MiKlip II – report about the use of the computing resources 2016-2019

Project for report: **Project 807 – MiKlip II all modules**

Project lead: **Jochem Marotzke**

Project manager: **Sebastian Hettrich**

Report period: **01.01.2016 – 31.12.2019**

I. MiKlip Overview and allocated computing resources for 2019

The German Federal Ministry for Education and Research has since 2011 funded a comprehensive national program on decadal climate prediction, MiKlip (Marotzke et al. 2016). A second phase, MiKlip II, has been approved until 2019 and started on 1 October 2015, building upon MiKlip to further improve the central decadal climate prediction system and by the end of the project to transfer the system for operational use to the German meteorological service DWD. The successful improvement and thus application of the prediction system depends on ongoing research of new initialisation, ensemble perturbations, and bias correction strategies that must be tested and, if applicable, incorporated into the prediction system. Furthermore, model resolution must be increased, which has been shown to improve the representation particularly of atmospheric processes, the limited representation of which currently reduces the forecast skill over continental areas.

The aim of MiKlip II is thus to further improve the decadal prediction system that was established during the first project phase, with the ultimate aim to provide a system that can be used operationally by the DWD. All five MiKlip modules (respectively represented in the projects below) work towards this aim with different research focusses, thereby making strong use of resources provided by the DKRZ, both through computing time allocated on shared resources and through the MiKlip Server.

Before 2017, the partners of the second phase of MiKlip (MiKlip II) have applied for computing time via the following five projects:

- project bu0801: MiKlip II Module A – Determination of initial conditions and initialisation,
- project bm0764: MiKlip II Module B – Processes and Modelling
- project bb0849: MiKlip II Module C – Regionalisation of Decadal Predictions
- project bm0807: MiKlip II Module D – Synthesis, and
- project bb0763: MiKlip II Module E – Evaluation of the MiKlip Decadal Prediction System.

The allocated times for 2019 including the additional allocations for quartal 3 and 4 are shown in table I.

Table I: Allocations for 2019

Project Number	Project Name	Mistral compute time [Node hours]	Lustre work [GiB]	HPSS arch [GB]	HPSS doku [GB]
bu0801	Module A	670	70,246	64,512	0
bm0764	Module B	245,950	208,893	286,419	40,917
bb0849	Module C	188,605	105,020	1,050,210	10,240
bm0807	Module D	911,253	1,374,099	0	0
bb0763	Module E	0	0	0	0
Sum ALL MiKlip		**1,346,478**	**1,758,258**	**1,401,141**	**51,157**

II. Table of content

1. Module A – Initialisation

Project **bu0801**

Project title: **MiKlip II Module A: Determination of initial conditions and initialisation**

Project leader: **Johanna Baehr** (CEN, UHH), **Andreas Hense** (Meteorologisches Institut University Bonn), **Detlef Stammer** (CEN, UHH)

Reporting period: **01.01.2016 – 31.12.2019**

1.1 Project Overview

Project bu0801 was dedicated to MiKlip II, Module A. We performed simulations with MPI-ESM with the goal (i) to improve estimates of initial conditions for the ocean, sea ice and the land soil moisture, (ii) based on those initial conditions to improve initialisation procedures and finally (iii) to optimise procedures to span the MiKlip forecast ensemble. If applicable, results from Module A contributed to improvements in the central prediction system (Module D, project bm0807).

Work in Module A has been distributed over four work packages (WP):

WP1, ModuleACoord (Uni HH): climate mode initialisation for decadal predictions,

WP2, PastLand2 (MPI-M HH): assimilation of soil moisture observations,

WP3.1, AODA-PENG2 Breeding (Uni Bonn): ensemble generation using bred vectors,

WP3.2, AODA-PENG2 EnKF (Uni HH): oceanic ensemble Kalman filter assimilation.

1.2 Achievements

Initialisation of oceanic and atmospheric states

Most resources in bu0801 were dedicated to experiments to improve the oceanic and atmospheric state for the initialisation of decadal predictions. At the core of the experiments, three distinct methods have been tested: oceanic climate mode initialisation (Polkova et al. 2019a), ensemble generation by breeding (Polkova et al. 2019b), and oceanic ensemble Kalman filter assimilation (Brune et al. 2018, Polkova et al. 2019b). For all three methods, decadal hindcasts have been produced following the protocol used for the central prediction system in Module D (Preop-LR): MPI-ESM-LR, 10-member, 10 year and 2 months hindcasts with initialisation every year at November 1st for 1960 to 2016. These hindcasts were part of the comparison of initialisation and ensemble generation methods within Miklip (Polkova et al. 2019b). In comparison to Preop-LR, all three methods generally improve air surface temperature hindcast skill in lead years 2-5 (Fig. 1.1). Most improvements come in regions with low skill in Preop-LR, e.g. the eastern tropical Pacific, the northeastern Pacific, and the Atlantic sub-polar gyre. Improvements in air surface temperature skill are largest with the ensemble Kalman filter, and slightly smaller with climate mode initialisation and bred vectors. The impact of the different initialisation methods becomes even more clear in the realisation of the upper ocean heat content in the North Atlantic sub-polar gyre (Fig. 1.2). Simple nudging as in Preop-LR (Fig. 1.2a) follows the heat content from the reanalysis, most prominently the minimum in 2002/2003, which could point to an error in the reanalysis. A similar minimum, but with a weaker amplitude, is inherited by both the climate mode and bred vector initialisations, because they partly rely on Preop-LR assimilation. The hindcasts initialised by oceanic ensemble Kalman filter (Fig. 1.2d) show a better realisation of upper ocean heat content in these years, because this method does not depend on any oceanic reanalysis and may therefore lead to a more model consistent realisation of the oceanic state variables.

Additionally, simulations have been performed to initialise decadal hindcasts with the anomaly transform method applied to the oceanic state (Romanova et al. 2017). The prediction skill of surface fresh water flux benefits from hindcast initialisation either by the oceanic anomaly transform or the oceanic ensemble Kalman filter, when compared to the standard MiKlip initialisation (Romanova et al. 2018).

Furthermore, Wiegand et al (2019) used experiments with the ensemble Kalman filter to successfully predict decadal trends in Northeast Pacific temperatures.

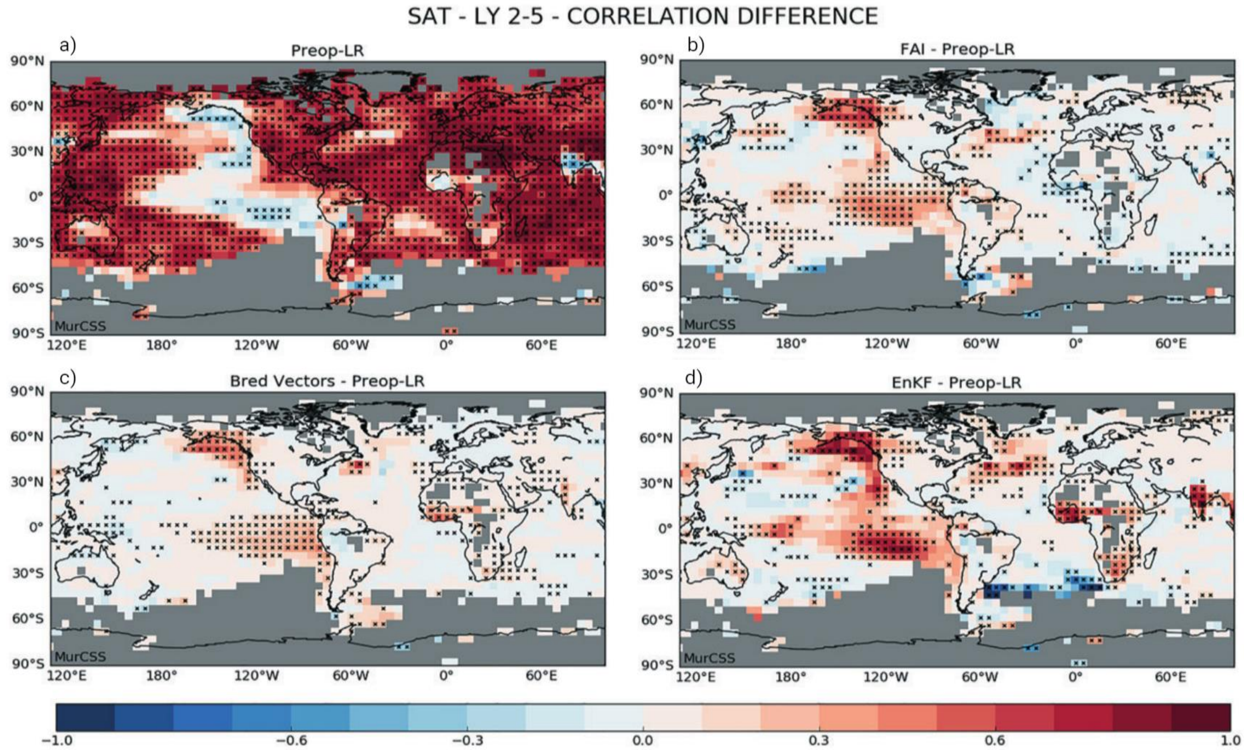

***Figure 1.1**: Correlation skill for surface air temperature (SAT) w.r.t. HadCRUT4 for lead years 2–5 from a) Preop-LR and the correlation skill difference to Preop-LR of b) climate mode initialisation (FAI), c) Bred Vectors, d) ensemble Kalman filter (EnKF). Stippling indicates statistical significance estimated with the bootstrap method that the value is positive at the 95% confidence level. Adapted from Polkova et al. (2019b).*

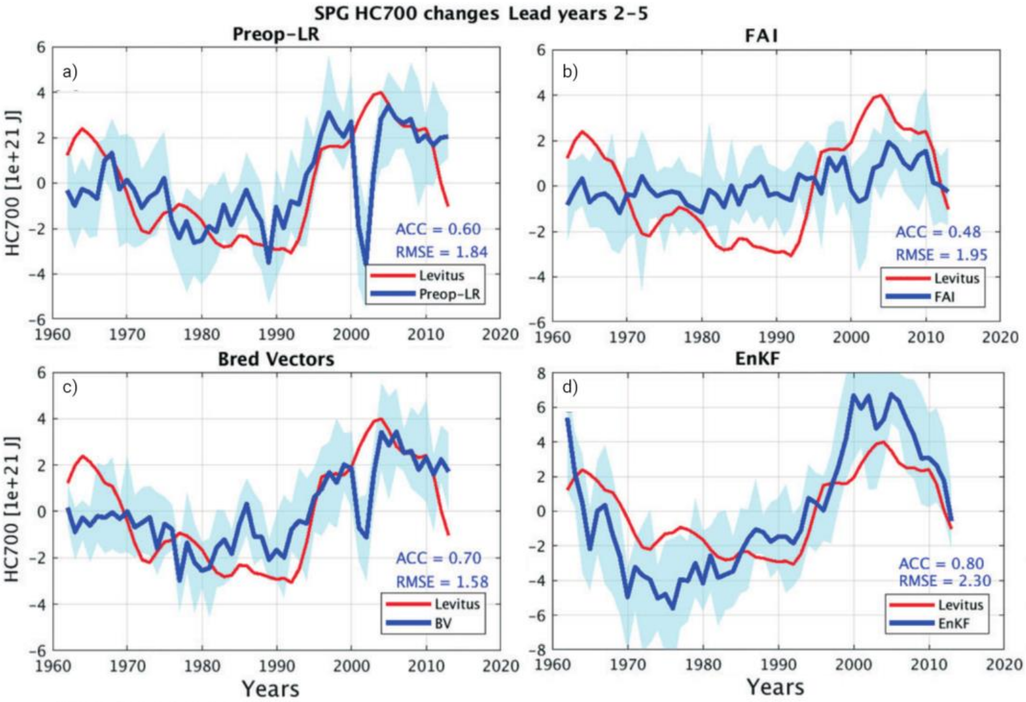

***Figure 1.2**: Time series of the North Atlantic sub-polar gyre upper ocean heat content from NOAA/NODC (red) and the initialised hindcasts at lead years 2–5 (blue): a) Preop-LR, b) climate mode initialization (FAI), c) Bred Vectors, d) ensemble Kalman filter (EnKF). In bold solid is the ensemble mean and shading indicates the range of the ensemble members. ACC is the anomaly correlation coefficient and RMSE is the root mean squared error w.r.t NOAA/NODC. Adapted from Polkova et al. (2019b).*

Initialisation of the hydrological state

Two hydrological observation datasets were analysed for their suitability for land surface assimilation: ESA_CCI soil moisture and GlobSnow snow water equivalent, both available for a period of about 1980 until almost 2015. Accordingly, two assimilation runs have been conducted based on Preop-LR assimilation from Module D: one with land data assimilation alone, one with land data assimilation in addition to assimilation of the atmosphere and ocean states. Subsequently, two hindcast sets have been conducted to and compared to Preop-LR hindcasts to test the impact of land data assimilation. For near surface air temperature, hindcasts initialised by land data assimilation alone show hardly skill that is higher than in the historical simulation (Fig. 1.3a). Likewise, the skill of hindcasts initialised with or without land data assimilation in addition to atmospheric and oceanic assimilation is rather similar for the global mean and falling to the level of the historical simulation after two to three lead years (Fig. 1.3a). Nevertheless, on a regional scale lead year 1 near surface air temperature hindcast skill may benefit from the additional land data assimilation (Fig. 1.3b).

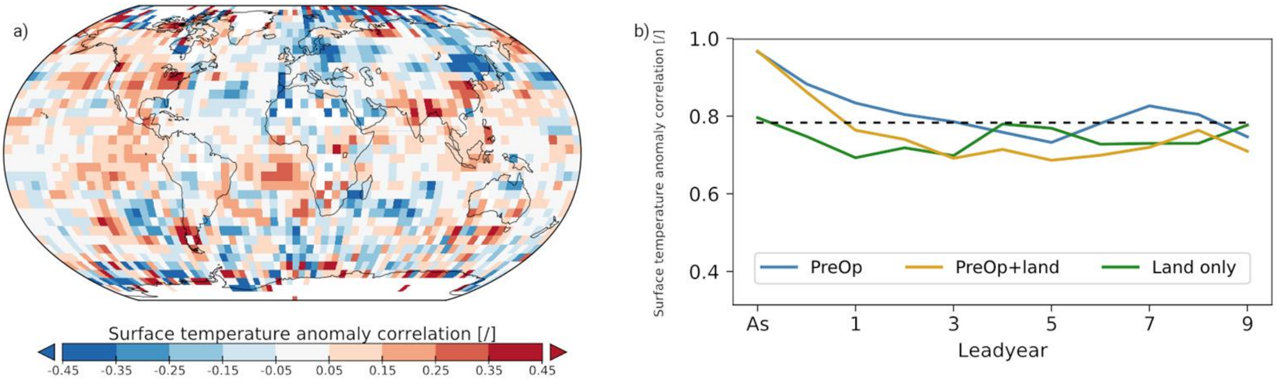

Figure 1.3: *a) Difference in lead year 1 surface air temperature correlation skill between hindcasts initialised with and without additional land data assimilation. b) Anomaly correlation coefficient (ACC) for the assimilation simulation (As) and increasing lead years for near surface temperature vs HadCRUT4. Atmospheric and oceanic assimilation with (Preop+land) and without (Preop) land data assimilation, land data assimilation only (Land only). The black dashed line indicates the skill of the historical simulation.*

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2. Module B – Processes and Modelling

Project: **bm0764**

Project Title: **MiKlip-II Module B: Processes and Modelling**

Module B coordinator: **Johann Jungclaus**

Sub-projects:

- **MOVIECLIP** (PIs: Johann Jungclaus, Jürgen Bader, Daniela Matei, Wolfgang Müller (MPI-M)),
- **ALARM-II** (Claudia Timmreck, Hauke Schmidt (MPI-M), Kirstin Krüger (Uni Oslo))
- **ATMOS-MODINI** (Richard Greatbatch (GEOMAR), Johann Jungclaus (MPI-M), Rüdiger Gerdes (AWI))
- **PROCUP** (Tatiana Ilyina, MPI-M)

Reporting period: **01.01.2016 – 31.12.2019**

2.1 Project overview

The overall aims of Module B are to gain a better understanding of the mechanisms of decadal variability and to improve the MiKlip prediction system by the incorporation of processes relevant for decadal climate prediction and by bias reduction including improved initialisation in the tropics. MiKlip Module B consists of the sub-projects "Alert for LARge volcanic eruptions in Medium-term climate prediction (ALARM-II)", "Correcting the North Atlantic cold bias and improving tropical initialisations in the MiKlip forecasting system (ATMOS-MODINI)", "Modes of Ocean Variability and their Implication for European continent CLImate Predictions (MOVIECLIP)", and "PRedictability of the Oceanic Carbon UPtake (PROCUP)", as well as two other projects that do not request DKRZ resources.

2.2 ALARM-II

Project Lead: Claudia Timmreck, Hauke Schmidt (MPI-M), Kirstin Krüger (University of Oslo)

The central goal of the MiKlip ALARM project is to study the response of the climate system to volcanic aerosol perturbations and its predictability. An assessment of the climate impact of large volcanic eruptions cannot be achieved without a deep understanding of post volcanic climate variability.

Volcanic Impact on NH winter variability

We have analysed historical CMIP5 simulations of the MPI-ESM1.1 in LR and in MR resolution (Giorgetta et al., 2013), as well as historical simulations with the MPI-ESM1.2 in HR resolution and with CMIP5 forcing (Müller et al., 2018). Results of the multilinear regression method analogous to Schmidt et al. (2013) show a significant warming in the upper stratosphere at high latitudes in the northern hemisphere (NH) winter for all model resolutions. Zonal wind and temperature are related by the thermal wind equation, so that the equatorial positive temperature signal caused by the volcanic forcing is reflected in westerly wind anomalies over wide areas of the stratospheric mid and high latitudes. However, it is difficult to interpret the differences between the model resolutions because the volcanic signal is disturbed by the large interannual variability in the NH winter. For a more detailed analysis of the volcanic disturbance depending on the model resolution, more ensemble members are necessary, as our analyses of the MPI-M "Grand Ensemble" (GE, Maher et al., 2019) have shown (Bittner et al., 2016).

Results of our work also show that the coupled climate models do not fundamentally underestimate the dynamic changes in the polar NH winter after tropical volcanic eruptions as previously assumed (e.g. Driscoll et al. 2012; Charlton-Perez et al., 2013); rather, a relatively large volcanic disturbance is necessary in addition to a sufficient number of ensemble members (Bittner et al., 2016). Direct conclusions about the dependence of the polar vortex amplification on the strength of the eruption are, however, only possible to a limited extent, since the volcanic eruptions under consideration differ not only in their strength but also in their geographical latitude and the season of the eruption. In the context of a master thesis (Azulay, 2019), a 100-member ensemble for idealised tropical volcanic eruptions with different emission intensities was created and analysed over a period of 3 years. First results show that the change of the polar vortex and the volcanic emission intensity do not behave linearly.

Volcanic impact on multi-year seasonal and decadal climate predictability

Furthermore, we have investigated to what extent the prediction of volcanic climate changes depends on the initialisation conditions. For this purpose, we used the MiKlip prediction system to perform decadal predictions for a Pinatubo-like eruption in June 2013 and 2015 (Illing et al., 2018). Both years differ in the phase of Pacific Decadal Oscillation (PDO) and North Atlantic Oscillation (NAO). While the predictions for global temperature and precipitation changes are relatively independent of the initial conditions, we find significant regional and seasonal differences. One of the largest differences is found in the first four years for Arctic sea ice cover in September (minimum), since during negative PDO phases Arctic warming is higher in winter and sea ice loss is greater than average (Screen and Francis, 2016). This can counteract the volcanic cooling effect.

In boreal autumn 2017 the likelihood of a large volcanic eruption was relatively high. Increased seismic activity was observed from Mt. Agung (Bali, Indonesia), which started on August 10th, 2017 and continued with intensity increasing throughout fall. The fall 2017 unrest of Mt. Agung raised the possibility of the effects of another climatic relevant eruption in late 2017/early 2018.

To investigate on one hand the possible climate impact and to test on the other our prediction system we have performed decadal climate forecasts with the MiKlip prediction system for an artificial Agung-like eruption starting in October 2017. We have simulated the evolution of the volcanic aerosol and the related radiative forcing with the global aerosol model ECHAM5-HAM with high vertical resolution (L90) and internally generated QBO (e.g. Niemeier et al., 2009; 2019). For this test case the SO_2 emission profile has been adapted from the 1963 eruption. In a second step these optical parameters are prescribed as monthly forcing data in the forecast system. Our results show surface air temperature would have been affected globally and regionally for a couple of years. Precipitation anomalies are only regionally significant for example a precipitation increase over the Gulf of Mexico in the 1st summer after the eruption.

Volcanically forced vs internal variability

We have also investigated the combined effects of internal variability and uncertainties in volcanic radiative forcing on climate change. Therefore, we performed nine experiments with the MPI-ESM1.2-LR and different combinations of the volcanic radiative forcing (medium, high and low estimation) for the time period between 1800 and 1830. The results show that climate change in the early 19th century can be explained by a combination of internal variability and volcanic radiative forcing. A comparison with temperature reconstructions from tree rings shows that the reconstructed temperature anomalies are in the range of the simulated ones, taking into account the uncertainties in volcanic radiative forcing. However, the time between the two eruptions is colder and the signal of the 1809 eruption weaker than in the reconstructions (Timmreck et al., in prep). Furthermore, results of a cluster analysis show that in boreal summer the uncertainties in the radiative forcing can dominate climate variability due to the strong direct radiation impact, whereas in winter the high internal variability dominates (Zanchettin et al., 2019). The climate simulations for the 19th century show a strong cooling in the summer of 1816 "year without summer" and, compared to volcanically undisturbed model runs and observations, an increased probability for a low-pressure system over Central Europe leading to an increase in precipitation (Schurer et al., 2019).

Contribution to CMIP6/VoMIP

It was originally planned that ALARM-II contribute to CMIP6 (Eyring et al., 2016) specifically to The Model Inter-comparison Project on the climatic response to Volcanic forcing (VolMIP, Zanchettin et al., 2016), and to a specific part (Component C) of the Decadal Climate Prediction Project (DCPP, Boer et al., 2016). Due to technical delays CMIP6 VolMIP simulations could be carried out only in the 2nd half of 2019. During the project time we have therefore more focused on work related to the volcanic impact on seasonal to decadal prediction and volcanic forcing vs internal variability, see above.

Publications related to project 764

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2.3 ATMOS/MODINI

Project lead: Richard Greatbatch (GEOMAR), Johann Jungclaus (MPI-M), Rüdiger Gerdes (AWI)

The MiKlip subproject ATMOS-MODINI has two parts. ATMOS has the goal to alleviate the North Atlantic cold bias in the MPI-ESM with the view of testing the hindcast skill of the corrected model. The MODINI part is to explore ways to improve the initialisation of the MiKlip system in the tropics. Thereby, MODINI uses reanalysis wind stress anomalies seen by the ocean model in the coupled system to drive the initialisation run that is subsequently used for decadal hindcasts.

Bias correction in MPI-ESM

In work package 5.2 we pursued the Implementation of the complete cold bias correction system in the MPI-ESM1.1, including any necessary correction to the surface fluxes; testing the impact on the mean state of the model, the effect of applying the flow field correction only in certain regions of the North Atlantic and testing the impact of the correction on the variability in the MPI-ESM1.1.

Some modification of the method was required from that used to implement the FFC in the Kiel Climate Model (KCM; Drews et al., 2015). The final, non-flow-interactive correction is applied over a larger area than the initial flow-interactive correction, in contrast to the KCM where both corrections were applied over the same domain. Also, whereas in the KCM it was necessary to also implement a correction to the surface freshwater flux, this turned out not to be necessary in the case of the MPI-ESM-LR model, an advantage since it avoids any interference with the freshwater budget in the model. The FFC removes the cold bias from the mean state. However, the decadal and longer time scale variability in the corrected model is reduced in power compared to that in the uncorrected model, an unexpected result. As a consequence, the Atlantic Multidecadal Variability is less well represented in the corrected than in the uncorrected MPI-ESM-LR model, contrasting with our finding using the KCM (Drews and Greatbatch, 2016, 2017).

Combining MODINI initialisation with the standard MiKlip initialisation in the MPI-ESM1.1 and testing the effect of implementing the MODINI correction in regions of different width about the equator

This work package evolved differently from expected. We began by participating in the comparison of initialisation methods that was organised by Module A (Polkova et al., 2019). This involved a lot of work since the script we were using turned out to be incorrect. In the end, using a correct script for initialisation, hindcasts were made using MODINI initialisation following the protocol laid down for the inter-comparison and covering the period 1959-2016. The results are disappointing (Polkova et al., 2019). Compared our earlier work (Thoma et al., 2015), there is only a marginal improvement over the Pacific compared to the other initialisation methods, probably because of errors in the wind stress product used for initialisation, a topic investigated by Pohlmann et al. (2017). The hindcasts shown by Thoma et al. (2015) cover the period since 1990 using the wind stress product from Saha et al. (2010) whereas, for the inter-comparison, most of the hindcasts cover the pre-satellite era when data quality is relatively poor. The poor performance discouraged us from combining MODINI with the standard MiKlip initialisation system. It would, nevertheless, be interesting to carry this out in the future. However, to do so, we would follow the simpler procedure used by Derome et al. (2001), rather than that planned at the time of writing the proposal.

Analysis of the high-resolution ocean model available in Kiel

The results from this work package have been published in Wang et al. (2017). As well as pointing to the importance of the deep circulation in the shaping the North Atlantic cold bias in models, the results show the role of advection by the mean flow for shielding the Labrador Sea from the rest of the North Atlantic leading to the formation of the so-called Lavender recirculation gyre (Lavender et al., 2000). Models currently used for decadal prediction, e.g. the MPI-ESM, are simply too coarse to capture this effect.

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2.4 MOVIECLIP

Project lead: Johann Jungclaus, Jürgen Bader, Daniela Matei, Wolfgang Müller (MPI-M)

MOVIECLIP aims at an assessment and improved representation of key oceanic and atmospheric processes in the MiKlip prediction system that are important for decadal predictability in the North Atlantic region and Europe. During the report period MOVIECLIP continued the analysis of the Atlantic Multidecadal Variability (AMV) in the MPI Grand Ensemble, conducted new experiments using an idealised AMV forcing, and worked on the contributions to the CMIP6 DCPP project.

Contributions of the ocean circulation to the Atlantic Multidecadal Variability in the MPI Grand Ensemble under changing external forcing

The aim of this work is to get a better understanding of the mechanisms that control North Atlantic large-scale temperature variations on decadal time scales. Particularly we address the question, whether ocean dynamics is involved in controlling the AMV or whether the AMV is a mainly atmospherically driven mode. The MPI Grand Ensemble consists of a 2000-year pre-industrial control run, a 100-member ensemble of historical simulations covering the time period from 1850 to 2005 and a 68-member ensemble of 155 year long runs with an idealised forcing with an incremental CO_2 increase by 1%/year.

We found strong statistical evidence that AMV has a regional component that is driven through ocean heat transport changes: The variability in the region east of Newfoundland substantially contributes to the AMV in observations, the pre-industrial control experiment and the historical ensemble. In contrast, the AMV imprint on this region is much weaker in the ensemble with strong CO_2 forcing Also, both, AMV and AMOC variability are strongly reduced in the ensemble with the forcing with an incremental CO2 increase by 1% per year. This might be partly explained by a reduced ability of the atmosphere to trigger convection variability in the Labrador Sea changes under strong CO_2 forcing (Hand et al., under review).

The Role of Ocean dynamics in shaping North Atlantic decadal to interdecadal variability in MPI-ESM1.2

Motivated by numerous studies drawing a link between the AMOC and long-term SST variability, idealised simulations are conducted, to determine the influence of ocean circulation on the climate system. A particular focus is put on interactions with dominant modes of atmospheric variability as the NAO, EA and Scandinavian pattern and the function of the response of the atmosphere to mediate the thermal signal within the North Atlantic region.

The conceptual idea of the experiments is to modulate the AMOC strength through adjustments of densities in the sinking regions on different timescales (20-120 years). Therefore a method of Delworth and Zeng (3), who implemented heat flux (HF) anomalies associated with the North Atlantic Oscillation (NAO), is applied. However, as this method hampers analysis of ocean-atmospheric feedback, the ocean circulation is driven internally by thermohaline restoring below 700m in the sub-polar ocean in another setup (THR). The AMOC is modulated sinusoidally in order to mimic decadal/multi-decadal variability. Any responses in the climate system that reflect the same temporal signature, for instance changes of sea ice extend or low frequency atmospheric circulation pattern, can thereafter explicitly be traced back to AMOC anomalies.

A hierarchy of model set-ups of the MPI-ESM1.2 LR is used. Both the heat-flux-forcing and the restoring methodology are applied to the fully coupled model. In addition, the density restoring methodology is implemented in a stand-alone ocean configuration and a slab-ocean atmospheric model with prescribed climatological ocean heat transport is included. The comparison of the ocean-only experiment, where SST is only affected by stochastic atmospheric forcing and AMOC related modulated ocean heat transport changes, with the fully coupled set-up, that includes atmospheric responses and feedbacks, allows to clearly segregating atmospheric and oceanic contributions (Master Thesis Julius Oelsmann).

Effects of model error in the North Atlantic on the atmosphere and corrections in the atmospheric model

Coupled global climate models such as e.g. the MPI-ESM show substantial errors in the simulated sea surface temperature in the extratropical North Atlantic (e.g., Jungclaus et al., 2013). Within the framework of a MSc thesis (Specht, 2018) we performed a series of sensitivity experiments with the associated atmospheric model component ECHAM6. The error in the North Atlantic sea surface temperature induces substantial changes in both latent and sensible heat flux. This has effects on precipitation and atmospheric circulation. Another result was that the atmospheric jet stream at the polar front migrated further south. This is related to a corresponding anomaly in the momentum convergence. To better understand the cause of this change, Rossby Wave breaking was analysed. A corresponding detection algorithm has been developed for cyclonic and anticyclonic Rossby wave breaking. The southward shift of the jet stream is caused by more frequent cyclonic wave breaking south of Greenland as well as less anticyclonic wave breaking in the Iberian peninsula. The more frequent cyclonic wave breaking provided the larger part of the change in the momentum convergence pattern (Specht and Bader, 2019).

In cooperation with the subproject ATMOS-MODINI, we conducted a pilot study on the implementation of a dynamic field correction (Drews and Greatbatch, 2016) in the ocean as part of a further MSc work (Steinert, 2017). Here, the correction was first implemented in the ocean model MPIOM and applied to both faulty areas in the North Atlantic and in the South Atlantic. While improvements were generally found in the corrected simulations, the work also pointed to further technical problems and limitations.

Causes and effects of long-term variations in the heat content of the North Atlantic

We investigated mechanisms of heat content changes, signal propagation and communication with the atmosphere. Future scenarios of global warming often show a zone of reduced warming or even cooling in the North Atlantic, which is also called "warming hole" (WH). While some authors (e.g, Rahmstorf et al., 2015) see the attenuation of AMOC as the main cause and propose to use a WH temperature index as an indicator of the state of AMOC, other studies see atmospheric processes as the cause (e.g., Ceppi et al., 2016). In a study (Keil et al., 2019), we investigated the climate change experiments with the MPI-ESM Grand Ensemble and additionally performed sensitivity studies with a model version without dynamically active ocean. We found that the convergence or divergence of oceanic heat transport actually provides the bulk of the "missing" heat in the area of the WH. On the other hand, it turned out that not only the fluctuations or the attenuation of the AMOC are involved, but also the heat transfer changes at high latitudes have to be considered. In addition, we found that the dependence of AMOC strength and WH temperatures changes during the course of the experiment, so that the WH index can only be regarded as a limited proxy for the AMOC variations.

As part of the work plan of WP 4.3, it was planned to evaluate coordinated experiments of the Coupled Model Inter-comparison Project (CMIP6) on decadal predictions. Delays in deploying the CMIP6 version of the MPI-ESM did not allow these Decadal Climate Projection Project (DCPP) simulations to be performed. Some of these will be created during the remaining term of MiKlip Module D in 2019. In a master thesis (Oelsmann, 2018) DCPP-like experiments with idealised AMV states could be performed and analysed. In this study, a novel technique for generating periodically fluctuating AMV abnormalities was developed.

Publications related to project 764

Hand, R., N.S. Keenlyside, N.-E. Omrani, J. Bader, and R. Greatbatch, 2018: The role of local sea surface temperature pattern changes in shaping climate change in the North Atlantic sector. Climate Dynamics, published online, doi:10.1007/s00382-018-4151-1.

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Müller, W. A., Jungclaus, J.H., Mauritsen, T., Baehr, J., Bittner, M., Budich, R., et al., 2018: A higher-resolution version of the Max Planck Institute Earth System Model (MPI-ESM1.2-HR). Journal of Advances in Modeling Earth Systems, 10, 1383–1413, doi:10.1029/2017MS001217.

Oelsmann, J., L. Borchert, J. Baehr, and J.H. Jungclaus: The role of ocean dynamics in shaping North Atlantic decadal to multidecadal. Manuscript in preparation.

MSc theses

Oelsmann, J., 2018: The role of ocean dynamics in shaping North Atlantic decadal to multidecadal variability in MPI-ESM1.2. MSc thesis, University of Hamburg, 69pp.

Specht, N., 2018: Effect of North Atlantic sea-surface temperature biases on the simulated atmospheric response in the extratropical Atlantic region: A model study. MSc Thesis, University of Augsburg.

Steinert, N., 2016: Application of a flow field correction method to the Atlantic Ocean in the MPI-ESM. MSc thesis, Free University Berlin, 49pp.

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Ceppi, P., et al., 2016: Observational evidence for a negative shortwave cloud feedback in middle to high latitudes. Geophys. Res. Lett., 43. 1331-1339.

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2.5 PROCUP

Project lead: Tatiana Ilyina (MPI-M)

The PROCUP aims to i) evaluate and improve the representation of the ocean biogeochemical processes in the MiKlip prediction system, ii) understand the multi-year variations of ocean carbon uptake in the context of the internal climate variability, iii) further investigate the predictability of the ocean carbon uptake and the underlying mechanisms in regarding to the governing physical, biological and chemical processes.

Evaluating and improving the representation of the ocean biogeochemical processes in the MiKlip prediction systems

The PROCUP was responsible for monitoring and evaluating representation of the ocean biogeochemical processes in the MiKlip simulations. In addition, the ocean biogeochemical processes need some decades to adjust to the new ocean physics due to assimilation. To eliminate the drift of ocean biogeochemical tracers in the beginning of the assimilation, we conducted pre-assimilation runs for the MPI-ESM-HR pre-operational prediction systems under CMIP5 and CMIP6 forcings, respectively. This pre-assimilation simulations were integrated for about 50 years with nudging atmosphere and ocean physical fields. The atmospheric CO2 concentration is fixed to the level in the beginning of the assimilation for the ocean biogeochemistry component HAMOCC. The dissolved inorganic carbon and the silicate concentration was reduced according to the observation magnitude. We provided the final restart files of HAMOCC from the pre-assimilation runs to Module D for the assimilation runs.

Understanding the current and future multi-year variations of ocean carbon uptake in the context of internal climate variability

Variability of the ocean carbon uptake in multi-year to decadal time-scale is largely regulated by the internal variability of the system. Understanding the internal variability of the ocean carbon uptake is very important for our decadal prediction study. We investigate the internal variability of the oceanic carbon flux in the context of the observed variations on decadal-scale using grand ensemble simulations based on the Max Planck Institute Earth System Model (MPI-ESM). We find that the internal variability plays an dominant role in modulating the decadal variations of ocean carbon uptake. MPI-ESM grand ensemble simulates negative and positive decadal trends of carbon uptake in the current and also the future ocean. The largest internal variability in the ocean carbon uptake is found in the Southern Ocean, the North Pacific, and the North Atlantic. Due to the large internal variability, it requires a large number of ensembles up to 79 to capture decadal forced (ensemble mean) signal of the ocean carbon uptake. Our manuscript based on this study has been published on Geophysical Research Letter.

Investigating the predictability of the ocean carbon uptake and the underlying mechanism

As previous decadal predictions focus on the physical states, and the North Atlantic was identified as the region with high predictive skill on temperature, Atlantic meridional ocean circulation, etc. The ocean carbon uptake is affected by the ocean physics. In this study, we first investigate the predictability of the ocean carbon uptake in the North Atlantic as a proof of concept. We find large multi-year variability in oceanic CO2 uptake and demonstrate that its potential predictive skill in the western subpolar gyre region is up to 4–7 years. The predictive skill is mainly maintained in winter and is attributed to the improved physical state of the ocean. These results have been published on Nature Communications.

We further extend our prediction study to the global scale. By assimilating atmosphere and ocean physical observations into the decadal prediction system based on the Max Planck Institute Earth System Model (MPI-ESM), we reproduce the ocean carbon uptake variations in consistent with the data-based estimates. The retrospective predictions starting from the assimilation states show a predictive skill of 2 years in the ocean carbon uptake globally. Regionally the predictive skill is up to 5 years in the Southern Ocean and the North Pacific. To understand the mechanisms in maintaining the predictability of the ocean carbon uptake, we separate the ocean surface pCO2, which is the main driver of the variability in carbon fluxes, into thermal and non-thermal components. We find that the thermal component contributes mainly to shorter-term (of <3 years) of predictive skill of the ocean carbon uptake, while the non-thermal component is responsible for longer-term (of >3 years) of predictive skill of the ocean carbon uptake. Our manuscript based on this work has been published on Science Advances.

Publications:

Li, H., T. Ilyina, W.A. Müller, F. Sienz, 2016: Decadal predictions of the North Atlantic CO2 uptake. Nature Communications, 7, 11076, doi: 10.1038/ncomms11076.

Li, H., and T. Ilyina, 2018: Current and future decadal trends in the oceanic carbon uptake are dominated by internal variability. Geophysical Research Letters, 45, 916-925, doi:10.1002/2017GL075370.

Li, H., T. Ilyina, W.A. Müller, P. Landschützer, 2019: Predicting the variable ocean carbon sink, Science Advances, 5: eaav6471. doi:10.1126/sciadv.aav6471.

3. Module C – Regionalisation of Decadal Predictions

Project: **bb0849**

Project title: **MiKlip II Module C – Regionalisation of Decadal Predictions**

Project leader: **Hendrik Feldmann**

Allocation period: **01.01.2016 – 31.12.2019**

3.1 Project overview

MiKlip II module C works on the downscaling of global climate predictions with the regional climate model COSMO-CLM (CCLM). The project aims are to improve the regional prediction system and to provide reliable information about regional decadal predictability for Europe.

The efforts of Module C are an essential contribution to the development of an operational decadal prediction system within in the BMBF funded program MiKlip II. All regionalisation efforts of the research program are bundled within this DKRZ project bb0849.

MiKlip II module C is organised in eight work packages (Cx-WPy), with four WPs requiring considerable computing time at DKRZ, where the other four use these data for analysis and post-processing. The project has currently 19 members of whom 11 participants use the major part of the resources.

Participating institutions are: KIT Karlsruhe, DWD, Goethe University Frankfurt (GUF), University of Cologne and the University of Würzburg

3.2 Main work objectives

The computational work performed within this project at DKRZ in 2019 can be grouped into four main topics

1. **Ensemble generation (C3-WP3)**: The generation of the core regional decadal ensemble including decadal climate forecasts for the next 10 years using COSMO-CLM. This topic includes also development steps towards an operational use of the prediction system.

2. **Regionally coupled European marginal seas (C1-WP1, C2-WP3)**: Development, testing and application of a regional coupled ocean/atmosphere prediction system using COSMO-CLM and NEMO

3.2.1 Objective 1: Ensemble Generation (WP: C3-WP3)

Contributors: Hans-Jürgen Panitz (KIT), Sascha Brand (DWD), Hendrik Feldmann (KIT)

Main WP Goals

Module C of MiKlip II works on further improving the regional component for the operational use of MiKlip decadal prediction system using the Regional Climate Model (RCM) COSMO-CLM (CCLM), which is the climate version of the operational weather forecast model of the German weather service (DWD), with a regional focus on (Central) Europe. The model domain for the regional decadal simulations of MiKlip II coincides with the domain chosen in MiKlip I, respectively in the frame of EURO-CORDEX. The horizontal grid-spacing has been fixed to 0.22° (≈25 km, 232x226x40 grid boxes).

The central task of this work-package is to produce an ensemble of regional decadal hindcast simulations using dynamical down-scaling with CCLM for the full MiKlip hindcast period from 1960 until the current year. This means about 5700 simulation years for a full hindcast set. Such a large ensemble is necessary to assess the skill of decadal predictions.

In total MiKlip II Module C know provides a large regional ensemble with more than 15.000 simulation years with a consistent setup of CCLM, which will be used in a follow-up projects like the BMBF research program ClimXtreme ("Klimawandel und Extremereignisse", extreme events and climate change).

Several publications using this regional ensemble for Europe have recently been published or submitted. Some highlights are listed below.

- Feldmann et al. (2019) provide the first full assessment of the skill and added value of regional decadal temperature predictions for Europe. Figure 3.1 indicates a shift of the skill scores towards higher levels from un-initialised "historical" simulations (green), over initialised global MPI-ESM hindcasts (red) towards a CCLM downscaling of the global hindcasts (blue) showing and added value of initialisation as well as downscaling.

- Reyers et al. (2019) investigate the characteristics of two different generations of downscaling ensembles with respect to skill and ensemble size dependence for temperature, precipitation and wind.
- Moemken et al. (2019) analyse the potential of regional decadal predictions of various climate indicators for user-relevant applications. Figure 3.2 shows the skill for potential applications related to agricultural climate indicators.
- Breil, Schädler and Laube (2018) developed a new depth-dependent saturated soil hydraulic conductivity function and implemented it in the Regional Climate Model COSMO-CLM coupled to the Land Surface Model VEG3D (CCLM-VEG3D), to improve the physical description of soils in regional climate simulations. Figure 3 shows impact and improvement of this new formulation.

Further publications, which arose from the MiKlip II Module C project are listed at the end of this report.

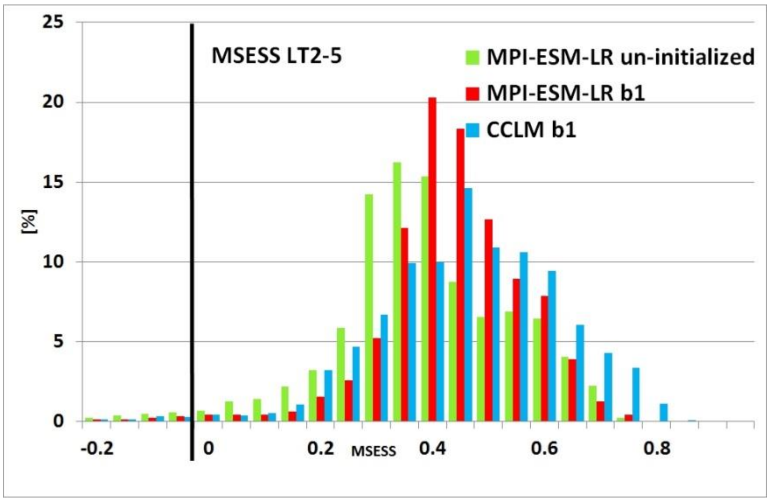

Figure 3.1*: MSESS Skill distribution over Europe for lead-time years 2-5 for CCLM b1 (blue) and MPI-ESM-LR b1 (red) and MPI un-initialised (green), from Feldmann et al. (2019).*

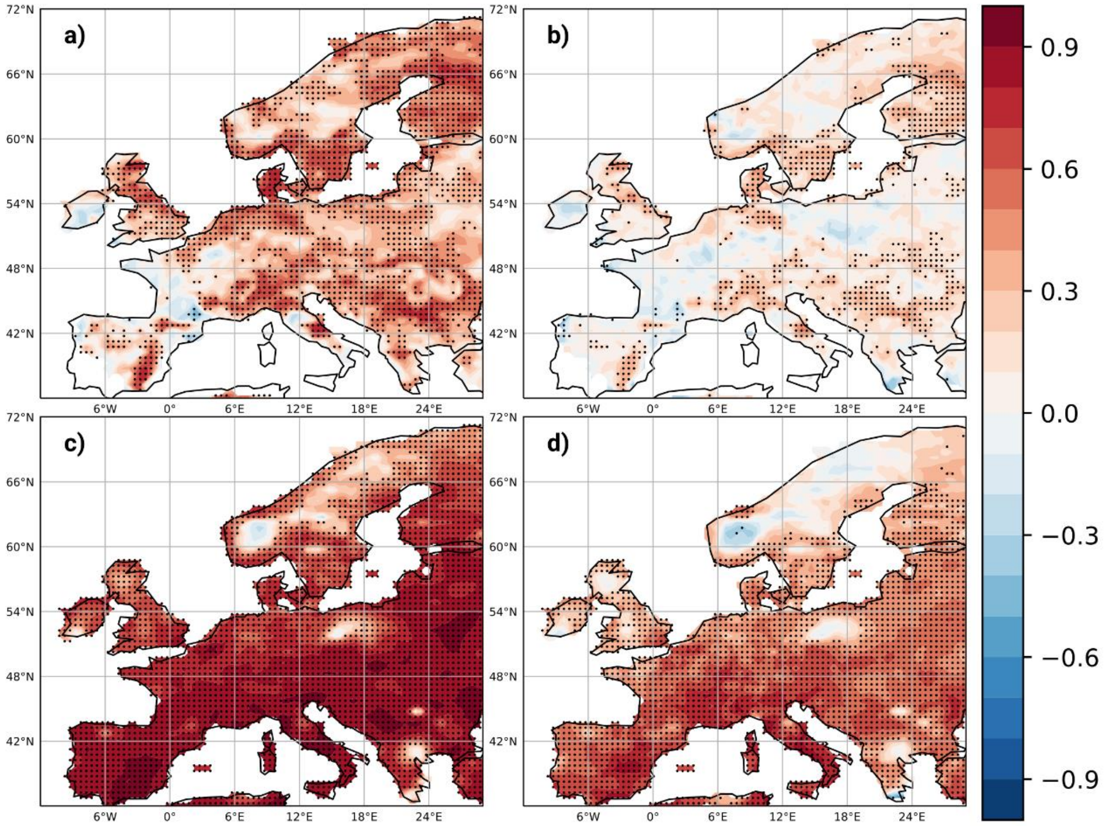

Figure 3.2: *Spatial distribution of anomaly correlation (first column) and RPSS (second column) for lead year 2-5 for growing season length (GSL; a, b) and growing degree days (GDD; c, d) for the MiKlip regional decadal hindcasts. Reference is the climatology. Black dots indicate significant skill at the 95% level – from Moemken et al. (2019).*

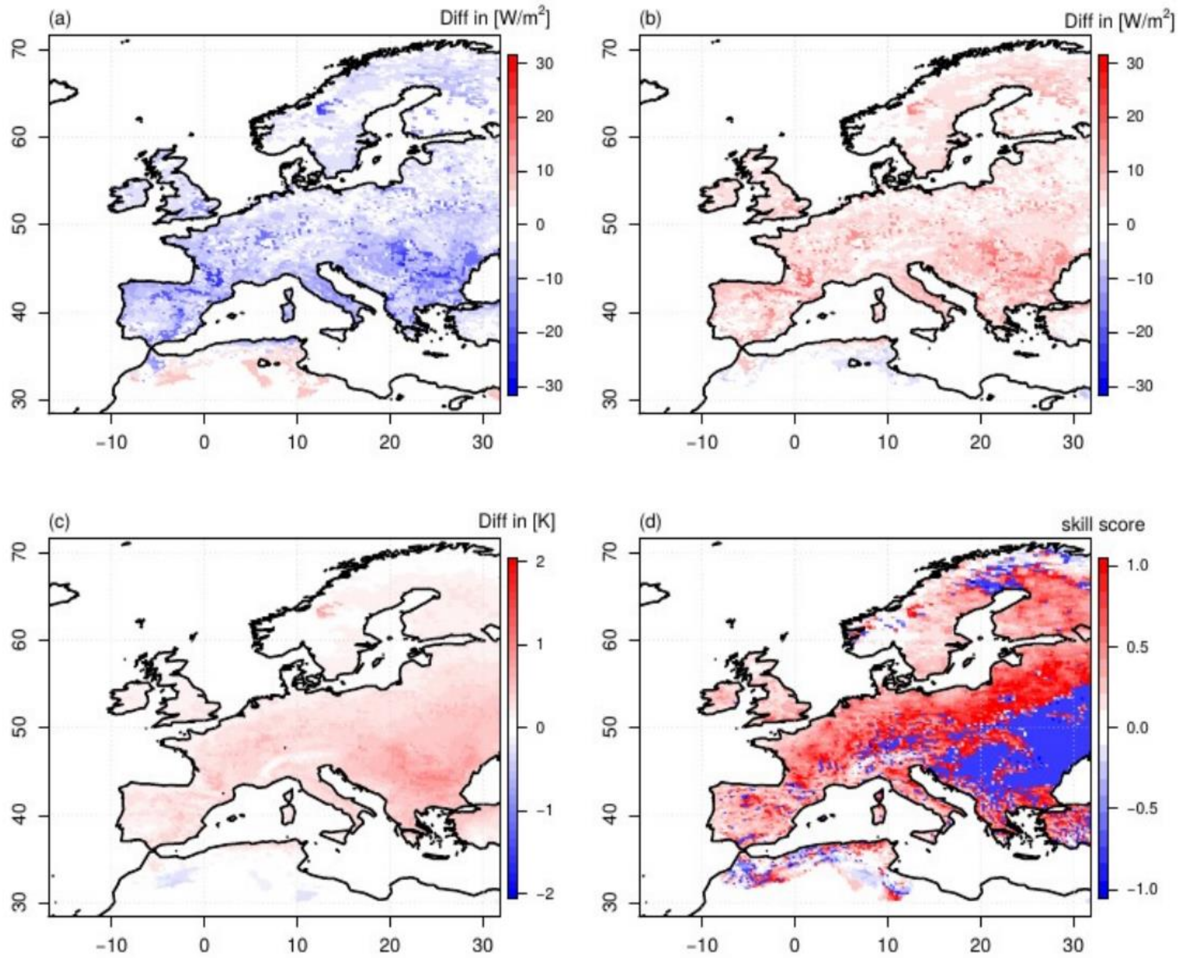

Figure 3.3: *Differences of the annual mean latent heat flux (a), sensible heat flux (b), 2m temperature (c) between simulations with an improved description of the soil-hydrologic conductivity and reference simulations. The added value of the new parametrisation is also shown by a positive mean square error skill score (MSESS, red colours) in (d) - from Breil, Schädler and Laube (2018).*

In 2018 the MiKlip decadal forecast web page (http://www.fona-miklip.de/decadal-forecast/decadal-forecast-for-2018-2027/) included the regional forecasts performed with CCLM (Figure 3.4). These forecasts will also be performed for the year 2019.

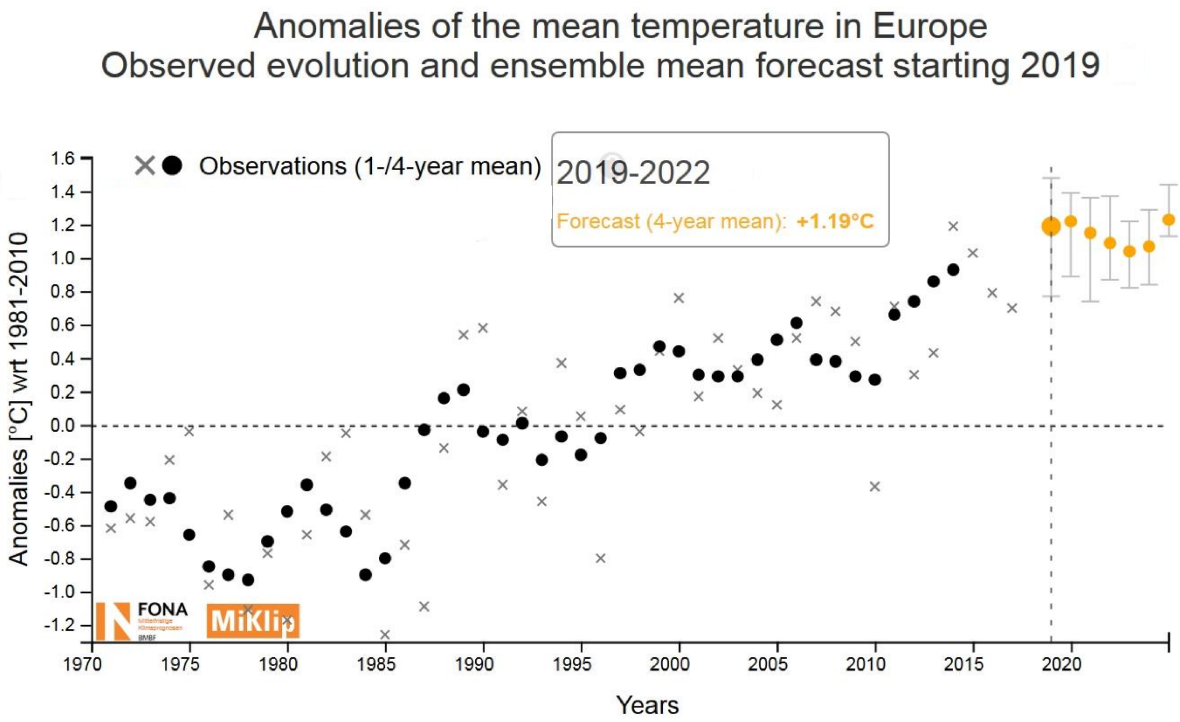

Figure 3.4: *Regional decadal forecasts with CCLM for the period 2019 – 2028 (from: https://www.fona-miklip.de/decadal-forecast/decadal-forecast-for-2019-2028/)*

3.2.2. Objective: Regionally coupled European marginal seas **(WPs: C1-WP1, C2-WP3-GUF)**

Contributors: Fanni Kelemen, Anika Obermann, Nora Leps, Bodo Ahrens (GUF)

Coupled 20th century simulations with CCLM and coupled European marginal seas have been performed and analyses in 2019. Within these experiments, CCLM has been coupled to the Mediterranean (NEMO-Med) as well as for the Nordic/Baltic Sea (NEMO-Baltic). CCLM itself uses the same grid and resolution as for the MiKlip Module C standard hindcasts with 232 x 226 x 40 grid points (lat x lon x vertical levels). The NEMO-Med domain uses 567 x 264 x 75 grid points and 619 x 523 x 56 grid points for NEMO-Baltic. Sensitivity studies have been performed with respect to the effects of sea-surface temperature (SST) changes.

Two publications arose from these efforts in 2019:

Added Value of Atmosphere-Ocean Coupling in a Century-Long Regional Climate Simulation (Kelemen et al., MDPI Atmosphere, 2019)

The 20th century long coupled atmosphere-ocean regional climate simulation with CCLM and NEMO is studied here to evaluate the added value of the coupled seas over the continental regions. The interactive coupling of the marginal seas, namely the Mediterranean, the North and the Baltic Seas to the atmosphere in the European region gives a complete modelling system. It is expected to be able to describe the climatological features of this geographically complex area even more precisely than an atmosphere-land climate model. The investigated variables are precipitation and 2m temperature.

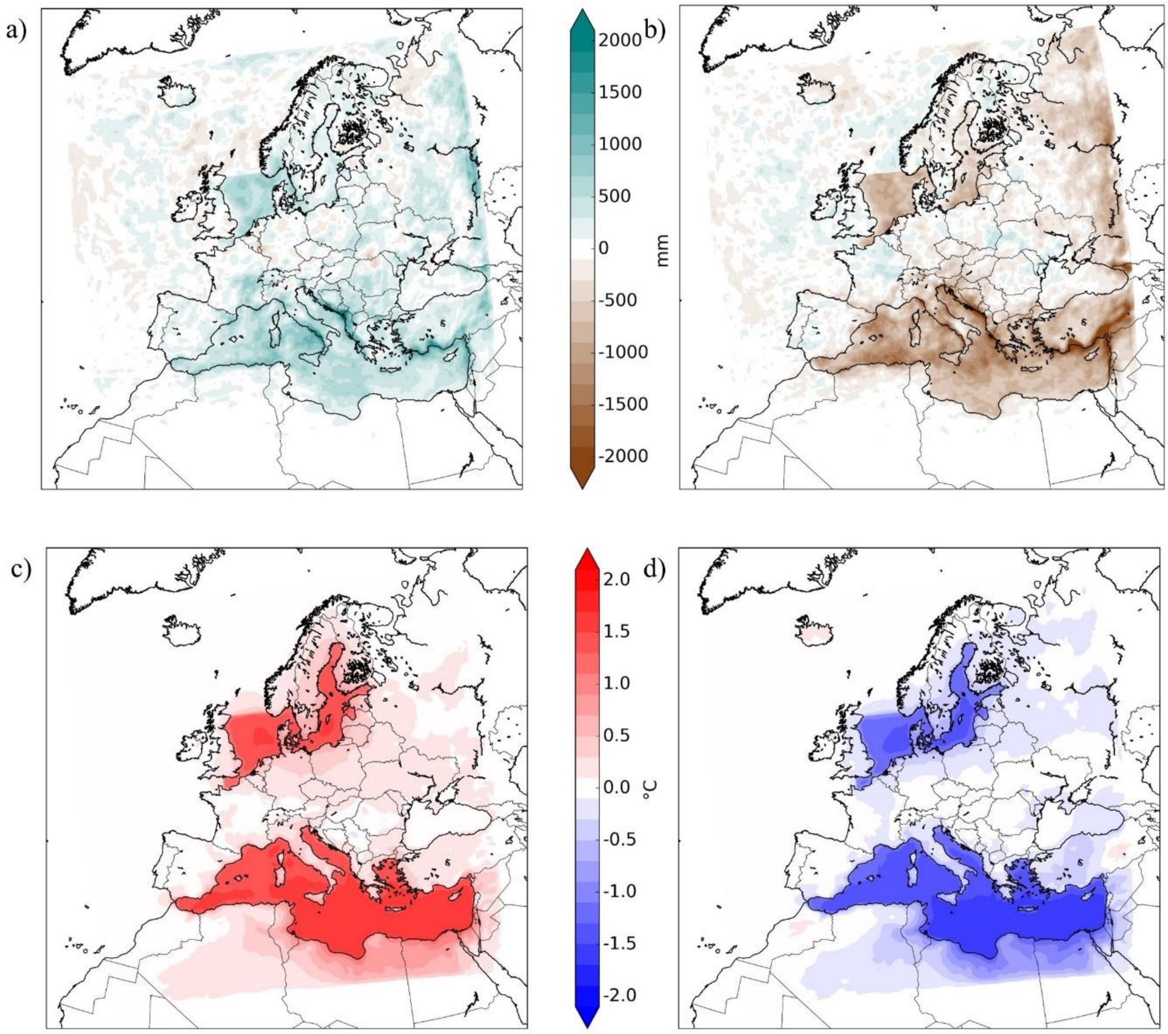

Figure 3.5: *Difference between the SST_0 and the SST-2 (left column, a,c) or the SST+2 (right column, b,d) simulations. The first row (a,b) shows the difference of the precipitation sums during the whole time period (2000-2003) and the second row (c,d) shows the differences in 2m temperature mean.*

Sensitivity studies are used to assess the impact of SST changes over land areas (Figure 3.5). The SSTs have been increased by 1 K (SST+1) and 2 K (SST+2) and lowered by 1 K (SST-1) and 2 K (SST-2) compared to the unchanged basic status (SST_0). The different SST values affect the continental precipitation more than the 2m temperature. The simulated variables are compared to the CRU observational data, and also to the HOAPS/GPCC data.

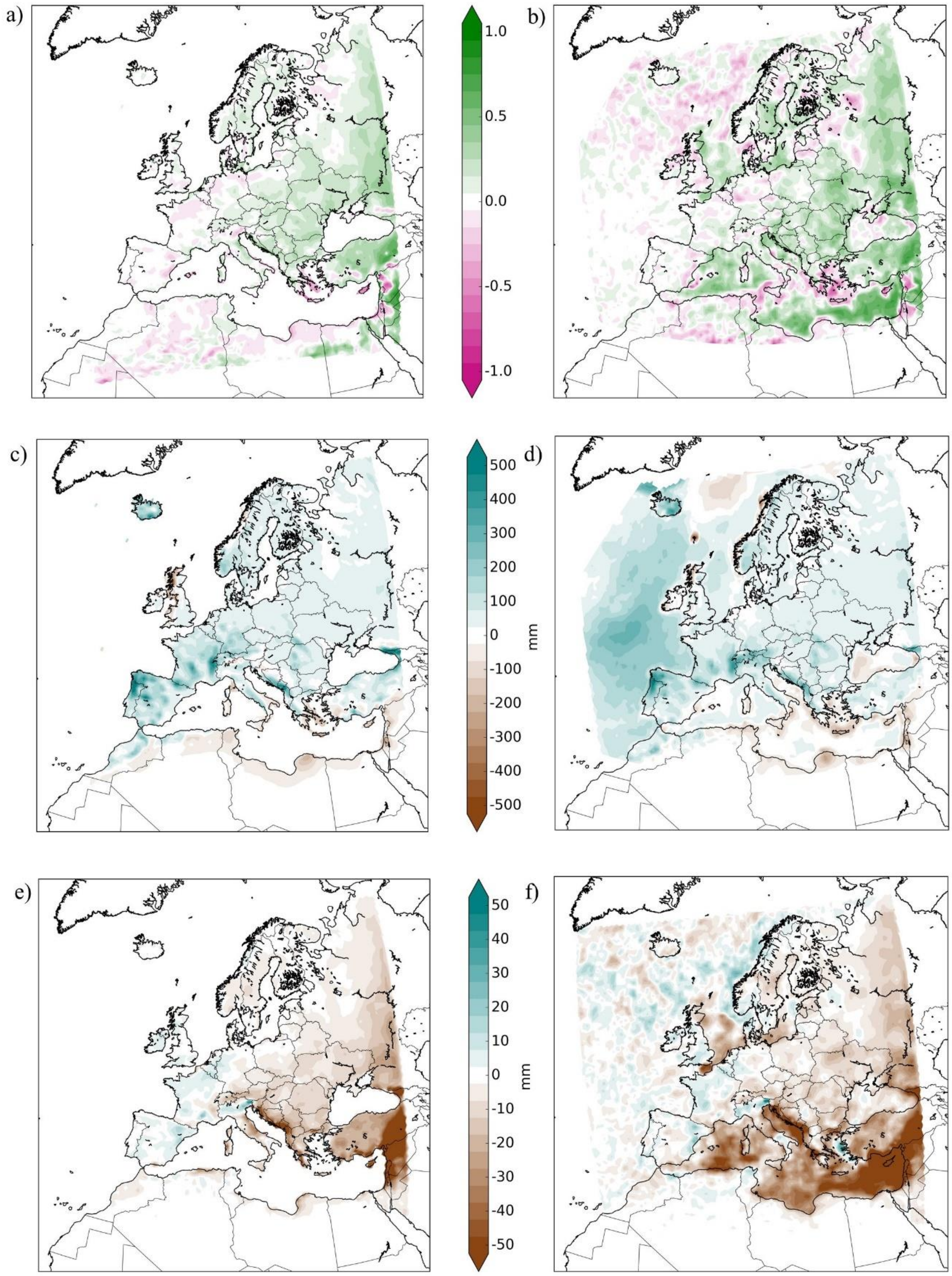

Figure 3.6: Mean winter precipitation sum: a) MSESS values comparing the coupled system to the uncoupled with respect to CRU (1901-2009) and b) with respect to HOAPS/GPCC (1988-2008), c) bias of the coupled system with respect to CRU and d)

HOAPS/GPCC, e) difference between the coupled and the uncoupled system for the time period 1901-2009 and for f) 1988-2008.

In the coupled simulation, added skill is found primarily during winter over the eastern part of Europe (Figure 3.6). Our analysis shows, that over this region the coupled system is dryer than the uncoupled system, both in terms of precipitation and soil moisture, which means a decrease in the bias of the system. Thus, the coupling improves the simulation of precipitation over the eastern part of Europe, due to cooler SST values and in consequence, drier soil.

A regional atmosphere-ocean climate system model (CCLMv5.0clm7-NEMOv3.3-NEMOv3.6) over Europe including three marginal seas: on its stability and performance (Primo et al., GMDD, 2019)

The frequency of extreme events has changed, having a direct impact on human lives. Regional climate models help us to predict these regional climate changes. This work presents an atmosphere-ocean coupled regional climate system model (RCSM, with the atmospheric component CCLM, and the ocean component NEMO) over the European domain, including three marginal seas: the Mediterranean, the North and the Baltic Seas. To test the model, we evaluate a simulation of more than one hundred years (1900-2009) with a spatial grid resolution of about 25km. The simulation was nested into a coupled global simulation with the model MPI-ESM in a low-resolution configuration, whose ocean temperature and salinity were nudged to an MPI-ESM-LR ocean-ice component forced with the 20th Century Reanalysis (20CR). The evaluation shows the robustness of the RCSM and discusses the added value by the coupled marginal seas over an atmosphere-only simulation.

The coupled system runs stable for the complete 20th century and provides a better representation of extreme temperatures compared to the atmosphere-only model (Fig 3.7). The produced long-term dataset will allow an improved study of extreme events, helping us to better understand the processes leading to meteorological and climate extremes and their prediction.

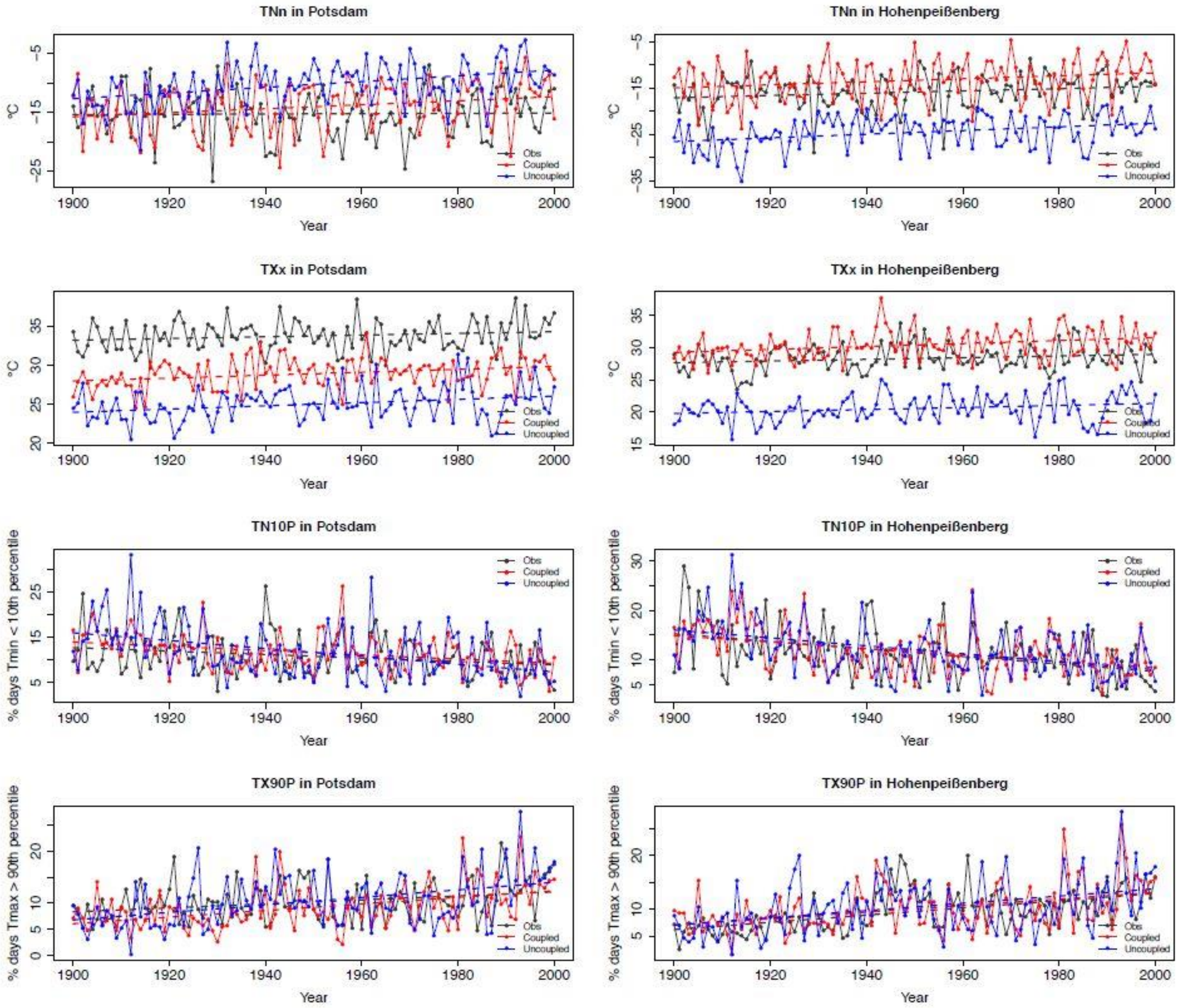

Figure 3.7: *Temporal evolution of four climate change indices in two stations of Germany, Potsdam (81m) and Hohenpeißenberg (977m). TNn represents the annual minimum value of daily minimum temperature; TXx, the annual 5 maximum value of daily maximum temperature; TX90p, the percentage of days when the maximum temperature is above the calendar day 90th percentile centred on a 5-day window for the base period 1961-1990. TN10p, the percentage of days when the minimum temperature is below the calendar day 10th percentile centred on a 5-day window for the base period 1961-1990. Linear trends are shown as dashed lines.*

3.3 Project publication with DKRZ acknowledgements

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Leps, N., J. Brauch, B. Ahrens (2019). Sensitivity of Limited Area Atmospheric Simulations to Lateral Boundary Conditions in Idealized Experiments. Journal of Advances in Modeling Earth Systems, 11. https:// doi.org/10.1029/2019MS001625

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Marotzke J. W. A. Müller, F.S.E. Vamborg, P. Becker, U. Cubasch, H. Feldmann, F. Kaspar, Ch. Kottmeier, C. Marini, I. Polkova, K. Prömmel, H.W. Rust, D. Stammer, U. Ulbrich, C. Kadow, A. Köhl, J. Kröger, T. Kruschke, J.G. Pinto, H. Pohlmann, M. Reyers, M. Schröder, F. Sienz, C. Timmreck, and M. Ziese (2016): MiKlip - a National Research Project on Decadal Climate Prediction. Bull. Amer. Meteor. Soc., 97, 2379–2394.

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4. Module D – Synthesis

Project: **bm0807**

Project title: **MiKlip II Module D – Synthesis**

Old title during MiKlip first phase (**A flexible forecast system for decadal climate predictions - FLEXFORDEC)**

Project lead: **Jochem Marotzke**

Reporting period: **01.01.2016 – 31.12.2019**

4.1 Project overview

Module D was responsible for the development of the global decadal climate prediction system and the accompanying central evaluation system, the transfer of the prediction system to DWD, and the setting up of pilot studies for the application of decadal climate predictions by government agencies and by the private sector. The project consortium consisted of 4 project partners: Max-Planck-Institute for Meteorology (MPI-M), Freie Universität Berlin (FUB), Deutscher Wetterdienst (DWD) and Climate Service Centre (GERICS).

Strategically, MPI-M led the coordination of MiKlip II and Module D, with the overall project led by J. Marotzke, the scientific and technical implementation led by W. Müller, and the MiKlip Office led by S. Hettrich. MPI-M took the lead in the development of the global climate prediction system and supported the transfer of the global model to operational use (**FLEXFORDEC**). FUB took the lead in the development of the central evaluation system (**INTEGRATION**), hosted on the MiKlip Server. FUB also supported DWD in the transfer of the evaluation system for operational use of global decadal climate predictions. DWD implemented both the global prediction and the central evaluation system on their local machines for operational use (**OPERATIONS**). Moreover, DWD provided a pilot study for the use of decadal climate predictions for government agencies (**SUPPORT**) and GERICS provided a pilot study for the use of decadal climate predictions for the private sector (**IPRODUCTS**). Requested allocation time has been applied by MPI-M and FUB only. Therefor this report focuses on achievements of **FLECFORDEC** and **INTEGRATION.**

In addition to the MiKlip II project objectives, **FLEXFORDEC** also coordinated the MPI-M contribution to the CMIP6 decadal climate predictions (organised by the WCRP Decadal Climate Prediction Project (DCPP) with W. Müller as co-chair, Boer et al. 2016) and took the responsibility for providing the CMIP6 DECK experiments for the high-resolution version of the MPI-ESM (MPI-ESM-HR, Müller et al., 2018). MiKlip was also partner of the WCRP Grand Challenge on Near Term Climate prediction (with W. Müller as a member, Kushnir et al., 2019).

During MiKlip II, Module D developed and provided the decadal climate prediction and evaluation systems of MiKlip II. As such the project was responsible for providing all project partners with the newest central simulations of the prediction system. For the two development stages in MiKlip II, Module D provided two set of hindcast (“pre_op” and “op”). The “pre-op” system is based on a higher-resolution version of the Max-Planck-Institute Earth System Model (MPI-ESM-HR, Müller et al., 2018). Module D project has taken on the responsibility for setting up the MPI-ESM-HR and the provision of hindcast and DECK experiments to the Earth System Grid Framework (ESGF) of CMIP6. The “op” system is based on recommendation of the MiKlip II project partners during DS4 and offers changes in the assimilation architecture of the prediction system.

Module D further launched a MiKlip webpage to publish latest decadal climate forecasts. Forecasts are published every year since 2017, and show global and regional surface temperatures for deterministic and probabilistic predictions (Kadow et al., 2019) with a 10-year outlook. The webpage provides a proof-of-concept for the transfer of decadal climate predictions to the operational workflow of the DWD.

4.2 Achievements

The "pre-op" system

For the fourth development stage of MiKlip (DS4, "pre-op") a higher resolution model configuration of MPI-ESM than those during the first phase of MiKlip (DS1-DS3) was envisaged, with a resolution of ECHAM6 of T127L95 and MPIOM resolution of TP04L40. This so called MPI-ESM-HR setup is based on the latest version of MPI-ESM-1.1 and was developed and tuned during the reporting period. The model was already implemented in the DKRZ HPC infrastructure Mistral. MPI-ESM-HR is well tuned and a description of the model, its tuning and results is found in Müller et al. (2018). Climate sensitivity is ~3K and similar to MPI-ESM-LR. The atmospheric global mean surface temperature exhibits no drift and stays on the target value of 13.8°C. The drift of global mean ocean temperature and salinity exhibits only little magnitudes and are comparable to earlier version of MPI-ESM-LR. The Atlantic meridional overturning at 26°N has a value of 16SV on time-average and is comparable to observational estimates. This shows that the coupled model is in a stable state. For CMIP6 major changes included the use of MAC-v2-SP for the anthropogenic tropospheric aerosols, ozone data, volcanic aerosols, solar irradiation and new land-use data (LUH2).

At first **FLEXFORDEC** has performed DECK simulations with CMIP5 forcing. This setup rose from the fact that CMIP6 forcing only has become available in 2017. In 2017 the CMIP6 forcing was available and, in association with the MPI-M contribution to CMIP6, the DECK experiments were repeated with the CMIP6 forcing. An extended spin-up of the control run was necessary in order to tune the sea-ice properties of the model and additionally to reach an acceptable equilibrium in the sedimentation rate of the HAMOCC component. This run was followed by the CMIP6 DECK experiments (control run, 1% CO2 increase, abrupt 4 x CO2 and 5 historical runs) for MPI-ESM-HR. These simulations are successfully completed. The ensemble size was increased to 10 historical runs.

As a first step to get the starting fields for the decadal hindcast simulations, an assimilation run was performed. The assimilation run is based on the nudging procedure as applied in the previous development stages. While nudging in the atmosphere has been rather unproblematic, nudging in the ocean, induces changes in both ocean heat content and ocean transport when compared to the corresponding unconstrained historical experiment, and as such posed an in-depth analysis of the nudging procedure (e.g. full-field and anomaly nudging). As opposed to the resulting evolution of the ocean heat content, induced changes in ocean transport differ severely between the nudging procedures indicating that the resulting transports are of spurious nature. In addition, ocean transports differ also remarkably when applying full-fields of different ocean state estimates. The spurious transport signals continue to be present in the free running hindcasts, a clear expression of memory in our coupled system. In forecast mode, on annual to inter-annual scales, ocean heat transport appears to be the dominant driver of North Atlantic heat content. Thus, in this region, the spurious transport inherited from the assimilation leads to an initialisation shock followed by a significantly reduced prediction skill of ocean heat content when using full-field instead of anomaly initialisation (Kröger et al., 2017). Therefore, we use anomaly initialisation in the ocean for the "pre-op" decadal prediction system.

For the atmosphere, temperature, vorticity, divergence and pressure data were nudged towards data from ERA40/ERAinterim. It was decided not to use the new ORA-S5 ocean reanalysis since problems were discovered, especially in the North Atlantic with this data set. Instead, the ORAS4 ocean reanalysis was used for nudging ocean temperature and salinity anomalies. As in the system with CMIP5 forcing sea ice concentration data from NSIDC is used together with a statistical relation between sea-ice concentration and sea-ice thickness. Starting from the initial conditions of the assimilation run decadal hindcast simulations with CMIP6 forcing are run with yearly initialisation during the period 1960-today. In total 10 ensemble members of the decadal hindcast simulations were run, 5 by MPI-M on the DKRZ computing architecture and 5 members by DWD on DWD computing architecture. So far 5 members of MPI-M have been CMORised and uploaded to ESGF.

The "pre-op" hindcasts are currently evaluated. Three noteworthy results, however, indicate the benefit of the "op" system: (i) The realistic quasi-biennial oscillation variability in historical and decadal hindcast simulations using CMIP6 forcing (Pohlmann et al., 2019), (ii) the decadal predictions of the warm summer temperature extremes (Borchert et al., 2019) and (iii) the decadal climate prediction skill of the northern hemisphere extra-tropical winter circulation through increased model resolution (Schuster et al., 2019).

Pohlmann et al. (2019) analyse the quasi-biennial oscillation (QBO) variability of historical and decadal hindcast simulations of "pre-op" and find a realistic variability of the QBO in historical simulations when changing from the CMIP5 to the CMIP6 external forcing. This agreement between the simulated and the observed QBO is improved by the initialisation of decadal hindcast simulations with CMIP6 forcing in the first 3 lead years. In the decadal hindcast simulations, the agreement is similar to a persistence forecast in the first 5 lead years and higher than the persistence forecast in the later lead years. They find a strong relation between the QBO and the ozone variability in the stratosphere and conclude that the change of the ozone data from CMIP5 to CMIP6 leads to the improved QBO variability and prediction skill in our simulations. This is the reference paper for the “pre-op” CMIP6 hindcast experiments

Borchert et al. (2019) show that predicting the probability for an extremely warm summer to occur in the next 10 years in several regions on the Northern Hemisphere is possible (figure 4.1). This originates from a physical connection of the occurrence of extreme summer temperature in the examined regions to predictable North Atlantic sea surface temperature. In the assimilation run with MPI-ESM-HR a robust response of summer temperature extremes in Northern Europe and North-East Asia to North Atlantic sea surface temperature via a circumglobal wave-like disturbances is found. When the North Atlantic is warm, warm summer temperature extremes occur with a probability of 20% and 24% in Northern Europe and North-East Asia, respectively. In a cold North Atlantic phase, these probabilities are 0% and 8%. A similar difference in probability of occurrence is found in the initialised climate predictions. Consequently, the likelihood of a warm summer temperature extreme occurring in the examined regions in the next 10 years can be inferred from predictions of North Atlantic SPG temperature.

Schuster et al. (2019) analyse the effect of different horizontal and vertical resolutions on the prediction skill of the northern hemisphere extra-tropical storm-tracks and blocking, cyclone and windstorm frequencies. Storm-tracks are significantly improved in MPI-ESM-HR primarily over the main source region of synoptic activity – the North Atlantic Current., Other extra-tropical measures also experience a significant improvement downstream thereof. The skill of the cyclone frequencies is significantly improved over the central North Atlantic and Northern Europe. Not only is the skill improved with the increase in resolution, but the “pre-op” system itself exhibits significant skill over large areas of the North Atlantic and European sector for all considered circulation metrics. These results are particularly promising regarding the high socio-economic impact of European winter windstorms and blocking situations.

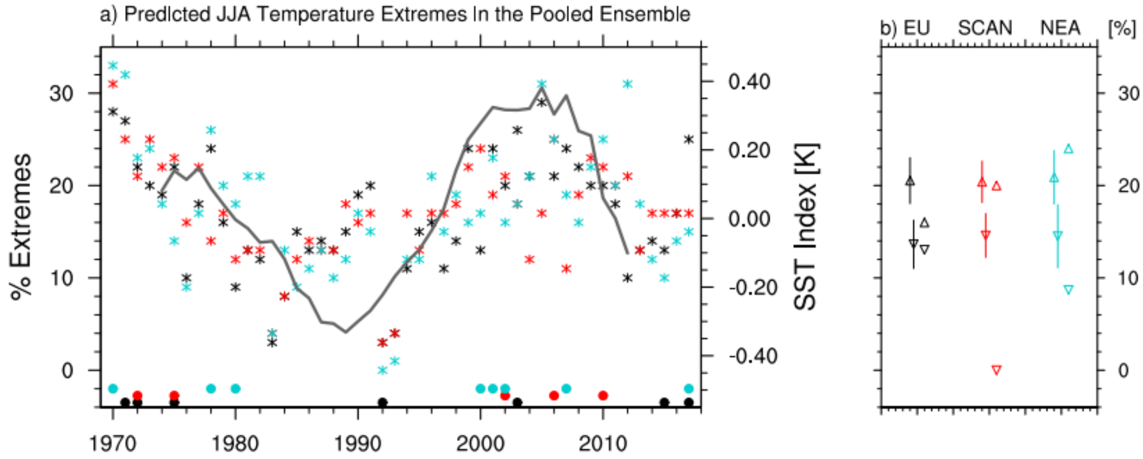

Figure 4.1*: (a) Probability of occurrence for summer SAT extremes in the Europe (EU, black), Scandinavia (SCAN red), and North-East Asia (NEA, cyan). Dots at the bottom show the occurrence of a summer SAT extreme in the respective region in the assimilation run. Asterisks indicate hindcast realisations that produce a warm summer SAT extreme in any given year. The grey line shows the 10-year running mean sub-polar gyre SST index from the assimilation run. (b) Probabilities of occurrence for summer SAT extremes in hindcast (triangles with uncertainty bar) and assimilation run (triangle without uncertainty bar) in different regions. Probabilities of occurrence are shown for warm (upward pointing triangles) and cold (downward point triangles) SPG phases. From Borchert et al. (2019)*

The "op" system

For the fifth development stage several initialisation strategies have been carried out by the Modul A project partners (see report 2018) and Module D. Module D has been engaged in two strategies: The Ensemble Kalman Filter approach (led by Module A AODA-PENG, Brune et al., 2018) and the Ensemble Dispersion Filter (INTEGRATION, Kadow et al., 2017)

The Ensemble Kalman Filter (EnKF) for MPIOM (MPI-ESM 1.0) has already been successfully implemented (Brune et al. 2015) in its global variant using the Parallel Data Assimilation Framework (PDAF) in MiKlip phase I. In MiKlip phase II an initialisation and simulation of hindcasts based on the improved weakly coupled assimilation system with PDAF/EnKF has been performed with the low configuration of MPI-ESM-LR. The weakly coupled ENKF outperforms the baseline 1 initialisation (nudging procedure) in many regions (Brune et al., 2018, figure 4.2).

INTEGRATION investigates a new re-initialisation method called ensemble dispersion filter (EDF). Here, individual members of the hindcasts are rescaled to the ocean state of the ensemble mean (details in Kadow et al. 2017). In 2017 the EDF was adapted to the MPI-ESM1.2, taking part in an assessment of new methods for MiKlip organised for MiKlip-Module A. With the new model system, 10 members, in the longer time frame 1960-2016 the EDF still boosts the prediction skill of its reference system up to 5 years ahead. The skill scores indicate an improvements in the climate-relevant regions of the Central and North Pacific, and the North Atlantic for 2m temperature. Other climate diagnostics like ocean heat content support these results. Due to the long assembling time to get the EDF within the new MPI-ESM1.2, more node hours were necessary to test the system for the MiKlip Module A assessment, which only requested up to 5 lead years. The longer runs up to 10 years are postponed. However, as the main boost-effects happen in the later lead years (4 and 5), probably the improvements are even stronger in the later stages (LY6-10).

In 2017, the MiKlip steering committee, recommended to test the ENKF for the decadal climate prediction system ("op"). ENKF can be seen as a "model-consistent" method as it generates the initial conditions in the model's climatology. This is different to the ocean reanalyses used so far, which have been developed on different ocean models. Moreover, the utilisation of ENKF in MPI-ESM makes the prediction system independent from other ocean re-analyses, for example ORA for which there has been difficulties in the transition from S4 to S5. FLEXFORDEC and Module A - AODA-PENG developed a set of hindcast with MPI-ESM-HR and compared the results to the lower-resolving configuration MPI-ESM-LR. The results show however, that using ENKF in the assimilation with MPI-ESM-HR requires more testing. An example is the Atlantic overturning circulation which is much too strong (~25Sv) in the ENKF MPI-ESM-HR setup.

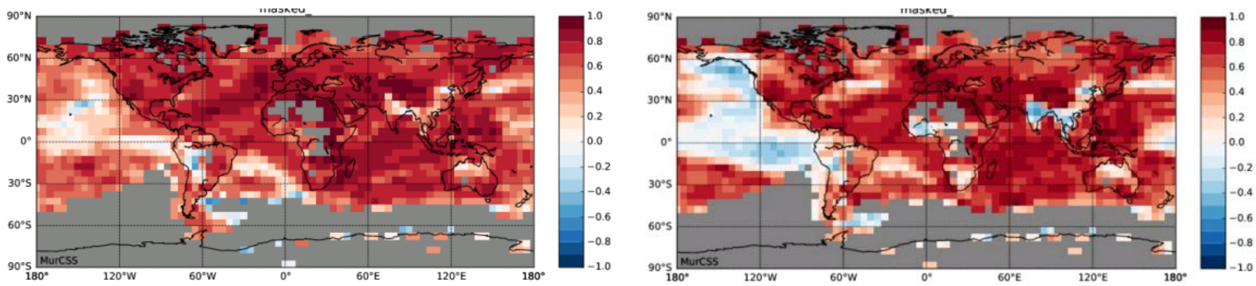

Figure 4.2: Anomaly correlation for year 2-5 of predicted surface temperature of (left) *MPI-ESM-LR with ENKF and (right) MPI-ESM-LR „pre-op". The reference is HadCRUT4. Here the period 1960-2007 is considered.*

The Forecast Webpage and Transfer to DWD

At the beginning of the reporting period, a webpage to publish decadal climate forecasts and MiKlip II project information has been designed (www.fona-MiKlip.de). The webpage is in English and German, and provides the description of the overall MiKlip project and a general description of how-to interpret a decadal climate prediction. Since 2016 regular decadal climate forecasts are published. Forecasts are based on the central global and regional climate prediction systems, and show surface temperatures for deterministic and probabilistic forecast for a 10-year horizon. The forecast webpage further contains an evaluation system with a traffic light system to interpret forecasts with respect to the reference forecasts, either climatology or historical runs or both. Further forecasts are post-processed by a calibration method developed in Module E.

The web page is a proof-of-concept of the decadal climate prediction and evaluation system and is being transferred to DWD for operational use. For this MPI-ESM has compiled at DWD computing infrastructure and assimilation and production of hindcast have been performed. Further the evaluation system developed by FUB (FREVA) has been documented and implemented into the DWD evaluation system for climate prediction (MAVIS).

4.3 Data Lifecycle

Central aim of MiKlip II is the long-term storage of the project data. For Module D this encompasses the experiments of all development stages namely: baseline 0, baseline 1, prototype, pre-op, op. “Pre-op” is identical to the CMIP6 data and the CMOR data are/will be published on ESGF. CMOR data of all other experiments will be published on CERA. For this MiKlIP II provides the tapes of the MiKlip archive. The raw data of the experiments will further be stored in the MiKLip archive. It is further agreed that the MiKlip Server will be transferred to the BMBF funded project ClimXtreme. The funding to maintain the MiKlip Server is already proposed (contact W. A. Müller – MPI-M, H. Thiemann – DKRZ) and confirmed by BMBF/DLR.

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5. Module E – Evaluation of the MiKlip Decadal Prediction System

Project: **bb0763**

Project title: **MiKlip II Module E – Evaluation of the MiKlip Decadal Prediction System**

Project lead: **Marc Schröder**

Reporting period: **01.01.2016 – 31.12.2019**

5.1 Description of work and summary of results

The PROVESIMAC project focuses on the evaluation of the decadal climate prediction system developed within the second phase of MiKlip (http://www.fona-miklip.de/) utilising satellite data. Satellite simulators for usage with MPI-ESM are developed for the Special Sensor Microwave Imager (SSM/I) and for the Special Sensor Microwave Imager and Sounder (SSMIS) utilising the CFMIP Observation Simulator Package (COSP, Bodas-Salcedo et al., 2011): An extended model output comprising additional variables projected onto the satellite orbit tracks (hereafter referred to as ‘curtain data’) is required to run the satellite simulator. The software components of the MPI-ESM model which are used to generate the curtain data have been updated for usage on the new Mistral server. Moreover, in order to minimise the extra amount of computing time required to generate the curtain data online during model integration, a 3-hourly output stream containing 3-d fields which can be run in a parallel i/o mode has been implemented. A workflow has been established to generate the required curtain data by subsequent projection of the 3-d data onto satellite orbits. The software was handed over to MiKlip II Module D. Subsequently, the model output data required to apply the satellite simulator to the pre-operational system was provided by Module D.

The COSP SSM/I satellite simulator is applied to the MiKlip II pre-operational hindcasts to evaluate the predictive skill of the system. Simulated brightness temperatures for selected channels which are sensitive to water vapour content and to precipitation are used.

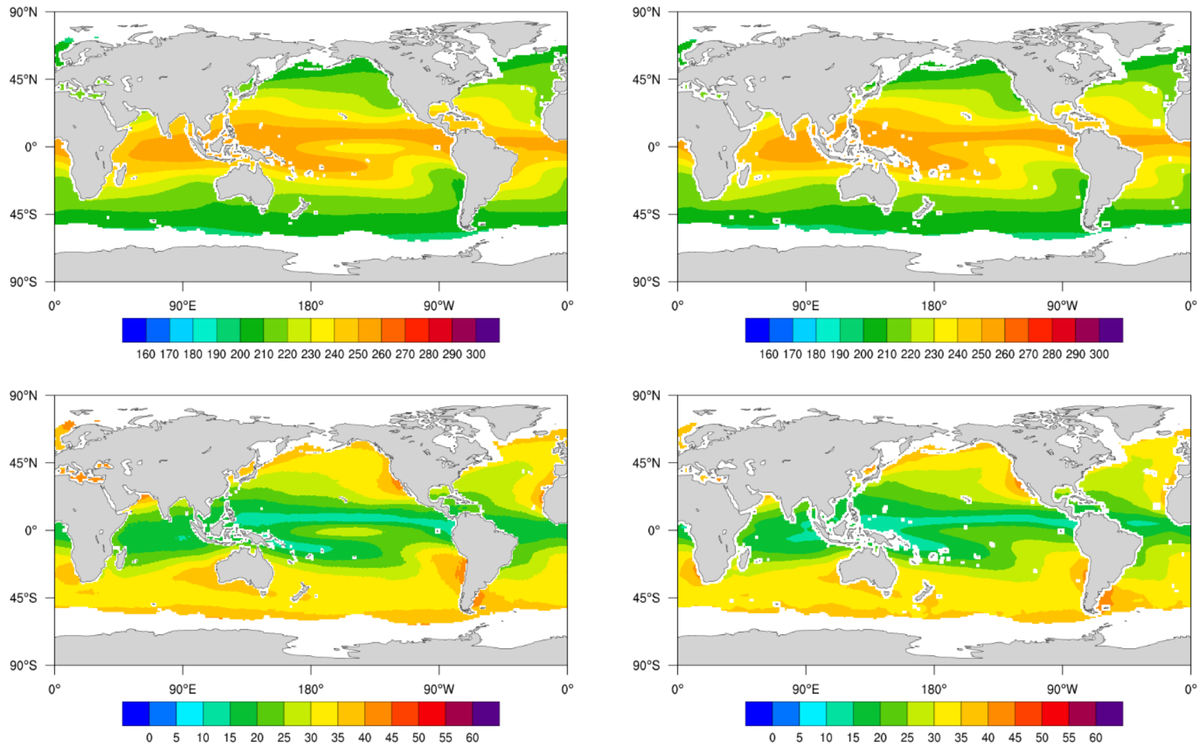

Figure 5.1: *Brightness temperature [K] multi-year averages of the SSM/I microwave imager for the 22 GHz channel (top) and the 85 GHz vertical minus horizontal polarisation channel (bottom). Left column shows results of the COSP SSM/I satellite simulator applied to the MiKlip II pre-operational system (lead year 1). Time period is 1988-2014 for 22 GHz and 1988-2008 for 85 GHz. Right column shows observations. Land areas are masked out due to lack of surface information.*

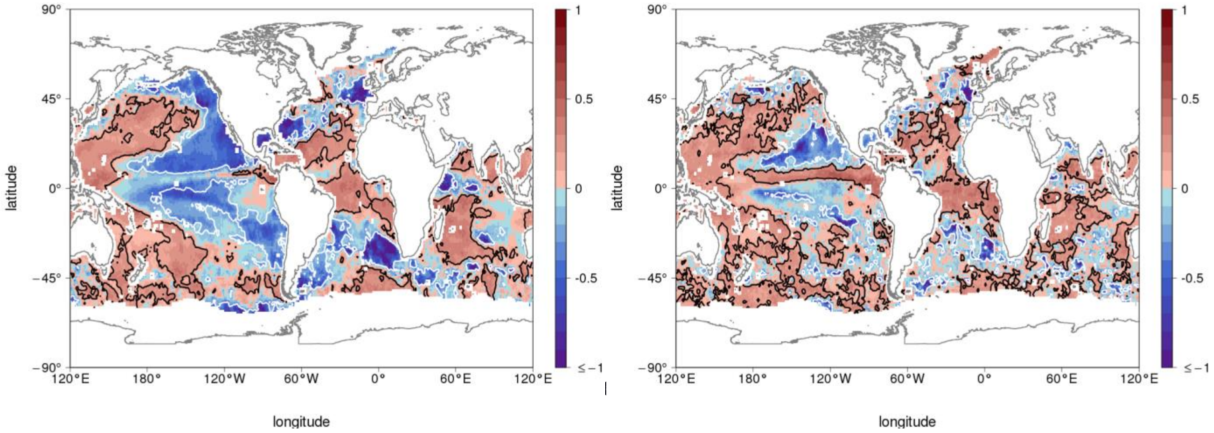

Figure 5.2: *MiKlip II pre-operational system forecast evaluation of brightness temperature for the 22 GHz channel (left) and the 85 GHz vertical minus horizontal polarisation channel (right) for lead year 2-5. The CRPSS is shown. Land areas are masked out due to lack of surface information. The covered time period is 1989-2014 for 22 GHz and 1989-2008 for 85 GHz. 9 realisations are used.*

On the reference side the SSM/I & SSMIS Fundamental Climate Data Record (FCDR) provided by the CM SAF (DOI: 10.5676/EUM_SAF_CM/FCDR_MWI/V003) is employed which covers the period from 1978 to 2015. Evaluation results focus on lead year 1 and on lead year 2-5.

The brightness temperature of the 22 GHz channel is sensitive to water vapor content whereas the difference of the 85 GHz vertical minus horizontal polarisation channel (p_v-p_h) is sensitive to the hydrometeor content amongst others. Results obtained for the COSP SSM/I satellite simulator applied to the MiKlip II pre-operational system resemble the general structure and amplitude of the observations for multi-year time averages for both channels (Fig. 5.1). Along the central equatorial Pacific there is evidence for a double ITCZ structure which is a common feature of GCMs.

Probabilistic evaluation results are shown for the 22 GHz and the 85 GHz (p_v-p_h) channel. For lead year 2-5 the Conditional Ranked Probability Skill Score (CRPSS, cf. Stolzenberger et al., 2016, for further information on method) indicates predictive skill for large parts of the western tropical/sub-tropical Pacific, the tropical/sub-tropical Atlantic and the Indian Ocean. Little predictive skill is found for the eastern Pacific (Fig. 5.2). In addition, the 85 GHz (p_v-p_h) channel shows predictive skill for the near-equatorial tropical Pacifc. These results suggest that the hindcasts reveal skill for large ocean areas even beyond lead year 1 when comparing against climatology as a reference forecast.

Related own publications and selected contributions to conferences

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