BAMS
Meeting Summary

# Current Challenges and Future Directions in Data Assimilation and Reanalysis

Arianna Valmassoi, Jan D. Keller, Daryl T. Kleist, Stephen English, Bodo Ahrens, Ivan Bašták Ďurán, Elisabeth Bauernschubert, Michael G. Bosilovich, Masatomo Fujiwara, Hans Hersbach, Lili Lei, Ulrich Löhnert, Nabir Mamnun, Cory R. Martin, Andrew Moore, Deborah Niermann, Juan José Ruiz, and Leonhard Scheck

**Joint WCRP–WWRP Symposium on Data Assimilation and Reanalysis**

***What***: Scientists from the three research areas—data assimilation, reanalyses, and observing systems—came together to discuss current progress and future challenges and to highlight the synergies between the communities.

***When***: 13–17 September 2021

***Where***: Online

**KEYWORDS:** Coupled models; Data assimilation; Reanalysis data; Machine learning

https://doi.org/10.1175/BAMS-D-21-0331.1
Corresponding author: Arianna Valmassoi, avalmass@uni-bonn.de
In final form 5 May 2022

**AFFILIATIONS: Valmassoi**—Hans-Ertel-Centre for Weather Research, and Meteorology Section, Institute of Geosciences, University of Bonn, Bonn, Germany; **Keller, Bauernschubert, and Niermann**—Deutscher Wetterdienst, Offenbach, Germany; **Kleist and Martin**—NOAA/NWS/NCEP/Environmental Modeling Center, College Park, Maryland; **English and Hersbach**—European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom; **Ahrens and Bašták Ďurán**—Institute for Atmospheric and Environmental Sciences, Goethe University Frankfurt, Frankfurt am Main, Germany; **Bosilovich**—Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, Maryland; **Fujiwara**—Hokkaido University, Sapporo, Hokkaido, Japan; **Lei**—School of Atmospheric Sciences, Nanjing University, Nanjing, China; **Löhnert**—University of Cologne, Cologne, Germany; **Mamnun**—Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany; **Moore**—Department of Ocean Sciences, University of California, Santa Cruz, Santa Cruz, California; **Ruiz**—Centro de Investigaciones del Mar y la Atmósfera (CIMA/UBA-CONICET), Instituto Franco-Argentino sobre Estudios del Clima y sus Impactos (UMI-3351 IFAECI/CNRS-CONICET-UBA), Buenos Aires, Argentina; **Scheck**—Hans-Ertel-Centre for Weather Research, and Deutscher Wetterdienst, Offenbach, Germany

The first Joint World Climate Research Programme (WCRP)–World Weather Research Programme (WWRP) Symposium on Data Assimilation and Reanalysis took place on 13–17 September 2021, and it was organized in conjunction with the ECMWF Annual Seminar on Observations. The last WCRP–WWRP-organized meetings were held separately for data assimilation and reanalysis in 2017 (Buizza et al. 2018; Cardinali et al. 2019). Since then, common challenges and new emerging topics have increased the need to bring these communities together to exchange new ideas and findings. Thus, a symposium involving the aforementioned communities was jointly organized by the German Meteorological Service (DWD), Hans-Ertel-Centre for Weather Research (HErZ), WCRP, WWRP, and the ECMWF Annual Seminar. Major goals were to increase diversity, provide early career scientists with opportunities to present their work and extend their professional network, and bridge gaps between the various communities.

The online format allowed more than 500 participants from over 50 countries to meet in a virtual setting, using the Gather platform (www.gather.town) as the central tool to access the meeting. A virtual conference center was created where people could freely move around and talk to other close-by participants. A lobby served as the main hub, and it connected the poster halls and the conference rooms for the oral presentations and the ECMWF seminar talks. The feedback from the participants was overwhelmingly positive.

Scientifically, the meeting offered opportunities to bring together the communities of Earth system data assimilation, reanalysis, and observations to identify current challenges, seek opportunities for collaboration, and discuss strategic planning on more integrated systems for the longer term. The contributions totaled 140 oral and over 150 poster presentations covering a large variety of topics with increased interest in Earth system approaches, machine learning, and increased spatial resolutions. Key findings of the symposium and the ECMWF Annual Seminar are summarized in the next section. The "Conclusions and remarks" section highlights the common and emerging challenges of these communities.

## Topics

***Operational data assimilation and infrastructure.*** Many participants were affiliated with operational numerical weather prediction centers and thus a significant portion of the program focused on related updates. One common theme was moving beyond medium-range forecasts. National centers have focused their data assimilation (DA) developments on both operational coupled Earth system models and new or improved high-resolution regional systems (cf. sections “Convective-scale data assimilation” and “Data assimilation developments”). Other areas of interest included the viability of higher-frequency updating and increased use of observations from the private sector (reported in sections “Convective-scale data assimilation” and “Observations”).

Several operational centers have embraced community model developments including data assimilation infrastructure, allowing more focus on scientific advancements and a significant reduction of duplication of efforts. The U.S.-based Joint Center for Satellite Data Assimilation (JCSDA), the Met Office, NOAA, NASA, and the U.S. Navy are collaborating on the Joint Effort for Data Assimilation Integration (JEDI; Auligne 2021), which received a lot of attention. However, the development of generic DA infrastructure is not limited to JEDI, as additional examples were shown featuring both the Parallel Data Assimilation Framework (PDAF; Nerger 2021) and the Data Assimilation Research Testbed (DART; Raeder et al. 2021). The progress presented at the symposium underlines the ongoing, successful efforts for collaborations among operational as well as nonoperational centers.

***Reanalysis.*** Since its first implementations for the atmosphere, reanalyses have expanded to include more components of the Earth system (land, ocean, sea ice, composition) as well as regional specializations (continents, seas, and the Arctic).

Reanalyses represent the synthesis between models and observations to produce the best possible Earth system representation over multiple decades while assimilating observations at small spatiotemporal scales. Global reanalyses continue to be a foundation for global climate analysis and research, especially where observations are limited, such as the stratosphere with the Stratosphere–Troposphere Processes and Their Role in Climate (SPARC) Reanalysis Intercomparison Project (S-RIP; Fujiwara et al. 2021). Continuity in space and time is a great asset for users to study an ever-growing and diversified number of applications of physical or socioeconomic nature. Heat waves (Thomas et al. 2021a), droughts (Arshad et al. 2021), or weather/climate interactions with dust (Mytilinaios et al. 2021; Basart et al. 2021) and other aerosols (Franke et al. 2021) represent active research topics related to reanalyses. Further, renewable energy applications have lead to a growing interest in wind data from reanalyses (Morris et al. 2021; Niermann et al. 2021; Thomas et al. 2021b; Spangehl et al. 2021).

Major international centers continue both forward production of existing systems and developing new projects, given the user interests. Examples of atmospheric global reanalysis systems discussed in the symposium’s sessions are JRA-3Q at JMA (Kobayashi et al. 2021; Kosaka et al. 2021; Harada et al. 2021; Naoe et al. 2021), ERA5 and planned ERA6 at ECMWF (Hersbach et al. 2021; A. Bell et al. 2021; Muñoz-Sabater et al. 2021), as well as MERRA-2, the planned MERRA-3, and GEOS-R21C at NASA GMAO (Bosilovich et al. 2021; El-Akkraoui et al. 2021). Many of these current and future full observing system reanalyses include an ensemble component to also provide an uncertainty estimate. Further, they exhibit a progressively increased resolution for longer time periods up to three-quarters of a century (e.g., 20-km JRA-3Q, 30-km ERA5). With continuing data rescue efforts (Andersson et al. 2021), reconstructions of even longer periods become possible such as 20CRv3 from NOAA/CIRES/DOE (Slivinski et al. 2021) reaching back to 1836. Several ocean reanalysis products were also presented, such as the CMCC Global Ocean Reanalysis System (Banerjee et al. 2021) and the ECMWF ORAP6 ocean and sea ice reanalysis (Zuo et al. 2021).

Due to growing computing capabilities and ongoing research, regional reanalyses are expanding into many areas at higher resolutions. Examples covered were regional reanalysis activities at DWD (Kaspar et al. 2021), the Copernicus regional reanalysis (Schimanke et al. 2021), a 5-km regional reanalysis over Japan (Fukui et al. 2021), the Indian Monsoon Data

Assimilation and Analysis (IMDAA) regional reanalysis over the Indian monsoon region (Rani et al. 2021), a high-resolution reanalysis for the Mediterranean Sea (Escudier et al. 2021), and a 20-yr high-resolution Red Sea reanalysis (Sanikommu et al. 2021). These datasets allow for the in-depth evaluation and study of the local weather and climate, not readily captured in global systems. Further, the Arctic continues to be of interest for reanalysis efforts (e.g., C3S Copernicus Arctic Regional Reanalysis; Schyberg 2021), owing to the limited observations, changing environment and development of sea ice and glacial representations in models.

As regional reanalyses are reaching kilometer-scale resolutions, significant interactions not only with the reanalysis producers (e.g., Kaspar et al. 2021; Fourrie et al. 2021), but also with the convective-scale DA community are envisaged.

***Convective-scale data assimilation.*** While convective-scale DA (CSDA) has been a focus of NWP research and developments for a while, the interaction between CSDA and reanalysis communities is expected to continue and grow. Further, CSDA is moving beyond regional applications as global NWP approaches the kilometer scales and high-resolution observational systems such as Doppler velocities (Lippi et al. 2021) can be utilized. CSDA continues to be improved and fostered by the development of regional NWP and the inclusion of corresponding observing systems at kilometer scales (e.g., Hu et al. 2021; Carley et al. 2021; Hernandez-Banos et al. 2021).

The symposium included discussions on specific challenges of CSDA, such as error representation of fine-resolution observations compared to coarse-resolution simulations, multiscale and non-Gaussian errors, and model errors that contribute to nonlinear error growth. Assimilating observations at CSDA scales, such as radar, satellite, and lightning observations, can improve analyses and forecasts (Miyoshi et al. 2021; Combarnous et al. 2021; Deppisch et al. 2021). Further, innovative observations, such as crowd-sourced data, have also shown promising results (Paschalidi et al. 2021, and presentations in the "Observations" section).

Convective-scale dynamics are driven by instabilities that require increased spatial resolutions $O(0.1–1)$ km and temporal resolution from hours to minutes. For nonlinear regimes, non-Gaussianity can become more severe, leading to suboptimal solutions in ensemble filters conditioned on Bayesian assumptions. In this regard, advanced DA strategies, like nowcasting objects, grafting look-alike storms, and warm bubbles, were proposed (Neef et al. 2021; Sodhi and Fabry 2021; Janjić et al. 2021).

Another strategy that has proven to be effective is the use of high-frequency observations through smaller perturbations and more linear error growth (Ruiz et al. 2021). Along these lines Miyoshi et al. (2021) assimilated phased-array radar observations every 30 s with 1,000 ensemble-members and at 500-m spatial resolution in real time. Advances have also been reported for non-Gaussian DA algorithms which may bring significant benefits for CSDA in years to come (see section "Data assimilation developments" for more details)

A major issue for high-resolution observations are significant observation error correlations. Yang et al. (2021) investigated this effect in Doppler velocities and found that including these correlations explicitly improves the representation of extreme precipitation events. Similar positive impacts have been reported by Fujita et al. (2021). To represent model errors in CSDA, other strategies were also proposed, including additive noise, uncertainties in physical parameterizations, and errors resulting from unresolved scales (Janjić et al. 2021; Waller et al. 2021).

Further, multiscale features of CSDA can be addressed by blending algorithms that combine large- and small-scale analyses from a global model and a regional model (Schwartz et al. 2021). In addition, adaptive localization approaches including scale-dependent localization, variable-dependent localization, and correlation-dependent localization as well as the impact of large ensembles on localization were discussed (H. Wang et al. 2021; Necker et al. 2021; Duc et al. 2021).

***Data assimilation developments.*** A wide variety of topics were presented in the broader area of methodological advances in DA, from the ongoing research of ensemble approaches to machine learning methods to coupled systems. As in previous symposia, there were submissions focusing on more theoretical aspects of the DA generally split between algorithms and information flow. For NWP applications, Kalman filters were very present in ensemble DA [e.g., Pannekoucke et al. (2021) with the parametric Kalman filter, Raboudi et al. (2021) with the time-dependent observation noise inclusion, or X. Wang et al. (2021) with the multi-scale local Gain Form Ensemble Transform]. Also, hybrid DA algorithms were popular with applications such as integrated hybrid EnKF (Lei et al. 2021) or a 20-yr eddy-resolving reanalysis for the Red Sea (Sanikommu et al. 2021). Further, the non-Gaussian DA algorithms presented include non-Gaussian hybrid data assimilation (e.g., the maximum likelihood ensemble filter; Fletcher et al. 2021), non-Gaussian observation errors (Hu and Van Leeuwen 2021), and particle filters. The latter approach continues to show great progress and potential as it is transitioned to more complex model applications. Examples of particle filters were given by Schenk et al. (2021) with a 4D-localized version; Feng et al. (2021) with an improved local non-linear ensemble transform filter; Kawabata and Ueno (2021) with an implementation of non-Gaussian assimilation methods for error estimation at the convective-scale; and Kotsuki et al. (2021), who showed increased stability for a local particle filter with a Gaussian mixture extension in intermediate global circulation model.

The emergence of machine learning (ML) and deep learning (DL) techniques in recent years were also visible at the symposium. The major aim was to use ML to support specific DA aspects, accelerate/improve parts of the DA or to address model errors and parameter uncertainties. ML was used to support computationally expensive traditional DA methods by Barthelemy et al. (2021), who proposed to use a neural-network to emulate a high-resolution background from a low-resolution NWP. Further, ML was employed to improve error estimates (e.g., Farchi et al. 2021) or ensure more consistent error models also in non-Gaussian DA (Hossen et al. 2021). The more classical ML use of model parameter estimation was addressed by Legler and Janjić (2021) in a shallow-water convective-scale model, or Bocquet et al. (2021), who used the dual EnKF to learn the state, global and local parameters based on either covariance or domain localization.

Coupled DA in Earth system models was discussed with respect to strengths and current limitations. Bhargava et al. (2021) showed the benefit of weakly coupled atmosphere–ocean SST assimilation, Reichle et al. (2021) presented atmosphere–land DA with the assimilation of SMAP brightness temperature, Kleist et al. (2021) detailed the recent and future updates for weakly coupled DA in the NOAA GFS, and O'Kane et al. (2021) showed a 60-yr retrospective product using a strongly coupled DA with ocean–sea ice and biogeochemistry components. Other work presented focused on the important topic of coupled covariances within the different Earth system compartments (e.g., Tang et al. 2021; Smith et al. 2021). Several authors mentioned the problems of underdispersed land ensembles (e.g., Reichle et al. 2021), with Draper et al. (2021) presenting vegetation and soil parameter perturbations as a possible way forward. Several authors also outlined methodological considerations of the choices between strongly and weakly coupled DA, e.g., different time scales in the components (de Rosnay 2021) or tuning of the preexisting system degrading overall efficacy of coupled model state estimates (Reichle et al. 2021).

Some contributions highlighted issues of assimilating new spatial observations in coupled DA (for more on observations, refer to section "Observations"). However, neglecting new observing systems in one compartment may imply benefits to other quantities. In fact, the assimilation of surface temperatures for the ocean (While et al. 2021) and land (Valmassoi and Keller 2021) show an improvement in the assimilated variable, but also an increase in biases in other parts of the system, at the base of the ocean mixed layer and the 2-m temperature, respectively.

***Observations.*** A more detailed look at the state of observations for Earth system sciences was enabled by the joint aspects of the symposium with the concurrent ECMWF Annual Seminar, where recent Observing System Experiment results were shown for different Earth system components (Bormann 2021; Remy 2021; Kolassa 2021). Advances in data assimilation are enabling an even better utilization of observations, as exemplified by Laloyaux (2021) (estimating model error) and Prigent (2021) (surface observations). While observations for nonatmospheric components of the Earth system do not yet, in general, fully meet requirements, encouraging progress was reported for land, ocean, sea ice, snow, and composition by several Annual Seminar speakers (Inness 2021; Benedetti 2021; Charlton-Perez 2021).

Several presentations in the symposium discussed new or not yet fully exploited satellite observations. The assimilation of targeted geostationary hyperspectral sounder observations with high temporal resolution was shown to be beneficial for typhoon forecasts (Han et al. 2021) and visible satellite channels improved convective scale cloud and radiation forecasts (Scheck et al. 2021). Chandramouli et al. (2021) presented an online method for estimating nonlinear biases to improve the assimilation of all-sky satellite observations. The rising number and importance of GNSS observations was noted by Bormann (2021), while impressive results with the Aeolus research mission was shown as well (Koepken-Watts 2021). Aeolus lidar wind observations revealed to be in good agreement with Environment and Climate Change Canada (ECCC) forecasts and ERA5 data (Chou et al. 2021) with their assimilation in NWP exhibiting a significant positive impact at DWD (Cress 2021). Contributions also addressed the potential impacts on planned satellite missions such as the Meteosat Third Generation (MTG) and the potential for assimilation of the flash extent accumulation (Combarnous et al. 2021) or infrared and microwave channels (Villeneuve et al. 2021).

While 99% of observations assimilated in global NWP are from satellites (English 2021), multiple speakers at the ECMWF Annual Seminar noted that in situ observations remain very important, not least for the Earth's surface (e.g., Siddorn 2021; Ingleby 2021; Sandells 2021). Recent developments using ground-based remote sensing in data assimilation were presented, especially to characterize the state of the atmospheric boundary layer. Here, an observation gap—especially for temperature, humidity, and wind profiles—remains, as satellites are not able to resolve the ABL to the required extent. Ceilometers, Doppler lidars (Kayser et al. 2021), and microwave radiometers (Knist et al. 2021) were shown to be on their way to becoming operationally assimilated. For Doppler lidar networks, Nomokonova et al. (2021) showed significant potential for short-term wind forecasts in the ABL, especially at wind turbine hub heights, with Observation System Simulation Experiments (OSSEs). Further, the EU COST action PROBE (Profiling the Atmospheric Boundary Layer at European Scale; www.probe-cost.eu; Loehnert et al. 2021) is coordinating efforts to set standards (Lehmann et al. 2021) and exploit (Merker et al. 2021) newly organized ground-based remote sensing networks for data assimilation applications.

There is also a rising interest in the assimilation of crowd-sourced or otherwise nonconventional observations, which are inexpensive, but may require more effort for quality control and bias correction. It was demonstrated that assimilating bias-corrected temperature and humidity observations from citizen weather stations leads to significant improvements in the first six forecast hours (Paschalidi et al. 2021). Vehicle-based sensor measurements (Acevedo et al. 2021; Z. Bell et al. 2021) and commercial wind turbine data (Kelbch and Keller 2021) were also discussed as promising observations for data assimilation and reanalysis.

The seminar reflected a large, growing, and increasingly diverse global observing system. With this increase of complexity, the number of observation anomalies also increases making quality control and cross calibration very important (Dahoui 2021; Zhang 2021; Bathmann 2021). A more continuous approach to data screening and assimilation may enable some problems to be spotted early (Lean 2021). Waller (2021) highlighted the need of a more detailed look at sources of observations' error correlation, notably the spatial one. The seminar presented also the expected future evolution of both the space sector (Coppens 2021; Donlon 2021; Donoho 2021) and in situ observations (Randriamampianina 2021).

## Conclusions and remarks

Through its design, the first Joint WCRP–WWRP Symposium on Data Assimilation and Reanalysis together with the ECMWF Annual Seminar on observations allowed for the three scientific communities to come closer together highlighting the impressive progress and addressing common challenges.

A major theme of the symposium was a trend toward the consolidation of data assimilation efforts with respect to shared infrastructure. With the increasingly growing complexity of current DA, such approaches aim to share the costs and split the efforts for achieving progress without significant increases in expenses by facilitating collaboration and exploiting synergies in operational centers and research institutes. Therefore, the successful use of observation types and methodological advances can be accelerated. However, we also found that these efforts are not at its goal, as a major recommendation from the symposium was the need for data-sharing infrastructure to facilitate expensive experiments that now only a few centers are able to implement.

As model resolutions in global NWP and reanalysis are constantly increasing, the need for methods to appropriately and efficiently handle the assimilation of data at multiple spatiotemporal scales is growing further. Issues formerly related only to limited area models are becoming more relevant also for global DA, such as multiscale features, non-Gaussian error distributions, and the model errors which contribute to fast error saturation. To tackle these challenges, several algorithms have been proposed and successfully applied. In particular, efficient non-Gaussian methods such as localized particle filters have been rapidly maturing in recent years and may soon begin to replace the first variational- or Kalman filter–based assimilation systems.

Further, machine learning methods are being introduced to the DA community at an astonishing speed with many promising results. However, more research is required to more fully exploit these techniques and to address the high-dimensional problems for which inexpensive solutions are needed, such as the estimation of complex model errors or observation error covariances.

The advances in data assimilation are enabling an even better utilization of observations, both in their characterization and in high-frequency assimilation. Several contributions have demonstrated that there is a significant potential for new observations and underutilized remote sensing data to be exploited in data assimilation, especially at the convective scale and through exploitation of "all-surface/all-sky" radiance assimilation within the context of coupled DA.

The popularity of reanalysis is continuing to increase, due to its invaluable contribution to climate monitoring and weather forecasting as well as in research and the commercial sector, and with new fields of applications still emerging. The applications are not limited to atmospheric-related events, since several products are available for the ocean, land surface, atmospheric composition, and cryosphere. Reanalyses are continuously improved not only by increasing their spatial resolution and assimilating more observing systems/observation types, but also by extending them from atmosphere-focused products to a more complete Earth system. Events such as this symposium help to bridge the gaps between different reanalyses, working toward the plan to provide coupled products in the coming years (e.g., ECMWF and NASA).

Coupled Earth system modeling and assimilation is also becoming more prevalent both in research and operational applications related to NWP, especially in connection with the pursuit of seamless prediction systems. The associated multiscale challenges have to be addressed in DA: be it the necessity to adapt the algorithms to include observing systems for other Earth system components, the need for weakly or strongly coupled DA, or the challenges of properly initializing each component of the Earth system. In this regard, a close collaboration between NWP and reanalysis communities is essential to exploit existing and future synergies.

**Acknowledgments.** We thank the Hans Ertel Centre for Weather Research (HErZ), the German Meteorological Service (DWD), the World Weather Research Programme (WWRP) and the World Climate Research Programme (WCRP), and especially the European Centre for Medium-Range Weather Forecasts (ECMWF) for their support in organizing the symposium.

**Data availability statement.** The presentations of the Joint Symposium can be accessed at https://www.dwd.de/EN/research/international_programme/wcrp_wwrp_symposium/wcrp_wwrp_symposium_en_node.html. A summary of the Annual Seminar is available on the ECMWF website at www.ecmwf.int/en/about/media-centre/news/2021/annual-seminar-looks-earth-system-observations.

## References


Acevedo, W., and Coauthors, 2021: Usage of crowd-sourced meteorological car data for new real time road weather forecast. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-4A, https://symp-bonn2021.sciencesconf.org/data/357200.pdf.

Andersson, A., F. Kaspar, and T. Birger, 2021: Data rescue of national and international meteorological observations at Deutscher Wetterdienst. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P4, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Arshad, A., S. Pourshirazi, Y. Zhang, and M. Ashraf, 2021: Modeling impact of climate warming on cotton growth and phenology in Pakistan from 1961 to 2010 based on provincial data. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P4, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Auligne, T., 2021: JCSDA's vision of a community data assimilation for research and operations. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-3, https://symp-bonn2021.sciencesconf.org/data/357293.pdf.

Banerjee, D., A. Cipollone, I. Dorotea, and M. Simona, 2021: The CMCC Global Ocean Reanalysis System (C-GLORS): A series of consolidated eddy-permitting ocean reanalyses. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-4C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Barthelemy, S., J. Brajard, L. Bertino, and F. Counillon, 2021: High-resolution Ensemble Kalman Filter with a low-resolution model using a machine learning super-resolution approach. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-1B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Basart, S., and Coauthors, 2021: Operating in risky sand and dust storm environments in Northern Africa, the Middle East and Europe: A portfolio of climate services. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O2-4B, https://symp-bonn2021.sciencesconf.org/data/356283.pdf.

Bathmann, K., 2021: Challenges in quality control. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/606464100.

Bell, A., P. Martinet, O. Caumont, B. Vie, F. Burnet, M. Borderies, J. Delanoë, and P. Vishwakarma, 2021: Expected benefit of cloud radar and microwave radiometer observations for future data assimilation during fog conditions. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-4C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Bell, Z., S. Dance, and J. A. Waller, 2021: Exploring the characteristics of a vehicle-based temperature dataset for convection-permitting numerical weather prediction. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-4A, https://symp-bonn2021.sciencesconf.org/data/356124.pdf.

Benedetti, A., 2021: Atmospheric composition observations: Overview, recent developments and gap analysis in the context of weather prediction. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/604582882.

Bhargava, K., C. Chang, E. Kalnay, C. Da, and T. Sluka, 2021: Impact of assimilating SST vs nudging in an atmosphere ocean coupled model. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Bocquet, M., Q. Malartic, and A. Farchi, 2021: State, global and local parameter estimation using ensemble Kalman filters for model error correction. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O3-1B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Bormann, N., 2021: Evaluating forecast impact of current and future observations. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/606600803.

Bosilovich, M., A. Collow, P. Stackhouse, N. Thomas, K. Patel, H. Amos, A. Prados, and S. Schollaert, 2021: Overview of MERRA-2 for applications, decision-making, and climate assessment. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-4B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Buizza, R., and Coauthors, 2018: Advancing global and regional reanalyses. *Bull. Amer. Meteor. Soc.*, **99**, ES139–ES144, https://doi.org/10.1175/BAMS-D-17-0312.1.

Cardinali, C., and Coauthors, 2019: Seventh International WMO Data Assimilation Symposium.

Carley, J., M. Matthews, M. Morris, M. Pondeca, J. Colavito, and R. Yang, 2021: Assimilation of web camera derived estimates of horizontal visibility. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O2-4A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Chandramouli, K., X. Wang, A. Johnson, J. Whitaker, and J. Otkin, 2021: Online nonlinear bias correction in ensemble Kalman filter to assimilate GOES-R all-sky radiances for the analysis and prediction of rapidly developing supercells. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Charlton-Perez, C., 2021: Snow-free land observations. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/604583309.

Chou, C., P. Kushner, S. Laroche, Z. Mariani, and P. Rodriguez, 2021: Validation of Aeolus L2B wind product with ECCC short-range forecasts and ERA5 over the Arctic. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-1C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Combarnous, P., F. Erdmann, O. Caumont, and E. Defer, 2021: An observation operator for geostationary lightning imager data assimilation in storm-scale numerical weather prediction systems. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O3-4B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Coppens, D., 2021: Future atmospheric observations: What might be important in the future, techniques to assess. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/607293844.

Cress, A., 2021: Validation and impact assessment of Aeolus Doppler Wind Lidar Observations at the German Weather Service. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-1C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Dahoui, M., 2021: Observations monitoring and related diagnostics. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/606421839.

de Rosnay, P., 2021: Towards consistent exploitation of Earth system observations in coupled assimilation systems. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/605734872.

Deppisch, T., and Coauthors, 2021: Assimilation of solar reflectances in a pre-operational online system with a local ensemble Kalman filter. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P5, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Donlon, C., 2021: Observing the Earth from space. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/607414554.

Donoho, N., 2021: Future earth system observations: What might be important in the future, techniques to assess. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/607459805.

Draper, C., G. Tseganeh, M. Barlage, J. Dong, A. Fox, D. Kleist, P. Pegion, and J. Whitaker, 2021: Modernising the land data assimilation and land model uncertainty estimation in NOAA's Global NWP Systems. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-4A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Duc, L., T. Kawabata, K. Saito, and T. Oizumi, 2021: 1000-member ensemble forecasts for extreme events: The 2019 typhoon Hagibis and the July 2020 Kyushu heavy rain. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P1, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

El-Akkraoui, A., and Coauthors, 2021: The NASA GMAO retrospective analysis for the 21st century GEOS-R21C. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-4C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

English, S., 2021: An Earth system view of observation. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/604580470.

Escudier, R., and Coauthors, 2021: A high resolution reanalysis for the Mediterranean Sea. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-1B, https://symp-bonn2021.sciencesconf.org/data/355568.pdf.

Farchi, A., M. Bocquet, M. Bonavita, and P. Laloyaux, 2021: Model error correction with data assimilation and machine learning. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-1B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Feng, J., X. Wang, and J. Poterjoy, 2021: A comparison of two local moment-matching nonlinear filters: Local Particle Filter (LPF) and Local Nonlinear Ensemble Transform Filter (LNETF). *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Fletcher, S., M. Goodlif, M. J. Hossen, A. Kliewer, M. Zupanski, and T. Wu, 2021: Non-Gaussian hybrid variational data assimilation. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O3-4C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Fourrie, N., O. Caumont, and P. Brousseau, 2021: Data assimilation impact studies with the AROME-WMED reanalysis during HyMeX SOP1. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O2-1B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Franke, P., A. C. Lange, and H. Elbern, 2021: Evaluation of European anthropogenic trace gas and aerosol emissions using 4D-var: First results of a full-year re-analysis for 2016. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-1C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Fujita, T., H. Seko, T. Kawabata, K. Sawada, D. Hotta, and Y. Ikuta, 2021: Enhancement of Variational Assimilation of High-Frequency and High-Resolution Radial Winds. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P5, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Fujiwara, M., and Coauthors, 2021: Overview of the SPARC Reanalysis Intercomparison Project (S-RIP) during 2013-2021. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-1B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Fukui, S., and Coauthors, 2021: Performance of a 5-km regional reanalysis over Japan with respect to summer precipitation. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-1B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Han, W., R. Knuteson, and R. Yin, 2021: Evaluation and assimilation of Geostationary Hyperspectral InfraRed Sounders (GeoHIS): Progress and challenges. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O3-4B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Harada, Y., S. Kobayashi, Y. Kosaka, J. Chiba, and T. Tokuhiro, 2021: Early results of the evaluation of the JRA-3Q reanalysis. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P4, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Hernandez-Banos, I., M. Hu, G. Ge, W. Mayfield, and L. F. Sapucci, 2021: Test and evaluation of data assimilation algorithms and configurations to improve the Rapid Refresh Forecast System for convection forecasts. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P1, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Hersbach, H., and Coauthors, 2021: The ERA5 reanalysis: A detailed record of the climate and weather for the past 70 years. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Hossen, M. J., M. Goodliff, and S. Fletcher, 2021: Using machine learning techniques to switch background error distributions to improve data assimilation. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P5, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Hu, C., and P. J. Van Leeuwen, 2021: A new way to infer non-Gaussian observation errors based on ensemble innovations. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Hu, M., and Coauthors, 2021: Building a JEDI- and FV3-based Rapid Refresh Forecast System (RRFS) upon decade of development and implementation of the High Resolution Rapid Refresh (HRRR). *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O2-1A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Ingleby, B., 2021: In situ atmospheric observations: Status, developments, gap analysis. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/604581214.

Inness, A., 2021: Atmospheric composition observations: Overview, recent developments and gap analysis in the context of environment prediction. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/604582383.

Janjić, T., Y. Zeng, F. Yuxuan, Y. Ruckstuhl, A. De Lozar, U. Blahak, and A. Seifert, 2021: Representation of model error in convective scale data assimilation. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-1A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Kaspar, F., M. Borsche, D. Niermann, J. Ostermoeller, T. Roesch, T. Spangehl, J. Keller, and R. Potthast, 2021: Regional reanalysis activities at DWD: Review and outlook. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Kawabata, T., and G. Ueno, 2021: An adaptive R estimator with a storm-scale particle filter. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Kayser, M., V. Lehmann, C. Knist, M. Löffler, R. Leinweber, and S. Klink, 2021: Long-term assessment of Doppler lidars for an operational use in a future network. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O3-1C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Kelbch, A., and J. Keller, 2021: The potential of assimilating wind power data for future reanalysis. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-4A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Kleist, D., T. Treadon, C. Thomas, H. Liu, E. Liu, and R. Mahajan, 2021: NCEP Operational Global Data Assimilation System (GDAS): Recent upgrades and future plans. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O2-2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Knist, C., M. Löffler, J. Vural, A. Schomburg, M. Kayser, V. Lehmann, and S. Klink, 2021: Assessment of microwave radiometers for operational network deployment and its observational value for forecasting models. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O3-1C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Kobayashi, C., T. Iwasaki, S. Kobayashi, Y. Kosaka, J. Chiba, T. Tokuhiro, Y. Harada, and H. Naoe, 2021: Brewer-Dobson circulation represented in JRA-3Q.

*WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O2-1B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Koepken-Watts, C., 2021: Atmospheric observations - Satellite: Overview, recent developments and gap analysis. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/604580892.

Kolassa, J., 2021: Land observations for model calibration and data assimilation. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/607228299.

Kosaka, Y., S. Kobayashi, J. Chiba, T. Tokuhiro, Y. Harada, C. Kobayashi, and H. Naoe, 2021: Representation of the past weather prior to the International Geophysical Year (1957–1958) in JRA-3Q. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-1B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Kotsuki, S., K. Oishi, and T. Miyoshi, 2021: Improving the stability of the Local Particle Filter and its Gaussian mixture extension: Experiments with an intermediate AGCM. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O3-4C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Laloyaux, P., 2021: Bias aware data assimilation. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/605610212.

Lean, P., 2021: Practical challenges using observations in operational numerical weather prediction systems. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/604854178.

Legler, S., and T. P. Janjić, 2021: Combining data assimilation and machine learning to estimate parameters of a convective-scale model. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Lehmann, V., and Coauthors, 2021: DWD pilot station evaluating ground-based remote sensing systems for future observing networks. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P4, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Lei, L., Z. Wang, and Z. Tan, 2021: Integrated hybrid data assimilation for an ensemble Kalman filter. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Lippi, D., J. Carley, and D. Kleist, 2021: Doppler radial wind assimilation in the GFS with an observing system simulation experiment. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-1C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Loehnert, U., and Coauthors, 2021: Ground-based atmospheric boundary layer profiling and data assimilation experiments within the EU COST Action PROBE. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-1C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Merker, C., B. Crezee, D. Leuenberger, A. Haefele, J. Vural, M. Hervo, G. Martucci, and M. Arpagaus, 2021: Towards operational assimilation of surface based microwave radiometer and Raman lidar data at MeteoSwiss. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-1C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Miyoshi, T., and Coauthors, 2021: Big Data assimilation: Real-time demonstration experiments of 30-second-update forecasting in Tokyo in 2020 and 2021. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Morris, M., P. Kushner, and O. Mercan, 2021: Using reanalysis to assess 'design-level' wind events with the potential for infrastructure damage in the built environment. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P1, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Muñoz-Sabater, J., and Coauthors, 2021: The ERA5-Land Global land surface reanalysis. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-4C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Mytilinaios, M., and Coauthors, 2021: Evaluation of a high-resolution dust regional reanalysis using in-situ and remote sensing observations. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O2-4B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Naoe, H., S. Kobayashi, Y. Kosaka, J. Chiba, T. Tokuhiro, Y. Harada, and C. Kobayashi, 2021: Evaluation of the latest Japanese Reanalysis for three quarters of a century (JRA-3Q) during a pre-satellite era. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P4, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Necker, T., D. Hinger, T. Honda, and M. Weissmann, 2021: Localization on convective scales: What can we learn from a 1000-member ensemble? *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Neef, L., R. Potthast, C. Welzbacher, and U. Blahak, 2021: Assimilation of nowcast objects in the regional forecast model ICON-LAM. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-1A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Nerger, L., 2021: A hybrid nonlinear-Kalman ensemble transform filter for data assimilation in systems with different degrees of nonlinearity. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Niermann, D., T. Spangehl, M. Borsche, and F. Kaspar, 2021: Evaluating extreme wind speed in regional and global reanalysis products. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P1, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Nomokonova, T., U. Löhnert, T. Necker, P. Griewank, and M. Weissmann, 2021: Estimation of the benefits of remote-sensing profilers for sustainable energy applications. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O2-3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

O'Kane, T., and Coauthors, 2021: CAFE60v1: The CSIRO Climate retrospective Analysis and Forecast Ensemble system: Version 1: System design, model configuration and data assimilation. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Pannekoucke, O., R. Ménard, M. Bocquet, R. Fablet, A. Perrot, S. Ricci, and O. Thual, 2021: Contributions of the parametric Kalman filter in practical and theoretical data assimilation. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O3-2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Paschalidi, Z., W. Acevedo, C. Sgoff, S. Ulbrich, T. Kratzsch, and R. Potthast, 2021: Assimilation of surface observations from citizen weather stations into a regional weather prediction system. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-4A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Prigent, C., 2021: Challenges in microwave radiative transfer parameterization of the Earth surface, passive and active, from low to high frequencies, for both atmosphere and surface characterizations. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/605649028.

Raboudi, N., B. Ait-El-Fquih, H. Ombao, and I. Hoteit, 2021: Ensemble Kalman filtering with colored observation noise. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Raeder, K., T. J. Hoar, M. El Gharamti, B. K. Johnson, N. Collins, J. L. Anderson, J. Steward, and M. Coady, 2021: A CESM+DART Atmospheric Reanalysis for Forcing Ocean, Land, and Other Surface Models. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Randriamampianina, R., 2021: The role of non-operational observations today and in the future. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/607524564.

Rani, S. I., J. P. George, E. N. Rajagopal, T. Arulalan, R. Renshaw, A. Maycock, and D. Barker, 2021: IMDAA regional reanalysis over the Indian monsoon region. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-1B, https://symp-bonn2021.sciencesconf.org/data/355105.pdf.

Reichle, R., S. Zhang, Q. Liu, C. Draper, J. Kolassa, and R. Todling, 2021: Assimilation of SMAP brightness temperature observations in the GEOS land-atmosphere data assimilation system. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Remy, E., 2021: Ocean Observing System Experiments (OSEs). *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/607409561.

Ruiz, J., G.-Y. Lien, K. Kondo, S. Otsuka, and T. Miyoshi, 2021: Reduced non-Gaussianity by 30-second rapid update in convective-scale numerical weather prediction. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-4A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Sandells, M., 2021: Snow land observations: Overview, recent developments. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/604583999.

Sanikommu, S. R., S. Langodan, P. Zhan, and I. Hoteit, 2021: A 20-year high resolution Red Sea reanalysis using a hybrid ensemble data assimilation. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-1C, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Scheck, L., S. Geiss, L. Bach, L. A. De, and M. Weissmann, 2021: Improving cloud and radiation forecasts by assimilating visible satellite images. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O3-4B,https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Schenk, N., A. Walter, and R. Potthast, 2021: 4D-localized particle filter method in KENDA for ICON-LAM. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Schimanke, S., L. Isaksson, L. Edvinsson, M. Ridal, L. Berggren, S. Hopsch, and M. P. Le, 2021: Copernicus European regional reanalysis. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Schwartz, C., G. Romine, and D. Dowell, 2021: Experiments with a continuously cycling 3-km ensemble Kalman filter over the entire conterminous United States for convection-allowing ensemble initialization. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-4A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Schyberg, H., 2021: The Copernicus Arctic regional reanalysis. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Siddorn, J., 2021: Ocean and wave observations: Overview, recent developments and gaps. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/604581635.

Slivinski, L., G. Compo, P. Sardeshmukh, and J. Whitaker, 2021: A synoptic to decadal evaluation of the 20th Century Reanalysis Version 3. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O4-2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Smith, P., A. Lawless, and N. Nichols, 2021: Incorporating flow dependent ocean information into weakly coupled atmosphere-ocean 4D-Var data assimilation: Experiments with an idealised system. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Sodhi, J. S, and F. Fabry, 2021: Large error correction in storms at convective scales by grafting look-alike modelled storms from other ensemble backgrounds. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-4A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Spangehl, T., M. Borsche, D. Niermann, F. Kaspar, and B. Tinz, 2021: Usage of reanalysis data for wind energy expansion in the North Sea and Baltic Sea. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P1, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Tang, Q., L. Mu, H. Goessling, T. Semmler, and L. Nerger, 2021: Weakly and strongly coupled data assimilation with the coupled ocean-atmosphere model AWI-CM. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-2, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Thomas, N., M. Bosilovich, A. Collow, R. Koster, S. Schubert, A. Dezfuli, and S. Mahanama, 2021a: Mechanisms associated with daytime and nighttime heat waves over the Contiguous United States. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-4B, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

——, ——, and A. Dezfuli, 2021b: Regionalization of MERRA-2 50-m wind speed over the United States for Energy Applications. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P1, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Valmassoi, A., and J. D. Keller, 2021: Data assimilation on the sub-kilometer scale for the urban environment. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O1-1A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Villeneuve, E., P. Chambon, and N. Fourrie, 2021: A statistical evaluation of Bayesian inversions from infrared and microwave cloudy observations for future instruments MTG-FCI, MSG-MWI and MSG-ICI. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P4, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Waller, J., 2021: Observation error covariances, can we handle spatial OBS error correlations. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/605543387.

——, S. Dance, and H. Lean, 2021: Evaluating errors due to unresolved scales in convection permitting numerical weather prediction. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Wang, H., and Coauthors, 2021: Assimilation of Aerosol Optical Depth (AOD) retrievals and PM2.5 in NCEP's Next-Generation Regional Air Quality Forecasting System. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-4A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Wang, X., H. Chipilski, C. Bishop, E. Satterfield, N. Baker, and J. Whitaker, 2021: A new multiscale data assimilation method: Multiscale Local Gain Form Ensemble Transform Kalman Filter (MLGETKF). *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, O5-4A, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

While, J., M. Martin, and R. King, 2021: Biases at the base of the mixed layer induced by 3DVar assimilation of sea surface temperature observations in ocean models. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Yang, X., and Coauthors, 2021: Development of kilometer scale regional data assimilation for Copernicus Arctic Regional Reanalysis. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P3, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.

Zhang, P., 2021: Radiometric calibration and recalibration: Theory, practice and future perspective. *ECMWF Annual Seminar on Observations*, Online, ECMWF, https://vimeo.com/604728768.

Zuo, H., M. A. Balmaseda, E. D. Boisseson, S. Tietsche, M. Mayer, and P. de Rosnay, 2021: The ORAP6 ocean and sea-ice reanalysis: Description and evaluation on climate and forecasts. *WCRP–WWRP Symp. on Data Assimilation and Reanalysis*, Online, Deutscher Wetterdienst, P4, https://symp-bonn2021.sciencesconf.org/data/book_of_abstracts_2021_09_13.pdf.