WORLD OCEAN CIRCULATION

PRODUCT USER MANUAL
ERASTAR
(THEME 1)

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1 Introduction

1.1 Purpose of the document

The present document is the Product User Manual dedicated to the content and format description of the ERA star stress-equivalent wind vector (U10S) and wind stress product.

This is the primary document that users should read before handling the product. It provides an overview of processing algorithm, technical product content and format and main validation results.

1.2 Document structure

In addition to this introduction, this document includes the following chapters:

- Chapter 2 describes the ERA star retrieval algorithm and the main characteristics of the product.

1.3 Applicable & Reference documents

- [RD-1] ESA WOC2019: http://woc2019.esa.int/index.php
- [RD-2] Synthesis of the WOC2019 User Consultation Meeting recommendations http://woc2019.esa.int/files/WOC2019_summary_synthesis.pdf

1.4 Terminology

ASCAT	Advanced SCATterometer on board Metop satellite series
ATBD	Algorithm Theoretical Basis Document
BUFR	Binary Universal Form for the Representation of meteorological data
CMEMS	Copernicus Marine Environment Monitoring Service
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	Fifth ECMWF Reanalysis
ESA	European Space Agency

FC	Forecast
GRIB	Gridded Binary or General Regularly-distributed Information in Binary form
HSCAT-A	HY-2A scatterometer
HSCAT-B	HY-2B scatterometer
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer
ITCZ	Inter Tropical Convergence Zone
KNMI	Royal Netherlands Meteorological Institute
NOAA	National Oceanic and Atmospheric Administration
OSCAT	Oceansat-2 SCATterometer
OSCAT2	SCATSat-1 scatterometer
PUM	Product User Manual
QUID	Quality Information Document
RB	Requirement Baseline
SSH	Sea Surface Height
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SoW	Statement of Work
TN	Technical Note
U10S	Stress-equivalent wind
UCM	User Consultation Meeting
URD	User Requirement Document
WBS	Work Breakdown Structure
WOC	World Ocean Circulation

2 ERAstar Product

2.1 Overview

The ERA* stress-equivalent wind (U10S) product is a correction of the ECMWF Fifth Reanalysis (ERA5) output by means of geo-located scatterometer-ERA5 differences over a few days temporal window. The version 2 products contain two different datasets: the nominal product over the period 2010-2020, which uses a temporal window of 15 days (except for 2010, in which a temporal window of 30 days is used); and an enhanced quality and resolution product for the years 2013, 2018 and 2020, which uses a temporal window of 3 days. Both products use, at any given time, all available scatterometer systems with global and continuous coverage. The enhanced product is only provided over those periods in which there is sufficient scatterometer sampling to allow the use of short temporal windows. The scatterometer-based corrections are computed from a combination of the following systems, i.e., the Advanced Scatterometers (ASCAT-A, -B, -C) onboard the EUMETSAT Metop satellite series, and the scatterometers onboard the ISRO Oceansat-2 (OSCAT) and SCATSat-1 (OSCAT2). ERA* can correct for local, persistent NWP model output errors associated with physical processes that are absent or misrepresented by the model, e.g., strong current effects (such as WBCS, highly stationary), wind effects associated with the ocean mesoscales (SST), coastal effects (land see breezes, katabatic winds), PBL parameterization errors, and large-scale circulation effects, e.g., at the ITCZ.

A comprehensive characterization of the ERA* U10S product is presented, including a qualitative comparison between the ERA5 and ERA* products, a U10S product quality assessment against independent scatterometer observations (i.e., those with non-global and/or discontinued coverage: HSCAT-A, RapidSCAT, and HSCAT-B), and a geophysical consistency analysis of the derived maps through spectral analysis. Several configurations of ERA* are assessed, including different scatterometer sampling combinations and temporal windows (from 1 to 30 days).

Overall, we find that the ERA* configuration with the largest scatterometer sampling (i.e., a combination of ASCATs and one OSCAT) over a 3-day temporal window provides the best performance, in terms of vector root mean square (VRMS) difference with respect to the mentioned independent scatterometer U10S. The ERA* relatively low error variance ($VRMS^2$) scores and relatively shallow spectral slopes (in between those of HSCAT-A/-B and ERA5) indicate that indeed smaller scale signal is introduced in the corrected ERA5 fields (i.e., ERA*).

However, in periods when the combination of one or several ASCATs and one OSCAT is not available, e.g., periods when OSCAT or OSCAT2 were not in orbit (2014-2016) or were operating but suffered long data interruptions (2010-2012, 2017, and 2019), the ERA* data quality is substantially degraded when using the 3-day temporal window, and a longer temporal window of 15 days is needed to achieve a significantly better U10S quality than that of ERA5. Moreover, in 2010, when only ASCAT-A and OSCAT data were available, because of the OSCAT long data interruptions (more than 3 months), a temporal window of 30 days is required to ensure good data quality. Overall, the baseline ERA* product outperforms ERA5 with an error variance reduction of about 3-9%, depending on the ocean region and the scatterometer combination. In addition, an enhanced-quality ERA* product using a 3-day time window is also provided, but only in those periods with sufficient scatterometer sampling, i.e., 2013, 2018, and 2020. Overall, the enhanced ERA* product outperforms ERA5 with an error variance reduction of about 6-11%.

2.2 Algorithm

2.2.1 Retrieval methodology

The proposed methodology, which is based in [Trindade et al., 2020], generates a scatterometer-based correction (*SC*) to produce ERA*, which is applied to both the zonal and the meridional wind components (u_{10s}, v_{10s}). Note that since the same formulation is used to correct the biases in both wind components, for simplicity, only the zonal component equations are shown in this Section.

The correction is based on the temporally averaged difference between scatterometer (u_{10s}^{SCAT}) and ERA5 U10S (u_{10s}^{ERA5}), at grid point (*i,j*) and time sample (*t*), as described in the following equation:

$$SC(i,j,t_f) = \frac{1}{M}\sum_{t=1}^{M}\left(u_{10s}^{SCAT_k}(i,j,t) - u_{10s}^{ERA5}(i,j,t)\right) \quad (1)$$

Here, $u_{10s}^{SCAT_k}$ and u_{10}^{ERA5}, respectively, correspond to the collocated scatterometer and ERA5 zonal U10S component, in which k refers to the number of sensors used in the *SC*. The data sets are collocated for a temporal window of *N* days, centered at t_f, i.e., $t_f \pm N/2$ days, where *M* is the number of scatterometer and ERA5 collocations at grid point (*i,j*) within the defined time window around the ERA5 time t_f.

Finally, the scatterometer correction, $SC(i,j,t_f)$ is added to the ERA5 U10S forecasts, $u_{10s}^{ERA5}(i,j,t_f)$ at time t_f as follows

$$u_{10s}^{ERA*(i,j,t_f)=u_{10s}^{ERA5}(i,j,t_f)+SC(i,j,t_f)} \quad (2)$$

The ocean forcing product derived from (2), u_{10s}^{ERA*}, is provided in a regular grid [Driesenaar et al., 2020] at 0.125 deg spatial resolution, and a temporal resolution of 1 h, following ERA5.

Since scatterometer measurements from different sensors are combined, the effects of the instrument sampling errors on the quality of the generated wind data set can be addressed. For the current ERA* product, the selected configuration is $k = 3$, which means that $u_{10s}^{SCAT_k}$ includes measurements from all available sensors with global and continuous coverage at any given time, i.e., ASCAT-A, -B, -C, OSCAT and/or OSCAT2, and $N = 3, 15, 30$, which means that the scatterometer-ERA5 differences are accumulated over temporal windows of either 3 (enhanced product), 15 or 30 days (nominal product). Also note that a 3-sigma filter is applied to the scatterometer-ERA5 differences to remove outliers due to transient weather effects.

The ASCATs and OSCATs U10S data have been reprocessed with the latest version of the EUMETSAT Ocean and Sea Ice Satellite Application Facilities (OSI SAF) ASCAT Wind Data Processor (AWDP) [Verhoef et al., 2020] and Pencil-beam Wind Processor (PenWP) [Verhoef et al., 2018], respectively. Also note that the latest version of the C-band (CMOD7) and Ku-band (NSCAT4DS) Geophysical Model Functions (GMFs) have been used to retrieve ASCAT and OSCAT2 winds, respectively. The ERA5 U10S forecast data have been used as background for ambiguity removal purposes. The ERA5 equivalent neutral wind (U10N) model output has been retrieved from the ECMWF MARS archive and then converted to U10S by KNMI, using the U10N-to-U10S conversion in [De Kloe et al., 2017]. Finally, the U10S-to-stress conversion (also in [De Kloe et al., 2017]) is used to compute ERA5 and ERA* wind stress vector, such that the final product contains both the ERA5 and the ERA* zonal and meridional components of U10S and stress.

Since the quality of the ERA* depends on the scatterometer sampling, the number of scatterometer samples per grid point (i,j) used in (1) is provided in the product, such that the user can decide whether to filter areas of low sampling number (e.g., less than 3 samples) or not. Note also that in those grid points where the number of samples is zero, the ERA5 U10S original product (served by KNMI) is kept (i.e., ERA*=ERA5). This happens over land and sea ice regions. In addition, some grid points very close to the coast also have no scatterometer samples. For convenience, a land/sea ice flag is also provided in the product, which is linked to the number of scatterometer samples in the following way: the flag is inactive (i.e., equal to zero) in those grid points where the number of samples is larger than zero, and the flag is active (i.e., equal to one) where the number of samples is zero.

Finally, since the U10S-to-stress conversion [De Kloe et al., 2017] is derived for open ocean, both ERA* and ERA5 stress data are only provided for ocean data (i.e., where the land/sea ice mask is equal to zero).

2.2.2 Limitations

Note that a good inter-calibration between C-band and Ku-band sensors is assumed in this methodology. However, these data sets do not account for latitude-dependent biases due to SST [Wang et al., 2017]. The effects of Ku-band SST errors, is only about 0.02 m/s per Kelvin and relevant on a global scale, where SST varies by 30 K. The remaining local wind observation errors are typically more than a factor of two smaller than NWP model errors. However, systematic wind speed and direction errors of OSCAT2 with respect to ASCATs have been recently found [Wang et al., 2019]. Current efforts at KNMI are focused on reducing the Ku-band system biases, which are directly linked to the instrument viewing geometry [Stoffelen and Portabella, 2006].

Note that due to poor scatterometer sampling, some *SC* configurations have gaps. By construction, these gaps are filled with ERA5 winds only, i.e., ERA* U10S will be the same as ERA5 U10S (see eq. 2). However, for a 2-day (or longer) time window (this product uses 3-day and longer windows) and 4 scatterometers (e.g., ASCAT-A, -B, -C, and OSCAT2), there is less than 0.2% of data gaps, mostly concentrated near the coastline. In particular, the sampling along the coast is irregular and somewhat different for each scatterometer. This will not only generate areas of no sampling, but also areas of low sampling number. Since the quality of the product depends on the scatterometer sampling, a different strategy for low-sampled regions should be further investigated. In addition, transient weather effects result in SC outliers. Strategies for removing outliers have been tested, since the ERA* does not aim at correcting for transient weather effects but local systematic effects. In addition, transient weather effects result in SC outliers. A preliminary strategy for removing outliers (3-sigma test) has been successfully applied to the SC computation. Further improvements in SC outlier removal will be implemented, since the ERA* does not aim at correcting for transient weather effects but for local systematic effects.

2.2.3 Differences with previous version (if relevant, phase 2)

In phase 1, it is concluded that a temporal window of 3 days leads to the best quality ERA* product over the year 2019. However, in phase 2, it is found that when OSCAT or OSCAT2 data interruptions occur, the ERA* data quality is degraded with respect to that of ERA5. For example, in the period 20 May – 19 June 2019, there is a data gap in OSCAT2 which leads to such quality degradation. As such, a longer temporal window of 15 days (30 days in 2010) is defined to ensure an ERA* product quality systematically higher than that of ERA5 throughout the entire period 2010-2020.

For those periods in which there is a combination of ASCATs and OSCATs with little or no data interruptions (i.e., 2013, 2018, and 2020), an enhanced quality ERA* product with a 3-day temporal window is also provided.

2.3 Product Description

The ERA* is a Level 4 (L4) product generated using both ERA5 and scatterometer data, and distributed in NetCDF-4 format following the Climate and Forecast (CF-1.8) Metadata conventions.

2.3.1 spatial information

The domain is global for all variables, based on an equidistant cylindrical projection with a constant longitude and latitude step of 0.125 degrees, with latitudes ranging from -89.9375 to 89.9375, and longitudes ranging from -179.9375 to 179.9375.

2.3.2 temporal information

Hourly for UTC times in accordance with the original ERA5 re-analysis and respective forecast step to the analysis.

2.3.3 product content

Stress is used as the parameter definer of the file content. The file contains the ERA* (i.e., the ERA5 corrected re-analysis) and the ERA5 re-analysis stress equivalent model wind components (u10s, v10s) expressed in m/s, and the derived model wind stress components (tauu, tauv) expressed in N/m^2. Note that the ERA5 U10S is provided by KNMI. Additionally, the scatterometer sampling is also provided, as well as a flag for presence of land or sea ice.

2.3.4 file name convention

The ERA* L4 files are named according to the NetCDF Climate and Forecast (CF) Metadata Convention version 1.8. The adopted file name convention is the following:

YYYYMMDDHH-WOC-L4-STRESS_ERAstar_GLO_0125_TWddD_1H_RyyyymmddTan_fc-v2.0-fv1.0.nc

L4 ERA* files (*ERAstar*) are delivered with a temporal resolution of one hour (*1H*). Therefore, the first string *YYYYMMDDHH* corresponds to the hour of the day of the corrected ERA5 U10S and stress field, with global (*GLO*) coverage on a regular grid with a spatial resolution of 0.125 degrees (0*125*).

The string *TWddD* corresponds to the length of the SC temporal window used.

Example: For a 15-day temporal window, the syntax is *TW15D*.

The string *RyyyymmddTan_fc* is the analysis date and UTC time and the forecast lead time (in hours). As such the former string differentiates in the case that two files are available for the same UTC time.

Example: For 09 UTC, on 15th February 2019:

File1. – shorter forecast range to analysis time
2019021509-WOC-L4-STRESS-ERAstar_GLO_0125_TW15D_1H_R20190215T06_03-v2.0-fv1.0.nc

File2. – longer forecast range to analysis time
2019021509-WOC-L4-STRESS-ERAstar_GLO_0125_TW15D_1H_R20190214T18_15-v2.0-fv1.0.nc

2.3.5 file format

The product is stored in NetCDF (network Common Data Form) format, specifically NetCDF-4. The structure/content of the file is detailed in the metadata section.

Table 1. Product Specification for 2019021509-WOC-L4-STRESS-ERAstar_GLO_0125_TW15D_1H_R20190215T06_03-v2.0-fv1.0.nc

Product Specification	*YYYYMMDDHH-WOC-L4-STRESS_ERAstar_GLO_0125_TWddD_1H_RyyyymmddTan_fc-v2.0-fv1.0.nc*
Geographical coverage	0°E→360°E; 90°S→90°N
Temporal window	3 days 15 days 30 days
Temporal resolution	Hourly files
Data Source	ASCAT-A onboard Metop-A ASCAT-B onboard Metop-B ASCAT-C onboard Metop-C OSCAT onboard Oceansat-2 OSCAT2 onboard ScatSat-1
Product Version	V2
Format	NetCDF-4
Horizontal resolution	Regular spacing 0.125°
Dimensions	time, lon, lat
Variables	Time in seconds since 1990-1-1 00:00:00 ERA* Model Zonal (Eastward) Stress Equivalent Wind Velocity [m/s] ERA* Model Meridional (Northward) Stress Equivalent Wind Velocity [m/s] ERA* Zonal (Eastward) Model Wind Stress [N/m^2] ERA* Meridional (Northward) Model Wind Stress [N/m^2] ERA5 Model Zonal (Eastward) Stress Equivalent Wind Velocity [m/s] ERA5 Model Meridional (Northward) Stress Equivalent Wind Velocity [m/s] ERA5* Zonal (Eastward) Model Wind Stress [N/m^2] ERA5* Meridional (Northward) Model Wind Stress [N/m^2] Number scatterometer samples Land/sea ice flag

2.3.6 metadata

The filename, dimensions, data variables, and global attributes included in the produced NetCDF files are the following (generated with ncdump -h):

```
netcdf \2019020109-WOC-L4-STRESS_ERAstar_GLO_0125_TW15D_1H_R20190201T06_03-v2.0-fv1.0 {
dimensions:
	lat = 1440 ;
	lon = 2880 ;
	time = 1 ;
variables:
	double lat(lat) ;
		lat:standard_name = "latitude" ;
		lat:long_name = "latitude" ;
		lat:units = "degrees_north" ;
	double lon(lon) ;
		lon:standard_name = "longitude" ;
		lon:long_name = "longitude" ;
		lon:units = "degrees_east" ;
	int64 time(time) ;
		time:standard_name = "time" ;
		time:long_name = "time" ;
		time:units = "seconds since 1990-01-01 00:00:00" ;
	short es_u10s(time, lat, lon) ;
		es_u10s:_FillValue = -32767s ;
		es_u10s:standard_name = "eastward_wind" ;
		es_u10s:long_name = "erastar stress equivalent model wind u component at 10 m" ;
		es_u10s:units = "m s-1" ;
		es_u10s:add_offset = 0. ;
		es_u10s:scale_factor = 0.01 ;
		es_u10s:method = "correction of ERA5 u10s estimates by means of geo-located scatterometer-ERA5 differences over a 15 temporal window" ;
	short es_v10s(time, lat, lon) ;
		es_v10s:_FillValue = -32767s ;
		es_v10s:standard_name = "northward_wind" ;
		es_v10s:long_name = "erastar stress equivalent model wind v component at 10 m" ;
		es_v10s:units = "m s-1" ;
		es_v10s:add_offset = 0. ;
		es_v10s:scale_factor = 0.01 ;
		es_v10s:method = "correction of ERA5 v10s estimates by means of geo-located scatterometer-ERA5 differences over a 15 temporal window" ;
	short es_tauu(time, lat, lon) ;
		es_tauu:_FillValue = -32767s ;
```

```
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            es_tauu:long_name = "erastar eastward wind stress" ;
            es_tauu:units = "Pa" ;
            es_tauu:add_offset = 0. ;
            es_tauu:scale_factor = 0.01 ;
      short es_tauv(time, lat, lon) ;
            es_tauv:_FillValue = -32767s ;
            es_tauv:standard_name = "surface_downward_northward_stress" ;
            es_tauv:long_name = "erastar nowthward wind stress" ;
            es_tauv:units = "Pa" ;
            es_tauv:add_offset = 0. ;
            es_tauv:scale_factor = 0.01 ;
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            e5_u10s:_FillValue = -32767s ;
            e5_u10s:standard_name = "eastward_wind" ;
            e5_u10s:long_name = "era5 stress equivalent model wind u component at 10 m"
;
            e5_u10s:units = "m s-1" ;
            e5_u10s:add_offset = 0. ;
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            e5_v10s:_FillValue = -32767s ;
            e5_v10s:standard_name = "northward_wind" ;
            e5_v10s:long_name = "era5 stress equivalent model wind v component at 10 m"
;
            e5_v10s:units = "m s-1" ;
            e5_v10s:add_offset = 0. ;
            e5_v10s:scale_factor = 0.01 ;
      short e5_tauu(time, lat, lon) ;
            e5_tauu:_FillValue = -32767s ;
            e5_tauu:standard_name = "surface_downward_eastward_stress" ;
            e5_tauu:long_name = "era5 eastward wind stress" ;
            e5_tauu:units = "Pa" ;
            e5_tauu:add_offset = 0. ;
            e5_tauu:scale_factor = 0.01 ;
      short e5_tauv(time, lat, lon) ;
            e5_tauv:_FillValue = -32767s ;
            e5_tauv:standard_name = "surface_downward_northward_stress" ;
            e5_tauv:long_name = "era5 nowthward wind stress" ;
            e5_tauv:units = "Pa" ;
            e5_tauv:add_offset = 0. ;
```

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                :institution_abreviation = "ICM" ;
                :references = "doi:10.1109/TGRS.2019.2946019" ;
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                :naming_authority = "http://cersat.ifremer.fr" ;
                :cdm_data_type = "grid" ;
                :comment = "These data were produced at ICM/CSIC as part of the ESA WOC project" ;
                :creator_name = "Giuseppe Grieco" ;
                :creator_url = "http://cersat.ifremer.fr" ;
                :creator_email = "giuseppe.grieco@cnr.it" ;
                :creator_institution = "ICM/CSIC" ;
                :project = "World Ocean Circulation (WOC) - European Space Agency" ;
                :time_coverage_start = "20190201T09:00:00" ;
                :time_coverage_end = "20190201T09:00:00" ;
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                :geospatial_lon_max = 179.9375 ;
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                :format_version = "WOC v2.0" ;
                :processing_level = "L4" ;
                :track_id = "bc2d5b0b-e77d-40cc-9419-901fb4e9854b" ;
                :publisher_name = "Cersat" ;
                :publisher_url = "cersat.ifremer.fr" ;
                :publisher_email = "cersat@ifremer.fr" ;
                :publisher_institution = "Ifremer / Cersat" ;
                :scientific_support_contact = "portabella@icm.csic.es" ;
                :technical_support_contact = "cersat@ifremer.fr" ;
                :key_variable = "es_u10s, es_v10s, es_tauu, es_tauv, e5_u10s, e5_v10s, e5_tauu, e5_tauv, count, quality_flag" ;
                :source = "erastar" ;
                :source_version = "2.0" ;
                :input = "nwp_20190201_06_03_125.grib" ;
                :processing_software = "ERA5star" ;
                :date_created = "2021-06-30T10:46:46" ;
                :date_modified = "2021-06-30T10:46:46" ;
}
```

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