Advancement and prospect of short-term numerical climate prediction

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Abstract **The defects of present methods of short-term numerical climate prediction are discussed in this paper, and four challenging problems are put forward. Considering our under developed computer conditions, we should innovate in the approcuch of numerical climate prediction on the basis of our own achievements and experiences in the field of short-term numerical climate prediction. It is possibly an effective way to settle the present defects of short-term numerical climate prediction.**

Keywords: short-term climate, numerical prediction, defects, innovation.

In the 20th century, the material civilization developed the most quickly in the human beings' history, and the science and technology made huge progress. But in the 21st century human beings still will face the threat of natural disasters frequently. The loss caused by the natural disaster increases with the economic development. In China, the number of meteorological disaster is about more than 70% of the natural disaster, and the economic loss caused by it costs 3%—6% of the national GDP. The ratio is higher than that of advanced countries. Climate prediction can make contribution to preventing and reducing meteorological disaster, and play an important role in national economy and social development.

Accurate and effective climate prediction is a main aim of atmospheric science for quite a long time. In the past, owing to the limited scientific capability and technique condition, numerical climate prediction was regarded as a dream. In the 20th century, atmospheric science has gone through a rapid development. And many key achievements have been made, such as the foundation of global observational networks, the successes of short-range and medium-range numerical weather forecast, the discovery of chaotic phenomenon, the formation of the concept of climate system, and the invention of numerical climate model. Then it comes the time that atmospheric scientists have the possibility to make numerical climate prediction from a dream into a real scientific problem.

In the 1950s, the short-range numerical weather forecast[1] and numerical simulation of atmospheric general circulation[2] succeeded successively. And in the early period of the 1980s, the operational medium-range numerical weather forecast system was put into service. After the success of medium-range numerical weather forecast, the monthly numerical climate prediction became the next goal of atmospheric scientists. One method to achieve it is to extend the valid time of medium-range numerical model, that is, dynamical extended range method. Though many achievements have been gained after scientists' arduous endeavors, model results of monthly prediction still can not be used in operational service[3—5]. Another way to make numerical climate prediction is to develop the sea-air coupling model to perform numerical tests of climate simulation and prediction on seasonal and extraseasonal time scale[6,7]. As a result of the efforts of more than 10 years, the model's features have progressed a great deal. But the seasonal and extraseasonal numerical climate prediction in advanced countries is still in testing stage, and it can not be used in operational service[8—11].

Climate disasters occur frequently in China, and the flooding and drought disasters greatly influence national economic construction and social development. The prediction of flooding and drought event on monthly and seasonal time scale, especially that in flood season, is an important task for Chinese atmospheric scientists. Using methods of synoptic climatology and statistics, Chinese scientists have researched into the problem of prediction of flooding and drought event for about 50 years, and have gained many significant achievements[12]. The flooding and drought distribution in China is related closely with interannual variation of East Asian monsoon. The mechanism of formation and variation of East Asian monsoon is complicated. The testing predictive results of almost all the best climate models indicate that the model predictive skill of Asian monsoon areas is the lowest in the whole world. So the prediction of flooding and drought climate in China is a difficult frontier problem.

Chinese scientists have also obtained outstanding achievements in the field of short-term numerical climate prediction[13]. For example, on extraseasonal prediction of precipitation, IAP's 2-layer atmosphere and 4-layer ocean model have a series of original creations, and have been tested operationally for many years[14—23]. T63 dynamical extended forecast model for monthly prediction has been established in Chinese National Climate Center, and has been put into quasi-operational service. In developed countries, the research of using AGCMs or CGCMs to perform numerical climate simulation and prediction has been done for quite a long time. With synthetic superiority on scientific conditions, such as atmospheric detection, computer, etc., great progress has been made in several aspects, such as improvement of climate model and techniques of ensemble forecasting. Overall, we fall behind developed countries in the field of numerical climate simulation and prediction. Thereby, we must trace the international advanced level continuously. And we should import, digest, assimilate and innovate. The first step of this work is to know the essence of foreign ideas and methods. We should not only learn their good qualities, but also know their defects. Aiming at the defects and combining our own experience and advantage, we should innovate in theory and method in the course of research. Then we can make an innovative approach of numerical climate prediction with Chinese characteristics.

1 Advances and defects of foreign short-term numerical climate prediction

Scientists have been devoting themselves to prolonging the valid time of numerical weather forecast continuously after the success of 24-h numerical weather forecast in the 1950s. In 1980, the valid time was up to 4.5 days, and it was raised to 7.5 days in 1989[24,25]. Naturally, the success of medium-range numerical forecast evoked the thought that whether people can make monthly numerical climate prediction through improving the medium-range weather model and extending valid predictive time. In fact, the research on monthly numerical climate prediction has indeed followed this thought, and the method is called dynamical extended forecasting. The research on dynamical extended forecasting has been done for the over 20 years, which was begun at the monthly dynamical extended range forecasting test in GFDL[26]. During the 20 years, the model resolution has raised step by step, e.g. the operational spectrum model in ECWMF has gone from T42, T63, T106, to now-using T213[24]. And consequently, the description of physical process in model has been finer, from indirect description to direct description, with more small-scale processes included[24,25]. The assimilation technique is applied in the model, from objective analysis and optimum interpolation to 3-D assimilation and 4-D assimilation[24,25]. The ensemble forecasting method emerged and developed, from Monte Carlo method[27], LAF (lagged-average) method[28], to BGM (breeding of growing modes)[29] and SV(singular vectors) method[30,31], from the single model ensemble method to the multi-model ensemble method[32]. On the whole, model resolution is thinner, and processes included in the model are much more, number of ensemble group is greater, and the calculation is more complicated and more time-consuming. The representative example of model refining is the emergence of unified model, which makes short-range, medium-range and long-range predictions in one model. The atmospheric model with 1-km resolution is also planned.

As a result of the endeavors just mentioned, skill of monthly numerical climate prediction test has notably increased. Taking AC of 500 hPa circulation as example, till middle and late stage of the 1980s, AC of 500 hPa circulation of numerical model reached 0.3—0.4[3,4], surpassed the level of persistence forecasting. But the enhancement of predictive skills in the recent 10 years is fairly slow. The model's AC of 500 hPa circulation in the late stage of the 1990s still stayed about 0.4[3—5,7,8]. The present improvement of prediction owing to the model progress chiefly comes from the contribution of the first 10 days in one month[33,34]. The level of monthly dynamical extended prediction still cannot satisfy the demand of operational service. Why is the numerical climate prediction especially that for monthly time scale stagnant for quite a long time? We think the main reason is that the current method of numerical climate prediction has the following four defects.

(i) Little improvement can be made on the description of climate process by over-refining of model resolution. Atmospheric predictability studies show[35—38], that the synoptic feature is chaotic in climate prediction, the predictive result of it in the numerical model is equivalent as the guessing result. The direct description of its influence on the stable climate feature is no better than paramiterization. It has not been validated that the large-scale behavior of climate can be represented by the combined effects of smaller-scale processes partly resolved and partly parameterized by the complex climate model[39]. Many numerical experiments show[40—45] that refining of model resolution cannot improve climate predictive skill. And predictive skill even decreases in the Asian monsoon area and the southeastern side of the Tibetan Plateau. In the examples those exhibit skills, the most obvious improvements are all in the beginning several days, the skills in days afterwards increase little. Increasing model resolution should correspondingly have denser observational data to rely on[25]. But it is a difficult task under the density of current networks. So the improvement through model resolution refining has no obvious effects, due to the lack of necessary observational data. Moreover, quantity of calculation multiplies when the effect of refining model resolution is overemphasized. Under the circumstance of underdeveloped computer power in China, this approach does not suit our national condition. Overemphasizing the effect of adding complexity to climate model cannot raise the predictive capability effectively, perhaps much attention should be paid to physical processes, physical principle and consistency of climate model itself.

(ii) The research on the influence of numerical error on climate model is inadequate. The object that numerical climate prediction deals with is the long-term behavior of atmospheric motion, while the theory and method to gain numerical solution are by means of resolving initial-value problem. Model predictability studies tell us[37,38] that the numerical solution obtained by integrating dynamical equation from a certain initial state is super-sensitive to the temporal and spatial stepsize when integrating time is beyond predictive limit, and the specific state of numerical integration is undetermined. The total error of numerical prediction can be divided into two parts, one is the error between true solution of model and real climatic state, and the other is the error between numerical solution and true solution. Owing to the lack of research on the error, which is caused by the nonlinear effects of discrete error and rounding error in numerical calculation, the share of two parts in total error is ambiguous. The respective effects of difference of individual ensemble member and numerical error in individual reality are indefinite in ensemble forecasting. All these factors make the improvement of climate model random and uncertain to some degree.

(iii) The study to represent the external source of atmospheric motion is insufficient. The understanding of ocean circulation, land layer and snow-ice layer in the climate system is much less than that of atmospheric circulation. The focus of improving climate model system is mainly in the atmospheric model. How to improve the processes related to ocean circulation, land layer and snow-ice layer in climate model is little discussed. The atmospheric system is a nonlinear system with forcing and dissipation. And the energy exchange of atmospheric system and other systems, including the energy input from external systems, influences the long-term variation of atmospheric motion. Ocean circulation, land layer and snow-ice layer are underlaying surfaces of atmospheric motion in the climate system, and they have the exchanges of momentum, energy and physics quantity flux with the atmospheric system, and decide the long-term evolution of atmospheric general circulation. But little attention is paid to improving the description of processes in underlaying surface. It is a main reason why the skill of numerical climate prediction enhances little.

(iv) Viewing numerical climate prediction as an initial-value problem influences using data in model. The present method of numerical climate prediction is to integrate the numerical model starting from initial state. Viewing numerical climate prediction as an initial-value problem makes only data at initial time utilized in the numerical model. At present, most of observations are made just in the middle and low layer of atmosphere, and observational data of underlaying surface like ocean and land are very inadequate. Thus the spatial data at every time point are sparse. Otherwise, the routine observational data have good continuity, atmospheric data and surface sea temperature with good quality have been accumulated for more than 50 years. But the climate prediction viewed as an initial-value problem leaves the data unused. It makes such a paradoxical situation: data are insufficient while lots of data leave unused.

Research on the numerical climate simulation and prediction started early, its method was formed at the time when the mathematical and physical foundation of numerical climate model was underdeveloped. The method has developed greatly over the past 20 years, but the basic frame is still based on the numerical integration of initial-value problem. It influences the course of incorporating new achievements of climate research into the numerical climate model. Lack of basic theory research and excessively relying on computer conditions cause the skill of numerical climate prediction rise slowly in rather a long period.

2 Strategy and advances of improvement on short-term numerical climate prediction

The defects, which exist in numerical climate prediction of developed countries, give us a chance to innovate. Aiming at the defects just mentioned, Chinese scientists have done some primary works. According to the practices of scientists in China, in order to innovate and make a breakthrough in the field of numerical climate prediction, several challenging problems should be faced.

(i) Determination and simulation of stable component in climate system. According to the different predictive lengths of monthly, seasonal and yearly climate prediction, different predictable stable processes should be determined. What are the main stable processes that influence the variation of monthly, seasonal and yearly climate? How are the equations that describe stable components set up? How can we contrive parameterizational schemes that describe the influences of chaotic motion on stable components? These problems are physical bases of establishing the suitable numerical climate model. They are important to the short-term numerical climate prediction. Considering the global feature of predictive object and grasping the main feature of its stable component can deepen the understanding of object and enhance predictive skill. For instance, seasonal variation of dynamical character of subtropical anticyclone is affected by interface of easterly and westerly. And it can be studied as a variable bound problem. Chinese scientists have made some basic attempts about it[1)]. To determine stable components of various scales together with the modes and influences of their interactions, lots of works need to be done.

(ii) The mathematical theory of numerical climate simulation and prediction. The climate model originates from partial differential equations. The difference between the solution of the equations and the real climate is mainly due to inaccurate parameterization of physical processes. The works of improving parameterization, mainly empha-

1) Wu Guoxiong, Chou Jifan, Liu Yimin et al., The Dynamical Problems of the Formation and Variation of Subtropical Anticyclone (in Chinese), Beijing: Science Press (in press).

sizing land process and cloud radiation nowadays, engender physical theory of climate prediction. Generally speaking, the true solution of the partial differential equations is unknown, numerical solution is obtained by integrating the numerical model. The objective of the study on relation of numerical solution and true solution is to decrease the error of numerical solution. It is a main task of mathematical theory of numerical climate prediction. It is a new field for research. Because the specific numerical solution of nonlinear ordinary equation is uncertain[46,47], algorithm with global convergence for the nonlinear dissipative system is needed to consider discrete error and rounding error together, just like symplectic algorithm in the conservative system invented by Feng[48]. It has been proved that the global behavior of the partial differential equations of climate system asymptotically approaches to an attractive set A with definite dimension in H space[49—52]. The difference equations are gained from spatial and temporal separating of differential equations. And the global behavior of the difference equations asymptotically approaches to an attractive set S^n with zero volume in R^n space[53]. The global asymptotic behavior of the numerical model, whose state variables are discrete too, are definite set $P_r(n)$ in R^n space[54—56]. They all are irrelevant to the initial value. A, S^n and $P_r(n)$ are controlled by equations, external parameters and algorithms. If $\lim_{r\to\infty,n\to\infty} dist^H(P_r(n),A)=0$, here $dist^H(A,B)$ is Housdorff's distance between set A and set B, then the numerical model is called global convergent. Only those global convergent algorithms can be suitably applied in the climate model. If the research of qualitative theory of differential equation and the research of numerical calculation supplement each other, numerical climate simulation and prediction will develop greatly[57].

(iii) Improving representation of ocean circulation, land layer and snow-ice layer in climate model. Under the circumstance of insufficient understanding of ocean circulation, land layer and snow-ice layer the inverse problem method can be applied to solving the problem of underlaying surface representation. Thus the use of achievements of inverse theory and computer resource, plus the application of 50-year observational data of climate system, can help to concentrate on the situation with worst quality, and then improve predictive skill. When some scientists discussed the problem of climate prediction, by using a coupling two-parameter simplified land (sea)-atm- ospheric model, they verified that the thermal anomaly of underlaying surface was caused by anomaly of previous atmospheric circulation, and can be represented by continuous evolution of previous atmospheric temperature field and pressure field[58]. On the basis of it, the method of inverse parameter using evolutive data was put forward. The parameter determination and model recognition were viewed as inverse problems, and corresponding means were given[59—61]. Once the numerical prediction is viewed as inverse problem and evolving problem, abundant evolutive data, not just initial atmospheric data and inadequate ocean data and snow-ice data, can be used in model to implement numerical prediction. It can greatly improve the description of processes on underlaying surface. It is an approach with Chinese characteristics to improve numerical climate prediction.

(iv) Sufficient utilization of physical law and data.

How can we make full use of physical law and observational data in numerical climate prediction, not only recent evolutive data but also historic data accumulated for decades? It is a new field that scientists abroad have not fully realized and therefore have not set foot in. Recent evolutive data can be incorporated into numerical model after changing numerical prediction from initial-value problem to evolving problem through works of Chinese scientists[62—65]. The concept of self-memory of atmospheric motion was put forward, and self-memory equations, which could include multi-time data, were deduced[66—68]. Anologue-dynamic method, viewing predictive object as a disturbance superimposing the anologue history, was put forward[69,70]. Applying EOF decomposing to model reality, the method to find definite degree of freedom that support climate attractor to decrease the degree of freedom of climate model was designed[71,72]. New method of constructing different initial values of members in ensemble prediction was put forward[73]. These methods are original in full use of historical data. The numerical tests show that predictive skills in 10-day and monthly prediction rise notably[68,71—74]. It is hopeful to raise predictive skill if these methods can be applied in flooding and drought prediction in the flood season, after further thorough research.

Among the four problems mentioned in this section, problem one and problem two stress on the improvement of numerical model (mathematical theory and physical theory of numerical climate prediction), and problem three and problem four stress on improving predictive skill by using observational data. The research to improve predictive skill by using historical data and the research to improve numerical climate model supplement each other. The former develops on the basis of the latter, and advances correspondingly with the latter.

3 Conclution

Climate prediction is a rather difficult scientific problem. In developed countries, emphasis to enhance predictive skill of numerical model is still on adding complexity into climate model (refining of model resolution and refining of parameterization of physical processes). Powerful computer resources are needed to support it. But the promotion of predictive skill especially in high and middle latitude areas is limited. It is obvious that several defects exist in the present method. They are disregarding chaotic feature, unknowing numerical error, and paradoxical situation of leaving data unused while feeling data insufficient. Probably the reason why the skill rises slowly is the lack of basic theory and that current method is unsuitable. In order to promote the skill of short-term climate prediction, especially that of flooding and drought prediction in the flood season in China, we must develop our own theory and method on the basis of our experiences and achievements, to avoid the defects of developed countries. In fact, IAP's 2-layer atmosphere and 4-layer ocean model have good effects on the prediction of Asian monsoon in AMIPI[13]. In China, it has been tested operationally for the nearly 10 years in the extraseasonal climate prediction, the effects are not bad. Its result was nearest to the real situation in 1999, and the results of 1998 and 2000 were quite good too[75,76]1). Analysis indicates[75,76]1) that the major factors that influence the rainfall in the flood season in China, like Western Pacific warm pool activity[77,78], are seized in the model. It is an important factor attributing to the success of prediction. We have good experience and our own superiority in the field of short-term numerical climate prediction. The computer power develops swiftly now. We should catch this chance, break away from the simple manners of reducing model resolution and increasing ensemble member, follow deep rational thoughts, take full advantage of new mathematical and physical achievements, and absorb rich experiences gained from research of synoptic climatology and statistics. Thus we can make an innovative way with Chinese characteristics in the field of numerical climate prediction.

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