Volume 1 - Technical Proposal

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GRASP

new Generation of Regional Arctic Sea ice Predictions

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Table of Contents

1. Technical Approach and Justification

1.1 Emerging Opportunities in the Rapidly Changing Arctic

The dramatic decline in Arctic sea ice has been an emblematic sign of ongoing global climate change. Profound reductions in sea ice areal coverage (Cavalieri and Parkinson, 2012) and thickness (Rothrock et al., 2008), among others, have already had substantial impacts on local ecosystems (Tynan, 2015; Kovacs et al., 2011), indigenous populations (Meier et al., 2014) and possibly lower-latitude climate (Vihma, 2014; Cohen et al., 2014). These rapid changes also open access to new resources and unlock economic opportunities. Thinner, younger ice facilitates operations of icebreakers in the High North. Increased marine accessibility promotes polar shipping (Stephenson et al., 2013; Smith and Stephenson, 2013) as an economically viable alternative to existing commercial routes (Liu and Kronbak, 2010). Ecotourism, resources extraction and fishing are other examples of activities that can take place in an open Arctic Ocean. However, further projected reductions in the sea ice cover (Massonnet et al., 2012; Stroeve et al., 2012) will not only place the Arctic as a new playground for future human activities. These changes will also raise important questions regarding risks, safety and security, three aspects that must be considered prior to any future activity in this harsh environment (Lloyd's, 2012; U.S. Navy, 2014).

Seasonal Arctic sea ice prediction is a very active research topic. It is of high interest to a wide range of stakeholders demanding to know more about sea ice conditions in the Arctic at strategic time scales from several weeks to several months. Recent studies have highlighted the *potential* to predict sea ice evolution at these time horizons and even beyond (Blanchard-Wrigglesworth et al., 2011; Chevallier et al., 2012; Guemas et al., 2014a for a review). In practice, however, the situation is quite different: current prediction systems struggle to deliver reliable and skillful seasonal forecasts (Stroeve et al., 2014), in particular at the regional scale. Dynamical climate models are particularly promising tools in this respect, because they can handle the non-stationary character of the ever-evolving Arctic mean sea ice conditions (Holland and Stroeve, 2011; Goosse et al., 2009), an aspect on which simple statistical models trained on past data will almost inevitably stumble. Dynamical models also have the advantage to simulate a comprehensive list of state variables from which user-relevant information can directly be inferred. This is not always the case in statistical models.

Model uncertainty in seasonal sea ice predictions (Fig. 1 for an example) is governed by three competing sources, the relative importance of which has been not adequately quantified.

(1) The model is uncertain by itself because it is an approximation of reality. Some crucial physical processes, such as the dependence of sea ice compressive strength on local thickness and concentration, are highly parameterized in the vast majority of current models using the so-called elastic-viscous-plastic (EVP) rheology (Hunke and Dukowicz, 1997). The coarse horizontal resolution (~1°) of contemporary climate models is another example of factor contributing to the uncertainty in the predictions. Higher oceanic and atmospheric resolutions (0.25° at least) are indeed required to at

least permit the explicit development of mesoscale ocean eddies and hence the representation of sea ice drift and deformation (Zhang et al., 1999) or frontal scale air-sea interactions (Bryan et al., 2010).

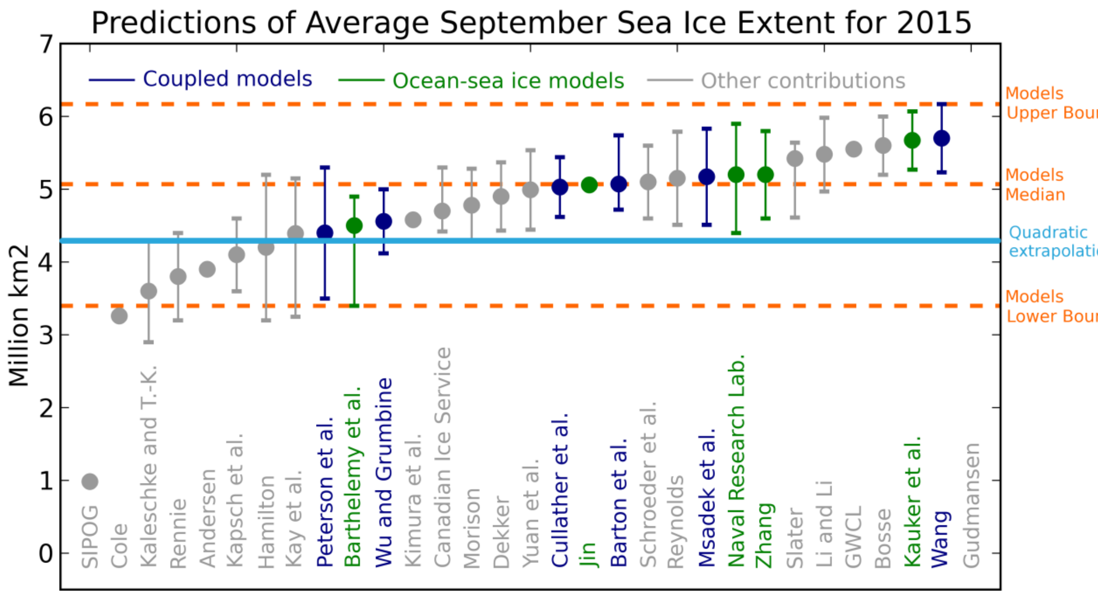

Figure 1 : June submissions to the 2015 Sea Ice Outlook for the prediction of September 2015 average sea ice extent. Dynamical model contributions are shown in color and predictions from other methods (statistical, heuristic, mixed) in grey. The figure highlights that the total uncertainty in predicted sea ice extent stems first from inter-model differences (resolution, physics) and differing initial conditions. This is shown by the spread between plain dots. Another part of uncertainty is irreducible and comes from inherent unpredictable evolution of the atmosphere and possibly the ocean and sea ice. This is shown by error bars surrounding each individual prediction. Figure courtesy of F. Massonnet, created for the Sea Ice Outlook June Report. (see more details on this analysis at http://www.arcus.org/sipn/sea-ice-outlook/2015/june).

(2) Initial conditions are uncertain due to observational gaps and errors. Mathematically speaking, sea ice seasonal prediction is essentially an initial-value problem (Blanchard-Wrigglesworth et al., 2011). A comprehensive specification of initial conditions is, however, not possible owing to the lack of homogeneous and continuous sea ice thickness and oceanic heat content data. This is a concern, given that these variables hold most of the memory (and thus predictive skill) for the system. Current dynamical forecast systems typically initialize their sea ice component from a sea ice reconstruction or climatology (Guemas et al., 2014b), but without direct information on sea ice concentration and thickness.

(3) The climate system (and *a fortiori* Arctic sea ice) is not fully predictable in itself because it is a nonlinear multi-component complex system. Even a perfect model initialized from perfect observations cannot predict deterministically exact sea ice conditions in the Arctic a season later. This is due to the well-known fact that small errors (undetectable at initial time) grow rapidly because of the chaotic evolution of

the climate system (Lorenz, 1963). Thus, at most, only the probability of occurrence of certain events can be predicted (but never the actual outcome). It is important to recognize that this third source of uncertainty is inevitable and to design forecasting systems accordingly. It is even more important to properly communicate the probabilistic nature of the forecasts to end-users of the predictions.

> The GRASP project (new Generation of Regional Arctic Sea ice Predictions) will assess the potential to deliver high-fidelity seasonal sea ice predictions thanks to the implementation of a novel sea ice rheology and advanced initialization in a state-of-the-art general circulation climate model (GCM), run at the highest resolution ever-tested in ensemble global climate prediction. Besides, an additional implied objective of the project will be to bring the European and U.S. Arctic sea ice prediction communities closer together. Both sides have notably contributed to this research area in recent years, but on distinct aspects of the problem. The project proposes concrete interactions through e.g. the Sea Ice Prediction Network in order to maximize mutual benefits and bring the global state of this research to higher levels.

1.2 Objectives: Refining the Design of Arctic Sea Ice Predictions and Improving their Skill

The **technical objective** of the GRASP project can easily be understood from the sketch of the next page (Fig. 2). The three-dimensional nature of the cube reflects three possible pathways to improve predictions of current dynamical models: increasing resolution (left-right axis), improving initial conditions (front-back axis) and model physics (bottom-up axis). Simply stated, we aim at porting the EC-Earth3 prediction system (see BOX 1 for technical details about this system) from vertex 1 to vertex 4b in order to enhance Arctic sea ice prediction capabilities. So far, none of these possible improvements has been explored elsewhere in the framework of global Arctic seasonal sea ice prediction.

The realization of this technical objective is paired with **three scientific objectives**, formulated hereafter as questions. Addressing each of these questions during GRASP will not only be beneficial for the project participants. Lessons learned will also help other groups running general circulation models (GCMs) to make enlightened decisions regarding their own future developments. The outcome of GRASP is indeed to identify which aspect(s) between resolution, rheology or initialization bear(s) the largest promise for predictions (and thus which developments should be prioritized). The three scientific questions making the backbone of GRASP are:

(1) What are the relative contributions of model physics, resolution, and initial conditions on the regional skill of Arctic sea ice prediction systems? What is the fraction of uncertainty that we cannot reduce? Are we bound to work with largely uncertain forecasts as is the case nowadays (Fig. 1)?
(2) How unrealistic is the EVP rheology for high-resolution sea ice models? Theoretical arguments suggest that the underlying assumptions of this rheology are only valid for

coarse (above ~1°) models. Do EVP sea ice deformation statistics follow the expected scaling properties at such resolutions (Rampal et al., 2008)? If not, are EVP linear kinematic features a numerical artifact, as suggested by Bouillon et al. (2013)?

(3) How are the characteristics of temporal and spatial sea ice variability dependent on model complexity? Are models with more degrees of freedom (both in the atmosphere and the ocean) more prone to irreducible, internally-generated errors? Should the number of ensemble members be revised accordingly for the predictions? Is model mean bias and climate prediction drift reduced in simulations at higher resolutions?

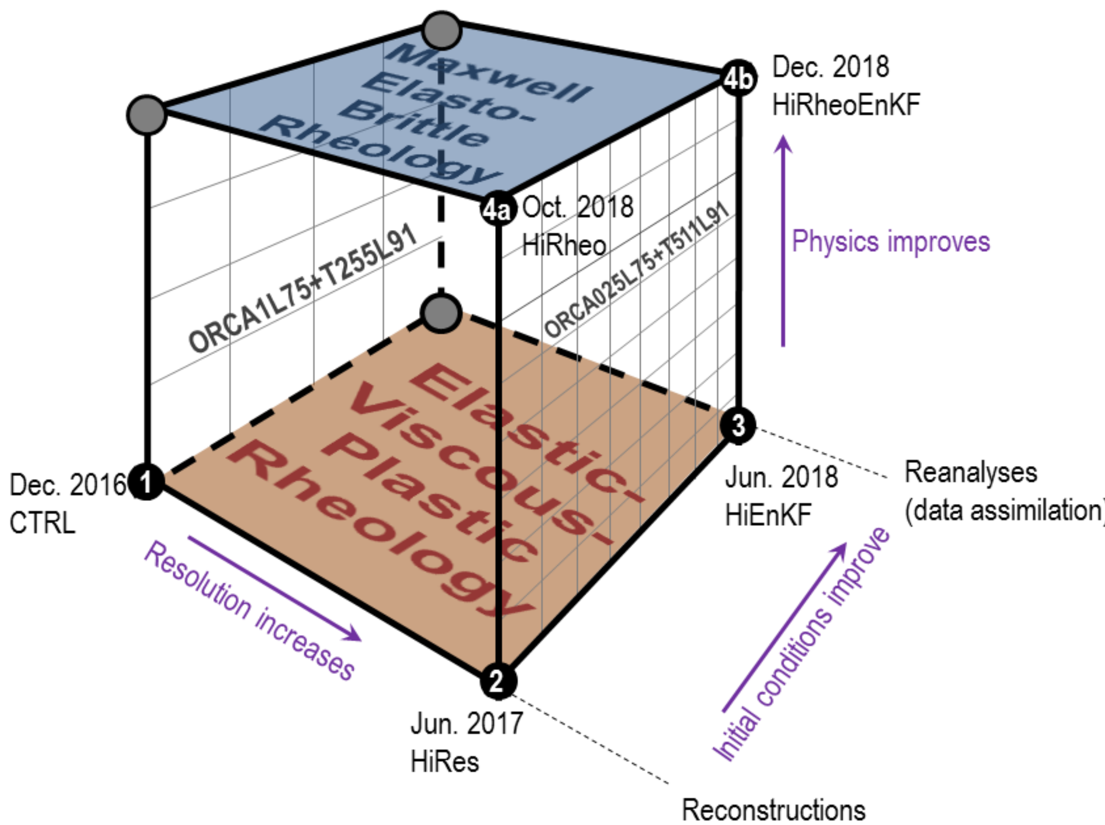

Figure 2 : Proposed approach and implementation. Starting from a reference, benchmark simulation (vertex 1), the EC-Earth3 prediction system will successively undergo an increase in horizontal resolution (vertex 2), be initialized from a sea ice reanalysis obtained from data assimilation instead of a simple reconstruction (vertex 3), and benefit from the newly developed Maxwell Elasto-Brittle sea ice rheology (vertices 4a and 4b). Grey vertices denote experiments that will not be run, either because they are irrelevant (e.g., it does not make sense to run the MEB rheology at coarse resolutions) or because of limited time/resources constraints.

The project has finally an **applied objective**: revisit classical model forecast verification metrics and better communicate information (including uncertainty) to stakeholders. It was recognized recently that pan-Arctic metrics such as total sea ice extent can be informative, but also confusing to assess prediction skill (Stroeve et al., 2015) since they can cancel regional biases of opposite sign and are in addition totally irrelevant from a regional point of view. In this sense, the duration exposure of coastal grid points to open water, the median predicted date of melt onset, the spatial distribution of sea ice compressive strength or the joint cumulative distribution of sea ice concentration and thickness are examples of much more meaningful metrics. It is also important to consider observational uncertainties during the course of model evaluation to reflect actual model skill.

The successful completion of these technical, scientific and applied objectives will be possible thanks to the established experience of the Barcelona Super Computing Center Earth Sciences Department (BSC-ES) to develop and run global climate forecasts and to engage with various stakeholders through e.g. its participation to the EU SPECS (www.specs-fp7.eu) and EUPORIAS (www.euporias.eu) projects. A critical step towards the realization of the project will also be possible thanks to the renowned expertise of the Georges Lemaître Centre for Earth and Climate Research (TECLIM) in sea ice model development (Fichefet and Morales Maqueda, 1997; Vancoppenolle et al., 2009) and the expertise of both groups in the domain of Arctic sea ice initialization and prediction (Guemas et al., 2014a, 2014b; Fučkar et al., 2014, 2015; Massonnet et al., 2015). The joint participation of the BSC-ES and TECLIM to existing and planned international efforts such as the EU project PRIMAVERA (http://www.primavera-h2020.eu) and the Year of Polar Prediction (www.polarprediction.net/yopp) will guarantee dynamic interactions between the two partners and be another key of success of the project.

1.3 Technical implementation

The project is split into five Work Packages (WP) as follows: WP1 includes the preparatory work, WP2 addresses the role of resolution, WP3 the role of initialization, WP4 the role of sea ice rheology and WP5 provides a synthesis of the recommendations for future research. Two visits are scheduled at the middle and end of the project to update U.S. Sea Ice Prediction Network (SIPN) partners with results obtained and benefit from their feedback. The attendance to international meetings is also integrated in the research plan, for all the participants of the GRASP project.

The general methodology to perform predictions is the same regardless of the level of complexity of the used model. Two types of simulations will be performed. A 5-member ensemble reconstruction spanning 1993-present will provide a collection of initial oceanic and sea ice states. These members will run in ocean-sea ice standalone configuration, forced by atmospheric reanalyses (DFS5.2, Dussin et al., 2014) subject to perturbations (following Guemas et al., 2014b). A set of 10-member ensemble *coupled* predictions will then be branched from the 5 ocean-sea ice restarts obtained from the reconstruction. Atmospheric initial conditions will be taken from the ERA-Interim reanalyses and perturbations (2 per ocean-sea ice restart) generated following a singular vector analysis (Palmer and Zanna, 2013) already implemented in EC-Earth3. Predictions will be started every 1st of February and November between 1993 and present, and run for periods of 8 and 4 months, respectively. For all prediction members, daily sea ice outputs will be saved for at least sea ice concentration, thickness and drift along the *x*- and *y*- directions.

WP1. Preliminary step: determining baseline prediction skill (M1-M12)

Involvement: VG – 30% | NF – 10% | FM – 5% | FDR – 5%

See the front page for the meaning of initials. The contributions are indicative, and the bulk of the work will be covered by a post-doctoral researcher (see Section 5).

A control sea ice reconstruction will be run over 1993-present following the methodology of Guemas et al. (2014b) with EC-Earth3 at standard resolution ORCA1L75 (see BOX 1 below) forced by the DFS5.2 atmospheric reanalysis. Restoring in ocean temperature and salinity will be applied in the ocean during this reconstruction, towards the ORAS5 reanalysis (Balmaseda et al., 2011).

Predictions will be issued from the initial sea ice states derived above; oceanic initial states will be taken from the ORAS5 reanalysis. This set of control predictions, denoted CTRL in the following, will be used as a benchmark for posterior predictions. Performance will be assessed in terms of deterministic as well as probabilistic scores at the regional level. This WP builds on the expertise of BSC-ES in producing and verifying dynamical seasonal predictions with EC-Earth3.

Deliverable (M12) - Short report on the performance of EC-Earth3 at standard resolution, with a standard initialization and a standard sea ice rheology.

BOX 1 | EC-Earth3 : a seamless climate prediction system

EC-Earth3 (www.ec-earth.org) is a state-of-the-art coupled general circulation model maintained and developed by a consortium of 28 European partners from 12 countries. Its atmospheric component is based on the European Centre for Medium-range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS) but the whole model has been adapted to run from sub-seasonal to centennial time scales (the “seamless approach”). EC-Earth community participated to the Coupled Model Intercomparison Project, phase 5 (CMIP5) and will be involved in almost all Model Intercomparison Projects (MIPs) of the upcoming CMIP6. EC-Earth3 has been tuned and released in two configurations. In its **standard version**, EC-Earth3 runs with an oceanic resolution of ~1° and 75 vertical levels (ORCA1L75) and ~70 km and 91 vertical levels in the atmosphere (T255L91). The BSC-ES is also running a **high-resolution** version EC-Earth3 (ORCA025L75 and T511L91) which is substantially higher than other state-of-the art systems. The ocean and sea ice components of EC-Earth3 are the Nucleus for European Modeling of the Ocean (NEMO3; www.nemo-ocean.eu) and the Louvain-la-Neuve sea ice model developed at TECLIM (LIM3, Vancoppenolle et al., 2009; www.climate.be/lim). LIM3 is a reference tool for climate and process studies and accounts for important processes such as the sub-grid scale distribution of sea ice thickness or the entrapment of brine during ice formation. The model has been extensively tested and used for climate studies.

WP2. Towards the highest resolutions ever tested in global prediction (M1-M18)

Involvement: VG – 5% | NF – 30% | FM – 10% | FDR – 5%

A high-resolution sea ice reconstruction will be generated following exactly the same protocol as the previous step, except that oceanic/sea ice resolution will be increased to ORCA025L75. This reconstruction will be compared to the standard reconstruction in terms of mean state and variability of the Arctic sea ice cover. The recently developed classification methodology of Fučkar et al. (2015) will be applied to identify robust modes of interannual sea ice thickness variability in the reconstructions and address the scientific question 2 raised in Sec. 1.2. Question 3 will also be addressed to determine the optimal radius of influence and other data assimilation parameters to be used during the initialization phase (WP3 hereafter). This analysis of sea ice variability will be repeated for all subsequent reconstructions.

In a second step, the corresponding high-resolution predictions (named HiRes) will be launched. The time-development of model drift will be looked at in detail and the hypothesis that higher-resolution partly reduces model systematic biases (scientific question 3) will be tested. Note that we do not plan to switch off, or adapt parameterizations in the ocean, atmosphere or sea ice model when making this sensitivity experiment to the resolution. By doing so, we hope to evidence the spontaneous increase in skill due to the better representation of meso-scale features with minimal tuning.

Deliverable (M18) - Article on the added value of increased resolution on seasonal prediction performance.

WP3. Sea ice initialization: ensemble Kalman filter data assimilation (M13-M30)

Involvement: VG – 5% | NF – 20% | FM – 30% | FDR – 5%

A high-resolution sea ice reanalysis will be generated using the ensemble Kalman filter data assimilation technique (EnKF, see BOX 2). The number of ensemble members and maximal radius of influence (two critical parameters in the EnKF scheme) will be determined from the variability analyses performed in the WP2. This reanalysis will assimilate sea ice concentration from a high-resolution (~0.25°) product of sea ice concentration that has recently been released by the European Space Agency (ESA) under the Climate Change Initiative (CCI) and covering our 1993-present window. Assimilating observed sea ice concentration at a horizontal resolution comparable with the model resolution is key to ensure a correct update of the model at assimilation time steps. Moreover, the ESA releases estimates of observational errors along with the sea ice concentration products themselves. This is invaluable information to feed the EnKF with. Sea ice thickness will not be explicitly assimilated but will be updated thanks to the multivariate nature of the filter (Massonnet et al., 2015). If time permits, sea ice thickness will be explicitly assimilated for specific test cases (the September 2012 and 2013 predictions initialized in May) to quantify the added value of this encouraging approach (Mathiot et al., 2012) in realistic cases.

BOX 2 | The ensemble Kalman Filter: a multivariate data assimilation method suited for Arctic sea ice prediction

Data assimilation is the mathematical formalization of the problem of state estimation. It seeks to maximize the a posteriori probability density function of the system state given incomplete observations, prior model knowledge and their respective statistics. Data assimilation has naturally extended to climate sciences in recent years with the emergence of seasonal and decadal prediction (where knowledge of initial state is important), and is mostly relevant in regions of the planet where and when observations are sparse. Therefore it makes perfect sense to think of data assimilation for the problem of Arctic sea ice initialization. The ensemble Kalman filter (EnKF; Evensen, 2003) is an advanced data assimilation technique that overcomes the classical problems of updating non-observed variables, as in the case with simple techniques such as nudging (Tang et al., 2013). The EnKF keeps track of the covariance matrix of model error by estimating, at each assimilation window, this matrix from a finite ensemble of simulations. As such, information is propagated between variables and over space whenever new observations are available. The benefits of the EnKF for Arctic sea ice studies have been already demonstrated in pilot studies (Lisæter et al., 2003; Mathiot et al., 2012; Massonnet et al., 2015) without interactive atmosphere, and are now to be confirmed in a fully-coupled framework.

The corresponding prediction runs, named HiEnKF, will then be launched. They will only differ from HiRes prediction runs on the initial sea ice and ocean restart files. Spatial metrics of performance for sea ice concentration will be developed to measure the ability of the model to predict summer sea ice edge location. It is indeed expected that the EnKF will partly correct the spatial biases of winter sea ice thickness in the model, and thus better forecast the grid-point probability of sea ice presence during the following summer. The latest predictions from HiRes and HiEnKF will be submitted to the 2017 Sea Ice Outlook hosted by the Sea Ice Prediction Network (http://www.arcus.org/sipn/sea-ice-outlook).

A two-week stay by one of the GRASP members at one of the SIPN partners premises will be organized during the realization of this WP to present the results of this sensitivity experiment and discuss the appropriateness of spatial diagnostics for stakeholders.

Deliverable (M30) - Article on the benefits of the ensemble Kalman filter for initializing sea ice predictions.

WP4. Sea ice physics: The Maxwell Elasto-Brittle rheology (M19-M34)

Involvement: VG – 5% | NF – 30% | TF – 20% | JR – 20% | FDR – 5%

3a) The Maxwell Elasto-Brittle rheology (MEBR, see Box 3) is currently being implemented by TECLIM partners (PhD thesis of J. Raulier, under supervision of T. Fichefet) in the LIM3 sea ice model at ORCA025L75 resolution. Once numerically stable, the BSC-ES will first calibrate the new model over the historical period under the guidance and expertise of J. Raulier. Similarly to WP1-3 above, a reconstruction will be proposed without data assimilation. The statistics of sea ice deformation and speed from the HiRes and HiRheo will be compared to each other and to independent, RADARSAT Geophysical Processor System (RGPS; Kwok et al., 2008) data from which observed deformation rates can be estimated. This will allow refuting (or not) the hypothesis that EVP is a sustainable rheology even for high-resolution (scientific question 2), a point of view promoted by some sea ice researchers. Finally, several climate prediction experiments will be run with different parameters to calibrate the MEBR schemes based on the climate prediction skill obtained. Most likely, these predictions will only cover recent years in order to keep computational time at reasonable levels (see the detailed analysis of CPU in Section 3).

3b) If time permits, the ultimate step would be to upgrade the HiRheo system with data assimilation, towards a fully-coupled high-resolution, advanced-rheology initialized prediction system (HiRheoEnKF). Daily sea ice drift data from the Ocean and Sea Ice Satellite Application Facilities (OSI-SAF, osisaf.met.no) will be assimilated using the EnKF. The project participants have already gained experience in using these products during earlier work on the calibration of dynamic parameters in LIM3 (Massonnet et al., 2014), so that the only possible obstacle to this final achievement is the restartability of the model after the data assimilation step. This technical step will be applied on years of extreme sea ice conditions (2012 and 2007).

BOX 3 | The Maxwell Elasto-Brittle rheology: accounting for intermittency and heterogeneity of the sea ice deformation field

Sea ice rheology describes the (complex) relationships between internal stress and strain (deformation) rates of the sea ice body. Recent studies (e.g., Girard et al., 2009) have highlighted that the commonly-used elastic-viscous-plastic rheology, in which sea ice flows as a viscous fluid for low strain rates and behaves plastically for typical stress conditions, is inappropriate to represent the observed scaling laws of ice deformation. The lack of realistic statistics of the deformation sea ice field was suggested to explain the underestimation of secular summer sea ice trends by contemporary models (Rampal et al., 2011). Owing to the role of sea ice deformation on lead and sea ice thickness distribution, and hence the representation of ocean-atmosphere fluxes, these concerns could also explain the uncertainty in current seasonal prediction systems. The Maxwell Elasto-Brittle rheology (MEBR) was proposed (Girard et al., 2011) to represent with higher fidelity these features. The MEBR constitutive law considers sea ice as an elastic plate in which the local elastic stiffness parameter decays whenever damage occurs, i.e., when local stress exceeds some threshold depending among others on the local thickness. This rheology is currently being implemented in LIM3 at TECLIM and will be tested experimentally (but not calibrated) in historical simulations during the PRIMAVERA EU project, starting November 1st 2015.

Deliverable (M34) - Article on the benefits of the Maxwell Elasto-Brittle Rheology on climate prediction skill in the Arctic.

WP5. Synthesis (M35-M36): Where should future efforts be placed?

Involvement: VG – 5% | NF – 10% | FM – 5% | TF – 5% | JR – 5% | FDR – 5%
All performance metrics, statistics, scores and diagnostics developed during the project will be compared between the CTRL, HiRes, HiEnKF and HiRheo retrospective predictions, respectively. Because these simulations differ from each other by one aspect at least, it will be possible to determine, at least qualitatively, which aspect(s) has(ve) to be improved in priority for other prediction systems and how each sources contributes the total uncertainty (scientific question 1). The produced data will also be made publicly available.

One of the GRASP members will spend a second period with U.S. partners from the SIPN, for about a month this time. He/she will have the opportunity to present the GRASP results from 36 months of research and give advices on the future of Arctic sea ice prediction research.

Deliverable (M36) - Final report comparing the added-value of a higher resolution, a better initialization and a more advanced physics on the seasonal prediction skill.

1.3 Feasibility, Added Value of the Project and Coordination with U.S. efforts

The proposed project involves a very large amount of simulations and data: five types of reconstructions; for each one, predictions at multiple initialization dates; for each initial date, multiple members. The automatic dispatching, management and classification of the simulations is a critical aspect to the success of this project. The BSC-ES has gained considerable experience in this respect by developing its own management software called “Autosubmit” (Manubens and Vegas, 2015). Likewise, the BSC-ES has developed an open-source R package (s2dverification, Manubens et al., 2015) to facilitate the evaluation of seasonal-to-decadal climate forecasts. Both tools will be key in following a strict protocol during the realization of sensitivity experiments and their evaluation.

The BSC-ES can count on a large amount of CPU hours and storage space available at BSC which holds Marenostrum3, a high performance computing platform (http://www.bsc.es/marenostrum-support-services/mn3). The BSC-ES has also been successful in obtaining computing hours through competitive calls such as PRACE. An estimate of CPU usage for the present project is given in Section 3.

The GRASP project is, by its design, complementary to many of the U.S. sea ice prediction initiatives (existing or planned). GRASP investigators are in tighter and tighter contact with Prof. Cecilia M. Bitz (U. Washington). Prof. Bitz is member of the SIPN leadership team, PI of the ONR funded project “An innovative network to improve sea ice prediction in a changing Arctic”) and will coordinate the initial implementation of sea ice data assimilation module in the CESM (NOAA funded project). Informal contacts with her and her team have suggested the long list of possible collaborations between

BSC-ES, TECLIM, UW and the SIPN consortium. Two anchor points highlighted in the project will hopefully strengthen U.S. – Europe collaborations on sea ice prediction during the visits scheduled in the program (at the end of WP3 and WP4):

- The GRASP investigators will share their expertise on seasonal global climate forecasting, bias-correction methods, methods of sea ice initialization and sea ice modelling by e.g. opening the possibility to welcome U.S. researchers from the SIPN for visits to our facility in Barcelona, Spain or in Louvain-la-Neuve, Belgium.
- The GRASP investigators also plan to expand their knowledge and expertise from SIPN members on various aspects such as the design of new, user-oriented metrics for the Arctic, the interpretation of the role of atmospheric modes of variability on summer sea ice or the physical mechanisms underlying seasonal sea ice predictability.

2. Future Naval Relevance

The Arctic Ocean, long capped by a vast sea ice cover all year-round, is now becoming increasingly accessible as multi-year sea ice extent is receding at dramatic rates. As an Arctic Nation through the state of Alaska, the United States and by extension the Navy "will be prepared to prevent conflict and ensure national interests are protected", even though the Arctic Region is "expected to remain a low threat security environment" (U.S. Navy, 2014). The possible presence of ice coupled to harsh weather conditions can make naval operations more challenging than anywhere else in the world.

The simulations performed during GRASP will produce an extended list of sea ice variables including e.g. the amount of ridged ice, the fraction of thin ice or compressive sea ice strength, all at an arbitrary frequency. The maximum sea ice compressive strength, the rate of sea ice thickening during sudden freeze-up periods, the probability of sea ice presence in selected sectors of the Arctic and the duration of ice-free season are examples of information that could be directly relevant for naval operations. The probability of ice-free conditions in coastal regions (in particular Alaska) is an example of metric of interest regarding important geopolitical and defense aspects. Whether these metrics will be better predicted in advanced dynamical prediction systems is a key applied question that we will address in the project.

3. Project Schedule and Milestones

	2016												2017												2018											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
WP1	Reconstruction + CTRL predictions + benchmarking																																			
WP2	Reconstruction + HiRes predictions + SIC/SIT variability and prediction skill analysis																																			
WP3													Reconstruction with SIC (SIT?) assimilation + HiEnKF predictions + spatial analysis of performance																							
WP4																			Reconstruction with new rheology (SID assimilation?) + tests on validity of EVP + HiRheo predictions and analyses																	
WP5																																			Wrap-up	
Mobility					ASIP meeting (4)							AGU (3)				EGU (3)	ASIP meeting (4)					At UW (1)		At UCL (1)				ASIP meeting (4)				UCL at BSC (1)				AGU (3) At UW (1)
Publication												Yearly report					High-resolution sea ice reanalysis: paper+data made available								Yearly report					Importance of initial conditions for summer and winter prediction (paper)					Synthesis: role of model complexity on predictive skill (paper+project report)	

SIC = Sea Ice Concentration
SIT = Sea Ice Thickness
SID = Sea ice drift
? = "if time permits"

AGU = American Geophysical Union general assembly
EGU = European Geophysical Union general assembly
EVP = Elastic Viscous Plastic

UCL = Short stay (2 weeks) at Université catholique de Louvain
UCL at BSC = 2 weeks visit from a UCL partner at BSC
UW = Short stay (2 weeks) at University of Washington or other SIPN partner
ASIP meeting = Arctic sea ice predictability meeting (hold every year since 2013)

Numbers in parentheses indicate the number of GRASP investigators (including the candidate) participating to the conference/visit

Estimated CPU time required to achieve the simulations

	WP1		***WP2***		***WP3***		***WP4***	
	Reconstruction	*Prediction*	*Reconstruction*	*Prediction*	*Reconstruction*	*Prediction*	*Reconstruction*	*Prediction*
Resolution	ORCA1 L75	ORCA1 L75/T255L91	ORCA025L75	ORCA025L75/T511L91	ORCA025L75	ORCA025L75/T511L91	ORCA025L75	ORCA025L75/T511L91
Rheology	EVP	EVP	EVP	EVP	EVP	EVP	MEBR	MEBR
Assimilation	OFF	OFF	OFF	OFF	ON	ON	OFF	OFF
Nb cores [-]	**48**	**119**	**256**	**1871**	**256**	**1871**	**256**	**1871**
Wallclock time [hours/sim-month]	**0,17**	**0,60**	**1,50**	**1,20**	**1,50**	**1,20**	**5,00**	**5,00**
Number of months in a year [months/year]	**12**	**12**	**12**	**12**	**12**	**12**	**12**	**12**
Nb members [-]	**5**	**10**	**5**	**10**	**20**	**10**	**5**	**10**
Nb startdates [-]	**1**	**46**	**1**	**46**	**1**	**46**	**1**	**46**
Length runs [years]	**23,00**	**0,50**	**23,00**	**0,50**	**23,00**	**0,50**	**23,00**	**0,50**
Total CPUhrs [1000 CPUhrs]	**11,04**	**197,06**	**529,92**	**6196,75**	**2119,68**	**6196,75**	**1766,40**	**25819,80**

GREEN = Realistic estimates with newest version of the model

ORANGE = current estimates, will very likely be lower with the new EC-Earth version

RED = uncertain, upper bounds are used

Grand total [1000 CPUhrs]: 42837,408

4. Reports

Two progress reports will be submitted (months 12 and 25) highlighting scientific achievements and financial status. A final report will be submitted at the end of the project (month 36)

5. Management Approach

Personnel. The project will fund one post-doctoral researcher for three years, and international mobility for the GRASP investigators (see Project Schedule and Milestones). The progression of project will be managed through weekly meetings to ensure full coherence between research within GRASP and the general objectives of the research centers involved. At all meetings with the supervisor, Dr Guemas, the advancements of the research will be discussed and the supervisor will provide adequate mentoring in the general background of the climate prediction and adapt the research program to the difficulties encountered and to make progress in the most promising aspects of the research undertaken. Regular meetings will take place involving the rest of the BSC-ES and TECLIM members to ensure an adequate integration of this activity into the rest of the research carried out in these centers. Periodic written reports detailing the progress and the issues raised during the development of the research plan will be prepared and stored to monitor the evolution of the work

Material and supplies. To store all the climate simulation outputs produced during GRASP, the storage system of the department will have to be expanded by around 60 TB of raw space. That requires the acquisition of 2 disk cabinets (1 head node costing about 5,000 € + 1 JBOD costing about 2,000 €) and 15 4TB disks (about 270 € each).

6. Current and Pending Project and Proposal Submissions

- PRIMAVERA

- "PRocess-based climate sIMulation: adVances in high-resolution modeling and European climate Risk Assessment". Assessment of high-resolution climate simulations in the framework of climate projections (1950-2050).
- Source: EU H2020 program; Status: funded (Nov 2015-Oct 2019). Total project budget: ~15 M€, 19 participants.
- Overlap with proposed project: 20% (no initialization aspects, different time scales)
- PI: Malcom Roberts, malcolm.roberts@metoffice.gov.uk
- Prime offeror of GRASP involvement: contributor, not paid directly.
- Amount of funding for BSC-ES: ~1.5 M€; for UCL: ~0.7 M€

- SPECS

- Seasonal-to-decadal climate Prediction for the improvement of European Climate; improvement of forecast quality at seasonal time scales and enhancement of communication tools.
- Source: EU FP7 program (GA 308378); Status: funded (Nov 2012-Sep 2016). Total project budget: ~15 M€, 18 participants.

- Overlap with proposed project: 10%
- PI: Francisco J. Doblas-Reyes, francsisco.doblas-reyes@bsc.es
- Prime offeror of GRASP involvement: contributor, not paid directly.
- Amount of funding for BSC-ES: ~1.5 M€; UCL: not involved.

- **EUPORIAS**
  - "European Provision of Regional Impacts Assessments on Seasonal and Decadal Timescales"
  - Source: EU FP7 program (GA 308291). Status : funded (Nov 2012-Jan 2017). Total project budget : , 24 participants.
  - Overlap with proposed project: 5% (more impact-oriented)
  - PI: Chris Hewitt/Carlo Buontempo, management@project.euproias.eu
- **PICA-ICE**
  - "Interannual Prediction of the Arctic Sea-ice cover and its Impact on the European Climate". Assessment of mechanisms for interannual variability of the Arctic sea ice and its impacts on lower latitudes.
  - Source: Spanish Ministry of Economy and Competitiveness (CGL2012-31987); Status: funded (Jan 2012-Dec 2015). Total project budget: 128 k€.
  - Overlap with proposed project: 0% (the project will be finished)
  - PI: Virginie Guemas, virginie.guemas@bsc.es
  - Prime offeror of GRASP involvement : PI
  - Amount of funding for BSC-ES: 128 k€.
- **Juan de la Cierva – Formación**
  - Grant obtained by François Massonnet: two-year contract of postdoctoral research starting in November 2015. Themes covered: development of initialization methods, investigation of bi-polar predictability and linkages to lower latitude climate
  - Source: Spanish Ministry of Economy and Competitiveness; Status: awarded, not started yet.
  - Supervisor: V. Guemas; Beneficiary: F. Massonnet.
  - Overlap with proposed project: 20% (data assimilation aspects).
- **VERITAS**
  - "VERification of high-resolution climate forecasts on Intraseasonal-to-interannual Timescales with Advanced Satellite datasets of the Climate Change Initiative"
  - Source: European Space Agency. Status: funded (Jan 2015-Dec 2016). Total budget:
  - Supervisor: F. Doblas-Reyes; Beneficiary: O. Bellprat (omar.bellprat@bsc.es)
  - Overlap with proposed project: 5% (assessment of observational uncertainties)

7. Qualifications (full CVs in attachment to the proposal)

Dr Virginie Guemas holds a PhD in Physics of the Climate from CNRM (Toulouse) + GAME (Paris). She is head of the Polar Prediction research line at BSC-ES and an expert on seasonal to decadal climate prediction. She is member of the WCRP (World Climate Research Program) CLIVAR (Climate and Ocean Variability, Predictability, and Change) SSG (Scientific Steering Group), principal investigator (PI) of the nationally funded PICA-ICE project focused on Arctic climate predictions (2013-2015) and Work Package leader within the EU H2020-funded PRIMAVERA project focused on high-resolution and model development to be started in November 2015. She contributed to the IPCC (Fifth Assessment Report). Her main contributions to the Arctic sea ice prediction were through:

(1) The generation of ensembles of sea ice initial conditions covering the full 1958-present period with a consistent methodology (Guemas et al, 2014b),
(2) The attribution of the 2012 record minimum Arctic sea ice extent (Guemas et al, 2013) to preconditioning and positive feedbacks,
(3) Her invited participation to the June 2013 Planning Meeting for the Year Of Polar Prediction (YOPP) planned for 2017-2019,
(4) Her participation to the APPOSITE project by the generation and analysis of potential predictability experiments with EC-Earth2.3 to assess the potential skill in predicting pan-Arctic and local sea ice conditions (Tietsche et al, 2014),
(5) Her review article on the predictability mechanisms, the potential prediction and the prediction skill with state-of-the-art forecast systems for the Arctic sea ice conditions on seasonal to decadal timescales (Guemas et al, 2014a).

Dr François Massonnet has a PhD in Sciences from Université catholique de Louvain, Louvain-la-Neuve, Belgium. He is now a post-doctoral researcher at UCL undertaking a long-term scientific visit at BSC-ES. He will be starting to work as a member of BSC-ES from November 2015. He is an expert on sea ice data assimilation. His research lines are among others seasonal-to-decadal climate predictability and prediction. He is a member of the CLIVAR/CliC/SCAR Southern Ocean Region Panel and is involved in the scientific preparation of the Year of Polar Prediction as a CliC fellow. He has also contributed to the IPCC (Fifth Assessment Report). His main contributions to the Arctic sea ice prediction were through:

(1) The development of an extensive set of metrics to measure the performance of Arctic sea ice simulations, including drift,
(2) The participation as an invited member to the Sea Ice Prediction Network (SIPN) activities to comment on modeling contributions (since 2014),
(3) The implementation of the ensemble Kalman filter for seasonal sea ice prediction and parameter calibration in large-scale sea ice models.

Dr. Neven S. Fučkar has a Ph.D. in Atmospheric and Oceanic Sciences from Princeton University, New Jersey, USA. He is presently a post-doctoral scientist working on the nationally funded PICA-ICE project and EU FP7 SPECS project at IC3 with a focus on Arctic sea ice dynamics and predictability in the framework of seasonal-to-decadal climate predictions. The other areas of his expertise are ocean dynamics and its role in climate dynamics and predictions, large-scale teleconnections, ocean-ice-atmosphere interactions, general circulation models and the development of harmonic and statistical methods for data analysis. Dr. Fučkar's main contributions to the Arctic sea ice and climate prediction field were through:

(1) The development of unsupervised learning methods such as nonhierarchical clustering methods for the determination of dynamical modes of variability and predictability sources,
(2) The advancement of statistical methods for drift and bias correction of dynamical climate predictions, including Arctic sea ice fields,
(3) The validation of Arctic sea ice simulations from a spectrum of seasonal-to-decadal forecast systems within SPECS project.

Prof. Francisco J. Doblas-Reyes holds a PhD in atmospheric physics from Universidad Complutense (Madrid, Spain). He is an expert in the development of seasonal-to-decadal climate prediction systems and the head of the BSC-ES. He is involved in the development of the EC-Earth Earth System Model since its inception. Prof. Doblas-Reyes received in 2006 the Norbert Gerbier-MUMM International Award of the UN World Meteorological Organization (WMO). He serves in several panels of the World Climate Research Programme (WCRP) and the World Weather Research Programme (WWRP) under the UN WMO (among them the steering group of the Polar Prediction Project), is a member of the European Network for Earth System modelling HPC Task Force and has participated in numerous national and European FP4, FP7 and H2020 projects. Currently, Prof. Doblas-Reyes is the principal investigator (PI) or co-investigator in 6 FP7 and H2020 European projects, is coordinator of the FP7 collaborative SPECS project and supervises numerous postdoctoral scientists and software engineers. He is a lead author of the IPCC and member of the steering group of the Polar Prediction Project.

Prof. Thierry Fichefet has a Ph.D. in Sciences from the Université catholique de Louvain (UCL, Louvain-la-Neuve) where he is Full Professor of climatology and physics. He has about 30 years of experience in global climate modelling, with focus on climate–cryosphere interactions. The sea-ice model (LIM) he has developed with his colleagues is considered as a reference in the community of climatologists and oceanographers, and is routinely used in about 30 different countries. A large number of original process studies were performed with this model coupled to various oceanic general circulation models. These studies have notably highlighted the key role played by sea-ice–ocean interactions in controlling the World Ocean's circulation. Thierry Fichefet has also contributed to the development of Earth system models of various levels of complexity. Those models were utilized in seminal studies of the last glacial–interglacial cycle, the glacial oceanic circulation, the abrupt climate change that occurred 8,200 years ago and the climate variability and changes during the Holocene. His team was also the first to have quantified the influence of a greenhouse-gas-induced melting of the Greenland ice sheet on the oceanic thermohaline circulation and climate over the next millennia. His current research mainly concerns climate variability and predictability in polar regions.

Jonathan Raulier is PhD student at the Université catholique de Louvain (UCL) where he is doing his thesis in the Georges Lemaître Center for Earth and Climate Research (TECLIM) since 2013. He is currently working on the integration of a new sea ice rheology, the Maxwell Elasto-Brittle Rheology, in the global sea ice model LIM3 in order to represent accurately the development of fractures, leads and sea ice deformation in LIM3.

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(names of investigators in **boldface**)

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