SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Coupled energy and freshwater budgets from and early upper air data enhancements for reanalysis
Computer Project Account:	spatlh00
Start Year - End Year :	2018 - 2020
Principal Investigator(s)	Leopold Haimberger
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Other Researchers (Name/Affiliation):	Michael Mayer, Johannes Mayer, Hans Hersbach, Steffen Tietsche

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

The special project accompanied an Austrian Science Funds project devoted to evaluating the global energy budget, with emphasis on the Arctic. For this purpose access to experimental or not yet publicly available reanalysis data were needed. It accompanied also a Copernicus activity (C3S 311c Lot2) to prepare early upper air data for assimilation into future generation reanalyses.

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

Diagnostic evaluations of energy and water budgets have been an important tool for climate research since several decades. If the tendency term of the prognostic forecast equations is known from the difference of subsequent analyses, the forecast equation can be used in “diagnostic mode” to indirectly estimate important flux quantities that otherwise need to be parameterized. For this purpose the forecast equations are typically integrated in the vertical, allowing for evaluation of the net surface energy balance or the net water flux (P-E) through the Earth’s surface. This task is facilitated by the availability of excellent satellite based energy flux estimates at the Top Of Atmosphere (TOA) and by improved flux divergence estimates from reanalyses. In addition, flux and state quantities are not only available for the atmosphere from ERA-Interim or ERA5, but also for the ocean. Looking at both budgets allows for additional consistency estimates. For example Mayer et al. (2014) showed that much of the additional enthalpy released from the Pacific ocean during El Nino events is stored in the neighbouring Atlantic and Indian Oceans.

A detailed global analysis of the atmospheric energy budget using ERA5 data for calculating the atmospheric energy flux divergence was published recently (Mayer et al. 2021). A follow-on study focussing on the surface energy balance and its evolution over Sea is in preparation. One component is a thorough comparison of the indirectly estimated surface energy balance with the ERA5 parameterized surface energy balance and buoys. There are still puzzling discrepancies which need to be better understood. Data sets tuned to fit well to the buoy data have global mean surface energy fluxes on the order of 20 W/m^2, which is of course spurious, while the indirect estimates fit well to observed changes of the oceanic heat content. There is some suspicion that the bulk formulae used for calculating the energy fluxes at buoy sites are the main sources of biases in the buoy fluxes, but this has to be independently confirmed.

In the special project, the Arctic was a special focus. Its budget, evaluated previously by Serreze and Barry (2014), was revisited using ERA5, ORAS5, and CERES data, together with an improved estimation method for the atmospheric vertically integrated horizontal energy flux divergence. The atmospheric and ocean heat transport into the Arctic were estimated to be a lot stronger in new estimates by Mayer et al. (2019, Fig. 1, using ERA5 and ORAS5 data), leading to multiannual budgets that were closed within 1 W/m^2. Only on seasonal time scales they still found significant residuals.

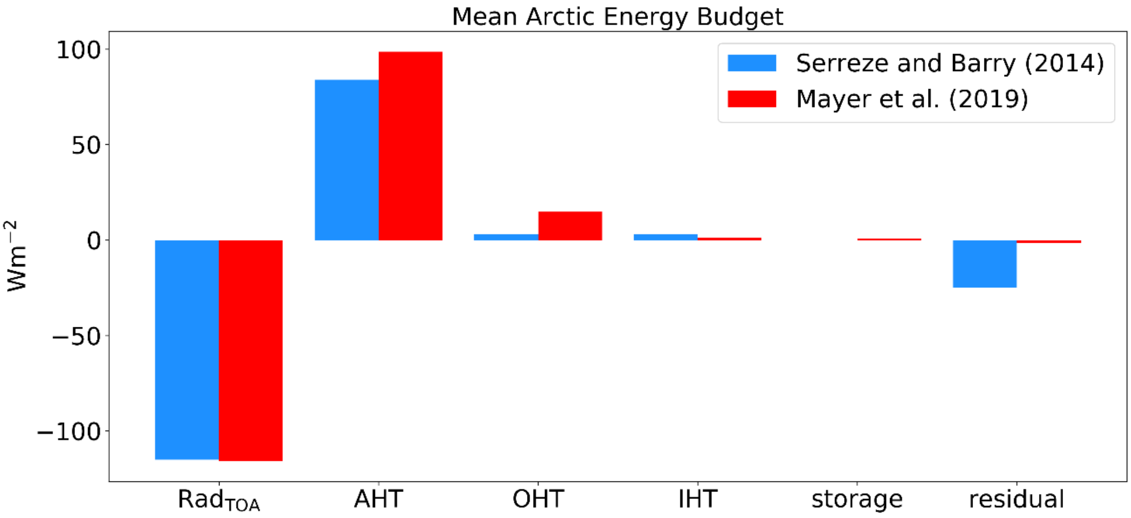

Fig. 1: Budget closure over the Arctic Ocean from Serreze and Barry (2014) and from a new estimate by Mayer et al. (2019).

Building upon the experience gained from the energy budget, a hydrologic budget evaluation was recently completed by Winkelbauer et al. (2021), that aimed to reconcile freshwater fluxes through the Arctic ocean gateways with atmospheric water transports into the Arctic area bounded by the catchments draining into the Arctic. Excellent agreement could be found also there, using the "right" data sources (Fig. 2). Some of the data sources, such as runoff from ERA5 exhibited spurious runoff reduction trends and also too weak seasonal runoff.

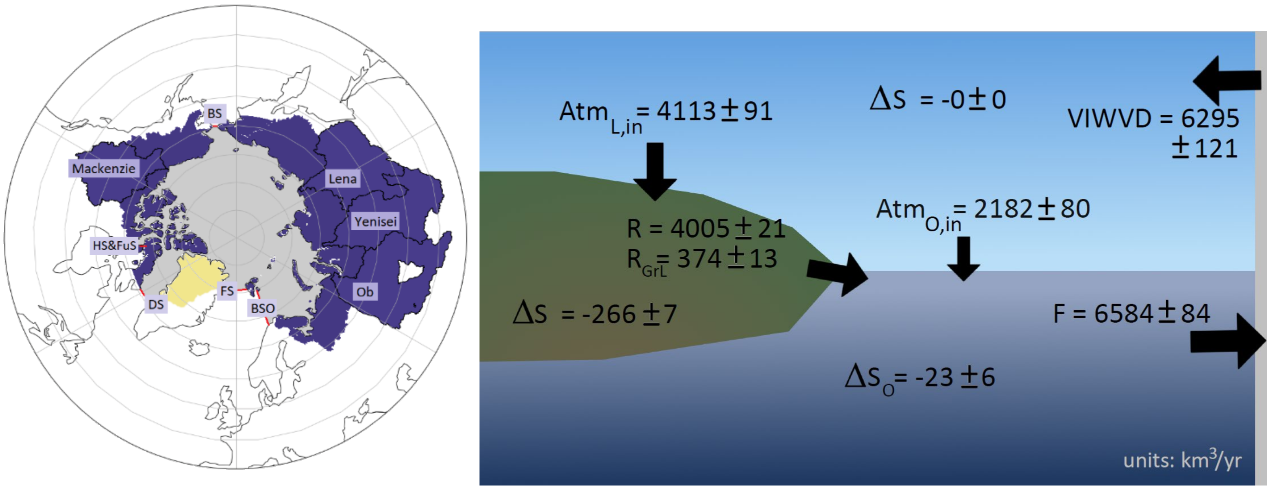

Fig. 2:Study region and water budget estimates from Winkelbauer et al. (2021). DS=storage in ocean, land surface (including glaciers) and atmosphere. VIWVD=Vertically integrated water vapor flux divergence averaged over Arctic region, $Atm_{L,in}$=P-E over the Arctic land mass, $Atm_{O,in}$=P-E over ocean, R, R_{Grl} are runoff estimates for the whole region and Greenland, respectively, F=water volume flux through ocean gateways estimated from ocean reanalyses and moorings. Uncertainties estimated from ensemble of calculations based on different reanalyses and different observation data sets.

The special project facilitated collaboration with ECMWF while preparing bias adjustments for ERA5 and its backward extension to 1950. It also supported a Copernicus contract for developing an early upper air service (C3S 311c Lot2). It was designed to serve not only observation data but also analysis and background departures of in situ upper air data from ERA5 and uncertainty estimates based on those (Desroziers, 2005). As depicted in the diagram below, the service consists of building not only the upper air data base but also an interface to the Copernicus Data Store (CDS) such that the data can be used in the Copernicus Toolbox or python applications using the CDS-API (Fig. 3 shows a flow chart). At the time of writing this report, the service was close to becoming public.

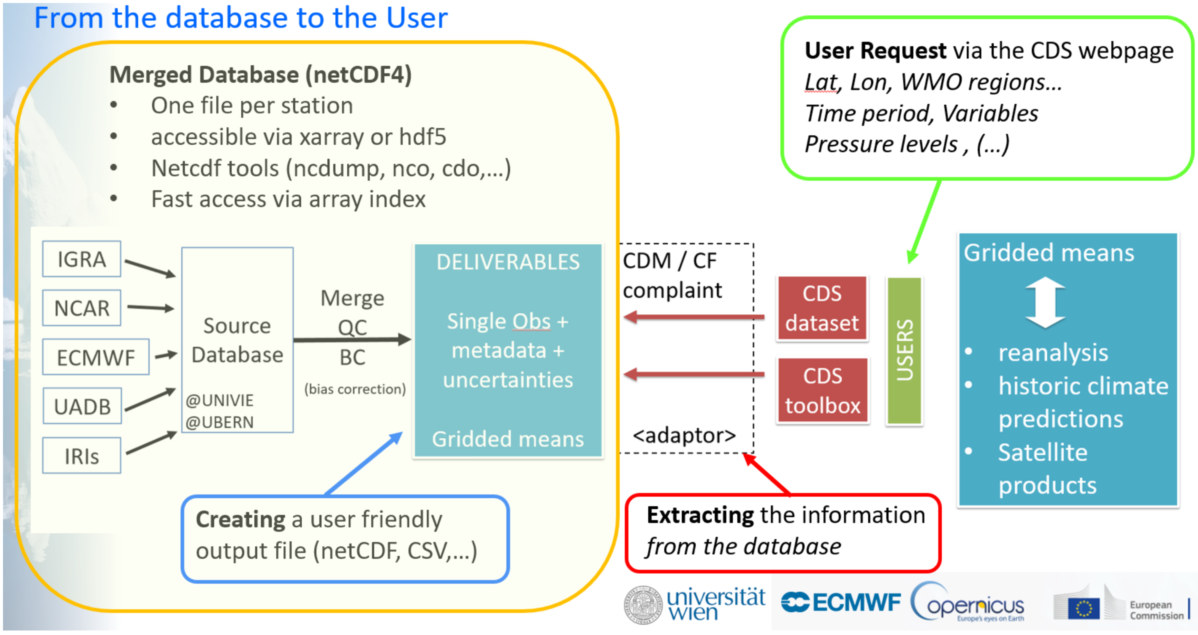

Fig. 3: Data flow diagram of C3S 311c service. The service is running on development servers at the time of writing this report, but should be available soon at https://cds.climate.copernicus.eu/#!/home.

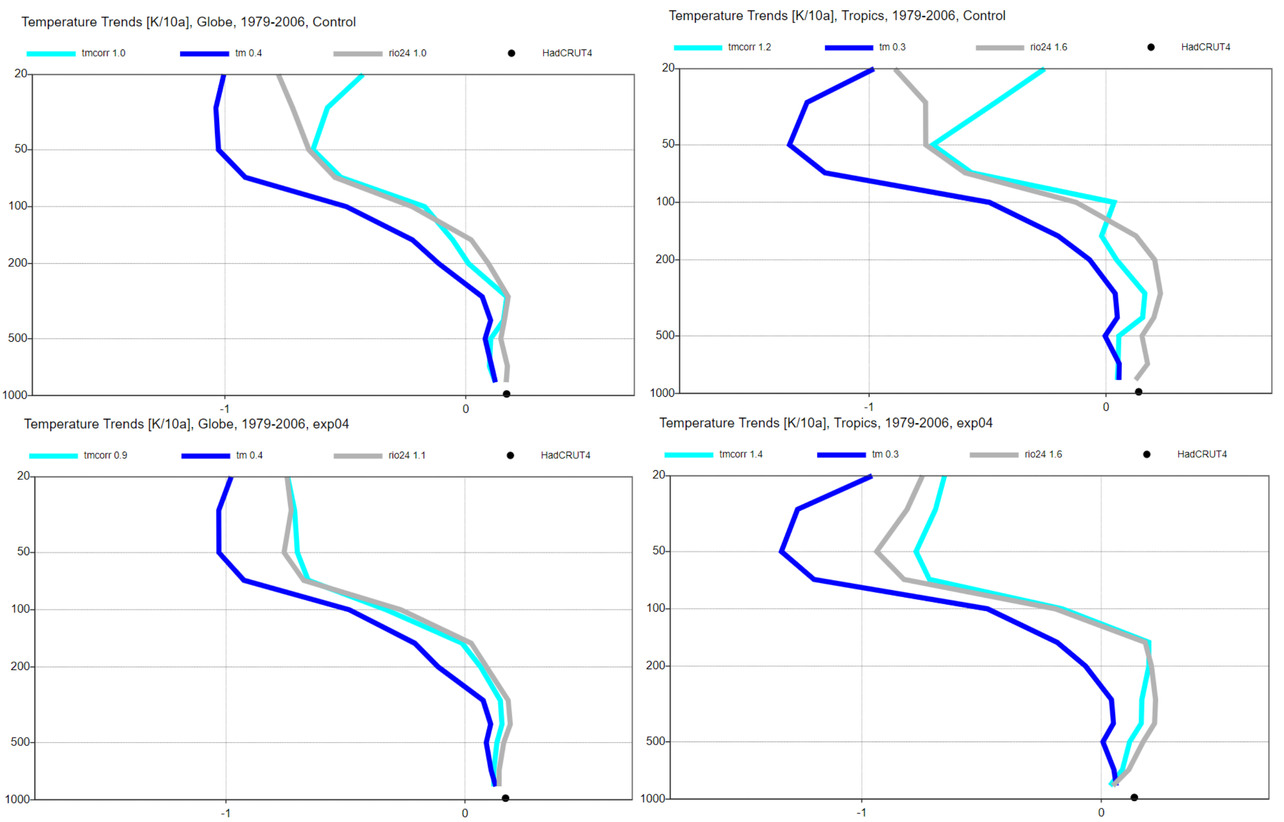

Figure 4: Global and tropical belt mean trends for RAOBCORE v1.4 (Haimberger et al. 2008, upper panels) and CUON (lower panels), for period 1979-2006. Black dot is tropical mean surface temperature trend from the HadCRUT4 surface temperature data set, sampled at 10x10 grid boxes where radiosonde data were available. For more details see Haimberger et al. (2021).

In addition to observations and its uncertainty estimates, homogeneity adjustments for temperature, humidity and wind were calculated using ERA5 as background, based on methods of Gruber and Haimberger (2008) and Haimberger et al. 2012). The improved background, and smaller methodical improvements lead to a more realistic vertical shape of global and tropical temperature trends in the Tropics for the satellite period (Fig. 4).

Besides those accomplishments, continuous access to the MARS archive in addition to the quickly improving Copernicus services allowed us to contribute to several review papers and climate state reports, most notably von Schuckmann et al. (2020), Steiner et al. (2020), Haimberger et al. (2020, 2021).

References (besides those listed in the section below):

Gruber, Ch. And Haimberger, L., 2008: On the homogeneity of radiosonde wind time series. Meteorol. Z. 17, 631-643.

Haimberger, L., C. Tavolato, and S. Sperka, 2012: Homogenization of the global radiosonde temperature dataset through combined comparison with reanalysis background series and neighboring stations. J. Climate 25, 8108–8131

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Mayer, M., Haimberger, L., and Balmaseda, M. A., 2014: On the energy exchange between tropical ocean basins related to ENSO. Journal of Climate 27, 6393–6403, https://doi.org/10.1175/JCLI-D-14-00123.1

Serreze, M. C., and R. G. Barry, 2014: *The Arctic Climate System.* Cambridge University Press, 415 pp.

List of publications/reports from the project with complete references

Haimberger, L., M. Blaschek, F. Ambrogi and U. Voggenberger, 2021: C3S Upper air temperature and humidity data final bias adjustments – Algorithm Theoretical Basis, DC3S311cLot2.2.1.4, available from Authors and https://cds.climate.copernicus.eu/#!/home

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von Schuckmann, K., Cheng, L., Palmer, M. D., Tassone, C., Aich, V., Adusumilli, S., Beltrami, H., Boyer, T., Cuesta-Valero, F. J., Desbruyères, D., Domingues, C., García-García, A., Gentine, P., Gilson, J., Gorfer, M., Haimberger, L., Ishii, M., Johnson, G. C., Killik, R., King, B. A., Kirchengast, G., Kolodziejczyk, N., Lyman, J., Marzeion, B., Mayer, M., Monier, M., Monselesan, D. P., Purkey, S., Roemmich, D., Schweiger, A., Seneviratne, S. I., Shepherd, A., Slater, D. A., Steiner, A. K., Straneo, F., Timmermans, M.-L., and Wijffels, S. E., 2020: Heat stored in the Earth system: Where does the energy go? The GCOS Earth heat inventory team, Earth Syst. Sci. Data, https://doi.org/10.5194/essd-12-2013-2020

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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

Future plans

The above research activities will continue in the next few years. A new special project titled “Mining 5th generation reanalysis data for changes in the global energy cycle and for estimation of forecast uncertainty growth with generative adversarial networks” is ongoing. This special project facilitates collaboration for building Copernicus Services (C3S 311a Lot2, 114-R&D-GLORAN-CMEMS LOT 8) and with Austro-Canadian researcher Prof. Alexander Bihlo, who develops new weather prediction methods based on machine learning.