Lagrangian single-column modeling of Arctic airmass transformation during HALO-($\mathscr{AC}$)^3

Michail Karalis[1,], Gunilla Svensson[1,2], Manfred Wendisch[3], Michael Tjernström[1]
[1]Stockholm University, Department of Meteorology and Bolin Centre for Climate Research, Stockholm, Sweden

[2]KTH Royal Institute of Technology, Department of Engineering Mechanics, FLOW, Stockholm, Sweden

[3]Leipzig Institute for Meteorology (LIM), Leipzig University, Leipzig, Germany

July 23, 2025

We would like to thank the ACP editor and all anonymous referees for their insightful review of the manuscript. Below you may find our responses (regular font text) to each of the referee's remarks (gray text) along with the respective changes made in the manuscript (**"bold text"**)

Referee #3

Summary

Karalis et al. aim to enhance the understanding of airmass transformation occurring during warm air intrusions (WAI) in the Arctic. They propose a new single-column Lagrangian framework for simulating realistic WAI events and justify this by their findings that the WAI behaves as a column in the atmosphere. A case study of a WAI from 12-14 March is used to evaluate the performance of their framework, in which they do a comparison against dropsonde measurements, ERA5 and IFS forecast data. By looking at heat, moisture content and the vertical thermodynamic and cloud structure they conclude that the model adequately reproduces the transformation. They state the value of the model as a source for identifying common features between airmass transformations and for identifying model biases.

The paper presents an interesting study aiming to enhance the understanding of warm air intrusions in the Arctic. My main recommendations revolve around highlighting the novelty and use of your work and clarifying the description of the methodology for this new approach. After these comments have been addressed I think the paper will be a valuable contribution for further work in understanding airmass transformation in the Arctic. Below I attach major and minor comments that hopefully will be useful in preparing a revised version of the manuscript.

We thank the reviewer for their detailed and constructive feedback. Their comments helped us iron out points of ambiguity in how we present our methods and findings and overall benefited the manuscript considerably.

Major comments

1. It was not very obvious from the Introduction how this paper innovates from the plain Lagrangian framework applied in Svensson et al., 2023, even though this becomes somewhat clearer later on in the methods section. The novelty and use of the single-column framework should be better highlighted in the text upfront in the introduction, throughout the results, and in the discussion/conclusions (see comment 2).

A: Thank you for pointing this out. The novel features of this study are

1. the development of a single-column modeling framework capable of simulating realistic warm-air intrusion cases and
2. comparison with observations also conducted from a quasi-Lagrangian perspective.

This may not become clear enough early on. In the new version of the manuscript, the novelty of the method is stressed more in the introduction:

L72-79: "~~The suite of Lagrangian observations available for this case makes it a suitable testbed for the development of a Lagrangian single-column modeling framework to study real WAI cases, as per Pithan et al. (2016, 2018)'s suggestions. We use the Atmosphere-Ocean Single-Column Model (AOSCM, Hartung et al., 2018) to investigate the processes that drive the airmass transformation. We compare our simulations to observations, ERA5 and IFS forecast data in order to assess the performance of the model and its potential as a tool to test and construct future model parameterizaton schemes.~~ **We develop a Lagrangian single-column modeling framework suitable for the study of real WAI cases, as per Pithan et al. (2016, 2018)'s suggestions. We use the Atmosphere-Ocean Single-Column Model (AOSCM, Hartung et al., 2018) and take into account the time-varying dynamic and surface conditions that are relevant for the Arctic airmass transformation. In this simple, novel framework we can investigate the physical drivers and timescales of the transformation, in isolation from the complex dynamics that are typically associated with warm-air intrusions. Through comparison with the large number of Lagrangian HALO-(AC)^3 observations available for this case, as well as ERA5 and IFS forecast data we assess the model's performance and its potential as a tool for testing and developing future model parameterization schemes."**

2. The airmass trajectories for this case are almost entirely north-south oriented. It seems thus that for such straight-line trajectories one could get a lot of the same information from a simple cross-section without running the single-column model in addition. Thus, it is important to highlight what the additional value of this approach is.

A: The aim of our study is to introduce a simple and efficient framework that is suitable for the study of Arctic airmass transformation, not only for this case but for a suite of them. Using our single-column modeling framework to study the airmass transformation has several benefits:

1. It is much faster and less resource-intensive than its 3D counterpart, which facilitates the application of a large number of experiments in a short amount of time.
2. It is able to reproduce the Arctic airmass transformation realistically similarly to the 3D model, as seen through comparison with ERA5, IFS-OF and observations.
3. It is fundamentally Lagrangian. In a time-height cross-sections extracted from Eulerian gridded products (reanalysis or model output) it is harder to distinguish between changes

induced by physical processes and the ones caused by advection. In the Lagrangian AOSCM horizontal advection is deactivated and mass is conserved. This helps more clearly demonstrate how the different physical processes affect the airmass evolution.

4. In this framework, the dynamic evolution of the large-scale flow is not resolved, but rather used as input/forcing. The advantage in preserving the flow when testing the effect of different model parameters or parameterization schemes.

These points are established in different sections of the manuscript. We offer a summary in our conclusions:

L543-551: "In conclusion, our Lagrangian AOSCM framework is a novel tool that facilitates the simulation of realistic WAI events and, therefore, the direct evaluation with observations and can virtually be applied to simulate any case of meridional airmass transport. ~~The use of the model on a wide range of warm-air intrusions and cold-air outbreak events that have been captured over time by ship and aircraft campaigns would be a valuable source of information in identifying common features between the respective airmass transformations and uncovering persistent model biases. The AOSCM shares the same physical parameterizations as in EC-Earth and OpenIFS and, according to our results, is able to reconstruct an airmass transformation similar to its global equivalent. A more expansive study using the Lagrangian AOSCM framework could be used for the mitigation of long-standing parameterization deficiencies related to the airmass transformation and consequently the Arctic climate, conducing to a long-term benefit for weather forecasts and climate projections~~. **The AOSCM shares the same physical parameterizations as EC-Earth and OpenIFS and, despite being conceptually simpler and significantly less resource-intensive, it is able to reconstruct an airmass transformation similar to its global counterpart. This makes the model well-suited for wider application to more warm-air intrusion and cold-air outbreak events that have been captured over time by ship and aircraft campaigns. A more expansive study using the Lagrangian AOSCM framework would be valuable for identifying common features among airmass transformations. The model's ability to separate physical processes from the complex dynamics of WAIs can help uncover persistent Arctic-related model biases, mitigate long-standing parameterization deficiencies and eventually improve weather forecasts and climate projections."**

3. The authors make a strong statement in the conclusion about the novelty of this study, but it is difficult to distinguish the contribution here from the works of others, which is discussed both in the conclusion and also to some extent in the results part. In order to make it easier for the reader to follow the argumentation of how these results are novel, a dedicated discussion section would be useful. This would also allow to focus more on the conclusions from this work in the final section.

A: Our results about the vertical coherence of the flow lay the foundation for the application of the Lagrangian AOSCM. Therefore, we think that, in many parts of our manuscript it is essential for the results to be interpreted right away in order to move on to the next chapter. Adding a separate discussion section may increase the length of the paper substantially and lead to unnecessary repetition. We would prefer to not proceed with any major structural changes. However, we can deal with the ambiguities that the reviewer has rightfully pointed out and fix the confusing merging of discussion points and conclusions.

We moved a part of the conclusions to the end of Sect. 3.3.6 "Physical and dynamical drivers" where discussing the effects of subsidence in the context of past research is more appropriate"

L510-517: "The role of subsidence has not been adequately accounted for in the mostly idealized WAI airmass transformation modeling studies that have been attempted to date (Pithan et al., 2018). Part of the reason lies in the lack of observations and/or observational methods for the large-scale vertical motion, making reanalysis products, such as ERA5, the most common source for forcing information in SCM and LES experiments. The HALO-(AC)^3 campaign (Wendish et al., 2024) attempted measuring the large-scale subsidence on multiple counts (Paulus et al., 2024), including a cold-air outbreak event. Their results showed variable agreement between measurements and ERA5 reanalysis, at times displaying a significant mismatch in the magnitude and even sign of vertical velocity (ω). In this context, it is difficult to determine whether the prescribed subsidence profiles in our simulations and their consequent impact of the airmass transformation are realistic."

In the Conclusions section we replaced the moved text with the following to making it more clear that the paragraph is a summary of the framework's potential limitations:

L537-540: "Furthermore, errors in our simulations may have arisen from the large dependence on the along-track prescribed ERA5 vertical velocity, the accuracy of which is inconsistent (Paulus et al., 2024). It is important to note that the strong updrafts applied in our simulations would normally be accompanied by low-level convergence and, therefore, advection of new air in the column which is prohibited in our framework."

4. The method is not sufficiently clear, in particular when it is being referred to an ensemble. Some additional details on how the trajectories and the ensemble are obtained would be helpful for the interpretation. I suggest to illustrate this with a conceptual figure instead of using a result figure in section 2.2/2.3.

A: We agree that a conceptual figure would be a valuable contribution, however, we have not been able to design such a figure that demonstrates the ensemble in a better way than the concrete example does.

5. Another step in the method that needs further justification is the meridional search for threshold values from trajectory points. It seems odd to go from a Lagrangian framework to a search for threshold values in an Eulerian perspective. Why not use a threshold in a Eulerian map of TCWV directly? When 'stepping outside' the trajectories, there is no more guarantee for that the airflow aligns and goes into the same direction.

A: While it is true that the flow across the WAI may vary, airmasses within a certain distance from the trajectories are shown to move similarly to the ones on the trajectories and, furthermore, experience a similar transformation. This can be seen in Fig. 2c where areas around the trajectories are shown to have similar IVT (integrated water vapor) values and vertical structure. IVT (Fig. 2c) and IWV (integrated water vapor, Fig. 3a) show similar spatiotemporal variability, indicating that the wind field is actually quite coherent around the trajectory ensemble. Further evidence of that can be found in Fig.1 where the MSLP (mean sea-level pressure) contours are roughly equally spaced at the respective location of the airmass at each timestep and Fig. 2a from the narrow and coherent appearance of the larger suite of trajectories.

The Integrated Vapor Transport (IVT) threshold of 100 kg m-2 s-1 is used to estimate the extent of the airmass in the direction perpendicular to the axis of advection. The benefit of visualizing this in a Lagrangian way is:

1. Establishing that the trajectory ensemble is part of a larger airmass that moves and transforms in a coherent way
2. Demonstrating the variability in the transformation of the airmasses beside the one we chose to focus on. This helps determine whether our conclusions about the important processes and timescales of the transformation are tied to this specific airmass or can be considered relevant to the airmass transformation in general under similar conditions.

We explain how this airmass tracking/visualization method helps interpret vertical coherence in the manuscript. We add the following lines in Sect. 3.1:
L214-216 : "~~Therefore, all trajectories within the ensemble can be regarded as representative of the same air column.~~ **In simpler terms, the flow within a certain distance from the trajectories is relatively unirform, both in IVT and vertical structure. Therefore, our trajectory ensemble is narrow enough to be regarded as representative of a single air column that is advected and transformed in a coherent way."**

We have also rewritten the captions of Figures 2 and 3 to ensure the visualization method is clear to the reader.

6. L180: This appears to be a fundamental conclusion to move ahead, but the vertical alignment is not clear from the results. Maybe it could be quantified with a dispersion metric to underline how the trajectories move together? Additionally, a figure showing this result would be helpful, for example showing the vertical position of traced air parcels over time.

A: The trajectories are calculated in latitude - longitude coordinates, so any dispersion metric applied on those would not be particularly meaningful considering the convergence of the meridians as the airmass progresses to the north. Plotting the vertical position of the parcels over time does not necessarily help with evaluating their vertical alignment either (Fig. AR3.1). The closest thing to a dispersion quantifier would be the horizontal spread of the trajectories or, in more specific terms, the distance of the parcels that are the farthest from each other at each timestep. As already stated in the manuscript, the horizontal spread grows from 0 (at the location of initialization) to around 260 km at the two ends of the ensemble. We have now refined the phrasing to ensure the information is clear.

L203-205: "~~Within this large suite of trajectories, smaller subsets can be found, comprised of one trajectory per pressure level, that exhibit a considerably narrower spread, to the point where they appear roughly vertically aligned. The subset closest to observations is pictured in (Fig. 2b), with maximum width around 260 km.~~ **Within this large suite of trajectories, we find a smaller subset, comprised of one trajectory per pressure level. The trajectories in this subset exhibit a considerably narrower spread (260 km at the point of maximum divergence), thus appearing roughly vertically aligned (Fig. 2b).**"

However, that metric alone can not be used to argue whether the trajectory ensemble is narrow enough to resemble the advection of column-like airmass. The analysis about the extent and variability in the WAI, presented in Sect. 3.2, is necessary to confirm that all trajectories belong in the same airmass.

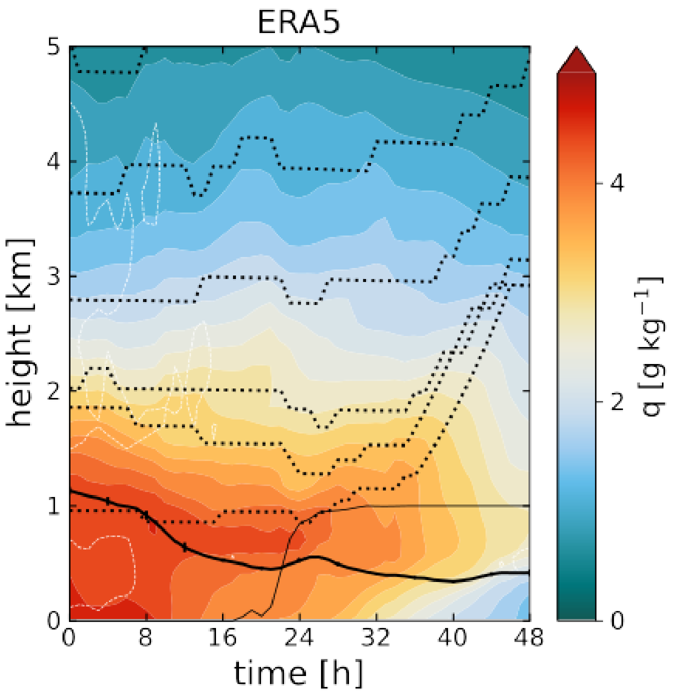

Figure AR3.1: Time-height cross-section of the ensemble average specific humidity from ERA5. Dotted lines represent the height of the trajectories. The thick solid line shows the evolution of the boundary layer height during the airmass transformation. The thin solid line marks the along-stream sea-ice concentration.

7. The title is not sufficiently connected to what is shown in the manuscript, which is a novel model framework illustrated by a single WAI case from a campaign. For that it is not necessary to promote the HALO-(AC)3 campaign in the title. I suggest a title along the lines of: "Lagrangian single-column modeling of Arctic airmass transformation during a major warm air intrusion"

A: We have considered changing the title according the reviewer's suggestion. However, the novelty of the framework partly lies in the availability of quasi-Lagrangian observations that can be used for comparison and model evaluation. Therefore, we believe HALO-(AC)3 should be kept as part of the title.

General comments

Several sentences and parts of the manuscript are hard to read and it is not easy to grasp the flow in a paragraph. This is probably due to interruption of the sentences by references and by a reversed order of the old and new information in sentences (see for example Gopen and Swan, https://www.americanscientist.org/blog/the-long-view/the-science-of-scientific-writing). See technical comment L214 and minor comment L155 and L156 for examples.

A: We apologize for the awkwardly structured sentences or poor use of language that may have led to unnecessary confusion. It can be challenging for a non-native speaker to describe complex ideas with simple sentences, thus we are grateful for the reviewer's honest feedback. In our effort to address all of the reviewers' comments we have edited a considerable portion of the manuscript, aiming for the best formulation possible in each instance. Considering that the other two anonymous referees described the text as well written, we hope that, through our changes, we have been able to address all major areas of ambiguity.

Figures

Figure 1 is too small, consider using 2 rows and 2 columns instead. The features are hard to distinguish, especially the green on top of the dark blue. The purple dots are nearly invisible.

Figure 2: this figure is also a bit small. The figure caption does not sufficiently make it clear how to understand this figure. This is also connected with the uncertainty of how the trajectories are obtained (see major comments).

A: We have now resized and reconfigured Fig. 1 and Fig. 2 to increase readability.

Figure 7: the caption lacks information on panel e, f and g.

A: We have added a description for the respective panels in the caption.

Minor comments

L21: Could be useful to give an indication of the typical timeline referred to here.

A: The timeline is described in **L26-31**. We change the phrasing to make the link between the sentences clearer.

L26: **"**According to their ~~conceptual model~~ **proposed timeline**, ...**"**

L69: The sentence is long and unclear, please rephrase. "The suite of Lagrangian observations available …"

A: We have made major revisions in the last paragraph of the Introduction to better highlight the novelty of the study, inspired by the reviewer's suggestions.

L72 -79 : "In this study, we extend the trajectory methodology in Svensson et al. (2023) on the WAI captured by HALO-(AC)3 on March 12, 2022 and find a similar column-like flow pattern. ~~The suite of Lagrangian observations available for this case makes it a suitable testbed for the development of a Lagrangian single-column modeling framework to study real WAI cases, as per Pithan et al. (2016, 2018)'s suggestions, using the Atmosphere-Ocean Single-Column Model (AOSCM, Hartung et al., 2018). We use the model to investigate the processes that drive the airmass transformation. We compare our simulations to observations, ERA5 and IFS forecast data in order to assess the performance of the model and its potential as a tool to test and construct future model parameterizaton schemes.~~ **We develop a Lagrangian single-column modeling framework suitable for the study of real WAI cases, as per Pithan et al. (2016, 2018)'s suggestions. We use the Atmosphere-Ocean Single-Column Model (AOSCM, Hartung et al., 2018) and take into account the time-varying dynamic and surface conditions that are relevant for the Arctic airmass transformation. In this simple, novel framework we can investigate the physical drivers and timescales of the transformation, in isolation from the complex dynamics that are typically associated with warm-air intrusions. Through comparison with the large number of Lagrangian HALO-(AC)3 observations available for this case, as well as ERA5 and IFS forecast data we assess the model's performance and its potential as a tool for testing and developing future model parameterization schemes."**

L76: This section seems to be more of a weather description based on the observational data. Consider using a more descriptive section title.

A: We have renamed Sect. 2.1 to **"Case Study and** observations**"** . This section offers details about the time and location of the studied warm-air intrusion episode as well as information about the observations used for the analysis. A proper weather description is not given until later in Sect. 3.1.

L147: Clarify the connection between the two sentences

A: L171-173 : "~~The presence of snow on ice, not allowed in OpenIFS, has also been~~ **Additionally, the use of the sea ice model LIM3 allows the presence of snow on ice, which has been** shown to mitigate surface energy and near-surface air-temperature biases (Pithan et al., 2016)**"**

L155: Rephrase as "The modeled profiles at the final timestep of the previous simulation are used as initial conditions for the following simulation at each transition point between surface regimes."

A: Done (**L181-182**)

L156: Rephrase as "Two additional preparatory simulations are performed over each sea-ice leg. The first one using… "

A: Done (**L182-183**)

L165: Consider whether the information on climatological perspective could be better placed somewhere else.

A: This is the only part of the manuscript where the large-scale setting is discussed and therefore the climatological perspective of the flow configuration is only be relevant here.

L189: Rephrase "To the degree that this feature is common along WAI, …. " It is unclear whether this is a statement or a question on whether they are common.

A: We rephrase:

L216-217: "~~To the degree that this feature is common among WAIs,~~ **Nevertheless, when this feature is encountered,** it facilitates the exploration of Arctic airmass transformations with simple 1D models such as the AOSCM."

L240. Section 3.3 contains mostly method material and should be moved to the methods section

A: We have moved the first two paragraphs of Sect. 3.3 to method sections 2.1 and 2.4. Changes can be found in:

L113-120 : "At the point of initialization, 96% of the total moisture content of the column is contained in the lowest 5 km. Therefore we consider the airmass transformation to be taking place within a 5 km deep layer above the surface and do not examine trajectories at lower pressure levels. Additionally, we do not seek for vertical alignment in trajectories at pressure levels higher than 900 hPa, that may fall within the boundary layer. This is due to the expectation that the friction- induced wind shear and veer (vertical gradients in wind speed and direction respectively) near the surface would cause air-parcels to move in different directions to the rest of the airmass. However, we also expect the interaction with the changing surface properties through vertical mixing to be driving changes in the boundary layer properties more strongly than any potential differential advection, leading us to treat the boundary layer as part of the advected air-column."

and

L152- 163 : "~~In order to follow the Lagrangian evolution of the airmass with the AOSCM, we set the advective tendencies to zero, inhibiting the inflow(outflow) of heat, moisture or momentum from(to) the ambient atmosphere.~~ **For Lagrangian applications, the AOSCM requires information on the airmass path which, in our case, is indicated by the vertically aligned trajectory ensemble (Sect. 2.2).** The atmospheric column is made aware of its poleward advection through the temporally varying surface conditions and large-scale dynamical forcing, the details of which (surface type, surface temperature and large-scale subsidence) ~~along the predesignated~~ **are** obtained from ERA5 reanalysis data **along the predesignated airmass tracks** ~~(Sect. 2.2).~~ **The alongstream conditions may slightly vary between the individual trajectories, despite the spatial and temporal proximity within the ensemble. Therefore, we use all initial profiles paired with their respective alongstream surface and dynamic conditions to perform ensemble simulations. This approach gives some insight on both the mean characteristics of the airmass transformation, but also reveal its sensitivity to potential variability in initial conditions and forcing factors.**

We set the advective tendencies to zero, inhibiting the inflow(outflow) of heat, moisture or momentum from(to) the ambient atmosphere. Pressure-gradient forcing leads to the emergence of inertial oscillations close to the surface, which lead to unphysical surface fluxes of heat and momentum. In order to suppress these spurious oscillations we nudge the horizontal wind to the

ERA5 profiles throughout the entire column and set the nudging timescale (τ_{nudge}) to be equal to the model timestep (15 min)**"**

L259: The reference to Fig. 4 is too early, the reader doesn't know what to look for yet.

A: We have removed the reference.

L266: Expand on this first description of Fig. 4, guide the reader through the details of the figure.

A: All figures are now introduced in detail in the introduction of Sect. 3.3 and the figure's updated caption.

L317: Rephrase as "At the end of the simulation, uncertainty in the heat content grows as well, due to slight variations in the forcing among the trajectory."

A: See next comment.

L318: Unclear sentence: "The same behavior is exhibited by the airmass in …"

A: We have rewritten this paragraph and moved it upward to **L329-333** where the ensemble uncertainty is already presented to make the text less repetitive and more coherent.

L328-332: "The upward tilt of the perpendicular lines indicates greater variability in heat compared to moisture content, in contrast to the beginning of the simulation, when the opposite was true. This feature is more pronounced in the AOSCM simulations but also apparent in ERA5 and IFS-OF. The similarities among the different products in the evolution of the airmass mean properties and variability suggest that the AOSCM, if appropriately forced, is, able to represent the physical processes that drive the airmass transformation"

L325: It is currently unclear now whether the warm and moist airmass is confined within the boundary layer or if the boundary layer depth is additional information. Rephrase sentence.

A: We rephrase to clarify.

L346-347: "Our initial airmass appears to be warm and moist, primarily within the boundary layer which reaches a depth of just over 1 km on average (Fig. 5a), but also above it, extending up to around 3 km"

L362: Add a reference here

A: We added a reference to the AOSCM cross-sections.

L383-384: "ERA5 and the IFS-OF (Fig. 5 middle and right columns) show a similar airmass transformation time-line with that simulated by AOSCM **(Fig. 5 left column**).**"**

L391: Unclear what this statement means: "The ensemble mean AOSCM, ERA5 and IFS-OF profiles in the center of each dropsonde cluster."

A: We apologize for the incomplete sentence. We added:

L413-414: "The ensemble mean AOSCM, ERA5 and IFS-OF profiles **are taken** in the center of each dropsonde cluster.**"**

We thank the reviewer once again for their thorough examination of the manuscript. We have also addressed all technical comments listed below in the revised version of the manuscript.

Technical comments

L43: Remove the double “and”

L50: sampling → sampled

L53: Connect to a narrative instead of “them” —> “… reveal the time-scales and processes that drive **them”**

L95: Connect to a narrative instead of “Their”

L143: Remove the last 6 words of the sentence: “for this part of the simulation”

L163: develops → developed

L190: Replace “while” with “then/and”

L214: Move the reference to Fig. 3d to the back of the sentence.

L216: Missing space

L250: Add: “stems from two reasons”, or drop the point markings.

L259: Connect to narrative instead of “Their”

L327: Drop the additional “the” before “threshold”

L387: Drop the additional “observed”

L416: therefore → replace with “thus”

L421: moistest → “most moist/humid”

L429: insert at → to zero at the top

L458: misplaced dot

L469: mid-April → mid-March

References

1. Hartung, K., Svensson, G., Struthers, H., Deppenmeier, A.-L., and Hazeleger, W.: An EC-Earth coupled atmosphere–ocean single-column model (AOSCM.v1_EC-Earth3) for studying coupled marine and polar processes, Geoscientific Model Development, 11, 4117–4137, https://doi.org/10.5194/gmd-11-4117-2018, publisher: Copernicus GmbH, 2018.
2. Paulus, F. M., Karalis, M., George, G., Svensson, G., Wendisch, M., and Neggers, R. A. J.: Airborne measurements of mesoscale divergence at high latitudes during HALO-(AC)3, https://doi.org/10.1175/JAS-D-24-0034.1, section: Journal of the Atmospheric Sciences, 2024.

3. Pithan, F., Ackerman, A., Angevine, W. M., Hartung, K., Ickes, L., Kelley, M., Medeiros, B., Sandu, I., Steeneveld, G.-J., Sterk, H. a. M., Svensson, G., Vaillancourt, P. A., and Zadra, A.: Select strengths and biases of models in representing the Arctic winter boundary layer over sea ice: the Larcform 1 single column model intercomparison, Journal of Advances in Modeling Earth Systems, 8, 1345–1357, https://doi.org/10.1002/2016MS000630, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1002/2016MS000630, 2016.

4. Pithan, F., Svensson, G., Caballero, R., Chechin, D., Cronin, T. W., Ekman, A. M. L., Neggers, R., Shupe, M. D., Solomon, A., Tjernström, M., and Wendisch, M.: Role of air-mass transformations in exchange between the Arctic and mid-latitudes, Nature Geoscience, 11, 805–812, https://doi.org/10.1038/s41561-018-0234-1, number: 11 Publisher: Nature Publishing Group, 2018.

5. Svensson, G., Murto, S., Shupe, M. D., Pithan, F., Magnusson, L., Day, J. J., Doyle, J. D., Renfrew, I. A., Spengler, T., and Vihma, T.: Warm air intrusions reaching the MOSAiC expedition in April 2020—The YOPP targeted observing period (TOP), Elem Sci Anth, 11, 00 016, https://doi.org/10.1525/elementa.2023.00016, 2023.

6. Wendisch, M., Crewell, S., Ehrlich, A., Herber, A., Kirbus, B., Lüpkes, C., Mech, M., Abel, S. J., Akansu, E. F., Ament, F., Aubry, C., Becker, S., Borrmann, S., Bozem, H., Brückner, M., Clemen, H.-C., Dahlke, S., Dekoutsidis, G., Delanoë, J., De La Torre Castro, E., Dorff, H., Dupuy, R., Eppers, O., Ewald, F., George, G., Gorodetskaya, I. V., Grawe, S., Groß, S., Hartmann, J., Henning, S., Hirsch, L., Jäkel, E., Joppe, P., Jourdan, O., Jurányi, Z., Karalis, M., Kellermann, M., Klingebiel, M., Lonardi, M., Lucke, J., Luebke, A. E., Maahn, M., Maherndl, N., Maturilli, M., Mayer, B., Mayer, J., Mertes, S., Michaelis, J., Michalkov, M., Mioche, G., Moser, M., Müller, H., Neggers, R., Ori, D., Paul, D., Paulus, F. M., Pilz, C., Pithan, F., Pöhlker, M., Pörtge, V., Ringel, M., Risse, N., Roberts, G. C., Rosenburg, S., Röttenbacher, J., Rückert, J., Schäfer, M., Schaefer, J., Schemann, V., Schirmacher, I., Schmidt, J., Schmidt, S., Schneider, J., Schnitt, S., Schwarz, A., Siebert, H., Sodemann, H., Sperzel, T., Spreen, G., Stevens, B., Stratmann, F., Svensson, G., Tatzelt, C., Tuch, T., Vihma, T., Voigt, C., Volkmer, L., Walbröl, A., Weber, A., Wehner, B., Wetzel, B., Wirth, M., and Zinner, T.: Overview: quasi-Lagrangian observations of Arctic air mass transformations – introduction and initial results of the HALO-(AC)3 aircraft campaign, Atmospheric Chemistry and Physics, 24, 8865–8892, https://doi.org/10.5194/acp-24-8865-2024, publisher: Copernicus GmbH, 2024