CopERnIcus climate change Service Evolution

D3.1 - Documentation of the intermediate set of land surface initialisation systems

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1 Executive Summary

The initialisation data sets for seasonal forecasts from the CERISE Phase 1, produced from the participating in WP3 institutions - Deutscher Wetterdienst (DWD), Meteo France (MF), Euro-Mediterranean Center on Climate Change (CMCC) and European Centre for Medium-Range Weather Forecasts (ECMWF), were delivered to ECMWF and are stored in the MARS archive. For intercomparison and further assessment, a set of monthly mean land surface data from each initialisation system is provided.

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2 Introduction

Different initialization data sets used for seasonal forecast in CERISE Phase 1 are produced with improved Earth Climate Models by including or refining the land surface analysis into the systems. Different institutions considered different control variables in dependence of the current development. They are selected depending on the strength of the impact on the state and should control mainly the soil moisture, leaf area index and snow depth.

2.1 Background

The scope of CERISE is to enhance the quality of the Copernicus Climate Change Service (C3S) reanalysis and seasonal forecast portfolio, with a focus on land-atmosphere coupling.

It will support the evolution of C3S, over the project's 4 year timescale and beyond, by improving the C3S climate reanalysis and the seasonal prediction systems and products towards enhanced integrity and coherence of the C3S Earth system Essential Climate Variables.

CERISE will develop new and innovative ensemble-based coupled land-atmosphere data assimilation approaches and land surface initialisation techniques to pave the way for the next generations of the C3S reanalysis and seasonal prediction systems.

These developments will be combined with innovative work on observation operator developments integrating Artificial Intelligence (AI) to ensure optimal data fusion fully integrated in coupled assimilation systems. They will drastically enhance the exploitation of past, current, and future Earth system observations over land surfaces, including from the Copernicus Sentinels and from the European Space Agency (ESA) Earth Explorer missions, moving towards an all-sky and all-surface approach. For example, land observations can simultaneously improve the representation and prediction of land and atmosphere and provide additional benefits through the coupling feedback mechanisms. Using an ensemble-based approach will improve uncertainty estimates over land and lowest atmospheric levels.

By improving coupled land-atmosphere assimilation methods, land surface evolution, and satellite data exploitation, R&I inputs from CERISE will improve the representation of long-term trends and regional extremes in the C3S reanalysis and seasonal prediction systems.

In addition, CERISE will provide the proof of concept to demonstrate the feasibility of the integration of the developed approaches in the core C3S (operational Service), with the delivery of reanalysis prototype datasets (demonstrated in pre-operational environment), and seasonal prediction demonstrator datasets (demonstrated in relevant environment).

CERISE will improve the quality and consistency of the C3S reanalysis systems and of the components of the seasonal prediction multi-system, directly addressing the evolving user needs for improved and more consistent C3S Earth system products.

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverables

This report describes the Phase 1 dataset of initial conditions for the seasonal forecast, which was provided by the DWD, MF, CMCC and ECMWF models. The methods and experiment protocol developed until delivery stage in month 33 (Sept 2025), after Phase 1, are described alongside the results.

2.2.2 Work performed in this deliverable

In WP3 of the CERISE project, each partner developed a Phase 1 demonstrator that includes surface data analysis and produces initial conditions that are as close as possible to the observational datasets. This data has been transferred to the MARS archive (see CERISE D3.2 "*One or more sets of land surface initial conditions for 1993-2022 for use in seasonal forecast demonstrators*" for more details) and is currently available to the climate consortium for analysis, investigation and initialisation of the seasonal forecast. This includes a set of monthly mean land surface data from each initialisation dataset, for DWD, MF, CMCC, and ECMWF. All demonstrators include land surface data assimilation to accurately initialise seasonal predictions from 1993 to 2023 (CMCC starts in 2002). The participating institutions use coupled or advanced Earth System Models, which incorporate the evolution of atmospheric (and oceanic) background state over time, as well as land and vegetation models. The aim is to create balanced initial conditions for seasonal numerical predictions. Land surface analysis schemes were adapted from the participating institutions' current operational analyses and implemented in the development of the systems. Here, we present a set of initialisation datasets completed by all participating institutions during the WP3 CERISE Phase 1 time period.

2.2.3 Deviations and counter measures

No deviations have been encountered.

2.2.4 Reference Documents

[1] Project 101082139- CERISE-HORIZON-CL4-2021-SPACE-01 Grant Agreement

[2] CERISE D3.2 - *One or more sets of land surface initial conditions for 1993-2022 for use in seasonal forecast demonstrators (SEN)*

2.2.1 CERISE Project Partners:

ECMWF	European Centre for Medium-Range Weather Forecasts
Met Norway	Norwegian Meteorological Institute
SMHI	Swedish Meteorological and Hydrological Institute
MF	Météo-France
DWD	Deutscher Wetterdienst
CMCC	Euro-Mediterranean Center on Climate Change
BSC	Barcelona Supercomputing Centre
DMI	Danish Meteorological Institute
Estellus	Estellus
IPMA	Portuguese Institute for Sea and Atmosphere
NILU	Norwegian Institute for Air Research
MetO	Met Office

3 Methods and experiment setup

3.1 DWD

DWD's data assimilation configuration of ICON XPP (Müller et al., 2025) was enhanced by incorporating a 2Dvar assimilation scheme for snow depth into the prediction system. The model runs on 25 ensemble members, with the assimilated data being the SYNOP observations. Two sets of initial conditions were produced based on the cycling period of the surface analysis applied to the snow water equivalent. The first dataset performs 2Dvar at the beginning of each month, while the second experiment runs the assimilation routines five times per month. The latter configuration allows more data to enter the system, producing more accurate initial states.

The Basic Cycling Environment (BACY) was used to test the land surface initialisation components integrated into the seasonal prediction system. BACY is well established at DWD for conducting pre-operational tests, with modifications made to the NWP suite. It organises the entire data assimilation cycle, including analyses of the atmosphere, ocean surface temperature and various land components, as well as ICON model forecast runs for the deterministic and ensemble systems. As part of the CERISE project, the following analysis schemes were implemented in Phase 1 and are planned for implementation in Phase 2, in addition to the data assimilation schemes for the atmosphere and the ocean. These setups extend the Phase 0 reference run, which was initialised with ERA5 in the ICON atmosphere using nudging of 6-hourly wind and temperature fields above a sea level height of 1.5 km at each time step, with given relaxation parameters. The ocean is constrained to the EN4 vertical profiles of temperature and salinity on the first day of each month using the LSEIK filter (Nerger et al., 2006). Phase 1 additionally includes the 2D-Var snow analysis, which runs with two cycling frequencies: one month and five days. The 2D-Var analysis is used to assimilate observations from synoptic stations for snow depth and screen-level temperature/dew point temperature (relative humidity). It is an iterative procedure that minimises the cost functional using the conjugate gradient descent algorithm. It is implemented with abstract function pointers to enhance the flexibility of using parameter-specific procedures that differ for the screen-level variables T2m, Rh2m, and snow. Ancillary physiographic data and soil and vegetation parameters are generated using the EXTPAR software package, which is maintained by the Center for Climate Systems Modelling (C2SM). They can be accessed at https://c2sm.ethz.ch/news/archive/2025/05/zonda-v10-is-here-making-icon-simulations-more-accessible.html. It is used within the COSMO consortium and the ICON community to create grid-specific files of aggregated and processed datasets based on high-resolution raw data. It is used within the COSMO consortium and the ICON community to create grid-specific files of aggregated and processed datasets based on high-resolution raw data. The basic datasets used in EXTPAR are described in Asensio et al. (2023). Phase 1 of the update basically consists of developing and integrating the 2D-Var snow analysis into the seasonal prediction system environment, adapting it for netCDF I/O. All experiments are performed on 25 ensemble members for the time period from 1993 to 2022. The surface analysis for snow depth is applied to the variable snow water equivalent. Two initialisation data sets are produced. The first, named CERISE1_ASS_1MO (C1), performs 2D-Var on the first day of each month of the integration period. The second dataset, named CERISE1_ASS_5D (C1.5), uses a snow analysis frequency of 5 days, applied from the first to the 26th day of the month. Increasing the analysis update frequency has a stronger impact on the observations entering the system. It should be noted that, due to a restructuring effort on the assimilation system, the ocean increments in CERISE1_ASS_5D did not enter the ocean restart files. This will likely affect the global values, especially those in the derived hindcast set.

3.2 MF

The joint assimilation of surface soil moisture (SSM) and leaf area index (LAI) satellite-based products is possible within the SURFEX modelling platform using the LDAS-Monde tool. MF used the LDAS-Monde tool within the SURFEX version 9 modelling platform in offline mode, which was forced by ERA5. THEIA AVHRR GEOV2 LAI (1993–2018) and CLMS GEOV2 LAI (2019–2022) were assimilated every 10 days using a simplified extended Kalman filter (SEKF) to update leaf biomass and surface soil moisture. The system follows a two-step sequence in which the ISBA model forecast is corrected via an analysis stage involving the propagation of observational information to control variables using finite-difference Jacobians. This flow-dependent structure enables consistent updates of LAI and soil moisture, which indirectly impact other land surface states over 24-hour assimilation windows. In Phase 1, analysed soil moisture derived from LAI assimilation is used. Conversely, an LAI climatology is used instead of analysed LAI.

Vegetation growth in ISBA was represented using the ISBA-A-gs configuration (Calvet et al., 1998; Gibelin et al., 2006; Calvet et al., 2008). This version of ISBA simulates the net CO_2 assimilation rate (A) and stomatal conductance (gs) of vegetation at leaf and canopy levels. This enables the simulation of LAI, respiration, and energy and water fluxes. ISBA-A-gs can represent feedback between LAI and root-zone soil moisture. Increasing LAI values tend to increase plant transpiration and reduce root-zone soil moisture through root water extraction. Conversely, decreasing root-zone soil moisture reduces photosynthesis, stomatal conductance (gs) and LAI. To more accurately represent root-zone soil moisture, the ISBA diffusion multilayer soil representation (Decharme et al., 2019) was employed. Soil moisture and temperature were calculated for 14 layers down to 12 m and 8–10 layers down to 1 and 2 m, depending on the characteristics of the vegetation.

LDAS-Monde has been employed in numerous studies to assimilate and validate various satellite products across diverse regions and scales (e.g. Albergel et al., 2017; Mucia et al., 2020). In this study, the variables analysed were leaf biomass and soil moisture at several depths (up to 1 m). Each analysed variable had 12 different values, corresponding to 12 land surface patch classes. The patch fraction for each model grid cell was calculated using the ECOCLIMAP-II land cover database (Faroux et al., 2013). The assimilation process was performed every 24 hours, with the analysed variables being used as the initial conditions for the subsequent 24-hour period.

3.3 CMCC

The CMCC CESM2/CLM5-BGC configuration has been enhanced through the integration of a daily Ensemble Adjustment Kalman Filter (EAKF) within an offline, 30-member land reanalysis system driven by expanded ECMWF EDA forcings. The system assimilates ESA-CCI surface soil moisture (SM) and snow cover fraction (SCF) daily products and GLASS LAI (every 8 days) after strict quality control (QC) and continuous adaptive inflation adjustments. The asynchronous schedule (SM and SCF daily, and LAI every eighth day) enables updates to soil moisture, snow water equivalent (SWE), snow cover and vegetation states to be made in a physically consistent way for seasonal forecast initialisation.

Updates to SM, SCF and LAI were propagated through model couplings to evapotranspiration, energy partitioning and carbon pools. Validation uses independent datasets: ISMN in situ soil moisture, FLUXNET towers and FLUXCOM (fluxes/productivity), GLEAM ET and satellite snow/albedo data were used to verify cryospheric seasonality and melt timing. Core diagnostics include innovation statistics, bias, root mean square error (RMSE) and unbiased root mean square error (ubRMSE), anomaly correlation, and ensemble spread–skill, with all results benchmarked against a no-data assimilation (DA) control under identical forcing. An offline CESM2/CLM5-BGC land reanalysis was performed for the period 2002–2022 using a 30-member ensemble forced by ECMWF EDA members. This yielded flow-dependent variations in precipitation, radiation, temperature, humidity and winds. The Ensemble Adjustment Kalman Filter (EAKF) performs deterministic daily updates via CMCC/SPREADS

(Cardinali et al., 2025; submitted to GMD). For each cycle, we archive the ensemble means and standard deviations (SDs) before and after assimilation. Observation operators map ESA-CCI SSM to the top layer of H_2O-SOI, ESA-CCI SCF to the CLM snow cover state (with covariances adjusting SWE) and GLASS LAI to the prognostic TLAI. Strict QC is applied to all observations during preprocessing, and assimilation runs asynchronously (SM+SCF daily and LAI every eighth day), so increments from each stream adjust the coupled water–energy–carbon states via cross-covariances. Covariance localisation and adaptive multiplicative inflation maintain filter reliability and spread–skill consistency. The outputs follow CMCC CLM5 conventions and expose daily states/fluxes and their ensemble uncertainty for diagnostics. The novelties versus Phase 0 are as follows: (i) joint assimilation of SM+SCF+LAI (dynamic LAI is rarely assimilated operationally); (ii) a dynamic vegetation constraint — LAI DA corrects phenology and plant pools rather than prescribing seasonality; (iii) end-to-end uncertainty quantification, enabling coupled water–carbon–energy analyses. Routed runoff and discharge are generated using the HYDROS routing scheme for basin-scale evaluation, which is consistent with DA-corrected land states. The Phase 1 setup (2002–2022) consisted of an offline CESM2/CLM5-BGC 30-member ensemble, which was forced by an expanded ECMWF EDA of 30 and cycled daily using a deterministic EAKF (SPREADS). The assimilated observations are ESA-CCI SSM (daily), ESA-CCI SCF (daily) and GLASS LAI (8-day, aggregated to the model grid), and the soil moisture is comparable to the model climatology. Assimilation is asynchronous (SM and SCF daily, and LAI according to its cycle), with operators mapping each product to the corresponding CLM5 state, thereby adjusting the covariances of SWE, canopy carbon and related variables. Spin-up follows a GSWP3 equilibrium-to-transient protocol to year-2000 conditions. The DA run and a parallel no-DA control share identical forcing. The outputs follow CLM5 history conventions on a ~0.5° global grid and provide daily water, energy and carbon states and fluxes (e.g. H_2OSOI/TSOI, H_2OSNO, TLAI, NEP/NEE), with ensemble means and standard deviations. Routed runoff and discharge are produced using the HYDROS scheme for hydrological evaluation.

3.4 ECMWF

As part of the IFS, an offline land data assimilation system has been developed that replicates the primary characteristics of the operational coupled land DA system employed at ECMWF. Similar to the IFS, the SEKF assimilates ERS-SCAT (1992–2006) and ASCAT (2007 onwards) surface soil moisture observations, as well as IMS snow cover and pseudo screen-level observations, over 12-hour assimilation windows. Although the SEKF algorithm is similar to the IFS algorithm, the SEKF is implemented in 'offline' mode and is driven by atmospheric reanalysis (ERA5). For convenience, the 12-hour assimilation windows run from 00:00 to 12:00 UTC and from 12:00 to 24:00 UTC, i.e. three hours ahead of the long-window DA in the IFS. Soil moisture increments are added at the end of the assimilation window. While the SEKF algorithm is similar to that of the IFS, its implementation in "offline" mode means it is constrained by the atmospheric reanalysis ERA5.

The SEKF configuration described in de Rosnay et al. (2013) is used, with finite differences rather than ERA5-EDA Jacobians, as the former was found to perform better. An SEKF snow analysis has also been implemented that assimilates Cryoclim (from 1987) and IMS (from 2010) snow cover observations, as well as in-situ snow depth observations. However, in the version of the LDAS used to produce the Phase 1 demonstrators, no data is assimilated over lakes.

For phase 1, seasonal hindcasts were initialised with four different surface analyses: ERA5, An “open-loop” land analysis (EC-land forced with ERA5, but without land-DA), one forced with the Offline-LDAS (described above) and a second LDAS where the soil-moisture assimilation was switched off, but the snow DA was switched on. Comparison of the last two allows us to understand the impact coming from the different land-surface components.

4 Results

4.1 DWD

The experiments outlined in project Phase 1 showed improved statistics for both the observation-first guess and the observation-analysis methods for measuring snow depth, compared to Phase 0 with both setups. The RMS difference has reduced, and the distribution has become more concentrated in the histogram curves. These basic results indicate proper behaviour of the analysis.

Cycling the surface analysis on a monthly basis results in only one third of the RMSD reduction compared to a five-day turnaround. This also affects the spatial structures of the increments. They become finer and more prominent. The higher impact of the observations in the assimilation system leads to a more realistic analysis state. For intercomparison with systems from other project partners, Fig. 1 shows global maps of surface temperature and snow water equivalent, averaged over the integrated time period. The respective time series are plotted in Fig. 2.

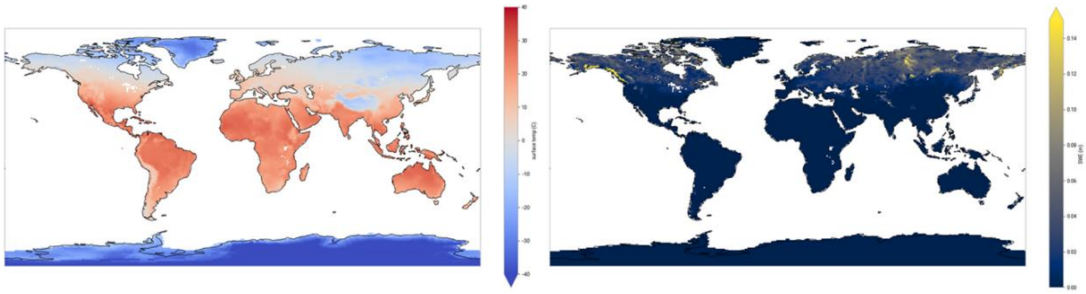

Figure 1 – DWD ensemble mean of the surface temperature (left) and snow water equivalent (right) averaged over the time period 1993-2022 for the exp. CERISE1_ASS_5D.

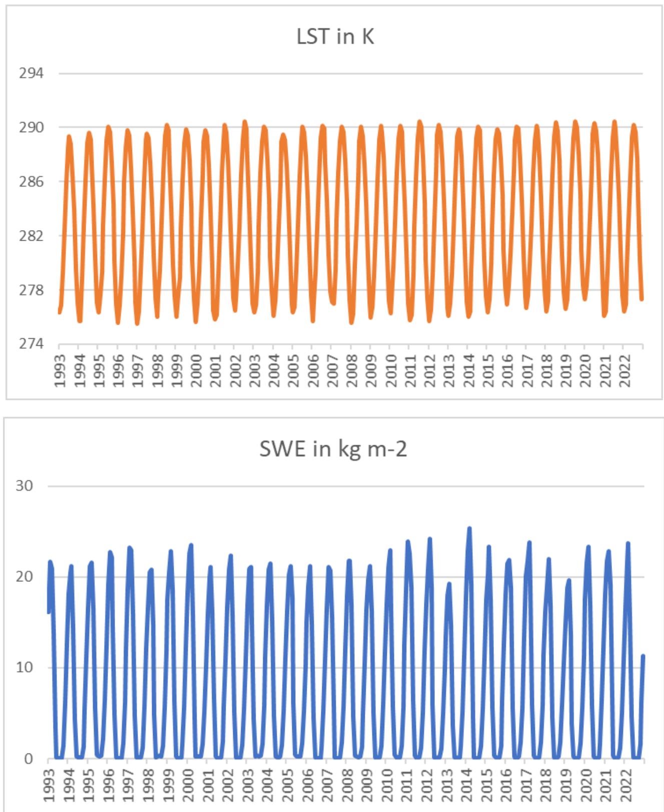

Figure 2 – DWD time series of the global monthly mean of the surface temperature (top) and snow water equivalent (bottom) for the exp. CERISE1_ASS_5D.

4.2 MF

Figures 3 and 4 show Phase 1 global maps of land surface temperature and snow water equivalent from 1 January 1993 to 31 October 2022. The simulated SWE values concern the seasonal snow cover and exclude the ice sheet water equivalent.

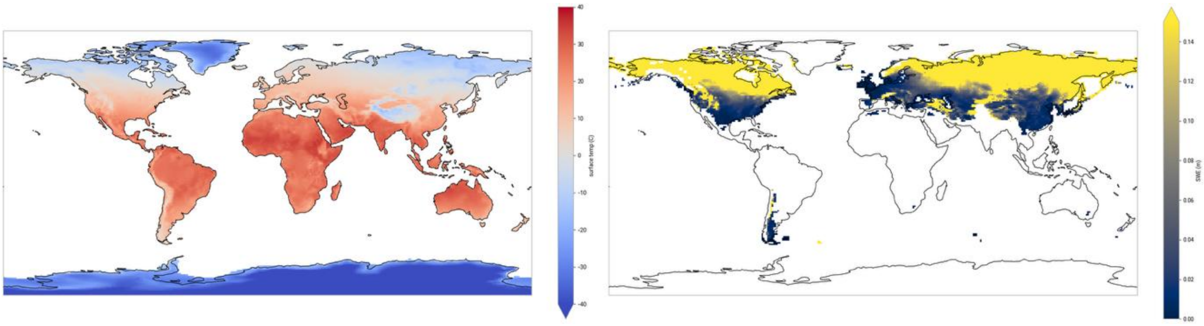

Figure 3 – MF mean of the surface temperature (left) and snow water equivalent (right) averaged over the time period 1993-2022.

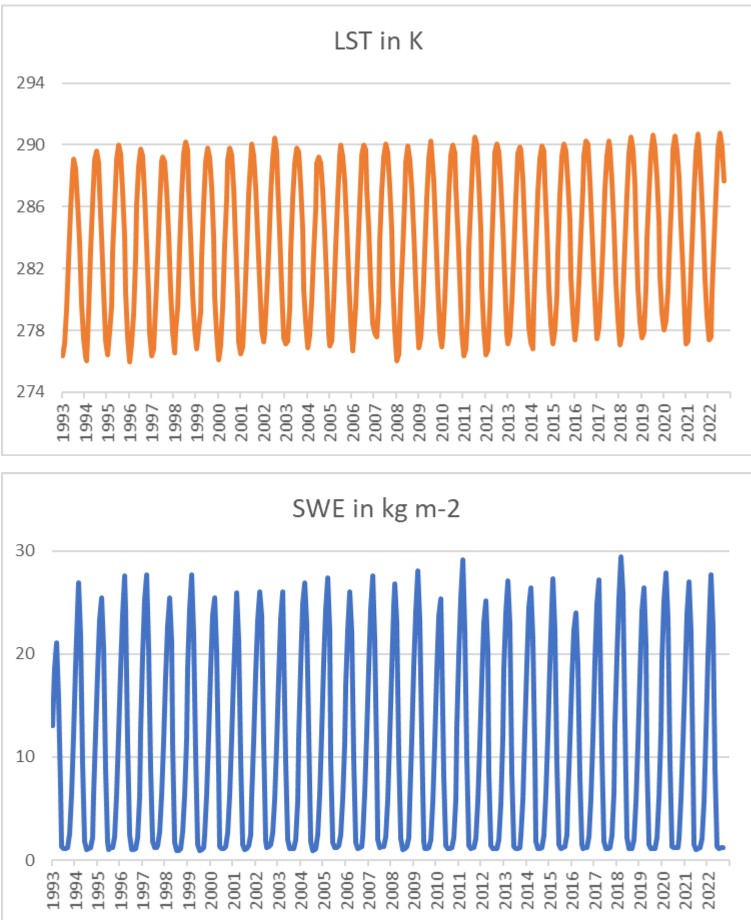

Figure 4 – MF time series of the global monthly mean of the surface temperature (top) and snow water equivalent (bottom) from 1993 to 2022.

4.3 CMCC

Figures 5 and 6 show that the DA outcome for 2002–2022 is physically consistent. The global mean skin temperature exhibits a stable annual cycle (boreal summer maxima and winter minima), while the global mean SWE varies in the opposite phase as expected from basic energy–cryosphere coupling. The 20-year mean maps show a realistic temperature gradient from the hot subtropics and continental interiors to the cold high latitudes and Antarctica, with SWE confined to the snow belts and major mountain ranges of the Northern Hemisphere. The orographic structure and amplitudes of the SWE are up to the upper end of the plotted scale (~10^3 kg/m²), which is well within climatological norms in boreal regions. This global analysis reveals no unit/scale inconsistencies or unphysical artefacts (e.g. negative SWE or implausible hot/cold spots).

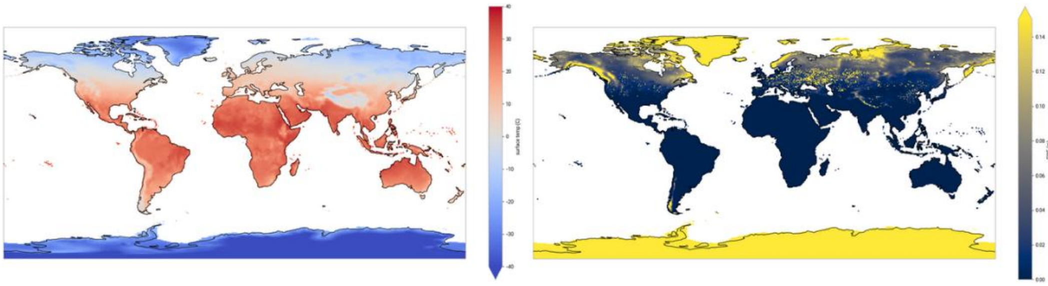

Figure 5 – CMCC mean of the surface temperature (left) and snow water equivalent (right) averaged over the time period 2002-2022.

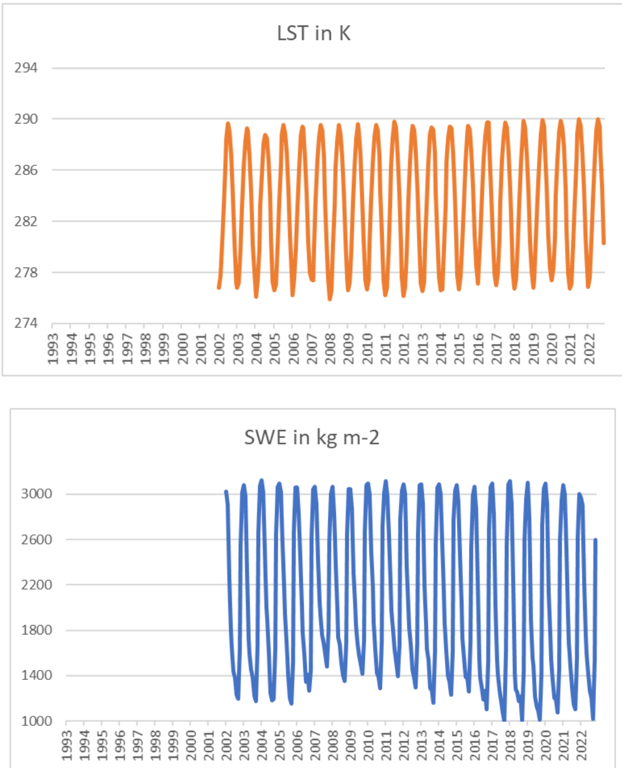

Figure 6 – CMCC time series of the global monthly mean of the surface temperature (top) and snow water equivalent (bottom) from 2002 to 2022.

4.4 ECMWF

When compared to independent soil moisture and soil temperature data from the International Soil Moisture Network, the LDAS has similar goodness-of-fit statistics to the open loop, except for root-zone soil moisture, for which the fit to *in situ* soil moisture observations is significantly lower, including lower anomaly correlations. The LDAS also behaves similarly when compared to *in situ* snow depth and snow water equivalent estimates (from SnowPEX). The LDAS benefits from removing spurious snow in mid-latitudes, which tends to melt too slowly.

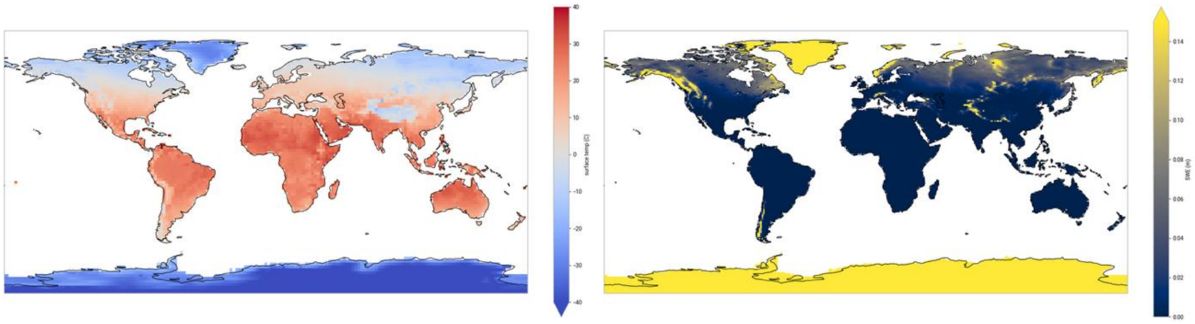

Figure 7 - Map of skin temperature (left) and snow water equivalent (right) from the IFS.

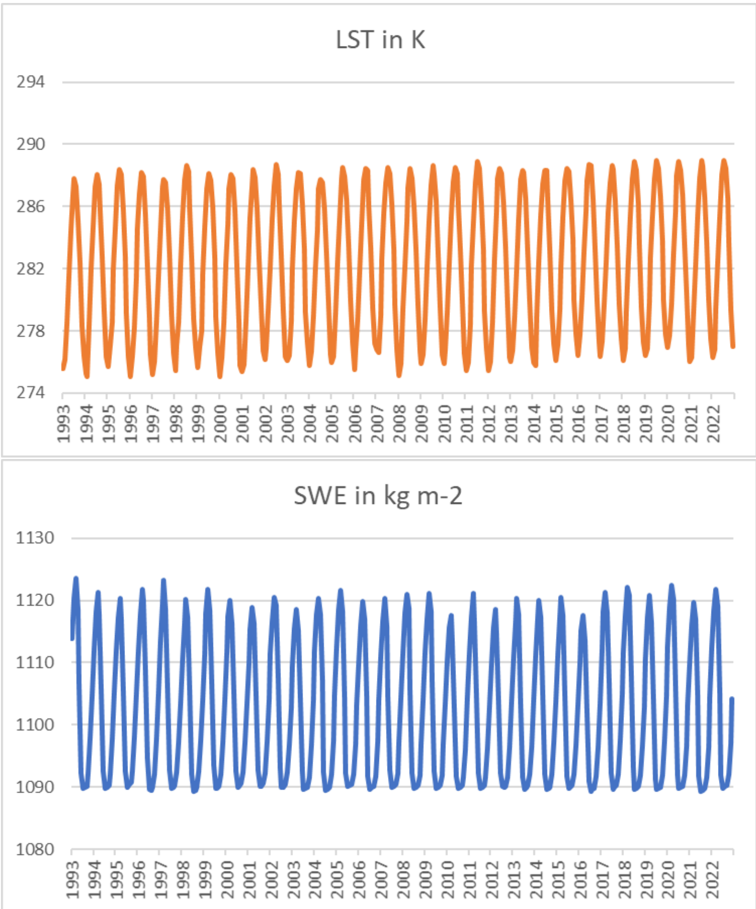

Figure 8 - ECMWF time series of the global monthly mean of the surface temperature (top) and snow water equivalent (bottom) from 1993 to 2022.

4.5 Basic verification of the consistency across demonstrators

Table 1 summarises the global mean values of the simulated snow water equivalent (SWE), leaf area index (LAI), and land surface temperature (LST) for all models. CMCC and ECMWF produce very high SWE values because their simulations include continental ice sheets. The global mean LST values are consistent across the models, ranging from 282 to 284 K. Note that the ECMWF value is approximately 1 K lower than those of the other models. This difference remains consistent over time, as shown in Fig. 9. The SWE values simulated by the MF are slightly larger than those simulated by the DWD (see Fig. 10), but the global mean values correlate well (R^2= 0.96).

Table 1 – Global mean values of Snow Water Equivalent, Leaf Area Index, Land Surface Temperature (SWE, LAI, and LST, respectively) from Phase 1 initial conditions produced by DWD, MF, CMCC, and ECMWF. The time period from 1993 to 2022 is considered, except for CMCC, for which the time period is from 2002 to 2022. The SWE values from CMCC and ECMWF include continental ice sheets..

	SWE (kg m-2)	**LAI (m2 m-2)**	**LST (K)**
DWD	8	2.1	283.5
MF	11	1.6	283.8
CMCC	2044	1.4	283.5
ECMWF	1102	-	282.6

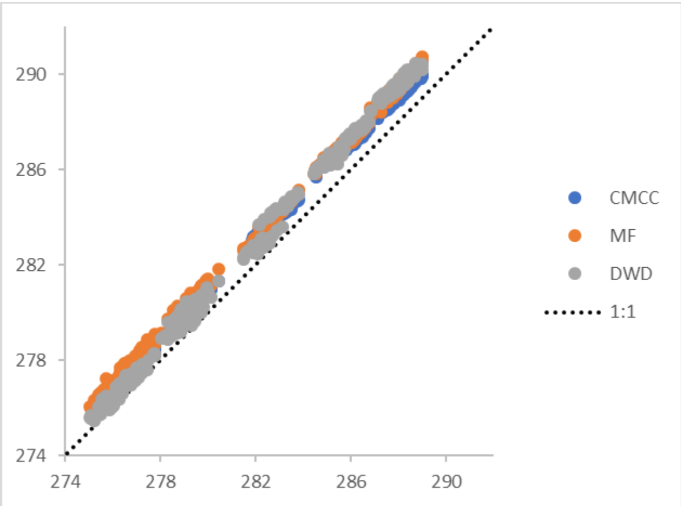

Figure 9 – Global monthly mean Land Surface Temperature (in K) from Phase 1 initial conditions produced by DWD, MF, CMCC (y-axis) vs. ECMWF (x-axis). The time period from 1993 to 2022 is considered, except for CMCC, for which the time period is from 2002 to 2022.

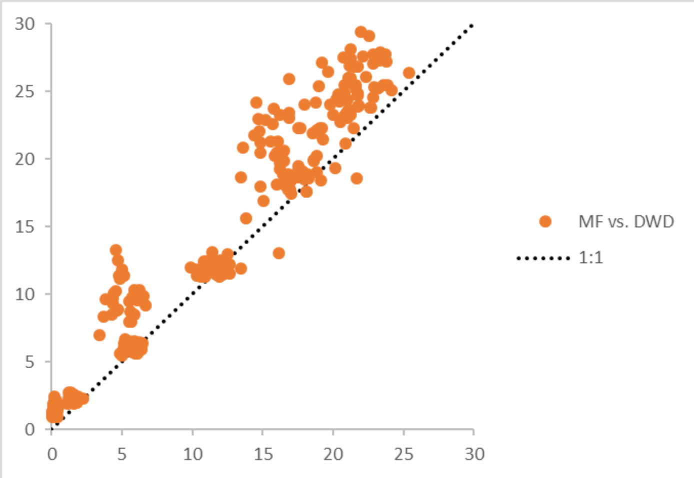

Figure 10 – Global monthly mean Snow Water Equivalent (in kg m^{-2}) from Phase 1 initial conditions produced by MF (y-axis) vs. DWD (x-axis). The time period from 1993 to 2022 is considered.

5 Conclusion

Creating balanced initialisation datasets and delivering them to the CERISE community is an essential step towards producing seasonal forecasts. It is also an important early stage in developing prototypes and demonstrators that could be approved as systems for predicting climate variability on seasonal timescales.

DWD has developed a system prototype/demonstrator based on the ICON-XPP model, incorporating surface analysis to provide the initial conditions for the seasonal forecasts. During Phase 1, two initialisation datasets were produced with a different cycling frequency for the snow depth data assimilation. The results showed better agreement with the observational data than in the Phase 0 reference experiment, i.e. increasing the analysis update frequency from monthly to five times daily brings the analysis closer to the observations and leads to a more realistic analysis. The results of the constrained run and C1.5 hindcasts are currently being evaluated.

MF employed a Simplified Extended Kalman Filter (SEKF) data assimilation methodology to assimilate THEIA AVHRR GEOV2 and CLMS GEOV2 LAI resulting in an offline, global land reanalysis driven by ECMWF ERA5 atmospheric forcing. In Phase 1, analysed soil moisture derived from LAI assimilation is used. Conversely, an LAI climatology is used instead of analysed LAI. The simulated snow water equivalent is consistent with the values simulated by DWD in Phase1.

CMCC employed an Ensemble Adjustment Kalman Filter (EAKF) data assimilation methodology to jointly assimilate ESA-CCI surface soil moisture and snow cover fraction (both daily) and GLAS LAI (8-day), resulting in an offline, 30-member, global land reanalysis driven by ECMWF EDA atmospheric forcing. The seasonality, spatial patterns and magnitudes are generally consistent with established observations and reanalyses, suggesting that the joint SM–SCF–LAI assimilation in CLM5 yields reasonable and scientifically credible states for water, energy and carbon evaluations.

ECMWF has developed an offline version of the land data assimilation system (LDAS) that reproduces the main features of the coupled land data assimilation system used operationally at ECMWF. Similar to the IFS, the SEKF assimilates ERS-SCAT or ASCAT surface soil moisture, IMS snow cover and pseudo screen-level observations over 12-hour assimilation windows. In general, the LDAS achieves similar goodness-of-fit statistics to the open loop. The LDAS benefits from the removal of spurious snow in mid-latitudes, which tends to melt too slowly.

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