Chapter 15

Data Assimilation Research Team

15.1 Members

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Koji Terasaki (Research Scientist)

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Shinichiro Shima (Visiting Scientist)

Shu-Chih Yang (Visiting Scientist)

Stephen G. Penny (Visiting Scientist)

Masaru Kunii (Visiting Scientist)

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15.2 Research Activities

The Data Assimilation Research Team (DA Team) was launched in October 2012 and is composed of 18 research and technical staff including 7 visiting members as of March 2016. Data assimilation (DA) is a cross-disciplinary science to synergize computer simulations and real-world data, based on statistical mathematics and dynamical systems theory. As computers advance and enable precise simulations, it will become more important to compare the simulations with real-world data. DA Team performs cutting-edge research and development on advanced DA 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 DA 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 DA, 2) DA methods and applications by taking advantage of the world-leading K computer and "big data" from new advanced sensors, and 3) exploratory new applications of DA in wider simulation fields. These advanced DA studies will enhance simulation capabilities and lead to a better use of high-performance computers including the leading-edge K computer.

In FY2015, 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 continued close collaborations with several research teams within the AICS Research Division. We have made substantial progress on the following research items:

Theoretical research

- A paper on the discrete Bayesian optimization approach to find optimal ensemble sizes in a multi-model ensemble Kalman filter (EnKF) was published (1 paper published).
- A new local particle filter method to treat non-Gaussian PDF was explored (1 paper submitted).

Leading research on meteorological applications

- We have successfully run the largest-ever ensemble DA experiments with 10,240 samples for the global atmosphere using real observations with the real-case Nonhydrostatic ICosahedral Atmospheric Model (NICAM) (1 paper published, press release on November 11, 2015).
- Impact of localization in ensemble Kalman filter was investigated with 10,240 samples using an intermediate AGCM (1 paper submitted).
- Non-Gaussian statistics in the global atmospheric dynamics were investigated with the 10,240-sample ensemble Kalman filter using an intermediate AGCM.
- Multi-scale data assimilation was investigated based on 10,240-member ensemble Kalman filter using an intermediate AGCM and NICAM.
- A DA system for Advanced Microwave Sounding Unit (AMSU)-A radiance data was developed with NICAM-LETKF.
- A DA system for JAXA's Global Satellite Mapping of Precipitation (GSMaP) data was developed with NICAM-LETKF.
- A high resolution experiment using NICAM-LETKF system assimilating the conventional, AMSU-A, and GSMaP observations has been performed on the K computer.
- The spatial and inter-channel observation error correlations of AMSU-A were investigated with the NICAM-LETKF system.
- An earlier study on the assimilation of global precipitation data with the low-resolution NCEP GFS model were summarized and published (2 papers published).
- A paper on the new quality control algorithm for the Osaka Phased Array Weather Radar (PAWR) was published (1 paper published).
- The LETKF system with the SCALE model (SCALE-LETKF) was developed and improved in collaboration with Computational Climate Science Research Team. Several new functions, including PAWR assimilation, Himawari-8 satellite data assimilation, relaxation-to-prior-spread (RTPS) method, offline-nested domains, were implemented with the SCALE-LETKF system.
- A near-real-time regional weather analysis and forecast system based on the SCALE-LETKF has been set up and run on the K computer. It has produced weather analyses and 5-day forecasts every 6 hours for more than 9 months.

- The "Big Data Assimilation" experiments for a local severe rainstorm case were performed with the SCALE-LETKF system, assimilating the PAWR data. The results were compared with the previous NHM-LETKF experiments and the nowcasting experiments (1 paper submitted).
- A project-wide paper for "Big Data Assimilation" with the first results of NHM-LETKF experiments was accepted for publication (1 paper accepted).
- Model output statistics have been investigated using machine learning algorithms and deep learning algorithms.
- Convective predictability was investigated by performing breeding experiments. Dependency on the model resolution was investigated.
- A precipitation nowcasting system was developed to take advantage of the dense and frequent PAWR data (1 paper published).
- A space-time extrapolation system for GSMaP with DA was developed using LETKF. The system has been running in real time since January 2016 (1 paper accepted in June 2016).
- A new Himawari-8 observation operator for SCALE-LETKF was developed and tested with a tropical cyclone case.
- Himawari-8 may capture clouds at an earlier stage of convective development before a radar captures large raindrops. This potential advantage was explored.
- The potential usage of Himawari-8 observation for estimating microphysics parameters through DA was explored.
- A 4-dimensional NHM-LETKF system was developed to investigate a fail-safe workflow and the relationship between the DA window length and forecast accuracy.
- A series of DA experiments for a sudden local severe rainstorm case in Kobe on September 11, 2014 was performed to investigate the predictability.

Computational optimization

- Huge-jobs, computing the "Big Data Assimilation" problem with the SCALE-LETKF, as big as near full nodes of the K computer were performed to measure the computational time and scalability of the code.

Wider applications

- A particle filter was applied to a dynamical vegetation model known as the SEIB-DGVM (Spatially-Explicit, Individual-Based Dynamic Global Vegetation Model). Uncertainties in the state variables and the parameters were greatly reduced by assimilating satellite based Leaf Area Index.
- Land surface DA system was developed with SiBUC (Simple Biosphere including Urban Canopy) model and LETKF.
- A global crop calendar was estimated with the satellite-sensed vegetation index (1 paper published).
- Impacts of satellite-based solar radiation data on land surface simulations were estimated (1 paper published).

Several achievements are selected and highlighted in the next section.

15.3 Research Results and Achievements

15.3.1 Big Ensemble Data Assimilation in Numerical Weather Prediction

Taking advantage of the K computer, we have successfully run the largest-ever ensemble DA experiments with 10,240 samples for the global atmosphere with the real-case Nonhydrostatic ICosahedral Atmospheric Model (NICAM) (Miyoshi et al. 2015) using the NICAM-LETKF (Local Ensemble Transform Kalman Filter) system developed in FY2014 (Terasaki et al. 2015). This research result was highlighted by RIKEN Press Release on November 11, 2015. The samples size of 10,240 is two orders of magnitude larger than the typical choice of about 100. The computational cost for the ensemble DA is proportional to the cubic power of the sample size, and active collaborations with AICS Large-scale Parallel Numerical Computing Technology Research Team (PI: Dr. T. Imamura) played an essential role in accelerating the computation by a factor of 8 using an eigenvalue solver "EigenExa" optimized for the K computer. The large sample size reduces the sampling error (Fig.

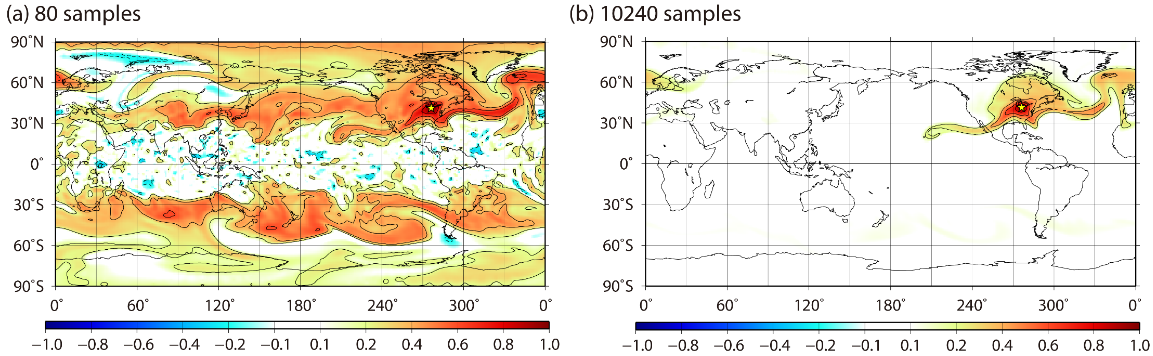

Figure 15.1: Horizontal maps of real atmosphere autocorrelations with (a) 80 samples and (b) 10240 samples. Adopted from Fig. 5 of Miyoshi et al. (2015), ©IEEE 2015.

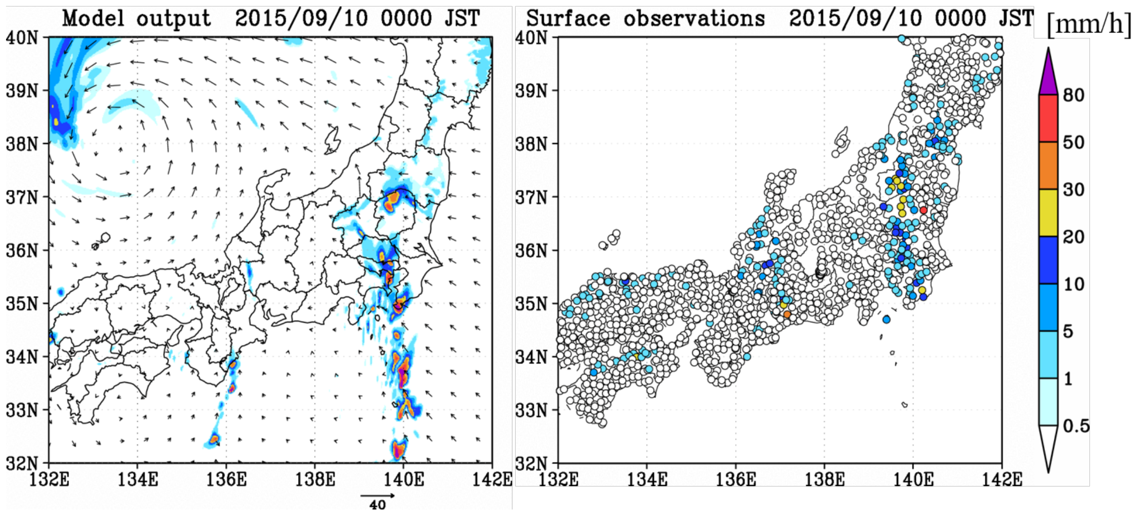

Figure 15.2: 1-hour accumulated rainfall amount at 0000 JST, September 10, 2015, when River Kinugawa had flooded and caused severe disasters, from a model simulation initiated at 1200 JST, September 8 (left) and surface rain-gauge observation (right) from NTT Docomo environmental sensor network.

15.1), and we discovered potential long-range correlations up to about 7,000 km (Fig. 15.1 b). This suggests potential use of faraway observations to improve numerical weather prediction (NWP), although we usually assume that the impact of observations is limited within a range up to 4,000 km or so. The large ensemble DA experiments would provide fundamental datasets to improve our knowledge on the flow-dependent error statistics including non-Gaussian and multi-scale structures, and would help develop advanced approaches for non-Gaussian and multi-scale DA, the topics at the center of theoretical DA research.

15.3.2 Near-real-time Implementation of Regional Numerical Weather Prediction (NWP)

The LETKF-based DA system has been newly developed with the regional NWP model "SCALE" in collaboration with Computational Climate Science Research Team (PI: Dr. H. Tomita). Real-world observation data are available from the US National Centers for Environmental Prediction (NCEP) in near real time, by about 3-hour delay from the real time. We have implemented the near-real-time 5-day NWP using the SCALE-LETKF system, and have been running continuously from May 7, 2015. Figure 15.2 indicates an example of a forecast in a case of the worst disaster in 2015 by flooding of River Kinugawa, Tochigi, Japan. The line-type system is well simulated. By continuously running SCALE-LETKF analysis and forecasts, we accumulate experiences and verification samples, which will be very useful for further improvements of DA and NWP system developments.

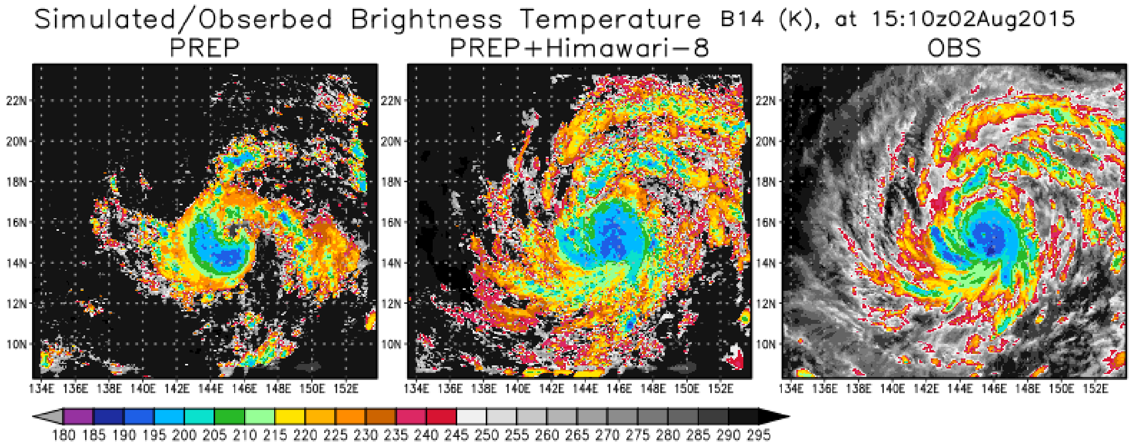

Figure 15.3: Geostationary satellite Himawari-8 band-14 brightness temperature (K) at 1510 UTC, August 2, 2015 (right) and simulated images with/without assimilating Himawari-8 data (center/left).

15.3.3 Effective Use of Satellite Big Data

Developing DA methods for effective use of various observation data is important. Satellite remote sensing provides a relatively uniform coverage of a broad area of the globe, and plays an essential role in NWP. However, the observed quantities are not direct to the prognostic variables of NWP models, and the data volume and variety keep increasing rapidly as sensor technology advances. Therefore, satellite DA requires algorithmic and methodological developments, and has become a major field in meteorology. We have been actively working on the research on effective assimilation of satellite-based precipitation data including the GPM (global precipitation measuring mission) core satellite data in collaboration with JAXA (Japan Aerospace Exploration Agency), microwave radiances from low-earth orbit satellites, and big data from the new-generation geostationary satellite Himawari-8 in collaboration with JMA (Japan Meteorological Agency) Meteorological Satellite Center and Meteorological Research Institute. Figure 15.3 shows an example of the impact of assimilating Himawari-8 infrared radiances in the case of Typhoon Soudelor 2015. The outer rainbands north of the vortex are greatly enhanced by assimilating Himawari-8 and becomes much closer to the observation.

15.3.4 New Application with Individual-based Dynamical Vegetation Model

As a new explorative application of DA, we have been working on land-surface and vegetation applications. We have successfully applied DA to the Spatially-Explicit Individual-Based Dynamic Global Vegetation Model (SEIB-DGVM) for the first time. The individual-based model simulates individual plants explicitly; some trees may die, while new trees may emerge. Therefore, the model prognostic variables such as tree height and root depth may change time to time and place to place. Typical DA methods assume the phase space to be predefined and never change. Alternatively, we applied a SIR (Sequential Importance Resampling) particle filter. The results were encouraging. Figure 15.4 shows the results with the real satellite-based MODIS (Moderate Resolution Imaging Spectroradiometer) LAI (Leaf Area Index) observations at a single location. It is not surprising that the uncertainties of the simulated LAI are reduced significantly (Fig. 15.4 a), but we also find that the uncertainties of unobserved model parameters and variables are reduced significantly (Fig. 15.4 b, c).

15.3.5 Theoretical and algorithmic developments

Theoretical DA research is an important part of DA Team's scope. Here, we highlight some of the major theoretical developments in FY2015. A paper on the discrete Bayesian optimization approach to find optimal ensemble sizes in a multi-model ensemble Kalman filter (EnKF) was published (Otsuka and Miyoshi 2015). Potential impact of assimilation order of observations in serial EnKF was investigated (Kotsuki et al., manuscript in preparation). A new local particle filter method

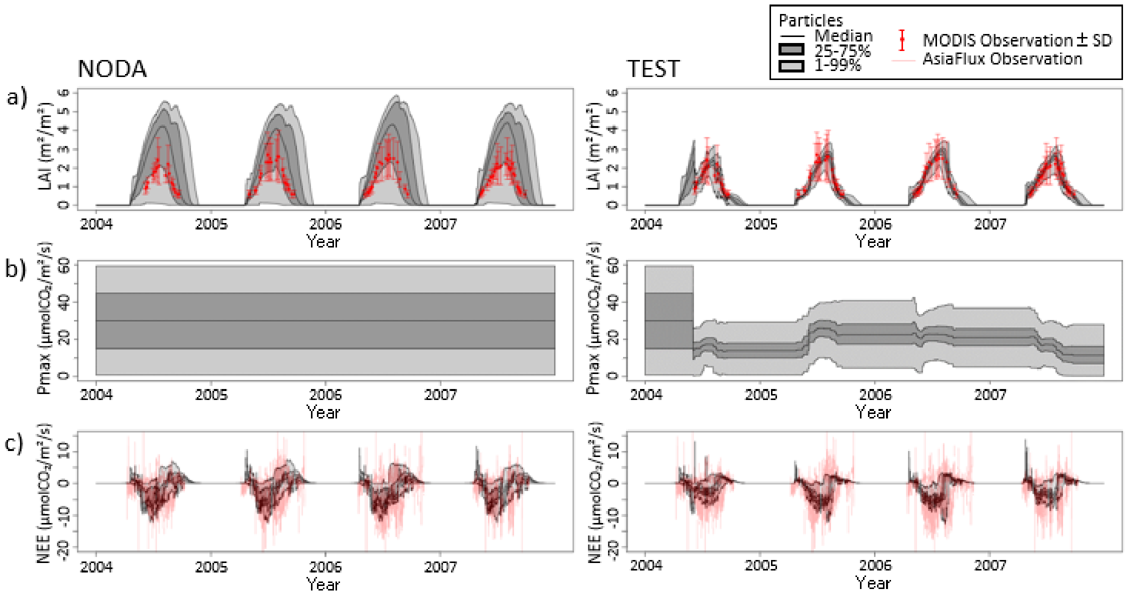

Figure 15.4: 4-year time series of (a) LAI, (b) a model parameter (maximum photosynthesis rate), and (c) a model variable (net ecosystem exchange) for the cases without DA (left) and with DA (right). Adopted from Arakida et al. (2016, *Nonlin. Processes Geophys. Discuss.*).

to treat non-Gaussian PDF was explored (Penny and Miyoshi 2016, *Nonlin. Processes Geophys. Discuss.*).

15.4 Schedule and Future Plan

In FY2015, DA team had one additional full-time research staff, and the team will grow further in FY2016. DA team has been exploring various aspects of DA including theoretical problems, meteorological applications, and wider applications, with large-scale computing to fully utilize "Big Data." We have very strong projects in weather forecast applications supported by the JST CREST program, JAXA, and MEXT FLAGSHIP 2020 project. We will continue our efforts in each topic in FY2016.

"Big Data Assimilation" (BDA) is one of the major activities that we have developed in FY2015. The prototype system showed promising results, but the computing speed with the K computer did not meet the requirement for real-time implementation. Also, the physical performance for the 30-minute forecast of precipitation patterns needs to be improved. In FY2016, we will continue to work on the development of the BDA system to further improve the computational and physical performances.

In FY2016, we also plan to enhance close collaborations with experts in mathematics, sensor technology, and various application fields. Enhancing collaborations with other AICS Research Teams will also be beneficial.

15.5 Publications

Journal Articles

[1] Lien, G.-Y., T. Miyoshi, and E. Kalnay: "Assimilation of TRMM Multisatellite Precipitation Analysis with a low-resolution NCEP Global Forecast System", Mon. Wea. Rev., Vol.144, p.643–661, 2016.

[2] Lien, G.-Y., E. Kalnay, T. Miyoshi, and G. J. Huffman: "Statistical properties of global precipitation in the NCEP GFS model and TMPA observations for data assimilation", Mon. Wea. Rev., Vol.144, p.663–379, 2016.

[3] Otsuka, S., G. Tuerhong, R. Kikuchi, Y. Kitano, Y. Taniguchi, J. J. Ruiz, S. Satoh, T. Ushio, and T. Miyoshi: "Precipitation nowcasting with three-dimensional space-time extrapolation of dense and frequent phased-array weather radar observations", Weather and Forecasting, Vol.31, p.329–340, 2016.

[4] Dillon, M. E., Y. G. Skabar, J. Ruiz, E. Kalnay, E. A. Collini, P. Echevarría, M. Saucedo, T. Miyoshi, and M. Kunii: "Application of the WRF-LETKF Data Assimilation System over Southern South America: Sensitivity to model physics", Weather and Forecasting, Vol.31, p.217–236, 2016.

[5] Hattori, M., J. Matsumoto, S. Ogino, T. Enomoto, and T. Miyoshi: "The Impact of Additional Radiosonde Observations on the Analysis of Disturbances in the South China Sea during VPREX2010", SOLA, Vol.12, p.75–79, 2016.

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[10] J. Ruiz and M. Pulido: "Parameter Estimation Using Ensemble Based Data Assimilation in the Presence of Model Error", Mon. Wea. Rev, Vol.143, p.1568–1582, 2015.

[11] Seko, H., M. Kunii, S. Yokota, T. Tsuyuki, and T. Miyoshi: "Ensemble experiments using a nested LETKF system to reproduce intense vortices associated with tornadoes of 6 May 2012 in Japan", Progress in Earth and Planetary Science, Vol.2:42, 2015.

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Conference Papers

None.

Invited Talks

[1] T. Miyoshi, "Data assimilation toward big data and post-peta-scale supercomputing: a personal perspective", International Workshop on Theoretical Aspects of Ensemble Data Assimilation for the Earth System, Les Houches, France, 5–10 April 2015.

[2] T. Miyoshi, "Numerical Weather Prediction: Chaos, Predictability, and Data Assimilation", ICTS Data Assimilation Program organized by CMI, Hong Kong Baptist University, 2015/4/20.

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[4] 三好建正, "スパコンを使った最先端の天気予報研究～「京」でゲリラ豪雨に挑む～", 第27回日本学術振興会産学協力研究委員会「水の先進理工学」第183委員会研究会, 東京, 4/22/2015.

[5] K. Terasaki, "Applying the Local Transform Ensemble Kalman Filter to the non-hydrostatic atmospheric model NICAM", AICS Café, Kobe, 15 May 2015.

[6] T. Miyoshi, "ポスト「京」による天気予報革命", HPCS2015 （ハイパフォーマンスコンピューティングと計算科学シンポジウム）, 東京, 5/19/2015.

[7] T. Miyoshi, "「ビッグデータ同化」でゲリラ豪雨に挑む", 第43回メソ気象研究会, 東京, 5/20/2015.

[8] T. Miyoshi, "ビッグデータ同化による天気予報革命", 日本気象学会春季大会, 公開気象講演会, つくば, 5/24/2015.

[9] T. Miyoshi, "'Big Data Assimilation' Revolutionizing Severe Weather Forecasting", JpGU Annual Meeting (Japan Geoscience Union), Makuhari, Japan, 5/26/2015.

[10] T. Miyoshi, "Satellite Data Assimilation: A Perspective", JpGU Annual Meeting (Japan Geoscience Union), Makuhari, Japan, 5/28/2015.

[11] Takemasa Miyoshi, "Covariance Localization and Inflation", 14th CAS-TWAS-WMO Forum Data Assimilation Summer School, Beijing, 2 July 2015.

[12] Takemasa Miyoshi, "Data Assimilation toward Big Data and Post-peta-scale Supercomputing: A Personal Perspective", 14th CAS-TWAS-WMO Forum Coupled Data Assimilation Symposium, Beijing, 7 July 2015.

[13] Shu-Chih Yang, "Adjusting ensemble for EnKF assimilation: applicatiopns to severe weather prediction", 14th CAS-TWAS-WMO Forum Coupled Data Assimilation Symposium, Beijing, 7 July 2015.

[14] T. Miyoshi, "'Big Data Assimilation' revolutionizing numerical weather prediction", 2nd Mini-Symposium on Computations, Brains and Machine, Wako, Japan, 14 July 2015.

[15] T. Miyoshi, "Satellite Data Assimilation: A perspective", the Weather-Chaos meeting, College Park, USA, 8/21/2015.

[16] T. Miyoshi, "Data Assimilation toward Big Data and Post-peta-scale Supercomputing: A Personal Perspective", OneNOAA Science Seminar Series, College Park, USA, 8/24/2015.

[17] Koji Terasaki, "Some aspects of the computation of the 3D normal-mode functions", MODES workshop, 26–28 August 2015.

[18] T. Miyoshi, "Numerical Weather Prediction: Chaos, Predictability and Data Assimilation", iTHES Colloquium, Wako, Japan, 15 September 2015.

[19] T. Miyoshi, "Big Data, Supercomputing, and Data Assimilation", Atmospheric and Oceanic Science Departmental Seminar Series, Maryland, USA, 7–9 October 2015.

[20] 三好建正, "「ビッグデータ同化」でゲリラ豪雨に挑む", サイエンティフィック・システム研究会　科学技術計算分科会　2015年度会合, 神戸, 2015/10/28.

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[23] T. Miyoshi, "Big Data Assimilation Revolutionizing Numerical Weather Prediction", Workshop Big Data and Environment, Buenos Aires, Argentina, 10–13 November 2015.

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[26] T. Miyoshi, "'Big Data Assimilation' Revolutionizing Weather Prediction", NTU, Taiwan, 26 November 2015.

[27] 三好建正, "天気予報、データ同化、気象防災におけるAI活用の展望", 理研シンポジウム「理研科学者が拓く"AI (革新知能)"」, 和光, 2015/11/28.

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[31] Takemasa Miyoshi, "Ensemble-based Data Assimilation of TRMM/GPM Precipitation Measurements", JAXA Joint PI meeting of Global Environment Observation Mission 2015 (PMM panel session), Tokyo, 20 January 2016.

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Posters and Presentations

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Patents and Deliverables

None.