on wave height trend accuracy for mean values and extremes is thus **under 1 mm/year for coastal areas**, with a similar need for wave periods that should be quantified. It is not at all clear that such a low value can be achieved with today's spatial coverage, and how bringing models forced by winds with dubious trends can be used for this. At any rate, even the GCOS requirement of 5 cm/decade, when achieved, should be enough to confirm or disprove the 0.5% per year (around 1 cm per year) trend associated with wave power trends up to 2.5% per year reported by Reguero et al. (2019).

- **Sea State Variables:** It is not just the **wave heights**. For many reasons (energy flux, extreme sea levels…) the **periods** and **directions** have a very important role, and this is well recognized in the user survey. It is thus very important to use both altimeters (via the cross-section) and wave-resolving instruments (SARs, SWIM on CFOSAT) for constraining the sea state climate. It may be surprising that fewer users would like to use partition data, but this may be due to the fact that little such data is available and the definition can be a bit fuzzy and method-dependent (e.g. Portilla et al. 2009). We will thus engage the user community (at UCM and through training events) on this question and see how the usefulness of such data can be improved. Given the very few users of SAR data, making the data more accurate and also more user-friendly is a key aspect.

5.2 Specific data requirements

ID	Requirement description	Source	Comment
DR-001	In Phase 1 the Sea_state_cci project shall develop an initial 18-year data set (2002- 2020), and shall provide, as a minimum, L2 products and higher level merged product time-series that shall collectively include the following sea state variables: Significant wave height; Directional wave spectrum; Mean wave period; Peak wave period; Mean wave direction at the peak of the spectrum; Appropriate derived-variables and supporting variables; Other variables required by the Climate Science Community.	ESA TR-2, TR-15, TR-16	
DR-002	Each CCI project team (the contractor) shall integrate data from the Copernicus Sentinels and other key satellite missions within the relevant CCI processing systems and ECV data products.	ESA R-16	Sentinel 1, 3 & 6 included in baseline Sentinel 2 in option 10.
DR-003	Each CCI project team (the contractor) shall ensure that the system is adequately dimensioned to accommodate the growing volumes of input and output data, and the increasing computational loads needed to process, reprocess, quality control, validate, and disseminate multi-decadal, global, ECV data products, of the required climate quality, in a timely manner.	ESA R-17	
DR-003	Sea_state_cci shall directly address GCOS Action O33.	ESA TR-1	
DR-004	The Sea_state_cci project shall develop and deliver Sea State ECV products primarily derived from satellite measurements.	ESA TR-7	
DR-005	The Sea_state_cci project shall deliver validated prototype products using agreed validation methods and metrics developed within a research environment to climate science users for assessment and feedback.	ESA TR-8	
DR-006	Sea_state_cci products shall cover the global ocean, including full coverage of both northern and southern hemispheres as far as possible.	ESA TR-9	
DR-007	All Sea_state_cci products shall cover the full mission lifetimes of the satellite missions selected.	ESA TR-10	
DR-008	Sea_state_cci products shall be available to users as Level-1 (where appropriate), Level-2 and Level-3 product versions, and potentially as higher-level derived products if required by the users.	ESA TR-11	

DR-009	Sea_state_cci products shall include aggregated versions of the data as required by climate science users (eg. daily, monthly, seasonally and annually).	ESA TR-12	
DR-010	Digital Object Identifiers (DOI) shall be assigned to all ECV data sets made publicly available.	ESA TR-13	
DR-011	As part of data merging methods, time-dependent and sampling biases in products from different instruments shall be investigated, and strategies shall be developed and implemented to correct for these effects.	ESA TR-17	WP2*70
DR-012	A common set of auxiliary/supporting data shall be developed and used for all satellite missions used within the Sea_state_cci project.	ESA TR-20	WP4200
DR-013	The Sea_state_cci project shall explore techniques using satellite measurements made at different frequencies (eg. C, S, Ku, Ka bands) to address GCOS Sea State ECV requirements.	ESA TR-22	
DR-014	The Sea_state_cci project shall develop innovative merging strategies and tools for sea state products generation.	ESA TR-23	WP2*70
DR-015	The Sea_state_cci project shall provide a validated estimate of uncertainty for each data product at product grid/pixel level using the approach of [ESA RD-33].Uncertainties shall be reported within the ECV products for every geophysical measurement.	ESA TR-25, TR-39, TR-40	
DR-016	The method used to derive and validate uncertainties, the characteristics of those uncertainty estimates and advice on how uncertainty estimates are to be used for each product shall be fully reported in the PUG.	ESA TR-26	
DR-017	User requirements for ECV product uncertainties shall be included in the user requirements analysis, including how the uncertainties should be expressed and used in the Sea_state_cci ECV products (e.g. how should the uncertainties be broken down into their random and systematic components).	ESA TR-30	WP1000
DR-018	The Contractor shall conduct significant research and development and explore innovative approaches and algorithms that could address known weaknesses in sea state retrievals from satellite data sets.	ESA TR-31	WP2000
DR-019	The Contractor shall conduct research and development and explore new algorithms to address crossing seas.	ESA TR-33	
DR-020	The Contractor shall investigate and account for satellite instrument biases, particularly regarding earlier less well calibrated instruments taking account of changes in calibration with instrument aging.	ESA TR-35	
DR-021	Based on the outcome of the Round Robin, The contractor shall select a set of definitive retrieval algorithms to be applied to data from different instruments.	ESA TR-36, TR-37, TR-38	WP2100

DR-022	The Contractor shall ensure the new capabilities of Copernicus Sentinel-3 SRAL (and in future Copernicus Sentinel-6) SAR altimeter instruments are fully exploited for the retrieval of sea state ECV products.	ESA TR-41	
DR-023	The Contractor shall ensure the new capabilities of Copernicus Sentinel-1 SAR imager instruments are fully exploited for the retrieval of the sea state ECV products.	ESA TR-42	
DR-024	A full validation of all sea state ECV products produced shall be performed against metrics pre-defined defined by the contractor and endorsed by the user community.	ESA TR-43, TR-44	WP4500
DR-025	Validation shall quantify the uncertainty of the sea state ECV products as well as the quality of the product uncertainty estimates themselves. The long-term stability of all ECV time series delivered shall be assessed.	ESA TR-45, TR-46	WP4500
DR-026	A database of relevant and ideally independent in situ Fiducial Reference Measurements and satellite measurements (ISDB) shall be developed to serve the Sea_state_cci project validation, research and development needs.	ESA TR-47	WP4100
DR-027	All measurements in the ISDB shall include uncertainty estimates. The methods used to derive and validate ISDB uncertainties and the characteristics of those uncertainty estimates for each product shall be fully reported in the PUG.	ESA TR-48, TR-50	
DR-028	The suite of Sea_state_cci ECV products produced shall be made publicly available together with the validation results immediately following the completed validation.	ESA TR-54	

6. References

[1] EUMETSAT Position Paper on Observation Requirements for Nowcasting & Very Short Range Forecasting in 2015-2025, B.W. Golding, S. Senesi, K. Browning, B. Bizzarri, W. Benesch, D. Rosenfeld, V. Levizzani, H. Roesli, U. Platt, T. E. Nordeng, J. T. Carmona, P. Ambrosetti, P. Pagano, and M. Kurz

[2] EUMETSAT Position Paper - Requirements of Observation for Regional NWP, N. Gustafsson, M. Capaldo, B. O. Estrada, and J. Quiby

[3] EUMETSAT Position Paper - Requirements of Observation for Global NWP, J. Eyre, J.-N. Thépaut, J. Joiner, L. P. Riishojgaard and F. Gérard

[4] An Ocean Theme for the IGOS Partnership, Final Report from the Ocean Theme Team, IGOS, 36 pp, www.igospartners.org

[5] IOC/UNESCO Report on “Observing the Ocean in the 21st Century”, ed. by Koblinsky, C.J. and Smith, R.N., 2001, 604 pp.

[6] Global Observing Systems Information Center, Space-Based Data Requirements for GOOS, http://www.gosic.org/space/GOOS_space.htm

[7] GMES Sentinel 3 Mission Requirements Document, ESA document EOP-SMO/1151/MD-md issue 1.0, 2004.

[8] NPOESS Integrated Operations Requirements Document, 2001.

[9] EUMETSAT Satellite Application Facility on Ocean and Sea Ice, User Requirements Document, EUMETSAT document number SAF/OSI/M-F/MGT/RQ/011, Version 2.0, 2005.

[10] GCOS, 2006. SYSTEMATIC OBSERVATION REQUIREMENTS FOR SATELLITE-BASED DATA PRODUCTS FOR CLIMATE. Supplemental details to the satellite-based component of the “Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (GCOS – 92)”.

[11] (WMO/TD No. 1143), The Second Report on the Adequacy of the Global Observing Systems for Climate in Support of the UNFCCC, 2003. See http://www.wmo.ch/web/gcos/gcoshome.html

[12] GCOS, 2011. SYSTEMATIC OBSERVATION REQUIREMENTS FOR SATELLITE-BASED DATA PRODUCTS FOR CLIMATE, 2011 Update. Supplemental details to the satellite-based component of the “Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)” December 2011, **GCOS – 154**.

[13] COST Action 714 Working Group 3, W. G., Measuring and analysing the directional spectra of ocean waves. Office for Official Publications of the European Communities, Luxembourg, 2005. ISBN 92-898-0003-8.

[14] Ardhuin, F., Ocean waves in geosciences. 2019. doi:10.13140/RG.2.2.16019.78888/5.

[15] Ardhuin, F., J. E. Stopa, B. Chapron, F. Collard, R. E. Jensen, J. Johannessen, R. Husson, A. Mouche, M. Passaro, G. Quartly, V. Swail and I. Young, Observing sea states, *Frontiers in Marine Science* (in review https://www.researchgate.net/publication/328791679_Observing_sea_states).

Allen, P. A. and Hoffman, P. F., “Extreme winds and waves in the aftermath of a neoproterozoic glaciation,” Nature, 433, 123–127, 2005. See commentary by D. J. Jerolmack and D. Mohrig, Nature, 2005, vol. 436, p. E1.

Ardhuin, F., Drake, T. G., and Herbers, T. H. C., “Observations of wave-generated vortex ripples on the North Carolina continental shelf,” J. Geophys. Res., 107, C10, 2002. doi:10.1029/2001JC000986.

Ashton, A., Murray, A. B., and Arnault, O., “Formation of coastline features by large-scale instabilities induced by high-angle waves,” Natue, 414, 296–299, 2001. doi:10.1038/35104541.

Aucan, J., Hoeke, R., Merrifield, M.A., 2012. Wave-driven sea level anomalies at the Mid-way tide gauge as an index of North Pacific storminess over the past 60 years. Geophys. Res. Lett. 39, 1–6. http://dx.doi.org/10.1029/2012GL052993 .

Autret, R., Dodet, G., Fichaut, B., Suanez, S., David, L., Leckler, F., Ardhuin, F., Ammann, J., Grandjean, P., Lallemand, P., and Filipot, J.-F., “A comprehensive hydro-geomorphic study of cliff-top storm deposits on Banneg island during winter 2013-2014,” Marine Geology, 382, 37–55, 2016. doi:10.1016/j.margeo.2016.09.014.

Bernard, P., “Historical sketch of microseisms from past to future,” Phys. Earth Planetary Interiors, 63, 145–150, 1990. doi:0031-9201(90)90013-N.

Bouchette, F., Schuster, M., Ghienne, J.-F., Denamiel, C., Roquin, C., Moussa, A., Marsaleix, P., and Duringer, P., “Hydrodynamics in holocene lake mega-chad,” Quartenary Research, 73, 226–236, 2010. doi::10.1016/j.yqres.2009.10.010.

Cox, R., “Very large boulders were moved by storm waves on the west coast of Ireland in winter 2013–2014,” Marine Geology, p. in press, 2018. doi:10.1016/j.margeo.2018.07.016.

de Leeuw, G., E. L Andreas, M. D. Anguelova, C. W. Fairall, E. R. Lewis, C. O’Dowd, M. Schulz, and S. E. Schwartz (2011), Production flux of sea spray aerosol, Rev. Geophys., 49, RG2001, doi:10.1029/2010RG000349.

Doble, M. J. (2003). *Pancake ice formation in the Weddell Sea. Journal of Geophysical Research, 108(C7).* doi:10.1029/2002jc001373

Dodet, G., Leckler, F., Sous, D., Ardhuin, F., Filipot, J. F., & Suanez, S. (2018). *Wave Runup Over Steep Rocky Cliffs. Journal of Geophysical Research: Oceans.* doi:10.1029/2018jc013967

Donelan, M. A., “On the decrease of the oceanic drag coefficient in high winds,” J. Geophys. Res., 123, C2, 1485–1501, 2015. doi:10.1002/2017JC013394.

Jähne, B. and Haussecker, H., “Air-water gas exchange,” Annu. Rev. Fluid Mech., 30, 443–469, 1998.

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

Grevemeyer, I., Herber, R., and Essen, H.-H., “Microseismological evidence for a changing wave climate in the northeast Atlantic Ocean,” Nature, 408, 349–351, 2000.

Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., Tselioudis, G., Cao, J., Rignot, E., Velicogna, I., Tormey, B., Donovan, B., Kandiano, E., von Schuckmann, K., Kharecha, P., Legrande, A. N., Bauer, M., and Lo, K.-W., “Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2°C global warming could be dangerous,” Atmos. Chem. Phys., 16, 3761–3812, 2016. doi:10.5194/acp-16-3761-2016.

Hanson, J. L. and Phillips, O. M., “Automated analysis of ocean surface directional wave spectra,” J. Atmos. Ocean Technol., 18, 277–293, 2001.

Kennedy, A. B., Mori, N., Zhang, Y., Yasuda, T., Chen, S.-E., Tajima, Y., Pecor, W., and Toride, K., “Observations and modeling of coastal boulder transport and loading during super typhoon haiyan,” Coastal Eng. Japan, 58, p. 1640004, 2016. doi:10.1142/S0578563416400040.

Marcos, M., Wöppelmann, G., Matthews, A., Ponte, R. M., Birol, F., Ardhuin, F., … Stopa, J. E. (2019). Coastal Sea Level and Related Fields from Existing Observing Systems. Surveys in Geophysics. doi:10.1007/s10712-019-09513-3

Passaro, M., Z. A. Nadzir, G. D. Quartly, Improving the precision of sea level data from satellite altimetry with high-frequency and regional sea state bias corrections, Remote Sensing of Environment 218 (2018) 245–254, doi: /10.1016/j.rse.2018.09.007

Poate, T. G., McCall, R. T., and Masselink, G., “A new parameterisation for runup on gravel beaches,” Coastal Eng., 117, 176–190, 2016.

Reguero, B. G., Losada, I. J., & Méndez, F. J. (2019). *A recent increase in global wave power as a consequence of oceanic warming. Nature Communications, 10(1).* doi:10.1038/s41467-018-08066-0

Reul, N. and Chapron, B., “A model of sea-foam thickness distribution for passive microwave remote sensing applications,” J. Geophys. Res., 108, C10, p. 3321, 2003. doi:10.1029/2003JC001887.

Shapiro, N. M., Campillo, M., Stehly, L., and Ritzwoller, M. H., “High-resolution surface-wave tomography from ambient seismic noise,” Science, 307, 1615–1617, 2005. doi:10.1111/j.1365-246X.2006.03240.x.

Shimura, T., Mori, N., and Hemer, M. A., “Variability and future decreases in winter wave heights in the western north pacific,” Geophys. Res. Lett., 43, 2716–2722, 2016. doi:10.1002/2016GL067924.
Stopa, J. E., Ardhuin, F., and Girard-Ardhuin, F., “Wave climate in the arctic 1992-2014: seasonality and trends,” The Cryosphere, 10, 1605–1629, 2016. doi:10.5194/tc-10-1605-2016.

Squire, V., Dugan, J., Wadhams, P., Rottier, P., and Liu, A., “Of ocean waves and sea ice,” Annu. Rev. Fluid Mech., 27, 3, 115–168, 1995.

Stopa, J., P. Sutherland, F. Ardhuin, Strong and highly variable push of ocean waves on Southern Ocean sea ice, Proc. Nat. Acad. Sci., 115(23), 5861-5865, doi :10.1073/pnas.1802011115

Sutherland, P., D. Dumont, Marginal ice zone thickness and extent due to wave radiation stress, 2018, J. Phys. Oceanogr., doi : 10.1175/JPO-D-17-0167.1

Thomson, J., S. Ackley, F. Girard-Ardhuin, F. Ardhuin, A. Babanin, G. Boutin, J. Brozena, S. Cheng, C. Collins, M. Doble, C. Fairall, P. Guest, C. Gebhardt, J. Gemmrich, H. C. Graber, B. Holt, S. Lehner, B. Lund, M. H. Meylan, T. Maksym, F. Montiel, W. Perrie, O. Persson, L. Rainville, W. E. Rogers, H. Shen, H. Shen, V. Squire, S. Stammerjohn, J. Stopa, M. M. Smith, P. Sutherland, P. Wadhams, Overview of the Arctic Sea State and Boundary Layer Physics Program, J. Geophys. Res., 2018. doi :10.1002/2018JC013766

Tran, N., Vandemark, D., Labroue, S., Feng, H., Chapron, B., Tolman, H. L., Lambin, J., and Picot, N., “The sea state bias in altimeter sea level estimates determined by combining wave model and satellite data,” J. Geophys. Res., 115, p. C03020, 2010. doi:10.1029/2009JC005534.

Veron, F., “Sea spray,” Annu. Rev. Fluid Mech., 47, 507–538, 2015. doi:10.1146/annurev-fluid-010814-014651.

Wiese, A., Staneva, J., Schulz-Stellenfleth, J., Behrens, A., Fenoglio-Marc, L., and Bidlot, J.-R.:Synergy of wind wave model simulations and satellite observations during extreme events, Ocean Sci., 14, 1503-1521, https://doi.org/10.5194/os-14-1503-2018, 2018.

Young, I. R., & Donelan, M. A. (2018). *On the determination of global ocean wind and wave climate from satellite observations. Remote Sensing of Environment, 215, 228–241.* doi:10.1016/j.rse.2018.06.006

Appendix 1 - Open comments from survey participants

- *Right now I am just a peripheral user of satellite data. However me and my group are planning to use this data more, as we would like to widen our wave observations away from single buoy / point observations.*

- *Thanks for the work done*

- *Keen to try your product soon*

- *At this stage, I'm still trying to process the satellite data that I downloaded on the CMEMS server (Jason 3 along track significant wave height) and once I'm done with that, I will be to comment and make suggestions when needed.*

- *I've never used satellite measurements but would be interested in possible applications in the nearshore*

- *The satellite data are not open data, their availability depends on the country of satellite ownesrhip, the country of user's residency, the nature of the organizations of all the interested parties and more.*

- *hope it works well for u!*

- *The datasets produced by the CCI might last for a decade so it is important to make the most of the project and ensure all parties (users, scientists, engineers, industry, ...) are satisfied as best as possible.*

- *I feel rather out of touch, due to other work commitments, but very happy to see all of this happening and I hope to be more involved later*

- *Nice survey.*

- *thanks for collecting this information*

- *thanks*

- *Thank you so much for the initiative. I really appreciate it!*

- *Thank you for the great work you do.*

- *None*
- *Thanks for the great work you are doing in this interdisciplinary area. Two further comments in support of your excellent work in this area:*

  1 - if an interdisciplinary user like me / my group members / isn't using a product it might be because they didn't know about it yet.

2 – with data-driven (e.g. machine learning) approaches, we just need lots of data and not to worry too much about each individual type of observable. Sometimes it is better not to pre-empt what is a useful observable.

- *It would be great to have a page with a list of data sources for all available historical and NRT SAR L2, L3 datasets including ERS-1/2, Envisat, and Sentinel-1A/B together with their pros and cons (e.g. good quality/bad quality/no quality), similarly for buoy data (both directional and otherwise) and also for altimetry data.*

- *Just a single summary page of links and pros and cons of using the data.*

- *I would prefer to have access to raw (less smooth) data, and do my own processing to them.*

- *It will have a great deal if one can be able to validate the wave models with the satellite data*

- *I'm not sure about merged altimeter data provided by IFREMER. But I contacted the concerned person I didn't receive any response. Then it's like use with your own risk. Can someone help me with my doubts in data inhomogeneity issues?*