Chapter 16

Data Assimilation Research Team

16.1 Members

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16.2 Overview of Research Activities

Data Assimilation Research Team (DA Team) was launched in October 2012 and is composed of 22 research and technical staff including 11 visiting members as of March 2020. Data assimilation is a cross-disciplinary science to synergize computer simulations and real-world data, using statistical methods and applied mathematics. As computers become more powerful and enable more precise simulations, it will become more important to compare the simulations with actual observations. DA Team performs cutting-edge research and development on advanced data assimilation methods and their wide applications, aiming to integrate computer simulations and real-world data in the wisest way. Particularly, DA Team tackles challenging problems of developing efficient and accurate data assimilation systems for "big simulations" with real-world "big data" from various sources including advanced sensors. The specific foci include 1) theoretical and algorithmic developments for efficient and accurate data assimilation, 2) data assimilation methods and applications by taking advantage of powerful supercomputers and "big data" from new advanced sensors, and 3) exploratory new applications of data assimilation in wider simulation fields. These advanced data assimilation studies will enhance simulation capabilities and lead to a better use of supercomputers including the K computer and its successor "Fugaku."

In FY2019, we continued on the ongoing data assimilation research in the following aspects: 1) theoretical research on challenging problems, 2) leading research on meteorological applications, 3) optimization of computational algorithms, and 4) exploratory research on wider applications. We also explored close collaborations with several research teams within the R-CCS. We have made substantial progress on the following research items:

Theoretical research

- A particle filter was applied to the cellular automata of 3 state sheep model.
- Model bias correction using a machine learning method (Long Short Term Memory, LSTM) was explored with the Lorenz96 model.
- Denial of detrimental observations based on the Ensemble Forecast Sensitivity to Observation (EFSO) was investigated (1 paper in revision).
- Weight structure of the Local Ensemble Transform Kalman Filter (LETKF) was investigated with a simplified atmospheric general circulation model (GCM) (1 paper in revision).
- A local particle filter (LPF) was developed and tested with a simplified GCM.
- An LPF was developed for GPGPU.
- Ensemble Kalman filters (EnKFs) and LPFs were compared using the Lorenz96 model.
- Reservoir computing and EnKF were combined to predict spatio-temporal chaotic systems (1 paper in preparation).

Leading research on meteorological applications

- A 30-second-update, real-time prediction system was deveoped with the SCALE-LETKF.
- The SCALE-LETKF realtime system toward a very short-term localized rainfall forecast was ported to Oakforest-PACS and tested in a realtime manner using the Multi-Parameter Phased Array Weather Radar (MP-PAWR) at Saitama University.
- The observational operator for PAWR in SCALE-LETKF was improved, and its impact on forecasts was investigated (1 paper published).
- An impact of a new observation system using a kite on a forecast of hevey rainfall was investigated.
- Impact of 30-second-update PAWR DA was investigated using the 100-m-mesh SCALE-LETKF for the west Japan heavy rainfall event in July 2018.
- An observation operator for high frequent lightning data assimilation was developed.
- Model acceleration by machine learning was investigated; convolutional neural networks were used to accelerate quasi-geostrophic model.
- To improve 3D precipitation nowcasting, neural networks were used to predict 3D radar images.
- Impact of assimilating lightning observations was investigated with the SCALE-LETKF.
- Efficient operation of water dam was investigated.
- Impact of assiilating Himawari-8 observations on precipitation events in Taiwan was investigated.
- Satellite observations at visible bands were simulated with the 1000-member SCALE-LETKF.
- Non-Gaussian PDF in DA was investigated using 1000-member, 1km-resolution assimilation experiments with assimilation windows ranging from 30 seconds to 5 minutes and assimilating PAWR observations in the SCALE-LETKF system. (1 paper in preparation)
- Conventional radar data assimilation experiments using the SCALE-LETKF system and RELAMPAGO field campaign observations. Analysis of the performance of the analysis and short range forecasts. (1 paper in preparation)
- Impact of dual phased array assimilation to severe convective weather forecasts investigated with the SCALE-LETKF was investigated.
- Sensitivity tests to optimize localication in the real-time SCALE-LETLF system were performed.
- We kept running the three-dimensional precipitation nowcasting system with the PAWR at NICT Kobe. A new system was developed for the MP-PAWR.
- A machine-learning system for the three-dimensional precipitation nowcasting system was developed with Convolutional LSTM.
- The sensitivity of a WRF-based convective-scale assimilation system on an afternoon thunderstorm in northern Taiwan was investigated (1 paper in press).
- Hybrid gain data assimilation using variational corrections in the subspace orthogonal to the ensemble was investigated (1 paper in press).
- Evaluation of stochastic perturbed parameterization tendencies on convective-permitting ensemble forecasts of heavy rainfall events in New York and Taiwan was performed (1 paper published).
- Convective-scale sampling error and its impact on the ensemble radar data assimilation system were investigated with a case study of heavy rainfall event on 16th June 2008 in Taiwan (1 paper in press).
- Impact of tropical cyclone initialization on its convection development and intensity was investigated with a case study of typhoon Megi (1 paper published).
- Convective-scale assimilation with the GNSS-ZTD and radar data was performed, and its impact on heavy rainfall prediction in Taiwan was investigated (1 paper published).
- Including the observation error correlation in DA was investigated with the NICAM-LETKF system. We found that reconditioning the observation error covariance matrix stabilizes the data assimilation and improves the analyses.
- Ensemble-based observation impact estimates was incorporated into the NICAM-LETKF (1 paper published).
- GPM/DPR-sensed heavy ice precipitation was compared with a 3.5-km NICAM simulation to design better cloud microphysics (1 paper in revision).
- We kept running the global precipitation nowcasting system with the Global Satellite Mapping of Precipitation (GSMaP) by JAXA, and the prediction was disseminated on our website and JAXA's website (1 paper published).
- Precipitation forecasts were improved by merging NICAM and spatio-temporal extrapolation forecasts (1 paper published).
- Spatially-varying model parameter was estimated with NICAM-LETKF (1 paper published).

- Survey of ensemble-covariance of CH4-emission and wind velocity with NICAM-RM-LETKF to evaluate unfavorable impacts of observation densities between PREPBUFR-wind and GOSAT-CH4 data.
- An observation operator for a new space-borne precipitation radar was developed (1 paper accepted).
- Impact of oversampling observations from a geostationary precipitation radar satellite to tropical cyclone forecasts was invesigated (paper to be submitted).
- An object-based verification method of precipitation pattern was investigated using pattern recognition techniques (1 paper published).
- An LETKF system to assimilate pattern features of precipitation areas was implemented with an intermediate atmospheric GCM. A feature based on the fractions skill score was investigated.
- Impact of the ocean mixed layer model in a regional atmospheric DA system was investigated for a case of typhoon Soudelor in 2015.
- Water level change in Lake Biwa under Typhoon Jebi in 2018 was reproduced by using SCALE and the Regional Ocean Modeling System (ROMS).
- Current filed in Lake Kinneret was simulated with 50-m mesh ROMS.
- A LETKF based ocean DA system was developed and tested with Argo assimilation in the western North Pacific.
- Bio-chemical fields in Tokyo-Bay are simulated to predict blue-green algae bloom.
- Relaxation methods of dynamical imbalance for ocean data assimilation systems were implemented.
- Performance of regional ocean data assimilation systems between 3D-VAR and LETKF was compared.
- Uncertainty quantification of a land surface model by machine learning based surrogate modelling was investigate (1 paper submitted).
- A prototype system of machine-learning-based dam operation optimization was developed in collaboration with Tokyo Electric Power Company Holdings, Incorporated.
- Land-atmosphere-coupled DA system was developed based on the NICAM-LETKF (1 paper in revision).
- Online- and offline-DA for paleoclimate reconstruction and its relation to the predictability were compared (1 paper in prep.).
- Observation operators for paleoclimate reconstruction were developed (1 paper accepted).

Computational optimization

- The NICAM-LETKF system was developed for "Fugaku" as a target application in collaboration with the Computational Climate Science Research Team and FS2020 (1 application submitted to Gordon Bell).
- The just-in-time data transfer (JIT-DT) of PAWR observations from NICT and Saitama University to R-CCS was improved in collaboration with the System Software Development Team.

Wider applications

- DA experiments were performed with the Moderate resolution Imaging Spectroradiometer (MODIS) leaf area index (LAI) observations and the Spatially-Explicit, Individual-Based Dynamic Global Vegetation Model (SEIB-DGVM) over Siberia.
- SEIB-DGVM DA experiments were performed with the MODIS LAI observations at Takayama Flux site in Japan.
- A particle filter was applied to a press-forming manufacturing simulation.

Several achievements are selected and highlighted in the next section.

16.3 Research Results and Achievements

16.3.1 Development of a real-time workflow of the big data assimilation system

In FY2019, we developed a 30-second-update, real-time prediction system assimilating the Phased Array Weather Radar (PAWR) observations by fully utilizing the Oakforest-PACS. In the previous fiscal year, we achieved a real-time execution of a 30-second-update PAWR DA cycle with a 250-m mesh on the supercomputer K. However, the computational domain was limited to the PAWR observation range of 60 km, and the boundary conditions for this domain were not provided in real time; a real-time system for the outer regions was yet to be developed. We also ported the entire system to the Oakforest-PACS in response to the upcoming shutdown of the K computer. In FY2019, we started to use the Oakforest-PACS as the main platform. Our

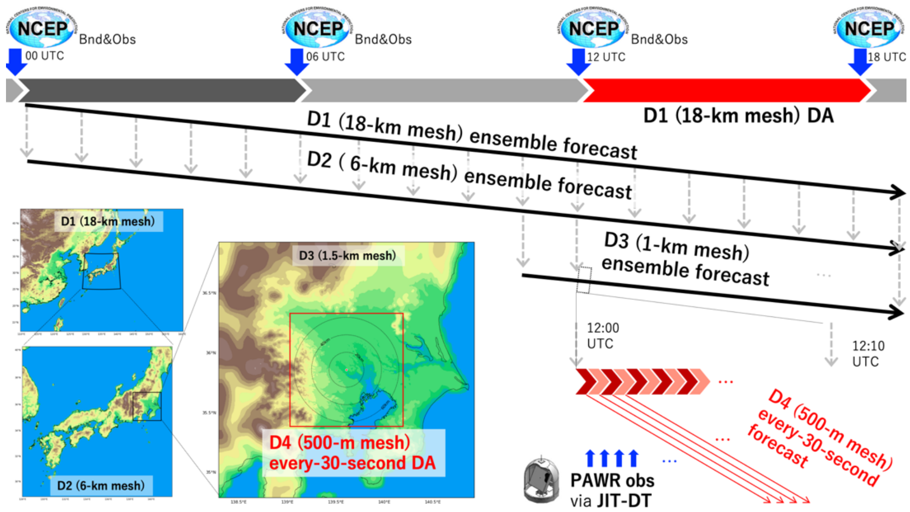

Figure 16.1: Workflow and computational domains of the 30-second-update, real-time SCALE-LETKF system.

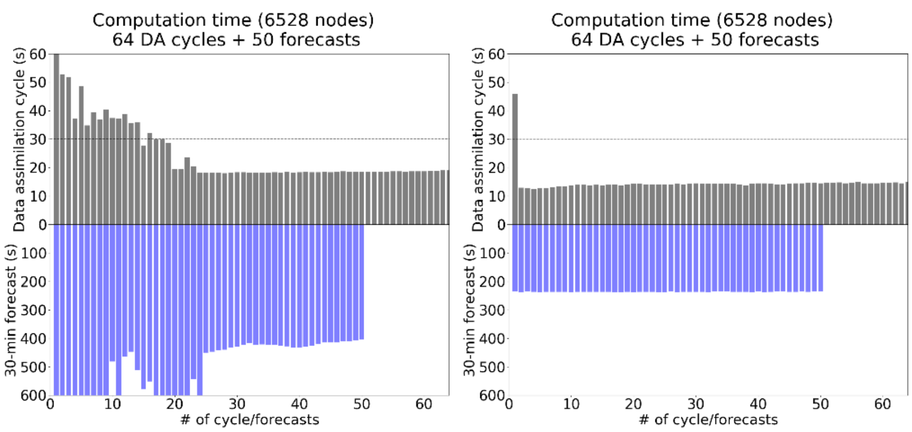

Figure 16.2: Elapse times of each DA and 30-minute forecast with a 250-m mesh. DA was performed for 64 cycles, and forecasts were performed for 50 initial conditions. Left: a test run in August 2019, right: a test run in November 2019.

system receives and assimilates PAWR observations every 30 seconds, and performs 30-minute deterministic forecasts from the analyses. Figure 16.1 presents the system design. The system consists of four computational domains. The outermost domain (D1, 18-km mesh) is the near-real-time SCALE-LETKF system developed by Lien et al. (2017), assimilating conventional observations provided by the National Center for Environmental Prediction (NCEP) every 6 hours. From the analyses by D1, ensemble forecasts over Japan (D2, 6-km mesh) and Kanto (D3, 1.5-km mesh) are performed to provide initial and boundary conditions for the innermost domain (D4). The D4 covers a region of $120\,\text{km} \times 120\,\text{km}$ with a 500-m mesh or a 250-m mesh, assimilating observations of PAWR at Saitama University every 30 seconds. The data transfer of PAWR uses the Just-In-Time Data Transfer (JIT-DT) developed by the System Software Development Team, R-CCS.

In FY2019, the 30-minute deterministic forecasting from the analyses of D4 was implemented as follows. Here, 10 MPI processes are assigned to the 30-minute forecasts in addition to the MPI processes for the 52 ensemble members. MPI communicators are prepared for DA and the 30-minute forecasts separately; computations are independent except for the exchange of DA analyses. The SCALE and LETKF are combined as a single binary file to avoid data exchange via file IO; data are exchanged on memory. Figure 16.2 displays the execution time for DA and forecast. An earlier version of DA did not run stably in 30 seconds, and the corresponding 30-minute forecasts took long (left). The system was updated to solve these problems; the latest version runs stably within 30 seconds. The first cycle of DA takes longer to initialize the system, and from the second cycle, the DA finishes stably within 30 seconds. The 30-minute forecasts also runs in 4 minutes (right). This is a big step to the real time prediction. We will prepare a dissemination system and web page for this

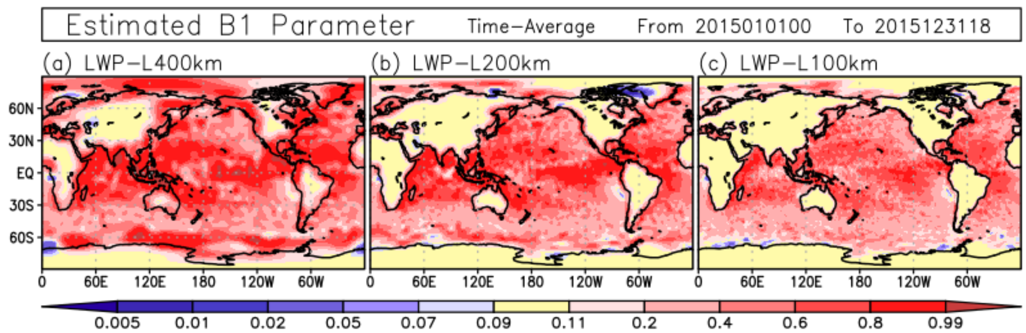

Figure 16.3: Spatial patterns of locally-estimated B_1, averaged over 12 months from January to December 2015 for the experiments with the horizontal localization scales of (a) 400, (b) 200, and (c) 100 km (LWP-L400km, LWP-L200km, and LWP-L100km, respectively). Red and blue colors indicate increases and decreases from the default value of $B_1 = 0.10$ due to parameter estimation. Adopted from Kotsuki et al. (2020).

prediction. We also need to verify and improve the prediction accuracy.

16.3.2 Model parameter estimation with data assimilation using NICAM-LETKF

This study aims to improve forecasts of numerical weather prediction (NWP) models by optimizing model parameters with data assimilation. Kotsuki et al. (2018) succeeded in improving global precipitation forecasts at 112-km-resolution NICAM (Nonhydrostatic ICosahedral Atmospheric Model) by estimating a parameter called B1 of Berry (1967)'s large-scale condensation scheme using satellite-observed precipitation data and the Ensemble Transform Kalman Filter (ETKF).

Extending the previous study, this study explores to use the model parameter estimation for mitigating radiation bias. Kotsuki et al. (2020, JGR) estimated the parameter B1 as a global-constant parameter with cloud liquid water (CLW) data observed by GCOM-W/AMSR2. The parameter estimation successfully reduced excessive bias in CLW, and mitigated overestimated outgoing shortwave radiation (OSR) bias of the NICAM. In addition, Kotsuki et al. (2020, JGR) extended to estimate spatially-varying B1 parameters using the Local ETKF (i.e., LETKF) (Fig. 16.3). The local parameter estimation resulted in better cloud representations and improved OSR bias in regions where shallow clouds are dominant (Fig. 16.4).

16.3.3 Application of machine learning methods to model bias correction: idealized experiments with the Lorenz-96 model

Model bias correction has been studied as an important subject in data assimilation. Model bias can be effectively alleviated by statistical model bias correction methods combined with a variational or sequential (Kalman filter-based) data assimilation method (Dee, 2005). Conventional methods have assumed a bias correction term of simple functional form such as a constant or a linear dependence on model state variables (Dee and Da Silva, 1998, Danforth et al., 2007). Recently, the data-driven forecast and estimation of governing functions of the system in arbitrary form, known as 'model detection' or 'system identification,' has been rapidly developed with the use of machine learning (Brunton et al. 2016, Vlachas et al. 2018). The application of such machine learning methods to data assimilation is a potential solution to model bias correction with unknown complexity.

In this study, an application of Long-Short term memory (LSTM) on model bias correction problems is explored in the context of data assimilation using the Local Ensemble Transformed Kalman Filter (LETKF). The proposed method is applicable for model bias which is dependent on current and past model states in an arbitrarily nonlinear manner. Localization of bias correction treatment is also implemented. The new method is examined by idealized numerical experiments using a multi-scale Lorenz-96 model (Lorenz 1996; Wilks 2005).

As the first step, LSTM-based scheme is examined in the case of offline bias correction, where the network is trained with the pair of forecast and analysis time sequence produced by LEKTF without correction. The bias correction with LSTM worked well and showed slightly better performance than simple polynomial fitting. However, the improvement is very subtle in the case of coupled Lorenz96 system, which have been used in previous studies. Therefore, experimental settings in which the use of LSTM has a clear advantage will be studied further. Figure 16.5 presents such an example; here, the "shear-Lorenz96" by Pulido et al. (2018) is

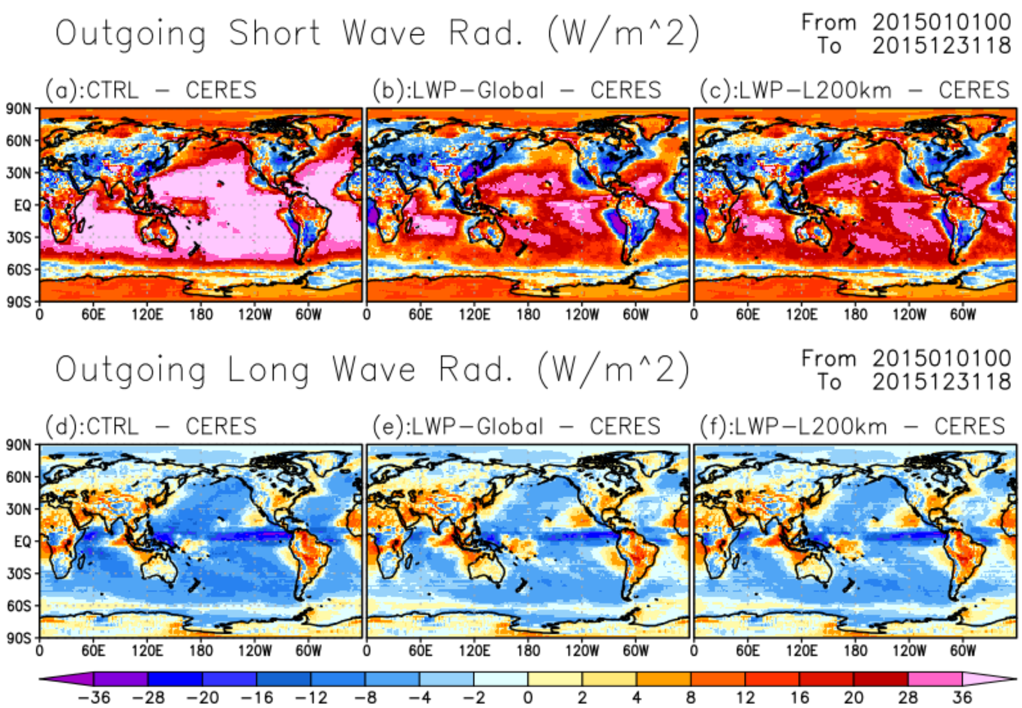

Figure 16.4: Global patterns of the time-mean bias relative to CERES data for (a, b, c) outgoing short wave radiation (OSR; W m^{-2}), and (d, e, f) outgoing long wave radiation (OLR; W m^{-2}), averaged over 12 months from January to December 2015. Panels (a, d), (b, e) and (c, f) show CTRL, LWP-Global (estimating B_1 as a global constant), and LWP-L200km experiments, respectively. Warm (cold) color represents overestimated (underestimated) outgoing radiations relative to CERES data. Adopted from Kotsuki et al. (2020).

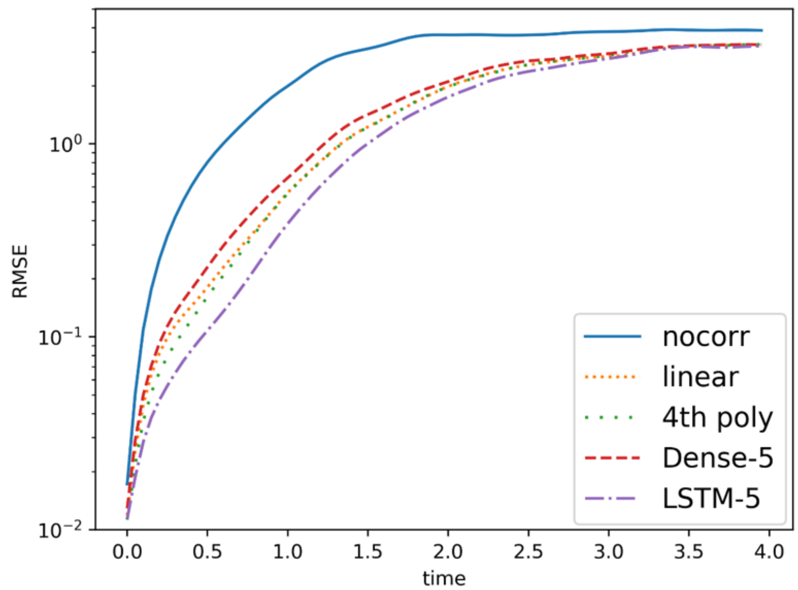

Figure 16.5: The comparison of average RMSE over 100 forecasts from different initial conditions in "shear-Lorenz96 (Pulido et al., 2018)" experiments. Each line corresponds to the experiment with different bias correction schemes; no correction, linear regression, 4th order polynomial regression, neural networks with dense layers, and LSTM. All bias correction schemes use the spatial localization with 5 neighboring grid points.

used. The next step will be the online bias correction, where the bias correction function is estimated with state variables by LETKF simultaneously, and the consideration of partial and noisy observation.

16.4 Schedule and Future Plan

DA Team aims to explore the frontier of large-scale DA problems, and to be a world's leader in DA research. With the goals in mind, we plan to continue working on the three fundamental foci: 1) theoretical and algorithmic developments for efficient and accurate DA (core focus), 2) DA methods and applications by taking advantage of the Japan's flagship supercomputer and "Big Data" from new advanced sensors (lead focus), and 3) exploratory new applications of DA in wider simulation fields (pioneer focus). We have very strong projects in weather forecast applications, and we will enhance the leading research to the world's top level. Also, we will pioneer new application fields that have direct connection with societal benefits. For direct benefit to society, "real-time" application is essential with efficient computational algorithms, which are also an important aspect of our research.

"Big Data Assimilation" (BDA) is one of the major activities that we have developed in the past years. The prototype system showed promising results, but the physical performance for the 30-minute forecast of precipitation patterns can be improved. We will continue to work on the development of the BDA system to further improve the computational and physical performances toward the upcoming "Fugaku" era.

Beyond the direct future of the BDA effort, we can extend the idea of BDA to a broader perspective: integration of "Big Data" and "Big Simulation." New sensors provide orders of magnitude more data, and simulations become more precise. Collaborative work with computer scientists will be essential to utilize the complex high-performance computer systems effectively. In addition, dense sensor data tend to have complicated error structures such as correlated errors, and the proper treatment is necessary to fully utilize the "Big Data." The current DA methods usually assume no observation error correlation. Based on our previous theoretical research on the observation-error correlations, we plan to develop methods to consider the observation error correlations in realistic NWP applications.

Treating the model errors and non-Gaussian probability distribution has been grand challenges in DA. "Big Ensemble Data Assimilation" with the largest-ever 10240 samples was a milestone providing fundamental data to investigate the non-Gaussian probability distribution. We have developed expertise and exclusive dataset to tackle these challenges. We have been pioneering a new implementation of Local Particle Filter (LPF) in collaboration with German Weather Service. We will continue the LPF development toward realistic applications.

DA is a cross-disciplinary science based on statistical mathematics and dynamical systems theory. In addition, DA connects simulations and real-world data. Therefore, it is naturally beneficial to enhance close collaborations with experts in mathematics, sensor technology, and various application fields. The current weather-forecast projects involve active collaborations with observation experts. In addition, we have been teaching semester-long courses on DA at the Department of Mathematics, Kyoto University, and this will lead to more collaborations with mathematicians. Moreover, TL Miyoshi has joint appointments at RIKEN iTHEMS (Interdisciplinary Theoretical and Mathematical Sciences Program) and RIKEN CPR (Cluster for Pioneering Research), and these will enhance broader collaborations. Collaborations with other R-CCS Research Teams will also be beneficial. The challenges for future DA systems require cross-disciplinary collaborations to most effectively use the massive supercomputers with more heterogeneous architecture design. Further, RIKEN's Engineering Network already gave us opportunities to collaborate among different disciplines among RIKEN centers. RIKEN President's Initiative for "DA innovation hub" also helped expand collaboration. We also started collaborations with industry partners for more direct benefit to society. Enhancing the broader collaborations is a key to success, i.e., to make a new scientific movement across the borders through DA as an innovation hub, to establish DA as a new scientific paradigm, and to change the world through innovation and education of DA.

16.5 Publications

16.5.1 Awards

[1] Shigenori Otsuka, RIKEN Oubu Research Incentive Award, Development of a novel three-dimensional precipitation nowcast method and its real-time demonstration, 3/10/2020.

16.5.2 Articles

[1] Takino, S., T. Honda, T. Miyoshi, and T. Tsukada 2019: Improving prediction of river-basin precipitation by assimilating every-10-minute all-sky Himawari-8 infrared satellite radiances – A case of Typhoon Malakas (2016). International Commission On Large Dams 2019 Symposium Proceedings, Volume 2, p339, ISBN:978-0-367-33422-2.

[2] Kotsuki, S., K. Kurosawa, S. Otsuka, K. Terasaki, and T. Miyoshi, 2019: Global precipitation forecasts by merging extrapolation-based nowcast and numerical weather prediction with locally optimized weights. *Wea. Forecasting*, **34**, 701–714, `https://doi.org/10.1175/WAF-D-18-0164.1`.

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[6] Kondo, K., and T. Miyoshi, 2019: Non-Gaussian statistics in global atmospheric dynamics: a study with a 10240-member ensemble Kalman filter using an intermediate atmospheric general circulation model. *Nolin. Processes Geophs.*, **26**, 211–225, `https://doi.org/10.5194/npg-26-211-2019`.

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[8] Kurosawa, K., Y. Uchiyama, and T. Kosako, 2020: Development of a numerical marine weather routing system for coastal and marginal seas using regional oceanic and atmospheric simulations. *Ocean Engineering*, **195**, 106706, ISSN 0029-8018, `https://doi.org/10.1016/j.oceaneng.2019.106706`.

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[11] 庄司悟, 岡崎淳史, 芳村圭, 2018: 気候プロキシデータ同化における観測インパクトの時空間偏在性に関する考察, 土木学会論文集*B1(*水工学*)*, **74**, I_49–I_54, Online ISSN 2185-467X, https://doi.org/10.2208/jscejhe.74.5_I_49.

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[13] Kotsuki, S., Y. Sato, and T. Miyoshi, 2020: Data assimilation for climate research: Model parameter estimation of large-scale condensation scheme. *J. Geophys. Res. Atmos.*, **125**, e2019JD031304, https://doi.org/10.1029/2019JD031304.

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[16] Amemiya, A., T. Honda, and T. Miyoshi, 2020: Improving the observation operator for the Phased Array Weather Radar in the SCALE-LETKF system, *SOLA*, **16**, 6–11, http://dx.doi.org/10.2151/sola.2020-002.

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16.5.3 Invited Talks

[1] Kotsuki S., Sato Y., Terasaki K., Yashiro H., Tomita H., Satoh M., and Miyoshi T.: Model Parameter Estimation with Data Assimilation using NICAM-LETKF. JpGU2019, Chiba, 5/29/2019.

[2] Arakida, H., S. Kotsuki, S. Otsuka, Y. Sawada, T. Miyoshi, Data assimilation experiments with MODIS LAI observations and the dynamic global vegetation model SEIB-DGVM over Siberia, JPGU2019, Chiba, 5/29/2019.

[3] Takemasa Miyoshi, Big data assimilation: A new science for weather prediction and beyond, 14TH INTERNATIONAL EnKF WORKSHOP IN VOSS, PARK HOTEL VOSSEVANGEN, VOSS, NORWAY, 6/4/2019.

[4] Takemasa Miyoshi, Big Data Assimilation: A New Science for Weather Prediction and Beyond, Seminar, DWD, Frankfurt, Germany, 6/13/2019.

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16.5.5 Poster Presentations

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[3] Taylor, J., LienG.Y., Satoh, S., Miyoshi, T. Impact of Radar Artifacts from Phased Array Weather Radar to Short-Range Convective Forecasts, JPGU2019, Chiba, Japan, 5/29/2019.

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[5] Otsuka, S., M. Ohhigashi, V. P. Huynh, P. Tandeo, and T. Miyoshi, A deep-learning approach to three-dimensional precipitation nowcasting. 39th International Conference on Radar Meteorology, Poster1-87, Nara, Japan, 9/16/2019.

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