Review of manuscript egusphere-2023-2989 submitted to Atmospheric Physics and Chemistry

Thermodynamic and cloud evolution in a cold air outbreak during HALO-(AC)^3: Quasi-Lagrangian observations compared to the ERA5 and CARRA reanalyses

by B. Kirbus et al.

The study evaluates the representation of a marine cold air outbreak (MCAO), i.e., off-ice flow of very cold Arctic air over a much warmer open ocean, in ECMWF's ERA5 and the high resolution CARRA reanalyses based on aircraft and dropsonde observations that were obtained during the HALO-(AC)^3 campaign. The MCAO event under consideration occurred on 1. April 2022 in Fram Strait, a region which is well-known for its frequent and intense MCAOs, where the originally Arctic air is rapidly transformed by heat and moisture uptakes from the ocean. The event was sampled by the HALO and the Polar 6 aircrafts in a quasi-Lagrangian manner providing unique observations of the MCAOs evolution with fetch from sea ice. These observations are used for two purposes: (i) The estimation of diabatic heating and moistening rates as the air masses are transformed over the ocean, and (ii) to evaluate how the two reanalyses represent the MCAO. Kinematic trajectories computed with winds from reanalysis are employed to confirm the Lagrangian matching and to study the air mass transformations in the reanalyses. Profiles of temperature and specific humidity, diabatic heating and moistening rates, surface fluxes, and cloud properties are systematically evaluated first over sea ice and then with increasing fetch from the sea ice edge. Overall, the two reanalyses agree reasonably well with observations, but the authors also find systematic biases, which in part appear to be related to an insufficiently sharp maginal ice zone. In addition, the findings reveal the benefits of higher spatial resolution in CARRA.

MCAOs are the key weather features in which heat and moisture is transferred from the ocean to the atmosphere - they are not restricted to the Arctic but the same physics also occurs at more temperate latitudes in flows across ocean fronts in the storm track entrance regions. Hence, it is of great importance that these processes are well represented in models and reanalyses. This study, thus, fills an important gap.

I truly enjoyed reading the manuscript and find the results significant. I have no doubt that the study is of great interest to the readership of ACP. Overall, the analyses appear sound, the manuscript is well written, and the figures are nicely designed and easy to read. I have a few suggestions for improvement, which are detailed below, which are all rather minor in nature. Once these points have been addressed, I recommend the manuscript be accepted for publication.

Specific comments:

1. Detailed observations of MCAOs, in particular also in the Nordic Seas, have been obtained in earlier field campaigns, documenting in particular the boundary layer evolution, heat and moisture budgets, as well as estimates of surface fluxes (e.g., Shapiro et al. 1987, Brümmer 1997, 1999, Vihma and Brümmer 2002…; detailed references are

given below). I think that these studies should be more extensively discussed in the introduction.

2. L30: Please explain what you mean by *decoupling*.
3. L45: Svingen et al. (2023) provide observational evidence for the importance of MCAOs for deep water formation.
4. L70ff: You raise an important point here. Kinematic trajectories only see the grid-scale winds but they are not aware of the sub-gridscale (turbulent) motions. As a result, a kinematic trajectory represents a volume of air floating with the mean winds with turbulent exchanges happening through its boundaries and appearing as sources / sinks. Perhaps this point could be made a bit more transparent? This is in contrast to the observed profiles, which in some sense suffer from the opposite problem: they capture all the small scale fluctuations, which are not necessarily representative of the mean.
5. L125ff: I am wondering how the transfer coefficients are computed. In general they are modeled as a function of static stability and surface properties such as the roughness length. How do you compute the transfer coefficients?
6. Section 2.3: I think it would help if the additional explanations of the quasi-Lagrangian approach given in the appendix B would be included here in the main part.
7. Section 3.2.2: Does the cold bias in the profiles over sea ice go along with a too deep cold BL? And related to that, how does the mean temperature across the entire BL compare to observations? As I understand, the mean biases presented in Table 1 are computed using the observed BLH not the BLH as represented in the reanalyses. Given the dipole structure of the biases in the vertical profiles, the mean biases will critically depend on how you define the BLH.
8. Section 3.3.2: The diabatic heating and moistening profiles are very interesting. How do the differences between observations and reanalyses fit together with the differences in surface fluxes? For example, at the later stages of the MCAO evolution, the diabatic heating profiles in ERA5 show that the warming extends too far up. This suggests, that overall there is too much energy input into the BL, which hin turn seems inconsistent with an underestimation of the surface sensible heat fluxes.
9. L408ff: I can’t fully reconcile the statement that ERA5 overestimates cloud liquid water content at all stages. For the time range 1-2h the values shown in Fig. 9b seem to agree quite well with observations, or am I missing something?
10. Generally, I feel that some of the figures presented in the Appendix are interesting but not key to the understanding of the study (specifically figures A3 - A8). Hence, I suggest moving them from the Appendix to the Supplement along with the corresponding text.

Editorial comments

l2: *intensive* -> *intense*

l8: delete *specific* in *investigated specific MCAO*

l11: Suggest to rephrase *As the air mass continued its drift southwards, …* as *With increasing fetch of the sea ice edge, …*

l12: *quasi-Lagrange* -> *quasi-Lagrangian*

l16: *… issues with* ***the representation*** *of …*

l63: ***at*** *high temporal resolution*

l99: *as* ***a*** *dedicated*

l108: *several* ~~***of***~~ *such flight legs*

l110: *reported* -> *performed?*

l120: vertical gradient (?)

l125: Please fix the reference ECMWF, 2016 by including the appropriate authors

l154: *The reanalysis data can be retrieved for…*

l189: Please spell out LAGRANTO (Lagrangian Analysis Tool)

l237: replace *obvious* by *evident*

l241: *liquid+ice* -> liquid and ice

l245: replace *issue* by *matter*

l246: *the sea ice concentrations* **in** *ERA5* ***are***

l274: please rephrase *respective observations derived BLH*

l294: *… vertical velocity is used* **for** *the three-dimensional…*

l404: here and elsewhere: *cloud ice* ***and*** *snow*

l405: fix ref to Maherndl et al (2023)

l423: *common intensity* – Do you mean *typical intensity?*

L453: *resolution* (singular)

Caption Fig. 2: … *diamond shapes show the location***s** *of released …*

Caption Fig. 3: … *indicated* **on** *the left hand side* … (please also fix in other captions)

Literature:

Brümmer, B., 1997: Boundary layer mass, water, and heat budgets in wintertime cold-air outbreaks from the Arctic sea ice. Mon. Wea. Rev., 125, 1824–1837

Brümmer, B., 1999: Roll and cell convection in wintertime Arctic cold-air outbreaks. J. Atmos. Sci., 56, 2613–2636

Shapiro, M. A., L. S. Fedor, and T. Hampel, 1987: Research aircraft measurements of a polar low over the Norwegian Sea. Tellus, 39A, 272–306

Svingen, K., A. Brakstad, K. Våge, W. von Appen, and L. Papritz, 2023: The Impact of Cold-Air Outbreaks and Oceanic Lateral Fluxes on Dense-Water Formation in the Greenland Sea from a 10-Year Moored Record (1999–2009). *J. Phys. Oceanogr.*, **53**, 1499–1517

Vihma, T., and B. Brümmer, 2002: Observations and modelling of the on-ice and off-ice air flow over the Northern Baltic Sea. Bound.-Layer Meteor., 103, 1–27