Assimilation and Forecast Studies on Localized Heavy Rainfall Events Using a Cloud-Resolving 4-Dimensional Variational Data Assimilation System

（雲解像 4 次元変分法データ同化システムを用いた局地豪雨に関するデータ同化および予報に関する研究）

Abstract

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Chapter 1 General Introduction

In this chapter, a brief history of data assimilation is introduced. In order to realize the progress of data assimilation, a historical forecast of a super-typhoon in 1959 is reviewed, and compared with a forecast of the same typhoon with a state-of-the-art numerical weather prediction (NWP) system. Then, the challenges, even for the state-of-the-art NWP system, to forecast localized mesoscale convective systems are described, and the demand for high-resolution assimilation with high-density observation network is discussed. Finally, the scope of this thesis is illustrated, and the prospect and structure are described.

Chapter 2 Nonhydrostatic Cloud-Resolving 4-dimensional Variational Data Assimilation System

In this chapter, detailed descriptions of the NHM-4DVAR system are given. A theoretical topic on the variational method is reviewed in Section 2.1. In Sections 2.2, formulations, control valuables of NHM-4DVAR v1 are described. NHM-4DVAR v1 considers perturbations to dynamical core and the advection of water vapor. Its horizontal resolution is 2 km, which is cloud resolving. Extension to cloud microphysics with warm rain is described in Section 2.3. Single-observation experiments described in Sections 2.3.4 and 2.4.5 are the first experiments which examined the efficiencies of rain water assimilation. Through these experiments, it is clarified that assimilating rainwater in a convection-free area is inefficient because the assimilation alone cannot maintain convection for long periods due to nonlinearity. In Section 2.4.5, the development of GPS slant total delays (STDs) at a cloud-resolving horizontal resolution is first described. Through single-observation experiments, it is clarified that the magnitude of the increment of GPS STD assimilation is large because all of the slant paths are within a narrow area of the lower troposphere above the observation site.

Chapter 3 Assimilation Experiment using NHM-4DVAR v1 with Radial Wind and GPS Precipitable Water Vapor Data - Nerima Heavy Rainfall Event on 21 July 1999 -

A case study on the Nerima heavy rain fall event occurred in the north of Tokyo on 21 July 1999 using the cloud-resolving 4D-Var system (NHM-4DVAR v1; see Section 2.2) is shown. This study is the world-first experiment assimilating multiple observations of surface, Doppler radial wind, GPS precipitable water vapor data (see Section 2.4.1-2.4.3) at a cloud-resolving horizontal resolution. Initiation and development mechanisms of an isolated thunderstorm are discussed. Analysis of observational data and forecasting results clarified that a surface convergence line of horizontal winds was caused by sea breeze and north-easterly winds. Consequently, the wind convergence was enhanced around Nerima. An air mass of high equivalent potential temperature was lifted over this enhanced convergence line to generate cumulonimbi that caused the Nerima heavy rainfall. The result first shows that it is possible for MCSs even in a meso β-γ scale to be predicted with accurate intensity, occurrence time and location, when preferable conditions are assimilated before convection initiation.

Chapter 4 Assimilation Experiment using NHM-4DVAR v2 with Radar Reflectivity Data - Suginami Heavy Rainfall Event on 4-5 September 2005 -

This chapter discusses a case study on the Suginami heavy rainfall event occurred in the Tokyo metropolitan area on 4-5 September 2005 using NHM-4DVAR v2 (see Section 2.3) with the observation operator of radar reflectivity (see Section 2.4.4), Doppler radial wind and GPS precipitable water vapor. The improvement of quantitative precipitation forecast is described, and a sustainment mechanism of MCSs is discussed. The 4D-Var assimilation reproduces a line-shaped rainband with a shape and intensity consistent with the observation. Assimilation of radar-reflectivity data intensifies the rainband and suppresses false convection. The simulated rainband lasts for 1 h in the extended forecast and then decays gradually. The low-level convergence sustained by northerly winds in the western part of the rainband is a key to prolong the predictability of the convective system. The result illustrates that assimilating rain water alone is not sufficient for improving forecast skill of long-lasting MCSs due to nonlinearity. This means that observing and assimilating environmental information outside MCSs are more important to extend predictability of MCSs.

Chapter 5 Assimilation Experiment using NHM-4DVAR v2 with GPS Slant Total Delay Data - Naha Heavy Rainfall Event on 19 August 2009 -

This chapter shows a case study on Naha heavy rainfall event occurred around Okinawa Island on 19 August 2009 with the assimilation method of GPS slant total delay data (See Section 2.4.4) as the first application to a cloud-resolving scale. Moreover, an initiation mechanism of the line-shaped rainband appeared around Okinawa Island is discussed. First, a high-resolution numerical experiment using JMA-NHM with 2-km horizontal grid spacing (NODA) is conducted. Then data assimilation experiments with GPS observations (i.e., GPS zenith total delay (GPS-ZTD), GPS precipitable water vapor (GPS-PWV), and GPS slant total delay (GPS-STD)) at the same resolution are performed. Generally, compared with NODA, the assimilations of GPS-ZTD and GPS-PWV are known to slightly improve the timing of the rainband initiation. On the other hand, the GPS-STD assimilation significantly improves the forecast skill of the water vapor and temperature fields over a wide area as well as the time of the occurrence for the rainfall event. This result shows that assimilating environmental information has capability to improve the predictability of MCSs.

Chapter 6 General Discussions

In this chapter, the scale of the environmental fields of initiation and sustainment of localized MCSs is discussed based on the results obtained in Chapters 3-5. Three case studies suggest that MCSs are initiated by a low-level convergence with a moist air over a horizontal scale of approximately 50 km. The predictability of meso β-γ MCSs is also found to depend on assimilating observations of wind, humidity, and temperature observations on a 50×50 km area around the MCS at low levels. On the other hand, due to nonlinearity, the assimilating rain water produces limited improvement. Thus, assimilating environmental information is important to improve the predictability of MCSs. Based on this discussion and the advanced data assimilation system (Chapter 2), the preferred observation systems (e.g., Doppler lidar, rapid scan by geostationary satellites) and assimilation systems for localized MCS forecasts (e.g., weak constraint 4D-Var, particle filter) are discussed.

Chapter 7 General Conclusions

Based on the three case studies, this thesis showed that (i) MCSs producing heavy rainfall events the warm season in Japan initiate when low-level wind with a moist air converges over a horizontal scale of approximately 30–50 km;,(ii) the MCS could be predicted with some skill when wind, temperature, and humidity data at low levels are well assimilated; (iii) it is difficult to sustain strong convection in a model for long periods, because assimilating observations inside the MCS (i.e., radar reflectivity) does not reduce the analysis error over a sufficiently wide area due to the nonlinearity involved in the cloud microphysics. Obtaining observations outside MCSs (i.e., Doppler Wind Lidars and rapid-scanning observations derived from geostationary satellites) is important to solve this problem. Due to nonlinearity, assimilating environmental observations rather than inside information within the MCSs is the key to improve the predictability of the MCS. A data assimilation system addressing nonlinearity and multi-scale treatments has to be developed to tackle these issues.