SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Wind stress in coupled wave-atmosphere models: storms and swells
Computer Project Account:	spfrardh
Start Year - End Year :	2013 - 2015
Principal Investigator(s)	Fabrice Ardhuin and Jean-Luc Redelsperger
Affiliation/Address:	CNRS, Brest, France
Other Researchers (Name/Affiliation):	Lucia Pineau-Guillou Ifremer, Brest, France

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The better performance of Meteo-France's operational wave model (MFWAM) in many regions of the world ocean (e.g. around Hawaii) shows that ECMWF wave forecasts can probably be improved by using different parametrizations for wind-wave generation and dissipation. However, MFWAM results are not consistent with expect wind stress variability. Our objective is thus to develop wave and boundary layer parametrizations to arrive at a consistent treatment of the both wave evolution and wind stress, leading to improved forecast capabilities in the context of the coupled atmosphere-waves IFS system. Wet considers both high wind conditions in extra-tropical storms of the North Atlantic, for which the stress at a given wind speed is expected to decrease with wave age, and low wind conditions on the global scale for which swells are known to modify the air-sea momentum flux. The first effect that is already taken into account in the IFS, but its magnitude is still debated. The swell effect will probably require a modification of the boundary layer parametrization.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

The project has been delayed as the main PI, F. Ardhuin has been requested in September 2014 to take the chairmanship of a 80 people lab and merging with another 30 people. This has led to the opportunity to combine the special project with an internal Ph.D. thesis work for one of the lab engineers, L. Pineau-Guillou, who has an extensive experience in storm surge and water level modelling. She has taken up the modelling and analysis tasks after two visits at ECMWF in June 2015, and has been working on this project 50% of her time in 2015. We thank ECMWF for the warm welcome she received and J.R. Bidlot for helping along after a formal one week training in 2015.

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

Experience with Special Project framework is very positive. We thank Service Desk for their fast assistance and J. R. Bidlot for kindly helping in case of technical problems.

Summary of results

(This section should comprise up to 10 pages and can be replaced by a short summary plus an existing scientific report on the project.)

1. Objectives

The objective is to analyse the drag variability caused by the sea state and to estimate its impact on winds. Five parameterizations have been tested, including ECMWF default parameterization (Janssen 1991), and MFWAM parameterization (Ardhuin et al.; 2010). In order to have a statistical approach, experiments have been led on 10 storms at mid-latitude in North East Atlantic.

2. Events selection

Events have been selected from analysis of ERA-Interim database (Dee et al. 2011). This database is a global atmospheric reanalysis produced by ECMWF, covering period 1979-up to now (database being continuously updated). The grid is a reduced Gaussian grid, with a spectral truncation T255, corresponding to a horizontal resolution of about 80 km. The vertical resolution is of 60 levels, with the top of the atmosphere located at 0.1 hPa. The temporal resolution is of 30 minutes, and outputs are very 3 hours.

Analysis has been undertaken over the 10 last years (2005-2014) and restricted to our area of interest: North East Atlantic, from 30°W to 10°E and 30°N to 65°N. Over these 10 years, the more energetic events have been selected, from both criteria: surface wind speed higher than 32 m/s and MSL (Mean Sea Level) pressure lower than 975 hPa. Analysis showed that 29 storms matched these criteria. They have been classified according to wind speed, and the 10 more energetic events are summarised in Table 1. Wind, MSL Pressure and SWH (Significant Wave Height) come from ERA-Interim Analysis, whereas Wind Gust and Total Precipitation come from ERA-Interim Forecast (not available in ERA-Interim Analysis), which explains the incoherence for Klaus storm, where wind gust is smaller than wind speed (37.8 m/s, compared with 41.8 m/s). The storm names have been attributed thanks to DWD (German Meteorological Office) synoptic charts. When the storm is too far from Europe, no name has been attributed (see for example storm of 8th December 2016, which has evolved close to Iceland and Greenland). Sometimes, a primary system is followed by a second one; in this case, several names are mentioned (see for example Kaat/Lilli for the 25th January 2014).

Storm date	Rank	Name	Wind	Wind Gust	MSLP	SWH	Total prec. (24h)
2005-01-11	9	Gero	34.9 m/s	49.0 m/s	952 hPa	9.8 m	59 mm
2005-09-26	7	Zeljko	35.9 m/s	46.3 m/s	967 hPa	8.2 m	27 mm
2006-12-09	5	Xynthia	37.6 m/s	50.4 m/s	951 hPa	9.0 m	29 mm
2007-12-10	3	*No name*	39.0 m/s	54.0 m/s	963 hPa	7.5 m	30 mm
2007-12-14	8	*No name*	35.2 m/s	48.4 m/s	948 hPa	12.4m	25 mm
2009-01-23	1	Hans/Klaus	41.8 m/s	37.8 m/s	944 hPa	9.4 m	44 mm
2013-12-15	6	Zaki	36.9 m/s	48.0 m/s	957 hPa	9.7 m	27 mm
2014-01-25	4	Kaat/Lilli	38.1 m/s	56.3 m/s	953 hPa	11.7m	31 mm
2014-03-07	10	Danli	33.9 m/s	41.0 m/s	965 hPa	7.4 m	41 mm
2014-12-08	2	Alexandra	39.6 m/s	45.5 m/s	964 hPa	7.8 m	25 mm

Table 1: Maximum of wind, wind gust, Significant Wave Height (SWH), minimum of Mean Sea Level Pressure (MSLP) and total precipitation over 24 hours for the 10 more energetic events, based on ERA-Interim analysis on North East Atlantic (30°E 10°W 30°N 65°N) and over period 2005-2014. Wind, MSL pressure and Significant Wave Height (Hs) come from ERA-Interim Analysis, whereas Wind Gust and Total Precipitation come from ERA-Interim Forecast (not available in ERA-Interim Analysis).

3. Experiments

Configuration for sensitivity tests is Integrated Forecasting System (cycle CY41r1) at resolution T1279 (~16 km) coupled to the 0.25° resolution (~27 km) WAM using 24 directions and 30 frequencies. Experiments have been carried out, starting from operational analyses and going up to 120 h (5 days). Output data are every 3 hours (instead of 12 h by default). Experiments, conducted in the framework of the project are presented Table 2.

Name	Type	Comments	Branch
b0h2	fc	coupled, IPHYS=0, T511	
b0h3	fc	uncoupled, T511	
b0h5	fc	coupled, IPHYS=1, T511	ar0x_CYC41R1_WAM_MeteoFrance
b0h9	fc	coupled, IPHYS=1, Charnock wave age dependant, T511	ar0x_CYC41R1_WAM_dev
b0h7	wam	2009 year with IPHYS=0	
b0h8	wam	2009 year with IPHYS=1	ar0x_CYC41R1_WAM_MeteoFrance
b0hb	fc	coupled, IPHYS=0, modified Charnock, T511	ar0x_CYC41R1_WAM_devmodcha
b0hd	fc	coupled, **IPHYS=0**, T1279	
b0he	fc	coupled, IPHYS=0, T1279, 2014 year	
b0hf	fc	coupled, **IPHYS=1**, T1279	ar0x_CYC41R1_WAM_MeteoFrance
b0hg	fc	coupled, IPHYS=0, **Charnock wave age dependant**, T1279	ar0x_CYC41R1_WAM_dev
b0hh	fc	coupled, IPHYS=0, **modified Charnock**, T1279	ar0x_CYC41R1_WAM_devmodcha
b0hi	fc	**uncoupled**, T1279	

Table 2: Experiments conducted in the framework of the project.

Tests have shown that influence of resolution on results was significant. For this reason, T1279 resolution (~16 km) has been chosen instead of T511 initial resolution T511 (~39 km).

4. Parameterizations

Five parameterizations have been tested:

- uncoupling WAM/IFS - experiment *b0hi*,
- coupling WAM/IFS with ECMWF default parameterization (Janssen 1991) - experiment *b0hd*,
- coupling WAM/IFS with MFWAM parameterization (Ardhuin et al. 2010) - experiment *b0hf*,
- coupling WAM/IFS with wave age dependant parameterization (Oost et al. 2002) – experiment *b0hg*,
- coupling WAM/IFS with **empirically-derived Charnock parameterization** – experiment *b0hh*.

Empirically-derived Charnock parameterization aims at confining the drag coefficient, in order to keep physical values (i.e. lower than 3.5 10^{-3} by high winds, as measured by Powell et al. 2003, see Figure 1). As the Charnock parameter is exchanged between WAM and IFS, it is modified according the following formula:

$$\beta(IJ) = \beta_{cst} + (\beta(IJ) - \beta_{mean}(ib)) * \alpha$$

$$\beta(IJ) = \beta_{mean}(ib) + (\beta(IJ) - \beta_{mean}(ib)) * \alpha$$ if wind is higher than threshold:

if wind is lower than threshold:

where β is Charnock parameter, β_{cst} is a constant value, β_{mean} is extracted from tables of mean Charnock computed from one year of simulation (2014, experiment *b0he*, see Table 2), and α is a constant valued between 0 and 1 aiming at reducing the Charnock variability. Values applied for experiment *b0hh* are:

- threshold=15 m/s,
- β_{mean}=tables computed from one year of simulation,
- β_{cst}=0.02,
- α=0.5.

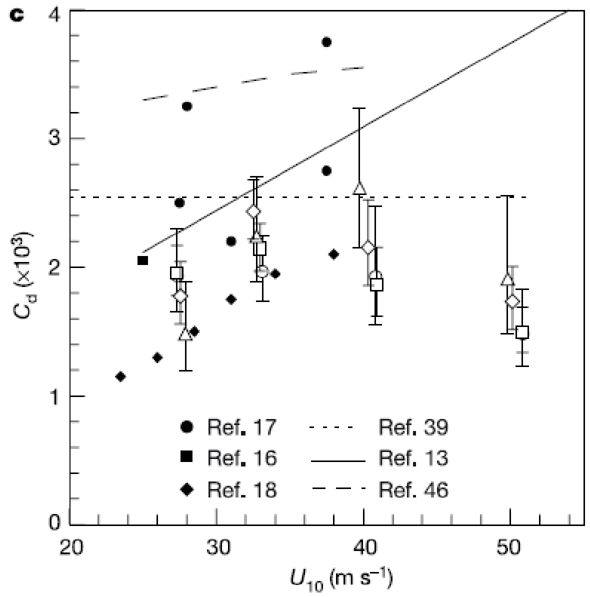

Figure 1: Drag coefficient measured for very high wind in tropical cyclones (Powell et. al 2003)

4. Results

4.1 Charnock parameter and drag coefficient

Figures 2 and 3 show Charnock parameter and drag coefficient during Kaat and Lilli storms, with ECMWF default parameterization and empirically-derived Charnock parameterization. For default parameterization, drag values are probably overestimated for high winds. Modelled drag coefficient can reach 0.004 for winds between 20 and 25 m/s, whereas observed drag coefficient for high wind speeds in tropical cyclones are lower than 0.003 (Powell et al.; 2013, see Figure 1). This could be due to an excess of energy level in the high wavenumber tail of the wave spectrum (Bidlot et al.; 2015). Results show that objective of empirically-derived Charnock parameterization is reached, with lower drag values.

Figure 4 shows Charnock parameter and drag coefficient during Kaat and Lilli storms, for the five tested parameterizations. All parameterizations show quite high drag values, except empirically-derived Charnock parameterization, which give drag values quite similar to uncoupled model. MFWAM parameterization shows the stronger values of drag, this is probably du to a lack of adjustment of some parameters, which will have to be optimized (e.g. BETAMAX, ZALP, TAUWSHELTER, ALPHA).

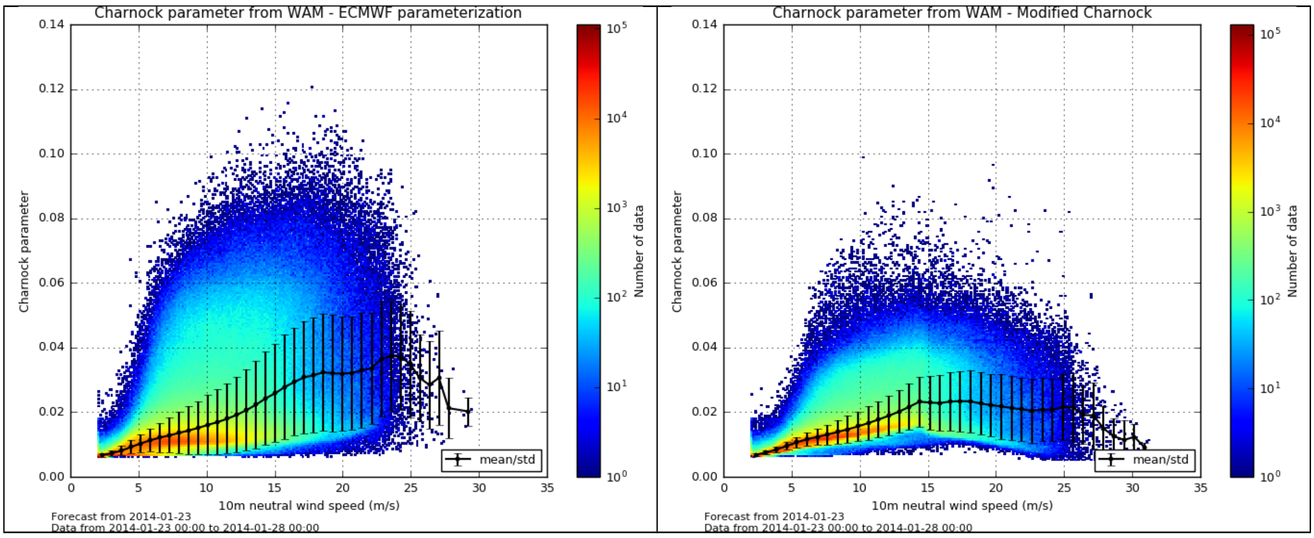

Figure 2: Charnock parameter during Kaat and Lilli storms (from 23rd to 27th January 2014), with ECMWF default parameterization (left) and empirically-derived Charnock parameterization (right)

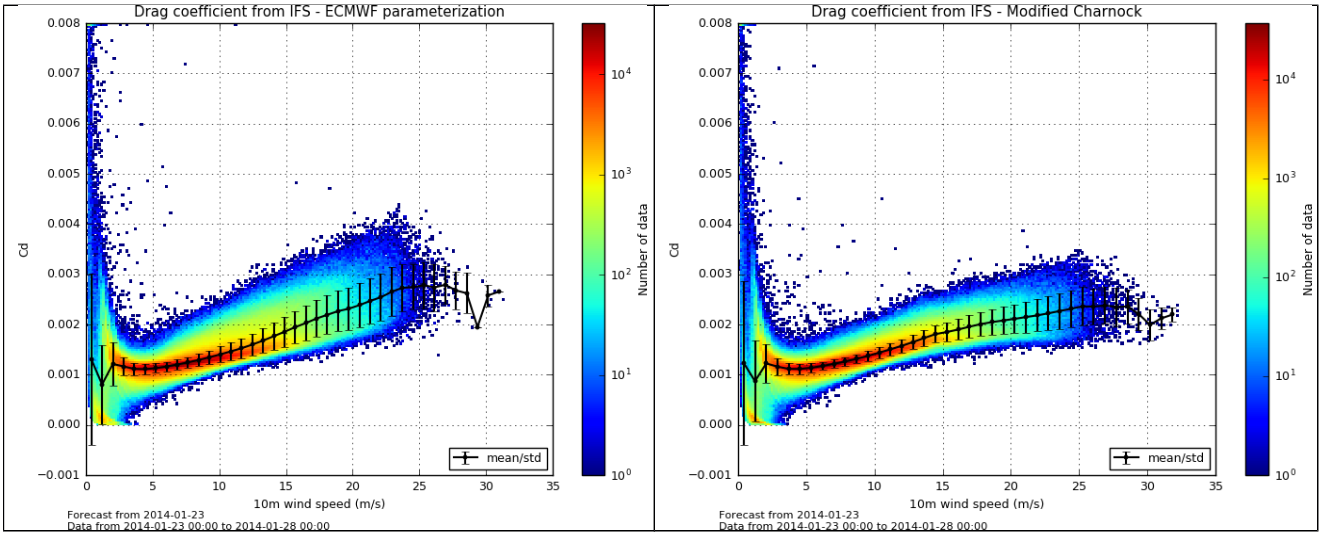

Figure 3: Drag coefficient during Kaat and Lilli storms (from 23rd to 27th January 2014), with ECMWF default parameterization (left) and empirically-derived Charnock parameterization (right)

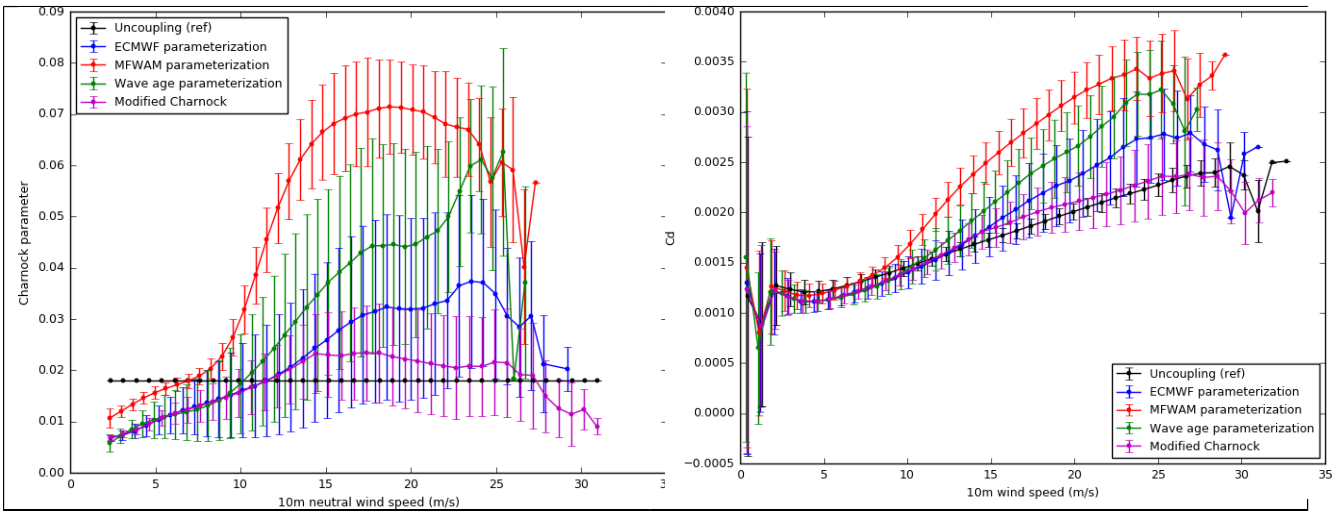

Figure 4: Charnock parameter (left) and drag coefficient (right) during Kaat and Lilli storms (from 23rd to 27th January 2014), for the five tested parameterizations

4.2 Impact of coupling on winds

Comparisons between coupled and uncoupled simulations are presented Figure 5. As previously described by Janssen et al. (2005) and other ECMWF reports, the coupling enhances the Charnock coefficient for high winds. This enhancement yields a higher drag coefficient and higher wind stress, which is partly compensated by a reduced wind speed at 10 m as the atmospheric boundary layer adjusts. There is a strong debate in the scientific community on what should be the right level of the drag coefficient Cd and its dependence on wave age. Many studies suggest that the Cd should not exceed 0.003 (e.g. Powell et al. 2003, Jarosz et al. 2007). There is also a known strong difference between wind speeds from ECMWF and other wind estimates. In particular, ECMWF winds above 20 m/s are typically 10% lower than NCEP (e.g. Rascle and Ardhuin, 2013), which can have a big impact on extreme sea states (Hanafin et al., 2012). Our working hypothesis is that the wave-atmosphere coupling used at ECMWF introduces some realistic variability of the wind stress, but that the level of the stress at high wind may be too high, which would be compatible with low bias in the wind speeds. Empirically-derived Charnock parameterization allows clearly confining Charnock and drag to lower values, leading to less lower winds.

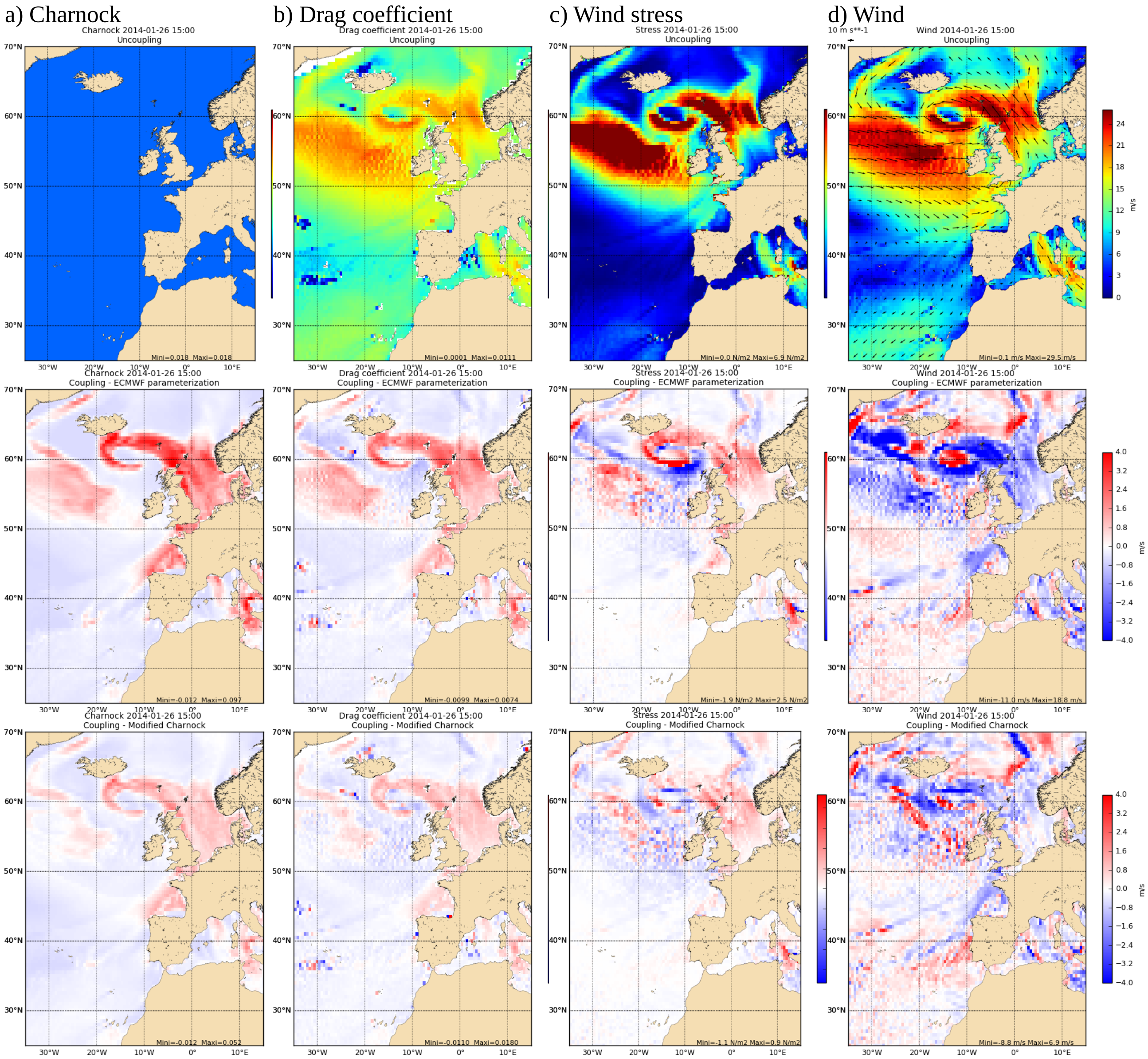

Figure 5: Charnock parameter (a), drag coefficient (b), wind stress (c) and wind (d) uncoupling (first line), coupling with ECMWF default parameterization (second line) and empirically-derived Charnock parameterization (third line) – second and third lines are differences with first line.

5. Conclusions and perspectives

This project showed impact of different drag parameterizations on winds. Empirically-derived Charnock parameterization allows clearly confining Charnock and drag to lower values, leading to higher wind speeds compared to the operational setting. Further work is ongoing in order to use independent buoys, platforms and satellite data. Preliminary result confirm that ECMWF wind speeds are biased low for wind speeds above 20 m/s, and the proposed parameterizations can improve on this (see Special Project 2016-2018 Improvement of wind stress parameterization in coupled wave-atmospheric models). However, the IPHYS=1 (MFWAM) option is not a good choice for a coupled system as it tends to give larger drag coefficients and even lower wind speeds than the operational setting.

6. References

Ardhuin F, Rogers E, Babanin AV, Filipot J, Magne R, Roland A, van der Westhuysen A, Queffeulou P, Lefevre J, 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, 2418, 2425, 2431, 2441.

Bidlot J.-R., Breivik Ø., Mogensen K., Alonso Balmaseda M., Janssen P. (2015). ECMWF Coupled Ocean-Wave-Atmosphere forecast system. Marine Environmental Monitoring, Modelling and Prediction Colloquium, 4th - 8th May 2015, Liège, Belgium.

Dee, D. P., and 35 co-authors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quart. J. R. Meteorol. Soc., 137, 553-597. DOI: 10.1002/qj.828.

Jennifer A. Hanafin, Yves Quilfen, Fabrice Ardhuin, Joseph Sienkiewicz, Pierre Queffeulou, Mathias Obrebski, Bertrand Chapron, Nicolas Reul, Fabrice Collard, David Corman, Eduardo B. de Azevedo, Doug Vandemark, and Eleonore Stutzmann (2012). Phenomenal Sea States and Swell from a North Atlantic Storm in February 2011: A Comprehensive Analysis. Bull. Amer. Meteor. Soc., 93, 1825–1832. doi: http://dx.doi.org/10.1175/BAMS-D-11-00128.1

Janssen, P. A. E. M. (1991). Quasi-linear theory of wind-wave generation applied to wave forecasting. J. Phys. Oceanogr., 21, 1631–1642

Janssen PAEM, Bidlot J-R, Abdalla S, Hersbach H. (2005). Progress in ocean wave forecasting at ECMWF. Tech. Memo. 478, ECMWF, Reading, UK.

Jarosz, E., D. A. Mitchell, D. W. Wang, and W. J. Teague (2007). Bottom-up determination of air-sea momentum exchange under a major tropical cyclone. Science, 315, 1707–1709, doi:10.1126/science.1136466.

Powell, M., Vickery, P. & Reinhold, T. (2003). Reduced drag coefficient for high wind speeds in tropical cyclones. Nature, 422, 279-283.

Nicolas Rascle, Fabrice Ardhuin. (2013). A global wave parameter database for geophysical applications. Part 2: Model validation with improved source term parameterization. Ocean Modelling 70, 174-188.

List of publications/reports from the project with complete references

No publication/report has yet been completed, but a paper is in preparation.

Future plans

(Please let us know of any imminent plans regarding a continuation of this research activity, in particular if they are linked to another/new Special Project.)

Project is linked with on going Special Project “Improvement of wind stress parameterization in coupled wave-atmospheric models” covering period 2016-2018.