Annual Journal of Hydraulic Engineering, JSCE, Vol.51, 2007, February

PREDICTION SKILL ASSESSMENT OF NWP MODELS IN SIMULATING DIURNAL CYCLE OF PRECIPITATION

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The present paper assesses skill of six current Numerical Weather Prediction (NWP) models in simulating the diurnal cycle of precipitation by utilizing the dataset of Enhanced Observing Period (EOP3 from Oct 1, 2002 to Sep 30, 2003) of the Coordinated Enhanced Observation Period (CEOP). Diurnal change of precipitation intensity and frequency of 16 CEOP sites are calculated from observed and modeled data for each site, and then normalized by mean intensity and frequency, respectively. The averaged diurnal cycle of precipitation shows an afternoon peak, a night time peak, and a low intensity in the early evening (18 LST). An analysis using satellite data indicates that the early-evening low intensity is due to rapid cease of convective precipitation in the early evening followed by the start of stratiform precipitation. All the models produce an afternoon peak of precipitation, but the start timing of the afternoon peak is predicted too early in the models. Moreover, no model produces the night time peak and the early-evening low intensity.

Key Words : *CEOP, Diurnal Cycle, NWP Models , Convective Precipitation, CST Method*

1. INTRODUCTION

Precipitation forecast information is an important factor for people to schedule their ordinary activities, but the nature of the precipitation in itself is very complex which makes the forecast of precipitation from Numerical Weather Prediction (NWP) models still a challenging. Among various modes of variation in precipitation (diurnal, synoptic, intra-seasonal, seasonal, annual and inter-annual), the diurnal variation is important as it provides an ideal test bed for evaluation and improvements of different model parameterizations[1), 2)]. Therefore, the diurnal cycle has been extensively analyzed using different data sources. However, most of the analyses have been confined for particular locations[2)], because high temporal-resolution data are often not available. Early studies primarily used surface observations [3), 4)] while recent studies used various form of satellite or radar derived precipitation [5), 6), 7), 8)]. Most of these studies have shown that the precipitation maximum tends to occur in the early morning over open oceans and in the late afternoon/early evening over lands. But this idealized view of the diurnal cycle of precipitation over land is modified by dynamics, by local orography, and by the initiation, propagation, and decay of mesoscale convective systems [5), 8), 9), 10)].

A number of studies have examined the variation modes of precipitation produced in the regional and global General Circulation Models (GCM) as well as in NWP models[1), 2), 8), 10), 11), 12)]. Previous studies have shown that annual cycle is well represented in many respects in the current generation of GCMs, but the diurnal cycle probably requires critical improvements in GCM and NWP models as well as in regional climate models. To make these models more relevant for regional applications, the diurnal cycle needs to be well represented in the models. Among many of the early studies, the datasets for model evaluation are either limited to particular regions and seasons or in many cases limited in temporal and spatial resolution. In addition, these model evaluations are limited to use of single model of availability and interest. Through intercomparison between models in different regions, systematic and common deficiencies can be diagnosed with high-quality intensive observations. The Coordinated Enhanced Observation Period (CEOP) with its different Enhanced Observing Periods (EOPs) has provided this opportunity. This study is a first step toward the prediction skill assessment of multi-models at multi-sites with high temporal and spatial resolution dataset to increase the understanding on the characteristics and mechanism of diurnal cycle of precipitation and its predictability.

2. DATASET DESCRIPTION

CEOP, an element of the World Climate Research Program (WCRP) initiated by the Global Energy and Water Cycle Experiment (GEWEX) [13], has provided an opportunity to evaluate the models in different regions and seasons. It is coordinating and archiving the multi-level (sub-surface, surface and atmospheric) multi-source dataset (In situ, Models, and Satellite) from more than 35 reference sites (www.ceop.net) of GEWEX Continental Scale Experiments (CSEs) in Asia, Australia, Africa, North and South America, and Europe ranging in latitude from 71^0N to 35^0S. These CSEs are, according to their regions, CAMP (CEOP Asia Australian Monsoon Project, 14 sites), GAPP (GEWEX Americas Prediction Project, 4 sites), LBA (Large Scale Biosphere-Atmosphere Experiment in Amazonia, 8 sites), BALTEX (Baltic Sea Experiment, 3 sites) and ARM Tropical Western Pacific [Darwin (DAR) and Manus (MNS)] and ARM North Slope of Alaska (NSA) in OTHER regions.

In this study, in situ and high temporal Model Output Location Time Series (MOLTS) precipitation data for the summer season of EOP3 period (Oct 1, 2002 to Sep 30, 2003) from 16 sites (Table 1) are used to assess the prediction skill of six NWP models. The summer months (Seasons in Table 1) are defined depending on the latitude of the reference sites i.e., for near equatorial sites: March, April, May (MAM); for northern hemisphere mid-latitude sites: June, July, August (JJA); and for southern hemisphere sites: December, January, February (DJF), considering the fact that summer precipitation contributes much larger in amount to the total precipitation. The six NWP models are BMRC (Bureau of Meteorology Research Centre, Australia) Operational Global Medium Range Prediction Model, ECPC (Experimental Climate Prediction Center, The Scripps Institution of Oceanography) Seasonal Forecasting Model (SFM) and Reanalysis model (RII), JMA (Japan Meteorological Agency) Global Spectral Model (GSM), NCEP (National Centers for Environmental Prediction, USA) Global Forecast System (GFS), UKMO (Met Office, UK) Global Unified Model. Hereafter, each model is represented with the name of the corresponding NWP center. The models have a spatial resolution ranging over 50 km ~ 90 km except that ECPC SFM and RII have a resolution of 280 km. Major characteristic of the models has been briefly summarized in Yang et al.[14]. BMRC provided 12~36 hourly data of 36-hr forecasts (once a day). JMA provided hourly data of 6-hr forecasts (4 times a day). ECPC SFM and RII provided 3-hourly data of 6-hr forecasts (4 times a day) and 36-h forecasts (once a day from 12UTC). NCEP provided 3-hourly data of 84-h forecasts (once a day). UKMO provided 3-hourly data of 36-h forecasts (once a day). BMRC and UKMO also provided hourly and 3-hourly analysis products, respectively. BMRC and JMA provided hourly MOLTS products whereas other models provided 3-hourly products.

The hourly infrared (IR) brightness temperature (T_b) for cloud data from Geostationary Meteorological Satellite (GMS-5) and Geostationary Operational Environmental Satellites (GOES-9) for 9 sites (Table 1, grayed sites) has also been used to understand the mechanism of the diurnal cycle of precipitation. The satellite data, with a spatial resolution of 5 km × 5 km, cover an area of 250 km × 250 km centered at MOLTS point.

3. IN SITU AND MODEL COMPARISON

The evaluation of model parameterization schemes against high quality observations on a diurnal scale is a key component in the development of NWP models. The methodology adopted for evaluation and inter-comparison of models is divided into three steps as: (i) making of diurnal cycle of precipitation at individual sites from in situ and MOLTS data, (ii) normalizing it by the corresponding average value, and (iii) making the composite by averaging of the diurnal cycle of precipitation over 16 sites. All the data are linearly interpolated at hourly interval if the temporal interval of MOLTS data is 3-hr.

(1) Observed Diurnal Cycle at Individual Sites

In situ observations of precipitation provide most widely accepted values, but the derivation of a spatial average from in situ data is difficult due to spatial and temporal variability of precipitation, particularly in regions of complex terrain or characterized by convective precipitation. The spatial variation can be smoothed by temporal averaging of sufficient long periods. We use three months period for making diurnal variation of precipitation and compare our results at individual sites with early studies.

Table 1 Comparison of precipitation amount in summer seasons between model forecast ("F"), analysis ("A") and observations. All the models over-estimate precipitation for **bold** sites and under-estimate precipitation for *italic* sites.

Characteristics of Reference sites					OBS. (mm)	FIRST 24 hr F & A Data					15-36 hr F & A Data				
CSE	Site code	Seasons	Lat	Lon		ECPC	UKMO		JMA	NCEP	BMRC		UKMO	NCEP	ECPC
						SFM6	F	A	F	F	F	A	F	F	SFM36
CAMP	TIB	JJA	32	91.9	363	303	350	403	407	99	131	198	480	219	433
	HIM	**JJA**	**28**	**86.8**	**352**	**1368**	**648**	**569**	**1334**	**1950**	**1157**	**769**	**434**	**2572**	**1387**
	NSC	JJA	25	121.2	449	215	539	755	381	368	166	211	493	409	228
	MON	JJA	46.3	107.3	140	8	90	85	184	50	42	42	84	66	10
	IMO	JJA	44.4	122.9	235	127	410	366	406	192	84	87	309	240	201
	WPO	MAM	7.1	134.3	770	930	981	977	998	1487	571	522	723	1362	1094
	EIS	MAM	-0.2	100.3	877	648	371	402	1121	1007	395	421	498	1117	879
CAMP Region Avg. Prec.(mm) =					455	514	484	508	690	736	364	321	432	855	605
ARM	*DAR*	*DJF*	*-12.4*	*130.9*	*1565*	*796*	*815*	*831*	*1210*	*926*	*537*	*522*	*691*	*981*	*1494*
	MNS	*MAM*	*-2.1*	*147.4*	*1268*	*928*	*838*	*893*	*952*	*903*	*536*	*586*	*1045*	*902*	*938*
	NSA	*JJA*	*71.3*	*-156.6*	*102*	*54*	*86*	*80*	*52*	*92*	*32*	*23*	*93*	*96*	*88*
ARM Region Avg. Prec.(mm) =					978	593	580	601	738	640	368	377	610	660	840
GAPP	BON	JJA	40	-88.3	244	27	375	360	464	553	95	57	319	596	102
	SGP	JJA	36.6	-97.5	175	87	419	400	400	385	90	89	443	434	329
GAPP Region Avg. Prec.(mm) =					210	57	397	380	432	469	93	73	381	515	216
BALTEX	CAB	JJA	52	4.9	63	29	116	150	159	164	31	26	139	227	85
	LIN	JJA	52.2	14.1	126	7	146	159	158	191	31	9	177	263	56
BALTEX Region Avg. Prec.(mm) =					95	18	131	155	159	178	31	18	158	245	71
LBA	SAN	MAM	-3	-55	636	698	467	437	710	885	507	440	520	865	883
	MAN	MAM	-2.6	-60.2	786	1040	655	777	606	1268	311	397	572	1282	1217
LBA Region Avg. Prec.(mm) =					711	869	561	607	658	1077	409	419	546	1074	1050
Avg Prec (mm) for 16 sites =					**509**	**454**	**457**	**478**	**596**	**658**	**295**	**275**	**439**	**727**	**589**

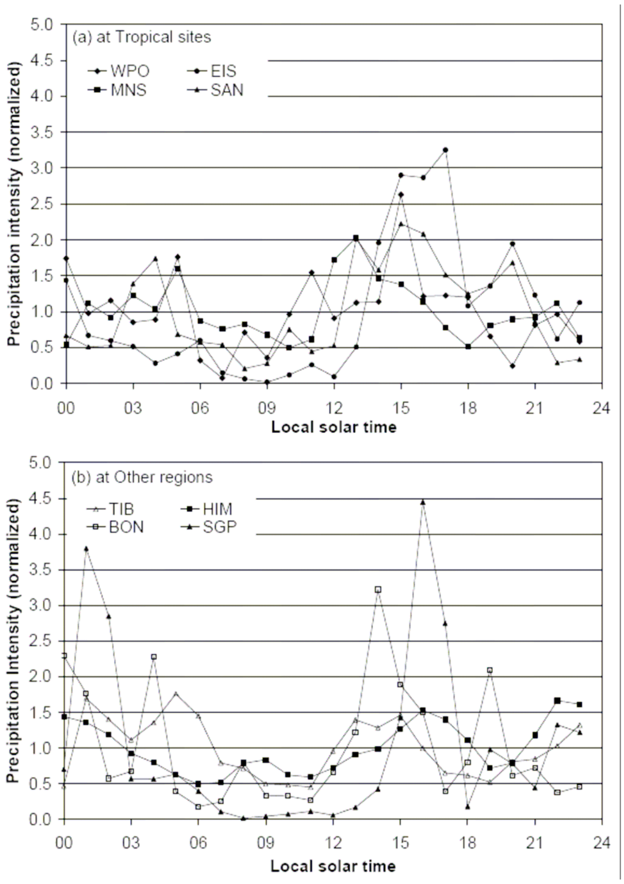

Figure 1 Normalized diurnal cycle of precipitation derived from in situ data. (a) at Tropical sites and (b) at Other sites. Three months (summer season) data are used.

It is found that the diurnal cycle of precipitation from in situ data of EOP3 summer season is well comparable to results in early studies that were derived from dense observations or satellite data, as summarized in Yang et al.[14].

Fig. 1 shows that the diurnal cycle of precipitation intensity at several tropical sites and at several higher-latitude sites. It is clear that each site has an afternoon peak and a night-time peak of precipitation. At the tropical sites, the afternoon peak is much stronger than the nighttime one. However, at higher latitudes, the afternoon peak is comparable to the nighttime peak and the timing of the nighttime peak varies from site to site.

(2) Overall Performance of Models

Table 1 shows the total precipitation amount in the summer seasons at individual sites for EOP3. All the models show systematical and significant over-estimates of precipitation for some sites like CAB (except BMRC) or under-estimates in some other sites (DAR, MNS and NSA). This might be related to some common deficiencies in precipitation schemes. However, the over-estimation of precipitation for the HIM site may be more related to the representation of topography in the models[15] as the southern slope of the Himalayas is too steep to be represented in a numerical model. In CAMP region, UKMO model estimates the precipitation amount better than the other models. BMRC underestimates it whereas JMA, NCEP and ECPC overestimates it. In the ARM sites, all the models underestimate precipitation except BMRC, whereas all the models over-estimates it in GAPP and BALTEX sites. In LBA region, NCEP overestimates precipitation while the other models underestimates it. The precipitation amount averaged over the 16 sites seems to be fairly well estimated by UKMO, under-estimated by BMRC and overestimated by JMA, NCEP and ECPC.

As NWP centers contributing to CEOP suggested the above results may be biased due to the use of dataset of the spin up period, we present the results of sensitivity analyses in Table 1. The table shows the amount of accumulated precipitation of 15~36-hr forecast after allowing 0~12-hr spin up in the forecast of UKMO, NCEP and ECPC models (The other models do not provide such longer forecasts at present). It shows that precipitation in ECPC model is sensitive to the spin-up period while not so in UKMO model. The models generally do not produce better results in the case of excluding the spin-up period than in the case of including this period, though there are improvements for some maritime sites (e.g. EIS, WPO, and MNS).

(3) Intercomparison of Diurnal Cycle of Precipitation

In comparison with the observation at individual sites, all the models produce too early start of afternoon precipitation both over lands and over islands, and too large amplitude over lands but too small amplitude over islands (not shown). Throughout the convectively active Tropics, the models systematically forecast the timing of the peak too early during the daytime. Over land sites, the modeled peak occurs predominantly near local noon, too soon after solar radiation reaches its maximum.

Fig. 2 shows the observed multi-site averaged diurnal cycle of precipitation intensity and frequency. It is clear that there is an afternoon peak around 14~16 LST, a nighttime peak, and in particular, an early-evening (18 LST) low intensity. All the models produce the afternoon peak, but no model produces the early-evening low intensity and the nighttime peak. The start time of the afternoon peak in JMA, NCEP, and ECPC_RII6 are relatively close to the observed one, but UKMO predicts 1-2 hours earlier than the observed one and BMRC and ECPC_SFM6/36 predict 4-5 hours earlier (Fig. 2a). Similar results can also be seen in the precipitation frequency (Fig. 2b). The amplitude of afternoon precipitation intensity is fairly well estimated by BMRC, ECPC_RII6 and UKMO whereas underestimated by JMA, NCEP and ECPC_SFM. There is no remarkable difference in the diurnal cycle of precipitation between forecast and analysis output for both UKMO and BMRC. This implies that the diurnal change of precipitation is mainly determined by model's nature rather than initial conditions.

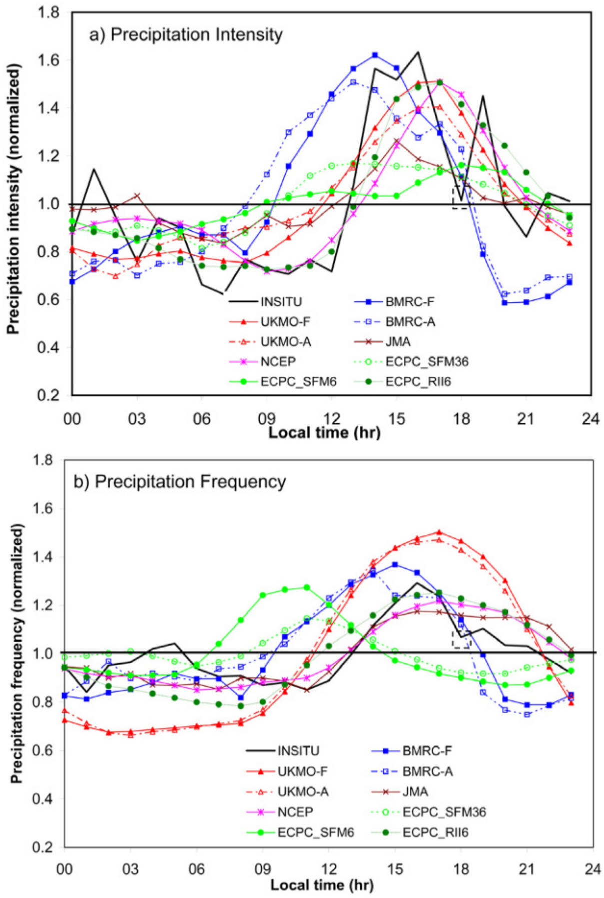

Figure 2 Multi-site averaged diurnal cycle of precipitation derived from in situ data and GCM output at 16 sites (Table 1) during their summer seasons. (a) Normalized precipitation intensity and (b) Normalized precipitation frequency. A and F denotes analysis and forecast data respectively. An early-evening (at 18 LT) minimum is marked by a dash box.

4. MECHANISM OF EARLY EVENING LOW INTENSITY

A local minimum of precipitation intensity and frequency at 18 LST from in situ data (Fig.2) is seen in the multi-site averaged product which is also common at most (13 out of 16, not shown) of the sites. Such a local minimum between two precipitation peaks in the evening have been found in very limited studies[2), 6)], but most of early studies have not found such characteristics because of using either lower temporal resolution dataset or harmonic analysis method. Moreover, no study has explained this mechanism. We speculate that this early evening minimum in precipitation is related to the life time of convective activities in the early evening. To understand it, the observed precipitation has to be separated in convective and stratiform component. As these components are not directly measured, we adopt Convective and Stratiform Technique (CST) [16]. This method has been extensively used to understand the convective activities of clouds using GMS IR (T_b) data. Another reason of using CST is that GMS has high temporal resolution (hourly) data, which is required for diurnal cycle studies. After identifying clouds as convective type, observed precipitation, if existing at that hour, is classified as convective precipitation. After separation of convective and stratiform precipitation, similar methodology explained in section 3 is then adopted to make the diurnal cycle of total, convective, and stratiform precipitation, respectively.

The CST is a technique to distinguish between convective components and stratiform components of meso-scale convective cloud systems using the slope of brightness temperature at the lowest temperature pixel. A simple flowchart of CST is shown in Fig. 3. To identify the locations of convective cores in each satellite image, the GMS-IR T_b field is scanned for identifying the relative minimum (T_{min}). The core is then located at a single pixel with the minimum temperature or at the centroid of the multi pixel minima in a square of 50 km × 50 km box centered over the reference site. After identifying the location of the core, the strength of the cloud is measured by the slope parameter (S). If the slope parameter is larger than a critical value, then the location being colder than its environment is identified to be a region of enhanced convection.

CEOP EOP3 has archived the GMS data at the nine grayed sites in Table 1.The diurnal cycle averaged over the nine sites for total, convective and stratiform precipitation is shown in Fig. 4. The intensities of total, convective and stratiform precipitation increase from 12 LST. The total and convective precipitation reach their peaks at 15 LST, but the stratiform precipitation has smaller variations. There is an increase in stratiform precipitation while a decrease in convetive precipitation since 18 LST. Therefore, the early-evening minimum in the total precipitation is caused by the rapid cease of convective precipitation and the start of stratiform precipitation in the early evening.

Table 2 shows the ratio of the convective and stratiform precipitation to the total precipitation. The ratio of the convective precipitation is about 36%, which is much lower than the prediction of the models. Therefore, the partition of stratiform and convective rainfall is not correctly represented in the models.

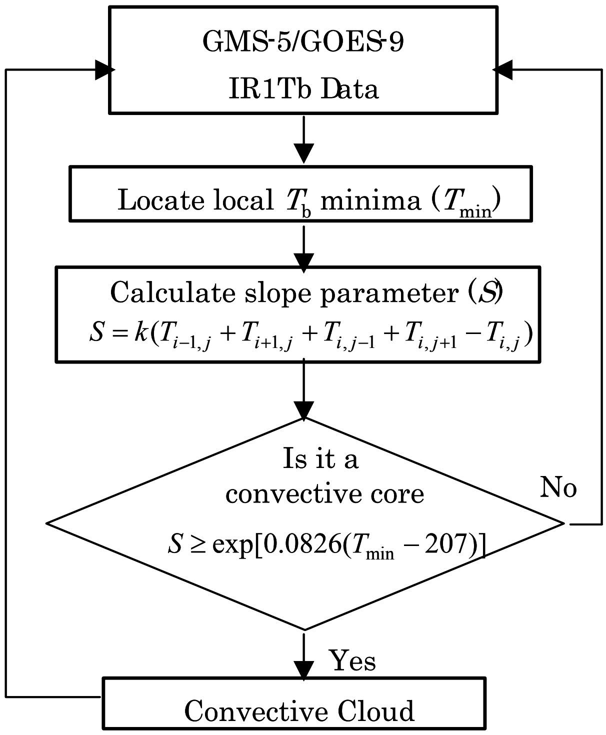

Figure 3 Flow chart of CST Method. S is the slope parameter, and ***i*** and ***j*** refer to the position of the pixel for which S is being calculated. Factor k depends on data resolution and the value of 0.25 is adopted for 5 km × 5km data resolution.

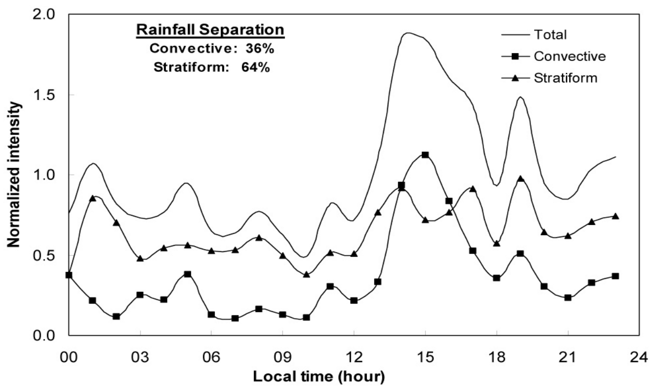

Figure 4 Multi-site averaged diurnal cycle of convective precipitation and stratiform precipitation derived by a convective and stratiform technique (CST) from in situ data at 9 sites (greyed sites in Table 1) during their summer seasons.

Table 2 Convective and stratiform precipitation partition

Methods/Models	Convective	Stratiform
CST Method	36	64
UKMO-F	84	16
NCEP	62	38
ECPC_SFM (0~6 hr)	80	20
ECPC_SFM (12~36 hr)	81	19
ECPC_RII (0~6 hr)	93	07

5. SUMMARY

The diurnal cycle of precipitation derived from in situ data of the EOP3 summer season is well comparable to that derived from dense observations or satellite data. In general, there is an afternoon peak and a nighttime peak of precipitation. Most of the sites also have a low intensity of precipitation around early evening (about 18 LST). This low intensity is due to the rapid cease of convective rainfall in the early evening followed by the start of stratiform rainfall at that time. All the models predict an afternoon peak but the forecast timing of the peak is quite different. BMRC & ECPC predict 4-5 hours earlier, UKMO predicts 1-2 hours earlier while JMA and NCEP predict well the start of daytime precipitation. Moreover, no model is able to predict the observed early-evening low intensity and the partition between stratiform and convective precipitation.

The model deficiencies might be associated with cumulus parameterization and boundary layer scheme in the models. In order to understand the mechanism of the diurnal cycle and improve relevant parameterization schemes, we need to continue model assessment using observational data over lands and oceans as well as remote sensing capabilities. It is more important to develop an inter-comparison platform by collaborating with NWP centers, for setting priority of target processes, providing results of sensitivity studies, and implementing comparisons.

ACKNOWLEDGMENT: This study is funded by the Japan Science and Technology Agency and the Special Coordination Funds for promoting Science and Technology. The authors are very grateful to representative of NWP Centers, PIs and researchers involved in CEOP in situ observations and data archiving centers, for their data collection, provision, archiving, discussions, and information of update status of models.

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(Received Sptember 30, 2006)