GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

Anlage 2
(zu Nr.4.1 NKBF 2017)

Sachbericht zum Verwendungsnachweis

Projekt Abrupt Climate Shifts and Extremes over Eurasia In Response to Arctic Sea Ice Change (ACE)

German-Sino Cooperation Program in Climate Research within the Promotion of Strategic Project Funding in Climate Research with China**,** Topic 2: Impacts of climate change in affected sectors

Kennzeichen FKZ: 01LP2004A,

für den Zeitraum 01.01.2023 — 31.12.2023 (Projektmonate 18 — 30)

Projektlaufzeit: 01. Juli 2021 – 30. Juni 2024

Antragsteller:
Prof. Dr. Gerrit Lohmann, Dr. Monica Ionita-Scholz, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research

sowie

Prof. Dr. Xun Gong, China University of Geoscience (Wuhan), Wuhan, China

Teil I: Kurzbericht für das Projekt ACE

Wir untersuchen die klimatischen Beziehungen zwischen der Arktis und den mittleren Breiten und konzentrieren uns dabei auf die abrupten Veränderungen und Extreme im eurasischen Klimasystem als Reaktion auf die zeitlichen Schwankungen in der Arktis. In diesem Projekt werden wir systematisch Daten für die arktischen und eurasischen Regionen analysieren, um die zeitlichen und räumlichen Charakteristika von abrupten Klimaänderungen und Extremen im Holozän und ausgewählten Abschnitten in der Erdgeschichte zu charakterisieren. Dies wird mit einer hochauflösenden Klimamodellierung unter Verwendung des gekoppelten Erdsystemmodells (AWI-ESM) kombiniert.

In einer unserer Studien untersuchen wir den Zusammenhang zwischen der herbstlichen Meereisveränderlichkeit in der Barents- und Karasee und extrem kalten Wintern in Europa. Anhand von Beobachtungsdaten und Wetterlagen erforschen wir die Variabilität und mögliche Verbindungen zwischen Meereis und atmosphärischer Zirkulation. Es zeigt sich ein Zusammenhang mit Verschiebungen zu einer negativen Phase der Nordatlantischen Oszillation und häufigeren atmosphärischen blockierenden Wetterlagen über Grönland und dem Nordatlantik. Unsere Ergebnisse deuten auf einen Zusammenhang zwischen der ungewöhnlichen Abnahme des Meereises in der Barents- und Karasee im Herbst und dem Auftreten intensiver europäischer Wetterextreme in den Folgemonaten hin. Dies unterstreicht die Notwendigkeit, diese Beziehung auf monatlicher Zeitskala genauer zu untersuchen, um unsere Vorhersagefähigkeiten für Extremereignisse in mittleren Breiten zu verbessern.

Zu der Durchführung des Projektes sind paar Bemerkungen angebracht. Durch die Pandemie und deren Folgen gab es weniger Austausch von Personen aus China als ursprünglich vorgesehen. Die ursprüngliche Aufgabenstellung sowie den wissenschaftlichen und technischen Stand, an den angeknüpft wurde, wurde pragmatisch gehandhabt: Wir entwickeln zum einen ein hochauflösendes Klimamodell, parallel werten wir Klimadaten aus, um die oben beschriebene Aufgabe zu bewältigen. Es gab auch kleine Änderungen im Projekt, u.a. durch neuartige hochauflösende Simulationen (mit bis zu 2 km horizontaler Auflösung in der Arktis) des Projektmitarbeiters Dr. Dmitry Sein. Diese wurden visualisiert und für die Öffentlichkeit auf https://youtu.be/Q2huLoUxMXA dargestellt. Die Zusammenarbeit mit der chinesischen Seite verlief ganz hervorragend. Wir konnten etliche gute Publikationen in guten internationalen Zeitschriften platzieren. Dabei arbeiten wir mit der CUG in Wuhan als auch mit der OUC in Qingdao zusammen. Bedingt durch Verzögerungen noch durch Corona und einen zu vollen Zeitplan, besuchte Gerrit Lohmann im Oktober 2024 für mehrere Wochen die chinesischen Partnerinstitute. Es wurden weitere Anknüpfungspunkte besprochen. Diese werden in verschiedenste Publikationen münden. Weiterhin gab Gerrit Lohmann mehrere Seminarvorträge und Vorlesungen zum Thema (auch bei der chinesischen Akademie).

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Teil II: Darstellung der durchgeführten Arbeiten

Hier wird auf die Ergebnisse in den ausführlichen Zwischenberichten verwiesen. Wir konnten hochrangige Publikation platzieren (siehe unten), als auch nachweisen, dass eine hohe Auflösung im Ozean für Klimaszenarien sehr wichtig ist. Im Folgenden wir darauf näher eingegangen. Der Text ist in ***englischer*** Sprache verfasst.

II. 1 The importance of an eddy resolving ocean for climate simulations

For a sustainable development of our society, credible long-term climate prediction and projection of future climate change are essential. State of the art Earth system models participating in the CMIP6 (Climate Model Intercomparison Project Phase 6) have improved the ability of the CMIP5 models to represent the main mechanisms of the global climate, such as the large-scale atmospheric circulation (Fernandez-Granja et al, 2021), the global energy balance (Wild, 2020), the monsoon systems (e,g Gusain et al, 2019), large scale climate modes as ENSO (Planton et al, 2021), providing seasonal to decadal climate predictions, and indicate how the future climate will change that are openly available for wide and interdisciplinary research related to climate change and sustainable development (e.g., the CMIP6 archive, Eyring et al., 2016).

However, these state-of-the-art ESMs still exhibit non-negligible errors or “bias” in the mean climate state as well as in its variability compared to the observed climate (e.g., Richter and Tokinaga, 2020), leading to large uncertainties in climate prediction and future climate projections. For the typical resolution in which the CMIPs simulations are carried out, important processes influenced by ocean eddies and atmospheric mesoscale features and their interactions can be missed as they are not properly resolved. In this sense, in the framework of eddy permitting HighResMIP experiments it has been shown that for a reliable ocean–atmosphere coupling along the Gulf Stream it is necessary to have at least eddy-permitting ocean resolution and comparable atmosphere resolution (Tsartsali et al, 2022). Moreover, state of the art global models are still not able to simulate important features of the regional climate which are influenced by steep orography, coastal upwelling. Global models that are eddy resolving in the ocean and have an atmospheric resolution capable of resolving mesoscale air–sea interaction may not only improve the representation of these small-scale processes, but also their interaction with the large-scale, which feeds back the small-scale processes to the large-scale atmospheric and oceanic circulation (Seo et al., 2023; Ma et al., 2016; Iles et al., 2020). The representation of heavy precipitation and extreme events as heat waves (Gao et al., 2023), hurricanes and coastal marine heat waves can also be improved by higher resolution. Although the different downscaling techniques, both with regional coupled models and statistical methods (Gutowski et al, 2020; Quesada Chacon et al., 2023), can mitigate this shortcoming, high resolution coupled models with eddy resolving ocean and atmospheric components that are able to represent adequately the land orography are necessary to provide physically consistent across spatial scales high resolution regional climate information.

Some problems common to models across the CMIP still persist in the HighResMIP simulations. The most relevant among them, such as the double-ITCZ, which could be alleviated by increased resolution over the tropical southern Atlantic but not in the tropical Pacific (Ma et al., 2023). Another long standing modeling issue is the ability of coupled models to simulate the storm tracks. It has been shown that the intensity and propagation of cyclones can be impacted considerably by errors in SSTs and SST gradients (de Vries et al., 2019). While such biases and uncertainties could have multiple causes, one of the most significant is the relatively coarse horizontal resolution at which the oceanic component of state-of-the-art models is typically run (usually coarser than 0.5 degrees, or ~50 km; de la Vara et al., 2020). This resolution does not adequately capture fine-scale processes in the ocean.

Because the ocean has a much larger heat capacity than the atmosphere, its thermodynamic impacts on the climate are quite large and remarkable even at small spatial scales (e.g., Minobe et al. 2008; Nkwinkwa-Njouodo et al., 2018). While the ocean mesoscale (less than 50km, for example) structure is ubiquitously observed globally, the western boundary currents (WBCs) in the extratropics are the regions where ocean fine-scale features are predominant and where ocean and atmosphere are strongly coupled and interact with each other (e.g., Xie 2004; Minobe et al., 2008; Cronin et al., 2010). Enabling the models to resolve ocean mesoscale properties and advancing our understanding on their influences of ocean fine-scale properties on the climate and mesoscale interaction in order to provide more reliable climate prediction and future climate projection.

Resolving mesoscale eddies in general ocean circulation models is still a challenging task in climate research, mainly because of the lack of computer resources and, to our knowledge, long-term (at least 150-200 years long) climate simulations with fully eddy-resolving ocean components have yet to be achieved. For example, for the CMIP6 models, the finest ocean model resolution in mid-latitudes is only eddy-permitting, while at high latitudes, it does not even reach this threshold. This is partly related to strong spatial variability of the first internal Rossby radius which roughly defines the size of mesoscale eddies generated through baroclinic instabilities. It varies between several ten kilometers in subtropics to just a few kilometers in Fram Strait in winter or on the ocean shelves. Most of the climate research is carried out with models formulated on structured meshes. Although the resolution of meshes commonly used in them is refined by approximately a factor of three in the direction from the equator to the poles, partly taking into account the latitudinal behavior of the phase speed of inertia-gravity waves and hence the first internal Rossby radius, it does not cover all the details of its behavior. Some state-of-the-art global ocean circulation models such as FESOM (Wang et al., 2014; Danilov et al., 2017), MPAS (Ringler et al., 2013) or ICON (Korn et al., 2017) are capable of working on unstructured meshes. The flexibility in the design of horizontal resolution of such meshes allows them to reach eddy resolution on a regional scale. Therefore, these models propose a paradigm similar to, but in many ways better than nesting, as the model remains global and maintains globally consistent balances.

The flexibility in mesh design allows for grid optimization from both physical and computational perspectives, and various methodologies have been proposed for implementing these refinements (Sein et al., 2016; Sein et al., 2017; Hoch et al., 2020). In FESOM, the Rossby radius is used as a reference, as there are indications that two grid cells per Rossby radius mark the boundary between eddy-resolving and eddy-permitting meshes (Hallberg et al., 2013). However, this criterion may not be sufficient to resolve all important oceanic circulation features (Sein et al., 2017). In particular, it leads to a resolution that is too coarse at low latitudes, which partially damps simulated eddy variability. Additionally, it should be noted that the Rossby radius does not accurately predict the behavior of maximally unstable waves in linear instability theory (see, e.g., Vollmer and Eden, 2013), indicating that adjustments to the Rossby-radius rule may be necessary.

In order to explore the impact of resolving the eddies on the simulated climate, we present and discuss the results of simulations performed on three different meshes, which allow as to analyze two different types of ocean model resolution:

a) eddy permitting (EP) with resolution between 0.5 and 1 baroclinic Rossby radius and
b) eddy resolving with resolution finer than R/2 (ER).

The ER mesh resolves the Rossby radius with four grid cells over most of the ocean. The limitation on the coarse side allows us to avoid excessive coarsening in the equatorward direction, which is the main lesson learned from Sein et al., 2017. Moreover, the increased ratio of the Rossby radius to grid cells reduces the sensitivity to mesh coarsening in subtropics and tropics. On the other hand, with existing computer resources it is impractical to carry out global simulations with even EP resolution everywhere, in particular on Arctic shelves, where R can be less than several hundred meters. Therefore, we will bound the mesh cell size to 2 km on the finer scale ER, to 4 km for the EP run and 25 km on the coarse scale and call the model EP or ER if the corresponding resolution is dominant. It should be noted that the ER mesh, referred to further as Rossby 4.2, compares in size with a 1/20 degrees global structured mesh. Therefore, we assess what is gained by increasing resolution in the global circulation and in particular regions of the world ocean when the oceanic mesh is increased. For the regional assessment, we focus on several regions, including the Gulf Stream and North-West corner, the Agulhas retroflection and the Southern Ocean, the Arctic Ocean.

2. Model setups

FESOM

The idea that the resolution should follow the behavior of the Rossby radius is an obvious one, and there are indications in the literature that two grid cells per Rossby radius marks the boundary between eddy resolving and eddy permitting meshes (Hallberg et al., 2013). However, the attempts to follow this principle in a global configuration (Sein et al., 2017) showed that it is sufficient not everywhere. In particular, it predicts a too coarse resolution in low latitudes, which partially damps the simulated eddy variability. Indeed, it should be recalled that the Rossby radius does not accurately predict the behavior of maximally unstable waves in linear instability theory (see, e.g., Vollmer and Eden, 2013), so that adjustments to the Rossby-radius rule might be needed.

However, the ability to vary the resolution poses the question as to how it should be varied. Even more importantly, given that computational resources are always limited, the question is on how to optimally deploy the refinements. The answer is not very straightforward for global simulations. Papers exploring this question have been recently published (Sein et al., 2016; Sein et al., 2017; Hoch et al., 2020), however the question is very far from being fully solved. The idea that the resolution should follow the behavior of the Rossby radius is an obvious one, and there are indications in the literature that two grid cells per Rossby radius marks the boundary between eddy resolving and eddy permitting meshes (Hallberg et al., 2013). However, the attempts to follow this principle in a global configuration (Sein et al., 2017) showed that it is sufficient not everywhere. In particular, it predicts a too coarse resolution in low latitudes, which partially damps the simulated eddy variability. Indeed, it should be recalled that the Rossby radius does not accurately predict the behavior of maximally unstable waves in linear instability theory (see, e.g., Vollmer and Eden, 2013), so that adjustments to the Rossby-radius rule might be needed.

The Finite volumE Sea ice Ocean Model (FESOM2, Danilov et al.,2017, Scholz et al.,2019) developed at AWI with Arakawa B-grid finite volume discretization on unstructured triangular meshes which allows to variably enhance resolution where desired. We focus on computational mesh design following a technique suggested in Sein et al., 2016, 2017. A brief idea is to distribute computational mesh nodes in the most efficient way. For this purpose, two main criteria were chosen. First, eddy resolving (permitting) resolution based on the local value of the baroclinic Rossby radius (Sein et al., 2017). Second, emphasizing the resolution in the regions of high ocean variability (Sein et al., 2016). Note that adjusting model resolution to the local Rossby radius will provide an extremely coarse model setup in tropical regions, where the latter exceeds 200 km and, in the opposite, extremely high resolution in high latitudes. To avoid extremely high resolution we implement a threshold value, setting the minimal resolution to r_{min}. To keep tropics and eddy active regions resolved better, resolution is adapted to the ocean variability in the similar way it was done in Sein et al., 2016. In practice, we construct two meshes, i.e. one adjusted to the half (eddy-permitting) or quarter (eddy-resolving) of the Rossby radius (R-mesh) and another, adjusted to the prescribed ocean variability (V-mesh). By the latter we mean a linear combination of sea surface height (SSH) variance, mean SSH gradients and mixed layer depth variability. Note that constructing V-mesh we also use resolution limits, i.e. v_{min} for areas with the highest variability and v_{max} vise versa. The resulting mesh is constructed as a combination of both R- and V-meshes where resolution is obtained as min(R-mesh, V-mesh). Because r_{min} is usually smaller then v_{min} whereas v_{max} is smaller then maximal Rossby radius, the resulting mesh resolution varies in the range (r_{min} , v_{max}).

The obtained resolution of two setups discussed in the paper are presented in figure 1. The first one (Fig.1a), eddy-permitting (EP), was generated according to the half of the Rossby radius using r_{min} =5 km in the Northern (NH) and r_{min} =10 km in the Southern hemisphere (SH). For the ocean variability (V-mesh) the resolution limits were chosen as (7km - 25 km) in Northern mid and high latitudes, whereas in tropics and SH they were (10km -25km). The second (Fig.1b), eddy-resolving (ER), was adjusted to the quarter of the Rossby radius with r_{min} =1.85 km (1 nautical mile) and V-mesh resolution range 5-

25km for both the hemispheres.

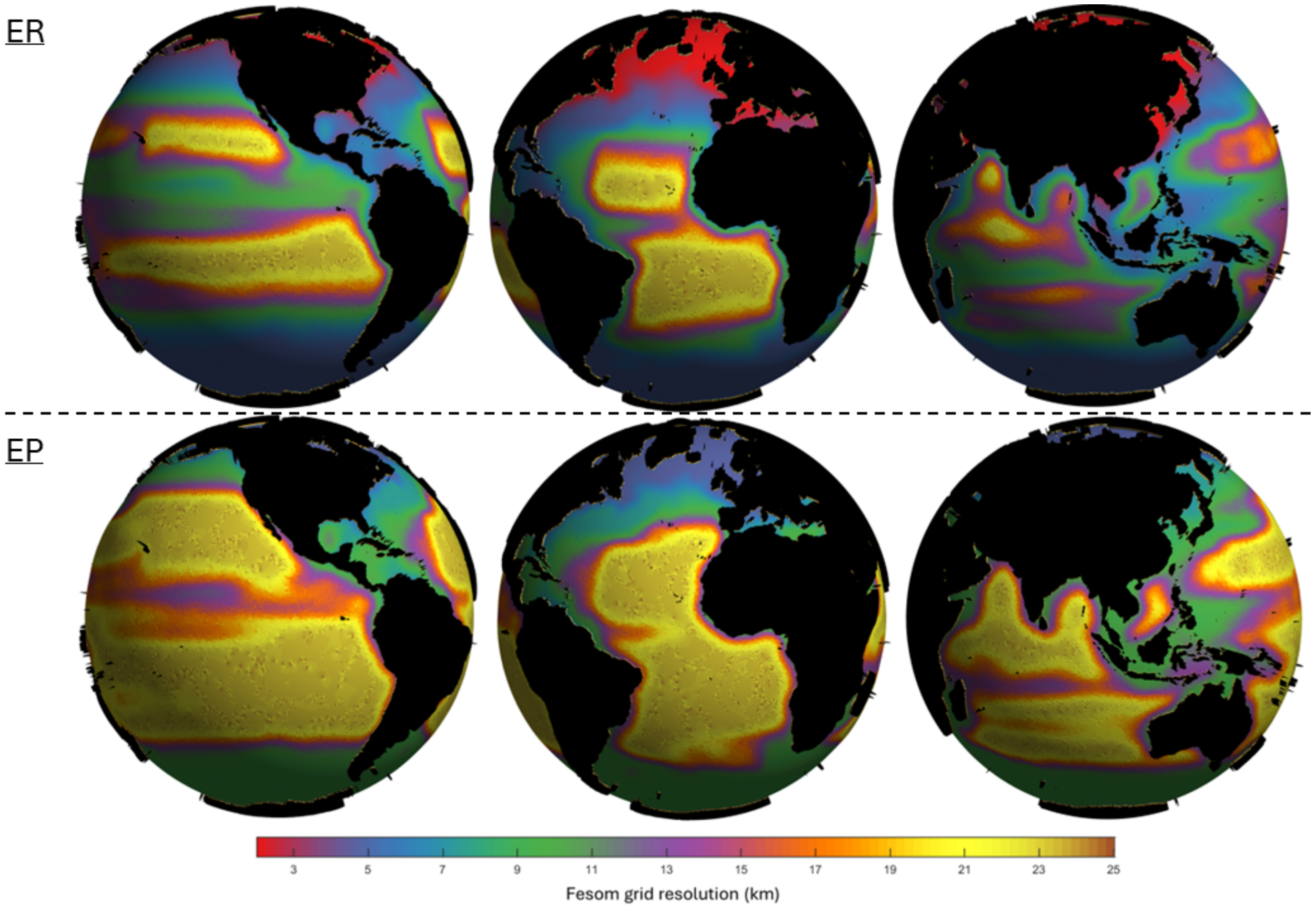

Figure 1. Model resolution (km)

Because till now there is no common criteria between the definition of eddy-permitting or eddy resolving resolution for the case of the global ocean, we suggest the following one. In case the model resolution is mostly (e.g. more than 70% of the ocean surface) below half of the Rossby radius we will call it eddy-resolving. If it is between the half of the Rossby radius and Rossby radius itself, we will call it eddy-permitting. The exact half of the Rossby radius is the value where the decision between “eddy-resolving” and “eddy-permitting” cannot be taken in a general way and depends on model discretization, i.e. its ability to resolve eddies on the scales close to spatial model step. For example, models based on E or even C-grid can usually resolve smaller eddies than those on A-grid employing the same spatial resolution.

Additionally, we should take in account that in the tropics a choice of Rossby radius as criteria of ocean eddies size can be incorrect. Vollmer and Eden (2013) showed that in the geographical range 40S - 40N the wavelength of baroclinic disturbances is smaller than Rossby radius and does not exceed 100-150 km. This finding was one of the reasons why in both our meshes we limited maximal spatial resolution to 25 km.

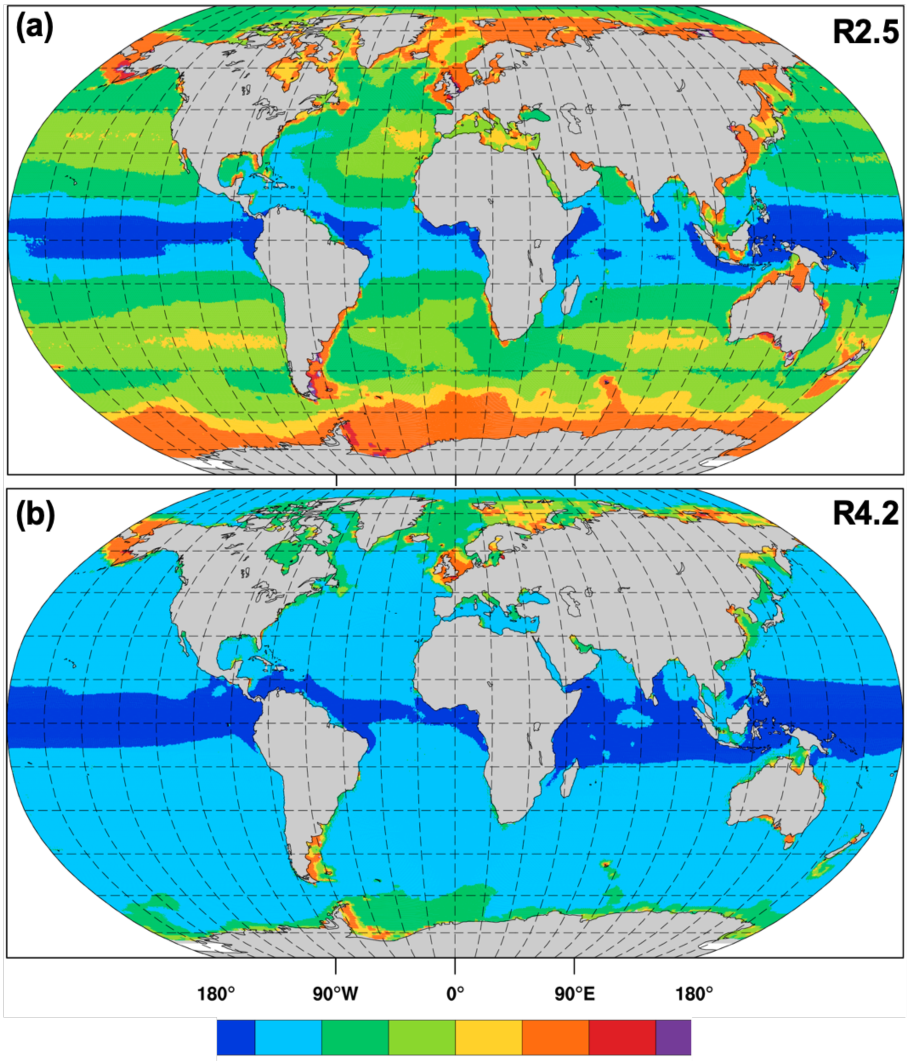

Figure 2. Resolution related to the baroclinic Rossby radius

Figure 2 illustrates model setups resolution related to the local Rossby radius. According to our mentioned above suggestion, ER mesh is eddy-resolving almost everywhere over the globe, except for some relatively small shelf areas.

Mesh	Horizontal Resolution	Surface nodes	Vertical levels	Performance (SYPD on 10000 cores)
EP (R2.5)	5-25 km	$3.2×10^6$	57	15
ER (R4.2)	1.85-25 km	$13.2×10^6$	57	0.75

Table 1. Oceanic setups summary. Simulated years per day (SYPD) are shown for 10000 cores which is close to EP scalability limit

A summary of the setups configurations and performance is shown in table 1. Note that 10000 cores for eddy-resolving setup (ER) is much below its scalability limit. In our experience it can be scaled up to 60000 cores simulating 4 years per day. Another option to increase eddy-resolving setup performance is the use of 47 vertical levels instead of 80. In this case simulation speed increases by factor 2-2.5 and can rich 8-10 SYPD on 60000 cores. Both configurations were initialized with PHC climatology (Steele et al.,2001) and FESOM2 ran stand alone for 110 years with CORE-II forcing (see Danabasoglu (2014) and other CORE-II papers) cyclically. After the FESOM2 stand-alone spin-up, it was ran coupled with OpenIFS atmosphere Tco319 (ca. 32km resolution) for EP ocean and Tco639 (ca. 16km resolution) for ER ocean starting from 1920. For 1920-2014 historical CMIP6 forcing and for

2015-2100 SSP585 future projection was used.

Historical simulations

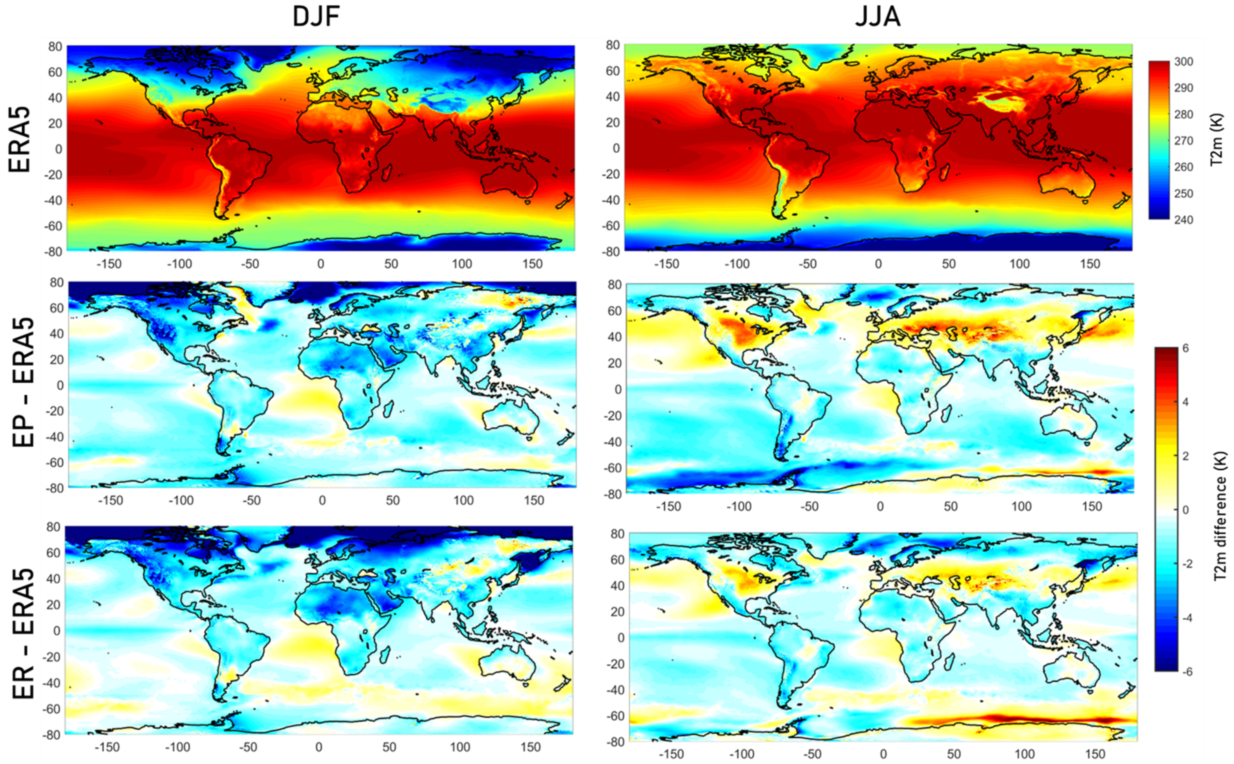

Figure 3. Mean (1985-2014) 2m air temperature and its biases relative to ERA5 reanalysis

Comparing the simulated and ERA5 2m air temperature (Fig.3) we can conclude that in general ER setup reproduces better the 2m air temperature over most part of the ocean, particularly in the Southern Ocean. However, in the Arctic, the ER setup tends to produce colder temperatures. This improvement is seasonally dependent. In DJF, the eddy-resolving (ER) simulation exhibits stronger cold biases in the 2m air temperature over the Russian sector of the Arctic, whereas in JJA, the differences are much smaller. Over the Southern Ocean, the higher resolution is associated with a warmer 2m air temperature. This adjustment reduces the cold bias observed in the eddy-permitting (EP) simulation over the western Southern Ocean but amplifies the warm bias over the eastern Southern Ocean. A strong improvement can also be seen in the Kuroshio region in JJA, where the strong positive bias in EP is significatively reduced. Over the continents the 2m air temperature looks much better in boreal summer over Eurasia, whereas in boreal winter the EP colder biases over Northern Africa and North America are reinforced.

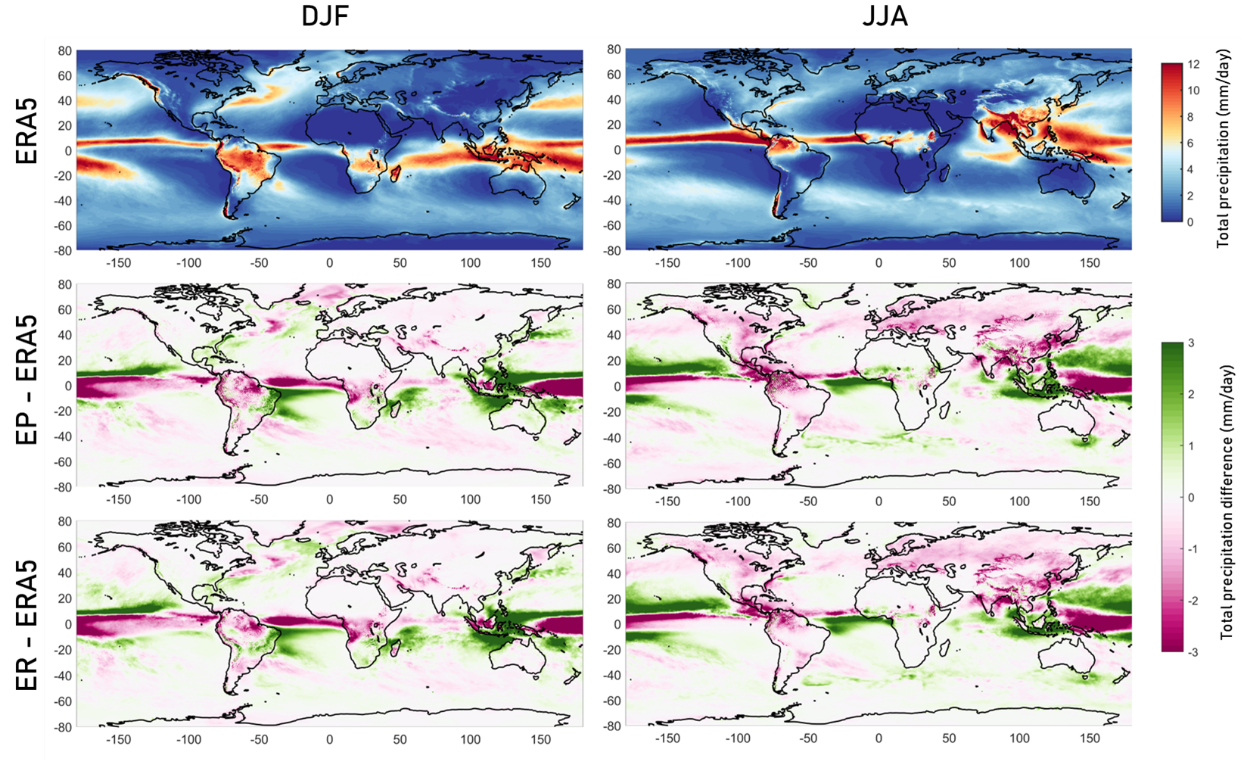

Figure 4. Mean (1985-2014) total precipitation and its biases relative to ERA5 reanalysis

The simulation of the precipitation does not appear to be significantly influenced by the resolution both over the ocean and over land. Total precipitation biases (Fig.4) are very similar in both the setups. The strongest biases are located in the tropical belt and are associated with wrong ITSZ position in the Tropical Atlantic and Tropical Pacific. Besides tropical biases, both EP and ER show dry biases over Europe and North America in JJA, which are probably related to biases in the land (soil moisture)–atmosphere feedback (Mueller and Seneviratne,2014).

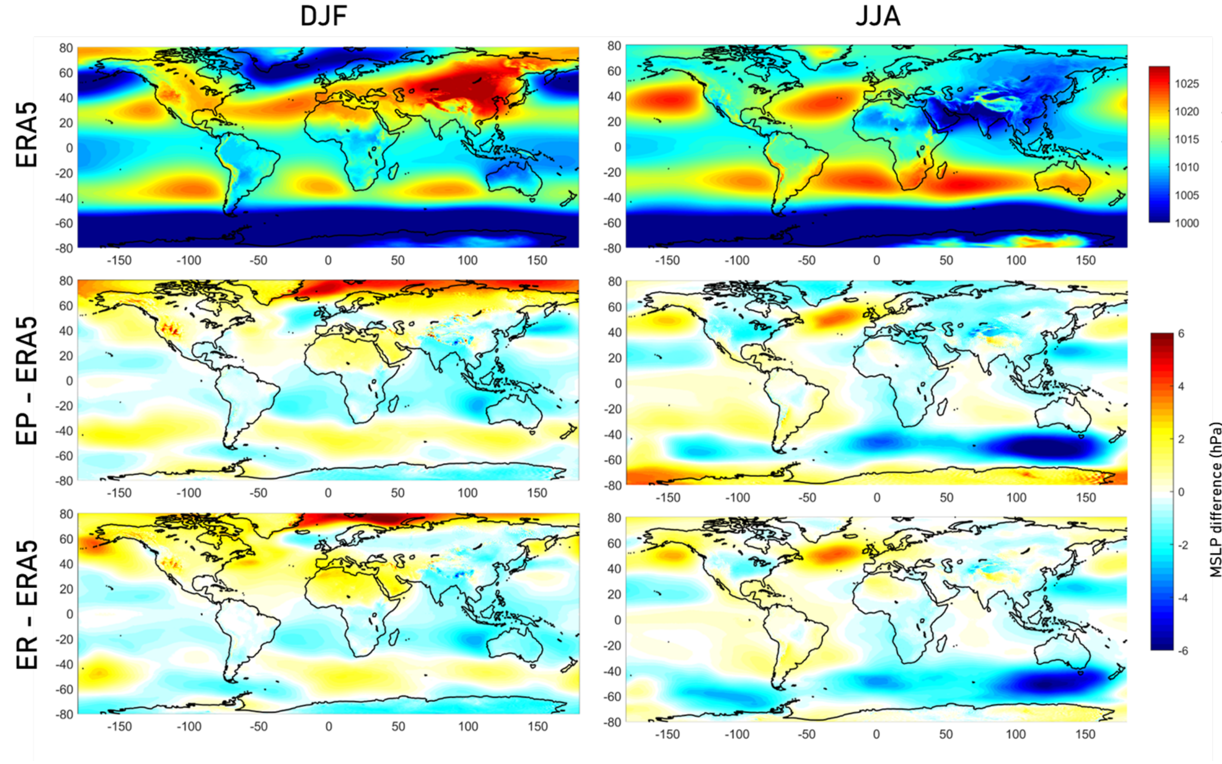

Figure 5. Mean (1985-2014) sea level pressure and its biases relative to ERA5 reanalysis

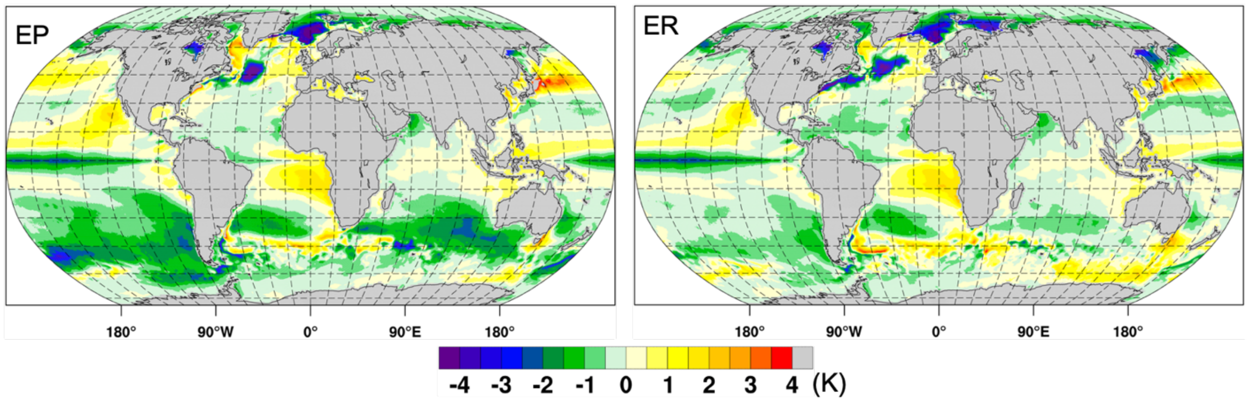

Figure 6. Annual mean (1985-2014) sea surface temperature biases relative to ERA5 reanalysis

Differences in simulated sea surface temperature between EP and ER setups are more pronounced (Fig.6) then those in atmospheric fields. Interesting is that they are much more significant in Southern Hemisphere.

SSP585 scenario climate change

Figure 7 shows the differences between the future and historical periods for sea level pressure (upper panels),2 meters air temperature (middle panels) and precipitation (lower panels) for DJF. Both the eddy-resolving (ER) and eddy-permitting (EP) simulations reveal strong warming associated with Arctic amplification. Significant temperature changes are also observed over Antarctica, the Tibetan Plateau, the eastern coast of South America, and western and southern Africa. A noteworthy feature is a region in the North Atlantic where warming reaches its minimum value. Additionally, the ER simulation generally shows lower warming, suggesting a potential role of eddies in mitigating the warming effect. Changes in precipitation are most pronounced in the tropics. The pattern of the changes seem to be related to the biases in the representation of the ITCZ with the equatorial Pacific showing minimal change, likely linked to the persistent cold equatorial sea surface temperature (SST) bias.

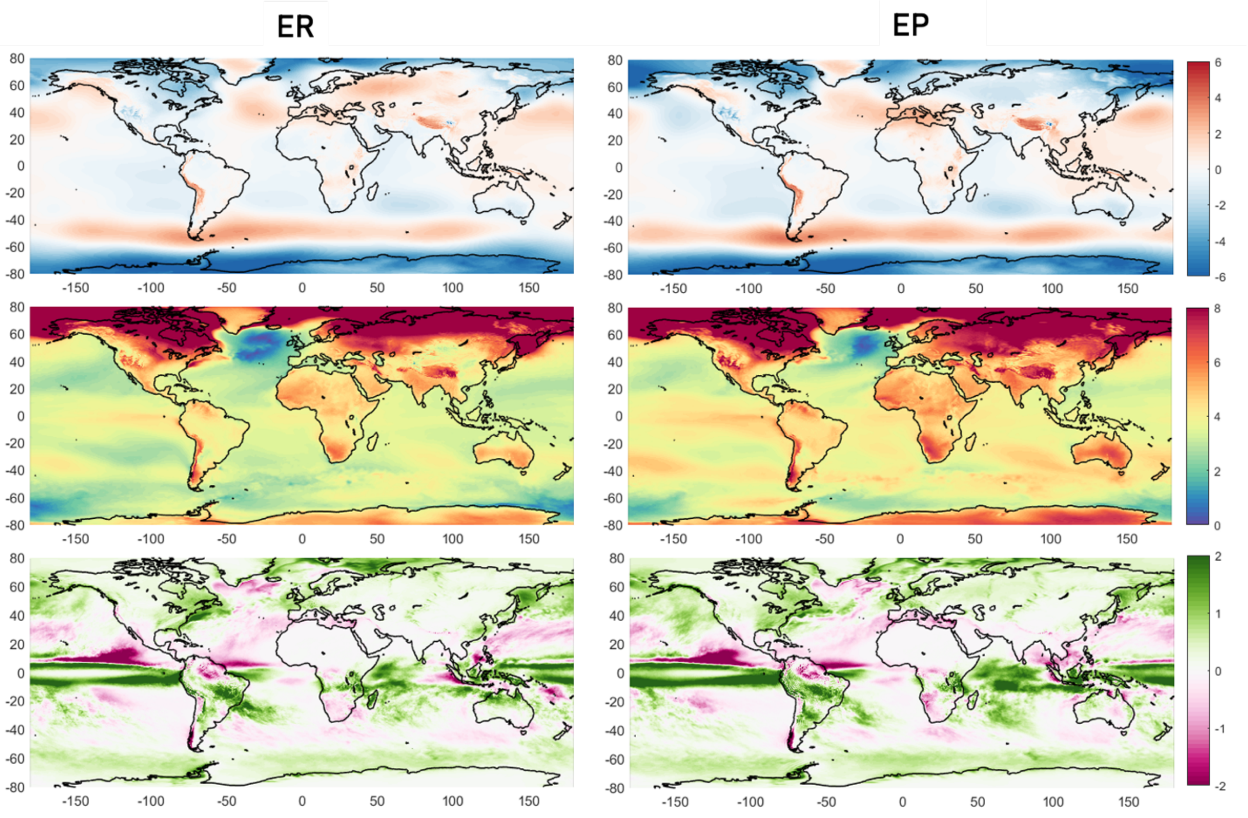

Figure 7. Mean DJF sea level pressure (upper), 2m temperature (middle), total precipitation (bottom) change (2070-2099) - (1985-2014).

Figure 8 shows the differences between the future and historical periods for sea level pressure (upper panels),2 meters air temperature (middle panels) and precipitation (lower panels) for JJA. Both the eddy-resolving (ER) and eddy-permitting (EP) simulations reveal a strong warming in the Southern Ocean, with the Arctic warming weaker than in DJF. Significant temperature changes are also observed over most of North America, Europe and Asia. Significant warming can be also observed in the northern part of South America and western and southern Africa. As in DJF, there is a region in the North Atlantic where warming reaches its minimum value, although this warming has a slightly value.In this season, the ER simulation also shows lower warming, suporting a potential role of eddies in mitigating the warming effect. Changes in precipitation are also stronger in the tropics, with high increases in the indian ocean and in the western tropical Pacific.

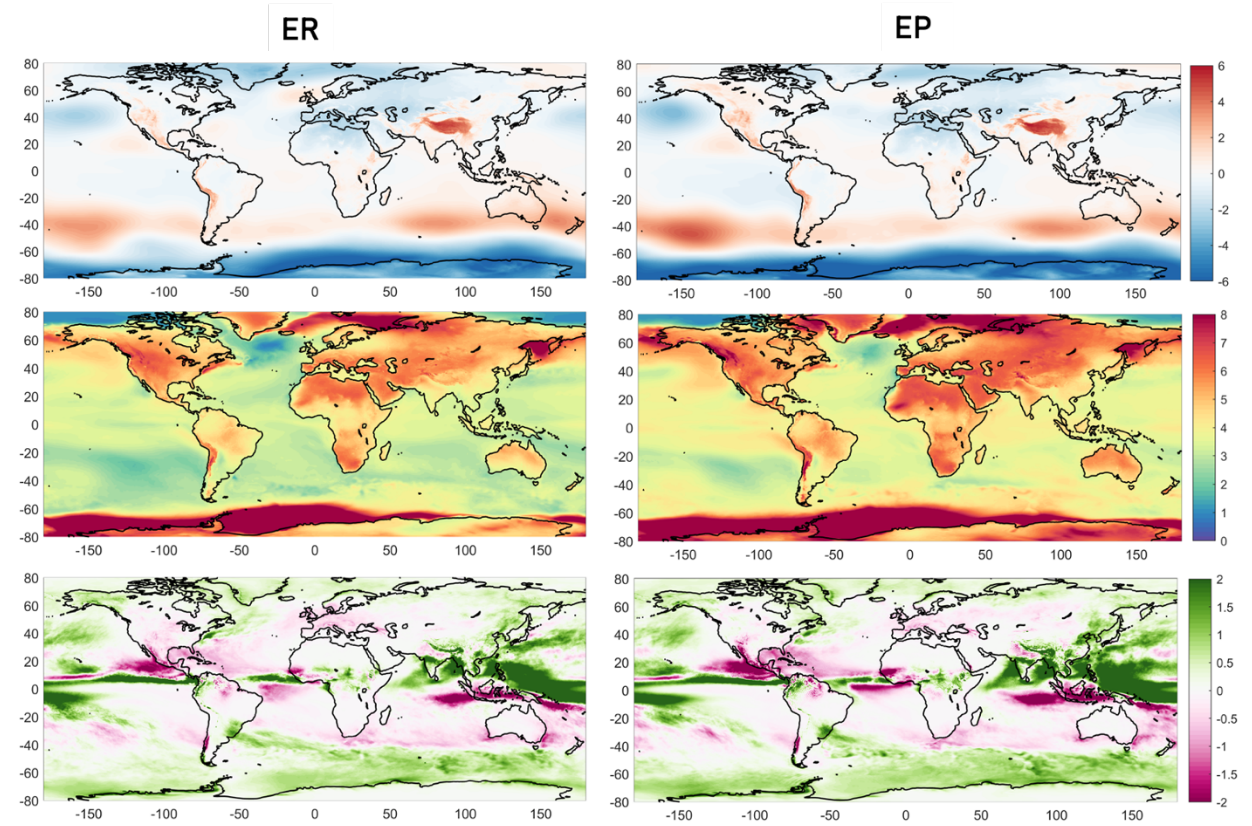

Figure 8. Mean JJA sea level pressure (upper), 2m temperature (middle), total precipitation (bottom) change (2070-2099) - (1985-2014).

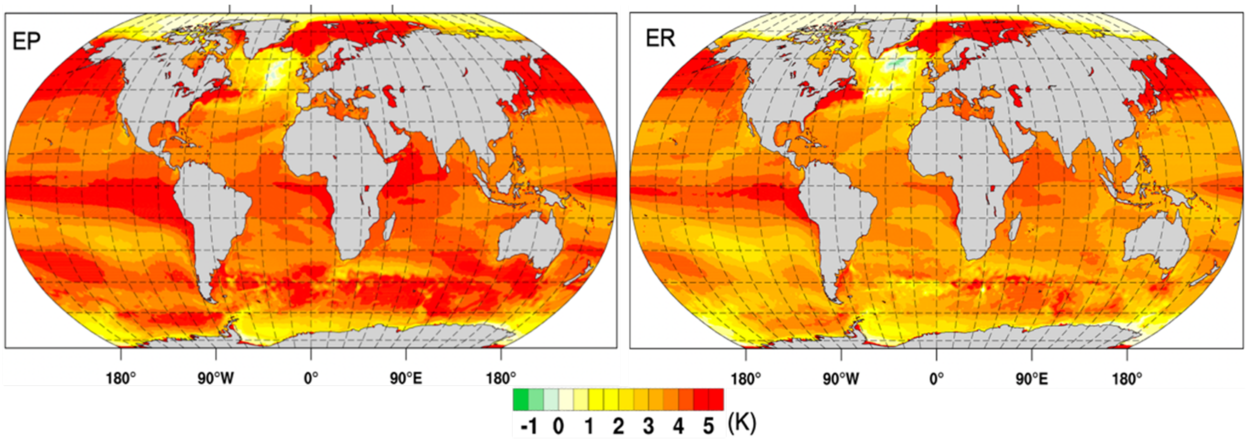

Figure 9. Annual mean sea surface temperature change (2070-2099) - (1985-2014).

The influence of the fine scale ocean processes, in particular mesoscale ocean eddies can be roughly split in 2 types: dynamical and thermodynamical. Thermodynamical type is considered as eddy atmospheric heat pumping from the surface to the deeper ocean and its further horizontal transport, e.g., Lv et al., 2022. Because of the absence of continues eddy resolving ocean simulations for the time rage of ca. 150 years this effect on the future is presently discussible. We suppose that this effect should damp the ocean surface warming (Fig.9).

Dynamical type was recently discussed in Beech et al. 2022. The analysis was based on CMIP6 simulations were done with AWI-CM1 in the framework of CMIP6. Authors found a future shift of the Gulf Stream and Agulhas currents, but not, e.g., Kuroshio, which is already observed (Martínez-Moreno et al., 2022). The reason was in FESOM setup, which was focused on Atlantic Ocean only and having coarser resolution in Pacific. In the framework of HighRes MIP (the part of CMIP6) project, the similar simulations were done. For this case the resolution in Kuroshio area was similar to the Gulf Stream and the near surface ocean current shift was obtained too (not published). Fig. 1 demonstrate the difference in ocean currents future change between non-eddy-resolving and eddy permitting ocean setups, described in Sein et al., 2018. In the first case we see increase or decrease of the western boundary currents (WBC), whereas in the eddy permitting case their shift is obtained.

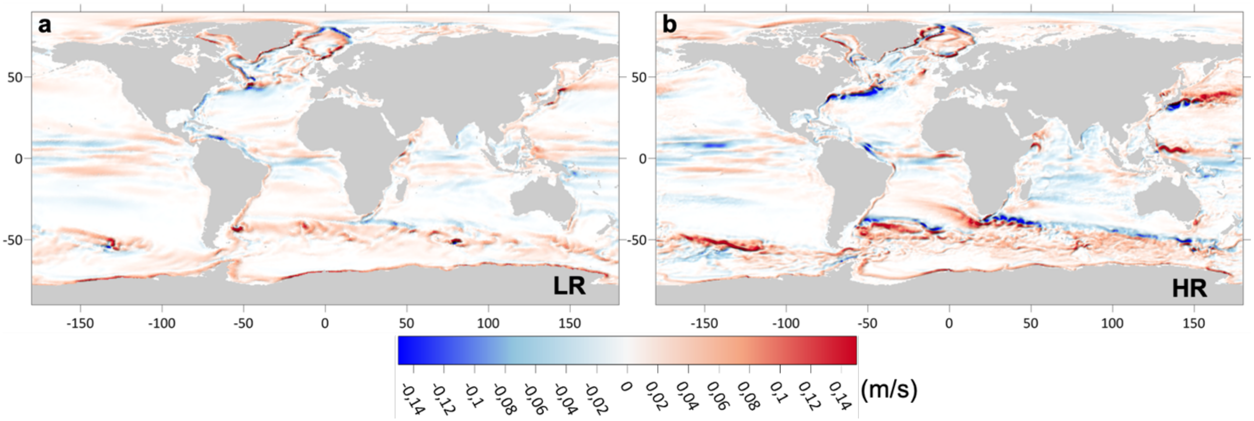

Figure.10. Change in the 30m ocean currents for non-eddy-resolving (a) and eddy permitting (b) ocean model, coupled to the same atmosphere.

II. 2 Bereits akzeptierte Fachaufsätze:

Cai, D., **Lohmann, G.,** Chen, X., and **Ionita, M.,** 2024: The linkage between autumn Barents-Kara sea ice and European cold winter extremes. Frontiers in Climate, Section Climate Monitoring 6:1345763. DOI:10.3389/fclim.2024.1345763

Doshi, S., **G. Lohmann,** N. Rimbu, **M. Ionita,** 2023: Spatiotemporal trend analysis of climate indices for the European continent. Journal of Water and Climate Change doi:10.2166/wcc.2023.183

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Die wichtigsten Positionen des zahlenmäßigen Nachweises

- die Notwendigkeit und Angemessenheit der geleisteten Projektarbeiten ergeben sich aus der Fragestellung

- der voraussichtliche Nutzen, insbesondere die Verwertbarkeit des Ergebnisses: Unsere Ergebnisse haben Auswirkungen auf konkrete Planungen für die nähere Zukunft. Das AWI-CM Klimamodell wird an der nächsten großen Modellvergleichsstudie im Rahmen von CMIP7/ PMIP7 teilnehmen. Unsere Erkenntnisse mit hochauflösenden Modellen werden wir in den nächsten Sachstandsbericht (IPCC) einbringen. In Gou et al. (2025) zeigen wir bereits eine hohe Abhängigkeit von Extremen durch die Modellauflösung. Wir stellen fest, dass höherdimensionale Modelle tendenziell Variabilität und Extremverhalten besser erfassen (Contzen et al. 2022). Dies unterstreicht unser Ziel, Klimavariabilität zu verstehen und zu quantifizieren, um die Modellierung durch die Verknüpfung von Beobachtungen mit Modellleistung zu verbessern. Das Verständnis, wie Wirbel auf die Klimaerwärmung reagieren und wie ihre Präsenz den Klimawandel beeinflusst, ist daher für viele Aspekte der Erdsystemwissenschaft von entscheidender Bedeutung.