1. **Project Description**
   - State of the art

The climate of polar regions is characterized by large fluctuations and has recently experienced dramatic changes. Over the last 30 years, the high latitudes of the Northern Hemisphere have warmed more than twice the global average and the Arctic sea ice extent has strongly decreased in all months of the year, with a pronounced reduction in summer (Stroeve et al. 2012; Stammerjohn et al. 2012). The pattern is more complex in the high latitudes of the Southern Hemisphere. Some regions have warmed less than the global average with some sea ice advance, in particular in the Ross Sea, while other regions have warmed significantly and displayed sea ice loss (Jones et al. 2016). Since the end of the 1990's, the Greenland ice sheet (GrIS) has been losing mass as a result of both an increase in surface melting and iceberg discharge (van den Broeke et al., 2016), which is suspected to have triggered a freshening and cooling of the Labrador Sea and subpolar gyre as well as a weakening of the Atlantic meridional overturning circulation (AMOC) over the past decade (Rahmstorf et al., 2015; Yang et al., 2016). The Antarctic ice sheet (AIS) has also lost mass in the past decades, with a spectacular thinning and weakening of ice shelves, i.e., the floating extensions of the grounded ice sheet (Rignot, 2008; Shepherd et al., 2012).

Despite recent advances, the mechanisms at the origin of those trends are very uncertain because of the limited amount of observations and the large biases of climate models in polar regions. Some characteristics such as the large decrease in Arctic sea ice extent or the strengthening of the westerly winds in the Southern Ocean can be, at least partly, attributed to the perturbations induced by human activities. Nevertheless, it is in the large majority of the cases not possible to disentangle the contribution of natural fluctuations from the response to anthropogenic forcings (Jones et al., 2016).

Volume changes of the GrIS are governed by both changes in surface mass balance (SMB; the sum of precipitation, sublimation/deposition, meltwater runoff, and windblown snow) and changes in iceberg discharge from a large number of outlet glaciers into the ocean. The ice sheet is believed to have been close to equilibrium until the early 1990s, but has been losing mass since 2000 at an increasing rate (Shepherd et al., 2012). The recent surface melt increase is consistent with global warming, enhanced by the Arctic amplification and general circulation changes observed in summer favouring advection of warm air masses over GrIS (Fettweis et al., 2013; Hanna et al., 2016). As shown by Fettweis et al. (2013), we observe since the end of the 1990's an exceptional persistence of anticyclonic conditions (gauged by negative North Atlantic Oscillation indexes) in summer over Greenland, enhancing the melt increase due to global warming. Ice sheet-wide surface velocity observations reveal complex spatial and temporal patterns of accelerated glacier flow in some parts (Moon et al., 2014), together with more variability and relatively steady flow elsewhere. Mechanisms put forward to explain dynamic variations in ice loss invoke both atmospheric and oceanic forcings. Outlet glacier speed-up has been linked to basal lubrication due to meltwater penetration at the bed (Zwally et al., 2002), while increased iceberg calving and the successive loss of buttressing of grounded ice by floating ice tongues has been attributed to the intrusion of warmer ocean waters in local fjord systems (Straneo et al., 2013).

The thinning of Antarctic ice shelves (Pritchard et al., 2012; Paolo et al., 2015) and the corresponding decrease in the restraint experienced by inland ice flow (Flament and Rémy, 2012; Payne et al., 2004; Zwally and Giovinetto, 2011) are recognized as major drivers of current Antarctic ice loss (IPCC, 2013). This ice shelf change is particularly pronounced in West Antarctica (Rignot, 2008; Shepherd et al., 2012), in response to increased oceanic heat transport beneath its floating ice shelves and resulting feedbacks (Jacobs et al., 2011), but evidence from around Antarctica confirms that the effect is not geographically limited (Greenbaum et al., 2015; Paolo et al., 2015; Favier et al., 2016).

Ice shelves are crucial gatekeepers of Antarctic ice sheet flow, because they restrain ice flow as they are often laterally constrained by embayments or locally grounded on rigid obstacles in the bathymetry (Favier and Pattyn, 2015; Matsuoka et al., 2015). Ice shelf thinning causes an instantaneous acceleration and a retreat of the grounding line (Goldberg et al., 2009; Favier et al., 2014), hence a rise in sea level. For marine ice sheets with a bedrock lying below sea level and sloping down towards the interior, this may lead to a marine ice sheet instability (MISI), a powerful positive feedback where unstoppable retreat of the grounding line continues until an upsloping area is reached. The process of ice shelf breakup and MISI may be reinforced by surface melting near the grounding line, leading to ice shelf thinning and weakening through processes such as hydro-fracture (marine ice cliff instability; MICI). Recent studies (DeConto and Pollard, 2016) point to potentially significant (3-5 m) sea level rise from Antarctic mass loss by 2200, but uncertainties in the precise coupled atmosphere-ocean-cryosphere mechanisms remain large.

Precipitation is the only source of mass to the Antarctic ice sheet. Atmospheric dynamical processes over the Southern Ocean, which are in turn affected by the state of the ocean surface, are thereby key for the moisture advection to the ice sheet (van Lipzig and van den Broeke, 2002; Raphael et al., 2016). In particular, atmospheric rivers played a key-role in the large snowfall events (Gorodetskaya et al., 2014). Although surface melt is currently a negligible term in the SMB, it does affect ice shelf stability due to hydrofracturing and thereby the stability of the marine ice sheets (DeConto and Pollard, 2016). Strong surface melt has been found near the grounding line of the ice shelves during katabatic wind conditions, due to entrainment of warm air into the very stable atmospheric boundary layer (Lenaerts et al., 2017). Variability in these melt conditions are likely a complex interplay between changes in large-scale temperature, strength of katabatic winds, and warm air intrusions onto the ice shelves.

The ocean and ice sheets have a large inertia, integrating the forcing over centuries. Specifically, the ice sheet's englacial temperature field reacts on millennial time scales, hence is influenced by surface temperature and ice sheet geometry changes since glacial periods. This has a large impact on the so-called climate commitment, meaning that whatever the decision that will be taken in the future, some changes are nearly unavoidable. This is particularly important for sea level changes for which past anthropogenic perturbations imply a rise that will continue for centuries. On these time scales, the ice sheets are often considered to become the dominant contributor to global sea level change.

Despite this long response time, understanding the climate changes in polar regions on the decadal time scale is important as several significant changes have recently been observed over both GrIS and AIS. Moreover, the decadal time scale corresponds to the period over which we have the largest amount of relatively accurate observational data and it therefore offers a great test bed for our understanding of the dynamics of the system and for the validity of available models. This is also the period of interest for decision makers as the choices performed now will have consequences on longer time scales.

Fluctuations on decadal time scales in the climate system have been the subject of intense research over the last decades. Those variations are governed by a forced component reflecting anthropogenic and natural changes in atmospheric constituents, and by an internally generated component resulting from the complex interactions across components and scales within the climate system (Meehl et al., 2014). Due to the novel scientific questions raised and the large potential for society in terms of climate information at these strategic time scales, decadal climate prediction has firmly established itself as a priority for climate research as reflected by the whole chapter devoted to the subject in the last Intergovernmental Panel on Climate Change Assessment Report (2013). The pilot studies of Smith et al. (2007), Keenlyside et al. (2008) and Pohlmann et al. (2009) demonstrated the technical feasibility of this novel type of predictions and highlighted particular promise for predictability in the North Atlantic. More recently, the ability to predict decadal climate variations has been confirmed to other parts of the world (Doblas-Reyes et al., 2013; Meehl et al., 2016). However, polar regions have been given little attention so far, for multiple reasons. First, the network of observational data required to initialize predictions is extremely sparse at high latitudes. Second, systematic biases in climate models are an inherent barrier to predictability, especially in the polar regions where a good representation of the mean climate state is critical. Finally, global climate models involved in current decadal prediction experiments run at a rather coarse (~1°) resolution and are therefore likely missing a whole variety of processes holding predictability that remains currently undetected. Advancing decadal predictions in the polar regions will therefore only be possible if the role of new components is recognized in imparting predictability to the whole system and if cutting-edge models are considered, while making full use of the ever-increasing observational data base at the disposal of the community.

For the ice sheets, only very few studied have tried to determine if the changes observed recently are the result of chaotic fluctuations of the polar climate and ice sheets or can be predicted knowing the conditions in the recent past. Hindcasting has been somehow explored, but without taking into account the coupling between the components (Aschwanden et al., 2013). To our knowledge, there is no existing study of processes steering decadal variability and predictability of the atmosphere-ice sheet-ocean system. However, some ice sheet processes have a clear imprint already at the decadal time scale, allowing to study them with observations obtained since the launch of satellites. This is a good timing to do so thanks to the progress that has been achieved recently and the availability of new data because of the high interest in polar regions and in prediction (YOPP, MOSAiC). New results with higher resolution climate general circulation models will be available in 2017 in the framework of CMIP6 (Coupled Model Intercomparison Project, phase 6). New techniques of initialization of ice sheets and more sophisticated regional climate models have been developed and it is now possible to perform with those models longer simulations thanks to the availability of powerful computers.

- Objectives and research hypothesis

Ground–breaking nature of the research

The ability of making predictions is at the basis of the development of meteorology and (to a lesser extent) climatology. A fundamental result, derived mainly from the pioneering work of Lorenz (1963), is that, because of the chaotic nature of the atmosphere, any deterministic forecast becomes useless after 5 to 15 days. In other words, the information brought by initial atmospheric conditions is lost rapidly. On longer timescales, typically of a few decades to a century, it is possible to estimate the changes in climate because of modifications of the boundary conditions (also called forcings). This is typically what is done to estimate future climate changes due to human activities.

However, the atmosphere is not the sole player in the climate system and the conditions in the ocean or the land surface and cryosphere may let a longer imprint, potentially bringing some predictability to the whole system on seasonal to decadal timescales. This prevents us to make weather forecast several months in advance, but may be useful to estimate the probability of some events such as a warm winter or a wet summer. As described in the state-of-the-art section, this has led in the last decade to the development of decadal climate predictions (Meehl et al., 2014) using coupled models including the atmosphere, ocean, sea ice and land surface processes. Ice sheets have also a long memory and knowing their evolution may lead to some predictability at the decadal time scale in the other components (Zunz and Goosse, 2015), but this has never been studied explicitly.

A major difficulty in this endeavour is the strong coupling within the atmosphere-ice sheet-ocean system and the associated complex feedbacks occurring on a wide range of time and spatial scales. The cascade of interactions poses both technical and scientific challenges as no clear separation between those scales can be imposed. Fast processes at the scale of a few hundreds of meters have a large-scale impact, while the changes occurring at the large scale in the ocean or the ice sheet condition the dynamics of the local processes. Any progress in the description of those multiscale interactions will thus be both an advance for our scientific understanding and will lead to improvement of practical applications such as the predictions of future changes.

Research hypotheses

Although the atmosphere itself may not be predictable after a few days, the information contained in the condition at a particular time provides useful information of the subsequent changes for ocean and ice sheets. Because of the strong interactions between the components in polar regions, this may then allow useful predictions at longer time scales for the whole climate system.

Our work will be based on two main research hypotheses:

Hypothesis 1: Despite the short-lived predictability of the atmosphere, skillful long-range climate predictions can be achieved in polar regions by taking advantage of the memory contained in the slower components of the climate system (ice sheets, ocean, sea ice).

Hypothesis 2: The exchanges of energy, mass and momentum between the ice, ocean and atmosphere at the regional or local scale (a few tens of kilometers or less) are essential to understand the dynamics of the system, even at scales of hundreds of kilometers, and thus to understand its variability, its predictability and its response to a perturbation.

Objectives

Our first objective is to ***improve the understanding of key processes that control the variability of the ice-ocean- atmosphere system at decadal time scale***. The focus will be on the interactions between the components at regional scale and on the links with larger spatial scales. A specific attention will be paid to the surface mass balance of ice sheets and ice shelves, as well as to the balance at the basis of ice shelves, and their influence on both the ice sheet dynamics and the changes in the ocean and atmosphere. The conditions potentially leading to instabilities such as MICI and MISI will also be explicitly addressed.

A second objective is to ***determine how those interactions will lead to some predictability***. The contribution of those interactions in the predictability of the whole system will be compared to the one of processes implying only one specific component, such as the slow ice sheet dynamics that may provide a memory over centuries to millennia, the role of oceanic heat transport and the impact of atmospheric variability, for instance associated to warm air intrusions and teleconnections with lower latitudes.

The main study period will cover the last 30 years as it is the ones for which we have the most reliable observations to initialize models and validate their results. In this framework, a key test for our understanding is to challenge our ability to predict retrospectively the observed evolution of the system in both hemispheres. For instance, let us consider the hypothesis that observed changes in past decades are associated with changes in oceanic heat storage at depth or a particular configuration of the ice sheet velocity field. Describing the links between the variables can support a hypothesis, but being able to accurately predict the changes knowing the initial conditions would provide a strong confirmation of the validity and importance of this hypothesis. Additionally, predictions will be performed and evaluated over the next 30 years.

The project will thus deliver both process understanding and an application of the theory for a key period (last decades) over which we have the best observational record. This will be highly valuable as hypotheses are currently available to explain recent changes in polar regions, but no explanation is totally convincing. This is will be then the basis for the improvement of estimates of future changes.

Importance-impact

It is often said that large progresses can be achieved at the boundary between disciplines. Ice sheet, ocean and atmosphere dynamics all belong to Earth sciences and thus may seem close to each other but, unfortunately, both for historical and technical reasons, the analyses of the coupling between them is still in its infancy. Several initiatives have been launched recently to study the impact of their interactions at global scale for centennial and longer time scales (Huybrechts et al., 2011; Bakker et al., 2017). The originality of our approach is to focus on regional and local processes and on shorter time scales, specifically focusing on the decadal predictability of the whole system. If successful, our results will first provide a new understanding of the mechanisms ruling the decadal changes of polar climates and ice sheets. This will form the basis for new studies, including at global scale, taking advantage of the precise analyses conducted here. Secondly, if our hypotheses are valid, this will offer a new paradigm, arguing that the ice sheet fluctuations observed recently are not just a kind of noise for which only proximal causes can be studied. Those fluctuations could then be related to the past state of the ocean and ice sheets and the changes can be partly predicted thanks to adequate observations and models including a representation of the key interactions between the components. This would also modify a general view that, at decadal time scales, ice sheet dynamics has no influence on the climate system and the ice sheets are mainly slaves of the ocean and atmosphere.

- Methodology

Achieving our goals will require the development of coupled regional models including the atmosphere, ocean, sea ice and ice sheets. Indeed, global models have a too low spatial resolution to represent adequately the key processes. Furthermore, when they are run at relatively high resolution, they require too much CPU time to perform the sensitivity experiments needed to understand the origin of the simulated changes and they may still not be adapted to the specific physical conditions of polar regions. The biases of current global models are also a big barrier in polar regions where mean state strongly impacts both the natural variability and the response to external forcings. This means that, despite the recent developments in global models that will provide more accurate boundary conditions, high-resolution regional models specifically developed for polar regions in both hemispheres are needed here. Those coupled models will include components that are well-known and routinely used by the partners. They are briefly described below.

The regional atmospheric model MAR. Over the Greenland ice sheet, we will use the fully parallelised version 4.0 of the regional climate model MAR, developed and extensively evaluated to study the recent Greenland climate (1900-2016) (Fettweis et al., 2013). MAR is a hydrostatic atmospheric model coupled with a surface scheme called SISVAT (Soil Ice Snow Vegetation Atmosphere Transfer) dealing with the energy and mass exchanges between surface, snow and atmosphere. A native resolution of 12.5 km will be used by MAR in this project over the whole CORDEX Arctic domain extended for covering a larger part of the North-Atlantic Ocean. SMB outputs at 1 km resolution will be provided over the Greenland ice sheet thanks to an offline downscaling technique (Noel et al., 2016). This method corrects interpolated 12.5 km fields to the 1 km subgrid topography with the help of local vertical gradients as developed by Franco et al. (2012).

The regional atmospheric model COSMO-CLM. COSMO-CLM is a non-hydrostatic regional climate model (Rockel et al., 2008), with numerous applications throughout the world including polar regions and the Antarctic ice shelves (Brunt Ice Shelf; Ebner et al., 2014). Antarctic wide model integrations at 27 km grid spacing are currently being performed and evaluated at KULeuven (Souverijns et al., 2016), within the framework of the AEROCLOUD project (www.aerocloud.be). COSMO-CLM is a key component in regional Earth system models and has been coupled with OASIS to many models, including the Community Land Model (CLM). By the coupling to CLM, the model benefits from recent and future CLM community efforts in improving firn processes (Lenaerts et al., 2017; Van Kampenhout, in prep.). Moreover, due to the non-hydrostatic character of the model, it can be applied over ice shelves at high resolution as it is capable of taking into account the small-scale processes, which play a key role in the spatial and temporal wind patterns over the steep coastal margins, especially at the grounding line.

The ocean and sea ice model NEMO. NEMO (Nucleus for European Modelling of the Ocean) is a state-of-the-art modelling system for oceanographic research, operational oceanography and climate studies (www.nemo-ocean.eu). In this project, we will use the most recent released version of this system (v3.6). Its oceanic component, OPA (Océan Parallélisé), is a finite difference, primitive equation ocean general circulation model (Madec and the NEMO Team, 2012). It includes a comprehensive representation of ice shelf–ocean interactions (Mathiot et al., in prep.), simulates the ocean circulation beneath ice shelves, accommodates time-varying ice shelf cavity geometry and contains an iceberg module (Marsh et al., 2015). The sea ice component of NEMO3.6 is LIM3, the third version of the Louvain-la-Neuve sea ice model (Vancoppenolle et al., 2009; Rousset et al., 2015). This model includes a sea ice thickness distribution with five categories and the sea ice halodynamics is explicitly modelled. In the standard configuration, ice dynamics is simulated by assuming that sea ice behaves as a two-dimensional elastic-viscous-plastic continuum in dynamical interaction with atmosphere and ocean, but a new Maxwell-elasto-brittle rheology (Dansereau et al., 2016) is currently embedded in NEMO3.6 and will be validated before the project starts.

The hybrid marine ice sheet model f.ETISh. The f.ETISh model (Pattyn, 2017) is a thermomechanically-coupled hybrid marine ice sheet model, solving for both grounded (sheet and stream flow) and floating ice dynamics, hence superposing the shallow-ice approximation (SIA) for deformational ice flow to the shallow-shelf approximation (SSA) for basal sliding and ice shelf flow (Bueler and Brown, 2009). Basal boundary conditions are specified either according to a conventional Weertman power-law sliding or based on a Coulomb friction law. The marine boundary is treated using a grounding-line flux condition (Pollard and Deconto, 2012; DeConto and Pollard, 2016) either based on power-law sliding or Coulomb friction. The model currently participates in the CMIP6-ISMIP6-InitMIP intercomparisons for both the Greenland and Antarctic ice sheets.

The ice sheet/ice shelf model BISICLES. BISICLES (http://BISICLES.lbl.gov) is a thermomechanically-coupled ice sheet/ice shelf model that solves the Schoof-Hindmarsh approximation (L1L2) of the full Stokes equations on an adaptive horizontal grid produced with the Chombo adaptive mesh refinement toolkit (the model is fully detailed in Cornford et al., 2015). It therefore makes the model extremely useful for solving detailed ice sheet response near grounding lines. Grounding line dynamics are better represented than in conventional SSA models or models based on grounding-line parameterizations (Pattyn and Durand, 2013). However, it is a more computationally-demanding model compared to f.ETISh, and therefore limits its use to basin-scale applications. Besides the physical basis of the model, a sub-kilometric spatial resolution is a necessary condition to guarantee grounding line migration (Pattyn and Durand, 2013). Ice rheology is controlled by the Glen's flow law and the interaction between the bed and the ice bottom surface by a Weertman-type nonlinear friction.

The ice sheet model GISM. The Greenland ice sheet model GISM is a further development from the three-dimensional thermomechanical ice flow model of Huybrechts and de Wolde (1999), and will be run at the highest possible resolution of 1 or 2 km. It has a new higher-order approximation of the force balance governing ice deformation and basal sliding that accounts for horizontal gradients of membrane stresses, which become important for areas of high velocity gradients near the margin (Fürst et al., 2011, 2013). Furthermore, the ice sheet model accounts for runoff-induced lubrication and for the direct effect of ocean warming on ice discharge in a parameterized way (Shannon et al., 2013, Fürst et al., 2015). The model was extensively used for IPCC-type of projections on the centennial time scale within the EU FP7 Ice2Sea project (Goelzer et al., 2013, Fürst et al., 2015). GISM participates in the CMIP6/ISMIP6/InitMIP model intercomparison project (Goelzer et al., in prep.).

The global coupled model EC-Earth. EC-Earth (Hazeleger et al. 2012; https://www.ec-earth.org/) is a state-of-the-art climate general circulation model (GCM) developed, maintained and run by a wide consortium of 33 European partners. EC-Earth participated in the Coupled Model Intercomparison Project, phase 5 (CMIP5); a new version is currently developed for participation to the upcoming CMIP6. In particular, EC-Earth will be one of the few models involved in the Decadal Climate Prediction Project (DCPP, Boer et al., 2016). In its standard configuration, EC-Earth runs at ~1° in the ocean and ~60km in the atmosphere, and output standard oceanic and atmospheric variables at sufficient frequency to force regional models at their boundaries. It must be underlined that the ocean and sea ice component of EC-Earth (NEMO) is the same as those of the regional models that will be run in PARAMOUR, minimizing the risk of physical inconsistency between the boundary conditions and the dynamical evolution within the domain of the regional models.

Domains studied. Both ice sheets and surrounding ocean regions will be studied as the processes ruling their dynamics is different. Investigating in the same project the behaviours of both the Greenland and Antarctic ice sheets offers thus the ability to test our hypothesis over the two samples of ice sheets currently present on Earth. Despite the use of regional models, the resolution of simulations covering the whole ice sheets will still be too low to study some specific processes, such as grounding line migration, justifying to study a third, smaller region around Totten glacier in Antarctica. Totten glacier is a highly dynamic glacier that has been influenced by the sub-shelf intrusion of warm ocean currents in recent years, similar to the Amundsen Sea area (Greenbaum et al., 2015; Paolo et al., 2015).

However, its drainage basin is more confined, making it more appropriate for testing a fully-coupled model setup, while sufficient data is available to constrain the different models.

Specifically, the three configurations will have the following characteristics:

1. Greenland, North Atlantic and Arctic: the whole Greenland, the Arctic and the Atlantic northward of 30°N.
2. Antarctica and Southern Ocean: the whole Antarctica and the Southern Ocean southward of 30°S.
3. Totten glacier region: Over land, the domain will covers a large part of Wilkes Land, East Antarctica and will comprise the drainage basin feeding into the Totten, Moscow University and Dalton ice shelves, corresponding to the IMBIE basin 13. The ocean domain will cover the region 68°S-58°S and 112°E-124°E.

For each of the studied domains, a specific coupled system will be set up: MAR-NEMO-GISM for Greenland, the northern North Atlantic and the Arctic, COSMO-NEMO-f.ETISh for the whole Antarctica and the Southern Ocean, and COSMO-NEMO-BISICLES for the Totten glacier region. It may seem a priori strange to have three different coupled systems in this project, but we consider that it is absolutely required to use the best tools for each domain, tools that have already been validated for the area and at the scale they will be used here. This is also the best way to optimize the available skills in Belgium, each group being able to contribute to the project taking advantage of its strong regional expertise with tools they know best. Technically, the coupling is described more specifically in WP1 below.

Model resolution. For the ice sheets, a resolution of 1 or 2 km will be applied over Greenland, while 5-10 km will be used for the larger Antarctic domain. Grounding-line resolution within the adaptive framework will be chosen smaller than 500 m to resolve grounding-line migration accurately for the Totten glacier area. MAR will have a resolution of 12.5 km. For COSMO-CLM, a grid spacing 27 km is selected over the Southern Ocean and Antarctica and 5 km for the Totten area. The resolution of NEMO for this latter configuration will be 2 km, while two resolutions will be used for the larger ocean domains (northern North Atlantic Ocean plus Arctic Ocean and Southern Ocean): 1/4° horizontal resolution for the developments and the majority of the experiments and 1/12° for a few sensitivity experiments.

Computer time requirements. Since the ice sheet and ice shelf models are computationally fast, running them will not be a limiting factor in the framework of the present project. One year of simulation of the 1/4° resolution configurations of NEMO requires about 3 hours of computational time on 256 cores, which is also very reasonable, while the 1/12°set up needs about 30 times more. The regional configuration of NEMO-LIM needs about 1.5 hours per year on 256 cores. For MAR, one year over the North Atlantic/Artic domain corresponds to 4 hours per year on 256 cores. The estimated costs for one year of integration of the Antarctic-wide configuration of COSMO-CLM is a bit more than 1 days on 224 processors with similar values for the high-resolution integrations over the smaller Totten glacier area. The coupled integrations will cover 30-year periods both in the past and in the future, very roughly corresponding to 30 days on 500 processor for each configuration. The standard and sensitivity experiments will amount to about 300 years, corresponding to around 300 days on 500 processors. This is a large amount and we will have to consider seriously the availability of CPU time in the planning of our simulations but this is compatible with the resources available in both Flanders and the Communauté Wallonie-Bruxelles, with the simulations being performed in parallel on the different infrastructures. The data storage on the supercomputing infrastructure and the transfer of key results to local servers will also have to be well managed in advance, but even if this corresponds to an order of magnitude larger than our standard individual projects, this is manageable using existing infrastructures and the equipment purchased in the project.

Data needs. A large amount of data is required for the model boundary conditions, initial conditions and evaluation of model results. It is not possible to present an exhaustive list here. As in our previous studies, the observations will be based on standard publicly available data sets, derived from in situ and satellite observations. Key choices will be the Essential Climate Variables (ECV) by ESA-CCI (Climate Change Initiative), such as surface elevation change (SEC), ice velocity (IV), grounding-line location (GLL), gravimetric mass balance (GMB) over the last decade(s), energy fluxes, surface mass balance from the PROMICE database over GrIS, sea ice concentration and thickness (SIC/SIT), sea surface temperature and currents, complemented with in-situ observations of snow accumulation, temperature, humidity, wind (near-surface values and atmospheric profiles) and the surface radiation balance. Furthermore, specific data sets will be used such as the acquired flight-line data to fill in data gaps within bedrock and surface topography of the Antarctic ice sheet (BEDMAP2) and direct measurements as well as model comparisons (Gwyther et al., 2014) of subglacial melt rates underneath ice shelves in the Totten glacier region. Particularly useful for validating the GISM are recently published maps of surface elevation change rates since 1900 derived from aerial stereo photogrammetry imagery and LIA moraines (Kjeldsen et al., 2015). Equally useful is a century-long record of Greenland icebergs passing latitude 48°N as a proxy for iceberg calving (Bigg et al., 2014) as well as the GRACE based total mass balance reconstructions from the 2000s (Shepherd et al., 2012). The initial oceanic states and conditions at the boundaries of the domains (30°S and 30°N) will be derived from atmosphere and ocean reanalyses (Dee et al., 2011; Zuo et al., 2015). These are the same fields as the ones used to initialize the simulations performed with EC-Earth that will be applied as boundary conditions in the prediction runs in order to minimize the shocks. PARAMOUR will finally take full advantage of novel datasets to be released during the project, mainly from the Year of Polar Prediction (YOPP, www.polarprediction.net/yopp), that will extensively focus analyses on specific processes and may therefore be particularly suited for the evaluation of model results obtained in the project.

- Work plan/packages including time table

WP 1. Model development and control simulations

Task 1.1. Improvements of individual models and of the interfaces

For all the individual models, in each of the configurations, we will apply the standard versions that have been widely tested, in order to limit the development to a strict minimum. 1/ The treatment of iceberg calving for marine terminated outlet glaciers in GISM will be improved taking advantage of flowline model studies on individual glaciers (Nick et al., 2013) and treatments successfully tested for the Antarctic ice sheet for grounding line migration (Pattyn et al., 2012) and calving (Levermann et al., 2012). 2/ NEMO includes a parameterization for the melting at the basis of the ice shelves as a function of ocean temperature (Mathiot et al., 2017), but it will be necessary to test how this will interact with ice sheet models at large scale and if the formulation is also valid for Greenland because of some specific geographical settings such as narrow fjords. If needed, an alternative parameterization based on the approaches taken by Fürst et al. (2015) or Cowton et al. (2015) will be developed. 3/ Landfast sea ice (i.e., sea ice that is held stationary by being attached to coastal features or grounded over shoals) tends to form in narrow bands of widely varying widths but rarely exceeding 200 km. Variability in its extent is important because this ice type fundamentally modifies the transfer of heat and momentum between atmosphere and ocean compared to pack ice and is closely related to coastal polynyas. To account for this feature, a representation of landfast ice that includes tensile strength, in order to improve the results of parameterization based only a grounding scheme (Lemieux et al., 2016), will be incorporated in NEMO.

Task 1.2. Initialization of the ice sheets

Decadal climate predictions and dynamic response of ice sheets over decadal time scales requires ice sheet/ice shelf initialization as close as possible to observed conditions, meaning that a classical spin up over glacial-interglacial time scales is not enough. Indeed, while the englacial memory is important on longer time scales (thousands of years), it has likely a smaller effect on decadal time scales. The field of initialization is relatively mature for the ocean and atmosphere but improvements of the implemented initialization methods are still required for ice sheet models. Different techniques can be tested: nudging, adjoint method. A first set of tests will involve the optimisation of model initialization techniques by adjusting the basal sliding parameter to reproduce the observed velocity field (Price et al., 2012) and/or the observed geometry (Pollard and DeConto, 2012). The fit between model and observations from such simple nudging could be then improved with minimization procedures using an adjoint model (Granzow, 2014; Lee et al., 2015). Specifically, model initializations that rely on an adjoint method employ a steady-state temperature field that has been obtained by linking ice core temperature measurements and subglacial conditions (frozen/temperate) to a thermodynamical model. This ensures that for the interior of the ice sheet, englacial temperatures are in agreement with measured temperatures. The same tools and methods will be shared for all the ice sheet model configurations used in the project to estimate the robustness of each method and its applicability in a wide range of conditions.

Task 1.3. Development and test of the coupled models

A first step will be to prepare the model configurations in the selected domains and resolution in uncoupled mode. For some models, this will imply the determination of the optimized spatial resolution for large-scale (f.ETISh) and regional (BISICLES) models in order to capture grounding-line dynamics and improvements on BEDMAP2, such as inclusion of new bed topography from flight lines, and improved bathymetry. The coupling will then be performed using the most recent version of the OASIS (Ocean–Atmosphere–Sea Ice–Soil) coupler developed at the Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique, Toulouse (https://verc.enes.org.oasis). The coupling between the oceanic and atmospheric components will be performed first, followed by the coupling with the ice sheet/ice shelf models. This will require to design interfaces or to update the existing ones in order to exchange the fields between the models (in particular, the surface mass balance, melting at the base of ice shelves and calving fronts, iceberg and meltwater fluxes from the ice sheet to the ocean, surface and ice shelf topography, freshwater flux, stress and heat fluxes at the atmosphere-ocean and atmosphere-ice interface, sea surface temperature, sea ice concentration). Some small adjustments will also be made in the codes to have the right outputs and to deal at the interfaces with different model resolutions and missing values near grid boundaries. Those developments will be facilitated by the large expertise of the partners in coupling of various models. For instance, since the NEMO model can accommodate time-varying ice shelf cavity geometry, its coupling with an ice shelf model is rather straightforward. The iceberg size distribution, which is needed by the iceberg model but not computed by ice sheet models, will be prescribed from present-day observational estimates.

Task 1.4. Control simulations over the period 1985-2015

When the coupled models are ready and tested over short periods, simulations over the period 1985-2015 will be launched for the three domains using the initialization method for ice sheets selected in Task 1.2. The model performance will be evaluated by comparing their results with available observations (see the method section). The goal of those simulations is to be as close as possible to observations so reanalyses will be used as boundary and initial conditions for the ocean and the atmosphere. A particular attention will be paid to the improvements (and maybe the additional biases) present in our simulations compared to the driving reanalyses in order to describe the added value of the coupled regional models. Those simulations will be the reference standard configurations that will be used in other work packages to analyses processes and test the predictability of the system.

WP 2. Estimate of the predictability of the coupled system

Task 2.1. Decadal predictability of the ice-ocean-atmosphere system

The control simulations will not allow to realistically estimate the predictability of the system as this would require that the conditions at the boundaries of the domain are known in advance, which is obviously not the case. Nevertheless, it is still possible to determine which part of the changes at high latitudes can be estimated from regional processes only or from the conditions at their boundaries, as proposed in Task 2.3.

In Task 2.1, a framework closer to predictions will be applied starting again from initial conditions in 1985 (retrospective predictions or hindcasts), and by driving the models at their boundaries by the output of decadal predictions performed with the climate model EC-Earth. A first step will be to test and analyse the predictability in polar regions of the global model. The goal will be then to determine if the regional models, including a better representation of small-scale features such as katabatic winds and the coupling with ice sheets, allow more skilful predictions than the global climate model. An ensemble of 3 to 5 experiments will be used to sample the variability of the system and its impact on the model results (see table below for an overview of all the coupled experiments). The size of the ensemble may seem small to have robust statistics, but the goal is to determine which simulated patterns are present systematically in all simulations (and in the observations) and which ones are not. The mechanisms at the origin of those predictable features will be analysed here and in the other work packages using additional experiments, as discussed below. Additionally, to understand the factors driving the cascade of predictability through time scales, it is crucial to enumerate, as exhaustively as possible, the typical time scales for each state variable of each component and match them together. To that end, we will conduct a persistence analysis on key state variables (e.g. ice sheet volume, fresh water discharge to the ocean from ice sheets, sea ice thickness and concentration, oceanic temperatures at different levels, air temperatures at different levels, precipitation) from existing reanalyses and observations. With the spectrum obtained, it will be possible to objectively understand how anomalies in slow modes cascade towards faster ones. This analysis will also provide insights on the specific couplings that should deserve particular attention in the assessment of decadal predictions.

Task 2.2. Predictability of the ice sheets.

Ice sheets generally react relatively slowly to imposed changes in surface mass balance (diffusive response), especially in the interior. This has led to limited interest in the study of its decadal predictability until recently (e.g., Aschwanden et al., 2013). However, this view is challenged by observations of dynamic mass loss over the last decades, justifying the urgent need for investigation on this subject. Task 2.1 will analyse the predictability of the whole system but, in parallel, it is necessary to estimate the predictability that is associated to the ice sheets alone and the role of an adequate initialisation. In this framework, simulations with the ice sheet models only, driven by a climatological forcing, will be performed with different initialisation methods and different initializing dates. The results will then be compared to the control coupled simulations to identify the direct contribution of the initialization of ice sheets on their own evolution. To elucidate whether different initializations lead to the same predictability, the model drift will be analysed on decadal to centennial time scales. Secondly, the model response to changes in oceanic and atmospheric forcings will be compared when different initialisation states are used. We expect that ice mass changes are highly dependent on basin geometry, strongly justifying a comparison of the results over the three domains studied and different periods. Finally, a further ensemble analysis of ice sheet response to forcing in atmosphere and ocean over the last 30 years (hindcasts) will be carried out in uncoupled mode and extended, taking into account the uncertainties on the initialization.

Task 2.3. Predictability of the system due to ice sheets, ocean initialization and atmospheric teleconnections.

Task 2.2 is focused on the predictability of the ice sheets. The next step is to determine if the estimates of the changes in the state of the ice sheets and of the freshwater fluxes to the ocean leads to a better representation of the oceanic and atmospheric states. To do so, a sensitivity experiment equivalent to the control simulations but with prescribed ice sheets (in particular prescribed climatological freshwater and iceberg fluxes to the ocean) will be carried out and compared to the control simulations. This comparison will also highlight the variables for which the coupling with the ice sheets brings additional information. An additional global hindcast will also be generated with EC-Earth (1985-2015) using as an additional forcing the freshwater fluxes coming from meltwater (ice sheet runoff and ice shelf and iceberg melting) as computed by the regional models. The impact of the freshwater release on the ocean stratification will be estimated and the results compared with the Labrador Sea and subpolar gyre freshening and cooling observed in the past decade, the AMOC changes and their retroaction on the hydrological cycle (precipitation, West African Monsoon, tropical cyclones).

In order to estimate the role of ocean initialization, a sensitivity experiment will be initialized from a different set of initial conditions (model climatology averaged over 1985-2015). We will investigate how this initialization affects the variability of the oceanic properties, including the freshwater content, and the overall stability of the water column. The influence on the oceanic heat fluxes toward the ice shelves will be investigated as well as the potential impact on the atmospheric temperature and humidity transport to the ice sheets. In this framework, the amplifying feedbacks implying sea ice will receive a particular attention because of their potentially large impact.

Finally, many studies suggest that changes in high latitudes are conditioned by the large-scale atmospheric circulation, in particular because of teleconnections originating in the tropics. This includes moisture advection and atmospheric rivers that are key processes in precipitation variability at high latitudes. Those teleconnections are taken into account in our models through the boundary conditions. Consequently, a sensitivity experiment will be performed in which those conditions are perturbed. As for stability reasons it is not possible to simply use climatological conditions, the boundary conditions will be applied from the same reanalysis as in the control but without respecting the chronology (e.g. 2014 followed by 1999, 1989, 2001). We will estimate how the decadal climate variability is impacted and thus estimate when and where the contribution of initial condition and regional dynamics dominates the one associated with the global scale atmospheric dynamics. In particular, precipitation distribution over the ice sheet will be studied together with sea ice extent and indicators of large-scale dynamics.

Table of the coupled experiments. All the experiments below will be performed in identical conditions for the three domains in order to be able to compare their conclusions.

1	Control simulations over 1985-2015
2	Simulations over 1985-2015 without coupling with ice sheets
3	Simulations over 1985-2015 with initial conditions from climatology
4	Simulations over 1985-2015 with atmospheric boundary conditions with perturbed chronology
5	3-5 members over 1985-2015 with boundary conditions from hindcasts with EC-Earth
6	3-5 members over 2015-2045 with boundary conditions from forecasts with EC-Earth

WP3. Understanding of key processes that play a role in the variability of the ice-ocean- atmosphere system over the last 30 years

Task 3.1. Analysis of key oceanic and sea ice processes

Studying the sensitivity of models to the representation of some processes informs us about the model dynamics but also on the role of the corresponding processes in reality. This is also important to determine if some conclusions are strongly dependent on choices taken during the model development or not. At this stage, we assume that this type of sensitivity experiments will be performed in uncoupled mode to limit the CPU requirements (except for short simulations) but, if additional CPU time becomes available (for instance related to some applications in international facilities), the most interesting ones can be repeated in coupled mode.

For the ocean and sea ice, the influence of a number of small-scale processes usually neglected or highly parameterized in global climate models will be assessed. The following processes will be considered: ocean tides, the geographical distribution of the meltwater flux associated with iceberg melting, snow erosion and transport by winds (i.e. blowing snow), landfast sea ice and the sea ice rheology. Regarding the latter process, the standard elastic-viscous-plastic rheology will be replaced by the Maxwell-elasto-brittle one. Tests at higher horizontal resolution (see method section) for the domains covering the Arctic/North Atlantic and the Southern Ocean will also be performed in order to determine the limitations due to ocean horizontal resolution (in particular the representation of eddies) in the control configurations.

Task 3.2. Analysis of key ice sheet processes

With the large-scale ice sheet models, a sensitivity analysis on uncertainties in basal boundary conditions (friction laws) and tuning parameters will be carried out, including the evaluation of Weertman power-law sliding for different exponents (viscous - plastic), Coulomb friction laws (linear-plastic), variability in ice shelf viscosity and isostatic response for different lithospheric thickness on short time scales (e.g., Pollard et al., 2016, but then on short time scales). A sensitivity to sub-shelf melt forcing (type of parametrization of sub-shelf melt linked to ocean variables) will be added to this.

At high resolution, the sensitivity to sub-shelf melting will be investigated. For GrIS, sensitivity studies will additionally concentrate on the parameters of the calving law and the melting treatment at calving fronts.

Task 3.3. Analysis of key atmospheric processes

Clouds play an important role over the Southern Ocean but they are known to be poorly represented by general circulation models. Improvements are expected in the regional models due to the lower grid spacing and a more detailed cloud microphysical scheme. In this task, sensitivity of clouds to the parameters in the microphysical scheme will be tested. In addition, the feedback processes that are related to clouds (cloud-radiation-sea ice or cloud-atmospheric dynamics-moisture transport) will be investigated in sensitivity experiments using the coupled models over 2010-2015. Furthermore, the feedbacks between scouring of the surface by the wind, reflective properties of the surface and meltwater production over the period 2010-2015 will be studied in a control run and in sensitivity experiments with modified parameters in the blowing snow and firn scheme, comparing the results to satellite observations of drifting snow (Palm et al., 2011). Furthermore, the role of atmospheric circulation changes will be specifically investigated as they for instance explain in large part the current observed melt increase of GrIS since the end of the 1990's.

Task 3.4. Synthesis of the mechanisms at the origin of changes over the last 30 years

The set of experiments performed in WP2 and in Tasks 3.1 to 3.3 offer a unique opportunity to study the origin of climate changes observed in polar regions over the past 30 years. While many studies focussed on one single process, in a specific region, the strong asset of the consortium is its wide range of expertise. We will not repeat here the specific processes listed above but we want to insist that we will be able to determine the links between concomitant events in the ocean, sea ice, atmosphere and ice sheets, and to follow in a consistent way the propagation of a perturbation between the different media and across time scales.

WP 4. Predictions and projections

Task 4.1. Predictions over the period 2015-2045

Climate predictions up to 2045 obtained with EC-Earth initialized in 2015 will first be analyzed. They will then be used as boundary conditions in an ensemble of 3-5 simulations performed with the regional coupled models (as in Task 2.1.) in order to estimate the interest of using regional coupled models in predictions. As above, all the components will be analyzed, with a particular focus on the coupling between the components and the processes controlling the mass balance of the ice sheets. One of the limitations of the regional models is the absence of feedbacks with large-scale dynamics. In order to take them into account at the first order, a new set of prediction runs will be performed with EC-Earth, using as an additional forcing the freshwater fluxes coming from meltwater as computed by the regional models during the first leg of simulations. The results of those experiments will be compared to similar ones over 1985-2015 performed in Task 2.3. This will allow estimating how these fluxes modify the large-scale oceanic state, potentially impacting sea ice and the atmosphere and eventually the ice sheet mass balance.

Task 4.2. Projections over the 21st century and commitment

The core of the project addresses the climate variability at the decadal time scale but it is still instructive to determine how the changes imposed over the next 30 years will impact the longer-term evolution of the Earth's climate system. Since the ice sheet models are computationally fast, they will be used in uncoupled mode. In a first group of simulations, the changes that will occur even if the climate remain stable after 2045 will be investigated (the so-called commitment) by running ice sheet models using a constant forcing corresponding to the last decade of the coupled simulations. One of the goals will be to investigate the likelihood of occurrence of marine ice sheet instability on longer time scales once the forcing is kept constant. Finally, the ice sheet models will be run up to 2100, driven directly by the outputs of EC-Earth (scenario SSP2-4.5; O'Neill et al., 2016), as classically done, and the magnitude of the changes will be compared to the one observed over the last 30 years and the next 30 years, focussing on the relative contribution of the forced response compared to the internal variability, as estimated over the period 2015-2045 from the ensemble of projections.

A flow chart with the time allocated and the involvement of each partner for each task is given below. The name of the partner coordinating each WP is added at the end of the title of each WP. The partner(s) responsible for each task has its (their) acronym in bold.

	Year 1		**Year 2**		**Year 3**		**Year 4**	
Semester	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
WP 1. Model development and control simulations (Coord: ULg)								
Task 1.1. Improvements of individual models and of the interfaces								
UCL								
ULg								
ULB								
KUL								
VUB								
Task 1.2. Initialization of the ice sheets								
ULB								
VUB								
Task 1.3. Development and test of the coupled models								
UCL								
ULg								
ULB								
KUL								
VUB								
Task 1.4. Control simulations over the period 1985-2015								
UCL								
ULg								
ULB								
KUL								
VUB								
WP 2. Estimate of the predictability of the coupled system (Coord. ULB)								
Task 2.1. Decadal predictability of the ice-ocean-atmosphere system								
UCL								
ULg								
ULB								
KUL								
VUB								
BSC								
Task 2.2. Predictability of the ice sheets.								
ULB								
VUB								
Task 2.3. Predictability of the system due to ice sheets, ocean initialization and atmospheric teleconnections								
UCL								
ULg								
ULB								
KUL								
VUB								
BSC								
WP3. Understanding of key processes that play a role in the variability of the ice-ocean-atmosphere system over the last 30 years (Coord: KUL)								
Task 3.1. Analysis of key oceanic and sea ice processes								
UCL								
Task 3.2. Analysis of key ice sheet processes								
ULB								
VUB								
Task 3.3. Analysis of key atmospheric processes								
ULg								
KUL								
Task 3.4. Synthesis of the mechanisms at the origin of changes over the last 30 years								
UCL								
ULg								
ULB								
KUL								
VUB								
BSC								

WP 4. Predictions and projections (Coord: VUB)								
Task 4.1. Predictions over the period 2015-2045								
UCL								
ULg								
ULB								
KUL								
VUB								
BSC								
Task 4.2. Projections over the 21st century and commitment								
ULB								
VUB								

- Bibliographical references

Aschwanden G. **et al.**, 2013. The Cryosphere 7, 1083-1093. **Bakker P. et al.**, 2017. Nature 541, 72-83. **Bigg G.R. et al.** 2014. Proc. R. Soc. A 470: 20130662. **Boer G. J. et al.**, 2016. Geosci. Mod. Dev. 9, 3751-3777. **Bueler E. and J. Brown**, 2009. J. Geophys. Res.: Earth Surf., 114, f03008. **Cornford S. L. et al.**, 2013. J. Comput. Phys., 232(1), 529-549. **Cowton T. et al.**, 2015. J. Geophys. Res. Oceans, 120, 796-812. **Dansereau V. et al.**, 2016. The Cryosphere, 10, 1339-1359. **DeConto R.M. and D. Pollard**, 2016. Nature, 531, 591-597. **Dee, D. P. et al.**, 2011. Quart. J. Roy. Meteor. Soc., 137, 553–597. **Doblas-Reyes F. J**., et al., 2013. Nat. Commun. 4, 1715. **Ebner L. et al.**, 2014. Ant. Sci., 26 (3), 309-326. **Favier L. and F. Pattyn**, 2015. Geophysical Research Letters, 42(11):2015GL064195 **Favier L. et al.**, 2016. The Cryosphere, doi:10.5194/tc-2016-144. **Fettweis X. et al.**, 2013. The Cryosphere, 7, 469–489. **Flament T. and F. Rémy**, 2010. J. Glaciol., 58, 830–840. **Franco B.**, 2012. The Cryosphere, 6, 695–711, 2012. **Goldberg D. et al.**, 2009.. J. Geophys Res. 114, F04026. **Goelzer et al.**, 2013. J. Glac 59(216), 733-749. **Fürst et al.**, 2011. Geosci. Mod. Dev. 4, 1133-1149. **Fürst et al.**, 2013. The Cryosphere, 7, 183-199. **Fürst et al.**, 2015. The Cryosphere, 9, 1039-1062. **Gorodetskaya I. et al.**,, 2014. Geophys. Res. Let. 41, 6199-6206. **Granzow et al.**, 2014. J. Glac. 60(224), 440-446. **Greenbaum J.S**. et al., 2015. Nature Geosci. 8, 294–298. **Gwyther et al.,** 2014. Ocean Sci., 10, 267–279, 2014. **Hanna E. et al.**, 2016. Int. J. Climatol., doi:10.1002/joc.467. **Hazeleger W.** et al., 2012. Clim Dyn. 40, 2611-2629. **Huybrechts P. and J. de Wolde**, 1999. J. Clim. 12(8), 2169-2188. **Huybrechts P**. et al., 2011. Surv. Geophys. 32(4), 397-416. **IPCC**, 2013. Climate Change 2013. Cambridge University Press. **Jacobs S.S.et a**l., 2011. Nature Geosci., 4, 519–523. **Jones J.M. et al**., 2016. Nat. Clim. Change, 6, 917-926. **Keenlyside N. S. et al**., 2008. Nature 453 84-88. **Kjeldsen et al**. 2015. Nature 528, 396-400. **Lee et al.** 2015. Ann. Glac. 56(70), 129-140. **Lemieux J.-F et al**., 2016. J. Geophys. Res.121, 7354-7368. **Lenaerts J.T.M. et al**., 2017. Nat. Clim. Change 7, 58–62. **Levermann et al.**, 2012. The Cryosphere, 6. 273-286. **Lorenz E.**, 1963. J. Atmos. Sci., 20, 130-141. **Madec and the NEMO Team**, 2012 : ISSN N°1288-1619, 357 pp. **Marsh, R. et al**., 2015: Geos. Mod. Develop. 8, 1547-1562. **Mathiot P. et al**., 2016. In prep. **Matsuoka K. et al**., 2015. Earth-Science Rev. 150, 724–745. **Meehl G. A. et al**., 2014. Bull. Amer. Meteor. Soc. 95, 243-267. **Meehl G. A. et al**., 2016. Nat. Commun. 7:11718. **Moon et al**., 2014. Science, 336, 576-578. **Nick J. et al.** 2013. Nature 497, 235-238. **Noël B. et al**., 2016.The Cryosphere, 10, 2361-2377. **O'Neill B.C.** et al., 2016. Geosci. Mod. Dev. 9 3461-3482. **Palm S.P. et al**., 2011. J. Geophys. Res., 116, D16123. Paolo F.S. et al., 2015. Science 348, 327-331. **Pattyn F. and G. Durand**, 2013. Geophys. Res. Lett., 40, 4316-4320. **Pattyn F**., 2017. The Cryosphere Discuss., doi:10.5194/tc-2017-8. **Payne A.J. et al**., 2004. Geophys. Res. Lett., 31, 2–5. **Pohlmann H. et al**. 2009. J. Clim. 22 3926-3938. **Pollard D. and R.M. DeConto**, 2012. Geosci. Model Dev., 5, 1273–1295. **Pollard D. et al**., 2016. Geosci. Model Dev. 9, 1697-1723. **Price J. et al**., 2012. PNAS 108(22), 8978-8983. **Pritchard H.D.et al**., 2012. Nature, 484, 502–505. **Rahmstorf S. et al.,** 2015, Nat. Clim. Change 5, 475-480. **Raphael M.N. et al.**, 2016. Bull. Am. Met. Soc. 97, 111-121. **Rockel B. et al.,** 2008: Meteorol Z 17(4):347–348. **Rousset C. et al.,** 2015. Geos. Mod. Develop. 8, 2991-3005. **Rignot E.**, 2008. Geophys. Res. Lett., 35, L12505. **Shannon S.R. et al.** 2013, Proc. Nat. Acad. Sc., 14156–14161. **Shepherd A. et al**., 2012. Science 338, 1183-1189. **Smith D. M. et al.**, 2007. Science 317, 796. **Souverijns N. et al.**, 2016. Cosmo Assembly. Lüneberg, 20-23 September 2016. **Stammerjohn S. et al.**, 2012. Geophys. Res. Lett., 39, L06501. **Straneo et al.**, 2013. Bull. Am. Met. Soc., 1131-1144.

Stroeve J. C. et al., 2012. Clim. Change, 110, 1005. **Vancoppenolle M. et al.**, 2009. Ocean Mod. 27, 33-53. **van den Broeke M.R. et al.** 2016. The Cryosphere, 10, 1933-1946. **van Lipzig, N. and M. van den Broeke**, 2002. Tellus. Series A, Dyna. Met. Oceano. 54A, 497-511. **Yang Q. et al**., 2016, Nature Comms, 7, doi: 10.1038/ncomms10525. **Zunz V. and H. Goosse**, 2015. The Cryosphere 9, 541-546. **Zuo H. et al.**, 2015. Clim. Dyn., 10.1007/s00382-015-2675-1. **Zwally et al.**, 2002. Science 297, 218-222. **Zwally H.J. and M.D. Giovinetto**, 2011. Surv. Geophys. 32, 351–376.

- Science communication and outreach activities

A/ Scientific community. The main expected impact of our research is a better understanding of the interactions between the atmosphere, the cryosphere and the ocean, and their role in the variability and predictability of polar climate. This topic is currently receiving a very large interest and our results will certainly attract the attention of the scientific community. In addition to the results obtained during the project, the originality of the tools that are developed opens a wide range of applications, ranging from very theoretical analyses in idealized domains to predictions with specific applications required by the users. Those applications can be developed in the teams of the partners of the present project but also in other groups interested in installing them on their local computers as all the codes we will develop will be publicly available. We will also make available publicly all the results of our simulations on local servers as well as on the CMIP site for the experiments complying with their requirements. The predictability of ice sheets at decadal to centennial time scales related to the adequate initialization of both the ice sheets and the ocean is also a new field that will very likely lead to new developments. The partners will ensure that their results are published in high-profile international peer reviewed journals. Furthermore, our results will be communicated to the scientific community by participating in working groups and by giving presentations at national and international scientific workshops and meetings. In particular, the open annual meetings of the project will be a key opportunity to transfer our results at national and international levels.

B/ Training of young scientists. The training of the 5 PhD students and 6 postdoctoral researchers hired on the project is at the heart of the proposal. This is important in light of the compelling international demand for excellent climate modelers that can provide society with precise model-based climate information. Furthermore, training of young scientists will be achieved by including key results of the project in the courses given by the partners in their respective universities and by proposing master theses related to the project. The seminar sessions (see document 'motivation of the consortium') are an important initiative for this training of young scientists that will be open to the community, including to master students. Additionally, an international summer school will be organized during the 4rd year of the project, opened to the whole community. The lectures will be based on the expertise gained by the partners during the project and on the complementary skills provided by selected foreign teachers.

C/ Policy. Climate changes in polar regions are of interest for the local communities but also because of their large-scale effects on climate and sea level changes. A better understanding of the processes ruling polar climate and ice sheets will further increase the credibility of the scientific results and thus of the policies devoted to mitigate the impact of climate changes. All teams are involved in the IPCC assessment work, implying that the prediction/projection results will, in particular, feed in the future IPCC Sixth Assessment Report.

D/ General public. We also intend to engage the general public in outreach activities to stimulate the interest on the unique and attractive environment of polar regions. The members of the network will continue to make conferences in universities, schools and societies. We have and will maintain active contact with journalists on reporting of our scientific results and will publish press releases as in the past they have received a good coverage in newspapers, on radio and on television. On the web site of the project, news will be regularly posted, explaining to a wide audience the main conclusions of our studies, as well as some key results achieved by the scientific community in subjects related to the project.