Authors’ Response to Reviews of

An ensemble-based coupled reanalysis of the climate from 1860 to the present (CoRea1860+)

Yiguo Wang, François Counillon, Lea Svendsen, Ping-Gin Chiu, Noel Keenlyside, Patrick Laloyaux, Mariko Koseki, and Eric de Boisseson

Earth System Science Data, `Manuscript ID: essd-2025-127`

RC: ***Reviewers’ Comment***, AR: Authors’ Response, ☐ Manuscript Text

1. General comments:

RC: ***The authors present an analysis of their comprehensive reanalysis CoRea1860+, which is driven by SST observational products and covering almost the whole of the historical time period (in a climate science sense) from 1860 until the present. The manuscript in its present form is a rock solid data description manuscript, which should be published in ESSD. The corresponding dataset under https://doi.org/10.11582/2025.00009 is accessible to me.***

I do have some comments below to improve or clarify some of the authors methodology and statements. I pledge the authors to consider them.

AR: We sincerely appreciate the reviewer’s positive evaluation of our manuscript, and we thank the reviewer for the thoughtful comments and constructive suggestions to improve the manuscript. We have carefully addressed the reviewer’s concerns and revised the manuscript accordingly.

Below, we present each comment from the reviewer (Reviewer Comment, **RC**) followed by our response (Authors’ Response, AR) and, where applicable, the corresponding changes made to the manuscript (highlighted within the black box ☐).

Please find our detailed, point-by-point responses below. We again thank the reviewer for his/her valuable time and effort in reviewing our manuscript.

RC: ***abstract l.15f "Furthermore, CoRea1860+ aligns well with the other datasets for surface air temperature, precipitation, sea level pressure, and 500 hPa geopotential height, especially in the tropics where air-sea interactions are most pronounced."***

This statement appears a bit too optimistic, given the coarse resolution of the stratosphere and the missing atmosphere observations. In particular the authors’ results concerning 500 hPa geopotential height, as good as they may be given the fact that only "SST" was assimilated, could be well improved with just some "truly" coupled reanalysis incorporating the few atmosphere observations, which are available prior to 1950.

AR: We thank the reviewer for this comment and agree that the statement is too optimistic. Indeed, the reference atmospheric reanalyses used in this study (i.e., ERA-20C, CERA-20C, and 20CRv3) have assimilated the atmospheric observations, which are sparse in time and space before the 1950s, and achieve a tighter reconstruction of atmospheric variability. We dampened our statement (L15-17) as follows:

> Furthermore, CoRea1860+ agrees with the reference atmospheric datasets to some extent for surface air temperature, precipitation, sea level pressure, and 500 hPa geopotential height, especially in the tropics where air-sea interactions are most pronounced.

RC: ***l.129f "This version incorporates emissions and new aerosol-cloud interaction schemes..."***
l.132f "the model employs the version 7 coupler"
Correction to the previous comment:
Please do not consider any comments for l.129f and l.132f.

AR: As the reviewer asked in the latest version of the review, no change was made to these lines.

RC: ***l.135 "The atmosphere component consists of 26 hybrid sigma–pressure levels, extending up to 3 hPa." Does it properly resolve the stratosphere for a proper QBO?***

AR: The atmospheric component of the used version of NorCPM is a low-top atmospheric model with a few layers in the lower stratosphere. We cannot expect it to capture stratospheric dynamics and stratospheric-tropospheric interactions, such as QBO.

RC: ***l.138 "The NorESM used in this study is forced by CMIP5 historical forcings before 2005," Why not CMIP6 external forcings? Expected differences from CMIP6 forcing?***

AR: We appreciate the reviewer's questions. For clarity, we added the following statements to the manuscript (L146-152):

> We have extensive experience with this NorESM version (e.g., Counillon et al., 2014, 2016). Most of our DA system has been specifically tuned for this setup (e.g., Wang et al., 2016, 2017; Kimmritz et al., 2018; Wang et al., 2022). While CMIP6 forcings represent the latest update, their implementation in NorCPM has introduced issues. For instance, Passos et al. (2023) have reported that the CMIP6-forced version of NorCPM suffers from artificial bugs in the land use updates, leading to unrealistic land–cryosphere cooling trends. These artefacts result in slightly larger global mean biases and RMSEs compared to the CMIP5-forced version. Further details can be found in the Supplement of Bethke et al. (2021). Therefore, we opted for producing the reanalysis with the robustly tested version of the system that uses the CMIP5 forcing configuration.

RC: ***l.148ff "Since 2011, the monthly SST data from the Optimum Interpolation SST version 2 (OISSTV2, Reynolds et al., 2002) are assimilated, because HadISST2.1 is only available until 2010." Why not HadISST, which goes through until present?***

AR: It is because HadISST does not provide uncertainties, which are one key quantity for data assimilation Evensen (2009). OISSTV2 provides weekly SST and weekly observation error variance, in addition to monthly SST. In our assimilation system, the observation error variance of the monthly data is estimated as the harmonic mean of weekly error variances provided by OISSTV2 (Bethke et al., 2021).

RC: ***l.161f "The SST data in the regions covered by sea ice are not assimilated. These regions are identified using the sea ice mask in HadISST2.1 or OISSTV2." How does the model's observed sea ice extend comply with the observed sea ice? Biases?***

AR: The version of NorESM used in this study underestimates the sea ice extent during winter and overestimates it during summer in the Northern Hemisphere. It overestimates both winter and summer extent in the Southern Hemisphere. Further details can be found in Figures 4 and 11 of Bentsen et al. (2013).

RC: ***l.186f "The climatology reference period is 1950-2009 covering a long observation-rich period." This time period is strongly influenced by climate change signal. Would other time periods be a better choice? I presume that only the satellite era represents an "observation-rich period" in terms of global SST coverage. Please comment on that.***

AR: We agree with the reviewer that flagging the period 1950–2009 as an observation-rich period was an overstatement. Only the satellite era can be considered an observation-rich period for SST data. The climatology period needs to be as long as possible to damp out the contribution of internal variability in the estimate of the climatology in the observational record (considering that the true climate is a single realization). We cannot use data beyond 2010 because HadISST2 is not available. Before 1950, the SST observation was strongly undersampled and thus inaccurate in some regions (e.g., the Southern Ocean). The period 1950–2010 appears as a long period when monthly SST estimates are relatively accurate for estimating monthly climatology. We have restricted it to 2009 to get a 60-year climatology period. In addition, Bethke et al. (2021) have tested different climatology periods within NorCPM, e.g., 1980-2010 and 1950-2010, and have found that the different climatological periods lead to similar multiyear AMOC variations. There were some discrepancies on the long-term trends of the North Atlantic subpolar gyre circulation and AMOC at high latitudes, but these differences were mostly related to spurious updates of the deep water masses that got corrected by using the vertical localization technique (Wang et al., 2022). For clarity, we revised the relevant statement (L196-198) as follows:

> Referring to Bethke et al. (2021), we define 1950-2009 when monthly SST estimates are relatively accurate for estimating monthly climatology as the climatology reference period to avoid subsampling the internal variability of the climate.

RC: ***Further below, the anomalies of OHC and AMOC are against 1950-2010.***

AR: To ensure consistency with the climatology period used in the anomaly-field data assimilation, we applied the 1950–2009 period for Figures 2 (OHC), 4 (AMOC), and 8 (SAT) in the revised manuscript. Please note that using either 1950–2009 or 1950–2010 as the climatology period results in only negligible differences in these figures, with no impact on the overall conclusions.

RC: ***l.243 "RAPID" Please add reference Moat et al. (2024) in this paragraph.***

AR: As suggested, we added the reference of RAPID to the manuscript (L255-256):

> **RAPID** (Moat et al., 2024) makes use of arrays of moorings to monitor the variability of the meridional overturning circulation at 26° N in the Atlantic and has sustained the observations since 2004.

RC: ***l.299, Figure 1 Please make the legend smaller and moved up a bit to reveal all of the time series.***

AR: We thank the reviewer for the suggestion. We revised Figure 1 of the manuscript as Figure R1.

RC: ***l.337ff 4.2.1 Ocean heat content***
Within this subsection, it is a bit confusing to jump forth and back several times between 0-300m OHC and 0-2000m OHC. Please consider to re-order the paragraphs so that 0-300m comes first and 0-2000m OHC second.

AR: As suggested, we modified the structure of Section 4.2.1. Please refer to the revised version of the manuscript (L356-398).

RC: ***l.384 Figure 3 Please consider to add the corresponding time periods as labels in plot, e.g. over Antarctica.***

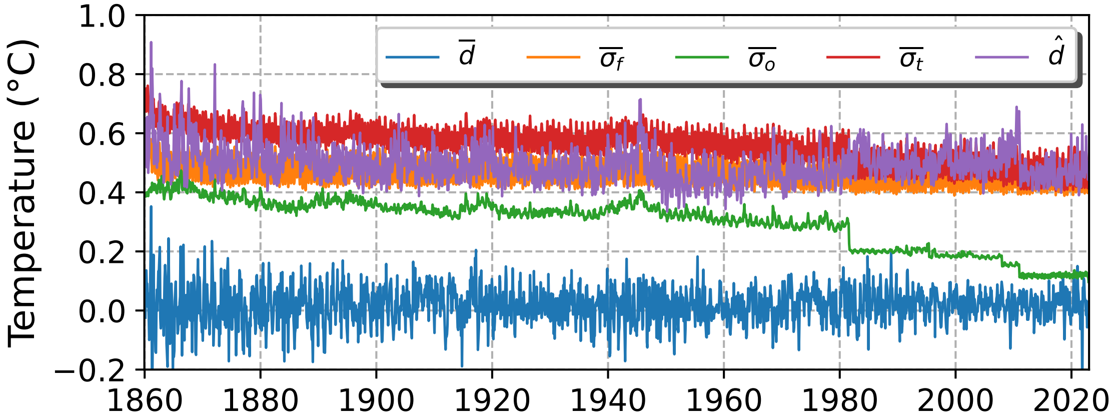

Figure R1: Global assimilation diagnostics for the assimilated variable – monthly SST anomalies: bias (blue line), background error (orange line), observation error (green line), total error (red line), and RMSE (purple line).

Table T1: Temporal mean and standard deviation of the maximum AMOC transport at 26° N over 2005–2021 for RAPID and 1950–2009 for the other datasets.

Dataset	Mean (Sv)	Standard deviation (Sv)
ORA-20C	11.4	1.7
SODA2.2.4	16.2	2.5
CHOR	15.6	2.0
CHORE	16.0	2.0
RAPID	16.7	1.4
CoRea1860+	32.0	1.8

AR: We revised Figure 3 of the manuscript as Figure R2.

RC: ***l.405 4.2.2 Atlantic meridional overturning circulation***
Please add a statement on absolute values for the AMOC, or the mean biases of the systems, in particular in context with Figure 4.

AR: We added a table on the temporal mean and standard deviation of the AMOC (Table T1) and some descriptions into the manuscript (L433-436):

> While CoRea1860+ exhibits a standard deviation in maximum AMOC transport at 26° N within the range of that of the reference datasets over 1950–2009 (except for RAPID over 2005–2021), its mean AMOC strength at 26° N is notably higher, with a time-mean of 32.0 Sv (Bentsen et al., 2013), exceeding that of the other datasets (Table 2).

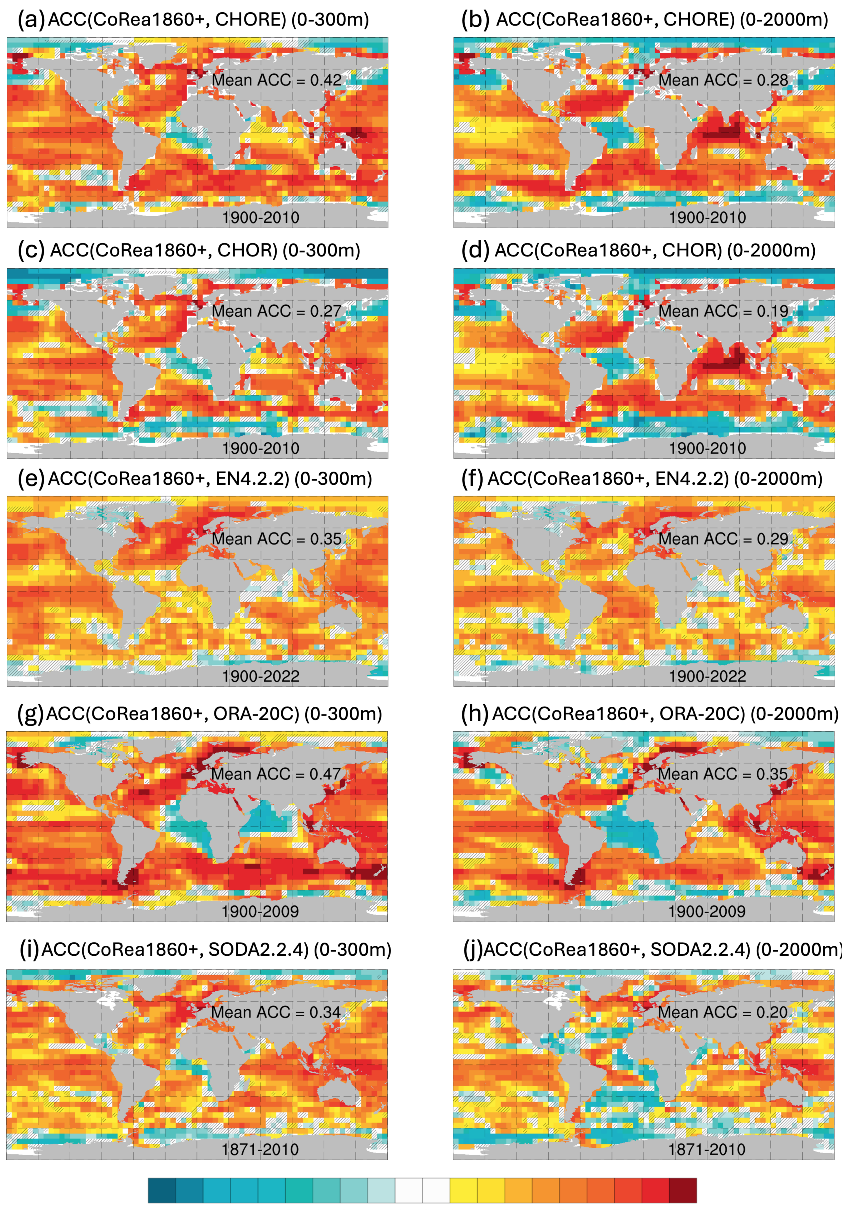

Figure R2: ACC of yearly OHC in 0-300m or 0-2000m of CoRea1860+ against different reference datasets. Grids that fail the significance test are marked with a slash. The period used to compute ACC corresponds to the overlapping period between CoRea1860+ and the specific reference dataset and is shown in Antarctica. The spatially averaged ACC is shown in Eurasia.

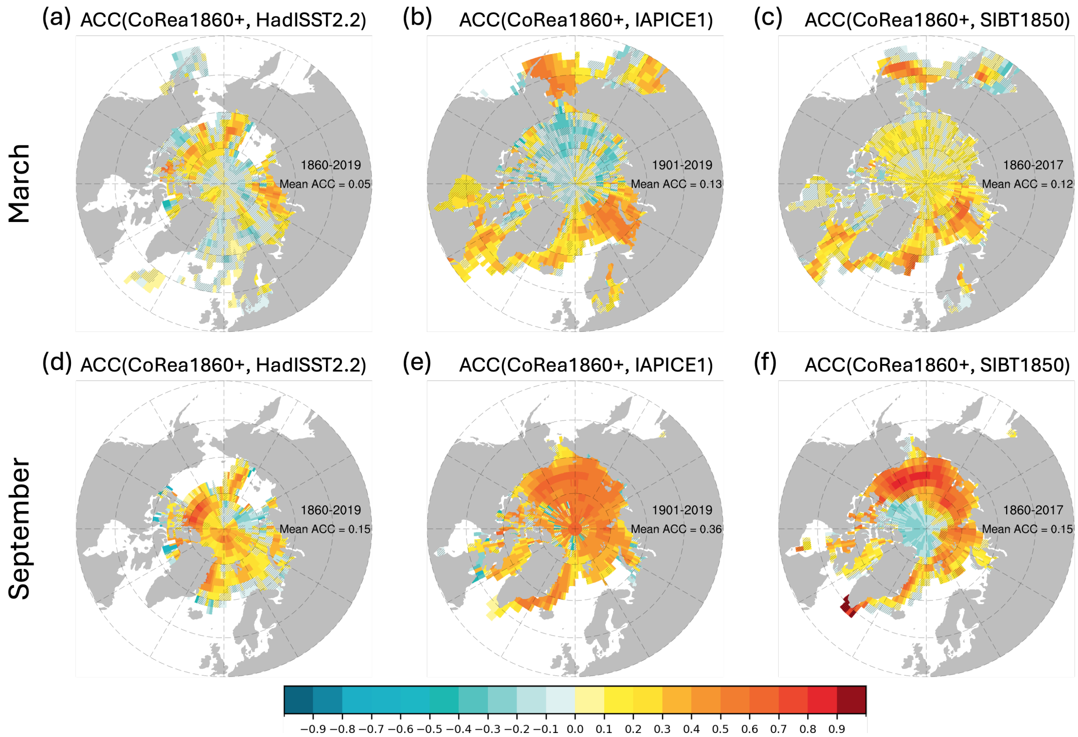

Figure R3: ACC of Arctic sea ice concentration in March or September of CoRea1860+ against HadISST2.2, IAPICE1, and SIBT1850. Grids that fail the significance test are marked with a slash. The period used to compute ACC corresponds to the overlapping period between CoRea1860+ and the specific reference dataset and is shown in Eurasia. The spatially averaged ACC is also shown in Eurasia.

RC: ***Please consider to depict AMOC cells as well, e.g. time mean and yearly standard deviation 1950-2010.***

AR: Please refer to our responses to the previous comment of the reviewer.

RC: ***l.454 Figure 6***
Please consider to add the corresponding time periods as labels in plot, e.g. over Siberia.

AR: As suggested, we added the corresponding time periods into each panel in Figures 6 and 7 of the manuscript. Please refer to Figures R3 and R4.

RC: ***l.532 Figure 9-11***
Please consider to add the corresponding time periods as labels in plot, e.g. over Antarctica.

AR: We added the corresponding time periods to each panel in these figures. Please refer to Figures R5, R6, R7 and R8.

RC: ***l.550ff 5 Conclusions***
Please shortly discuss "shortcomings" or expectations in terms of missing atmosphere observations and the (I presume) rather coarse resolution in the stratosphere, which presumably inhibits QBO?

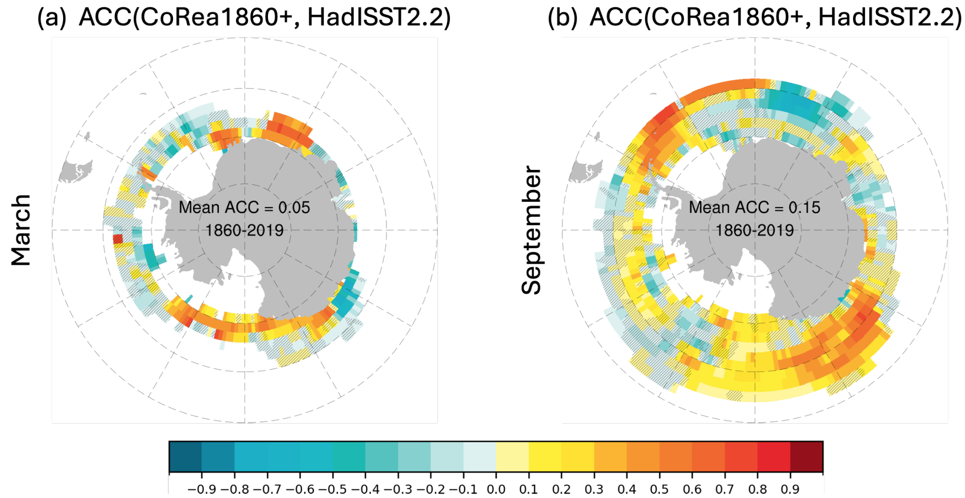

Figure R4: ACC of Antarctic sea ice concentration in March or September of CoRea1860+ against HadISST2.2. Grids that fail the significance test are marked with a slash. The period used to compute ACC corresponds to the overlapping period (i.e., 1860-2019) and is shown in Antarctica. The spatially averaged ACC is also shown in Antarctica.

AR: As suggested, we added some statements to the conclusions section to discuss the limitations of the current version of CoRea1860+ (L608-613):

> However, CoRea1860+ does not assimilate atmospheric observations, which limits its ability to fully represent atmospheric variability. The atmospheric component has a horizontal resolution of approximately 2°, while the ocean and sea ice components are resolved at about 1°, both of which are relatively coarse. In addition, CoRea1860+ employs a low-top atmospheric model with limited vertical resolution in the lower stratosphere, which restricts its ability to simulate stratospheric dynamics and stratosphere–troposphere interactions. The use of an anomaly-field assimilation framework also means that large model biases persist. We plan to address these limitations in future versions of CoRea1860+.

RC: ***l.562 Figure 9-12***
Please consider to add the corresponding time periods as labels in plot, e.g. over Antarctica.

AR: We added the corresponding time periods to each panel in these figures. Please refer to Figures R5, R6, R7 and R8.

RC: ***l.571ff "CoRea1860+ demonstrates a reasonable representation of the variability of OHC across different regions and depiction of AMOC variability." Please comment on if the OHC characteristics could actually be expected to be well met by this assimilation approach, and on the absolute values of AMOC in context with the variability characteristics.***

AR: We thank the reviewer for the comment. We have described the assimilation implementation in section 2.3 (L206-211) as follows:

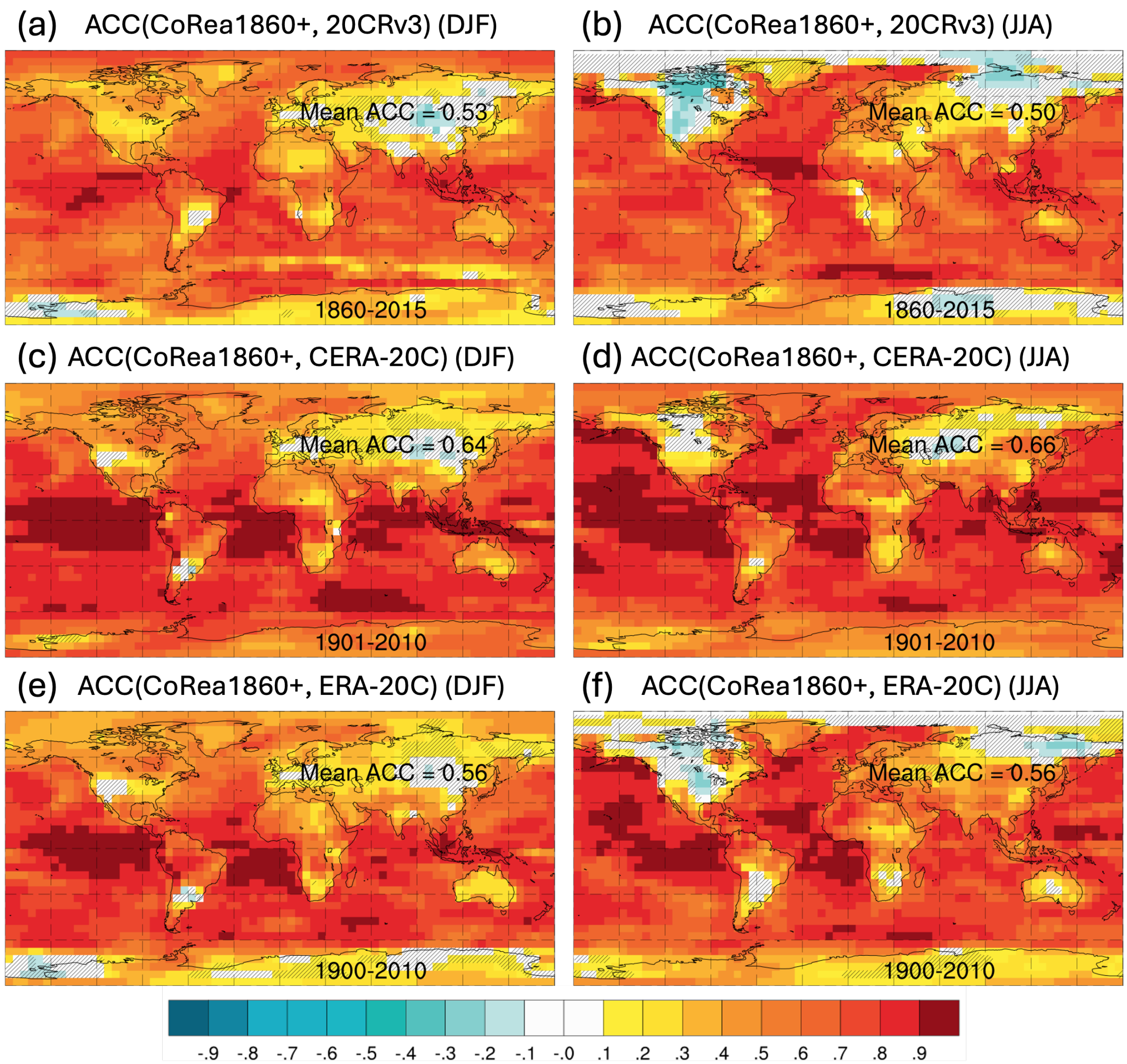

Figure R5: ACC of SAT in DJF or JJA of CoRea1860+ against 20CRv3, CERA-20C and ERA-20C. Grids that fail the significance test are marked with a slash. The period used to compute ACC corresponds to the overlapping period between CoRea1860+ and the specific reference dataset and is shown in Antarctica. The spatially averaged ACC is shown in Eurasia.

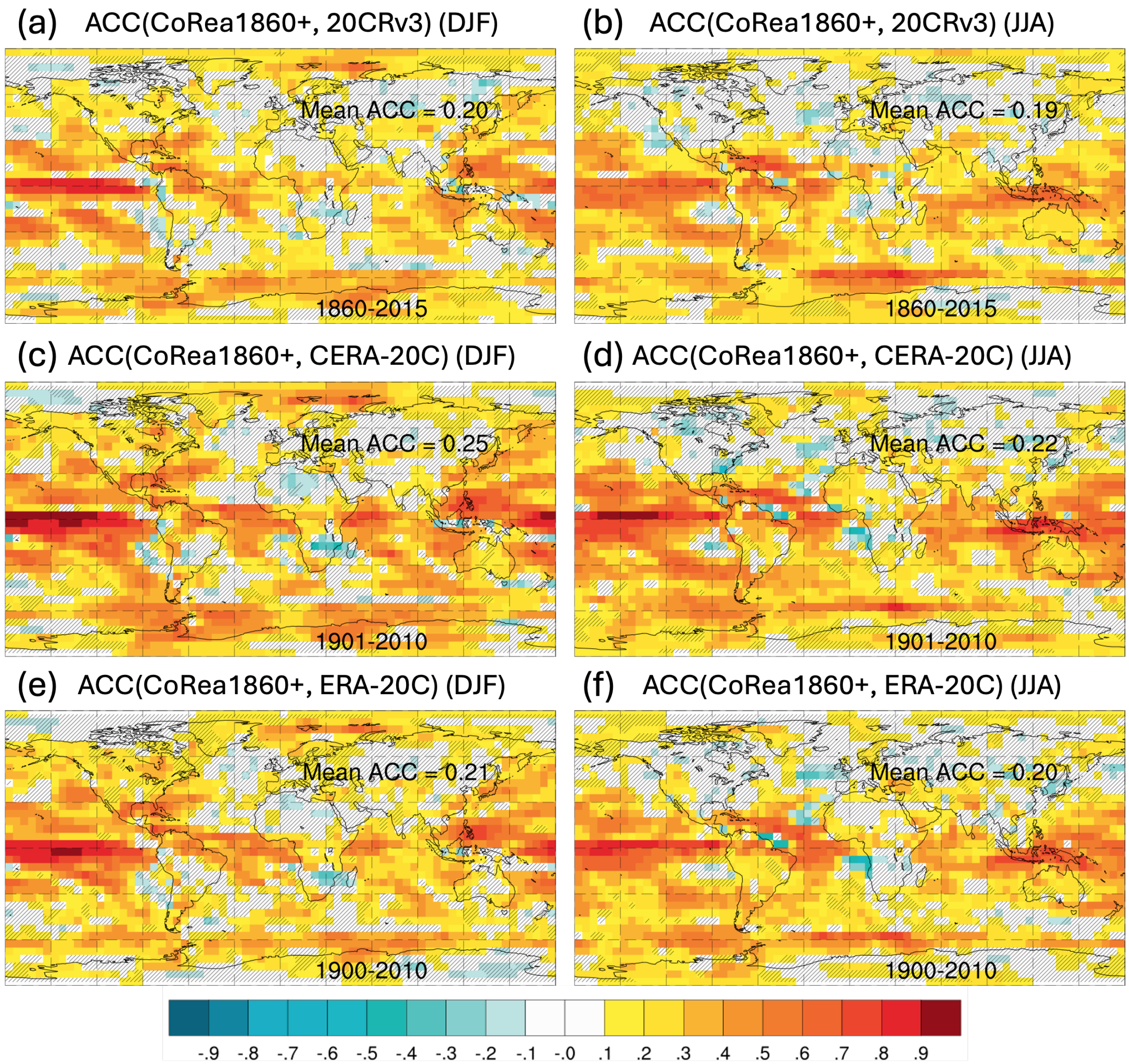

Figure R6: ACC of PRECP in DJF or JJA of CoRea1860+ against 20CRv3, CERA-20C and ERA-20C. Grids that fail the significance test are marked with a slash. The period used to compute ACC corresponds to the overlapping period between CoRea1860+ and the specific reference dataset and is shown in Antarctica. The spatially averaged ACC is shown in Eurasia.

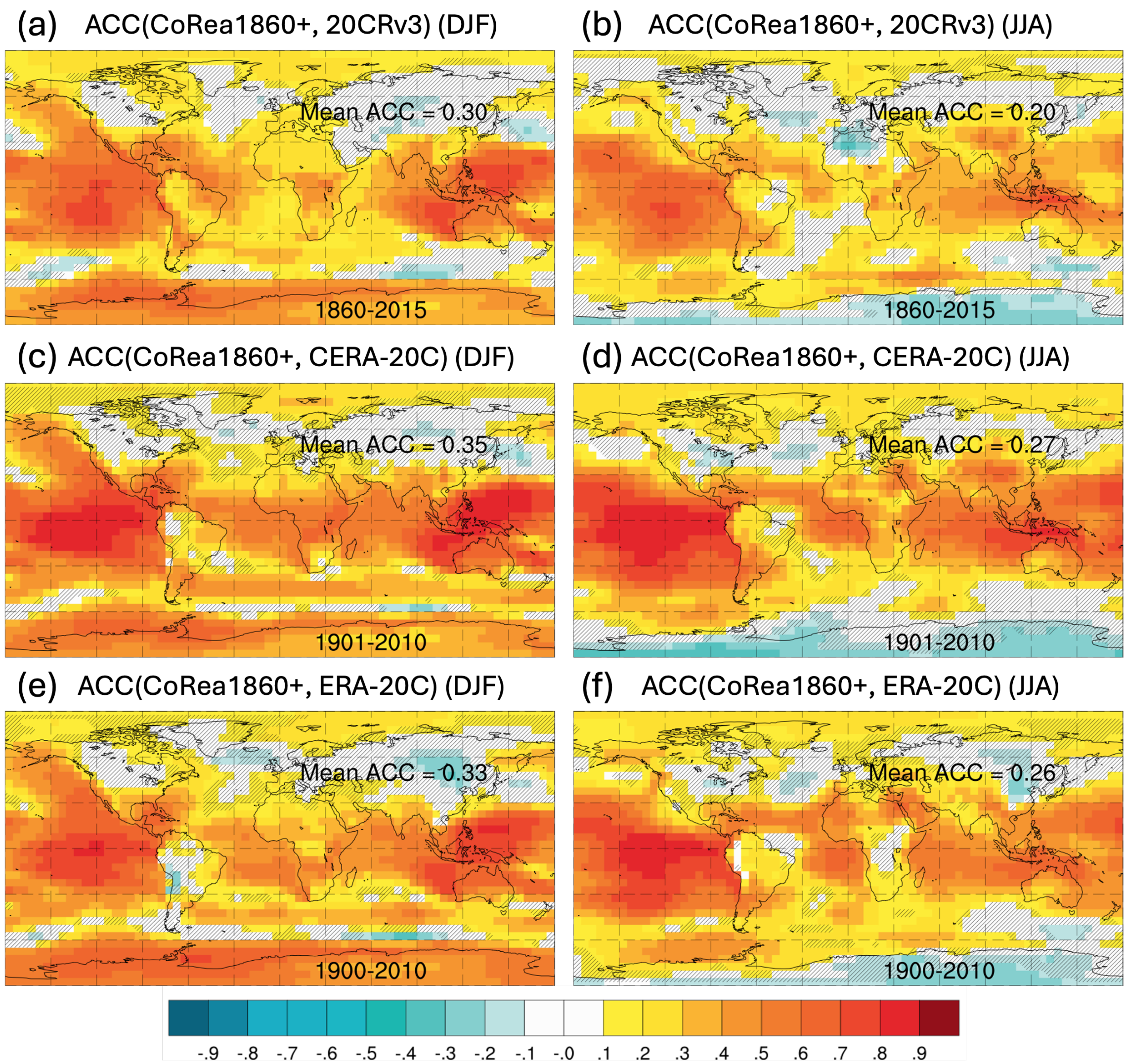

Figure R7: ACC of SLP in DJF or JJA of CoRea1860+ against 20CRv3, CERA-20C and ERA-20C. Grids that fail the significance test are marked with a slash. The period used to compute ACC corresponds to the overlapping period between CoRea1860+ and the specific reference dataset and is shown in Antarctica. The spatially averaged ACC is shown in Eurasia.

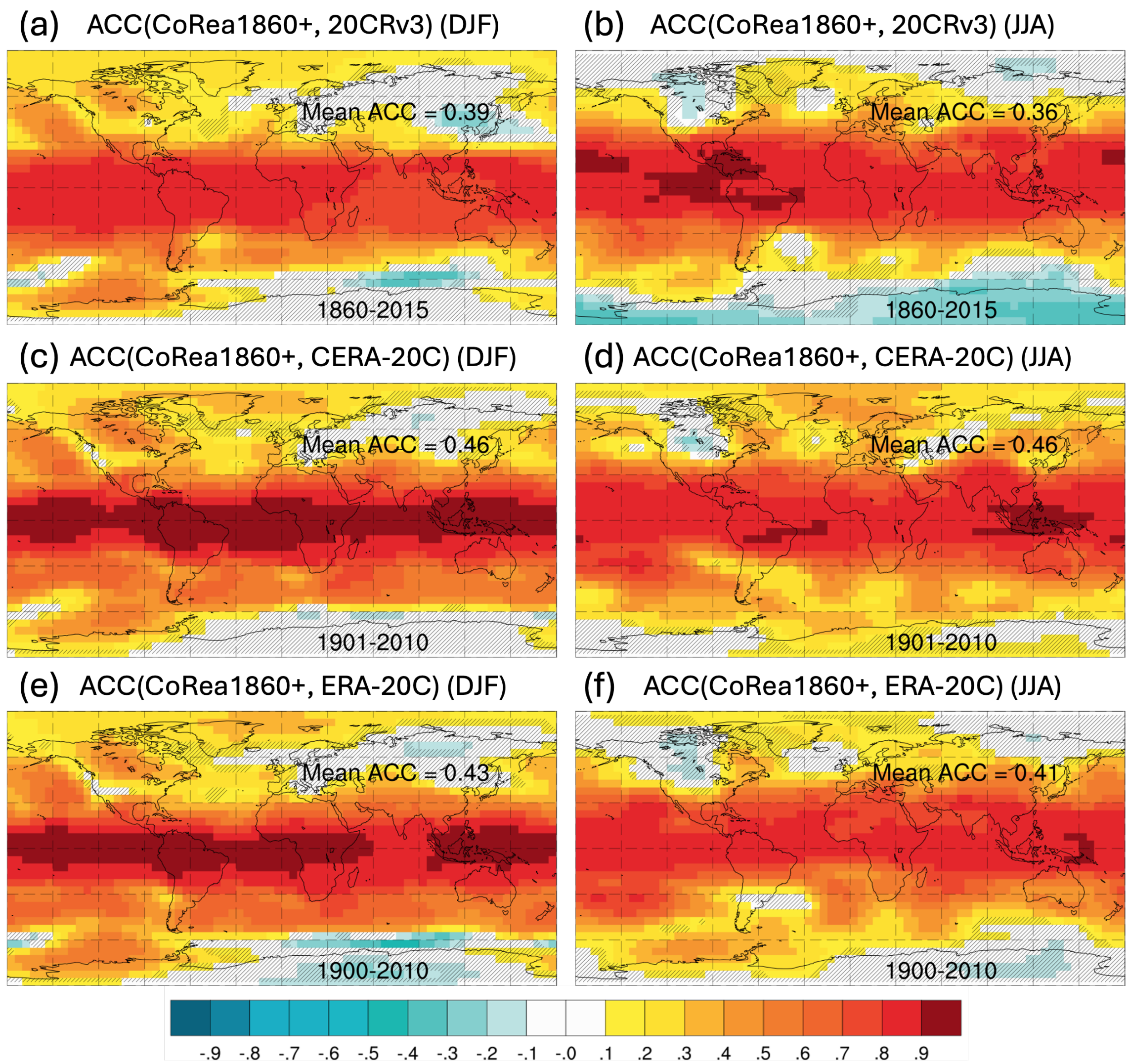

Figure R8: ACC of Z500 in DJF or JJA of CoRea1860+ against 20CRv3, CERA-20C and ERA-20C. Grids that fail the significance test are marked with a slash. The period used to compute ACC corresponds to the overlapping period between CoRea1860+ and the specific reference dataset and is shown in Antarctica. The spatially averaged ACC is shown in Eurasia.

> All ocean state variables (e.g., temperature, salinity, velocity, and layer thickness) are updated in isopycnal coordinates through the assimilation of SST data. Previous studies (e.g., Gavart and Mey, 1997; Counillon et al., 2016) have shown that performing assimilation in isopycnal coordinates efficiently utilizes surface observations. One challenge in this process is that layer thickness, an ocean state variable in BLOM, is inherently non-negative. However, due to the Gaussian assumptions of the EnKF, negative values may occasionally arise. To address this, we apply the aggregation approach proposed by Wang et al. (2016), ensuring that heat content, salt content, and mass remain physically consistent without artificial drifts.

To further address this comment, we revised the relevant text and added more descriptions (L621-626) as

> CoRea1860+, which assimilates SST data, captures the temporal variability of the OHC across different regions and the AMOC. This is primarily due to two factors. First, assimilating SST allows the system to update the interior ocean through ensemble-derived covariances (Counillon et al., 2016; Wang et al., 2022). Second, during model integration, the upper-ocean updates—strongly correlated with SST—are gradually propagated into the deeper ocean. The mean state of the AMOC in CoRea1860+ remains close to that of the free model simulation without DA (Table 2 and Bentsen et al., 2013), as the anomaly-field assimilation framework primarily adjusts anomalies rather than the full fields.

RC: ***l.587ff "CoRea1860+ demonstrates reasonable variability in sea ice concentration and extent (SIE) for both the Arctic and Antarctic regions." Similar comment as before: could the well met sea ice characteristics be expected or not from this assimilation approach?***

AR: We have stated how the SST assimilation updates the sea ice component of the system during the assimilation step in the manuscript (L211-216) as follows:

> Sea ice concentration across individual thickness categories is jointly updated by the SST assimilation, allowing SST observations to influence the sea ice component at the DA step (Kimmritz et al., 2018). After assimilation, a post-processing step ensures the physical consistency of ocean state variables and updates other sea ice state variables. For instance, the volume of each sea ice category is proportionally scaled according to the updated sea ice concentration (Kimmritz et al., 2018, 2019). This implies that SST observations are used to update the ocean and sea ice components at every monthly assimilation step.

In addition, during model integration, the upper ocean updates are gradually propagated into the sea ice model state. Bethke et al. (2021) have compared two NorCPM reanalyses: one updates the sea ice during the ocean data assimilation and another doesn't update the sea ice. Their results have demonstrated that it is beneficial for the system to update the sea ice model state during the ocean data assimilation.

For clarity, we revised the relevant text (L643-645):

> CoRea1860+ demonstrates variability in sea ice concentration and extent (SIE) for both the Arctic and Antarctic regions, as the sea ice state can be updated through SST assimilation (Bethke et al., 2021) and subsequent model integration (Wang et al., 2019).

RC: ***l.599f "demonstrates reasonable atmospheric variability due to robust air-sea and air-sea ice interactions." How does "reasonable" in this context compare with "reasonable" in the context above with OHC, AMOC,***

sea ice? The atmospheric characteristics are probably well worse than one would expect to get from a "truly" coupled RA including atmospheric observations?

AR: We acknowledge the reviewer's point and agree that CoRea1860+, which does not assimilate atmospheric data, does not represent the atmospheric state as accurately as the ocean and sea ice components, particularly over mid-latitude continental regions. For clarity, we revised the text (L657-658) as follows:

> CoRea1860+, which assimilates SST observations into its ocean and sea ice components and does not use atmospheric observations, represents atmospheric variability to some extent mostly due to robust air-sea and air-sea ice interactions.

References

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, O., Drange, H., Roelandt, C., Seierstad, I. a., Hoose, C., and Kristjánsson, J. E.: The Norwegian Earth System Model, NorESM1- Part 1: Description and basic evaluation of the physical climate, Geoscientific Model Development, 6, 687–720, , 2013.

Bethke, I., Wang, Y., Counillon, F., Keenlyside, N., Kimmritz, M., Fransner, F., Samuelsen, A., Langehaug, H., Svendsen, L., Chiu, P.-G., Passos, L., Bentsen, M., Guo, C., Gupta, A., Tjiputra, J., Kirkevåg, A., Olivié, D., Seland, Ø., Solsvik Vågane, J., Fan, Y., and Eldevik, T.: NorCPM1 and its contribution to CMIP6 DCPP, Geoscientific Model Development, 14, 7073–7116, , 2021.

Counillon, F., Bethke, I., Keenlyside, N., Bentsen, M., Bertino, L., and Zheng, F.: Seasonal-to-decadal predictions with the ensemble Kalman filter and the Norwegian Earth System Model: a twin experiment, Tellus A, 66, 1–21, , 2014.

Counillon, F., Keenlyside, N., Bethke, I., Wang, Y., Billeau, S., Shen, M. L., and Bentsen, M.: Flow-dependent assimilation of sea surface temperature in isopycnal coordinates with the Norwegian Climate Prediction Model, Tellus A, 68, 1–17, , 2016.

Evensen, G.: Data Assimilation: the Ensemble Kalman Filter, Springer, Berlin, Germany, 2009.

Gavart, M. and Mey, P. D.: Isopycnal EOFs in the Azores Current Region: A Statistical Tool forDynamical Analysis and Data Assimilation, Journal of Physical Oceanography, 27, 2146–2157, , 1997.

Kimmritz, M., Counillon, F., Bitz, C., Massonnet, F., Bethke, I., and Gao, Y.: Optimising assimilation of sea ice concentration in an Earth system model with a multicategory sea ice model, Tellus A: Dynamic Meteorology and Oceanography, 70, 1435 945, , 2018.

Kimmritz, M., Counillon, F., Smedsrud, L. H., Bethke, I., Keenlyside, N., Ogawa, F., and Wang, Y.: Impact of Ocean and Sea Ice Initialisation On Seasonal Prediction Skill in the Arctic, Journal of Advances in Modeling Earth Systems, 11, 4147–4166, , 2019.

Moat, B., Smeed, D., Rayner, D., Johns, W., Smith, R., Volkov, D., Elipot, S., Petit, T., Kajtar, J., Baringer, M., and Collins, J.: Atlantic meridional overturning circulation observed by the RAPID-MOCHA-WBTS (RAPID-Meridional Overturning Circulation and Heatflux Array-Western Boundary Time Series) array at 26N from 2004 to 2023 (v2023.1)., , 2024.

Passos, L., Langehaug, H. R., Årthun, M., Eldevik, T., Bethke, I., and Kimmritz, M.: Impact of initialization methods on the predictive skill in NorCPM: an Arctic–Atlantic case study, Climate Dynamics, 60, 2061–2080, , 2023.

Wang, Y., Counillon, F., and Bertino, L.: Alleviating the bias induced by the linear analysis update with an isopycnal ocean model, Quarterly Journal of the Royal Meteorological Society, pp. 1064–1074, , 2016.

Wang, Y., Counillon, F., Bethke, I., Keenlyside, N., Bocquet, M., and Shen, M.-l.: Optimising assimilation of hydrographic profiles into isopycnal ocean models with ensemble data assimilation, Ocean Modelling, 114, 33–44, , 2017.

Wang, Y., Counillon, F., Keenlyside, N., Svendsen, L., Gleixner, S., Kimmritz, M., Dai, P., and Gao, Y.: Seasonal predictions initialised by assimilating sea surface temperature observations with the EnKF, Clim Dyn, 53, 5777–5797, URL https://doi.org/10.1007/s00382-019-04897-9, 2019.

Wang, Y., Counillon, F., Barthélémy, S., and Barth, A.: Benefit of vertical localization for sea surface temperature assimilation in isopycnal coordinate model, Frontiers in Climate, 4, , 2022.