Predictability Variation in Numerical Weather Prediction: a Multi-Model Multi-Analysis Approach

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The purpose of this project is to explore predictability variation associated with high-impact weather events such as mid-latitude and tropical cyclones and blocking anticyclones. Multiple models and multiple analyses are used to disentangle the source of error. As a first example and test case, track forecasts of Tropical Cyclone Lupit from 12 UTC 21 October 2009 were conducted using the Atmospheric General Circulation Model for the Earth Simulator (AFES). The predicted tracks show sensitivity to initial conditions, consistent with experiments using other models. It is speculated that the difference in asymmetric convective activity near the cyclone centre is responsible for the difference in tracks. An ensemble forecast shows that Lupit migrates westward in the majority of members, but in some members Lupit travels northward in consistent with the best track, showing that the initial value ensemble is effective in this case.

Keywords: Atmospheric General Circulation Model, Data Assimilation, Forecast Skill, High-Impact Weather, Typhoon

1. Introduction

As a result of remarkable improvement of data assimilation techniques and numerical weather prediction models, five-day forecasts today have accuracy comparable to two-day forecasts in a quarter of a century ago [1]. Predictability is, however, varying daily and may be similar or different among forecasts from different operational centres. This project addresses daily variation of predictability in weather forecasts. Before our approach is introduced, the possible source of error is reviewed.

1.1 Numerical Weather Prediction

Weather forecasts are produced from output of numerical weather prediction (NWP). Global NWP is conducted by integrating an atmospheric general circulation model (AGCM) forward in time from initial conditions. The source of error lies in the model and in the initial state.

AGCM is the discretized form of the governing equations of the atmosphere. AGCM can explicitly represent a limited portion of the atmospheric processes that span a wide range of spatio-temporal scales. The processes smaller than the grid interval are represented by grid-scale values under some assumptions. This is called parametrization. The difference of the model from Nature is referred to as *model uncertainty*. Differences in discretization, numerics and parametrization result in a diversity of models.

The initial state is produced from the forecast (first guess) and observations using a data assimilation scheme. There are a number of data assimilation schemes. In addition, assimilated observations are different among systems due to the different sources and screening procedure (called *quality control*).

Table 1 compares the models, data assimilation systems and generation methods of initial perturbations for ensemble forecast. The Japan Meteorological Agency (JMA) uses the four-dimensional data assimilation (4DVar) and the singular vector method to generate initial perturbations in ensemble

Table 1 Models, data assimilation methods and perturbation generation methods used at different institutions. See List of Acronyms for abbreviated terms.

Institution	Model	Data Assimilation	Perturbation
JMA	GSM	4DVar	SV
NCEP	GFS	3DVar+EnKF	BV
UKMO	UM	4DVar	EnKF
ECMWF	IFS	EnsDA	SV
JAMSTEC	AFES	EnKF	EnKF

forecast. The National Centers for Environmental Prediction (NCEP) employs a hybrid data assimilation system, in which the forecast covariance obtained from the ensemble Kalman filter (EnKF) is used in three-dimensional data assimilation (3DVar). The breeding vector method is used generate perturbations at NCEP [2]. The European Centre for Medium-range Weather Forecasts (ECMWF) conducts multiple 4DVar (EnsDA). The United Kingdom Met Office uses 4DVar in analysis, but EnKF to generate initial perturbations. At JAMSTEC, the local ensemble transform Kalman filter (LETKF) [3,4], an efficient EnKF algorithm on a parallel computer, is applied to the AGCM for the Earth Simulator (AFES) [5,6].

The subtle difference in the initial state grows due to some instability in the atmosphere. Because of the diversity of models, the growing modes are somewhat different among the forecast systems, even if the models are integrated from the exactly the same initial condition.

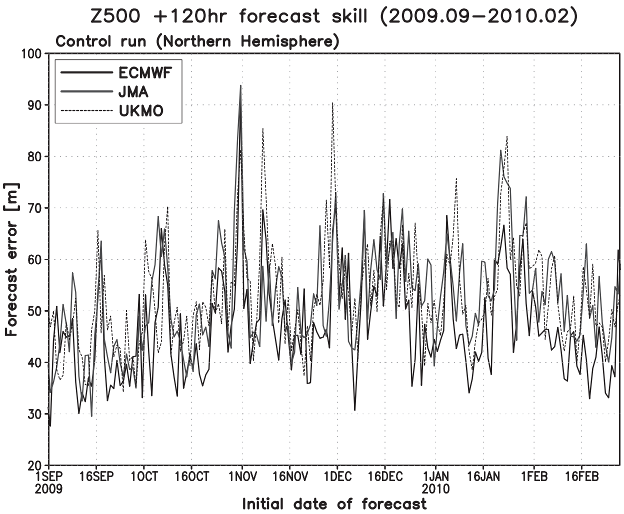

Fig. 1 Skills of 120-hr forecasts during 1 September 2009 and 28 February 2010 from ECMWF (black solid), JMA (grey solid) and UKMO (dotted) in terms of the root-mean square error of the 500-hPa geopotential height from the analysis of respective centres.

1.2 Daily Variation of Forecast Skills

Figure 1 shows the daily variation of the root mean square error of the 500-hPa geopotential height of 120-hr forecasts from ECMWF, JMA and UKMO. The error varies around 50 m synchronously in general, but sometimes quite differently. In fact, the centres with largest and smallest error change day to day. One day the error of the forecast of one of centres suddenly increases to larger than 90 m. Such a jump can often be associated with the failure of the forecast of a high-impact weather event.

1.3 Multi-model multi-analysis approach

The aim of this project is to obtain some insight into the variation of forecast error. Multiple models and analyses are used to identify the source of error. Initial states from different centres are used in a model to examine the initial value sensitivity. Multiple models are integrated from the same initial condition to measure the performance of the models. Through such multi-model multi-analysis experiments, it is expected that the mechanisms for predictability variation would become clear.

2. Typhoon Track Forecast Experiments

As a test of the multi-analysis experiments, a track forecast of Typhoon Lupit 2009 was conducted. Figure 2a shows the track of Lupit from 12 UTC on 21 October in the JMA best track data (black), ECMWF analysis (green) and ALERA2 (blue). Lupit migrates westward then turns northeastward. This recurvature was not predicted with GSM from the JMA analysis at 12 UTC on 21 October, but with GSM from the ECMWF analysis [7]. AFES is used here to examine the model sensitivity.

2.1 Model and Initial Conditions

The version of AFES used is identical to the one used to produce ALERA2 [8,9] that includes the improved statistical cloud scheme [10].

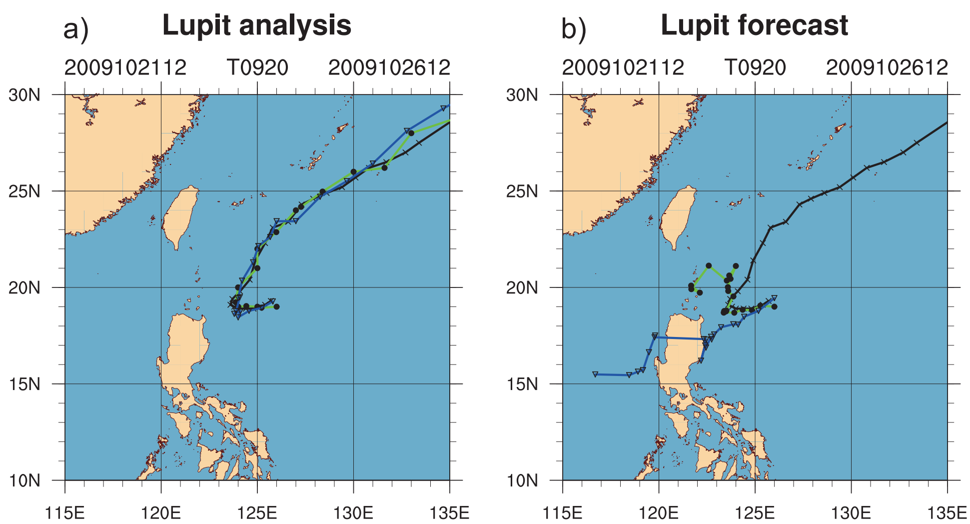

Fig. 2 Tracks of Lupit in (a) ECMWF analysis (green) and ALERA2 (blue) and in (b) forecasts from ECMWF analysis (green) and from ALERA2 using AFES T239L48. The black curve denotes the JMA best track. Tick marks are plotted every 6 h.

Deterministic and ensemble forecast experiments were conducted. The deterministic experiments were conducted to examine the sensitivity to combination of models and initial conditions. The ensemble experiments were conducted to examine the sensitivity to perturbed initial conditions.

The resolution for the deterministic experiments is T239L48 (truncation wave number of 239 using the triangular truncation, which corresponds to 0.5° horizontal resolution and 48 vertical levels). The initial conditions for the deterministic experiments were interpolated from the ensemble mean of ALERA2 and the ECMWF operational analysis obtained from the Year of Tropical Convection (YOTC) archive.

AFES-LETKF ensemble prediction system version 2 (ALEPS2) is prepared to conduct ensemble experiments. ALEPS2 is similar to ALEDAS2 but with extended forecast and without data assimilation. The horizontal resolution is the same as that of ALERA2 (T119) and no interpolation is required. In the ensemble experiments, 63 analyses of ALERA2 were used as initial conditions.

2.2 Deterministic Forecasts

Lupit migrates westward with AFES from the analysis ensemble mean of ALERA2 (Fig. 2b). This track is similar to that with GSM from JMA analysis. With the ECMWF analysis, the recurvature is reproduced although Lupit weakens near 20°N and does not migrate northward further. Similar results are obtained with GFS (*T. Miyachi, pers. comm.*). These results indicate that Lupit is sensitive to initial conditions but models.

2.3 Convective Activity

Both steering winds and beta gyre are weak before the recurvature. In order to obtain insight into the features of initial conditions, the sea-level pressure (SLP) and the out-going long-wave radiation (OLR) are plotted (Fig. 3). OLR is regarded as a proxy of convective activity here. At forecast time 6 h (FT6), Lupit in the experiment from the ECMWF analysis is more intense, symmetric and concentrated at the centre. Lupit in the experiment from ALERA2 has stronger convective activity to the south of the centre. As a result, the typhoon is slightly elongated southward to create a stronger westward flow that advects the cyclone. In addition, the sea-level pressure is expected to drop in the south of the centre. This is consistent with the southwestward migration in the experiment from ALERA2.

At FT60, when the recurvature occurs, there is a striking difference in convective patterns. Lupit in the experiment from ECMWF analysis has a strong spiral band from the north to the east. Due to this diabatic effect, the cyclone is expected to migrate northeastward. In contrast Lupit in the experiment from ALERA2 has weaker convective activity in its north and the

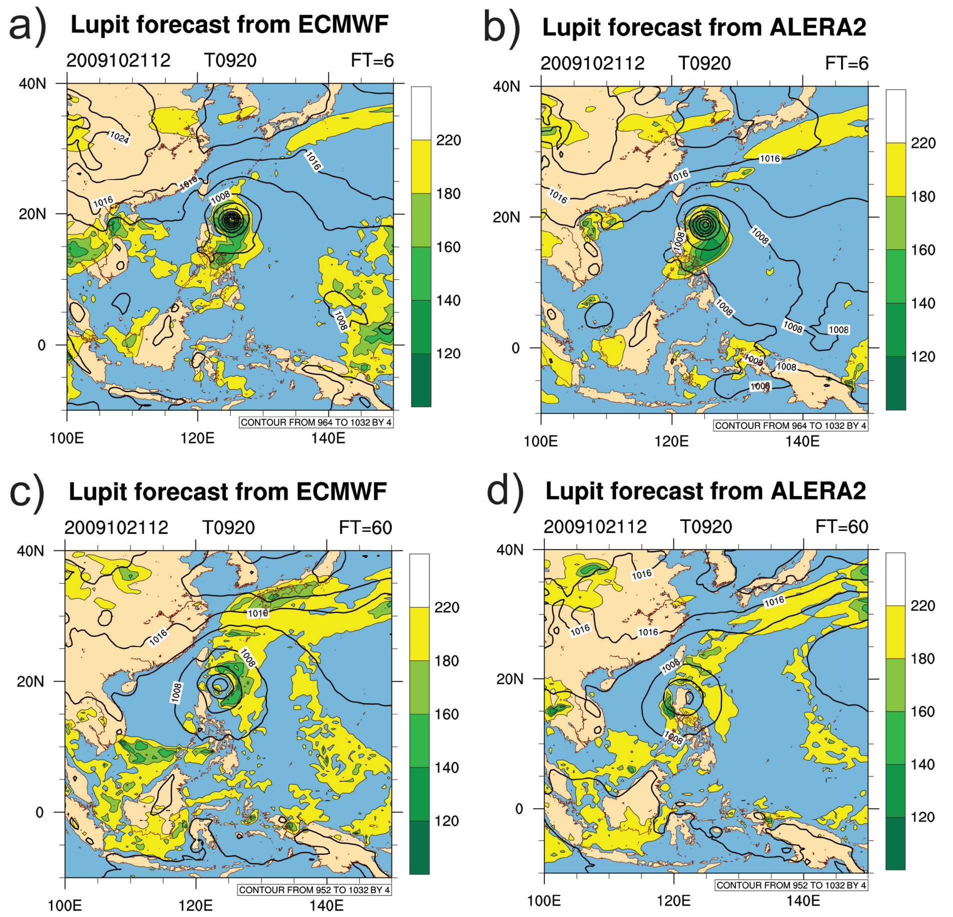

Fig. 3 Distribution of the sea-level pressure (hPa, contours) and out-going long-wave radiation (Wm^{-2}, colour shades) in the deterministic experiments from ECMWF analysis (a, c) and from ALERA2 (b, d) at forecast time 6 h (a, b) and 60 h (c, d).

east. Instead convection is active to the southwest of the centre.

Further detailed examinations, such as vorticity budget analysis, are required to understand the sensitivity of the track to the initial conditions.

2.4 Experimental Ensemble Forecasts

The forecast from the ensemble mean (Fig. 4, red) exhibits the track similar to that in the deterministic experiment from ALERA2 in spite of the difference in the horizontal resolution. Although Lupit migrates westward in the most of the ensemble members, the recurvature is reproduced in 4 members. This result confirms the sensitivity to initial conditions in this case.

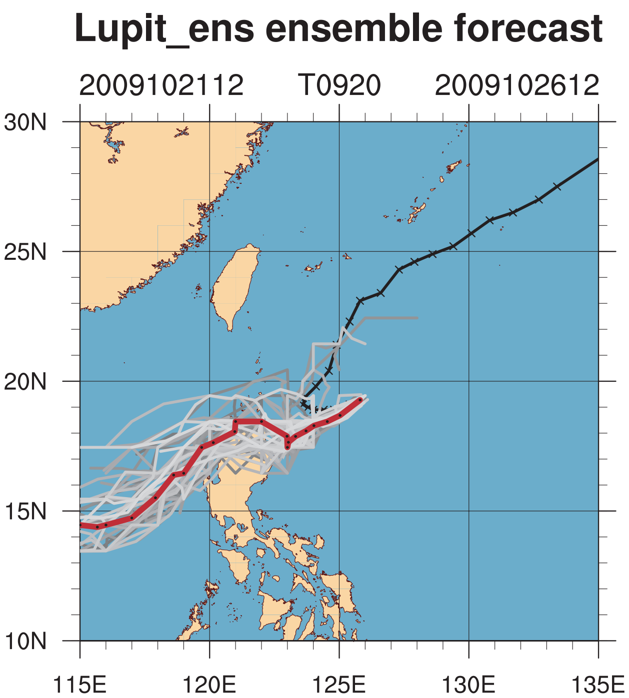

Fig. 4 Tracks of Lupit in the ensemble experiment from ALERA2 using AFES T239L48. Gray curves represent forecasts from 63 perturbed initial conditions. The red curve represents the forecast from the ensemble mean.

3. Concluding Remarks

In this project, the multi-model multi-analysis approach is employed to explore the variation of atmospheric predictability. In order to conduct multi-model multi-analysis experiments on the Earth Simulator, an experimental test bed multi-analysis experiments and an ensemble prediction system, ALEPS2 has been developed during FY2013. Using these tools, deterministic and ensemble forecast experiments were conducted. Typhoon Lupit in October 2009 was chosen as a test case. The results are consistent with those in the literature [7]. It is argued that the relative sensitivity to models and to initial conditions can only be confirmed by the use of multiple models. In addition some implications are obtained by examining the sea-level pressure and out-going long-wave radiation fields. More comprehensive experiments are planned in FY2013.

4. List of Acronyms

3DVar
Three-Dimensional Variational method

4DVar
Four-Dimensional Variational method

AFES
AGCM for the Earth Simulator

AGCM
Atmospheric General Circulation Model

ALEDAS2
AFES–LETKF ensemble data assimilation system 2

ALEPS2
AFES–LETKF ensemble prediction system version 2

ALERA, ALERA2
AFES–LETKF experimental ensemble reanalysis (version 2)

BV
Breeding Vector

ECMWF
European Centre for Medium-range Weather Forecasts

EnKF
Ensemble Kalman Filter

EnsDA
Ensemble Data Assimilation

FT
Forecast Time

GFS
Global Forecast System

GSM
Global Spectral Model

IFS
Integrated Forecast System

JAMSTEC
Japan Agency for Marine-Earth Science and Technology

JMA
The Japan Meteorological Agency

LETKF
Local Ensemble Transform Kalman Filter

NCEP
National Centers for Environmental Prediction, USA

OLR
Out-going Long-wave radiation

SLP
Sea-Level Pressure

SV
Singular Vector

UKMO
United Kingdom Met Office

UM
Unified Model

YOTC
Year of Tropical Convection

Acknowledgement

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数値天気予報における予測可能性変動メカニズムの解明

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本プロジェクトは、中高緯度及び熱帯低気圧やブロッキング高気圧のような顕著現象に伴う予測可能性変動について調査する。複数のモデルと複数の解析を用いて、誤差の要因を解明する。最初の例として、地球シミュレータ用大気大循環モデル AFES を用いて、台風 2009 年第 20 号の進路予測を 10 月 21 日 12 世界協定時から行った。予測された進路は、他のモデルで行った場合と同様に初期値に敏感である。海面気圧と外向き赤外放射の分布から、非対称的な対流活動が進路に影響を与えていたことが示唆される。アンサンブル予測実験では、ほとんどのメンバーにおいて台風は西進するが、一部のメンバーにおいては台風は北進する。この結果は、この事例では初期値アンサンブルが有効であることを示している。

キーワード : 大気大循環モデル , データ同化 , 予報精度 , 顕著現象 , 台風