FY2011 Annual Report of "Data Assimilation and Predictability Studies for Improving Tropical Cyclone Intensity Forecasts"

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LONG-TERM GOALS

This project aims to understand and improve the forecast of Tropical Cyclone (TC) lifecycle evolution and intensity, focusing on both large-scale environment and mesoscale phenomena in the TC system, which are major components responsible for intensity change. Two major challenges in TC intensity forecasting are the general lack of observations in the vicinity of TCs and the adaptive representation of the forecast error covariance. This project attempts to address both challenges for improving TC intensity forecasting.

OBJECTIVES

Intensive T-PARC (THORPEX[1] Pacific Asian Regional Campaign) observations and other available observations will be assimilated with the LETKF (Local Ensemble Transform Kalman Filter) into the CFES (Coupled ocean-atmosphere general circulation model For the Earth Simulator) and the WRF (Weather Research and Forecasting) mesoscale model to study 1) the characteristics and role of coupled ocean-atmosphere covariance, 2) the impact of each observation assessed by an efficient ensemble sensitivity analysis method, 3) a better way to assimilate observations in the vicinity of the TC center and potential usefulness of Lagrangian data assimilation (LaDA), 4) several new data assimilation techniques to improve the performance of LETKF, and 5) the predictability of TC intensity due to the uncertainty of initial conditions.

APPROACH

[1] THORPEX (The Observing System Research and Predictability Experiment) is an international research and development program of the World Meteorological Organization (WMO).

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This project has two major components with the CFES and WRF models. LETKF experiments with the CFES model is performed on the Earth Simulator (ES) supercomputer system. First, Co-I Enomoto (Earth Simulator Center) performs data assimilation experiments with the atmospheric part of CFES (AFES: Atmospheric general circulation model For the Earth Simulator). With the AFES-LETKF system, the impact of LaDA of T-PARC's driftsonde observations is investigated by PI Miyoshi and Co-PI Ide. Miyoshi, Enomoto, and Co-I Komori develop the LETKF system with CFES and perform data assimilation and ensemble prediction experiments. Miyoshi and Co-I Yang study the characteristics of coupled ocean-atmosphere covariance and its impact on TC forecasts.

Experiments with the WRF model are performed on the newly acquired cluster server through this project support. First, the WRF-LETKF system is developed by Miyoshi and Researcher Kunii at the University of Maryland (UMD). Data assimilation and ensemble prediction experiments are performed to study the impacts of the T-PARC observations on TC intensity forecasts and predictability. Higher resolution experiments are performed to simulate mesoscale phenomena in the TC system.

Ensemble sensitivity analysis of observations and new data assimilation techniques to improve the LETKF are common to both CFES and WRF components. Miyoshi and Co-PI Kalnay study sensitivity analyses of observations. Miyoshi and Co-I Li work on theoretical developments of adaptive estimation methods of covariance inflation and observation errors. Miyoshi and Co-PI Bishop study adaptive localization methods. Miyoshi and Yang apply the running-in-place method to find its impact on TC intensity forecasts.

Our work plan for the upcoming year includes a few final system developments and further scientific explorations. We will complete the development of the CFES-LETKF system and two-way-nested heterogeneous WRF-LETKF system for higher-resolution experiments.

WORK COMPLETED

In the component of global data assimilation, in FY2010, AFES-LETKF data assimilation experiments were performed with the Earth Simulator with real observations in 2008. In FY2011, the CFES ensemble system was developed, and the CFES-LETKF coupled system is near completion.

In the component of mesoscale data assimilation, in FY2010, the WRF-LETKF system was developed and assessed with T-PARC observations in the case of Typhoon Sinlaku (2008) (1 paper published). In addition, we have made three fundamental achievements: 1) a new adaptive inflation method has been developed for improving the LETKF (1 paper published), 2) the impact of observation error correlations on data assimilation was examined (1 paper submitted), and 3) importance of the initial conditions in TC forecasts using the Japanese operational global system has been published (1 paper published). In FY2011, the ensemble sensitivity system to compute the impact of observations on forecasts has been developed and applied to the case of Sinlaku with particular focus on T-PARC dropsonde observations (1 paper accepted). In addition, we have made three major achievements: 1) satellite temperature and humidity profile data from the AIRS (Atmospheric Infrared Sounder) retrieval products have been assimilated and have shown significant positive impact on the track and intensity forecasts of Sinlaku (1 paper submitted), 2) the impact of ensemble perturbations of sea-surface temperature (SST) fields on Sinlaku’s analysis was investigated (1 paper submitted), 3) the running-in-place method to handle the issue of the EnKF spin-up was implemented and tested in an observing systems simulation experiment (OSSE), showing significant improvements of typhoon assimilation in a stage of rapid intensification (1 paper submitted).

RESULTS

The most significant achievement in FY2011 was the new development and application of the ensemble sensitivity system with the WRF-LETKF, which revealed the importance of T-PARC dropsonde data in the case of Typhoon Sinlaku (2008). The ensemble sensitivity method of Liu and Kalnay (2008) estimates the impact of observations on forecasts without observing systems experiments (OSEs), similarly to the adjoint sensitivity method of Langland and Baker (2004) but without using an adjoint model. Here, the ensemble sensitivity method was for the first time applied and assessed with real observations. The ensemble sensitivity method was implemented with the WRF-LETKF system with an additional introduction of a targeted area where the impact was evaluated. The results in the case of Sinlaku showed that upper-air soundings had the largest positive impact on the 12-h forecasts and that the targeted impact evaluation performed as expected and was computationally efficient. Figure 1 (a) shows mean-sea-level pressure (MSLP) analysis (coutours, hPa) and the estimated impacts (blue-red shades, J kg^{-1} with the kinetic energy norm) of the dropsonde data from the Taiwanese DOTSTAR reconnaissance flight assimilated at 0000 UTC September 11. Negative values shown in blue correspond to forecast-error reduction, i.e., improvement of forecast due to assimilating the observation. The 13th dropsonde data were unavailable and shown by black. Figure 1 (b) shows Sinlaku's best track (BEST, black) and 36-h forecast tracks with assimilating all dropsonde data (CTRL, red) and without assimilating negative-impact dropsonde data (#6, 7, 8, 12, and 15) (DENY, blue). Denying negative-impact observations improved the forecasts, validating the estimated observation impact. Further investigations with more TC cases showed that the dropsonde data near the TC center (within a 200-km radius) had generally negative impact, which could be improved by using a higher-resolution model. The development of two-way-nested heterogeneous WRF-LETKF system, which enables higher-resolution experiments efficiently, is underway.

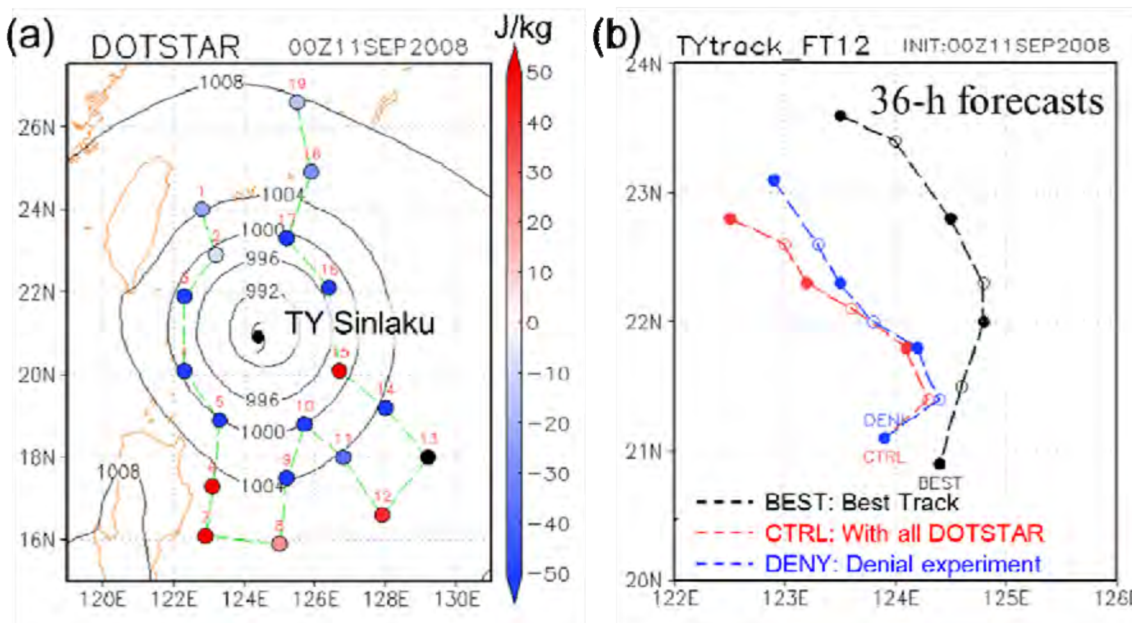

Fig. 1

Another notable achievement was obtained by assimilating satellite temperature and humidity profile data from the AIRS (Atmopsheric Infrared Sounders) retrieval products. Figure 2 (a) indicates observed track of Sinlaku (BEST, black) and 72-h forecast tracks of WRF-LETKF experiments only with assimilating conventional observations (CTRL, blue) and with additional AIRS retrieval data (AIRS, red). AIRS has significant positive impact on the track forecast in this case. Moreover, on average of 28 different initial times of the Sinlaku case, the track forecast was significantly improved due to AIRS data, particularly for longer-lead forecasts (Fig. 2 b). If we look at the intensity forecasts, Fig. 2 (c) shows TC central pressure forecasts, each line indicating 72-h forecasts from various initial times. The intensity forecasts were significantly improved by assimilating AIRS data (i.e., red curves better fit to the best track). This is a promising result for improving TC intensity forecasts through data assimilation, although the deep structure of observed Sinlaku was not simulated well with the current 60-km WRF setting. Higher-resolution experiments are highly desired and will be performed once the two-way-nested heterogeneous WRF-LETKF system is developed.

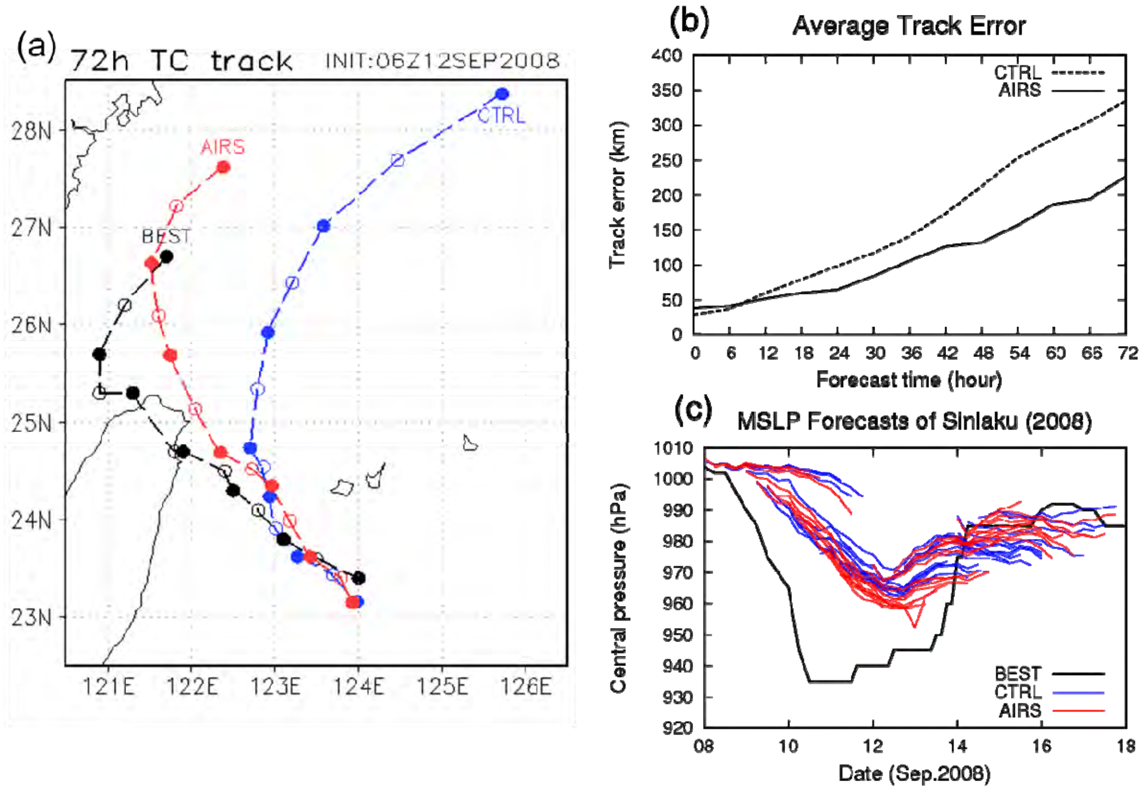

Fig. 2

We also investigated the role of the air-sea interaction in atmospheric data assimilation by considering SST ensemble perturbations in the WRF-LETKF. Figure 3 shows the 6-h forecast MSLP fields (contours, hPa) and 6-h accumulated precipitation (shades, mm) on 0000 UTC September 11, 2008 from the (a) NCEP final analysis and (b) WRF-LETKF without SST ensemble perturbations and (c) with SST perturbations. The SST perturbations show significant impact on capturing Sinlaku's stronger stucture, which is more realistic and closer to the best track. Further investigations on the forecast error structures revealed a significant difference in the horizontal error correlations represented by the ensemble. Figure 4 shows the horizontal background error correlations estimated from forecast ensemble perturabtions (a) without and (b) with SST perturbations, for temperature at the 5^{th} model level (~ 925 hPa). The correlations between each grid point and the grid point shown by the cross mark (x) are shown. Since SST has larger-scale patterns and is correlated well with low-level atmospheric temperature, Fig. 4 (b) shows larger-scale horizontal correlations. The ensemble correlations are used for the LETKF analysis, thus the near-sufrace temperature observations are assimilated with much different spatial scales. This may be a reason why we found the improved analysis due to SST perturbations. This would motivate further investigations on the role of air-sea coupling on atmospheric and oceanic data assimilation cycles with a fully-coupled system.

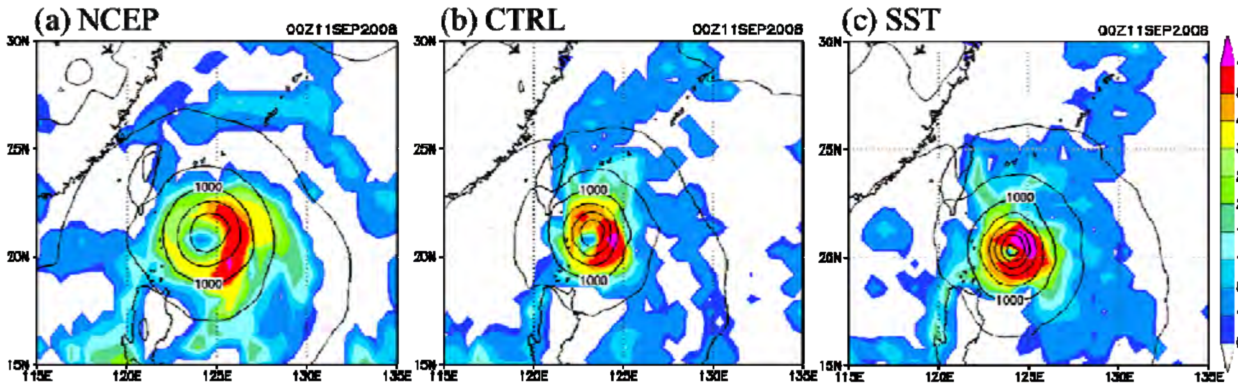

Fig. 3

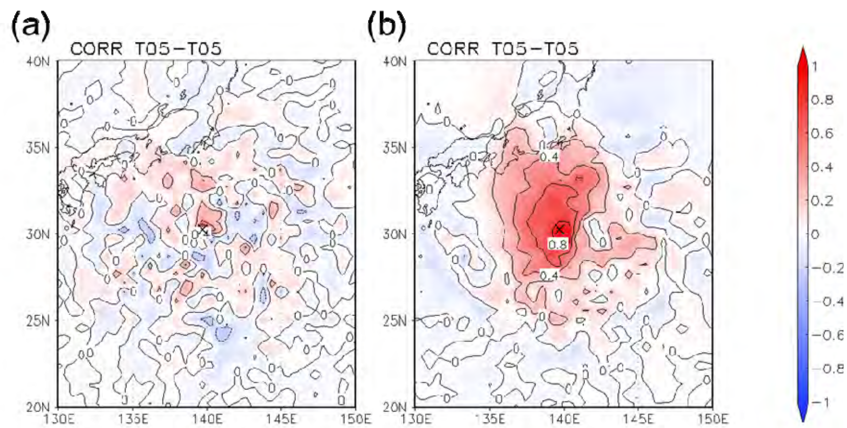

Fig. 4

We also investigated the effect of the "running in place" (RIP) method (Kalnay and Yang 2010) on accelerating the spin-up in a typhoon simulation with the WRF-LETKF system. To initialize the mesoscale ensemble Kalman filter (EnKF), it is common to use initial conditions interpolated from the global analysis products and initial ensemble perturbations constructed based on the 3D-Var background covariance (Torn et al. 2006). Such initial conditions inevitably lack mesoscale information, and the perturbations would not have mesoscale flow dependence. Therefore, mesoscale EnKF usually has a 2-3-day spin-up period before it reaches its asymptotic level of accuracy (Liu, H. 2008, personal communication). In addition, for the case of TC data assimilation, such spin-up usually corresponds to the generating and developing stages of TCs, when observations are so important but limited in the open sea. Thus, the impact of observations would be underestimated and should be used more effectively with an EnKF assimilation system during the spin-up. To improve the analysis quality during the spin-up, the RIP method was implemented with the WRF-LETKF system. Results from observing systems simulation experiments (OSSEs) showed that the RIP method was able to accelerate the adjustment of the dynamical structures of the typhoon during the spin-up and improve both the forecast track and intensity. Figure 5 shows the evolution of west-east vertical cross section of the velocity (arrows) and wind speed (shades, m s^{-1}) for the nature run (TRUTH), and LETKF analyses with and without RIP, denoted by LETKF-RIP and LETKF, respectively. LETKF-RIP better captures the rapid intensification of the TC, at least with a 12-h lead time. Therefore, with RIP, observations are more effectively used and have more influence on TC assimilation and prediction.

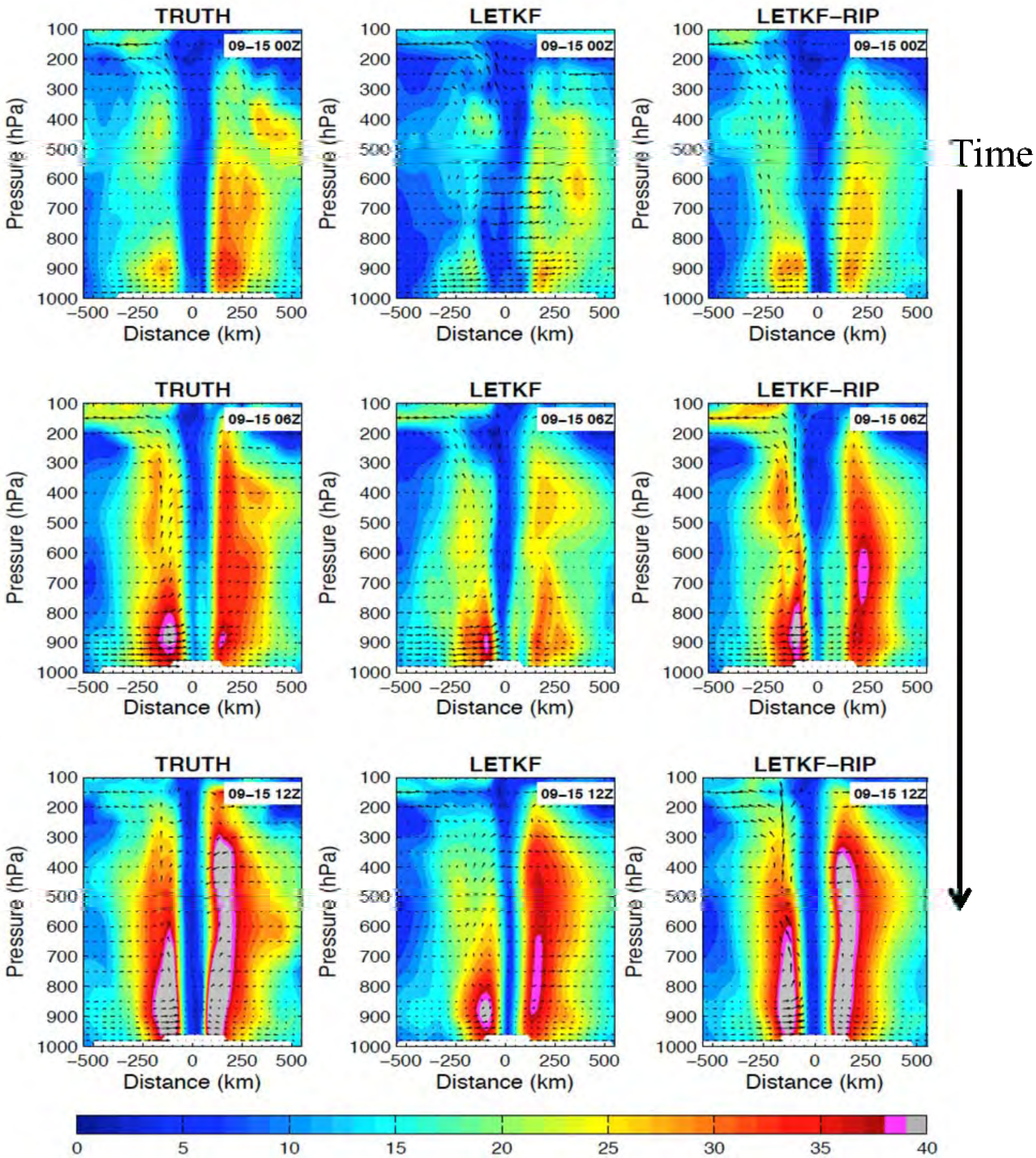

Fig. 5

IMPACT/APPLICATIONS

National Security, Economic Development, and Quality of Life

The goal of this project is to improve the LETKF and the prediction of TCs, with particular focus on the TC lifecycle evolution and intensity. Better prediction of TCs with quantitative measure of its uncertainty has the significant impact on National Security, Economic Development, and Quality of Life, since military operations, economic activities, and people's life are affected by extreme weather.

Science Education and Communication

Data assimilation provides a bridge between the nature and computer simulations, and the LETKF is a general and practical approach to data assimilation. This project aims to improve the LETKF, which may have potential impact on Science Education, particularly on emerging and rapidly expanding applied mathematics and scientific computing fields.

TRANSITIONS

National Security, Economic Development, and Quality of Life

The Japan Meteorological Agency (JMA) and INPE/CPTEC (Brazilian Institute for Space Research and Brazilian Weather Service) are developing the LETKF for possible future operations, and the findings from this project have been directly transferred to their preoperational systems. This is an important path of transitioning the achievements of this project to the operational NWP, which in turn benefits to National Security, Economic Development, and Quality of Life. We would like to seek similar paths to the US institutions.

Science Education and Communication

The LETKF system is widely available through the internet (http://code.google.com/p/miyoshi/), which has been used in Science Education for students and researchers at UMD and many other places worldwide, including the JMA, Tohoku University (Japan), University of Buenos Aires (Argentina), and INPE/CPTEC (Brazil). In addition, the fundamental improvements as a result of this project have been applied in many studies at the UMD and other places worldwide.

RELATED PROJECTS

There are several related and mutually beneficial projects.

1. The Tropical Cyclone Structure-2008 (TCS-08) program is sponsored primarily by the Office of Naval Research (ONR) with funding also from the National Science Foundation for shared aircraft resources. The objectives of TCS-08 address mechanisms and predictability of tropical cyclone formation, intensification, and structure change. The observation data are a key part of T-PARC and are assimilated in our NOPP project.
2. The Impacts of Typhoons on the Ocean in the Pacific (ITOP) program is also sponsored by ONR and is a multi-national field campaign that aims to study the ocean response to typhoons in the western Pacific Ocean. Our NOPP project is closely related and has mutual benefit. The new techniques pioneered with T-PARC/TCS-08 observations can be independently tested with the ITOP/TCS-10 observations.
3. The Japan Meteorological Agency (JMA) and INPE/CPTEC are developing the LETKF for possible future operations, and our achievements to improve the LETKF are beneficial to their development, and their results help us to know how our achievements apply to the real-world operational NWP.
4. Steve Penny (UMD graduate student) is completing his doctoral dissertation based on the LETKF coupled with the MOM2 global ocean model to perform advanced ocean data assimilation. His current results indicate a very large improvement when compared with SODA (Simple Ocean

Data Assimilation), a reanalysis based on a standard state-of-the-art 3D-Var data assimilation system. The adaptive inflation scheme improved his MOM2-LETKF results significantly.

5. Steve Greybush (UMD graduate student) is completing his doctoral dissertation this Spring has also benefited from the adaptive inflation in his LETKF application to Mars atmosphere, with very encouraging results.
6. Ji-Sun Kang (UMD postdoctoral researcher) has benefited from adaptive inflation in the estimation of the surface fluxes of carbon from atmospheric CO_2 data assimilation. Her experiments led to the concept of "variable localization" that in turn improves the LETKF.
7. Luciano Pezzi (INPE/CPTEC, Brazil) uses the LETKF for regional ocean data assimilation and had very encouraging results with adaptive inflation.
8. Prof. Shu-Chih Yang (Taiwan Central University) is testing her new "quasi outer loop" approach for TC data assimilation with encouraging results. She is a Co-I of our NOPP project, and this is clearly mutually beneficial.
9. Prof. Hong Li (Shanghai Typhoon Institute, China) has applied the ensemble sensitivity analysis method using the LETKF to a low-resolution global atmospheric model for assessing the impact of different types of simulated observations in ideal experiments. She is a Co-I of our NOPP project, and this is clearly mutually beneficial.
10. Juan Ruiz (University of Buenos Aires, Argentina) uses the LETKF system for model's parameter estimation. His experience with imperfect model experiments had direct benefit to our study on adaptive inflation in designing ideal experiments.

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HONORS/AWARDS/PRIZES

PI Miyoshi was selected in a very competitive search for Assistant Professor in Data Assimilation at the Atmospheric and Oceanic Science Department, University of Maryland. This position was created with support from NOAA/NWS/NCEP.