RESEARCH HIGHLIGHTS

IBS CENTER FOR CLIMATE PHYSICS

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Institute for Basic Science

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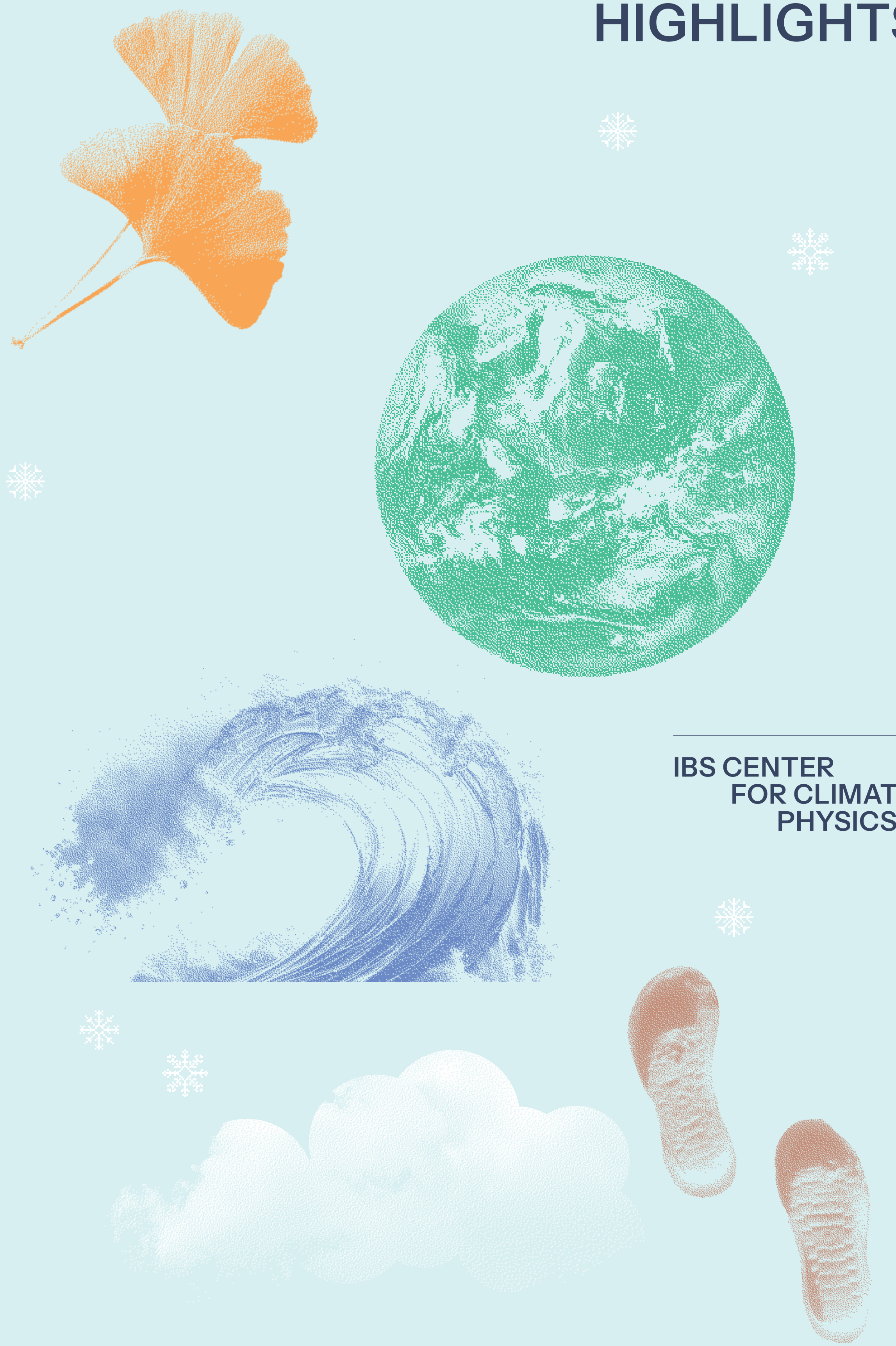


IBS CENTER FOR CLIMATE PHYSICS

DIRECTOR'S MESSAGE

Over the past century increasing anthropogenic greenhouse gas emissions have become the main driver for global climate change. In response to the corresponding increased downward infrared radiation, the earth's surface warms, Arctic sea-ice retreats, sea level rises, climate and weather patterns shift. The absorption of anthropogenic CO_2 by the ocean affects ocean chemistry, leading to Ocean Acidification and fish-hypercapnia. To cope and adapt to the resulting environmental and ecological changes, humanity needs robust estimates of both, forced climate change and internally generated variability on global and regional scales.

Many decisions on adaption and mitigation need to be made over the next decades to limit climate damage costs and prevent long-term irreversible loss of coastlines, human livelihoods and ecosystems. Making such decisions has proven difficult, in particular in the context of the prevailing uncertainties in our physical understanding of the climate system. Some of the most persistent uncertainties are related to the overall sensitivity of our earth system to greenhouse gas forcing, cloud-feedbacks, regional patterns of future rainfall changes, the nature of carbon cycle/climate feedbacks, potential ice-sheet thresholds and the magnitude of the projected global and regional sea-level rise. Addressing these scientific challenges requires a concerted multi-disciplinary effort.

Here at the IBS Center for Climate Physics (ICCP) in Busan, South Korea, we provide a world-class international research environment to improve our basic understanding of climate and its variability, to develop new research frontiers in earth system science and to perform skillful decadal earth system forecasts and improved longterm projections by means of high-performance computer simulations.

Prof. Axel Timmermann,
Director, IBS Center for Climate Physics

CHAPTER. 1

VISION OF THE CENTER

VISION OF THE CENTER

1.1
INSTITUTE FOR BASIC SCIENCE (IBS)

South Korea's Institute for Basic Science was established in November 2011 with the vision of *"Making discoveries for humanity and society".* To achieve this vision, the IBS has four simple guiding principles.

① Scientific excellence of researchers	② Openness through research collaboration
③ Creativity of research themes	④ Autonomy in research

The IBS supports curiosity-driven research which allows scientists to unleash their creative potential, address new scientific questions and expand the frontiers of science. For this the IBS provides center Directors with a stable longterm funding environment and research autonomy. The IBS currently supports 30 centers covering a wide range of subjects such as in physics, chemistry, life science, math, earth science and multidisciplinary sciences. For each IBS center a founding director (or Chief investigator) was selected through an extensive and thorough international review process. IBS centers strive to become world-leading global research hubs to make breakthrough discoveries and train the next generation of science leaders.

1.2
INSTITUTE FOR BASIC SCIENCE CENTER FOR CLIMATE PHYSICS

The Center for Climate Physics (ICCP) was launched by founding director Prof. Axel Timmermann in January 2017. The proposal to establish a center focusing on climate physics was supported by the IBS and by Pusan National University (PNU, South Korea), which hosts ICCP.

The mission of the IBS Center for Climate Physics (ICCP) is to enhance the basic understanding and improve the predictability of natural climate variability, anthropogenic climate change and their impacts on our global oceans, the hydrological cycle, regional processes, planetary life, ice-sheets and sea level.

The vision of ICCP is to make breakthroughs in understanding our climate system - its past, present, and future behavior, its predictability and its interactions with humans. ICCP provides fundamental scientific knowledge on the evolution of all the components of the climate system, including the atmosphere, hydrosphere, cryosphere, biosphere, geosphere and the anthroposphere. ICCP integrates theoretical, numerical, statistical, field, lab and observational research to make ground-breaking discoveries in climate science, catalyze paradigm shifts and launch new research directions.

Since its inception, the ICCP has developed into an internationally leading institute in the area of climate physics. It has published over 340 publications, organized 3 IBS conferences, 4 international workshops, and has held over 140 seminars since 2017. Establishing the ICCP and facilitating faculty recruitment of three professors to PNU (Prof. Christian Franzke, Prof. Wonsun Park, Prof. Eun-Young Kwon), Prof. Axel Timmermann

***Climate Physics* refers to the quantitative description, simulation, analysis and observation of complex earth system phenomena in the atmosphere, hydrosphere, biosphere, cryosphere, anthroposphere and their interactions.**

was instrumental in nucleating a world-leading hub, with expertise ranging from climate dynamics, earth system modeling, biogeochemistry and climate anthropology. ICCP also supports the research of two affiliate faculty members (Prof. Kyung-Ja Ha, Prof. June-Yi Lee) from other departments, which in turn contribute key expertise, notably in monsoon dynamics and climate predictability. ICCP provides a multi-disciplinary research environment to address and resolve some of the most challenging climate science questions. The fundamental research outcomes provide major leaps in our understanding of the physics of the earth system, its feedbacks, instabilities, sensitivities, and its effects on marine and terrestrial life on a wide range of timescales.

Our research is societally relevant, and it can help the general public, as well as policymakers develop better adaption strategies to minimize climate-induced risks.

Over the past 8 years ICCP has diligently pursued the mid- and longterm visions and synergistic strategies laid out in the original research proposal of the center. Through the generous funding provided by IBS and Ministry for Science and ICT, we have made fundamental contributions to advancing the overall field of climate physics, whilst also establishing a new research field – Climate Anthropology.
We have contributed to international and domestic activities and organizations (coordinating lead author of IPCC AR6, President of Korean Meteorological Society, WMO panel memberships, editors of relevant journals in earth science). We developed an extensive international collaborative research network, including labs in the USA, Germany, Norway, Italy, Australia, Japan, China and India.

Furthermore, through the purchase of our supercomputer Aleph, ICCP has become a

ICCP in Numbers

Rank. top-tier journal ratio	1st	Total Number of ICCPians	100
Number of nationalities	17	Number of Graduations	14
ICCP authored papers	340	Aleph Supercomputer (PFlops)	1.44
Gender Ratio (%)	53:47	Mass spectrometers	5
Most highly cited paper (WoS)	710	Fraction of papers in Science and Nature (%)	2.9
International Awards 10 / Domestic Awards	36	Number of visitors	140

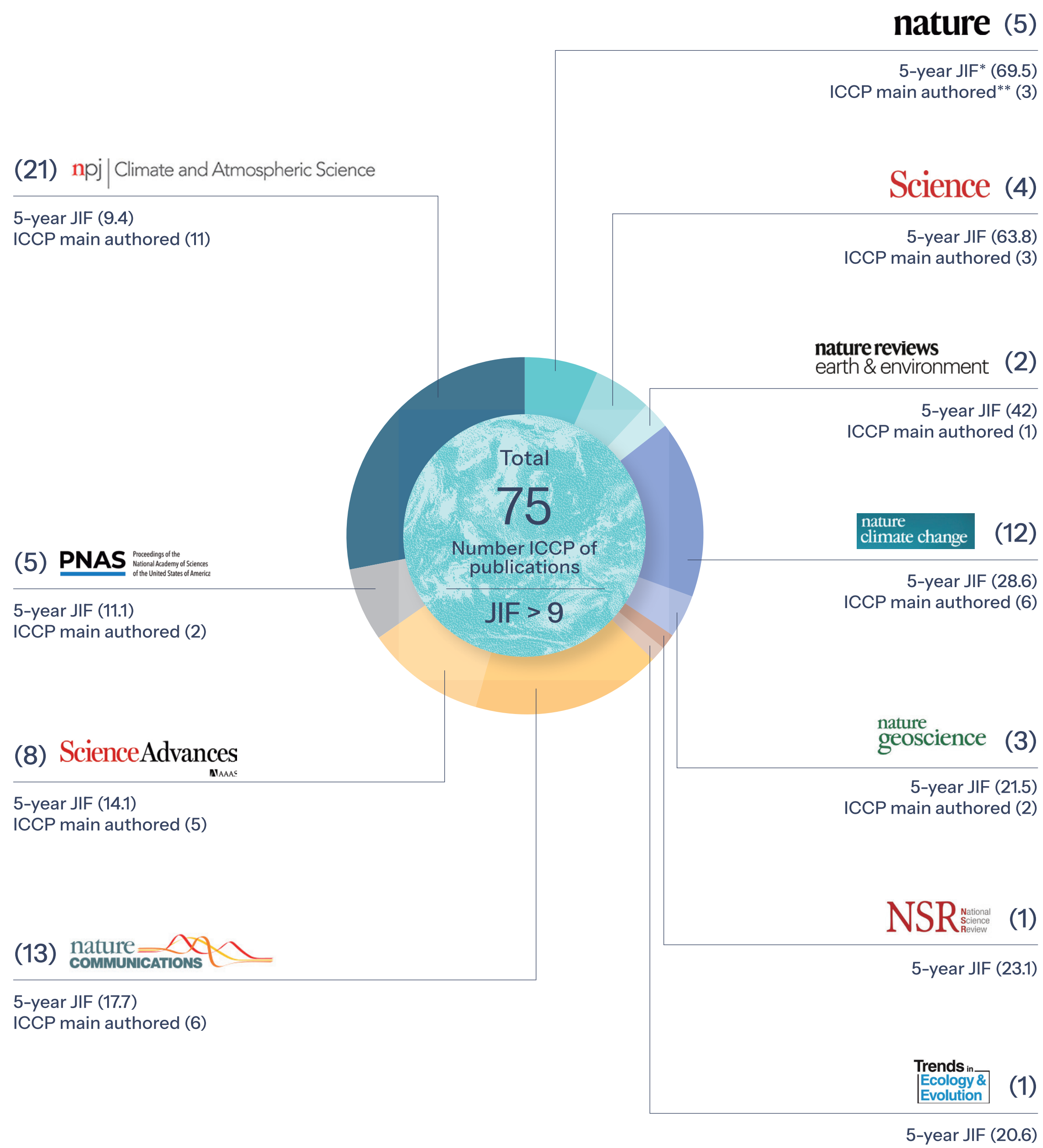
Since 2017, ICCP has employed 100 members from 17 countries, who published 340 scientific publications, 2.9% of them in the journals *Science and Nature*. According to the Web of Science, ICCP ranks first among world-leading climate institutions in terms of the percentage of studies published in *Nature, Science, Science Advances, Nature Communications.* Our scientists have received 10 international and 36 domestic awards and 14 of our master and PhD students graduated within the last 8 years. ICCP operates Aleph – one of South Korea's fastest supercomputers – and 5 mass spectrometers to simulate and reconstruct climate, respectively.

major powerhouse for climate supercomputing in Asia. This allowed our team to conduct some of the highest resolved global warming simulations, one of the most extensive large ensemble simulations and the longest transient paleo-climate model simulation.

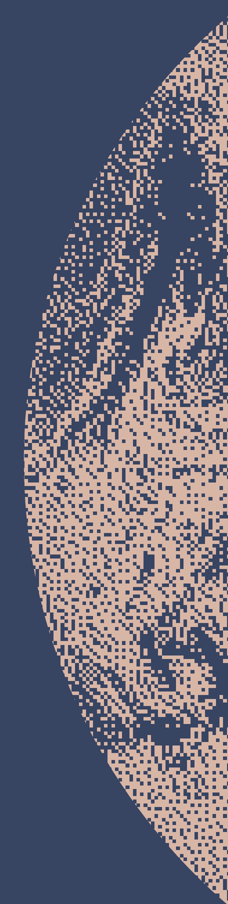
ICCP has developed a broad portfolio of outreach activities, which included a climate round-table discussion with the German Federal President Steinmeier and Korean climate activists (image, page 7), panel discussions with former US Vice President Al Gore, meetings with members of the German parliament, climate activist training in Seoul, ICCP open houses, citizen science programs, public lectures, museum activities, TV documentaries, TV and radio interviews, summer schools, high school internships and other events.

List of high-profile publications (5-year Journal Impact Factor > 9) published by ICCP scientists since 2017

* JIF, as of September 2024
** first, corresponding or co-corresponding author from ICCP





CHAPTER. 2

RESEARCH

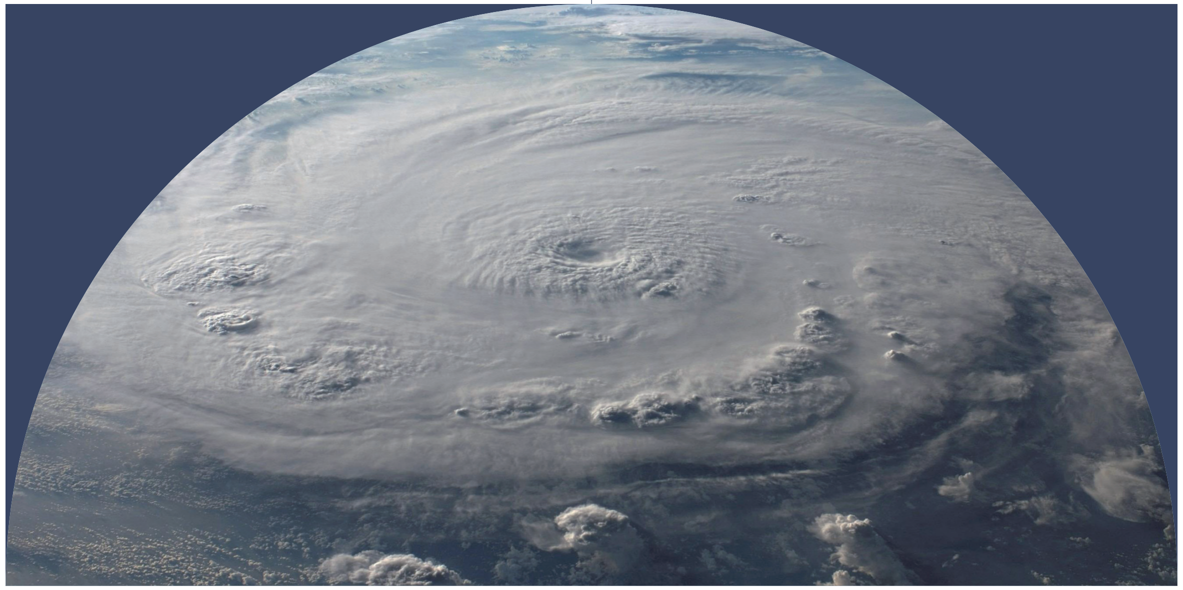
❶ RESEARCH THEMES

EARTH SYSTEM DYNAMICS

Our research on natural climate variability includes several key research areas :

- **Modes of natural climate variability:** This research area is dedicated to understanding the mechanisms that generate climate fluctuations on timescales of months to decades. Our research has contributed to a better understanding of the physical mechanisms responsible for the major modes of climate variability such as the Boreal Summer Intraseasonal Oscillation, the Madden Julian Oscillation, the Indian Ocean Dipole, the El Niño Southern Oscillation, and the Interdecadal Pacific Oscillation, as well as their coupling. ICCP researchers published numerous papers on these research questions – some highlights are presented further below.

- **Large-scale atmospheric circulation dynamics and teleconnections:** This research topic focuses on the coupling between climate phenomena via atmospheric teleconnection mechanisms. Using the phase synchronization concept we showed that the coupling between Hadley and Walker circulations occurs mainly during the decay phase of an El Niño event, when a meridionally asymmetric Walker circulation couples the zonal and meridional atmospheric overturning circulations. Furthermore, the coupling between ENSO and the Indian Summer monsoon was studied extensively. It was demonstrated that the multi-decadal changes in this relationship are consistent with a noisy ENSO teleconnection hypothesis and do not require external influences. Our scientists also identified an important atmospheric linkage that documents how decadal-scale shifts in the tropical Madden Julian Oscillation can contribute to the formation of long-term climate trends around Antarctica and the Southern Ocean. In another study, we addressed whether the recent multidecadal strengthening of the atmospheric Walker circulation is due to external (greenhouse gas) forcings. By analysing observational datasets, satellite data, reanalysis and climate model simulations, we demonstrated that the unusual trend is still in agreement with the null hypothesis of unforced (natural) variability.



- **Climate variability and energy cycles:** One way of better understanding the atmospheric dynamical processes associated with atmospheric modes of variability (e.g. NAO) is examining the energy budget and forcing terms. This is based on a local version of the Lorenz Energy Cycle which also includes moisture. Using this framework, we examined storms and extreme events in detail to elucidate the role played by diabatic heating, cloud-radiation interactions and scale-interactions and their relative roles in organizing large-scale atmospheric variability.

- **Asian Monsoon systems:** This research thrust focuses on the naturally occuring variability of the major global monsoon systems. More specifically, we examined the underlying mechanisms for extreme rainfall events over Asia. Moisture budget analysis of atmospheric reanalysis data revealed that anomalous monsoonal rainfall over East Asia is usually connected to strong continental heating, resulting in enhanced land-sea contrast. This process affects the western North Pacifc Subtropical High, which in turn changes the wind covergence in the East Asian region, leading to enhancement of regional rainfall. In some areas thermodynamic process can further contribute to rainfall enhancements. This work provided the general framework to understand the climatological drivers of recent trends in rainfall and extreme events over South Korea. We also examined how aerosol reductions over China during the Covid-19 lockdown impacted climate over Eastern Asia and found a discernible impact on early spring temperatures, but only weakly signicant effects on rainfall. Another observational study identified low soil moisture levels over the Iranian desert as a potential pre-cursor for the onsert of the Indian Summer Monsoon.

- **Synoptic extreme events:** ICCP researchers have studied synoptic atmospheric extreme events, which can lead to devastating impacts for local populations. This work includes studies on tornados and their linkage to ocean temperatures, the detection and dynamics of atmospheric rivers through new topological methods, the nature and mechanisms of sting jets over the North Atlantic, the dynamics and recent trends in North Atlantic winterstorms and tropical cyclone landfalls and extreme rainfall events on the Korean Peninsula.

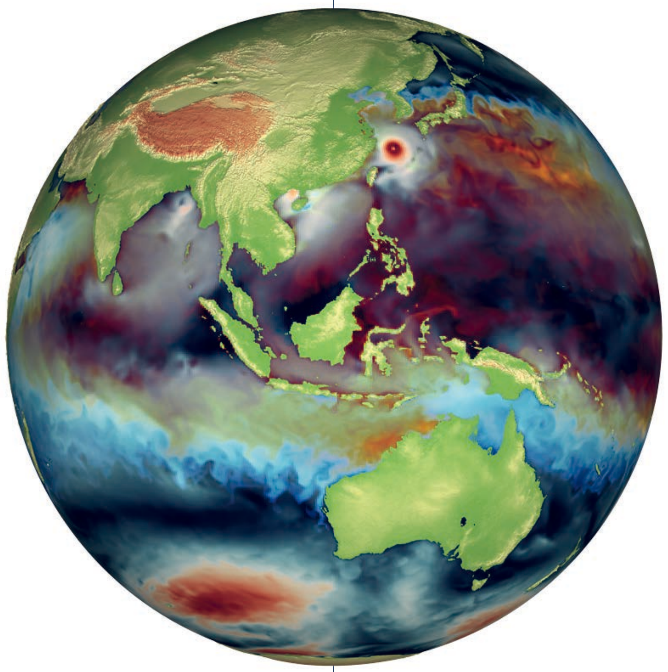
- **Asian heatwaves:** It is important to differentiate between dry and moist heatwaves. The former have severe impacts on agriculture, whereas the latter impact the well-being of humans and livestock. To determine the underlying patterns, mechanisms and feedbacks between moisture and extreme heat, we conducted several diagnostic and modeling studies on compound heatwaves. In northeastern Asia dry heatwave region, convergence of anomalous wave activity fluxes creates an anticyclonic circulation, which in turn increases surface temperatures. In contrast, moist heatwaves in the southeastern part of Asia are triggered by locally generated anticyclonic anomalies, and surface warming is amplified by cloud and water vapor feedbacks.

- **Climate and fire:** By combining observational, satellite data and climate model simulations, ICCP scientists examined the role of ENSO and the Indian Ocean Dipole on vegetation and wildfires in eastern Africa. The research demonstrated that ENSO's influence on wildfires in Tanzania can be muted due to interannually-occuring temperature anomalies in the Indian Ocean. During Summer wildfires in the extratropics often occur after persistent days of high pressure conditions. ICCP members examined the linkage between large-scale stationary waves and the synchronized development of wildfires across the northern Hemisphere using observational datasets and earth system model simulations. Our analyses identifies large-scale (potentially predictable) wavenumber 5-7 pre-cursors of wildfires and the subsequent effects on air-quality. In addition, ICCP scientists, in collaboration with colleagues from Yonsei University, Seoul developed a new conceptual model that efficiently describes the coupled climate-vegetation-fire dynamics with just a few basic equations. In a recent study, using the CESM2 Large Ensemble, we further discovered that interannual subarctic biomass burning can generate decadal-scale variations in atmospheric temperatures due to a spectral reddening processes, which involves permafrost thawing. This represents an entirely new pathway of how fires can influence climate and decadal timescales.

5 representative publications

1. Dynamics of Extreme Surface Winds Inside North Atlantic Midlatitude Cyclones, Jun-Hyeok Son, Christian L.E. Franzke, Seok-Woo Son, **Geophysical Research Letters**, vol. 51, 14, e2024GL110330, doi: 10.1029/2024GL110330 (2024)
2. Interannual fires as a source for subarctic summer decadal climate variability mediated by permafrost thawing, Ji-Eun Kim, Ryohei Yamaguchi, Keith B. Rodgers, Axel Timmermann, Sun-Seon Lee, Karl Stein, Gokhan Danabasoglu, Jean-Francois Lamarque, John T. Fasullo, Clara Deser, Nań Rosenbloom, Jim Edwards, Malte F. Stuecker, **npj Climate and Atmospheric Science**, vol. 6, 1, article 84, doi: 10.1038/s41612-023-00415-1 (2023)
3. Reconciling opposing Walker circulation trends in observations and model projections, Eui-Seok Chung, Axel Timmermann, Brian J Soden, Kyung-Ja Ha, Lei Shi, Viju O John. **Nature Climate Change**, vol. 9, pp. 405-412, DOI: 10.1038/s41558-019-0446-4 (2019)
4. El Niño–Southern Oscillation complexity, Axel Timmermann, Soon-Il An, Jong-Seong Kug, Fei-Fei Jin, Wenju Cai, Antonietta Capotondi, Kim M. Cobb, Matthieu Lengaigne, Michael J. McPhaden, Malte F. Stuecker, Karl Stein, Andrew T. Wittenberg, Kyung-Sook Yun, Tobias Bayr, Han-Ching Chen, Yoshimitsu Chikamoto, Boris Dewitte, Dietmar Dommenget, Pamela Grothe, Eric Guilyardi, Yoo-Geun Ham, Michiya Hayashi, Sarah Ineson, Daehyun Kang, Sunyong Kim, WonMoo Kim, June-Yi Lee, Tim Li, Jing-Jia Luo, Shayne McGregor, Yann Planton, Scott Power, Harun Rashid, Hong-Li Ren, Agus Santoso, Ken Takahashi, Alexander Todd, Guomin Wang, Guojian Wang, Ruihuang Xie, Woo-Hyun Yang, Sang-Wook Yeh, Jinho Yoon, Elke Zeller, Xuebin Zhang. **Nature**, vol. 559, 7715, pp. 535-545, DOI: 10.1038/s41586-018-0252-6 (2018)
5. Disentangling Impacts of Dynamic and Thermodynamic Components on Late Summer Rainfall Anomalies in East Asia, Hyoeun Oh, Kyung-Ja Ha, Axel Timmermann. **Journal of Geophysical Research: Atmospheres**, vol. 123, 16, pp. 8623-8633, DOI: 10.1016/j.atmosenv.2018.06.012 (2018)

Publications in this research theme appeared in journals such as Geophysical Research Letters (21), Journal of Climate (11), Climate Dynamics (14), npj Climate and Atmospheric Science (6), Nature Communications (3), Nature Climate Change (2) etc.



Snapshot of wind speed and SST in CESM1 high resolution simulation

EARTH SYSTEM SENSITIVITY

One of our largest research thrusts in ICCP focuses on the response of the earth system to anthropogenic forcings. It covers the following areas:

- **Modes of climate variability in a warmer world:** We have conducted several studies focusing on the sensitivity of major climate modes (such as MJO, ENSO and IOD) to greenhouse warming. In particular the use of ICCP HR-CESM1.2 simulations provided new insights into the role of mesoscale oceanic processes on ENSO dynamics and a simulated suppression of future ENSO variance. Moreover, the ICCP/NCAR CESM2 large ensemble has been used to study the robustness of projected changes in climate modes and the emergence of anthropogenic signals above the natural background level. In a collaborative study with NCAR/CESM colleagues, we provide a more generalized large-ensemble framework to discuss the ubiquity of changes in climate statistics, including modes of climate variability.

- **Monsoons in a warmer world:** The East Asian summer monsoon (EASM) is a key component of the Asian climate system with impacts on agriculture and water resources for millions of people. It varies on a variety of timescales and ICCP researchers use a wide range of methods to elucidate the underlying dynamics of these fluctuations, as well as to identify potential anthropogenic trends. Several CMIP-based assessments have been carried out to identify the areas that will experience the largest rainfall increase in response to greenhouse warming and the detectabiliy of these projected changes against natural variability. Other research has focused on the effect of greenhouse warming on the evaporative demand over East Asia, which is relevant for agriculture. ICCP researchers also published an overview paper how the East Asian Summer Monsoon responds to greenhouse warming using the HR-CESM1.2 model simulations conducted at ICCP.

- **Weather phenomena in a warmer world:** This project focuses on the response of tropical cyclones and storms to greenhouse warming. The research uses the HR-CESM1.2 simulations to examine future projections of atmospheric rivers (AR) and tropical cyclones (TC). ARs are elongated water wapor filaments in the atmosphere, that can cause extreme flooding in some areas (e.g. California) and contribute substantially even to the annual mean rainfall amount. We developed a new detection algorithm, that is less biased towards water vapor, but captures more the dynamical and topological structures of the atmospheric flow and water vapor filaments. According to this new algorithm, the number of atmospheric rivers will remain relatively stable in future, even for atmospheric CO_2 doubling. However, the associated rainfall per AR will increase substantially. The analysis of tropical cyclones in a warmer world, using the HR-CESM1.2 shows that a future reduction of rising motion in the tropical atmosphere will attenuate tropical cyclone development, which explains the projected future suppression in tropical cyclone seeds and overall numbers in the Pacific and Indian Ocean. Although for a CO_2 doubling the total number of tropical cyclones is expected to decrease in future, developing events will have much higher chance to intensify beyond category 3 due to higher humidity and energy levels in the atmosphere. Moreover, future TCs will bring more rainfall to coastal regions, as they make landfall.

- **Lake systems in a warmer world:** Lake systems have not received much attention by the global climate change community, in part due to the fact that their dynamics and thermodynamics were only crudely parameterized in recent earth system models or captured only in offline models. We launched several research studies focusing on the effect of greenhouse warming on lake ice, lake stratification, emergence of no-analogue conditions in global lakes. To this end the CESM2 large ensemble simulations (LENS) have proven very useful, because CESM2 includes a relatively sophisticated 1 dimensional lake model (part of the Community Land Model (CLM), version 5), which parameterizes lake mixing more realistically and accounts for coupling with the atmosphere. Furthermore, we used the HR-CESM1.2, which resolves the Caspian Sea and the Black Sea at 1/10 degree horizontal resolution, to study their response to greenhouse warming. In this project we focused on temperature and wind-driven circulation changes as well as on the net water balance and resulting lake level projections. Our manuscript was the first study that uses a high resolution climate model to address the future state of these important inland water bodies.

- **Wildfires in a warmer world:** It has been widely accepted that greenhouse warming will affect wildfire activity in many regions. However, given that wildfire models are still relatively simple for the majority of CMIP6-type models, the underlying mechanisms and the robustness of the projected patterns remain elusive. In our CESM2 large ensemble

simulations (CESM-LENS), the CLM5 includes a relatively complex wildfire model, which interacts with soil moisture and permafrost. In the SSP370 simulations with the CESM-LENS we see an abrupt increase in wildfire activity in the Siberian and Canadian Arctic, which can be explained by soil drying, due to the rapid onset of permafrost thawing and drainage of waters. ICCP researchers also improved the fire module in the CESM2 model and developed a more realistic lightning scheme, which uses information about the atmospheric state. Greenhouse warming simulations with this new module implemented in CESM2 are currently underway.

- **Ice-sheets in a warmer world:** Most CMIP6 models do not include interactive ice-sheets and future simulations of Greenland and Antarctica are commonly conducted as offline simulations, which do not include the full coupling with the climate system. To improve this situation, we developed a new coupled modeling framework which includes a) LOVECLIM and the CESM1.2 as climate models and b) the bi-hemispheric Penn State ice-sheet model. The coupled LOVECLIM + Penn State ice-sheet model (which also includes an explicit iceberg model) has been used to quantify the effect of greenhouse warming on the stability of the Greenland and Antarctic ice-sheets and to understand the role of atmosphere/ocean/ice-sheet coupling in the Southern Hemisphere. We ran several greenhouse gas emission scenarios and found that the model simulates an irreversible ice-loss and unabated acceleration of sea level for the SSP2-4.5 and SSP5-8.5 emission scenarios – with the Antarctic ice-sheet and Greenland ice-sheet contributing together up to 135 cm over the next 130 years. According to the model simulations, only the SSP1-1.9 emission scenario, which limits global warming to ~1.5 °C relative to 1850–1900, leads to a gradual slow-down in the rate of global sea level rise. We also found that the ocean subsurface warming accelerates basal melting in Antarctica, which can trigger the Marine Ice-sheet instability. However, this effect is partly compensated in terms of global sea-level contribution by the fact that Antarctic meltwater forcing will cool down the Southern Hemisphere substantially, which will also leads to a reduction in surface melting. This important atmospheric response has previously not been considered in the context of future sea level rise. Similar experiments are currently underway with the new coupled 1.9 degree CESM1.2+Penn state ice-sheet model.

- **Oceans in a warmer world:** The coupled ocean-eddy resolving simulations (HR-CESM1.2 and OpenIFS-FESOM2) conducted at ICCP open a unique opportunity to study the ocean eddies, and their response to future warming. To this end we calculated finite sized Lyapunov exponents (FSLE) of upper ocean currents to study the impact of future wind and stratification changes on ocean shear, divergence, and particle dispersal. Analyzing the HR-CESM1.2 simulations, we found major changes in FSLE in the Arctic Ocean, due to a reduction of Arctic sea ice. Otherwise on a global scale the ocean eddy fields seem to be relatively stable, even with respect to quadrupling of CO_2. A more detailed analysis into the energy and momentum budget terms of eddies has further revealed the causes for regional changes and the importance of wind and density-driven shifts in ocean fronts and increased stratification in these simulations. Previous studies have documented the important role of vertical (circumpolar deep water intrusions) and lateral processes (Antarctic slope current) for the Antarctic sub-shelf heat budget, melting and potential grounding line retreat of the West Antarctic ice-sheet. We studied the projected changes of ocean currents around Antarctica and their potential contribution to sub-shelf melting using the HR-CESM1.2 model simulation in present-day, $2xCO_2$ and $4xCO_4$ simulations. ICCP researchers discovered that future sea-ice melting and the resulting different salinity gradients will intensify the Antarctic Slope current, which can accelerate sub-shelf melting. As part of the "Oceans in a warmer world" project we also studied the impact of tropical rainfall (and its projected future changes) on the equatorial ocean circulation, stratification and sensitivity to wind stress forcing. Using the 1.9 degree resolution CESM 1.2 model we conducted several tropical water hosing experiments that show a strong sensitivity of the background state and its variability to future projected enhancement of rainfall on the equator.

- **Next-generation climate model projections:** Clouds, a crucial element of the atmospheric heat balance, are still not properly resolved in the current generation of CMIP6 models. To push our current greenhouse warming modeling capabilities even beyond those of ICCP's HR-CESM1.2 simulations the ICCP started a new collaboration with the Alfred Wegener Institute, Bremerhaven, Germany to conduct cloud-"permitting" (storm-resolving) model simulations with the AWI-CM3 (OpenIFS + Fesom). To this end we completed a series of transient 10-year long coupled simulations at 9 km atmosphere and 4-25 km ocean resolution. These simulations, which represent the conditions for the 2000s, 2030s, 2060s, 2090s following the SSP 5-8.5 scenario were initialized from a transient greenhouse warming simulation at 31 km resolution. The simulations used about 67 million CPU hours on the ICCP/IBS Aleph and KMA Guru supercomputers and the data are currently being analysed extensively to study: i) Sub-mesoscale ocean variability and its response to future warming, ii) The role of clouds in future climate changes (feedback analysis), iii) Scale dependence of extreme events and frontal dynamics; iv) Dynamics of tropical cyclones (role of clouds, convection, eye-wall dynamics); v) Future climate change in montane regions (e.g. Alps, Himalaya, Rocky Mountains, Andes, vi) high resolution representation of modes of climate variability. New 4 km resolution coupled snapshot simulations are currently being prepared for the Aleph supercomputer.

5 representative publications

1. Future Indian Ocean Warming patterns, Sahil Sharma, Kyung-Ja Ha, Ryohei Yamaguchi, Keith B. Rodgers, Axel Timmermann, Euiseok Chung, **Nature Communications**, vol. 14, article 1789, doi: 10.1038/s41467-023-37435-7 (2023)
2. Future sea-level projections with a coupled atmosphere-ocean-ice-sheet model , Jun Young Park, Fabian Schloesser, Axel Timmermann, Dipayan Choudhury, June-Yi Lee, and Arjun Babu Nellikkattil, **Nature Communications**. doi: 10.1038/s41467-023-36051-9 (2023)

3 Ubiquity of human-induced changes in climate variability, Keith B. Rodgers, Sun-Seon Lee, Nan Rosenbloom, Axel Timmermann, Gokhan Danabasoglu, Clara Deser, Jim Edwards, Ji-Eun Kim, Isla R. Simpson, Karl Stein, Malte F. Stuecker, Ryohei Yamaguchi, Tamas Bodai, Eui-Seok Chung, Lei Huang, Who M. Kim, Jean-Francois Lamarque, Danica L. Lombardozzi, William R. Wider, and Stephen G. Yeager, **Earth System Dynamics**, vol.12, 4, pp. 1393-1411, DOI: 10.5194/esd-12-1393-2021 (2021)

4 Future high-resolution El Niño/Southern Oscillation dynamics, Christian Wengel, Sun-Seon Lee, Malte F. Stuecker, Axel Timmermann, Jung-Eun Chu, Fabian Schloesser, **Nature Climate Change**, vol.11, pp. 758-765, DOI: 10.1038/s41558-021-01132-4 (2021)

5 Reduced tropical cyclone densities and ocean effects due to anthropogenic greenhouse warming, Jung-Eun Chu, Sun-Seon Lee, Axel Timmermann, Christian Wengel, Malte F. Stuecker, Ryohei Yamaguchi, **Science Advances**, vol.6, 51, eabd5109, DOI: 10.1126/sciadv.abd5109 (2020)

Publications in this research theme appeared in journals such Geophysical Research Letters (6), Environmental Research Letters (9), Earth's Future (6), npj Climate and Atmospheric Science (10), Nature Communications (7), Nature Climate Change (6), Nature (3), Communications Earth & Environment (5) etc.

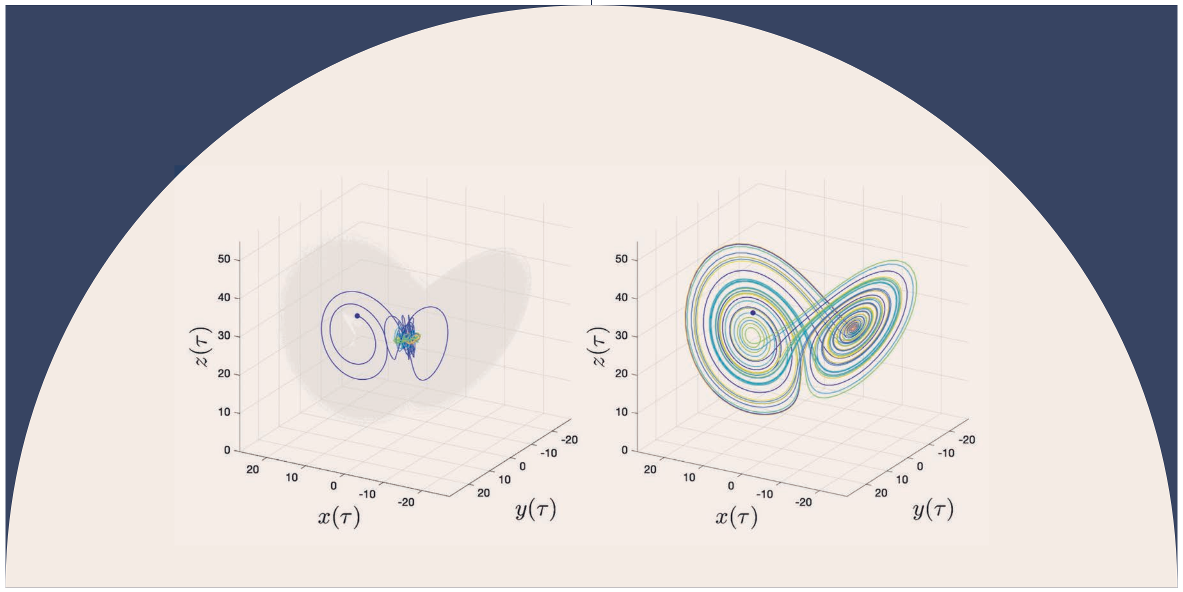
Future warming projection from 9 km climate model

EARTH SYSTEM PREDICTABILITY

Explaining and predicting Earth System changes for the next several decades and beyond is one of in the new World Climate Research Program (WCRP) Lighthouse Activities initiated in 2020. ICCP scientists have explored variability and predictability of Earth System components, such as modes of variability, total soil water, wildfire, sea level, and statistics of climate extremes, on subseasonal to interdecadal timescales mainly based on long-term simulations and 10-year hindcasts with the low-resolution version of CESM1. In addition to that, we have completed new sets of model experiments with data assimilation and hindcasts with CESM2 to further enhance our capability of understanding and predicting Earth system variability and changes across time scales with a more realistic climate model.

Specifically ICCP scientists studied:

- **Predictability theory of earth system components:** To test the fidelity of climate prediction models, it is important to benchmark them against physical null hypothesis models. These exist for SST and soil moisture, but have not been developed systematically for other climatic variables. Using a stochastic modeling framework, we developed a new null hypothesis model for surface runoff. Based on water balance and threshold run-off criteria, we are able to find analytical solutions for the underlying Fokker Planck equations, which can serve to benchmark comprehensive earth system models used in multi-year to decadal predictions.



- **Multi-year initialized CESM1 and CESM2 predictions:** To explain and predict near-term Earth System variability and changes, we performed decadal hindcasts with the CESM1 (3x3 degrees resolution) and CESM2 models (nominal 1x1 degree horizontal resolution) (using 3-dimensional ocean temperature and salinity anomaly data assimilation system) including biogeochemistry and future forcing from a new NDC-compatible pathway. Our model set-up reduces bias drifts and coupling shocks which translates into better forecast skill and eliminates the necessity to apply a posteriori corrections to the forecasts. The original CESM1 set-up demonstated longterm predictability for drought, vegetation and wildfire over North America. This is also found in the forecasts conducted with the CESM2 model, which includes a more sophisticated land surface model. The 20-member CESM2 multi-year forecast were run on the ICCP/IBS supercomputer Aleph and generated about 2 PBytes of data. The data are currently being analysed by a team of scientists from the ICCP, the Bjerknes Centre in Norway and Utah State University in Logan, United States. We have identifed the physical sources of multiyear preditability marine biogeochemical predictability and developed improved forecast skill metrics, that do not rely on ensemble mean averaging.

5 representative publications

1. Summer midlatitude stationary wave patterns synchronize Northern Hemisphere wildfire occurrence, Hien X. Bui, Axel Timmermann, June-Yi Lee, Eric D. Maloney, Yi-Xian Li, Ji-Eun Kim, Jacquelyn Shuman, Sun-Seon Lee, and William R. Wieder, **Geophysical Research Letters**, vol. 49, 18, e2022GL099017, doi: 10.1029/2022GL099017 (2022)
2. A low order dynamical model for runoff predictability, Roman Olson, Axel Timmermann, June-Yi Lee, Soon-Il An, **Climate Dynamics**, vol.56, 1-2, 399-422, DOI: 10.1007/s00382-020-05479-w (2021)
3. Improved Predictability of the Indian Ocean Dipole Using Seasonally Modulated ENSO Forcing Forecasts, Sen Zhao, Fei-Fei Jin, Malte F Stuecker, **Geophysical Research Letters**, vol. 46, 16, pp. 9980-9990, DOI: 10.1029/2019GL084196 (2019)
4. A drift-free decadal climate prediction system for the Community Earth System Model, Yoshimitsu Chikamoto, Axel Timmermann, Matthew J. Widlansky, Shaoqing Zhang, Magdalena A. Balmaseda. **Journal of Climate**, vol. 32, 18, pp. 5967-5995, DOI: 10.1175/JCLI-D-18-0788.1 (2019)
5. Multi-year predictability of climate, drought, and wildfire in southwestern North America, Yoshimitsu Chikamoto, Axel Timmermann, Matthew J Widlansky, Magdalena A Balmaseda, Lowell Stott. **Scientific reports**, vol. 7, 1, pp. 6568, DOI: 10.1038/s41598-017-06869-7 (2017)

Publications in this research theme appeared in journals such Climate Dynamics (3), Bulletin of the American Meteorological Society (2), etc.

EARTH SYSTEM HISTORY

This ICCP research theme focuses on the mechanisms of past climate change. Scientists in our center conduct field and lab work to reconstruct the past history of the climate system using speleothems. We also embark on ambitious climate modeling projects to simulate the response of the climate system, ice-sheets, vegetation to past forcings, such as ice-sheet meltwater forcing on millennial timescales or Milanković forcing on orbital timescales. This research theme integrates different modeling approaches with paleo-climate reconstructions and data analysis. The following paragraphs provide a brief summary of some of the completed and ongoing research projects.

- **Paleo-climate reconstruction methods:** Several climate field reconstruction methods assume stationarity between the leading patterns of variability identified during the instrumental calibration period and the reconstruction period. We examined how and to what extent this restrictive assumption may generate uncertainties in reconstructing past tropical Pacific climate variability. Based on the Last Millennium ensemble simulations previously conducted with the Community Earth System Model and by developing a series of pseudoproxy reconstructions for different calibration periods, we find that the overall reconstruction skill for global and more regional-scale climate indices depends significantly on the magnitude of externally

forced global mean temperature variability during the chosen calibration period. This effect strongly reduces the fidelity of reconstructions of decadal to centennial-scale tropical climate variability, associated with the interdecadal Pacific oscillation (IPO) and centennial-scale temperature shifts between the Medieval Climate Anomaly and the Little Ice Age.

- **Mechanisms for abrupt climate change:** Our research on abrupt climate change focuses on threshold points in the ice-sheet, AMOC and permafrost systems and their large-scale impact on the climate system. The research encompasses several studies which are based on freshwater perturbation studies that we conducted using the CESM1.2 model in various resolutions. To mimick ice-sheet instabilities during the 1.126 Ma terminal stadial event and the 16 ka abrupt climate change event, we prescribed anomalous freshwater fluxes to the North Atlantic in various forcing scenarios. The simulation of the 1.126 Ma rapid climate change event - possibly the first massive millennial-scale Pleistocene cooling event in the North Atlantic – was compared extensively with paleo-proxy data and further served as input of a hominin habitat model. Based on these simulations, it was argued that this event may have triggered the depopulation of Europe by *H. erectus* at that time, in accordance with archeological evidence. This paper was published with ICCP-co-corresponding authorship in 2023 in *Science*. The 16 ka abrupt climate change event, with evidence for a massive cooling across Europe and Eastern Asia, has been at the core of some model simulations and high-resolution isotope and trace element analyses of speleothem data.

- **Tropical cyclones and past climate change:** Using the HR-CESM1.2 simulations in a series of paleo-snapshot simulations for extreme precessional conditions (125 ka and 115 ka), we examined the role of orbitally-induced changes in the seasonal cycle of solar insolation on the genesis and dynamics of tropical cyclones. Tropical cyclones are well resolved in these model simulations and this allowed us for the first time to test the fidelity of diagnostic tropical cyclone metrics (e.g., Genesis Potential Index, GPI) under very different climate background conditions. By comparing GPI-based estimates of tropical cyclone development with the actual simulated tropical cyclones densities and amplitudes for these two paleo time-slices and future climate change snapshots and 2xCO_2, we were able to confirm that GPI is a useful predictive tool to characterize tropical cyclones responses to climate change – past, present and future.

- **Milanković cycles in climate, ice-sheets, vegetation and carbon cycle:** ICCP scientists launched several research projects to study the impact of orbital forcing on climate, ice-sheets and the carbon cycle. This research is carried out with the CESM1.2, the LOVECLIM intermediate complexity model and offline carbon cycle and ice-sheet models, such as cGenie and the Penn State Ice-Sheet Model. Our earlier studies using LOVECLIM model and a transient simulation which covered the climate history of the last 784 ka, addressed whether paleo-climate model simulations can be used to infer the equilibrium climate sensitivity (ECS) using paleo-climate constrains. We found that paleo-climate data are consistent with the upper range of the IPCC AR5 estimates of ECS. The 784 ka simulation was also used to force an offline carbon cycle model. Our results show the importance of Southern Ocean processes in controlling glacial-interglacial CO_2 variations, mostly through sea-ice air-sea gas capping, brine-enhanced bottom water formation and a modulation of carbon exposure times. In addition to the southern hemisphere, we have also demonstrated how northern hemisphere ice-sheet build-up and the reduced fluxes of the Arctic rivers can contribute to the overall increase of glacial mean ocean salinity and further enhanced glacial ocean stratification and carbon sequestration. In 2022 we completed a transient paleo-climate model simulation covering earth's history of the past 3 Ma years using the CESM1.2 model in 3.8 degree horizontal resolution. This longest climate model simulation conducted to date uses an orbital acceleration of 5, which means the entire model simulation includes 600,000 model years. This simulation has become the main basis for a number of studies in ICCP, which include 3 Ma transient offline vegetation model simulations using the BIOME4 model, offline simulation with the cGENIE carbon cycle model, which assimilate temperature and salinity data from the CESM1.2 run, an offline simulation with the bi-hemispheric Penn State Ice-sheet model, forced with the 3 Ma CESM1.2 model data, and various human habitat and agent-based model simulations, described further below.

- **Water isotopes and Monsoon systems:** Water isotopes have become a powerful tracer to study regional and large-scale atmospheric dynamics. Water isotopes are also captured in speleothem calcite (apart from a usually small temperature effect), which allows scientists to reconstruct atmospheric circulation and precipitation changes using stalagmites. South Korea has many limestone caves, which makes it possible to reconstruct past changes of the East Asian Monsoon system back in time. ICCP follows a two-pronged approach: we collect monthly rainwater samples in Busan and previously at 12 other sites across Korea through the KWIN program (see outreach section), as well as cave drip water samples. These samples are regularly analysed with ICCP's water isotope analyser. In combination with the isotope-enabled CESM (iCESM) and water vapor back-tracking tools, ICCP scientists study the underlying dynamical processes that are responsible for seasonal to interannual changes in $\delta^{18}O$, δD and deuterium excess. This information is then used, in combination with in-site cave calcite growth experiments in the interpretation of the speleothem $\delta^{18}O$, which is measured at ICCP's two Isotope Ratio Mass spectrometers (MAT253 Plus and Delta Q). This research sheds new light on past changes of the East Asian monsoon system and the mapping between atmospheric circulation changes and water istotopes.

- **Reconstructing past climate changes using speleothems:** The main goal of this research project is to develop a rainfall, atmospheric circulation and temperature reconstructions of climate covering at least the last 4 glacial cycles in South Korea and other regions. To this end ICCP scientists have conducted extensive oxygen and carbon and clumped isotope, trace element, Tex86, U/Th analyses on a number speleothems. In combination with isotope-enable orbitally-forced CESM simulations and the 3 Ma CESM1.2 simulation, we elucidated the mechanisms of orbital-scale climate variability of the East Asian Summer Monsoon. It was demonstrated that water isotope variability in the western part of the EASM domain is strongly controlled by precessional changes in Indian summer monsoon intensity and associated moisture transport changes. In contrast, in the eastern part of the EASM domain, including the Korean Peninsula and Japan, precessional variability in precipitation-$\delta^{18}O$ is muted due to compensating effects of oceanic and continental moisture sources. We also reconstructed temperatures from South Korean speleothems using both clumped isotopes, and organic biomarkers (Tex86), which are generated by archaea living in cave environments. The orbital-scale variability shows a strong in-phase relationship with CO_2 forcing, but also noticable deviations during glacial inceptions which highlight the potential role of dust forcing. In another ongoing project, we are reconstructing sub-annual climate variations from speleothems that we obtained during our fieldwork in Botswana. Climate in the Botswana Kalahari is partly impacted on interannual timescales by the Indian Ocean Dipole. Using 6 speleothem samples from this area, we are obtaining deeper insights into the low-frequncy modulation of the IOD. This research is quite time-consuming, because we pursue rather comprehensive multi-proxy approach. To this end ICCP researchers obtained over 80 U/Th ages at a radiometric dating facility in Xi'an, China and a number of radiocarbon dates. We are now combining standard isotope analysis (in-house), with ultra-high resolution trace element measurements (in-house), and speleothem fabric analysis, which relies on Scanning Electron Microscopy (at PNU) and Raman Spectroscopy (at UNIST).

- **Past-to-future climate-ice sheet model simulations:** ICCP researchers in collaboration with colleagues at the University of Hawaii coupled the LOVECLIM earth system model of intermediate complexity to the Penn State ice-sheet model and ran fully coupled transient glacial-interglacial cycle simulations with this model from Marine Isotope Stage 7 to Marine Isotope Stage 6. The same model was then used for future climate change simulations to develop improved projections of future sea-level rise. Using a similar coupling script, we then developed the coupled CESM1.2 + Penn State ice-sheet model which has been used in a series of transient paleo-climate model simulations. We focused mostly on simulating the last glacial cycle. The coupled model exhibits multiple equilibria and tuning the model parameters to obtain a realistic glacial/interglacial trajectory took almost 3 years. The runs are now being analyzed in terms of ice-sheet dynamics, ice-sheet climate interactions and abrupt ice-sheet instabilities.

To obtain a longer-term view of the Antarctic ice-sheet and its response to orbital-scale forcings, we used the 784 ka LOVECLIM and the 3 Ma CESM1.2 simulations and forced the Penn State ice-sheet model offline. The results demonstrated an important hitherto unknown response of the Antarctic ice-sheet to precessional forcing as well as an abrupt transition in ice-dynamics during the Mid-Pleistocene transition ~ 1 million years ago.

5 representative publications

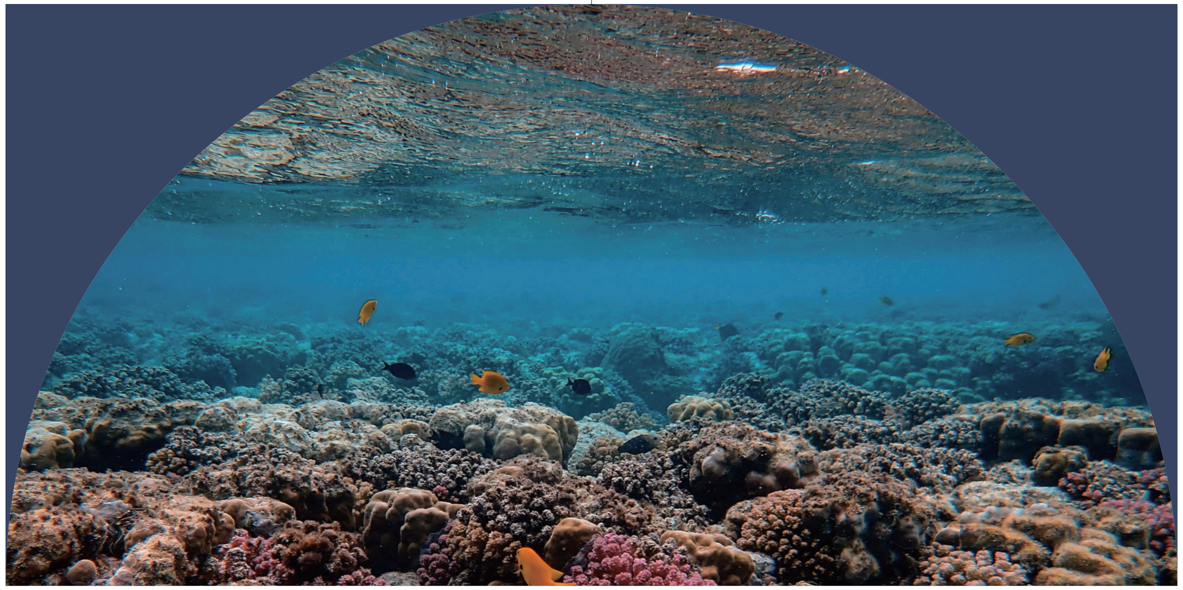
1. Trace element partitioning: effects of prior calcite / aragonite precipitation on cave drip water compositions, Jasper A. Wassenburg, Anupam Samanta, Lijuan Sha, Hosun Lee, Denis Scholz, Hai Cheng, Brigitte Stoll, Yassine Ait Brahim, Alexander Budsky, Sebastian F. M. Breitenbach, **Communications Earth & Environment**, 5, 488 (2024)
2. A transient coupled general circulation model (CGCM) simulation of the past 3 million years, Kyung-Sook Yun, Axel Timmermann, Sun-Seon Lee, Matteo Willeit, Andrey Ganopolski, Jyoti Jadhav, **Climate of the Past**, vol. 19, 10, pp. 1951 – 1974, doi: 10.5194/cp-19-1951-2023 (2023)
3. Simulating Marine Isotope Stage 7 with a coupled climate-ice sheet model, Dipayan Choudhury, Axel Timmermann, Fabian Schloesser, Malte Heinemann, David Pollard, **Climate of the Past**, DOI: 10.5194/cp-2020-46 (2020)
4. Timing and magnitude of Southern Ocean sea ice/carbon cycle feedbacks, Karl Stein, Axel Timmermann, Eun Young Kwon, Tobias Friedrich, **Proceedings of the National Academy of Sciences of the United States of America**, vol. 117, 9, pp. 4498-4504, DOI: 10.1073/pnas.1908670117 (2020)
5. Nonlinear response of the Antarctic Ice Sheet to late Quaternary sea level and climate forcing, Michelle Tigchelaar, Axel Timmermann, Tobias Friedrich, Malte Heinemann, David Pollard, **The Cryosphere**, vol. 13, 10, pp. 2615-2631, DOI: 10.5194/tc-13-2615-2019 (2019)

Publications in this research theme appeared in journals such Climate of the Past (3), Science Advances (2), Earth and Planetary Science Letters (2), Nature (1) etc.

CLIMATE, LIFE AND CARBON CYCLE

This research theme aims at identifying and quantifying the impact of past, present and future climate change on human systems, marine biogeochemistry, terrestrial ecosystems and the global carbon cycle. Our research in these areas has generated a number of high-profile papers (including 2 in Nature and 3 in Science as lead or corresponding authors). The paragraphs below provide an overview of the completed and ongoing research projects during the last 8 years.

- **Past Climate effects on human dispersal:** To study the impact of Milanković cycles and Dansgaard-Oeschger variability on past human dispersal, competition, cultural exchanges and extinction, we developed a human dispersal model (HDM), which has been applied in various studies. The HDM includes the dispersal and interaction of different hominin groups, megafauna and also the development of culture through cultural learning. The model is forced by climate data from the 3 Ma Pleistocene CESM simulation. More specifically, we adopted precipitation and temperature downscaling in combination with net primary production calculated from BIOME4 to implement the climatic effects on food and resource availability. The model has been used to study the extinction of Neanderthals through competitive exclusion with *H. sapiens* and the role of of past climate change in this process. Additional simulations have been conducted that introduce culture as a booster for carrying capacity as well as a dynamical stochastic state-dependent culture equation. Our results demonstrate that even a small increase in the cultural learning rate of one species can over time lead to a competitive exclusion of a less well-developed human species.



- **Past Climate effects on natural selection and genetic diversification:** To understand how past environmental changes contributed to cladogenic transitions and species successions or interactions, it is paramount to first determine the habitats in which different hominin groups lived. Using the transient 3 Ma Pleistocene simulation in combination with an extensive hominin fossil database we developed climate envelope models for 5 different hominin groups *(Homo sapiens, Homo neanderthalensis, Homo heidelbergensis, Homo erectus, Homo ergaster/habilis)*. The reconstructed temporal evolution of the climate envelope model provides information on the potential spatio-temporal overlap of different hominin groups, with relevance for understanding potential interbreeding and species successions. We demonstrated that astronomically forced changes in temperature, rainfall and terrestrial net primary production had a major impact on archaic species distributions. Analysis of the simulated hominin habitat overlap from ~300-400 thousand years ago further suggests that anti-phased climate disruptions in southern Africa and Eurasia contributed to the evolutionary transformation of *Homo heidelbergensis* populations into *Homo sapiens* and Neanderthals, respectively. This climate envelope modeling framework is further applied to determine the times and regions of potential habitat overlap and interbreeding between *Homo neanderthalensis* and *Denisovans.* We find that central Asian climate change, mostly driven by past changes in atmospheric CO_2 and ice-sheets, created an east-west interbreeding seesaw between the two different groups. We also implemented genetic traits (mitochondrial DNA) into an agent-based human model, which simulates the life cycles of individual agents (male and female hominins), their reproduction, death and search for food. This model has been forced for the last 2 million years with data from the 3 Ma climate model simulations and estimates of habitat suitability of different species. The simulations reveal a major genetic bottleneck of human species around 0.9 Ma, in agreement with deep genetic reconstructions and the timing of the 24-23 chromosome merger.

- **Climate effects on terrestrial mammals:** So far there has been no global dynamical model that simulates the spatio-temporal evolution of land mammals. This means that it has been virtually impossible to determine how mammals react to past or future climate change, except for a rough analysis of habitat suitabilities. Over the past 3 years we developed the first model simulating the dispersal and spatio-temporal biomass evolution of global mammals (ICCP Global Mammal Model, IGMM). The model combines the 3 Ma transient CESM1.2 simulation with an extensive paleo mammal database and scaling laws from metabiology, predator-prey and competition dynamics. Metabiology is used to estimate diffusion rates, birth rates, carrying capacity and other key biological parameters needed for the dynamical reaction/diffusion model. The model simulates realistic habitats for 2170 mammal species as well as their estimated time-evolution over the Pleistocene. The IGMM has been used to study the impact of past climate change on mammal diversity and extinctions.

- **Climate impacts on heat-induced mortality and infectious diseases:** A globally warmer world will lead to more heat stress, extreme events and spread of infectious diseases to new areas. In this research project we estimate the impacts of future climate change on human health, focusing presently on the spread of Malaria and the risk of heat-related illnesses. To this end we have forced the Malaria model VECTRI with data from the CESM2 Large Ensemble to determine more accurately the time of emergence of anthropogenic climate change in Malaria infection rates globally. To address the issue of future heat-related illnesses we investigated the linkage between climate change and climate-induced fatalities using globally aggregated data and wet-bulb temperature dynamics in the CESM2 Large Ensemble.

- **Constraining marine biogeochemical cycles using inverse models:** This research project focuses on constraining key marine biogeochemical process in an ocean-biogeochemical model using existing observational data. To this end we use inverse models to obtain better estimates of riverine, coastal and ground water discharge carbon fluxes into the ocean. Using the ^{13}C data of Dissolved Inorganic Carbon as an observational constraint, we found that previous estimates of the land to ocean carbon fluxes were underestimated by a factor of two. Other applications of the inverse modeling approach include an estimation of the optimal relationship between C:P stoichiometric ratios and phosphate as well a better understanding of the role of upper ocean biology in $CaCO_3$ cycling.

- **Marine heatwaves in marine protected areas:** Global warming will increase the frequency of heat waves on land and in the ocean. Marine Protected Areas (MPAs) host a considerable fraction of global marine biodiversity and provide important ecosystem services. Obtaining accurate regional projections of climate change and marine heat waves has been hampered by the fact, that many of the MPAs are located in coastal regions, which are not well resolved in typical CMIP6-type of climate models. To overcome this shortcoming of coarser resolution models, we studied changes in the frequency of surface and subsurface heatwaves in the OpenIFS/FESOM2 global warming simulations, with an ocean resolution of 4-10 km in coastal areas. This ongoing research will provide important information on potential shifts in climate niches of marine species.

- **Anthropogenic impacts on oceanic pCO_2 and marine carbon cycle:** Atmospheric CO_2 changes will not only affect the average pCO_2 in the ocean, but also its variability. Two recent ICCP studies focused on the effect of increasing atmospheric CO_2 concentrations on the seasonal and interannual variability of the upper ocean pCO_2. We demonstrated that in many areas a strong intensification of the respective variability occurs, owing mostly to a lower buffering capacity that enhances the response of pCO_2 to surface temperature and dissolved inorganic carbon changes. Other research conducted in this project includes the re-emergence of anthropogenic carbon in the subtropical cells and the corresponding changes in transient climate sensitivity.

- **Variable plankton stoichiometry and future productivity changes:** Variable plankton stoichiometry has now been implemented in some earth system models, including the CESM2. Interestingly many of these models show a future increase in marine productivity, as compared to models, which use fixed Redfield ratios. In a series of CESM2 sensitivity we investigated the effect of fixed versus flexible stoichiometry. We demonstrated that the variable C:P ratios allow phytoplankton to grow even in areas of stratification-induced nutrient decline. This research provided crucial insights into how marine life will respond to future climate change.

- **Linking past biogeochemical changes with future projections:** Paleo-climate data suggest major vertical reorganizations of the oceanic $\delta^{13}C$ values during the Paleocene-Eocene Thermal Maximum (55 million years ago). In this research project we used an offline carbon cycle model with observationally-constrained circulation to examine how past changes in vertical marine $\delta^{13}C$ gradient compare with the ongoing redistribution, due to the marine Suess effect from fossil fuel burning. We showed that future fossil fuel burning will eventually reverse the marine gradient, leading to a situation which occurred for the last time ~55 million years ago. This study allowed us to quantitatively compare recent changes of the global carbon cycle with those that occurred during the Cenozoic and infer how quickly past changes took place relative to the past. The outcome highlights that we will soon enter a marine no-analogue situation, which hasn't existed at least since the last 55 million years.

5 representative publications

1. Climate shifts orchestrated Hominin interbreeding events across Eurasia, Jiaoyang Ruan, Axel Timmermann, Pasquale Raia, Kyung-Sook Yun, Elke Zeller, Alessandro Mindanaro, Mirko Di Febbraro, Danielle Lemmon, Silvia Castiglione, Marina Melchionna, **Science**, vol. 381, 6658, pp. 699 – 704, doi: 10.1126/science.add4459 (2023)
2. Human adaptation to diverse biomes over the past 3 million years, Elke Zeller, Axel Timmermann, Kyung-Sook Yun, Pasquale Raia, Karl Stein and Jiaoyang Ruan, **Science**, vol. 380, 6645, pp. 604-608, doi: 10.1126/science.abq1288 (2023)
3. Nutrient uptake plasticity in phytoplankton sustains future ocean net primary production, Eun Young Kwon, M. G. Sreeush, Axel Timmermann, David M. Karl, Matthew J. Church, Sun-Seon Lee, Ryohei Yamaguchi, **Science Advances**, vol. 8, 51, eadd2475, doi: 10.1126/sciadv.add2475 (2022)
4. Climate effects on archaic human habitats and species successions, Axel Timmermann, Kyungsook Yun, Pasquale Raia, Jiaoyang Ruan, Alessandro Montanaro, Elke Zeller, Christoph Zollikofer, Marcia Ponce de León, Danielle Lemmon, Matteo Willeit, Andrey Ganopolski, **Nature**, Vol. 604, pg. 495-501, DOI: 10.1038/s41586-022-04600-9 (2022)
5. Human origins in a southern African palaeo-wetland and first migrations, Eva K. F. Chan, Axel Timmermann, Benedetta F. Baldi, Andy E. Moore, Ruth J. Lyons, Sun-Seon Lee, Anton M. F. Kalsbeek, Desiree C. Petersen, Hannes Rautenbach, Hagen E. A. Förtsch, M. S. Riana Bornman, Vanessa M. Hayes, **Nature**, vol. 575, 7781, pp. 185-189, DOI: 10.1038/s41586-019-1714-1 (2019)

Publications in this research theme appeared in journals such Global Biogeochemical Cycles (12), Nature Climate Change (4), Science Advances (4), Geophysical Research Letters (5), Quaternary Science Reviews (3), Science (3), Nature (2), etc.

2 RESEARCH CONCEPTS

▪ Past-to-future

One hallmark of our center is that we integrate our understanding of paleo-climatic processes into our research on future climate responses. For this purpose, we specifically launched several past-to-future modeling cross-cutting activities, which include transient Pleistocene to future climate model simulations with the CESM1.2 model covering the past 3 million years. The 3 Ma paleo simulation has been tested extensively against a plethora of paleo-proxy data to confirm that the regional and global mean temperature changes agree with the reconstructions. The same paleo-validated version of CESM1.2 has then been used for a series of future climate change simulations using various greenhouse gas emission scenarios to obtain more realistic estimates of future climate change. Our past-to-future perspective has also been implemented for our coupled climate-ice sheet model simulations. This is crucial because of the long spin-up time of ice-sheets, the presence of multiple equilibria and the fact that an ice-sheet is never in equilibrium with the orbitally-changing forcing. We therefore ran the LOVECLIM earth system model of intermediate complexity, coupled to the Penn State-ice-sheet model in various past-to-future simulations. In order to obtain a realistic present-day initialized state for the Greenland and Antarctic ice-sheets and ice-shelves, one must run the coupled model from 30,000 years ago to present. A 30,000 year-long spin-up with fixed present-day boundary conditions would yield very different, and unrealistic results. The seamless past-to-future model simulations with the coupled climate-ice sheet model provided realistic estimates of future ice-sheet changes and their corresponding contributions to global sea level rise. Another application of the past-to-future concept is the computation of emergence times. We have completed several studies that address when the anthropogenic signal will emerge from the natural variability level. These studies, which are mostly based on the CESM2 Large Ensemble focused on the Walker circulation, ocean biogeochemical trends, carbon cycle trends, and trends in the annual and interannual variability of oceanic pCO_2, rainfall, ENSO variance, lake systems, hydroclimate and marine biogeochemical processes.

▪ Frontier climate modeling

Thanks to the unique IBS/ICCP supercomputing infrastructure (Aleph, Cray XC50-LC) available to ICCP researchers, we were able to conduct a series of unprecedented climate model simulations:

- One of the highest resolution century-long global warming simulations. The data have been extensively used by ICCP researchers and the international community.

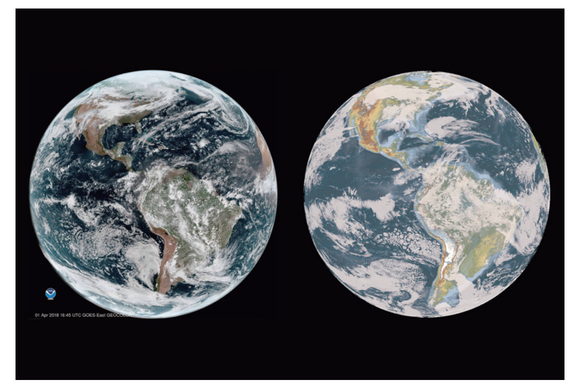
- The highest resolved paleo climate model simulations (CESM1.2 1/10-degree ocean, 1/4-degree atmosphere) for the Eemian (125 ka) and the MIS5d period (115 ka) to date.

- The longest transient coupled general circulation model simulation (CESM1.2, 3.85 degree resolution) conducted to date, which covers 600,000 model years and 3 million orbital years. This simulation serves as the basis for a number of studies in ICCP, including offline ice-sheet, vegetation, carbon cycle model simulations as well as simulations with human habitat and agent-based models.

- One of the most comprehensive large ensemble simulation to date (CESM2, 1x1 degree nominal resolution in atmosphere and similar in the ocean, except for equatorial refinement) with 100 ensemble members (ICCP/NCAR collaboration). This simulation provided unprecedented insights into the future changes of the probability distribution of the atmosphere, ocean, land, vegetation and marine biogeochemistry and has been used extensively by the international climate research community in over 40 research publications.

- In collaboration with the Alfred Wegener Institute (AWI) in Bremerhaven, Germany, we conducted cloud-permitting global warming simulations at 9 km and 4 km resolution. These simulations will serve as the main workhorse for future ICCP research projects and collaborative research with the AWI, University of Hawaii, City University of Hongkong and other institutions.

▪ Integrating models and observations



The ICCP integrates observational, numerical and theoretical research. The paleo-climate research team obtains paleo-climate records from Korean speleothems, runs the isotope enabled CESM model for transient paleo boundary conditions and uses water parcel backtracking algorithms to obtain a holistic view on the drivers of observed paleo climate change on centennial to orbital timescales.

ICCP scientists have further embarked on collaborative studies with paleoceanographers, which resulted in several important publications. In these collaborations a detailed comparison between our model results and the paleoceanographic reconstructions generated new insights into the drivers of paleo climatic variability. The analysis of our 3 million year transient model simulations provides some hints what the data of a new ~1 million-year old Antarctic ice core, which will be extracted soon through a collaboration of 14 European institutions, might look like. We are also involved in another paleoceanographic study (in collaboration with colleagues from the University of Cologne and Oregon State University), which addresses the role of the Mid Pleistocene transition on the Antarctic-ice sheet and synchronization mechanisms between between climate and ice-sheet variability as seen in multi-proxy data of a new ocean sediment core from Iceberg Alley in the Southern Ocean. This collaboration benefits again from the 3 Ma CESM1.2 simulation we conducted as well as offline ice-sheet model simulations.

ICCP researchers also use inverse modeling technique to infuse observational data directly into marine biogeochemical models. By assimilating e.g., marine $\delta^{13}C$ data of Dissolved Inorganic Carbon into an ocean/biogeochemical model and optimizing carbon river fluxes into the ocean as the control variable, we were able to obtain new estimates of the carbon flux into the ocean, which are twice as high as previously suggested.

Other integrative projects make use of advanced statistical methods to develop data-informed dynamical models, including machine learning algorithms for future climate change downscaling and future detection of changes in atmospheric rivers and tropical cyclones.

▪ Multidisciplinary approach

Research in our center follows a highly multi-disciplinary approach, as exemplified by projects on: i) climate effects on human evolution and genetics; ii) climate, permafrost and wildfires; iii) future climate impacts on marine and terrestrial biogeochemistry; iv) climate and infectious disease outbreaks; v) applications of deep learning algorithms in climate research (collaboration with former Data Science Group at IBS and SNU), vi) climate impacts on past and future mammal populations, vii) examine the impact of past climate change on the cultural evolution of *H. sapiens*, viii) application of geobiological methods (Tex86) to reconstruct past climate changes using speleothem samples.

▪ Creating new disciplines

Our research on human migration modelling is combining elements of ecology, metabiology, climate research, anthropology, genetics and archaeology. The final goal is to develop and apply realistic and quantitative models to address fundamental questions on the origin of our species, its interaction with the environment and the emergence of culture. This approach is highly multi-disciplinary and by infusing climatological and demographic information into our modeling tools and applying realistic paleo-data validated climate model simulations, we can test existing hypotheses or formulate new ideas pertaining to the evolution of hominins during the Pleistocene. This marks the beginning of new quantitative research field, which we refer to as “Climate Anthropology”. To synergize the international community in this field, we held the IBS Conference on Climate and Human Evolution in October 2024. Furthermore, we published a review paper “Past Climate Change effects on Human evolution” in Nature Reviews Earth and Environment in 2024 (5-year Journal Impact Factor: 54.5).

▪ High-risk/high gain

As an IBS center we are committed to conducting high-risk/high gain research with unpredictable outcomes. Some of our ongoing flagship projects are

- Development of the first numerical dynamical model for terrestrial mammals: we completed the development of a new ecosystem model, that simulates the spatio-temporal biomass of ~2231 species of terrestrial mammals (including extinct groups). The model is a combination of concepts from meta-biology, biogeography, predator-prey dynamics, and reaction-diffusion modeling. Our ongoing research is now addressing how past climate changes influenced mammal biodiversity and past extinctions. To our knowledge, there is no such model available, and we anticipate that its future simulations will make a major contribution to theoretical ecology, paleo-biology, and ecology. We are now applying a similar approach to build new dynamical models for vegetation and fish in the ocean.

- Determining the impact of past climate change on human genetic diversity: we launched a new research project which addresses whether past climate changes had an impact on human genetic diversification. To this end we used a new Julia-language-based agent model, for which we have implemented genetic tags for mitochondrial DNA. The agents in the model, representing hominin individuals obtain food from the simulated evolution net primary production (using Biome 4 vegetation model) weighted by the hominin habitat suitability. This new modeling approach provided some fundamental insights into past climate effects on genotypes and selection mechanisms. Our current research with this model focuses on a human bottleneck event 0.9 Ma, which was found with bioinformatic methods in extant human genome data and which is also simulated by our agent based model in response to the Mid-Pleistocene transition.

❸ SCIENTIFIC METHODS

ICCP researchers study the coupled earth system and its components using a wide range of scientific methods. These include:

- Theoretical modeling (e.g., Fokker Planck models for predictability, Dynamical Systems' theory of fast/slow systems, eco-cultural modeling, high dimensional Lotka-Volterra systems, ergodicity theory).

- Supercomputer earth system modeling (e.g., ultra-high-resolution modeling, large-ensemble modelling, inverse biogeochemical modeling, isotope modeling, transient paleoclimate modeling etc.).

- Advanced statistics (e.g., scaling behavior, generalized extreme value statistics, machine learning, statistical downscaling, complexity theory, emergence time calculations).

- New modeling approaches to simulate humans (e.g., agent-based models and reaction-diffusion multi-species models, species distribution models, phylogenetic imputation, mean-field agent-based models).

- Field work (e.g., cave monitoring, Korean water isotope network, calcite farming, speleothem sampling in South Korea, Botswana, Armenia, cave exploration).

- Lab Work (e.g., environmental isotope geochemistry, isotope and trace elements of speleothem calcite samples, Raman spectroscopy, Time of Flight SIMS, Scanning electron microscopy).

This unique toolbox, which integrates modeling, statistical and observational work (Figure 1) allows ICCP scientists to address new multi-disciplinary research questions and provide a stimulating research environment to train the next generation of international climate researchers. In this regard ICCP has become a science powerhouse that provides its researchers opportunities to acquire new skills in a multitude of fields - from isotope geochemistry to climate supercomputer modelling. We also encourage scientists with a modeling background to obtain experience in our labs or even join field trips and observationally-trained researchers to embark on modeling or statistical projects.

Below we will provide some more detailed information on the Research Tools and Methods that ICCP researchers have at their disposal to embark on new scientific challenges.

▪ Frontier earth system modeling

ICCP and IBS HQ purchased in 2018, the Aleph supercomputer (Figure 2), a liquid-cooled Cray XC-50 with with 468 Skylake compute nodes with 40 cores each and 192 GB RAM per node, 8.52 PiB Lustre parallel file system and 43 PB tape archive, 4 data analysis nodes with 768 GB memory and 2 TB NVMe SSD.

The system has been used by ICCP scientists to conduct ultra-high resolution, large ensemble and long transient climate model simulations as well as coupled climate-ice-sheet model projections, computer simulations of asteroid collisions and COVID-19 related reduction of atmospheric aerosols over Eastern Asia (to just name a few). The 4 data analysis nodes are available for fast and efficient statistical analysis, postprocessing, image processing and animations. We use the Community Earth system model of NCAR, USA in various configurations. ICCP scientists also coupled the Penn State ice-sheet model to CESM, and a variety of in-house generated models (including human dispersal models) are run on Aleph. We completed a series of 9 km global warming simulations with the AWI-CM3 (OpenIFS+FESOM) which allows us to study climate change cloud-permitting/storm resolving resolutions. The ICCP supercomputer simulations, run on Aleph are a main catalyzer for collaboration in ICCP.

Figure 1.
Illustration of scientific tools used in ICCP for multi-disciplinary research.

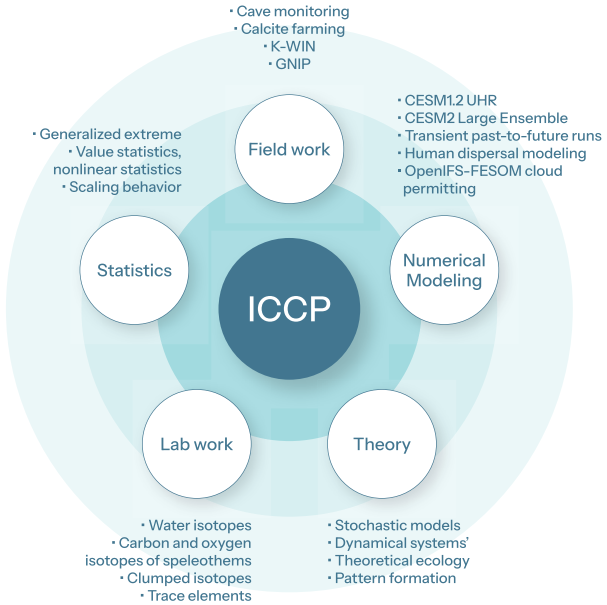


Figure 2.
Image of Aleph supercomputer, located at IBS headquarter center, Daejeon. Aleph is dedicated to 85% to ICCP-related climate research.

Figure 3.
Illustration of the synergy created by the CESM2 large ensemble and multi-year forecast simulations conducted on Aleph supercomputer.

Each simulation is designed to maximize the scientific footprint in the center and the international community. We decide on the amount of data and variables stored during the simulation to enable research in a variety of fields and for specific applications (e.g., CORDEX). This is further illustrated in Figure 3, which shows the "ecosystem" of climate physics projects that originated from our CESM2 simulations.

▪ Theoretical methods, Advanced Statistics and ecosystem modelling

ICCP scientists employ a wide range of theoretical and statistical tools. Stochastic dynamics (including Fokker Planck equation modeling) has been applied in two recent studies to elucidate the predictability of run-off and the dynamics of ENSO. By collaborating with mathematicians from Cornell University (Prof. John Guckenheimer), we also studied El Niño mode switching mechanisms using a dynamical systems' modeling framework, which focused on identifying "generalized Hopf" codimension 2 bifurcations. The results provide a more in-depth mathematical view into the predictability limits of ENSO.

Scientists in ICCP also developed new probabilistic methods to conduct non-exclusive hypotheses testing. This approach, which combines elements of Bayesian statistics and Markov chain Monte Carlo methods, allows for proper treatment of climate-model dependencies to obtain weighted future climate change projections. Furthermore, we developed Generalized Pareto Distribution models to derive new economic damage functions for weather and climate extremes and estimate the climatic impact on infectious disease outbreaks.

The hominin modeling activities in ICCP focus on developing a variety of theoretical models, which include reaction/diffusion models with Lotka Volterra predator/prey and competition dynamics for muti-species, cross diffusion, interbreeding and and selection terms. We have started to conduct a detailed analysis of complex pattern formation processes that emerge from the combination of these dynamical terms in higher dimensional ecosystems. We have also implemented genetics in an agent-based model for early human species to study the effect of past climate change on human genetic diversification. Our research also accounts for fractional diffusive processes and phenotype selection mechanisms using simplified multi-species dispersal models. Recently we developed a new ecocultural resource model, that captures the interaction of climate, population density, culture and resource exploitation. This simple model is one of the first to include a new dynamical culture equation for which state-dependent stochastic innovative increments contribute to the overall accumulation of culture (minus intergenerational loss factors), which in turn boosts carrying capacities.

▪ Isotope and trace element analysis

To reconstruct past climate changes, ICCP scientists analyze oxygen, stable carbon, clumped isotopes, trace elements of various speleothem samples, water samples from cave drip water and monthly rainwater in South Korea. To conduct this analysis, we purchased several mass spectrometers (see also section 10 Center Research Facilities and Equipment).

a. Our Thermo Fisher Mat 253 Plus isotope ratio mass spectrometer is connected with an automated carbonate preparation device (Kiel IV), in which calcite samples from stalagmites are dissolved with phosphoric acid to create

CO_2 gas, which is then delivered into the isotope ratio mass spectrometer (IRMS) to determine its oxygen, carbon and clumped isotopic composition. The instrument is the only one in South Korea which measures clumped isotopes (Figure 4). The isotopic analysis of speleothem samples allows ICCP paleoclimate scientists to reconstruct changes in past climate conditions with an unprecedented resolution.

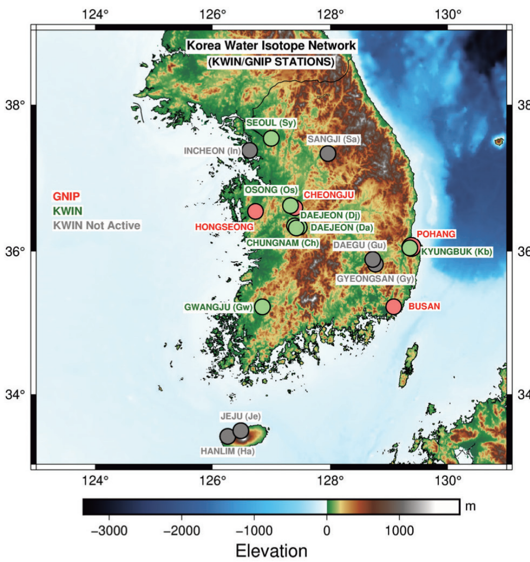
b. A Thermo Fisher Delta Q isotope ratio mass spectrometer coupled to a gas bench carbonate preparation, acid ingestion device has become the workhorse for high throughput oxygen and carbon isotope analyses of speleothem samples.

c. Trace elements of stalagmite, flowstone and rock samples are measured using a Laser Ablation (ASI Spectrum) Inductively Coupled Plasma Mass spectrometer (Agilent). This system can be also decoupled from the laser to measure trace elements in solutions. This is particularly interesting for the analysis of key minerals that are contained in drip water samples from caves. The ICPMS has become a useful tool to determine trace element concentrations in speleothem samples at extremely fine resolution – sometimes even resolving sub-annual details.

d. Water isotopes (for hydrogen and oxygen) of rain water and cave drip water are analysed on a Los Gatos cavity ring down laser system. The data from monthly measurements of oxygen isotopes are shared with the International Atomic Energy Agency in Vienna as part of the Global Network of Isotopes in Precipitation (GNIP) program.

Figure 4.
The Mat 253 Plus IRMS coupled to the Kiel IV automated carbonate preparation device with Porapak filter system.

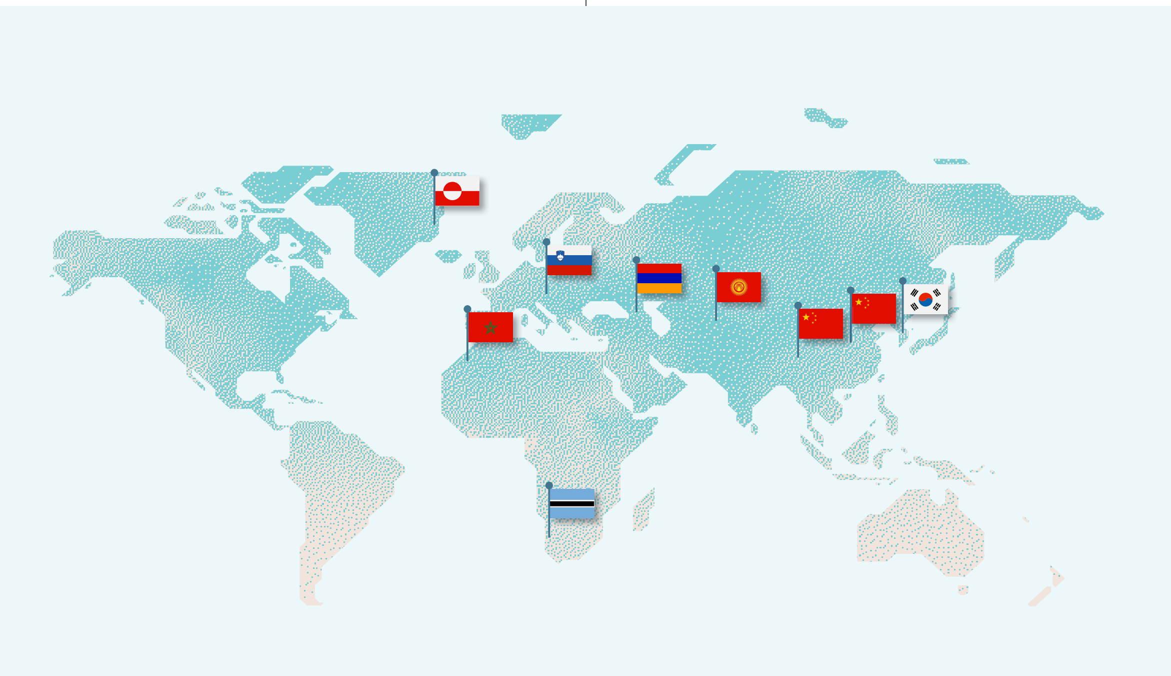
Figure 5.
Korea Water Isotope Network monitoring sites (KWIN), green sites active in 2023, gray sites discontinued. Red dots indicate official IAEA GNIP sites, the Busan site is maintained by ICCP, the Pohang site is discontinued).



Field work and monitoring

ICCP maintains a weather station on the roof of our building along with 2 monthly rainwater samplers. Rainwater samples are analyzed monthly for water isotopes and the data and weather station data are submitted to the Global Network of Isotopes in Precipitation of the IAEA. South Korea currently runs 2 Global Network of Isotopes of Water (GNIP) stations (one at ICCP) and 12 additional monthly monitoring sites were established by ICCP through the Korean Water Isotope Network (KWIN) high-school program. (Figure 5) ICCP also operates an extensive cave monitoring program in Ondal cave, Danyang-gu and in Daeya cave and Yeongyeon cave in Gangwon area in South Korea. Through regular visits we measure cave environmental parameters (relative humidity, water level height, temperature, CO_2 concentration). Furthermore, we ran calcite growth experiments of various caves in South Korea and in Botswana, where different sites speleothems are grown on glass plates. The obtained calcite is then analysed on our IRMS for $\delta^{18}O$, δ13C and clumped isotopes and the data are compared with the $\delta^{18}O$ of rainwater from the area and dripwater from within the cave. This allows us to understand calcification processes and the effect on isotopic fractionation in an optimal, controlled and in-situ way. By combining isotope measurements of calcite, drip water with in-situ measurements of cave temperatures and CO_2, as well as clumped isotope thermometry and Tex86 geobiological analysis, we can compare different methods against each other to obtain optimal geochemical/climate proxy calibrations for the caves of interest for our research.

Figure 6.
Locations of speleothem samples obtained by IBS Center for Climate Physics either through fieldwork or collaborations, from Greenland, Morocco, Botswana, Slovenia, Armenia, Kyrgyzstan, China, South Korea.



Many of speleothems are taken from regions that are either affected by East Asian summer Monsoon systems of the Westerlies. Our goal is to reconstruct past shifts in hydroclimate, temperature and atmospheric circulation using the analytical tools available in our lab. Conducting field work in other countries and obtaining speleothem samples usually requires a long spin-up time, in which we have to identify local scientific collaborators, field guides, obtain official research and sampling permits and export permits to send the samples back to South Korea. At this point, ICCP has collected several hundred kilos of high quality speleothem samples that will be analyzed over the coming years.

Table 1.
Most computing intensive simulations conducted and analyzed jointly by ICCP scientists.

ICCP Core Simulations	Date of Completion	Amount of Data Created [PBytes]	ICCP Publications
CESM1.2 3 Ma paleo run	2021.08.28	0.73	6
HR-CESM1.2 Present-day	2019.10.30	0.74	11
HR-CESM1.2 Pre-industrial	2022.01.14	0.53	
HR-CESM1.2 2xCO_2	2019.11.28	0.53	
HR-CESM1.2 4xCO_2	2020.01.06	0.53	
HR-CESM1.2 MIS5E	2021.06.21	0.53	
HR-CESM1.2 MIS5D	2021.10.13	0.51	
CESM2 Large Ensemble	2021.04.18	5.18	15
CESM2 Extension run	2022.07.16	0.68	1
CESM2 Prediction run	2023.04.18	1.40	1
OpenIFS-Fesom2 TCO319 simulations	2023.12.07	1.03	1
OpenIFS-Fesom2 TCO1209 simulation	2024.07.01	0.89	1

CHAPTER. 3

RESEARCH OUTCOMES

Earth System Dynamics

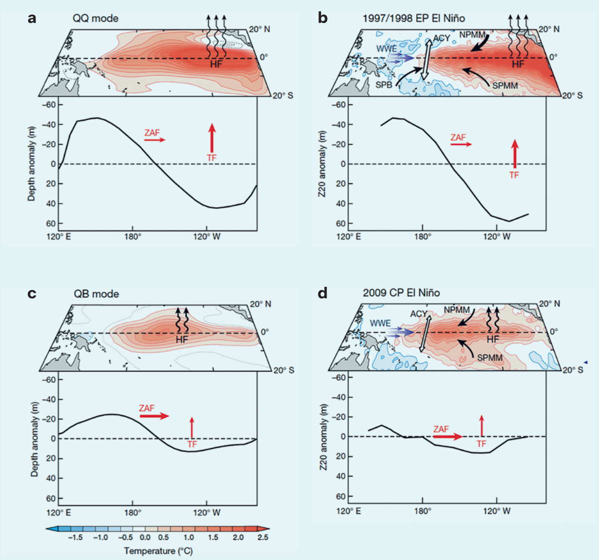
1

EL NIÑO–SOUTHERN OSCILLATION COMPLEXITY

The complexity of ENSO can be explained by the interplay of a annual cycle, two fundamental ENSO eigenmodes, and state-dependent noise.

Some El Niño events are weak, others are strong. Some occur in the central Pacific, others in the east. These differences will determine which areas will be hit hardest by climatic extremes and which ones will be spared. Predicting El Niño events accurately therefore requires a deeper understanding of its diversity. Our analysis shows that when the upper tropical Pacific Ocean stores more heat, El Niño events tend to peak in the Eastern Pacific and during boreal winter, whereas a cooler upper ocean system leads preferably to the development of Central Pacific El Niño events, which exhibit a weaker seasonal coupling. By calculating the ENSO eigenmodes of a coupled atmosphere-ocean model for different temperature, wind and ocean current configurations (Figure 7) we found that Eastern Pacific El Niño events are characterized by a return time of 3-7 years (QQ mode), whereas Central Pacific events tend to recur on average every 2-3 years (QB mode). The different character of these two modes is determined by how strongly atmosphere and ocean interact with each other. In the observations however, the co-existing Eastern and Central Pacific warm/cold swings are far from periodic. The tropical Pacific climate systems require additional excitation, either through random weather events or through atmospheric circulation changes induced by temperature changes in the Indian and Atlantic Oceans. These interactions are an important source for El Niño irregularity, and limit how far ahead Tropical Pacific climate anomalies can be predicted. This multi-authored study, led by ICCP scientists has been cited over 725 times since 2018 (source, Web of Science September 30th, 2024) and it has become a key reference paper by climate scientists worldwide, who are interested in ENSO complexity.

Figure 7.
a) Simulated quasi-quadrennial eigenmode (SST anomaly pattern and thermocline depth); b-d, same as a), but for observed Eastern Pacific El Niño, the simulated quasi-biennial eigenmode, the observed Central Pacific El Niño, respectively.



Axel Timmermann et al,. Nature vol. 559, 7715, pp. 535-545, DOI: 10.1038/s41586-018-0252-6 (2018). [JIF 69.5]

2

NORTH AMERICAN APRIL TORNADO OCCURRENCES LINKED TO GLOBAL SEA SURFACE TEMPERATURE ANOMALIES

Large-scale ocean temperature anomalies influence tornado statistics over Great Plains regions in April, but not in other months.

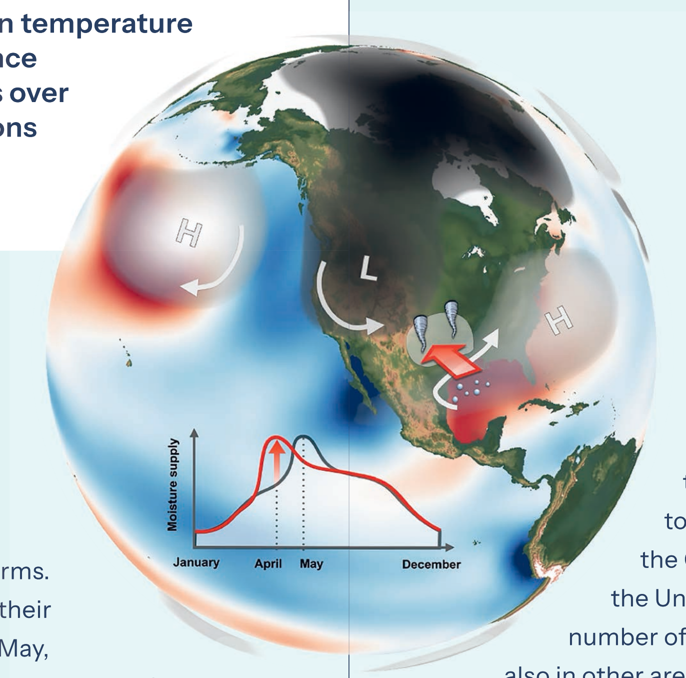


Figure 8.
Temperature and atmospheric pressure conditions that lead to enhanced flow of moist and quickly-spinning air into the Great Plains region and increased tornado occurrences in April. H and L refer to unusually high and low atmospheric pressure.

Tornadoes are extreme sub-mesoscale weather phenomena which can occur in conjunction with supercell thunderstorms. Over North America their occurrence peaks in May, but some of the most extreme and destructive events have been observed in April (Figure 8). What has remained a unclear is whether the variation in the number of tornadoes from year to year is simply random, or whether there are large-scale (potentially predictable) climatic drivers. Using a wide variety of observational data and ocean-temperature forced atmosphere general circulation model simulations, we document that the statistics of tornadoes in April is significantly impacted by the large-scale Pacific-North America (PNA) pressure pattern, which itself is influenced by global ocean sea surface temperature anomalies. Our study documented that ocean temperature anomalies can influence thunderstorm and tornado generation in the Great Basin region of the United States. With the number of tornadoes increasing also in other areas of the northern hemisphere (such as Europe and a recent sightings in South Korea), our study provides a framework to understand how climate can control extreme submesoscale weather phenomena.

Jung-Eun Chu, Axel Timmermann, June-Yi Lee,
Science Advances, vol. 5, 8, DOI: 10.1126/sciadv.aaw9950 (2019), [JIF 14.1]

3

EAST ANTARCTIC COOLING INDUCED BY DECADAL CHANGES IN MADDEN-JULIAN OSCILLATION DURING AUSTRAL SUMMER

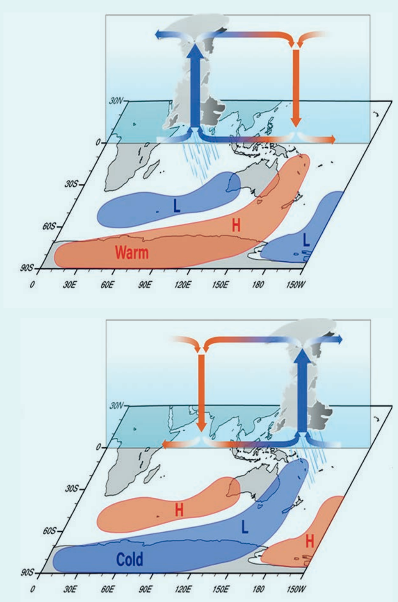
Shifts in tropical rainfall clusters associated with MJO contributed to decadal-scale East Antarctic cooling.

Over the last four decades scientists have observed a persistent austral summer cooling on the eastern side of Antarctica. This puzzling feature has received world-wide attention, because it is not far away from one of the well-known global warming hotspots – the Antarctic Peninsula. Our study uncovered a new mechanism that explains the regional warming/cooling patchwork over Antarctica. At the heart of the mechanism are MJO-related clusters of rainfall events in the western tropical Pacific, which release massive amounts of heat into the atmosphere by condensation of water vapor. As the MJO rainfall clusters move into the western Pacific towards the location of the Solomon Islands (Figure 9), the corresponding global atmospheric wave tends to cool East Antarctica three to eleven days later. In contrast, when the MJO-related rainfall occurs in the Indian Ocean, East Antarctic shows a pronounced warming. During recent decades, MJO rainfall and pressure changes preferably occurred over the western tropical Pacific but decreased over the Indian Ocean. This situation has favored cooling of Eastern Antarctica during austral summer. Our analysis shows that up to 20% to 40% of the observed summer cooling trend in Eastern Antarctica from 1979 to 2014 can be attributed to the long-term changes in the character and longitudinal core location of the MJO. Other contributing factors include the ozone hole and the Interdecadal Pacific Oscillation – a slowly varying weaker companion of the El Niño-Southern Oscillation. Our study highlights that climate change even in remote regions such as Antarctica, can be linked to processes that happen nearly 10,000 km away.

Figure 9.
Changes in East Antarctic temperature due to MJO rainfall clusters. (Upper) East Antarctic warming associated with an anomalous high pressure (H) excited by the MJO rainfall events in the Indian Ocean. (Lower) East Antarctic cooling associated with an anomalous low pressure (L) caused by the MJO rainfall events in the western tropical Pacific. The blue (red) line indicates anomalous atmospheric low (high) pressure at sea level.

East Antarctic Warming Induced by IO MJO Convection

East Antarctic Cooling Induced by WP MJO Convection



Pang-Chi Hsu, Zhen Fu, Hiroyuki Murakami, **June-Yi Lee**, Changhyun Yoo, Nathaniel C. Johnson, Chueh-Hsin Chang, Yu Liu, Science Advances, vol.7, 26, eabf9903, DOI: 10.1126/sciadv.abf9903 (2021) [JIF 14.1]

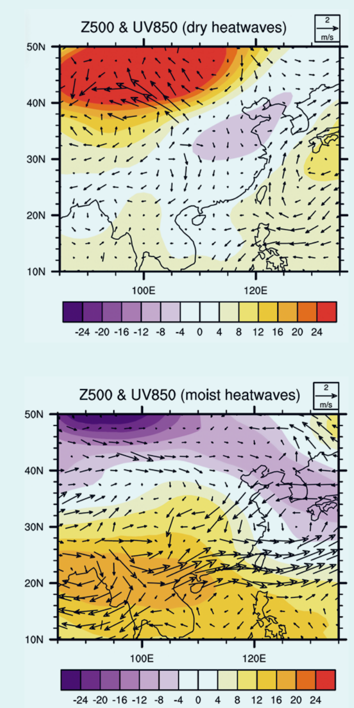
4

DYNAMICS AND CHARACTERISTICS OF DRY AND MOIST HEATWAVES OVER EAST ASIA

Dry heat waves in northwestern Asia are amplified by convergence of wave activity flux, whereas wet heat waves in southeastern Asia experience intensification due to cloud and water vapor feedbacks.

The increasing frequency of heatwaves over East Asia (EA) is impacting agriculture, water management, and people's livelihood. However, the effect of humidity on high-temperature events has not yet been fully explored. Using observations and future climate change projections conducted with the latest generation of Earth System models, we examined the mechanisms of dry and moist heatwaves over EA. Dry heatwaves occur mainly in northwestern EA, while moist heatwaves are prevalent over southern EA. These heatwaves intensified in duration and frequency over the past 60 years. In the dry heatwave region over northern EA, anticyclonic circulation anomalies amplify after the onset of heatwaves under the influence of the convergence of anomalous wave activity flux, resulting in surface warming via adiabatic processes (Figure 10). In contrast, the moist heatwaves in southeastern Asia are triggered by the locally generated anticyclonic anomalies, with the surface warming amplified by cloud and water vapor feedback. Model simulations from phase six of the Coupled Model Intercomparison Project document that dry heatwaves are expected to occur more frequently in the future, particularly after 2040, with stronger intensity in response to projected increases in greenhouse gas concentrations. There are significant differences in the frequency of moist heatwaves compared to dry heatwaves. In future scenarios, moist heatwaves are expected to occur from May to August and can persist until October.

Figure 10.
Anomaly composites relative to long-term daily mean (climatology) of geopotential height at 500 hPa (shading) [m] and wind at 850 hPa (vectors) [m/s], for dry heatwave days (upper) and moist heatwave days (lower).



Kyung-Ja Ha, Ye-Won Seo, Ji-Hye Yeo, Axel Timmermann, Eui-Seok Chung, **Christian L.E. Franzke**, Johnny C.L. Chan, Sang-Wook Yeh, Mingling Ting , npj climate and atmospheric science, vol. 5, article 49, DOI: 10.1038/s41612-022-00272-4 (2022) [JIF 9.5]

Earth System History

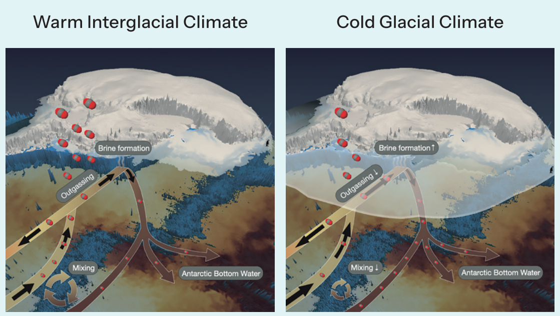
1

TIMING AND MAGNITUDE OF SOUTHERN OCEAN SEA ICE/CARBON CYCLE FEEDBACKS

Sea-ice plays a key role in controlling deep-ocean stratification under glacial conditions, which contributes to the draw-down and sequestration of atmospheric CO_2.

In this study, we investigated what role sea ice in the Southern Ocean surrounding Antartica played in past climate transitions. We found that under glacial conditions sea ice not only inhibits outgassing of carbon dioxide from the surface ocean to the atmosphere (as previously proposed), but it also increases storage of carbon in the deep ocean (Figure 11) by ocean dynamical processes. These processes "lock away" extra carbon in the ocean that would otherwise escape to the atmosphere as CO_2, warm the planet, and reduce glacial amplitudes. To investigate the physical effects of sea ice on the ocean, we used a transient paleo-climate model simulation conducted with an earth system model of intermediate complexity which covered the last 784,000 years of Earth's climate history, in combination with an offline carbon cycle model to quantify the impacts of sea ice and ocean circulation changes on atmospheric carbon dioxide. Our results show that sea ice has the largest impact on carbon storage via enhanced formation of Antarctic Bottom Water and reduced air exposure times of upwelled DIC-rich deep waters, driving a 30 ppm drawdown of atmospheric CO_2. The increased sea ice formation during glacial periods causes an increase in the density difference between the bottom water and the water above. The reduced mixing means more carbon can be stored in the deep ocean. Importantly, this process is related to the creation of sea ice in the Southern Ocean, which can occur early within a glacial cycle. Later in the glacial cycle, the sea ice covers a large enough area of the Southern Ocean that it can "cap" the carbon dioxide outgassing from the upwelling water, causing a further 10 ppm reduction of the level in the atmosphere.

Figure 11.
During cold climates (right), sea ice around Antarctica grows, preventing outgassing of carbon from the ocean to the atmosphere. Also, brine formation increases, which causes the Antarctic Bottom Water to become denser, decreasing mixing with waters above. The two processes result in an increased sequestration of carbon in the deep ocean.



Karl Stein, Axel Timmermann, Eun Young Kwon, Tobias Friedrich, Proceedings of the National Academy of Sciences of the United States of America, vol. 117, 9, pp. 4498-4504, DOI: 10.1073/pnas.1908670117 (2020) [JIF 11.25]

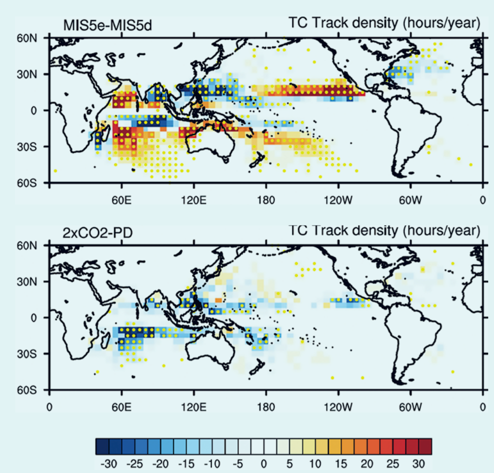
2

MOISTURE CONTROL OF TROPICAL CYCLONES IN HIGH-RESOLUTION SIMULATIONS OF PALEOCLIMATE AND FUTURE CLIMATE

The tropospheric moisture structure is the key element determining the responses of tropical cyclones to past and future forcings.

The intensity of tropical cyclones (TCs) is expected to increase in response to greenhouse warming. However, how future climate change will affect TC frequencies and tracks is still under debate. To further elucidate the underlying sensitivities, we study TCs response to different past and future climate forcings. Using the high-resolution TC-resolving global HR-CESM1.2 with ¼° atmosphere and ⅒° ocean resolution we conducted a series of paleo-snapshot and future greenhouse warming simulations targeting the last interglacial (Marine Isotope Stage (MIS) 5e, 125 ka), glacial sub-stage MIS5d (115 ka), present-day (PD), and CO_2 doubling ($2{\times}CO_2$) conditions. Our analysis reveals that precessional forcing creates an interhemispheric difference in simulated TC densities (Figure 12) whereas future CO_2 forcing impacts both hemispheres in the same direction. In both cases, we find that TC genesis frequency, density, and intensity are primarily controlled by changes in tropospheric thermal and moisture structure, with warmer hemispheres exhibiting on average a reduction in TC density.

Figure 12.
Difference in tropical cyclone track density between extreme precessional conditions (northern hemisphere summer perihelion minus aphelion conditions) (upper) and CO_2 doubling versus present-day conditions (lower).



Pavan Harika Raavi, Jung-Eun Chu, Axel Timmermann, Sun-Seon Lee, Kevin J.E. Walsh, Nature Communications, vol. 14, article 6426, doi: 10.1038/s41467-023-42033-8 (2023) [JIF 17.7]

A TRANSIENT COUPLED GENERAL CIRCULATION MODEL (CGCM) SIMULATION OF THE PAST 3 MILLION YEARS

We conducted the longest transient climate model simulation to date, comprising 600,000 model years, associated with 3 million years of paleo-climate evolution.

To quantify the sensitivity of the earth system to orbital-scale forcings during the Pleistocene, we conducted an unprecedented quasi-continuous coupled general climate model simulation with the Community Earth System Model version 1.2 (CESM1.2, ~3.75 °C horizontal resolution), which covers the climatic history of the past 3 million years (3 Myr). In addition to the astronomical insolation changes, CESM1.2 is forced by estimates of CO_2 and ice-sheet topography which were obtained from a simulation previously conducted with the CLIMBER-2 earth system model of intermediate complexity. The computer model data were compared against a plethora of paleo-proxy data and large-scale climate reconstructions. For the period from the Mid-Pleistocene Transition (MPT, ~0.9 Ma) to the late Pleistocene we find good agreement between simulated and reconstructed temperatures in terms of phase and amplitude (~5.7 °C temperature difference between Last Glacial Maximum and Holocene) (Figure 13). Our model-proxy data comparison also extends to the westerlies, the monsoon systems and the El Niño–Southern Oscillation. We further describe two major modes of planetary energy transport, which played a crucial role in Pleistocene climate variability and the Mid-Pleistocene Transition. Comparison of this paleo-simulation with greenhouse warming simulations reveals that for an RCP8.5 greenhouse gas emission scenario, the projected global mean surface temperature changes over the next 7 decades would be comparable to the late Pleistocene glacial-interglacial range; but the anthropogenic warming rate will exceed any previous ones by a factor of ~100.

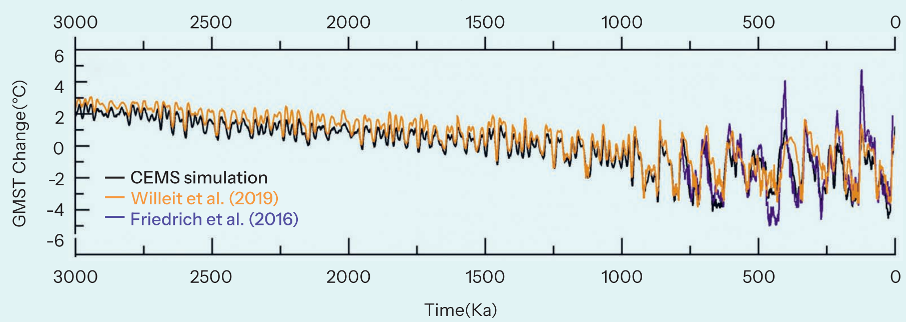


Figure 13.
Simulated global mean temperature from our CESM1.2 simulation (black), and two earth system model of intermediate complexity simulations (orange, purple) showing the overall Pleistocene cooling and the mid-Pleistocene transitions, leading to enhanced glacial-interglacial variability around 900 ka.

Kyung-Sook Yun, Axel Timmermann, Sun-Seon Lee, Matteo Willeit, Andrey Ganopolski, and Jyoti Jadhav, Climate of the Past, (2023) https://doi.org/10.5194/cp 19-1951-2023 [JIF 4.5]

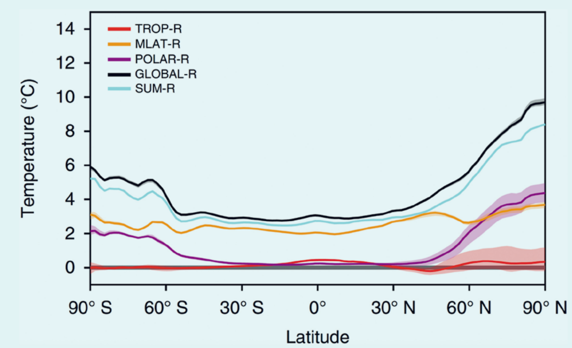
Earth System Sensitivity and Earth System Modeling

POLAR AMPLIFICATION DOMINATED BY LOCAL FORCING AND FEEDBACKS

Regional atmospheric radiative processes over the Arctic, associated with lapse rate and cloud feedbacks, play a key role in the Arctic Amplification process.

This study reveals the mechanisms controlling the amplification of future Arctic warming, relative to the rest of the globe. Using computer model simulations with regionally constrained future CO_2 forcings (tropics, mid-latitude, polar and global), we showed that a large fraction of the Arctic amplification can be explained by regional forcings and feedbacks (POLAR-CPL in Figure 14), whereas other experiments using tropical (TROP-CPL) and mid-latitude forcings (MLAT-CPL) do not contribute much to the polar amplification. Moreover, we demonstrate that fueled by high temperature and moisture, tropical air can easily move upwards, creating an unstable atmospheric column. In contrast, the Arctic atmosphere is much more stable which in turn enhances the CO_2-induced warming in the Arctic near the surface. In the tropics – due to the unstable atmosphere – CO_2 mostly warms the upper atmosphere and energy is easily lost to space. This is opposite to the Arctic, where less outgoing infrared radiation escapes the atmosphere, which further amplifies the surface-trapped warming. This study shows clearly that the remote effects from the tropics and midlatitudes on Arctic climate (e.g., TROP-CPL, MLAT-CPL in Figure 14) even though present, are not the dominant source of Arctic amplification. This research highlights that atmospheric radiative processes, associated with lapse rate and cloud feedbacks in the Arctic, play a key role in amplifying the global warming signal over sea-ice and ice-sheet covered areas.

Figure 14.
Zonal mean climate responses for TROP-CPL (solid red), MLAT-CPL (solid orange), POLAR-CPL (solid magenta) and GLOBAL-CPL (solid black). Shading indicates the ensemble range. The sum for the regional experiments is indicated by solid cyan.



M. F. Stuecker, C. M. Bitz, K. C. Armour, C. Proistosescu, S. M. Kang, S-P. Xie, D. Kim, S. McGregor, W. Zhang, S. Zhao, W. Cai, Y. Dong, F.-F. Jin, Nature Climate Change, doi: 10.1038/s41558-018-0339-y (2018) [JIF 28.6]

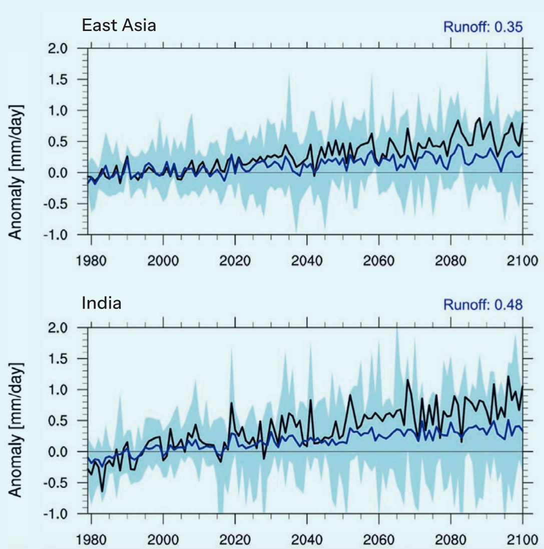
2

FUTURE CHANGES OF SUMMER MONSOON CHARACTERISTICS AND EVAPORATIVE DEMAND OVER ASIA IN CMIP6 SIMULATIONS

Climate models simulate over Eastern Asia an earlier monsoon onset in future and a later retreat.

Future climate change is expected to influence the characteristics of regional monsoon systems. However, large regional uncertainties still remain. Using 16 models which participated in the Coupled Model Intercomparison Project Phase 6, we studied the impact of greenhouse warming on the length of the summer rainy season and precipitation extremes over the Asian subregional monsoon domains (East Asia, western North Pacific, India, and Indo-China Peninsula). Apart from the overall increase in rainfall and runoff (Figure 15) the models simulate over Asia an earlier inception and a later termination of the summer rainy season, whereas over India, only the termination time will be affected. The model simulations also exhibit an intensification of extreme rainfall events, as well as an increase of seasonal drought conditions. Our results demonstrate the high volatility of the Asian summer monsoon system and further highlight the need for improved water management strategies in this densely populated part of the world.

Figure 15.
Time series of summer anomalous precipitation (PR, black) and runoff (blue) averaged over East Asia and India during the period from 1979 to 2100. Blue shading represents the minimum and maximum anomalous runoff among seven CMIP6 models.



Kyung-Ja Ha, Sueyoon Moon, Axel Timmermann,
D Kim Geophysical Research Letters 47 (8),
e2020GL087492 JIF 5.58]

3

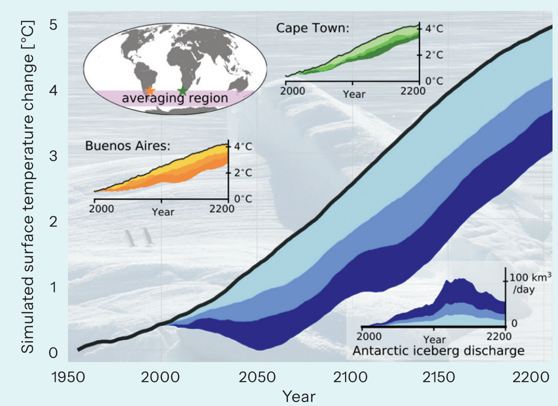
ANTARCTIC ICEBERG IMPACTS ON FUTURE SOUTHERN HEMISPHERE CLIMATE

Future Antarctic iceberg calving will slow down global warming in Southern Hemisphere.

Unabated Global Warming threatens the stability of the Antarctic ice sheet. Ice loss can occur in the form of melt-induced (liquid) freshwater discharge into the ocean, or through (solid) iceberg calving. With a projected future retreat of the Antarctic ice sheet, scientists expect an intensification of iceberg discharge. Icebergs can persist for years and are carried by winds and currents through the Southern Ocean until they reach warmer waters and ultimately melt. The melting process cools ocean waters like ice cubes in a cocktail glass. Furthermore, freshwater discharge from icebergs impacts currents by lowering ocean salinity. Whether this “iceberg effect” can slow down or alter future climate change in the Southern Hemisphere has remained an open question. In our study we quantified for the first time this effect of Antarctic iceberg calving on future Southern Hemisphere climate. We ran a series of Global Warming simulations with the LOVECLIM intermediate complexity model, which include the combined freshwater and cooling effects of icebergs on the ocean.

The results demonstrate that the effect of Antarctic melting and icebergs needs to be included in computer model simulations of future climate change. Depending on how quickly the West Antarctic ice sheet disintegrates, the iceberg effect can delay future warming in cities such as Buenos Aires and Cape Town by 10-50 years (Figure 16).

Figure 16.
Future iceberg discharges from the disintegrating West Antarctic ice-sheet (lower right inlay figure) can lead to a substantial reduction of human-induced warming in the Southern Hemisphere. Anthropogenic warming averaged over the pink shaded region without iceberg effect (black) and for weak (cyan), medium (blue) and strong (dark blue) iceberg discharge scenarios. The other two inlay figures depict the iceberg effect on human-induced warming for the model grid points closest to Buenos Aires (Argentina, orange) and Cape Town (South Africa, green).



F. Schloesser, T. Friedrich, **Axel Timmermann**, R. DeConto, D. Pollard, Nature Climate Change vol. 9, 9, pp. 672-677, DOI: 10.1038/s41558-019-0546-1 (2019) [JIF 28.6]

4

STRONG REMOTE CONTROL OF FUTURE EQUATORIAL WARMING BY OFF-EQUATORIAL FORCING

Off equatorial climate forcing plays a key role in determining the equatorial sea surface temperature response to greenhouse warming due to weakening of Hadley cell.

In response to future fossil fuel burning, climate models simulate a pronounced warming in the tropical oceans. This enhanced equatorial warming can influence the El Niño phenomenon and shift weather and rainfall patterns across the globe. Despite being robustly simulated in computer models of the climate system, the origin of this accelerated tropical warming has remained unclear. Our study, which used regionally constrained CO_2 forcing, showed that the expected future warming in the tropics originates mostly from warming that occurs in subtropical regions (Figure 17). In response to increasing greenhouse gas emissions, future subtropical warming will slow down the atmospheric Hadley cell. This will lead to a weakening of the surface trade winds, less upwelling of cold ocean water, and a resulting warming of the sea surface. In addition, a weaker Hadley cell also means that less humid air is rising, and cloud coverage is reduced in most of the tropics, increasing the amount of sunlight reaching the surface. To arrive at these conclusions, the Community Earth System model (version 1.2) was run for present-day and future CO_2 conditions. By imposing the extra energy related to the future CO_2 change, either in the tropics or subtropics, we found that surprisingly human-induced subtropical warming causes about 40% more future tropical surface ocean temperature change than if the same amount of extra energy would enter Earth's atmosphere directly in the tropics.

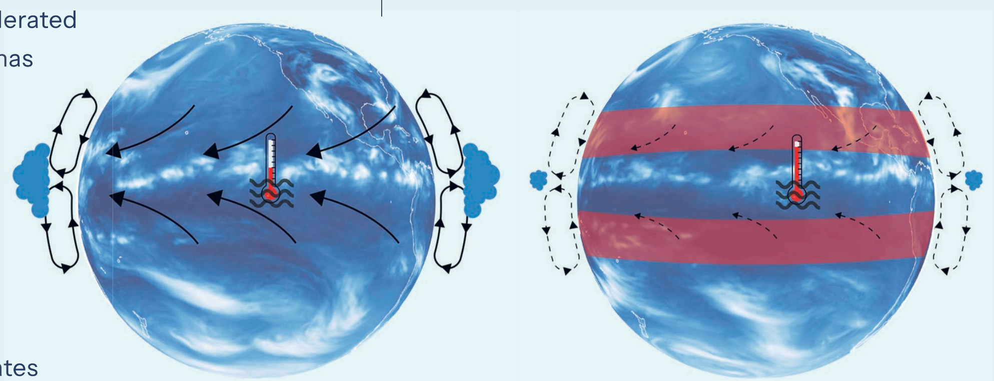


Figure 17.
Compared to the present situation (left) subtropical warming leads to a weakening of the Hadley cell (right), less clouds in most of the tropics, a reduction in the upwelling of cold ocean water and a resulting increase in tropical temperatures. This process explains a large fraction of the accelerated tropical warming found in climate models in response to increase greenhouse gas emissions.

Malte F Stuecker, Axel Timmermann, Fei-Fei Jin, Cristian Proistosescu, Sarah M. Kang, Doyeon Kim, Kyung-Sook Yun, **Eui-Seok Chung, Jung-Eun Chu**, Cecilia M. Bitz, Kyle C. Armour, Michiya Hayashi. Nature Climate Change, vol. 10, 124-129, DOI: 10.1038/s41558-019-0667-6 (2020) [JIF 28.6]

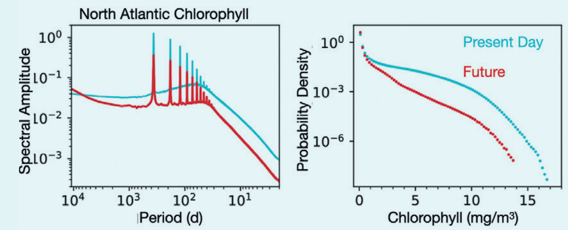
5

UBIQUITY OF HUMAN-INDUCED CHANGES IN CLIMATE VARIABILITY

Large changes in earth system variability are to be expected as a result of greenhouse warming.

There is growing public awareness that climate change will impact society not only through changes in mean temperatures and precipitation over the 21st century, but also in the occurrence of more pronounced extreme events, and more generally in natural variability in the Earth system. Such changes could also have large impacts on vulnerable ecosystems in both terrestrial and marine habitats (Figure 18).
A scientific exploration of projected future changes in climate and ecosystem variability is described in our study, representing the result of a broad collaborative partnership between the IBS Center for Climate Physics (ICCP) at Pusan National University in South Korea and the Community Earth System Model (CESM) project at the National Center for Atmospheric Research (NCAR) in the US. We conducted a set of 100 global Earth system model simulations on the ICCP/IBS supercomputer Aleph over 1850-2100, working with a "business-as-usual" scenario for relatively strong emissions of greenhouse gases over the 21st century. The runs were given different initial conditions, and by virtue of the butterfly effect they were able to represent a broad envelope of possible climate states over 1850-2100, enabling sophisticated analyses of changes in the variability of the Earth system over time. For the project, approximately 100 million CPU hours of supercomputer time were used, and approximately 5 Petabytes of disk space – 40% of those stored on the Earth System Grid – were required for storage of the model output. The main finding of the study is that the impact of climate change is apparent in nearly all aspects of earth system variability, ranging from temperature and precipitation extremes over land to increased number of fires in California, to changes in bloom amplitude for phytoplankton in the North Atlantic Ocean (Figure 18). Each of these changes has important impacts for sustainable resource management. This paper has been cited over 187 times since December 2021 (Web of Science, as of September 30th, 2024) and the simulations have been used by a plethora of additional studies by the international science community.

Figure 18.
Changes in the ensemble mean power spectrum (left) and aggregated probability density (right) of chlorophyll concentrations (mg/m^3) in the North Atlantic obtained from CESM2 LENS. Red lines indicate the period 2070-2099 and blue lines that of 1960-1989 CE.



Rodgers, K. B., Lee, S.-S., Rosenbloom, N., **Timmermann, A.,** Danabasoglu, G., Deser, C., Edwards, J., Kim, J.-E., Simpson, I., **Stein**, K., Stuecker, M. F., **Yamaguchi, R., Bodai, T.**, Chung, E.-S., Huang, L., Kim, W., Lamarque, J.-F., Lombardozzi, D., Wieder, W. R., and Yeager, S. G, Earth Syst. Dynam., 12, 1393-1411, https://doi.org/10.5194/esd-12-1393-2021, 2021. [JIF 7.9]

6

FUTURE HIGH-RESOLUTION EL NIÑO/SOUTHERN OSCILLATION DYNAMICS

Future equilibrated warming decreases ENSO variability in highest resolution global warming simulations.

To study the response of the tropical Pacific to greenhouse warming in a climate model, which properly represents mesoscale atmospheric and oceanic processes, we used the high resolution HR-CESM1.2 (1⁄10 and ¼ degree resolution in ocean, atmosphere, respectively) in a series of quasi-equilibrium century-long present-day, $2xCO_2$ and $4xCO_2$ simulations. By capturing small-scale climatic processes at the highest computationally possible resolution, this model shows much weaker tropical SST biases than coarser resolution models. For increasing CO_2 concentrations, ENSO variabiliy decreases (Figure 19). This response can be explained by the fact that future El Niño events will lose heat to the atmosphere more quickly due to the evaporation of water, which has the tendency to cool the ocean. In addition, the reduced future temperature difference between the eastern and western tropical Pacific will also inhibit the development of temperature extremes during the ENSO cycle. However, these two factors are partly offset by a projected future weakening of tropical instability waves. Normally these oceanic waves, which can encompass up to 30% of the earth's entire circumference, develop during La Niña conditions. They replace colder equatorial waters with warmer off-equatorial water, thereby accelerating the demise of a La Niña event. Our computer simulations, which resolve the detailed structure of these waves, demonstrate that the associated negative feedback for ENSO will weaken in the future. In the HR-CESM1.2 simulations the balance between positive and negative ENSO feedbacks is very different from those in coarser-resolution models, which do not properly resolve tropical instability waves.

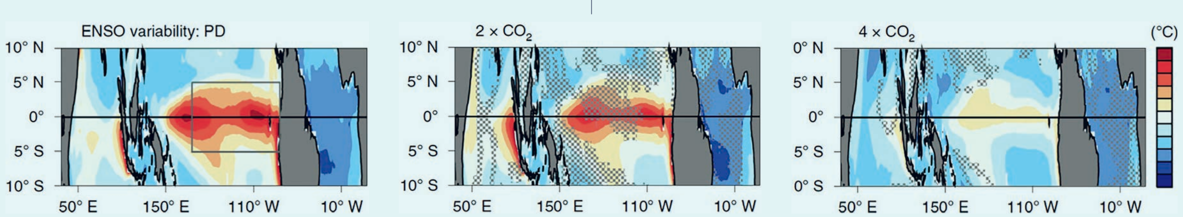


Figure 19.
Simulated standard deviation of SST anomalies in HR-CESM1.2, Present-day (left), $2xCO_2$ (middle), $4xCO_2$ (right) simulations. Stippled areas are not significant at 95% confidence limit (F-test).

Christian Wengel, Sun-Seon Lee, Malte F. Stuecker, Axel Timmermann, Jung-Eun Chu, Fabian Schloesser, Nature Climate Change, DOI: 10.1038/s43017-021-00199-z (2021) [JFI 27.6]

7

EMERGING UNPRECEDENTED LAKE ICE LOSS IN CLIMATE CHANGE PROJECTIONS

Lakes which are seasonally covered by ice will experience no-analogue conditions within the next 4-5 decades. Local feedbacks will accelerate lake warming and ice retreat in the Canadian Arctic and over Tibet.

Seasonal ice in lakes plays an important role for local communities and lake ecosystems. In this study ICCP scientists along with colleagues from the Korea Polar Research Institute (KOPRI) used Large Ensemble simulations conducted with the Community Earth System Model version 2, which includes a lake simulator, to quantify the response of lake ice to greenhouse warming and to determine emergence patterns of anthropogenic lake ice loss. The model simulations show that the average duration of ice coverage and maximum ice thickness are projected to decrease over the next 80 years by 38 days and 0.23 m, respectively. In the Canadian Arctic, lake ice loss is accelerated by the cold-season polar amplification (Figure 20). Lake ice on the Tibetan Plateau decreases rapidly due to a combination of strong insolation forcing and ice-albedo feedbacks. Comparing the anthropogenic signal with natural variability represented by the Large Ensemble, we find that lake ecosystems in these regions may be exposed to no-analogue ice coverage within the next 4-5 decades. This study represents the first global study with a coupled earth system model that addresses the future of lake-ice in response to greenhouse warming. The results are highly relevant for local communities which rely on lake ice conditions in wintertime for transportation or recreational activities.

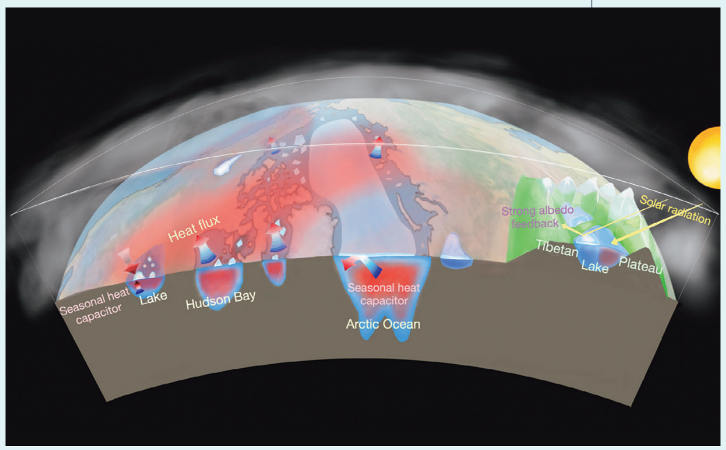


Figure 20.
Blue-red arrows represent net surface heat fluxes. Red shading in the Arctic Ocean, Hudson Bay and in lakes indicates autumn and winter-time heat storage. Dark (light) red shading over land indicates intensified (weaker) warming due to polar amplification processes. Lakes in the Canadian Arctic are influenced strongly by sea-ice retreat and winter-time warming over the Arctic Ocean and the Hudson Bay. Rapid lake ice retreat over the Tibetan Plateau is amplified by a very large bi-seasonal lake ice-albedo feedback due to high incoming solar radiation.

Lei Huang, Axel Timmermann, Sun-Seon Lee, Keith B. Rodgers, Ryohei Yamaguchi, Eui-Seok Chung, Nature Communications, vol. 13, 1, article 5798, doi: 10.1038/s41467-022-33495-3 (2022) [JIF 17.7]

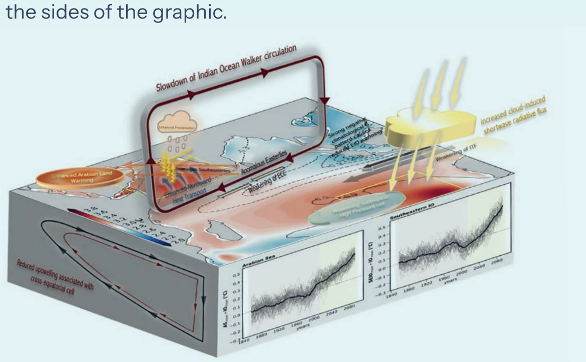
8

FUTURE INDIAN OCEAN WARMING PATTTERNS

An ocean upwelling thermostat off Java and Sumatra and negative air-sea feedbacks determine large-scale global warming pattern in the Indian Ocean.

Even though Global Warming is happening globally, some areas warm faster than others in response to increasing greenhouse gas concentrations. The corresponding climate change temperature difference pattern causes large-scale changes in winds and weather systems, impacting societies and ecosystems. Previous work has mainly focused on the well-known Arctic amplification pattern and on the projected east/west temperature difference in the equatorial Pacific, which in turn can impact regions far outside the tropics. Little attention has been paid so far to the mechanisms that cause uneven heating in the Indian Ocean and related impacts on wind and rainfall in the adjacent land area. By analyzing data from one of our ICCP/CESM Large-Ensemble simulation conducted with the Community Earth System Model, version 2, we identified why over the next decades the tropical eastern Indian Ocean is expected to warm less than the Arabian Sea and the Southeastern Indian Ocean. A key area to explain the uneven Indian Ocean warming is the area west of Indonesia, where under present-day conditions colder deep waters occasionally upwells to the surface (Figure 21). This connection between surface and deeper ocean waters serves as a thermostat, which explains the weakened future regional warming signal relative to other Indian Ocean areas. In the tropics, air rises in warmer areas and tends to sink in colder regions. The reduced eastern equatorial Indian warming is therefore accompanied by higher than normal sea level pressure and winds which blow towards the Arabian Sea. Changes in the winds automatically influence the ocean circulation. Stronger future winds blowing from Indonesia towards the Arabian Peninsula push more tropical waters towards the Arabian Sea. This leads to an accelerated warming of the ocean there. Enhanced future warming in the Arabian Sea will further reduce atmospheric surface pressure and generate more rainfall, also in the adjacent regions. In fact, climate models show on average a 50% intensification of mean rainfall over the southern Arabian Peninsula and parts of western India by year 2100, if CO_2 emissions are not cut drastically.

Figure 21.
Ensemble mean of climatological air-sea feedback (G) pattern (contours) during the period 1980–2000 and changes (future minus historical) in SST (shaded) for the 50 members of CESM2-LE. A 15-year running mean time series of the SST from 1850–2100 for 50 ensemble members (thin) and ensemble mean (thick) over the Arabian Sea and Southeastern Indian Ocean is shown on the sides of the graphic.



Sahil Sharma*, **Kyung-Ja Ha**, Ryohei Yamaguchi, **Keith B. Rodgers**, **Axel Timmermann**, Eui-Seok Chung, Nature Communications. doi: 10.1038/s41467-023-37435-7, (2023) [JIF 17.7] *PhD student as first author

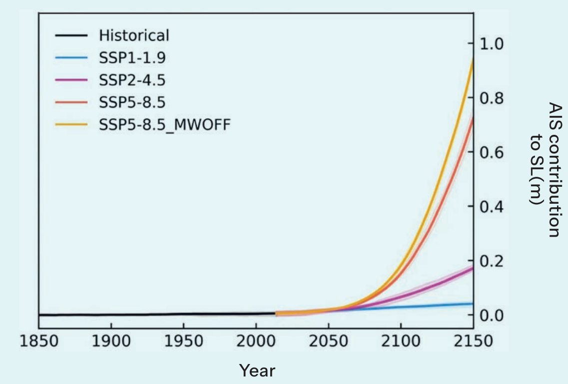
9

FUTURE SEA-LEVEL PROJECTIONS WITH A COUPLED ATMOSPHERE-OCEAN-ICE-SHEET MODEL

Warming beyond 1.8 °C above pre-industrial levels will cause irreversible loss of ice from West Antarctica and accelerated sea level rise, according to first fully coupled climate-ice-sheet model projection.

Coastal populations worldwide are already bracing for rising seas. However, planning for counter-measures to prevent inundation and other damages has been extremely difficult since the latest climate model projections presented in the 6th assessment report of the Intergovernmental Panel on Climate Change (IPCC) do not agree on how quickly the major ice sheets will respond to global warming. Melting ice sheets are potentially the largest contributor to future longterm sea level change, and historically the hardest to predict because the physics governing their behavior is notoriously complex. Moreover, computer models that simulate the dynamics of the ice sheets in Greenland and Antarctica often do not account for the fact that ice sheet melting will affect ocean processes, which, in turn, can feed back onto the ice sheet and the atmosphere and precipitation/snowfall over Antarctica. Using a new computer model, which captures for the first time the coupling between ice sheets, icebergs, ocean and atmosphere, we found that an ice sheet/sea level run-away effect can be prevented only if the world reaches net zero carbon emissions before 2060. Ice sheets respond to atmospheric and oceanic warming in delayed and often unpredictable ways. Previously, scientists have highlighted the importance of subsurface ocean melting as a key process, which can trigger runaway effects in the major marine based ice sheets in Antarctica. However, according to our new fully coupled supercomputer simulations, the effectiveness of these processes may have been overestimated in recent studies. We see that sea ice and atmospheric circulation changes around Antarctica also play a crucial role in controlling the amount of ice sheet melting and reducing its effect relative to an uncoupled simulation (Figure 22).

Figure 22.
Contribution of Antarctic ice-sheet to global mean sea-level rise simulated for different greenhouse gas emission scenarios (SSPs) in fully coupled climate-ice-sheet model, MWOFF refers to simulation without meltwater feedbacks.



Jun Young Park*, Fabian Schloesser, **Axel Timmermann**, **Dipayan Choudhury**, **June-Yi Lee**, and **Arjun Babu Nellikkattil**, Nature Communications. doi: 10.1038/s41467-023-36051-9 (2023) [JIF 17.7] *PhD student as first author

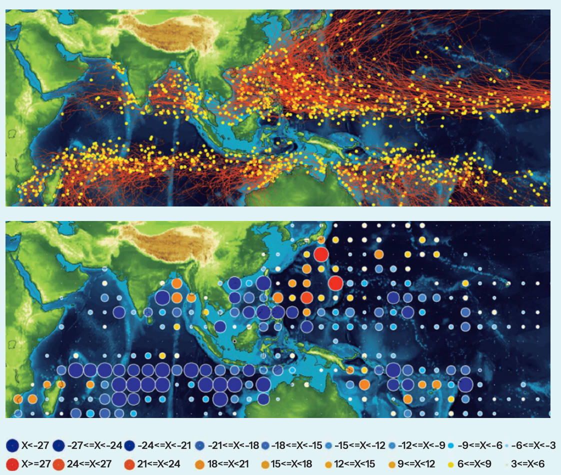
10

REDUCED TROPICAL CYCLONE DENSITIES AND OCEAN EFFECTS DUE TO ANTHROPOGENIC GREENHOUSE WARMING

Global warming will intensify landfalling tropical cyclones of category 3 or higher in the Indian and Pacific Oceans and increase the extreme precipitation of landfalling events.

Tropical cyclones (including typhoons and hurricanes) are the most fatal and costliest weather disasters on our planet. How tropical cyclone properties – in particular in coastal areas – will change in response to global warming has remained highly uncertain. By running one of the most computing-intensive and detailed global warming simulations (atmospheric and oceanic horizontal 25 km and ~10 km, respectively) for present-day atmospheric greenhouse gas composition and doubled and quadrupled CO_2 concentrations, we found, that the summer-time Hadley circulation will weaken in future due to the accelerated atmospheric warming at an elevation of 5-15 km, relative to the ground. A future reduction of rising motion in the tropical atmosphere will make it more difficult for tropical cyclones to develop, which explains the projected future suppression in tropical cyclone seeds and overall numbers in the Pacific and Indian Ocean (Figure 23). Although for a CO_2 doubling the total number of tropical cyclones is expected to decrease in future, developing events will have much higher chance to intensify beyond category 3 due to the higher humidity and energy levels in the atmosphere. Nevertheless, the rainfall associated with each event will continue to increase, amplifying the risk for extreme coastal flooding.

Figure 23.
Upper panel: Genesis locations of tropical cyclones (yellow dots) and subsequent tracks (red lines) over the Indian Ocean and the Western Pacific Ocean simulated by the supercomputer model simulation for present-day conditions; Lower panel: simulated changes in tropical cyclone number density (hours/year) in response to future CO_2 doubling.



Jung-Eun Chu, Sun-Seon Lee, Axel Timmermann, Christian Wengel, Malte F. Stuecker, Ryohei Yamaguchi, Science Advances, 6(51), eabd5109, doi: 10.1126/sciadv.abd5109, 2020 [JIF14.1]

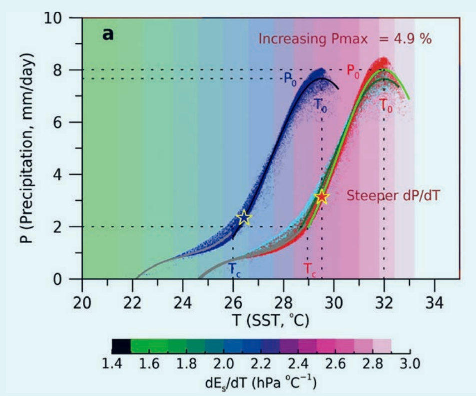
11

INCREASING ENSO-RAINFALL VARIABILITY DUE TO CHANGES IN FUTURE TROPICAL TEMPERATURE-RAINFALL RELATIONSHIP

Global Warming will boost tropical Pacific rainfall extremes due to combined shifts in atmospheric circulation and thermodynamics.

The El Niño-Southern Oscillation (ENSO) is the most energetic naturally occurring year-to-year variation of ocean temperature and rainfall on our planet. The irregular swings between warm and wet "El Niño" conditions in the equatorial Pacific and the cold and dry "La Niña" state influence weather conditions worldwide, with impacts on ecosystems, agriculture and economies. Climate models predict that the difference between El Niño- and La Niña-related tropical rainfall will increase over the next 80 years, even though the temperature difference between El Niño and La Niña may change only very little in response to global warming. This study uncovers the reasons for this robust fact. Using the latest generation of climate models, we demonstrated that all climate models show a pronounced intensification of year-to-year tropical rainfall fluctuations in response to global warming, even though the year-to-year changes in ocean temperature do not show such a clear signal. The key to understanding this important climatic feature lies in the relationship between tropical ocean surface temperature and rainfall (Figure 24). There are two important aspects to consider: 1) the ocean surface temperature threshold for rainfall occurrence, and 2) the rainfall response to ocean surface temperature change, referred to as rainfall sensitivity. The ocean surface temperature threshold for intense tropical rainfall shifts towards a higher value in a warmer world and does not contribute directly to an increase in rainfall variability. However, in a warmer the atmosphere can hold more moisture which means that when it rains, rainfall will be more intense. Moreover, enhanced warming of the equatorial oceans leads to upward atmospheric motion on the equator. Rising air sucks in moist air from the off-equatorial regions, which can further increase precipitation, in case other meteorological conditions for a rain event are met. This increase in rainfall sensitivity (Figure 24) is the key explanation why there will be more extreme ENSO-related swings in rainfall in a warmer world.

Figure 24.
Scatter plot of CMIP6 multi-model mean monthly SST and rainfall at all grid points in the tropics [20°S–20°N], obtained from the time averages of historical simulation of 1950–1999 (blue) and SSP5-8.5 simulation (red). The colored shading indicates the slope of saturated vapor pressure change to SST change (dEs/dT). The star symbols show the mean position of Niño3 region.



Kyung-Sook Yun, June-Yi Lee, Axel Timmermann, Karl Stein, Malte F. Stuecker, John C. Fyfe, Eui-Seok Chung, Communications Earth & Environment, vol. 2, article number 43, DOI: 10.1038/s43247-021-00108-8 (2021) [JIF8.4]

12

ABRUPT INCREASE IN ARCTIC-SUBARCTIC WILDFIRES CAUSED BY FUTURE PERMAFROST THAWING

Future thawing of permafrost can trigger abrupt increases in wildfire activity in the subarctic region.

Unabated 21st-century climate change will accelerate Arctic-Subarctic permafrost thawing which can intensify microbial degradation of carbon-rich soils, methane emissions, and global warming. The impact of permafrost thawing on future Arctic-Subarctic wildfires and the associated release of greenhouse gases and aerosols is less well understood. In our study we present a comprehensive analysis of the effect of future permafrost thawing on land surface processes in the Arctic-Subarctic region using the CESM2 large ensemble forced by the SSP3-7.0 greenhouse gas emission scenario. Analyzing 50 greenhouse warming simulations, which capture the coupling between permafrost, hydrology, and atmosphere, we find that projected rapid permafrost thawing leads to massive upper soil drying, due to an increase in soil water percolation (Figure 25).
In summer, soil evaporation decreases in response to the abrupt transition to a soil drying, with an associated dramatic increase in sensible heat fluxes from the surface to the atmosphere. The abrupt increase in sensible heat fluxes can intensify surface air warming and increase atmospheric dryness, abruptly increasing wildfire intensity – regionally by several orders of magnitude. Furthermore, vegetation in permafrost regions gradually increases due to CO_2 fertilization and warming under high greenhouse emissions scenario, leading to an increase in available fuel for combustion and contributing to the intensification of wildfires over Canada and the Siberian subarctic.

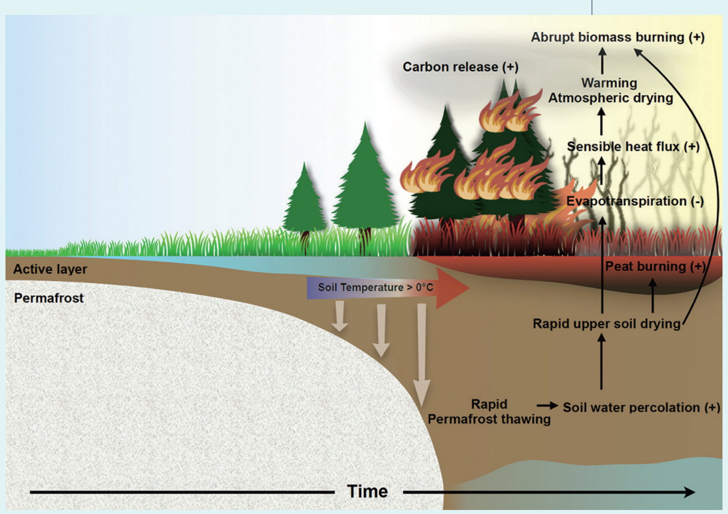


Figure 25.
Schematic diagram highlighting pathways for an abrupt increase in wildfires following permafrost thaw.

In-Won Kim, **Axel Timmermann**, Ji-Eun Kim, Keith B. Rodgers, **Sun-Seon Lee**, Hanna Lee, and William R. Wieder, Nature Communications, (2024), doi: 10.1038/s41467-024-51471-x [JIF17.7]

Climate, Life and Carbon Cycle

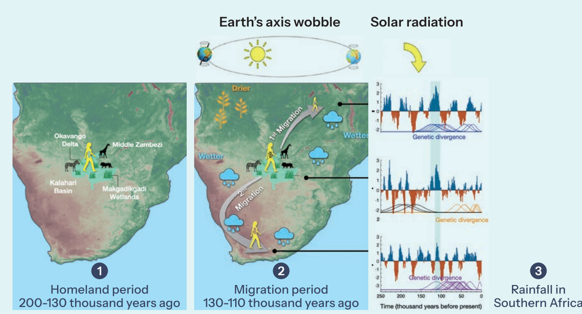
1

HUMAN ORIGINS IN A SOUTHERN AFRICAN PALAEO-WETLAND AND FIRST MIGRATIONS

Orbital forcing can explain first human migrations inside Africa, which contributed to the development of humans' genetic, ethnic and cultural diversity as we know it today.

It has been clear for some time that anatomically modern humans emerged in Africa roughly 200 thousand years ago, likely from the ancestral hominin species *H. heidelbergensis*. What has long been debated is the likely area of this emergence and subsequent dispersal of our earliest ancestors. Merging 198 new, rare mitogenomes to the current database, our study refines the evolutionary tree of our earliest ancestors. By combining the L0 mitochondrial lineage timeline with the linguistic, and anthropological data and linking this with geological and climate evidence we conclude that ~200 thousand years ago, Southern Africa may have been a likely region for early human occupation, in particular a large wetland area surrounding the megalake Lake Makgadikgadi. Major genetic divergence in the modern humans' earliest maternal sub-lineages occurred between 130 and 110 thousand years ago, indicating major migration events, first northeast, than southwest. To investigate what may have triggered these early human migrations, we analyzed climate supercomputer model simulations which capture Southern Africa's climate history of the past 250 thousand years. The simulations suggest that the precessional variability caused rainfall changes which opened green, vegetated corridors, first 130 thousand years ago to the northeast, and then around 110 thousand years ago to the southwest, allowing our earliest ancestors to migrate away form Southern Africa (Figure 26). This study is the first to combine the disciplines of genetics, geology and climatic physics to rewrite our earliest human history and make a contribution towards establishing the new research field of "Climatological Anthropology". Additional support for the conclusions drawn in this study came from our recent Nature paper in 2022, which identified Southern Africa as a key habitat overlap region between *H. heidelbergensis* (mother species) and *H. sapiens* (daughter species) around 200-300 thousand years ago.

Figure 26.
Anatomically modern humans lived in a vast wetland in the Kalahari region from 200-130 thousand years ago. Around 130 thousand years ago, with earth's orbit and solar radiation changing (upper panel), increased precipitation and vegetation northeast of the homeland (right panel) allowed to leave the homeland area (middle panel). About 15 thousand years later a green corridor opened to the southwest which allowed to migrate towards the west coast of Southern Africa.



Eva K. F. Chan, **Axel Timmermann**, Benedetta F. Baldi, Andy E. Moore, Ruth J. Lyons, **Sun-Seon Lee**, Anton M. F. Kalsbeek, Desiree C. Petersen, Hannes Rautenbach, Hagen E. A. Förtsch, M. S. Riana Bornman, Vanessa M. Hayes, Nature vol. 575, 7781, pp. 185-189, DOI: 10.1038/s41586-019-1714-1 (2019) [JIF 69.5]

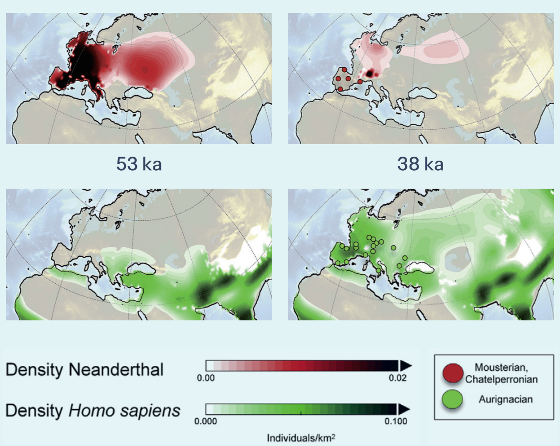
2

QUANTIFYING THE POTENTIAL CAUSES OF NEANDERTHAL EXTINCTION: ABRUPT CLIMATE CHANGE VERSUS COMPETITION AND INTERBREEDING

A new realistic computer model simulation shows that the extinction of Neanderthals was likely due to competitive exclusion, not climate.

Anatomically Modern Humans are the sole survivor of a group of human species that inhabited our planet during the last ice age and that included, among others, *Homo neanderthalensis* and *Homo denisova*. Whether previous hominin extinctions were triggered by external factors, such as abrupt climate change, volcanic eruptions or whether competition and interbreeding played major roles in their demise remains unresolved. A spatially resolved numerical hominin dispersal model (HDM) with empirically constrained key parameters was used that simulates the migration and interaction of Anatomically Modern Humans and Neanderthals in the simulated rapidly varying climatic environment of the last ice age. The model simulations document that rapid temperature and vegetation changes associated with Dansgaard-Oeschger events were not major drivers of global Neanderthal extinction between 50 and 35 thousand years ago, but played important roles regionally, in particular over northern Europe. According to a series of parameter sensitivity experiments conducted with the HDM, a realistic extinction of the Neanderthal population (Figure 27) can only be simulated when *Homo sapiens* is chosen to be considerably more effective in exploiting scarce glacial food resources as compared to Neanderthals.

Figure 27.
Population growth of Anatomically Modern Humans and Neanderthals for realistic competition and interbreeding scenario: Evolution of Neanderthal population density (individuals/km^2) (red shading); green shading, same as red, but for *Homo sapiens* population density; circles: sites of radio-carbon-dated Mousterian, Châtelperronian and Aurignacian techno-complexes.



Axel Timmermann, Quaternary Science Reviews, DOI: 10.1016/j.quascirev.2020.106331 (2020) [JIF 4.16]

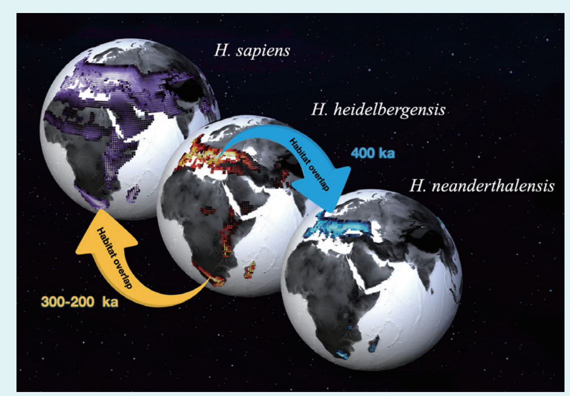
3

CLIMATE EFFECTS ON ARCHAIC HUMAN HABITATS AND SPECIES SUCCESSIONS

Habitats of human species were strongly modulated by Milanković cycles and species habitat overlap analyses suggests 200-300 ka area of origin of H. sapiens in Southern Africa.

It is believed that climate shifts during the last 2 million years played an important role in the evolution of our genus Homo. However, given the limited number of representative palaeo-climate datasets from regions of anthropological interest, it has remained challenging to quantify this linkage. In this study we conducted an unprecedented transient Pleistocene coupled general circulation model simulation which was then combined with an extensive compilation of fossil and archaeological records of early human species. Using Mahalanobis-distance based habitat models allowed us to study the spatiotemporal habitat suitability for five hominin species over the past 2 million years. Our study demonstrates that astronomically forced changes in temperature, rainfall and terrestrial net primary production had a major impact on the observed distributions of these species. During the Early Pleistocene, hominins settled primarily in environments with weak orbital-scale climate variability. This behaviour changed substantially after the mid-Pleistocene transition, when archaic humans became global wanderers who adapted to a wide range of spatial climatic gradients. Analysis of the simulated hominin habitat overlap from approximately 300–400 thousand years ago further suggests that antiphased climate disruptions in southern Africa and Eurasia contributed to the evolutionary transformation of *Homo heidelbergensis* populations into *Homo sapiens* and Neanderthals, respectively (Figure 28). This study has been downloaded more than 130,000 times from the Nature website and has already been cited more than 59 times (Web of Science, September 2024). It was discussed in 102 international and most major domestic news outlets.

Figure 28.
Average habitat suitability for 3 human species and areas of maximum habitat overlap during transition time from mother species (H. heidelbergensis) to daughter species (H. neanderthalensis 400 thousand years ago and H. sapiens 300-200 thousand years ago). The areas represent estimates of the Area of Origin during the speciation time.



Axel Timmermann, Kyung-Sook Yun, Pasquale Raia, **Jiaoyang Ruan**, Alessandro Mondanaro, **Elke Zeller**, Christoph Zollikofer, Marcia Ponce de León, **Danielle Lemmon**, Matteo Willeit, Andrey Ganopolski, Nature, doi: 10.1038/s41586-022-04600-9, [JIF 69.5]

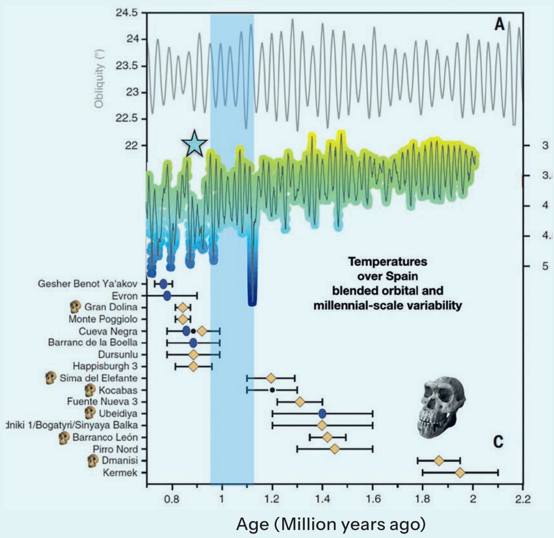
4

EXTREME GLACIAL COOLING LIKELY LED TO HOMININ DEPOPULATION OF EUROPE IN THE EARLY PLEISTOCENE

A freshwater induced rapid weakening of the AMOC likely caused a regional extinction event of H. erectus in Southern Europe 1.126 million years ago.

Archaic humans, known as *Homo erectus* moved from Africa into central Eurasia around 1.8 million years. From there on they spread towards western Europe, reaching the Iberian peninsula around 1.5 million years ago (Ma). Experiencing initially rather mild climatic conditions, these groups eventually established a foothold in southern Europe, as documented by several dated fossils and stone tools from this period. But given the increasing intensity of glacial cycles in Europe from 1.2 Ma onwards, it remains unknown for how long early humans lived in this area and whether the occupation was interrupted by worsening climate conditions (Figure 29). To better understand the environmental conditions, which early human species in Europe experienced, we combined data of a deep ocean sediment cores from the eastern subtropical Atlantic with new supercomputer climate model and human habitat model simulations covering the period of the depopulation event. We discovered that around 1.126 million years ago, the climate over the eastern North Atlantic and the adjacent land suddenly cooled by 7 °C. To quantify how early humans may have reacted to such an unprecedented climate anomaly, we conducted new computer model simulations with the Community Earth System Model for this period. By adding glacial freshwater to the North Atlantic, we were able to reproduce key features of the terminal stadial event, such as the reconstructed cooling and drying over southern Europe. We then used this global climate model simulation as an input for a human habitat model, which determines whether certain environmental conditions were suitable for early Homo erectus or not. We found that over many areas of southern Europe, early human species such as Homo erectus would have not been able to survive.

Figure 29.
Obliquity from 0.7-2.2 Ma, simulated temperature in Spain from 3 Ma transient paleo CESM simulation along with estimate of 1.126 Ma cooling event (middle panel), Age of H. erectus and H. antecessor sites in Europe.

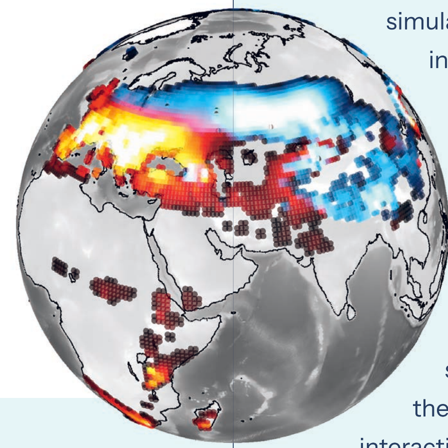


Margari, V., Hodell, D.A., Parfitt, S.A., Ashton, N.M., Grimalt, J.O., **Kim, H.**, **Yun, K.-S.**, Gibbard, P.L., Stringer, C.B., **Timmermann, A.** & Tzedakis, P.C. (2023): Science, doi: https://doi.org/10.1126/science.adf4445, [JIF 63.8]

5

CLIMATE SHIFTS ORCHESTRATED HOMININ INTERBREEDING EVENTS ACROSS EURASIA

The interbreeding between Neanderthals and Denisovans was in part controlled by climate-induced mergers of their habitats.



Modern-day people carry in their cells a small quantity of DNA deriving from other human species, namely the Neanderthals and the elusive Denisovans. Back in 2018, scientists announced to the world the discovery of an individual, later nicknamed Denny, who lived 90,000 years ago and who was identified as a daughter to a Denisovan father and a Neanderthal mother. Denny, along with fellow mixed-ancestry individuals found at Denisov a cave, testifies that interbreeding was probably common among hominins, and not limited to our own species *Homo sapiens*.
To unravel when and where human hybridization took place we pursued a different approach. Using existing paleo-anthropological evidence, genetic data and supercomputer simulations of past climate, we found that Neanderthals and Denisovans had different environmental preferences. More specifically, Denisovans were much more adapted to cold environments, characterized by boreal forests and even tundra, compared to their Neanderthal cousins who preferred temperate forests and grassland (Figure 30). This means that their habitats of choice were separated geographically, with Neanderthals typically preferring southwestern Eurasia and Denisovans the northeast. However, according to our realistic computer simulations the scientists found that in warm interglacial periods, when Earth's orbit around the Sun was more elliptic and northern hemisphere summer occurred closer to the Sun, the hominin habitats began to overlap geographically. When Neanderthals and Denisovans shared a common habitat, there were more encounters and interactions among the groups, which would have increased the chance of interbreeding. The simulation of past habitat overlaps does not only put the first generation Neanderthal/Denisovan hybrid Denny into a climatic context, but it also agrees with other known episodes of interbreeding ~78, 120 thousand years ago. Future paleo-genetic reconstructions can be used to test the robustness of the new supercomputer model-based predictions of potential interbreeding intervals around 210 and 320 thousand years ago. To further determine the climate drivers of the east-west interbreeding seesaw, we looked more closely at how vegetation patterns changed over Eurasia during the past 400 thousand years. We found that elevated atmospheric CO_2 concentrations and mild interglacial conditions caused an eastward expansion of temperate forest into central Eurasia which created dispersal corridors for Neanderthals into Denisovan lands.

Figure 30.
Preferred habitats of Neanderthals (red) and Denisovans (blue) according to climate niche modelling.

Jiaoyang Ruan, **Axel Timmermann**, Pasquale Raia, **Kyung-Sook Yun**, **Elke Zeller**, Alessandro Monadanaro, Mirko Di Febbraro, **Danielle Lemmon**, Silvia Castiglione, Marina Melchionna (2023): Science, doi: https://doi.org/10.1126/science.add4459, [JIF 63.8]

6

HUMAN ADAPTATION TO DIVERSE BIOMES OVER THE PAST 3 MILLION YEARS

The analysis of human presence data for the last 3 million years along with the simulated biome evolution reveals that early hominins preferred to live in ecotones – regions with different nearby ecosystems.

Our genus Homo evolved over the past 3 million years – a period of increasing warm/cold climate fluctuations (Figure 31). How early human species have adapted to the intensification of climate extremes, ice- ages, and large-scale shifts in landscapes and vegetation remains elusive. To address this questions, we used a compilation of more than three thousand well-dated human fossil specimens and archeological sites, representing six different human species, in combination with realistic climate and vegetation model simulations, covering the past 3 million years. According to our analysis earlier African groups preferred to live in open environments, such as grassland and dry shrubland. Migrating into Eurasia around 1.8 million years ago, hominins, such as *H. erectus* and later *H. heidelbergensis* and *H. neanderthalensis* developed higher tolerances to other biomes over time, including temperate and boreal forests (Figure 31). Eventually, *H. sapiens* emerged around 200,000 years ago in Africa, quickly becoming the master of all trades. Mobile, flexible, and competitive, our direct ancestors, unlike any other species before, survived in harsh environments such as desert and tundra. When further looking into the preferred landscape characteristics we found a significant clustering of early human occupation sites in regions with increased biome and ecosystem diversity. The results indicate that ecosystem diversity played a key role in human evolution. In our study we propose that a new Diversity Selection Hypothesis according to which Homo species, and *H. sapiens* in particular, were uniquely equipped to exploit heterogeneous biomes.

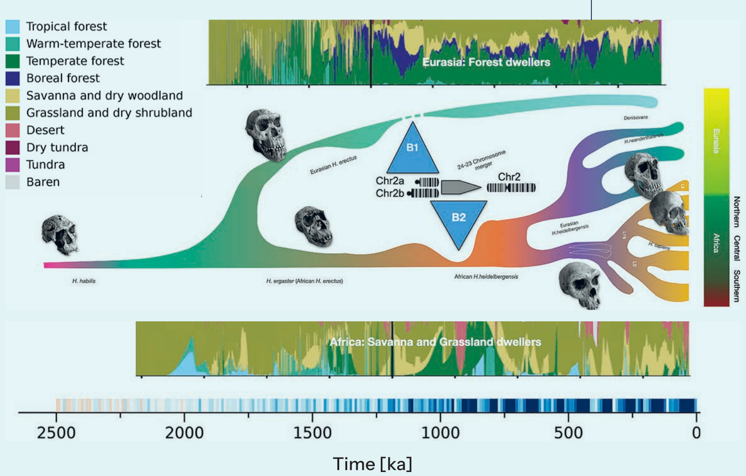


Figure 31.
Schematic of phylogenetic tree of human species and biome preferences of Eurasian (upper) and African (lower) populations.

Elke Zeller*, Axel Timmermann, Kyung-Sook Yun, Pasquale Raia, **Karl Stein, Jiaoyang Ruan** (2023): Science, doi: https://doi.org/10.1126/science.abq1288 [JIF 63.8] *PhD student as first author

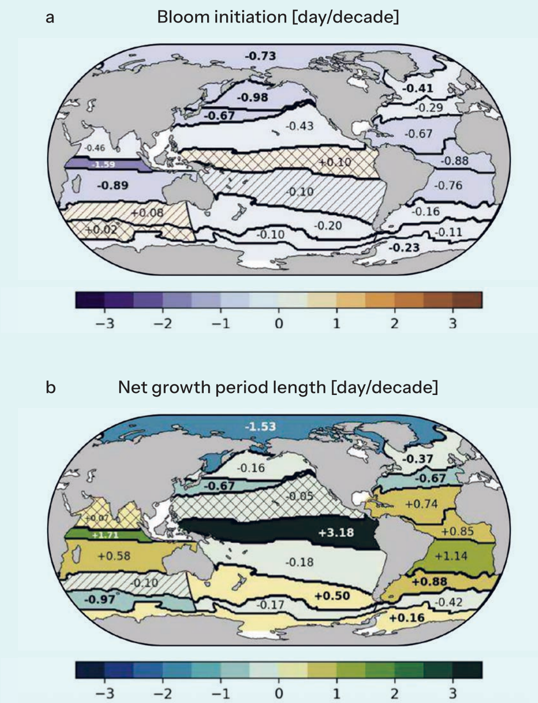
7

TROPHIC LEVEL DECOUPLING DRIVES FUTURE CHANGES IN PHYTOPLANKTON BLOOM PHENOLOGY

Seasonal phase-shifts between phytoplankton and zooplankton productivity are to be expected with future warming.

Anthropgenic climate change can shift the seasonality of marine productivity, with far-reaching consequences for the marine food web. However, so far the mechanisms underlying these changes in phytoplankton bloom phenology are not well understood. To address this issue, we used the 30-member Large Ensemble of climate change projections conducted with the GFDL earth syste model. The study reveals earlier bloom initiation in most ocean regions, yet changes in bloom peak timing vary widely by region (Figure 32). Shifts in both initiation and peak timing are induced by decoupling between altered phytoplankton growth and zooplankton predation, with increased zooplankton predation (top-down control) playing an important role in altered bloom peak timing over much of the global ocean. Only in limited regions is light limitation a primary control for bloom initiation changes. In the extratropics, climate-change-induced phenological shifts will exceed background natural variability by the end of the twenty-first century, which may impact energy flow in the marine food webs. This study provides novel insights into the effect of future climate change in marine biology, by focusing for the first time on the intricate seasonal phase-shifts between phytoplankton and zooplankton productivity.

Figure 32.
Anthropogenic phenological shifts in both bloom initiation and peak bloom timing results in spatially diverse impacts on net growth period. Ensemble mean trends (1990-2100) of (a) bloom initiation, (b) net growth period length, over biomes.



Ryohei Yamaguchi, Keith B. Rodgers, Axel Timmermann, Karl J. Stein, Sarah Schlunegger, Daniele Bianchi, John P. Dunne, and Richard Slater, 2022, Nature Climate Change, doi: 10.1038/s41558-022-01353-1 [JIF, 29.6]

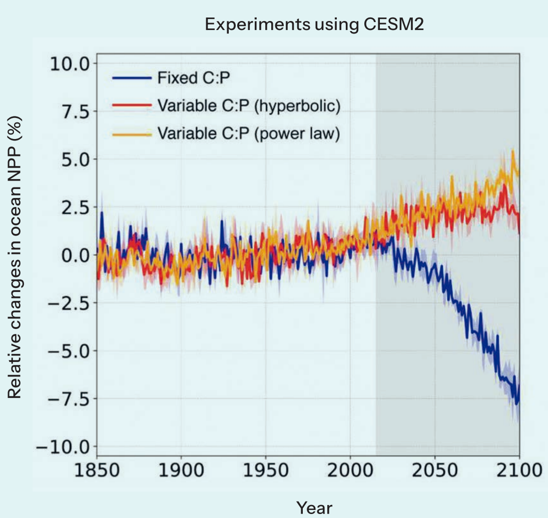
8

NUTRIENT UPTAKE PLASTICITY IN PHYTOPLANKTON SUSTAINS FUTURE OCEAN NET PRIMARY PRODUCTION

Phytoplankton nutrient plasticity implies that global marine production may increase in future, not decrease as previously suggested in earlier earth system model projections.

Annually, marine phytoplankton convert approximately 50 billion tons of Dissolved Inorganic Carbon to particulate and dissolved organic carbon, a portion of which is exported to depth via the biological carbon pump. Despite its important roles in regulating atmospheric carbon dioxide via carbon sequestration and in sustaining marine ecosystems, model-projected future changes in marine net primary production are highly uncertain even in the sign of the change.
In this study ICCP scientists together with colleagues from the University of Hawaii and JAMSTEC used an Earth system model to show that frugal utilization of phosphorus by phytoplankton under phosphate-stressed conditions can overcompensate the previously projected 21[st] century declines due to ocean warming and enhanced stratification. Our results (Figure 33), which are supported by observations from the Hawaii Ocean Time-series program, suggest that nutrient uptake plasticity in the subtropical ocean plays a key role in sustaining phytoplankton productivity and carbon export production in a warmer world.This study is the first to demonstrate the importance of phytoplankton plasticity in future climate change scenarios. It also reconciles the wide uncertainty range in CMIP6 model projections described in the AR5 IPCC report by demonstrating that models which include plasticity usually show an increase in future net primary productivity, whereas those that do not have plasticity included exhibit a decrease in global ocean productivity.

Figure 33.
Percentage change in Global Ocean Net Primary Productivity obtained from CESM2 greenhouse warming simulations under SSP3-7.0 emission scenario and using fixed phytoplankton nutrient stoichiometry (blue) and variable ones, obtained from empirical data (orange, red).



Kwon, E.Y., M.G. Sreeush, A. Timmermann, D.M. Karl, M.J. Church, S.-S. Lee, R. Yamaguchi, 2022: Science Advances, doi: 10.1126/sciadv.add2475 [JIF 14.1],

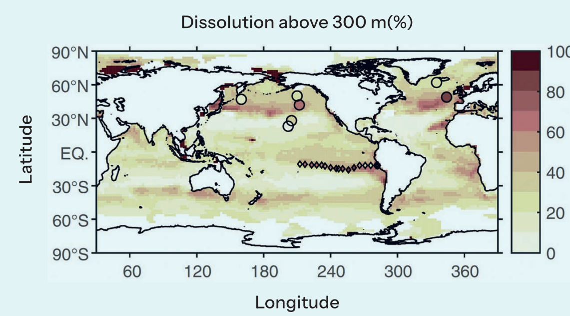
9

BIOLOGICAL EXPORT PRODUCTION CONTROLS UPPER OCEAN CALCIUM CARBONATE DISSOLUTION AND CO_2 BUFFER CAPACITY

Upper ocean heterotrophic respiration is an important source for calcium carbonate dissolution and alkalinity.

Marine biogenic calcium carbonate ($CaCO_3$) cycles play a key role in ecosystems and in regulating the ocean's ability to absorb atmospheric carbon dioxide. However, the drivers and magnitude of $CaCO_3$ cycling are not well understood, especially for the upper ocean. Here, we provide global-scale evidence that heterotrophic respiration in settling marine aggregates may produce localized undersaturated micro-environments in which $CaCO_3$ particles rapidly dissolve (Figure 34), producing excess alkalinity in the upper ocean. Our optimized model, cross-validated by independent sediment-trap data, suggests that upper ocean $CaCO_3$ dissolution is sensitive to biological export production and subsequent respiration of organic carbon. In the deep ocean, $CaCO_3$ dissolution is primarily driven by the conventional thermodynamics of $CaCO_3$ solubility. This thermodynamically driven dissolution is responsible for the reduced flux of $CaCO_3$ burial to marine sediments beneath the more corrosive deep waters of the North Pacific. The previously overlooked process of upper ocean $CaCO_3$ dissolution, driven by heterotrophic respiration of organic carbon within the ocean's twilight zone, accounts for about 40% of the total $CaCO_3$ dissolution in the global ocean. Upper ocean dissolution can increase the neutralizing capacity for respired CO_2 by up to 6% in low-latitude thermocline waters. Without upper ocean dissolution, the ocean might lose 20% more CO_2 to the atmosphere through the low-latitude upwelling regions.
Future projections of the global ocean carbon sink, therefore, require Earth system models to include biologically mediated $CaCO_3$ dissolution in the upper ocean.

Figure 34.
Simulated fraction at which the $CaCO_3$ exported from the euphotic zone is dissolved until it reaches a depth of 300 m. The filled circles show the sediment trap data-based estimates.



Eun Young Kwon, John P. Dunne, Kitack Lee, Science Advances, vol. 10, 13, article eadl0779, doi: 10.1126/sciadv.adl0779 (2024) [JIF 14.1]

ICCP RESEARCH HIGHLIGHTS

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