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A Digital Atmosphere by Numerical Weather Prediction Model

Dehui Chen Xu Tang

China Meteorological Administration

Abstract Numerical Weather Prediction (NWP) is a most advanced technique used in meteorology around the world and plays a more and more essential role in weather forecasts for taking precaution against and lightening meteorological calamities, large engineering and public services. The NWP techniques have a tight relationship with Geographic Information System (GIS), High Performance Computer (HPC) and its network, satellite remote sensing observation, etc. It could be said that the concept of digital earth was relatively earlier introduced in the NWP area.

A "digital atmosphere" with NWP method, as a part of digital earth, will be discussed in this paper. The digital atmosphere is divided by "primitive observed atmosphere", "initialized atmosphere for NWP model", "predicted atmosphere by NWP model". The operational NWP development history is as well as briefly presented.

1. Introduction

Since V. Bjerknes (1904) gave a first step towards a fundamental theory of Numerical Weather Prediction (NWP), a "hazy" concept of "digital earth" was introduced in meteorology. According the NWP approach, it was recognized that using a numerical method, the problem of predicting atmosphere is fundamentally an initial-value problem in mathematics physics, and that the future states of atmosphere can be determined by application of the physical laws governing it's behavior. It means that weather would be predicted by treating the atmosphere as discretion, in other word, a "digital atmosphere".

Based on the theorem of V. Bjerknes (1904), L.F.Richardson (1921)[1]made his pioneering efforts to make a first weather map prediction by using a 10-inch slide rule and a table of five-place logarithms. Even though he failed in his attempt, his discouraging results were published in a special book by Cambridge University Press. The lack of meteorological (in particular, upper air) data information, and the gross inadequacy of computational facilities are two major causes of his failure.

In fact, the invention of radiosonds, which resulted in the widespread use of upper air data in 1930s, and the invention of the electronic computer in late 1940s, which provided an efficient computational tool, both let to produce a first successful numerical prediction of geopotential height field at 500hPa by Charney, Fjörtoft and Von Neuman (1950) [2] with a simplified barotropic model using the invented electronic computer at Princeton University.

In 1954, a joint group from USA-air force, navy and weather service was set up for NWP research. It marked the beginning of systematic and operational development of NWP.

In the past century, especially in the most recent 20～30 years, with the increasing development of HPC techniques (peak-performance and memory), Numerical Weather Prediction was significantly advanced. A lot of countries in the world (USA, UK, France, the countries of Europe Union, Canada, Japan, China, Australia, India) established one after one their own NWP centers. NWP became a key-method and key-way for daily weather forecasts[3]. Among the existing NWP models, two major kinds of models can be distinguished: Global NWP Models (GM) and Regional NWP Models (RM) (or limited area NWP models). The former means that the models' domain covers global earth-atmospheric sphere, and it has not the lateral boundary; the latter means that the models' domain is limited in an interesting area[4]. With increasing development of HPC and increasing quantities of meteorological observations, NWP's accuracy will be further raised. It will play a more and more essential role in weather forecasts for taking precaution against and lightening meteorological calamities, large en-gineering and public services.

The purpose of this paper is to discuss how the concept of digital earth is applied in NWP field by posing a "digital atmosphere". In first section, we will give a brief review on the NWP's development history and its important role in present daily weather prediction; the meteorological observation system and "primitive observed atmosphere", data analysis and assimilation system and "initialized atmosphere", NWP model and "predicted atmosphere" will be discussed in sections 2～4, respectively. Finally, some remarks and general discussion will be presented in section 5.

2. Meteorological Observation System and Primitive Observed Atmosphere

It began long ago to cloud observation and simple weather prediction in human activity against natural disasters. Nobody could exactly explain the beginning of the meteorological observation. However, meteorology could not be considered as a "real science" before invention of barometer (Torricelli, 1643), by which atmosphere was at first time quantitatively observed as pressure parameter. From then on, local weather was qualitatively analyzed with the pressure element. About 180 years latter, the first pressure map was draw in 1820: a first "*primitive observed atmosphere*" map.

Meteorological observation system is globally established in wide cooperation of the world under coordination of World Meteorological Organization (WMO) for the major purpose of meteorological science research, meteorological disaster monitoring and meteorological prediction (including numerical weather prediction). It also preciously provide historic records of atmosphere to utilization of our future generations.

Today's meteorological observation system is much more modern. It is composed of surface, radiosond, radar, remote sensing, satellite, airplane, ship observations. The observed atmospheric elements include temperature, pressure, humidity, wind, weather, visibility, satellite images (visible, infrared, water vapor, micro-waves), radar echoes, etc. And Global Positioning System will become an important meteorological observation data source in coming future for meteorological science. The observation data sets from all stations around the world are transferred and exchanged effectively by a huge Global Telecommunication System (GTS) of WMO. We can receive about 40000 observation reports per day in National Meteorological Center/China Meteorological Administration (NMC/CMA). A network of global surface observation stations is illustrated in Fig.1.

3. Data Analysis and Assimilation System And Initialized Atmosphere

It is known that the primitive observation data sets are inhomogeneous in time and space (horizontal as well as vertical). It is necessary that the data sets would be homogeneously analyzed by interpolating in grid points of the model. They also have to be assimilated at the same initial time for NWP: generating a "*initialized atmosphere*". Data analysis and assimilation is one of the most effective initialization technique to obtain a high quality initial data of NWP model.

The so-called "data analysis and assimilation" is defined as: the observation data sets are analyzed and merged into the first guess from the model predicted fields, in keeping them within the bounds of atmospheric physics and statistical cha-racteristics, in order to assimilate all kinds of observation data with NWP model. This process could be cycled four times per day to generate the "most harmonized initial values" of NWP model. Since 1980s, the progressive correction method (called "Cressman's method), Optimal Interpolation (OI) method and Variational Assimilation (VAR) were operationally used in many meteorological centers of the world. The 3 Dimensional-VAR (3D-VAR) and 4 Dimensional-VAR (4D-VAR) are the most advanced techniques in present. The Kalman Filtering (KF) will become a major method for next generation of data analysis and assimilation. The so-called "variational assimilation" means that the unconventional observation data (i.e., satellite radiance observation data, remote-sensing data) is directly (without retrial) merged by using a variational method into the analysis and assimilation system. 3 Dimensional-VAR (3D-VAR) and 4 Dimensional-VAR (4D-VAR) were operationally implemented in NCEP/USA, ECMWF, France and Canada[3].

A cycle of Global Data Assimilation System (GDAS) is showed in Fig.1: All observational data are received from Global Telecommunication System (GTS), decoded and put into the real-time Element Data Base (EDB). All kinds of observational data, which are the SYNOP from land stations, SHIP, TEMP, PILOT, SATEM, SATOB, DRIBU and AIREP data, in form of the BUFR file are first extracted from EDB whenever starts the data assimilation job. They are preprocessed and quality-controlled, and then an Analysis Observation File (AOF), which compacts all kinds data mentioned above, used in the subsequent analysis step are formed. Using all of these data preprocessed, the height and wind are incrementally analyzed with a 3-D multivariate Optimum Interpolation (OI) method in the gaussian type of the grid points on the 15 mandatory pressure levels, and similarly the relative humidity is done but a 3-D univariate OI method. The analyzed increments are then added to the first guess fields on the levels of the model. The incremental method used for analyses can obviously reduce the interpolating errors. Actually, the analyses are proceeded in a large volume of space which can include lots of analysis grid points, just like that done at the previous version of analysis scheme at ECMWF, that makes more observational data can be used to contribute to a point of analysis value. Finally the analyses are transformed to the spectral coefficients and provided to the forecast model.

4. Numerical Weather Prediction Model and Predicted Atmosphere

An operational NWP system is composed of data pre-processing, analysis and assimilation, model forecast and post-processing. The “model forecast” is an essential component in a NWP system for “weather prediction”, in other word, for generating “*predicted atmosphere*”.

NWP basic idea[5]: given an initial atmospheric conditions, the mathematics physical equations, which govern the behavior of atmosphere, are solved by using numerical methods of discretion, so that the weather in future time could be “exactly calculated”. The numerical discretion of NWP is a process to generate a “digital atmosphere”. The atmospheric space above the earth surface is divided in box by box (called “grid point”), the length of forecast time is divided in step by step (called time step). Then, the integration is performed grid-point by grid-point and step by step. In general, the box size is about 10～100km, and the time step is about 1～60minutes. It is obvious that the calculation times are enormous. It absolutely has to request super-computer to accomplish this huge task. For this reason, “numerical weather prediction” can be popularly called as “weather forecast by computer”.

In theory, a “predicted atmosphere” could “tell us” all weather information (wind, rain, temperature, humidity, cloud, etc.) in any future time within a forecast period and in any point within a modeling domain. There are in world many operational NWP models with horizontal resolution from 20～80km, vertical resolution of 20～60 levels, and the highest top of the model can reach the stratosphere. However, the observation errors, the rare resolution of observation network, the model simplified hypothetical errors, the no-linearity of atmosphere, and their interactive influences will always result in “un-deterministic” predictions. We just can obtain a “approximated weather forecast”.

In China, it was not too late (in 1954) to begin our NWP development project. The first Chinese NWP map was made as a “gift” to the 10th anniversary of New China: a geopotential field map, which covers the Europe-Asia region and North hemisphere, was predicted by using a “filtered model” and a Chinese electricitic computer. Table-1 give a brief review of development of NWP systems in NMC/CMA. Table -2 is similar than Table-1, but just in future of 5～８years[6].

5. Remarks And Discussion

The problem of digital earth in meteorological science was discussed through “primitive observed atmosphere”, “initialized atmosphere” and “predicted atmosphere”. The primitive observed atmosphere is a record of real atmosphere. Its quality depends upon the observation technical level. It is a precious “treasure” to be archived for long time. The initialized atmosphere is not a real atmosphere. It needs both to be approach to real atmosphere and to be harmonious with numerical model. Its quality depends on the observation quality, as well as on the analysis and assimilation technical level. The predicted atmosphere is a “*prophecy*” of atmospheric state in future time. The performance and the initial value quality of numerical model is essential to “*prophesy*” an atmosphere which is much more approach to real one. However, there is always some differences between the predicted atmosphere and the real one due to the observation errors, the model errors and the no-linearity of atmosphere.

The atmosphere is an important component of an earth system. There are complex influences on radiation, evaporation and land-atmosphere in global energetic and water cycle. There are tight relation of inter-disciplines of meteorological science, geographics, hydrology, oceanography, biology and environmental science, etc. However, the numerical prediction depends on mathematics, physics, chemistry, high performance computer. Hence, a problem of NWP is an inter-discipline complicated problem[7].

In addition, with progress of space techniques and space discovery, we would recognize that the digital Earth meteorological problem just is a “small” problem of all digital space meteorological problems. We will encounter digital Moon meteorological problems, digital Venus meteorological problems, digital Mars meteorological problems, etc. The concept of digital Earth meteorology will be further developing. However, the theory and experiences of meteorology will become a research base for space meteorology. In lack of “meteorological” data sets in other celestial bodies, NWP technique would be a good and effective method of simulation.

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Time	**Models**	**Grid size**	**Vert. Levels**	**Ana. & assi.**	**Area**
July 1980 to May 1983	A-model	300km	3-P-levels	Cressman	Europe-Asia
Feb. 1982 To Dec. 1999	B-hemisphere model	381km	5-σ levels	Cressman	N-hemisphere
June 1982 To March 1992	B-L.A.M.	190km	5-σ levels	Cressman	Asia
June 1991 To June 1995	T42L9	320km	9-σ levels	OI	Global
March 1992 To April 1995	LAFS	200km	15-σ levels	OI	Asia
June 1995 To May 1997	T63L16	200km	16-η levels	OI	Global
May 1995 To March 1998	HLAFS	110km	15-σ levels	OI	Asia
June 1997 To 1999	T106L19	120km	19-η levels	OI	Global
April 1998 To Sept. 1999	HLAFS	60km	20-σ levels	OI	Asia

Table-1 A brief review of the operational NWP systems in NMC/CMA

Time	**Models**	**Grid size**	**Vert. Levels**	**Ana. &Assi.**	**Area**
June 2000	T239L31	55km	31-η levels	3D-VAR	Global
June 2001	V-LAFS	25km	31-σ levels	OI	Asia
June 2001	NH-Meso	10～15km	31-σ levels	Dyn. Nudging	BJ-region
June 2005	NH-Meso	5km	40-h-levels	4D-VAR	Asia
June 2005	T618L31	25km	40-η levels	3D-VAR	Global
June 2008	Meso-global	20km	40-h-levels	4D-VAR	Global

Table-2 Development project for the operational NWP systems in NMC/CMA

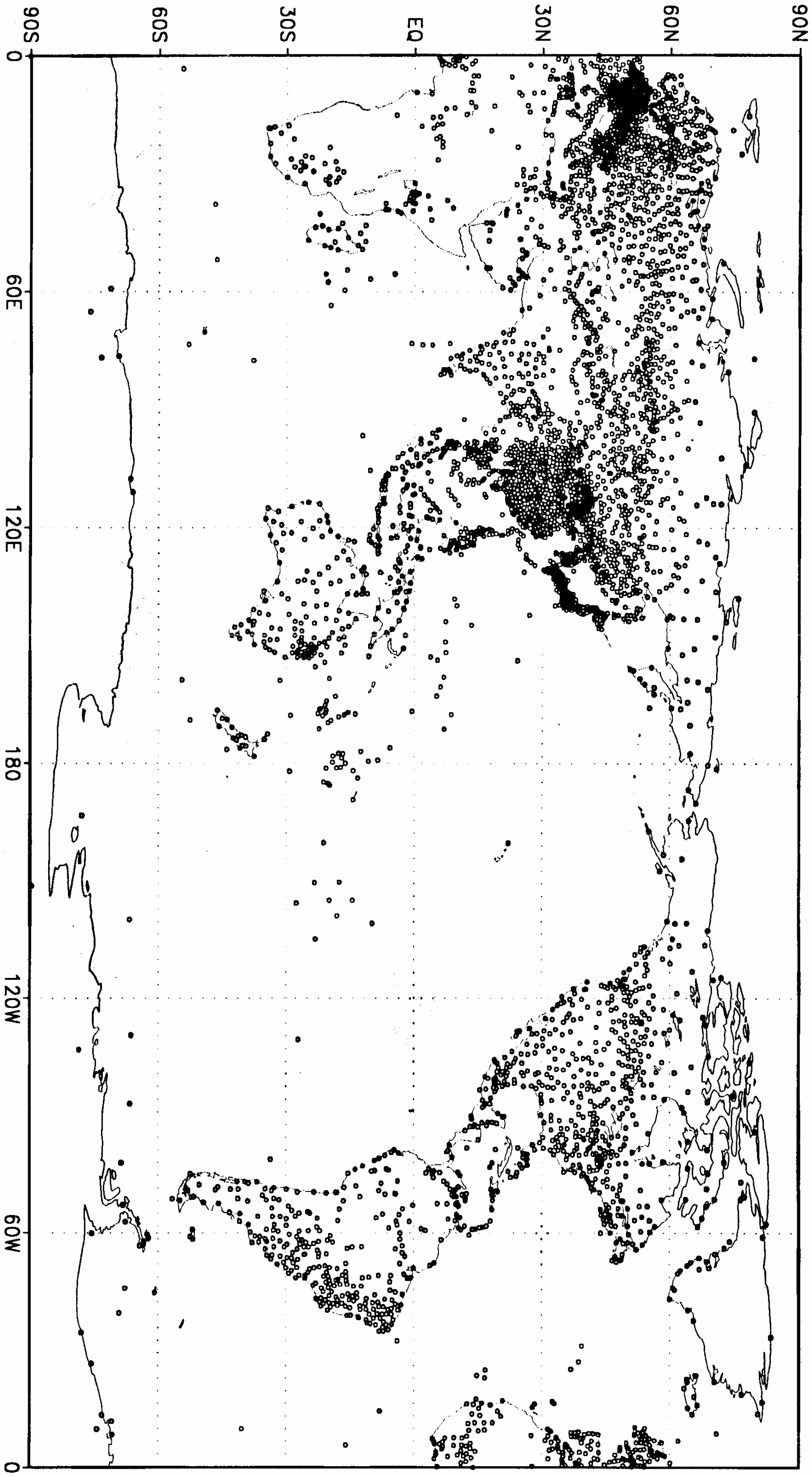

Figure-1 OBSERVATIONS DISTRIBUTION

Obs Type: SURF:land No. of Obs: 6588 Date&Time: 98040100

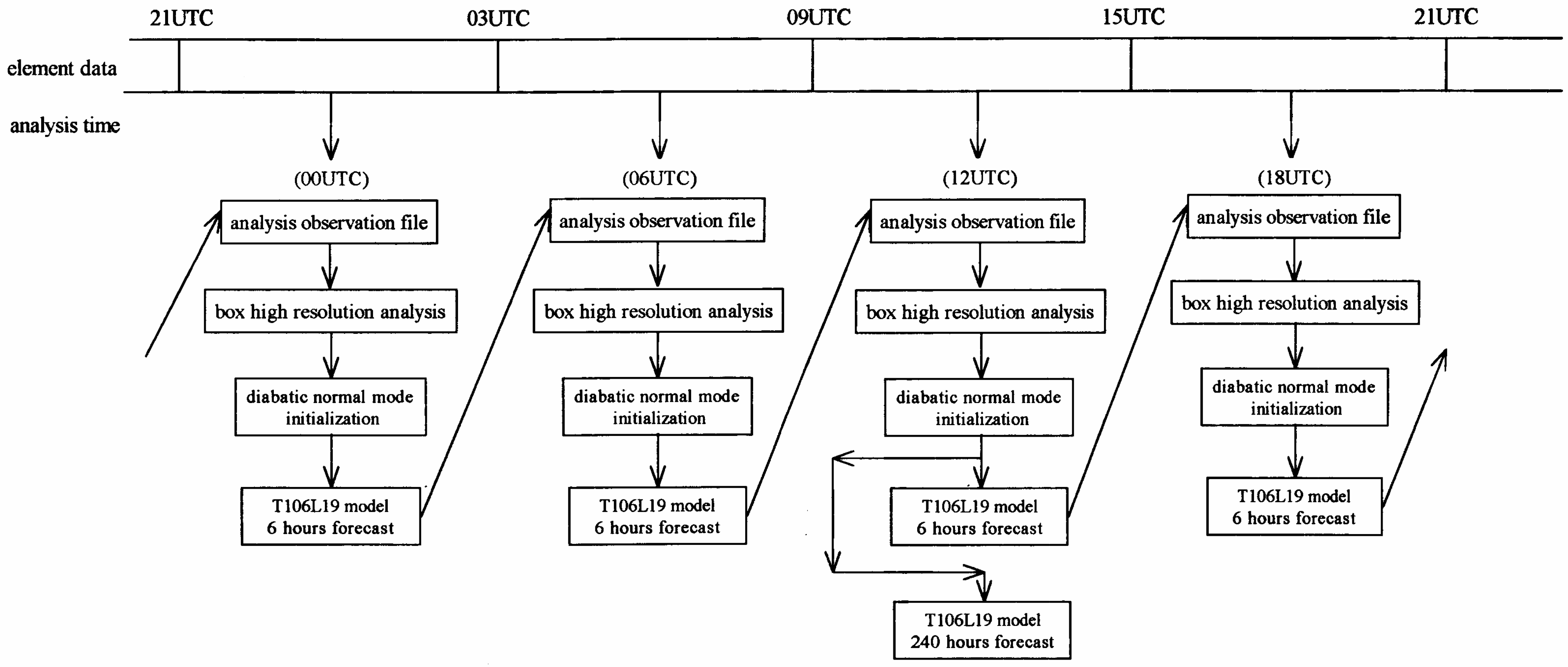

Figure-2 global data assimilation system flow chart