SPECIAL PROJECT FINAL REPORT

Project Title:	Mining 5th generation reanalysis data for changes in the global energy cycle and for estimation of forecast uncertainty growth with generative adversarial networks
Computer Project Account:	spatlh00
Start Year - End Year :	2021 - 2023
Principal Investigator(s)	Leopold Haimberger[1] Alexander Bihlo[2]
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The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The project was devoted to identifying changes in the global energy and freshwater cycles as well as potential inhomogeneities, particular in the early period of ERA5 (1950-1978), which has been completed in 2020. It also supported diagnostic evaluations of the subarctic and arctic regions in both atmosphere and ocean.

In the second branch of this project, very recent methods of machine learning for ensemble prediction were tried out. In particular, deep convolutional adversarial generative networks were trained to learn from the ERA5 reanalysis and ensemble data to forecast the ensemble spread of various meteorological fields, including geopotential height and temperature.

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

We did not encounter significant technical problems

Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

The special project framework is appropriate for the purposes we pursue with it.

Summary of results

This project had two branches, one on enhancing the state of the art in energy budget evaluations, one on establishing machine learning methods for ensemble prediction. In both fields significant results could be achieved that are well received in the research community.

We can report about the publication of a novel tool for evaluating horizontal transports across waterstraits (StraitFlux, Winkelbauer et al. 2024b), which was extensively used e.g. for a comparison of almost 40 CMIP6 historical model runs against transports from GREP ocean reanalyses (Winkelbauer et al. 2024 a). Fig. 1 is taken from the latter paper and shows how various components of the coupled atmospheric and oceanic budgets differ. The most prominent differences can be found for horizontal energy transports into the Arctic (panel g).

Development of Straitflux started with a study on the Arctic hydrological cycle (Winkelbauer et al. 2021). The tool has also been used for calculating transports through the RAPID array (Mayer et al. 2023) and the Indonesian ThroughFlow (Fritz et al. 2023).

Mass consistent energy budget terms have been published also in Copernicus (Mayer et al. 2021, 2022)
https://cds.climate.copernicus.eu/cdsapp#!/dataset/derived-reanalysis-energy-moisture-budget?tab=overview
up to 2022. An update to 2023 has recently been calculated but has yet to be made accessible via the Copernicus portal. The energy budget evaluations have also been interpreted scientifically, especially trends and homogeneity of global energy budget quantities have been studied (Mayer et al. 2023)

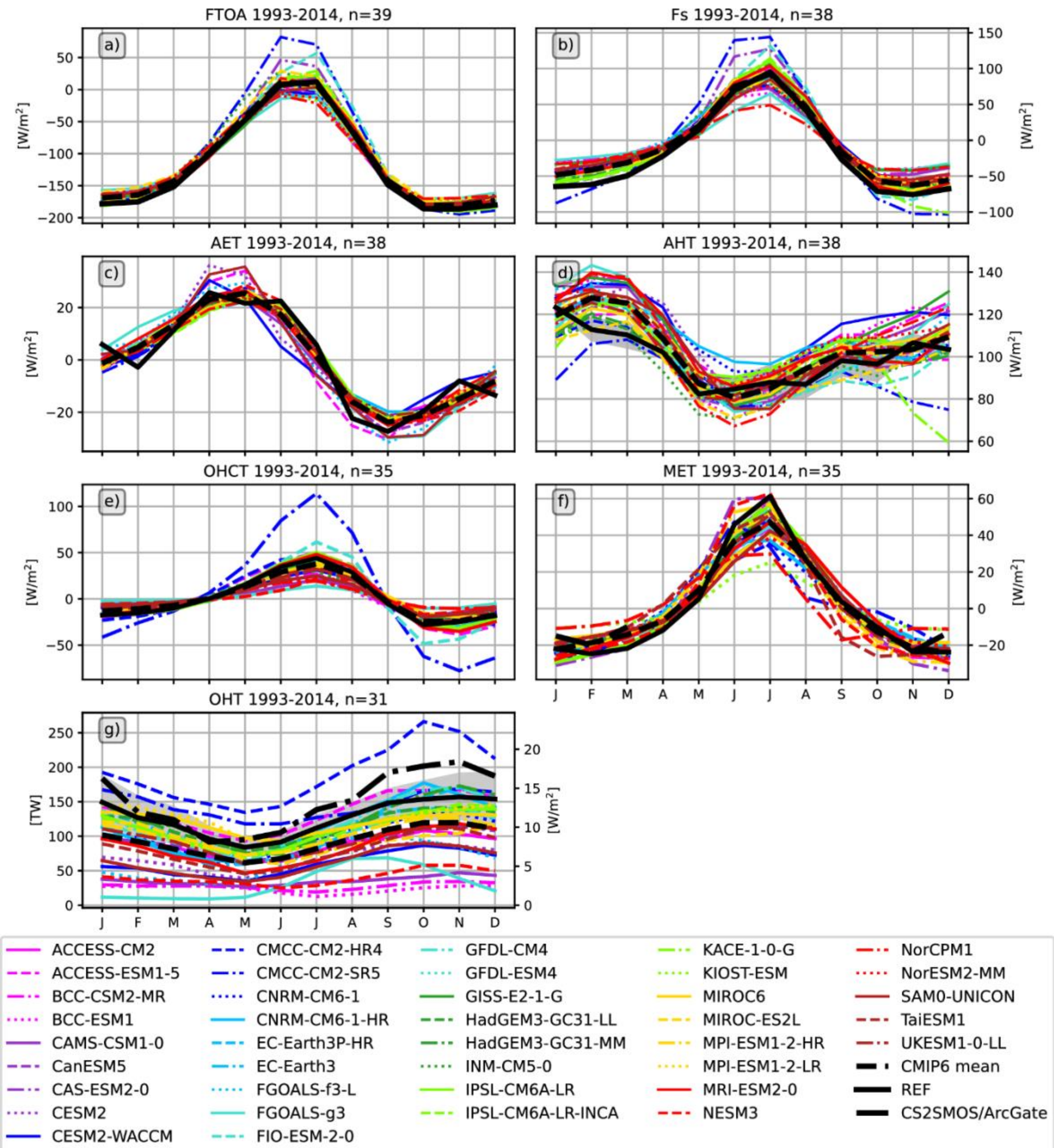

Fig. 1: Mean annual cycles of the key terms of the coupled Arctic energy budget: a net radiation at the top of the atmosphere F_{TOA}, b net vertical energy flux at the surface F_S, c atmospheric energy tendency AET, d atmospheric heat transport AHT, e full-depth ocean heat content tendency, f melt energy tendency (MET), and g the oceanic heat transport across the main Arctic gateways. Shading indicates the uncertainty range of the reference values and is either based on the 2σ standard deviations of monthly mean values (F_S, F_{TOA}, AET, AHT) or calculated from the spread of the GREP ensemble (OHCT, MET, OHT). (From Winkelbauer et al. 2024a, their Fig. 9)

Ensemble prediction systems are invaluable for weather forecasting but come with high computational costs due to the necessity of running several perturbations of the deterministic control forecast. To address this, we propose using deep-learning algorithms to predict the ensemble spread—a measure of forecast uncertainty—solely from a deterministic control forecast. Adapting the pix2pix architecture to a three-dimensional model and training it on years of operational weather data for the 500 hPa geopotential height, we show that our method can eliminate the need for costly ensemble prediction systems. The trained models can accurately replicate the statistical properties of traditional ensemble predictions, significantly reducing computational demands while maintaining high forecast accuracy (Brecht and Bihlo, 2023).

The advent of machine learning has the potential to revolutionize numerical weather prediction. Revisiting the first successful numerical weather forecast from 1950, which was obtained using the Electronic Numerical Integrator and Computer (ENIAC) and the barotropic vorticity equation, we investigate how forecasts would differ if machine learning-based solvers were used instead of standard numerical discretizations. Specifically, we recreate these numerical forecasts using physics-informed neural networks, demonstrating that these networks provide a more accurate and efficient methodology for solving meteorological equations on the sphere compared to the original ENIAC solver (Brecht and Bihlo, 2024b).

Improving precipitation forecasts, which are often less accurate due to unresolved small-scale processes, also benefits from advancements in machine learning. Traditionally, generating an ensemble of high-resolution simulations is computationally prohibitive. We propose a novel approach using generative adversarial networks to generate ensemble weather predictions for high-resolution precipitation without requiring high-resolution training data. Our method learns the complex patterns of precipitation, producing diverse and realistic precipitation fields from a single control forecast. Evaluated through metrics such as RMSE, CRPS, rank histograms, and ROC curves, our generated ensembles closely match the ECMWF IFS ensemble, demonstrating the feasibility and accuracy of this approach (Brecht and Bihlo, 2024a).

List of publications/reports from the project with complete references

R. Brecht and A. Bihlo, 2024a. Towards replacing precipitation ensemble predictions systems using machine learning. Atmospheric Science Letters (accepted), arXiv:2304.10251.

R. Brecht and A. Bihlo, 2024b. M-ENIAC: A machine learning recreation of the first successful numerical weather forecasts Geophys. Res. Lett. 51, e2023GL107718, arXiv:2304.09070 .

R. Brecht and A. Bihlo, 2023. Computing the ensemble spread from deterministic weather predictions using conditional generative adversarial networks, Geophys. Res. Lett. 50, e2022GL101452.

Fritz, M., Mayer, M., Haimberger, L., and Winkelbauer, S.: Assessment of Indonesian Throughflow transports from ocean reanalyses with mooring-based observations, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-435, 2023.

Mayer, J., Mayer, M., and Haimberger, L. (2021). Consistency and Homogeneity of Atmospheric Energy, Moisture, and Mass Budgets in ERA5. Journal of Climate 34, 10, 3955-3974, https://doi.org/10.1175/JCLI-D-20-0676.1

Mayer, J., Mayer, M., Haimberger, L. (2022): Mass-consistent atmospheric energy and moisture budget monthly data from 1979 to present derived from ERA5 reanalysis, v1.0, Copernicus Climate Change Service (C3S) Climate Data Store (CDS), https://doi.org/10.24381/cds.c2451f6b

Mayer, J., Haimberger, L., and Mayer, M. (2023): A quantitative assessment of air-sea heat flux trends from ERA5 since 1950 in the North Atlantic basin, Earth System Dynamics, Jg. 14, Nr. 5, S. 1085-1105. https://doi.org/10.5194/esd-14-1085-2023

Winkelbauer, S, Mayer, M, Seitner, V, Zsoter, E, Zuo, H & Haimberger, L 2021, 'Diagnostic evaluation of river discharge into the Arctic Ocean and its impact on oceanic volume transports', HESS, https://doi.org/10.5194/hess-2021-318

Winkelbauer, S., Mayer, M. & Haimberger, L. Validation of key Arctic energy and water budget components in CMIP6. Clim Dyn 62, 3891–3926 (2024). https://doi.org/10.1007/s00382-024-07105-5

Winkelbauer, S., Mayer, M., and Haimberger, L.: StraitFlux – precise computations of water strait fluxes on various modeling grids, Geosci. Model Dev., 17, 4603–4620, https://doi.org/10.5194/gmd-17-4603-2024, 2024.

Future plans

The above research activities are continued within an ongoing new special project *“Applying hydrodynamic constraints to coupled energy budget analysis and to physics-informed machine learning based forecasting”*.