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Convective circulations in the Earth system under changing climate

Final Report

I. Introduction

In an effort to address problems related to the changing climate, we mainly focused on atmospheric teleconnections with particular attention paid to the Arctic region; along with climate-motivated laboratory experiments. In this research, we used the term teleconnection in an extended sense, so that even atmospheric phenomena such as lightning activity and its (tele)connection, correlation with large cold air outbreaks are part of the concept. Our results revealed universal features in various processes ranging from large-scale winds' influence on global sea-level rise and sea ice sensitivity, through the robust reorganization of continents and oceanic currents 34 million years ago which triggered the glaciation of Antarctica, to some general, dominant features of climate extremes under a changing climate, related to the predictability of extremes and their change.

II. Results

II.1. How large-scale winds influence global sea-level rise

While climate models project that Greenland ice sheet (GrIS) melt will continue to accelerate with climate change, models exhibit limitations in capturing observed connections between GrIS melt and changes in high-latitude atmospheric circulation. Here we imposed observed Arctic winds in a fully-coupled climate model with fixed anthropogenic forcing to quantify the influence of the rotational component of large-scale atmospheric circulation variability over the Arctic on the temperature field and the surface mass/energy balances through adiabatic processes. We showed that recent changes involving mid-to-upper-tropospheric anticyclonic wind anomalies – linked with tropical forcing – explain half of the observed Greenland surface warming and ice loss acceleration since 1990, suggesting a pathway for large-scale winds to potentially enhance sea-level rise by ~0.2mm/year per decade. We further revealed fingerprints of this *observed teleconnection* in paleo-reanalyses spanning the past 400 years, which heightens concern about model limitations to capture wind-driven adiabatic processes associated with GrIS melt [Topál et al., 2022].

II.2. Constrained timing of a seasonally ice-free Arctic

The Arctic has been suggested to see seasonally ice-free conditions within two-to-three decades under high-emissions scenarios. However, the time of emergence of the first ice-free month remains uncertain due to a wide range of estimates for Arctic climate sensitivity to anthropogenic forcing. We proposed a recalibration of the sea ice and Greenland ice sheet response to climate change, based on the finding that the sensitivity of the Arctic cryosphere to atmospheric circulation in climate models substantially differs from the observed one. Assuming that the Arctic climate sensitivity of models recalibrated by observations remains unchanged in coming decades, our approach yields a delay in the projected timing of the first September sea-ice-free Arctic and widespread Greenland melting of roughly a decade compared to the uncalibrated ensemble. This indicates the importance of accounting for the role of large-scale atmospheric forcing and circulation changes in Arctic climate change [Topál and Ding, 2023].

II.3. Where are the coexisting parallel climates? – A new consistency condition

We have shown in the CESM1-LE that the growth rate of uncertainty (an analog of the Lyapunov exponent) can be determined right after initialization. Concerning a credible simulation, the observed signal should wander within the spread of an ensemble converged to the attractor all the time. We argue that the existence of "parallel climate realizations" is reflected by the probability distribution of the ensemble in a credible simulation. We formulated a novel, extended credibility condition, which requires the climate ensemble to be a converged one. This condition also holds for low-dimensional models with their own ensembles. Surprisingly, no low-order physical or engineering systems subjected to time-dependent forcings are known for which a comparison between simulation and experiment would be available. In climate research practice, our approach provides the evaluation of converged ensemble-based statistics of teleconnections. As illustrative examples, the CESM1-LE climate model and a chaotic pendulum were taken. [Herein et al., 2023a].

II.4. Extreme behavior, characteristic time of the emergence of extremes

In ensemble simulations of the climate, extreme behavior can be explored via a novel approach [41], based on zooming in into the ensemble. To this end, additional, small sub-ensembles are used, and plume diagrams initiated on the same day of a year are generated from these sub-ensembles. Trajectories within the plume diagram strongly deviate on the time scale of a few weeks. By defining the extreme deviation as the difference between the maximum and minimum values of a quantity, a growth rate for the extreme deviation can be extracted. An average of these taken over the original ensemble characterizes the typical, exponential growth rate of extremes. The reciprocal of this can be considered to be the characteristic time of the emergence of extremes and is on the order of a few days. Measuring these times in the climate model PlaSim in several years along the last century, results for the global mean surface temperature turned out to be roughly constant, while for pressure a decaying trend was found in the emergence time of extremes in the last decades [Herein et al., 2023b].

II.5. Cold Air Outbreaks (CAOs) – Arctic-tropic connection

Schumann resonances (SRs) are global electromagnetic resonances of the Earth-ionosphere cavity maintained by lightning. We analyzed 19 days of global lightning activity in January 2019 based on SR intensity records. The results are compared with independent lightning observations provided by ground-based and satellite-based lightning detection. We found that daily average SR intensity records from different stations exhibit strong similarity in the investigated time interval. The inferred intensity of global lightning activity varies by a factor of 2–3 on the time scale of 3–5 days which we attributed to CAOs emerging from both polar regions. Using NOAA and Berkeley Earth surface temperature data, we showed that these giant CAOs spread to low latitudes and come into contact with tropical air masses ("teleconnection"), cooling them and significantly reducing the number of lightning flashes [Bozóki et al., 2023].

II.6. The opening of the Drake Passage

We investigated a laboratory-scale minimal model of the Drake Passage opening. This opening event coincided with a pronounced global cooling around the Eocene--Oligocene transition (EOT), a pivotal event in Earth's climate history. Using our physical laboratory model we revisited the fluid dynamics of this marked reorganization of ocean circulation.

We showed, seemingly contradicting paleoclimate records, that in our experiments opening the pathway yields higher values of mean water surface temperature than the "closed" configuration. This mismatch points to the importance of the role ice albedo feedback plays in the investigated EOT-like transition, a component that is not captured in the laboratory model. Our conclusion is supported by numerical simulations performed in a global climate model (PlaSim) of intermediate complexity, where both "closed" and "open" configurations were explored, with and without active sea ice dynamics. PlaSim results indicate that sea surface temperatures would change in the opposite direction following an opening event in the two sea ice dynamics settings, and the results are therefore consistent both with the laboratory experiment (slight warming after opening) and the paleoclimatic data (pronounced cooling after opening). It follows that in the hypothetical case of an initially ice-free Antarctica the continent could have become even warmer after the opening, a scenario not indicated by paleotemperature reconstructions. [Vincze et al., 2021].

We mention that our paper conducted significant media coverage (ELKH news, MTA news, radio and TV reports).

Also in the framework of an international collaboration, we have conducted a 3-month measurement campaign in the Geophysical Fluid Dynamics Institute of the Florida State University, which houses the world's largest differentially heated rotating annulus tank. We performed long pointwise temperature sensor measurements in both "open" and "closed" Drake Passage configurations in this set-up. The analysis of these temperature records will help us better understand the connections between equator-to-pole temperature contrast and the probability distributions of extreme events in the mid-latitude atmosphere in this conceptual model. Processing, analysis and publication of these measurements are expected in the coming year(s).

II.7. A new astrochronological age model - Triassic-Jurassic transition and climate change

We presented a cyclostratigraphic study of the Csovar section (Hungary), a continuous carbonate succession from an intraplatform basin that yielded significant geochemical and paleontological data from around the Triassic-Jurassic boundary (TJB). We analyzed ten elemental time series and stable isotope data series and detected cyclicities with periodicities similar to the orbital cycles of the ~405 kyr long and ~124 kyr short eccentricity, the ~34 kyr obliquity, and the ~17–21 kyr precession. The astrochronologic age model suggests that the ~52 m thick section was deposited in 2.9–3 Myr, with an average sedimentation rate of 1.73–1.79 cm/kyr. We established that the section contains the last ~1.3 million years of the Rhaetian and most of the Hettangian, supporting a <2 Myr duration for this stage. The duration of the initial carbon isotope anomaly (ICIE) is estimated at ~40–80 kyr. Previously recognized meter-scale sequences are in agreement with the long eccentricity cycles up to the level of the ICIE but subsequently this relationship becomes less clear, possibly reflecting the effects of the end-Triassic climatic/environmental perturbations and associated changes in the depositional environment superimposed onto overarching astronomical forcing. We proposed a cyclicity-based environmental model for sedimentation in the Csovar basin where the observed antiphase behavior of the carbonate accumulation and the terrigenous input and dissolved silica was driven by a combination of aquiferand limno-eustasy and the ″megamonsoon″ system that dominated the climate of the peri-Tethyan realm. This study highlights that intraplatform carbonate successions can be suitable archives to preserve orbital cyclicities and the new astrochronological age model helps improve our understanding of the ETE and other events in the TJB interval [Vallner et al., 2023].

II.8. Extreme temperature fluctuations in laboratory models

Using two laboratory-scale conceptual fluid dynamic models of the mid-latitude atmospheric circulation we investigated the statistical properties of pointwise temperature signals obtained in long experiment runs. We explored how the average ``equator-to-pole'' temperature contrast influences the range and the jump distribution of extreme temperature fluctuations, the ratio of the frequencies of rapid cooling and warming events, and the persistence of ``weather'' in the set-ups. We found simple combinations of the control parameters -- temperature gradient, rotation rate and geometric dimensions -- which appear to determine certain scaling properties of these statistics, shedding light on the underlying dynamics of the Rossby wave-related elements of the mid-latitude weather variability [Vincze et al., 2023].

Scientific impact and basic metrics

We mention that Bin Guan (JPL, UCLA) invited us to publish a chapter about the Northern Annular Mode in the book Atmospheric Oscillations, to be completed next year.

We published *8 Q1 papers*, and their cumulative *impact factor is 71.887*.

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Peer-reviewed journal

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