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ORIGINAL PAPER

Case studies of seasonal rainfall forecasts for Hong Kong and its vicinity using a regional climate model

David Tai-Wai Hui · Karen Kit-Ying Shum · Ji Chen · Shyh-Chin Chen · Jack Ritchie · John O. Roads

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Abstract Seasonal climate forecasts are one of the most promising tools for providing early warnings for natural hazards such as floods and droughts. Using two case studies, this paper documents the skill of a regional climate model in the seasonal forecasting of below normal rainfall in southern China during the rainy seasons of July–August–September 2003 and April–May–June 2004. The regional model is based on the Regional Spectral Model of the National Centers for Environmental Prediction of the United States. It is the first time that the model has been applied to a region dominated by the East Asian Monsoon.

The article shows that the regional climate model, when being forced by reasonably good forecasts from a global model, can generate useful seasonal rainfall forecasts for the region, where it is dominated by the East Asia monsoon. The spatial details of the dry conditions obtained from the regional climate model forecast are also found to be comparable with the observed distribution.

D. T.-W. Hui · K. K.-Y. Shum
Hong Kong Observatory, 134A Nathan Road,
Kowloon, Hong Kong, China

J. Chen (✉)
Department of Civil Engineering, The University of Hong Kong,
Pokfulam, Hong Kong, China
e-mail: jichen@hkucc.hku.hk

S.-C. Chen
US Department of Agriculture Forest Service,
Riverside, CA, USA

J. Ritchie · J. O. Roads
Experimental Climate Prediction Center, Scripps Institution of Oceanography,
University of California, San Diego,
La Jolla, CA 92093-0224, USA

D. T.-W. Hui
e-mail: dhui@hko.gov.hk

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1 Introduction

The rainy season over southern China spans the period from April to September. In the region, the most devastating and widespread natural hazards associated with the rainstorms and typhoons during the rainy season are frequent floods and landslides. However, the regional rainfall during this period is also a primary source of fresh water for the local people, and below normal rainfall usually leads to serious droughts, which also result in severe loss of lives and property (Chen and Chau 2000).

Seasonal forecasting is a promising tool for providing early warnings for the natural hazards, such as those posed by floods and droughts (Murphy et al. 2001). Some examples of natural disaster mitigation using this type of forecasts have been given by Nicholls (2001). Stern and Easterling (1999) also suggested that societies should take advantage of accurate forecasts to reduce loss and improve society's well-being. In addition, Palmer (2005) and Barnston et al. (2000) stressed that whether seasonal climate forecast with the modest level of skill can have significant utility strongly depends on the presentation of the forecast and the ways that the end-users respond to the forecast.

Numerical dynamical models are able to generate a consistent set of forecasts for different climate variables at the same time (Roads 2004). In addition, the application of these models makes it possible to diagnose and to understand the response of climate in a certain part of the world to the lower boundary forcings which are the source of climate predictability in various temporal ranges (e.g., ECMWF 1999; Goddard et al. 2001; WMO 2002a).

Due to the advantage of being able to add finer spatial details, the usefulness of regional models nested into global climate models for seasonal forecasts has been studied intensively (e.g., Hong and Leetmaa 1999; Cocke and Larow 2000; Fennessy and Shukla 2000; Kimura 2001; Roads 2004). A number of users have begun using regional models for studying climate predictability through dynamical downscaling of the corresponding ECPC GSM forecasts (Nobre et al. 2001; Roads 2004; Sun et al. 2006). Nevertheless, these studies pertain mainly to regions in North America.

For China, Ding et al. (2004) have demonstrated that a regional climate model (called RegCM-NCC), based on the second-generation finite-difference regional climate model RegCM2, has skill in predicting the major rain belts over China. Using a modified version of the RegCM-NCC model, Chan et al. (2004) concluded that the rainfall amount and pattern over South China could be largely reproducible.

The Hong Kong Observatory (HKO) began disseminating annual rainfall forecast in Hong Kong since 2001 using a statistic technique to meet community interest. This interest was stirred by the 1997 El Niño-Southern Oscillation (ENSO) event which resulted in Hong Kong receiving the highest annual rainfall on record (Chang and Yeung 2003). In addition to the annual rainfall forecast, in 2001 the HKO began experimenting with a regional climate model (RCM). This model is based on the National Centers for Environmental Prediction's (NCEP) Regional Spectral Model (RSM) described by Juang and Kanamitsu (1994) and adapted from the Experimental Climate Prediction Center of the Scripps Institution of Oceanography in the

University of California, San Diego, USA. The main objective is to provide seasonal rainfall and temperature forecasts for Hong Kong and its vicinity through dynamical downscaling global model forecast outputs (Chang and Yeung 2003). These dynamical forecasts have been disseminated to the public since March 2006 via HKO's homepage (http://www.hko.gov.hk/wxinfo/season/season.htm) and represent, to the authors' knowledge, the first such seasonal forecasts made with the model in the East Asian Monsoon region. Some RCM ensemble forecasts have also been attempted (Hui et al. 2002), and these results would be reported separately in the context of monthly forecasts in due course.

It was found that the RCM was particularly skillful in its real-time forecasts for the drought conditions in July–August–September of 2003 and April–May–June 2004 which are normally the rainy or flood season in southern China where Hong Kong is located. This paper documents the skill of the RCM's forecasts in these two cases as a demonstration of the potential for application of the RCM in this region. A documentation of the model system is also provided.

In Sect. 2, a brief description of the RCM in the HKO is given. Sections 3 and 4 depict the scope and the methodology used in this study, respectively. Section 5 presents the study results, and the article ends with a conclusion.

2 The RCM in the HKO

2.1 Overview of the RCM

The RCM is a primitive equation model in sigma coordinates. It is based on the regional spectral model of Juang and Kanamitsu (1994). The technical details of the model can be found in Juang et al. (1997) and Hong and Leetmaa (1999). A brief summary is given below for the purpose of completeness.

The HKO RCM is nested in the ECPC global spectral model (GSM) which provides the RCM with the necessary initial and boundary conditions. A description of the ECPC GSM seasonal global forecasts can be found in Roads et al. (2001) and a description of the corresponding regional USA forecasts is provided by Roads (2004). The ECPC GSM has a triangular truncation of T62 (192 $\times$ 94 global Gaussian grid) and 18 irregularly spaced vertical levels (T62L18). The initial conditions for the ECPC GSM forecasts come from the NCEP Global data assimilation Analysis (GDAS) operational analysis with the resolution of T126L28 or higher. The history of the change of GDAS resolutions and the method for transforming high NCEP analysis to lower resolution initial conditions (T62L18) are described in Roads (2004).

The RCM has the same physics package and parameterizations as the current ECPC GSM. This physics package includes long-wave and short-wave radiation, boundary layer processes, large-scale condensation, gravity wave drag, cumulus parameterization based on a simplified Arakawa-Schubert scheme (Arakawa and Schubert 1974), diurnal cycle with zenith angle for shortwave radiation, non-local PBL (Hong and Pan 1996), shallow convection, simple hydrology with snow melt and accumulation, and runoff generation. The RCM provides a regional extension to the GSM, and thus in principle provides an almost seamless transition between the RCM and the GSM (Roads 2004). A minor structural difference is that the GSM utilizes vorticity and divergence equations, whereas the RCM utilizes momentum equations in order to have simpler lateral boundary conditions (Roads 2004).

The RCM uses spectral transformation for perturbation (Juang et al. 1997). The advantage of using perturbation is that the climate of the regional model does not differ too much from that of the global model. At the lateral boundaries, the RCM's orography is blended into that of the GSM's via a blending technique devised by Hong and Juang (1998). The identical physics package with the GSM, the perturbation and the orography blending all reduce errors due to lateral boundaries and to differences between the global and regional model climatologies. These features make the RCM attractive for regional climate simulations (Hong and Leetmaa 1999).

2.2 RCM set up

Details of the RCM adaptation process in the HKO can be found in Hui et al. (2001, 2002, 2004). Its brief summary is given below.

Figure 1 shows the computer network system used in the HKO. This system consists of an IBM F50 machine for running the model, which features 4 Power-PC 604e CPUs and 1GB RAM, two PCs on Linux platform, and a broadband Internet connection. The IBM F50 machine is linked to the Internet by the 1.5 Mb/s broadband, through which the initial and boundary conditions are downloaded from the ECPC FTP site.

In the HKO, two Linux-based PCs were set up for post-processing of the RCM model output, controlling system work flow and utility development, and hosting a web site on the HKO Intranet for displaying the model results on the internal terminals (Fig. 1). More importantly, these two Linux-based PCs provide hard-disk

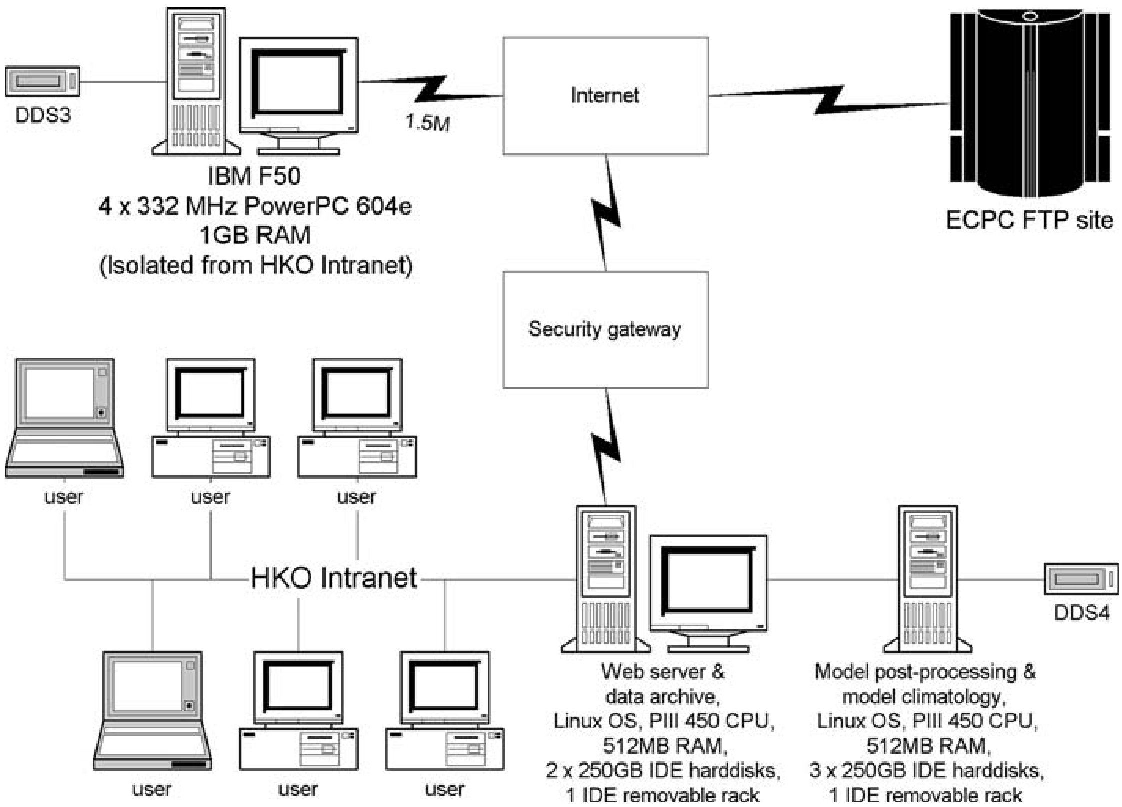

Fig. 1 Hardware set-up of the RCM system in the Hong Kong Observatory

storage of more than 1.2 terabyte, facilitating the archive and retrieval of model output and historical climate data. This network is designed also for the purposes of modularity, portability, and expansibility.

3 Scope of study

3.1 The study region and model domain

Taking into consideration the limited computing power and the operational need of focusing on Hong Kong and its vicinity, the RCM's forecast or inner domain consists of 49×50 grids with a resolution of 15 km centered on Hong Kong (Fig. 2a). Geographically this domain is located between the longitudes 111°E and 118°E, and latitudes 19°N and 26°N, covering the Pearl River Delta (PRD) and Guangdong province in southern China as well as the northern part of the South China Sea. There are nine major cities in the inner domain, Hong Kong (HK), Guangzhou (GZ), Macao (MC), Heyuan (HY), Meixian (MX), Shantou (ST), Shaoguan (SG), Wuzhou (WZ), and Yangjiang (YJ). These cities are marked as crosses in Fig. 2(a). The observations of the rainfall gauging stations in these nine cities are used in the paper to evaluate the RCM's forecasts.

The initial and boundary conditions used to drive the RCM come from a subset of the output of the ECPC GSM. These data are acquired once every Saturday and the boundary conditions are nested into the RCM at a 6-hour interval. The domain of these conditions is known as the outer domain shown in Fig. 2(b). The dots on the outer domain indicate the spatial resolution of the ECPC GSM output.

3.2 Season selection

The inner domain of the RCM, southern China, encompasses an area dominated by the East Asian Monsoon (Ding 1994; Chang 2004). The rainy season of the region lasts from April to September, and receives about 80% of the annual rainfall. Among the period, the April–May–June (AMJ) 3-month period is called the pre-flood or pre-summer rainy season, and heavy rainfalls in these three months are usually caused by moist low level southwesterly airflow associated with a monsoon trough at the northern flank of the subtropical high (Tao and Chen 1987; Ding 1992).

With the subtropical high migrating northwards at the end of the pre-summer rainy season, the southwest monsoon, the inter-tropical convergence zone (ITCZ), and tropical cyclones become the dominant weather and climate factors in the period of July–August–September (JAS). This three-month period is called the post-flood or post-summer rainy season.

Rainfalls in the pre- and post-summer rainy seasons over the region on one hand may cause floods, and on the other hand provide fresh water for the local inhabitants. In southern China, especially parts of Guangdong province, a prolonged dry spell began in the 2003 post-summer rainy season and persisted into 2004 (SEPA 2004, 2005). In 2003 JAS, HY in Guangdong received a seasonal rainfall of 32% below the standard climate normal defined by the World Meteorological Organization (WMO 1989). Another four cities, namely HK, MC, MX, and WZ, received rainfall anomalies ranging from –10 to –19%. The drought situation was even worse

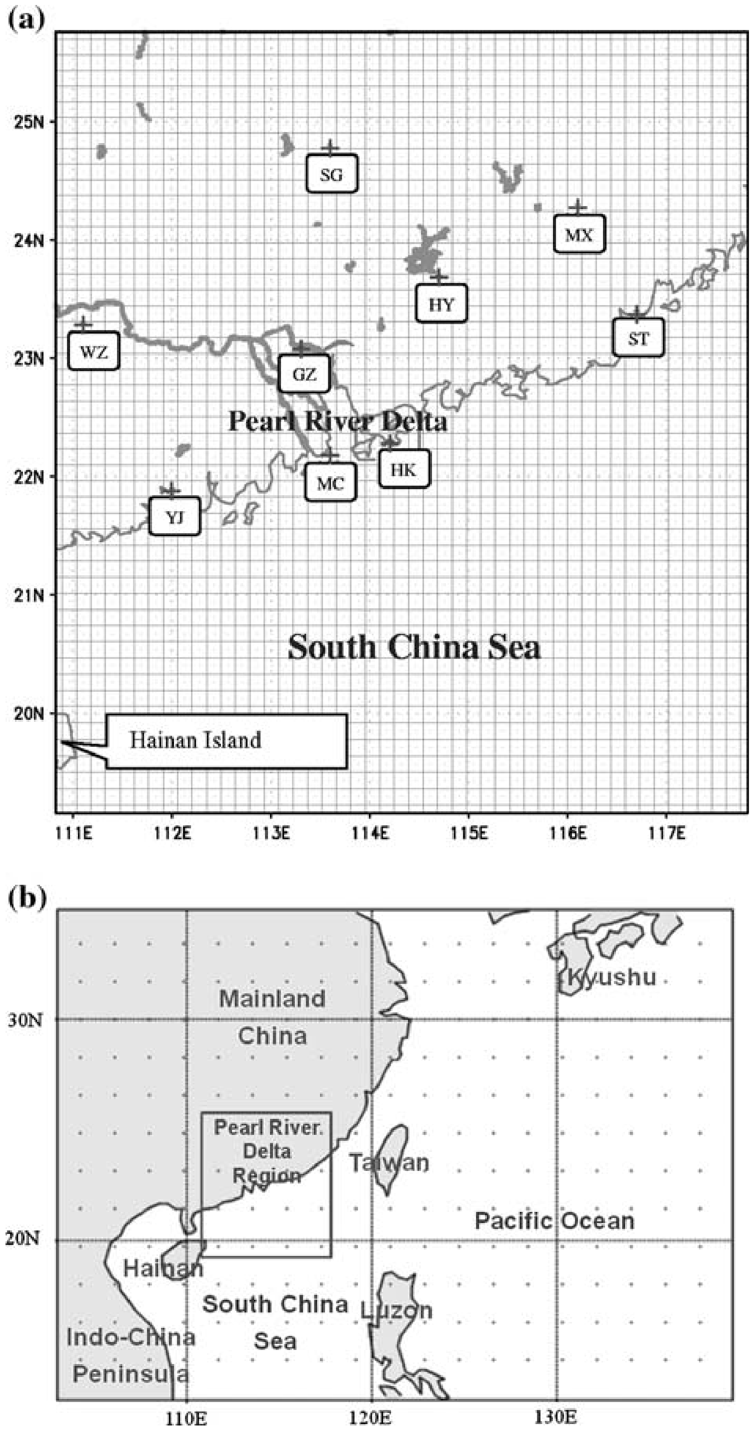

Fig. 2 Model domain. (**a**) The RCM inner domain with 15-km resolution grids centered on Hong Kong and covering the Pearl River Delta, Guangdong Province and the northern part of the South China Sea. The domain also shows nine major cities, HK (Hong Kong), GZ (Guangzhou), MC (Macao), WZ (Wuzhou), YJ (Yangjiang), ST (Shantou), HY (Heyuan), SG (Shaoguan), and MX (Meixian). (**b**) The outer domain of the RCM over which the boundary and initial conditions of the RCM provided by the ECPC GSM. It covers most part of mainland China and East Asia. The rectangle indicated as 'Pearl River Delta Region' is the inner domain shown in (**a**)

in 2004 AMJ when HK, MC, GZ, HY, MX, and ST had rainfall anomalies ranging from –22 to –62%. During this period, more than 14 million acres of farmland over southern China suffering from water shortage were reported (GMB 2005). Thus, RCM's skill in 2003 JAS and 2004 AMJ are evaluated in this study.

4 Methodology

4.1 RCM initialization and 12-week rainfall forecast

The initial and boundary data used to force the RCM in the HKO come from a subset of the output of the ECPC GSM (see subsection 3.1).

The RCM initialization uses a successive 12-week climate forecast from the GSM to produce an extended RCM forecast up to 12 weeks ahead starting from 00UTC every Saturday. In detail, the boundary conditions are adjusted with a 6-h interval during the entire 12-week period. The initial conditions at the RCM forecast starting time are obtained from the ECPC GSM output, and thereafter for each 6-h interval the initial conditions for the RCM come from the previous time step of the RCM output. Figure 3 shows the data flow of the RCM 12-week forecast in the HKO.

4.2 Forecast skill evaluation

4.2.1 Standardizing RCM forecast rainfall and observed rainfall

To avoid the evaluation of RCM forecast skill being biased by differences between the RCM forecast climatology and the observed rainfall climatology, following Roads et al. (2001) the RCM rainfall forecast skill is evaluated by comparing the standardized RCM rainfall with the standardized observed rainfall. The standardization method is given below.

The standardized RCM forecast rainfall, F', is calculated as

$$F' = \frac{F - C_f}{\sigma_f} \tag{1}$$

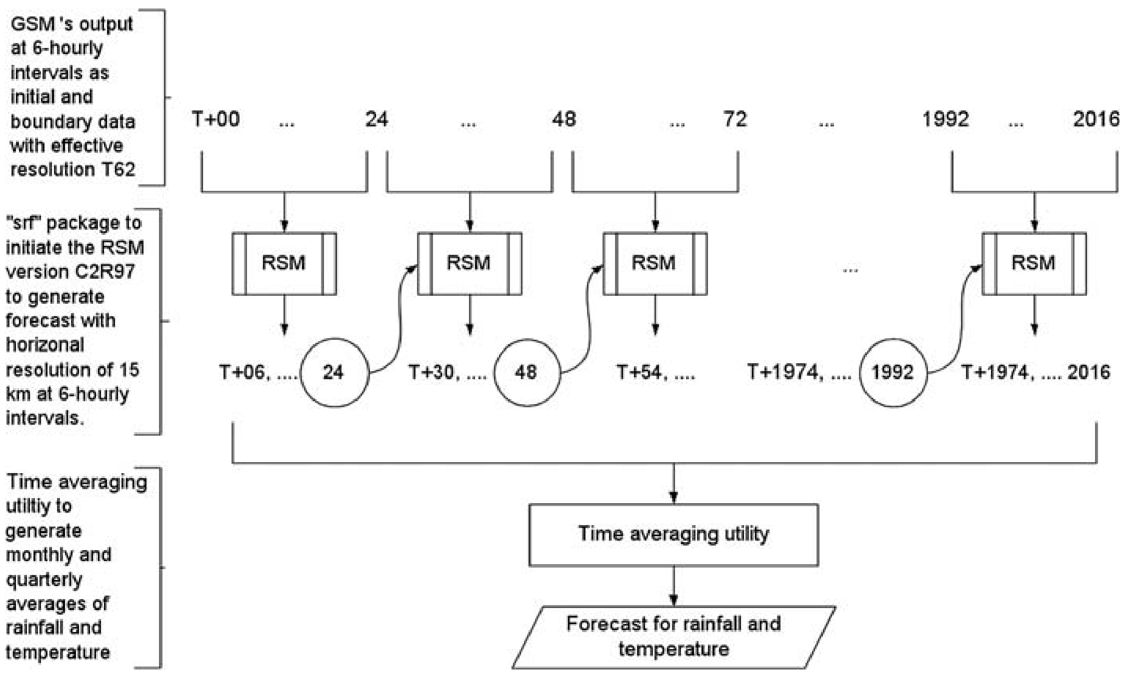

Fig. 3 Schematic diagram of RCM's data flow and the time number is in the units of hour

where F is the RCM rainfall forecast for a given 12-week period, C_f the RCM long-term mean rainfall (i.e., the model rainfall climatology) calculated from the hindcasts during the period of 1998 to 2001 for the same 12-week period, and σ_f the corresponding standard deviation of the rainfall hindcasts. It should be noted that only hindcasts since 27 September 1997 were available for compiling the model climatologies of the RCM and ECPC GSM (Roads et al. 2001) when the HKO started to generate real-time RCM forecasts since 2002. This is the reason for choosing the 4-year span from 1998 to 2001 as the model climatology period for calculating the standardized rainfall anomalies for AMJ and JAS. Furthermore, the forecasts in 2003 and 2004 were not used in the compilation of model climatology; otherwise, C_f and σ_f would be contaminated by their own forecasts.

Similarly, the standardized observed rainfall O', is computed from

$$O' = \frac{O - C_o}{\sigma_o} \tag{2}$$

where O is observed rainfall in a given 12-week period. C_o and σ_o are respectively the mean and standard deviation of the observed rainfall for the same 12-week period calculated over the four-year period from 1998 to 2001. This four-year period is same as that for compiling the model climatology.

Referring to the WMO's suggested method for evaluating forecast skill (WMO 2002b), the standardized forecast and observation are graded into three groups. The standardized data of greater than 0.5 is classified as above normal rainfall (wet status), between 0.5 and –0.5 as near normal rainfall (normal status), and less than –0.5 as below normal rainfall (dry status). However, focusing on exploring the forecast skill of the dry conditions, we only use two groups, dry conditions (less than –0.5) and non-dry conditions (larger than or equal to –0.5) in this study (see Section 5 for details).

4.2.2 Scaled Hanssen and Kuipers score

The forecast skill is also evaluated from the Scaled Hanssen and Kuipers Score ($SHKS$) given by (Wilks 1995; WMO 2002b).

$$SHKS = \frac{HR - FAR + 1}{2}, \tag{3}$$

where HR is the hit rate or the number of correct forecasts to the total number of forecasts for an event to occur, and the FAR the false-alarm rate or the number of forecasts that are false to the total number of forecasts for an event to occur. Thus

$$HR = \frac{O_1}{O_1 + O_2}, \tag{4}$$

where O_1 represents the number of correct forecasts or hits, and O_2 the misses; and

$$FAR = \frac{NO_1}{NO_1 + NO_2}, \tag{5}$$

where NO_1 represents the number of false alarms, and NO_2 the number of correct rejections.

Therefore, *SHKS* is 0 when forecasts are totally missed and is 1 when all forecasts are perfectly hit. As mentioned in subsection 3.2 since predicting dry conditions over southern China in rainy season is of particular interest in the study period, the *SHKS* of the RCM is computed based on the forecasts of the binary events, i.e., ‘‘dry’’ and ‘‘non-dry’’ conditions (see subsection 4.2.1 for defining the dry and non-dry conditions).

5 Results

The seasonal rainfall predictability in 2003 JAS and 2004 AMJ are studied using the HKO RCM 12-week forecast. The starting dates of the two experimental forecasts are July 5, 2003, and April 3, 2004 (see Figs. 4, 5), respectively.

Nine rainfall gauge stations (standing for nine cities (see subsection 3.1), hereafter we only use nine city names instead of gauge stations) in southern China (see Fig. 2(a) and Table 1) are chosen for exploring the detail spatial distribution of the RCM forecast. In Table 1, Figs. 4, 5, NN stands for non-dry conditions and BN for dry conditions.

5.1 2003 JAS seasonal rainfall forecast

Figure 4(a) shows the RCM 2003 JAS seasonal rainfall forecast over southern China. The model forecast suggests that most of the study region have non-dry conditions, i.e., standardized model rainfall larger than –0.5. However, the RCM forecast also indicates the dry conditions in eastern Guangdong in the period.

During 2003 JAS, from the observations, Table 1 and Fig. 4(a) shows that five cities within the study domain received non-dry conditions rainfall and another four cities had below normal rainfall. Comparing the RCM forecasts with the standardized rainfall observations, we found that the accuracy of the model forecast is about 66.7%, i.e., 6 out of 9 cities of the RCM predicted rainfall are rationally regarded as correct. These six cities are GZ, YJ, WZ, SG, MX and ST. Also from the figure, we see that rainfall forecasts for another three cities (i.e., HK, MC, and HY) deviate from the observed rainfall. Although rainfall at HY is not exactly predicted, from Fig. 4(a), we still can find that RCM simulation has the potential to display the dry conditions near HY and MX.

To further illustrate the RCM forecast skill, we present the ECPC GSM 12-week rainfall for 2003 JAS in Fig. 4(b). The GSM chart predicts that the entire land surface within the inner domain has non-dry conditions. In this case, the GSM properly predicts non-dry conditions at five out of nine cities (see Fig. 4(a) and Table 1). Though it does not capture the dry conditions over the area around HY, it indicates the existence of an area of dry conditions near the coast. Through the comparison between Fig. 4(a), (b), we can see that the RCM output can add spatial details to GSM rainfall forecast and successfully predicts the dry conditions near HY in the season.

5.2 2004 AMJ seasonal rainfall forecast

The difficulties in predicting seasonal rainfall in AMJ over southern China are mainly due to the random nature of convective rainfall. Hong and Leetmaa (1999)

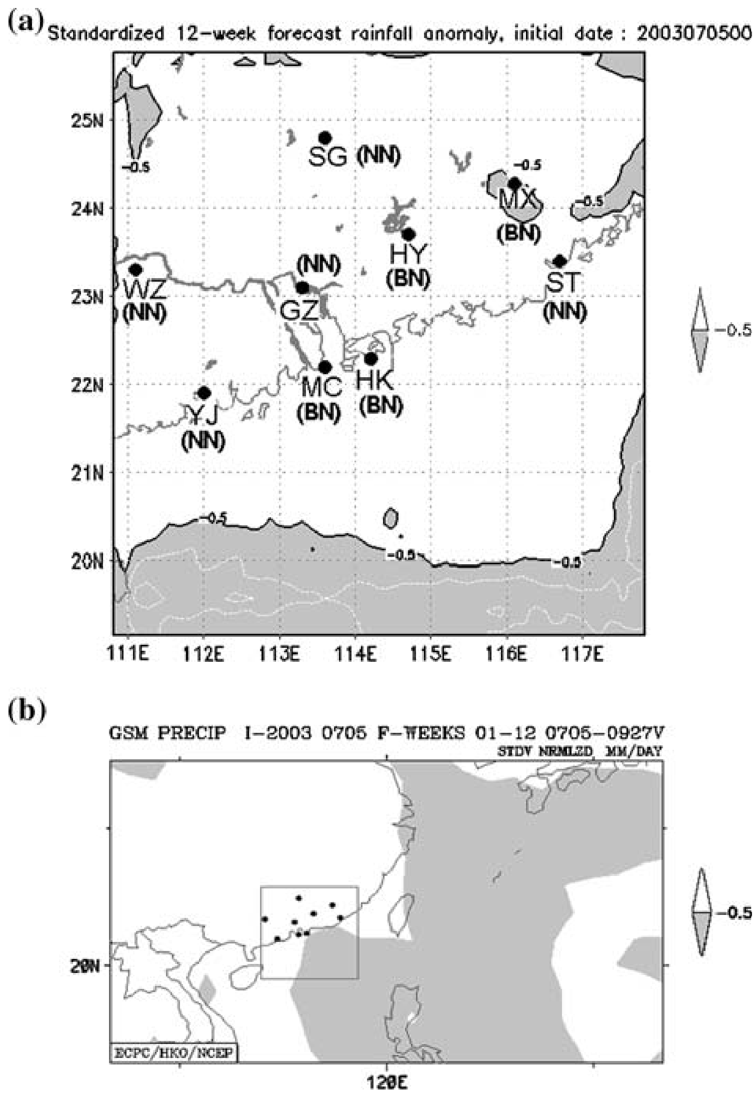

Fig. 4 (**a**) Standardized RCM seasonal prediction rainfall for 2003 JAS (July–August–September). The initial date 2003070500 indicates that the RCM forecasts started at 00 UTC on July 5, 2003. Standardized rainfall observations at the nine cities are also presented. NN and BN denote respectively observed near-normal or non-dry and below-normal or dry conditions, (see Table 1). (**b**) ECPC GSM forecasts for the outer domain. The rectangle with nine dots in Fig. 4(b) marks the inner domain of the RCM; the nine dots mark the locations of the nine cities in (**a**)

indicated that there are limitations in the Simplified Arakawa-Schubert scheme, which is adopted in the GSM and the RCM, to capture heavy and grid point rainfall in some rainstorm studies. Given such caveats in the study, the main task of the AMJ forecast here is to depict the dry conditions.

Figure 5(a) shows the RCM forecast of the 2004 AMJ rainfall. The forecast properly captures the dry conditions in the 2004 AMJ in six cities, GZ, HK, MC, HY, MX and ST. The accuracy of the RCM forecast is 66.7%. Though the observed non-dry conditions rainfall at the remaining three cities over the northwestern part of the domain (YJ, SG and WZ) is not predicted, from the figure, it can be found that these cities with observed non-dry conditions rainfall do close to the area with non-dry rainfall predicted by the RCM.

This experiment for 2004 AMJ is also a good example to illustrate the potential utility of dynamical downscaling technique for predicting seasonal rainfall using

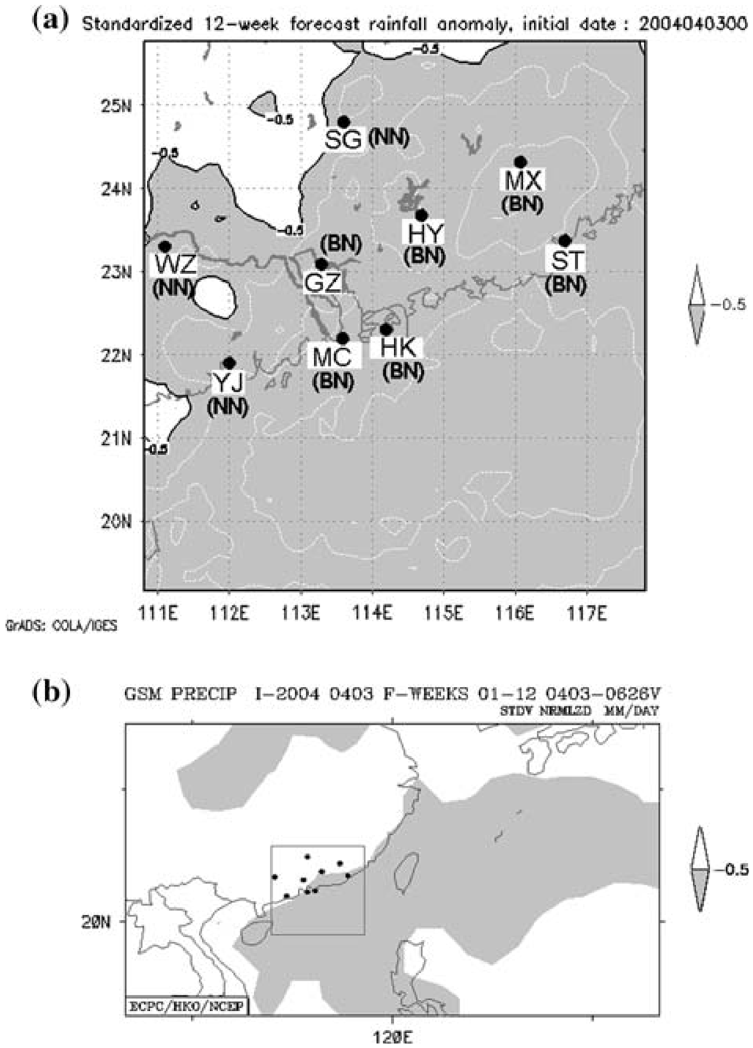

Fig. 5 (**a**) and (**b**) Same as Fig. 4(a), (b) but for 2004 AMJ (April, May and June)

Table 1 Rainfall observations at nine cities in the RCM domain (also see Figs. 2, 4, 5)

Stations	Latitude (°N)	Longitude (°E)	2003 JAS	2004 AMJ
Hong Kong (HK)	22.3	114.2	BN	BN
Macao (MC)	22.2	113.6	BN	BN
Guangzhou (GZ)	23.1	113.3	NN	BN
Yangjiang (YJ)	21.8	111.9	NN	NN
Wuzhou (WZ)	23.4	111.3	NN	NN
Shaoguan (SG)	24.7	113.5	NN	NN
Heyuan (HY)	23.7	114.6	BN	BN
Meixian (MX)	24.2	116.0	BN	BN
Shantou (ST)	23.3	116.6	NN	BN

NN represents the near-normal or non-dry conditions, and BN below-normal rainfall or dry conditions

physical-based numerical models like the RCM used in the HKO. The RCM is able to predict the widespread dry conditions over most part of Guangdong at the seasonal scale (Fig. 5(a)) which turns out to be correct vis-a-vis the mostly non-dry conditions predicted by the GSM (see Fig. 5(b)). Particularly, the severe rainfall deficit around HY was well captured by the RCM. This successfulness of the RCM can be attributed in part to a higher horizontal resolution used in the regional model, comparing with that used in the GSM.

5.3 Discussion of RCM seasonal rainfall predictability in 2003 JAS and 2004 AMJ

Based on the RCM predicted rainfall and observations for the nine cities, 18 forecast-observation pairs for 2003 JAS and 2004 AMJ are formed for computing the *SHKS*. Table 2 summarizes the model performance for these two time periods. The overall *SHKS* for 2003 JAS and 2004 AMJ is 0.66 (see Equations (3), (4) and (5) for details of computing the value). This result, even though based on only two experimental model runs, reveals that the overall hit rate of predicting dry conditions in these two rain seasons is higher than the false alarm rate and the RCM should be potential to provide a valuable forecast of persistent dry conditions in the rainy season over southern China.

To further corroborate the potential of using the RCM to predict dry conditions observed in subsections 5.1 and 5.2, we make use of the NCEP reanalysis data (Kalnay et al. 1996; http://www.cdc.noaa.gov/cgi-bin/PublicData/getpage.pl) for examining the atmospheric conditions associated with dry conditions over southern China in the two seasons.

During the rainy season of southern China, many systems/factors are at play. Lin (2000) summarizes the findings of meteorologists in China and points out that the seasonal rainfall over the region is closely related to the magnitude of low level moisture-laden winds during AMJ and the strength of the subtropical high in JAS. For these reasons, we focus on checking the anomaly of geopotential height at 500hPa in 2003 JAS and the anomaly of meridional wind at 850 hPa in 2004 AMJ.

Studying the NCEP reanalysis data, we found, during 2003 JAS, the below normal rainfall over the region is most likely caused by a stronger than normal subtropical ridge extending from the western North Pacific (Fig. 6). The NCEP reanalysis indicated that the seasonal average of geopotential height at 500 hPa over the study inner domain was +20 gpm (geopotential meter) higher than normal. Indeed, this positive anomaly of geopotential height was well captured by the RCM forecast. This could be one of the reasons for the reasonably good seasonal rainfall forecast over the region in 2003 JAS.

In 2004 AMJ, the weaker than normal moisture-laden southerly winds over the inner domain observed in the NCEP reanalysis data was properly predicted by the RCM, which is believed to be the reason for the RCM successful forecast of the dry conditions over the region. The predicted meridional wind speed anomaly with –0.5 m/s (negative for southward wind) by the RCM is also consistent with the same direction but with –0.9 m/s magnitude wind found in the NCEP reanalysis data.

Table 2 Contingency table for rainfall forecast-observation pairs in 2003 JAS and 2004 AMJ

RCM prediction \ Observation	Dry conditions	Non-dry conditions
Dry conditions	7	3
Non-dry conditions	3	5

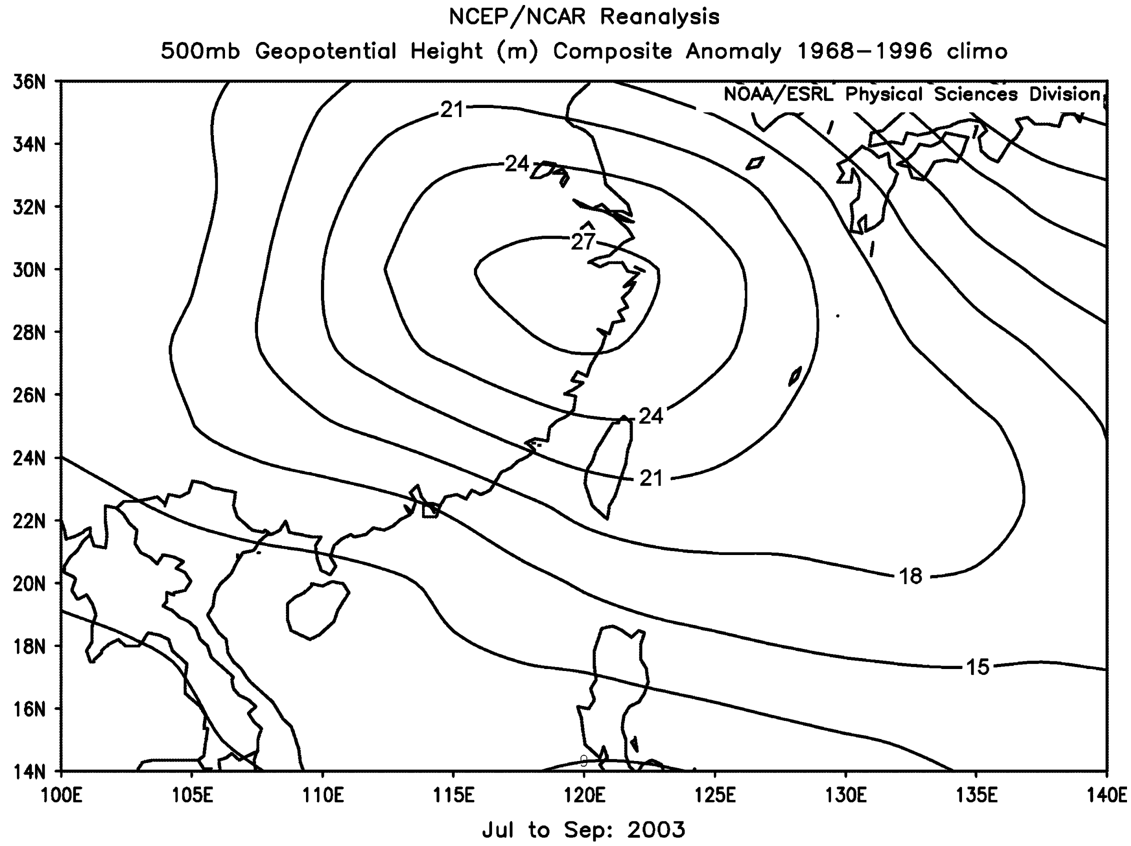

Fig. 6 2003 JAS geopotential height anomalies at 500 hPa (based on NCEP reanalysis available at http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl)

6 Conclusions

A regional model based on NCEP's Regional Spectral Model was used to generate seasonal forecasts for Hong Kong and its vicinity. It was found that the dry conditions in July–August–September 2003 and April–May–June 2004, which is normally the rainy season, were quite well forecasted. The overall Scaled Hanssen and Kuipers Score was 0.66. In particular, in the second case the spatial distribution of dry conditions was much better captured by the regional model, than by the global model into which the regional model was nested.

This is the first time that NCEP's Regional Spectral Model has been applied to the East Asian Monsoon region. The two case studies indicate that the model has potential skill in providing useful seasonal forecasts for Hong Kong and its vicinity albeit it is noted that the model climatology is short and its representativeness may be limited. HKO will continue to conduct experiments with the regional model to further understand its capability and limitations as a seasonal forecasting tool for the region. It is also worth noting that the above seasonal forecasts were generated using limited computer resources.

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