UNDERSTANDING AND PREDICTING ANTARCTIC SEA ICE VARIABILITY AT THE DECADAL TIMESCALE "PREDANTAR"

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The last decades are characterized by contrasting behaviors of the sea ice in the two polar regions of the Earth (Turner and Overland, 2009). While the sea ice in the Arctic has been largely shrinking, the extent of sea ice surrounding Antarctica displays an increase estimated to be between 0.13 and 0.2 million km^2 between November 1978 and December 2012 (Vaughan et al., 2013). The recent study of Eisenman et al. (2014) suggests that the magnitude of this positive trend may have been overestimated due to a change in the algorithm used to process the satellite data. However, even the lowest estimate of the trend in Antarctic sea ice extent over the last decades indicates a slight increase that is rather puzzling in a global warming context.

The evolution of the Antarctic sea ice is driven by the combination of different mechanisms involving both external forcing and internal variability of the system. For instance, the stratospheric ozone depletion (Solomon, 1999) has been pointed out as a potential cause of the increase in sea ice extent. Nevertheless, this hypothesis is not compatible with several recent model analyses (e.g. Bitz and Polvani, 2012; Sigmond and Fyfe, 2010, 2013; Smith et al., 2012) and the response of Antarctic sea ice to ozone depletion may involve complex mechanisms that require further investigations (Ferreira et al., 2015).

The observed evoution of Antarctic sea ice cover may be associated to changes in the atmospheric circulation or in the ocean stratification (e.g., Bitz et al., 2006; Goosse and Zunz, 2014; Goosse et al., 2009; Holland and Kwok, 2012; Kirkman and Bitz, 2010; Landrum et al., 2012; de Lavergne et al., 2014; Lefebvre and Goosse, 2008; Stammerjohn et al., 2008; Zhang, 2007). For instance, the melting of the Antarctic ice shelves (e.g., Pritchard et al., 2012; Rignot et al., 2008; Shepherd et al., 2012; Velicogna, 2009) and the increase in precipitation at high southern latitudes resulting from the enhanced hydrological cycle (e.g., Liu and Curry, 2010) under global warming conditions may lead to a freshening of the surface of the Southern Ocean. This freshening induces a stronger vertical stratification of the ocean that in turn reduces the exchange of heat between the relatively warm intermediate layer and the colder upper layer of the ocean. This reduction of the vertical heat flux in the ocean favors the formation of sea ice at the surface and can thus account for the observed expansion of Antarctic sea ice.

Those changes in oceanic and atmospheric circulation and in Antarctic sea ice cover have been tentatively attributed (at least partly) to the multi-decadal, internally driven, variability of the system (e.g., Gagné et al., 2015; Mahlstein et al., 2013; Polvani and Smith, 2013; Swart and Fyfe, 2012; Zunz et al., 2013). In particular, the observed increase in sea ice extent since 1979 may have been preceded by a large decrease in ice extent during the 1960's (e.g., Cavalieri et al., 2003; Cotté and Guinet, 2007; Curran et al., 2003; Gagné et al., 2015; de la Mare, 1997, 2009). This hypothesis is supported by the few observational data that are available prior to 1979. Nevertheless, the time period for which reliable observations of the Antarctic sea ice are available is too short to properly investigate the internally driven change in sea ice cover. In this context, the results of climate model simulations constitute a complete set of data that can compensate for the lack of observations. Unfortunately, climate models often display large biases in the Southern Ocean for both the mean state and the variability of the system (Arzel et al., 2006; Bracegirdle et al., 2008; Mahlstein et al., 2013; Zunz et al., 2013).

The research activities undertook within the framework of the PREDANTAR project first aimed at making the most of imperfect models and incomplete observations in order to improve our understanding of the complex mechanisms that rule the changes in Antarctic sea ice and to perform better predictions. Coupled climate models are here used to identify the processes implied in the observed changes in the Southern Ocean. Through the present project, post-processing tools providing an assessment of model errors and corrections were developed and applied for both simple models and more complex ones. Additionally, data assimilation techniques were implemented in order to obtain optimal reconstructions of the Antarctic sea ice cover. Those reconstructions constitute valuable estimates of the changes in the state of the ice cover in the Southern Ocean over the last 30 years that compensate for the lack of observations over that period. Based on this improved understanding of the drivers of the changes in Antarctic ice cover, a methodology has been developed in order to improve the predictions and the projections of the changes in that region. In particular, the impact of the initialization of prediction simulations with a state obtained thanks to different data assimilation techniques was assessed showing how a reasonable skill in predicting decadal trend in sea ice extent may be achieved.

Calibration or post-processing aims at improving the predictions once they have been issued by the model. The purpose is to correct either the impact of model errors on the predictions and/or the evaluation of the uncertainty associated with these forecasts. These improvements are strongly related with the concepts of resolution and reliability, for which the predictions must be as close as possible to the truth (high resolution) and at the same time, their uncertainty estimation must be a good measure of the error (high reliability). In the context of the project, calibration techniques have been developed for both deterministic and ensemble predictions and have been proven successful provided the correction is performed for skillful forecasts and for short times. Moreover, the linear post-processing approach enables us to disentangle the importance of model errors and their potential origin in short term predictions of the NEMO-LIM coupled ice-ocean model used to build a Southern Ocean re-analyses.

These techniques have also been used in the perspective of the correction of long-term predictions under static or transient external climate forcing in both reduced-order idealized climate models and in an intermediate complexity climate model (LOVECLIM). As it turns out, transient dynamics of the external forcing are affecting considerably the possibility to use post-processing (bias correction or more sophisticated approaches) under strong climate changes, and care should be taken in using the approach that should be evaluated carefully on a case-by-case basis. Furthermore, a simple bias correction has been found to provide the dominant correction for model error for long-term predictions (annual, inter-annual and decadal time scales), while more sophisticated local and non-local techniques do only provide marginal corrections.

In order to contribute to the understanding of the variability in the Southern Ocean, a reanalysis assimilating sea surface temperature, sea ice concentration and sea ice drift has been realised. As the sea ice drift is strongly related to the winds, a specific procedure for the ice drift has been adopted. The correlation between the 3-day mean surface wind field and the ice-drift is strong and this relationship was used to adjust the wind field using pseudo-wind field observations based on sea ice drift data. The wind field corrections have been independently validated to show the efficiency of the approach.

Based on this adjusted wind, a reanalysis using the coupled ice-ocean model NEMO-LIM2 for the period 1985 to 2006 using 50 ensemble members has been performed. The reanalysis was validated using the World Ocean Database. As the focus of the reanalysis is the Southern Ocean, the impact of the assimilation on the ACC (Antarctic Circumpolar Current) was also assessed by comparing the mean sea surface height of the model to the mean dynamic topography derived from various observations. The assimilation improved the position and strength of the ACC.

For such low resolution models a large part of the error is due to a bias. Exploratory approaches have been implemented in order to reduce the model bias by parameter estimation. The general idea to address this problem is to add a stochastic forcing (at first constant in time) to the dynamical equations and to estimate this forcing using data assimilation. Simple tests with the Lorenz 96 model have confirmed the validity of this approach. Results of this approach with the NEMO-LIM2 model are also encouraging and show a possible way to reduce the bias of low resolution climate models.

The analyses of the model results provided through the 5th Coupled Model Intercomparison Project (CMIP5) have highlighted systematic biases in the mean state and in the internal variability of the simulated Antarctic sea ice cover. Nevertheless, a positive trend in ice extent over the last three decades, although being rare among the CMIP5 historical simulations, is compatible with the internal variability simulated by the CMIP5 models. In those models, the heat supplied by both the ocean below and the atmosphere above the sea ice clearly impacts the sea ice cover. The relative contribution of those two mechanisms in determining the sea ice conditions is strongly model-dependent. Additional investigations based on the results of a model of intermediate complexity have allowed identifying a process related to ice-ocean interactions that potentially accounts for many characteristics of the recent observed changes in Antarctic ice cover. This mechanism consists of a stabilization of the water column due to the changes in the seasonal cycle of ice formation.

The predictive skill of an Earth-system model of intermediate complexity for the Antarctic ice cover was first assessed in idealized conditions that allow getting rid of the model biases. In this idealized study, nearly no predictability was found for the Antarctic sea ice at interannual timescales, likely because of unpredictable atmospheric processes that dominate the signal at those timescales. Besides, relatively high predictability was highlighted for the trend in sea ice extent at multi-decadal timescales. An adequate initialization of the ocean underlying the ice, achieved thanks to a data assimilation procedure, has been identified as a key element to ensure satisfying predictions of the trends in ice extent. In realistic conditions, our results indicate that the initialization of the system through data assimilation can also improve the simulated trends in ice extent and concentration over the period 1980–2009.

The Antarctic sea ice, although being a relatively small and thin ice blanket over the Southern Ocean, strongly impacts the Antarctic ecosystem and the evolution of the climate at both local and global scale. In particular, the Antarctic sea ice influences the oceanic heat exchanges, the carbon uptake and the sea level rise through interactions with the Antarctic ice sheet. Understanding its behavior and predicting its evolution thus constitute an issue of concern in a sustainable development context. The causes of the recent increase in Antarctic ice extent are still not firmly identified at this stage. Nevertheless, the knowledge related to the mechanisms that rule the Antarctic sea ice variability has been clearly improved thanks to the work carried out in the framework of the PREDANTAR project. This project also allowed testing different techniques, based on post-processing tools and on data assimilation procedure, aimed at improving the reconstructions and the predictions of the Antarctic ice cover. This will strongly contribute to improving future predictions and projections not only for the Southern Ocean but also at global scale. Furthermore, although this work was essentially focused on the sea ice in the Southern Ocean, the post-processing and data assimilation techniques implemented within the framework of PREDANTAR can be used to improve the predictability at decadal timescales in other regions and for other climate variables.

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