Introduction to Meteorology

34 Numerical weather prediction

Introduction

Currently, most weather forecasts are produced by using computers. We solve complex equations that govern the atmospheric motions utilizing computers to predict the weather based on observations of temperature, wind, water vapor, collected from thousands of locations around the world. The forecasting of future atmospheric conditions is called numerical weather prediction (NWP) and is the core of modern weather forecasting. “Numerical” does not simply mean "number", however, it stands for that the principles, processes, and results of predictions are quantitative on the basis of on numerical methods. We will talk about the basic principles and features of the NWP.

Contents

1. Numerical weather prediction model
2. Principles of numerical weather prediction model
3. Numerical forecasting process

Learning objectives

1. Describe the basic principles of NWP model.
2. Describe the coordinate system used in the model.
3. Describe the types and advantages/disadvantages of the NWP model.
4. Describe the boundary conditions required for the NWP model.
5. Describe the modeling process and parameterization principles.

Learning Activities

1. Numerical weather prediction (NWP) model

1) History of NWP model

NWP is a series of processes that numerically integrate the governing equations for the dynamical and physical principles of the atmospheric phenomena using a computer and analyze the present state and then predict the future weather conditions quantitatively.

British meteorologist, Richardson in 1922, argued that weather forecast can be produced by solving the governing equations with numerical methods rather than analytical methods.

He attempted to predict the surface pressure after 6 hours using observations, but it resulted in an unrealistic increase in atmospheric pressure of 60hPa in 6 hours.

It turned out that the large error was caused by a combination of various factors, such as lack of observation data, lack of analytical and numerical solution techniques.

The era of numerical forecast began in the 1950s, as the development of computers has gradually

improved these problems. In particular, Charney (1948) and scientists in Princeton University played leading roles.
They emphasized a simplification of governing equations with respect to the complexity of the atmospheric phenomena and developed a quasi-geostrophic model to solve problems.

Subsequently, Charney and Eliassen (1949) quantitatively predicted the disturbances of the middle latitude westerlies and proved the possibility of numerical forecasting.

Learning Activities

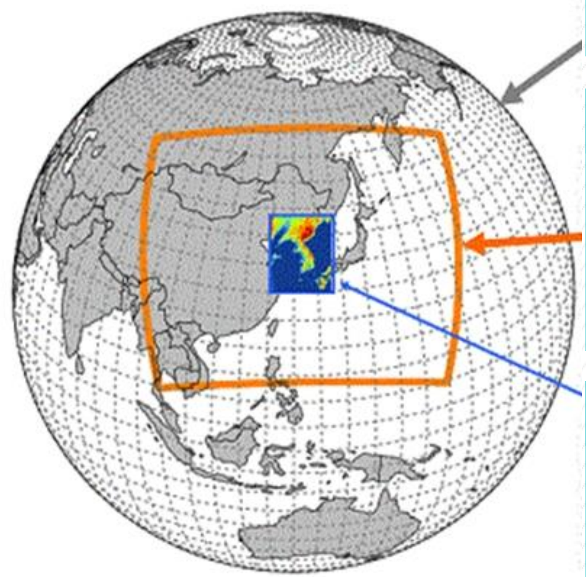
1. Numerical weather prediction (NWP) model

2) Types of NWP models

NWP models currently used for operations can be categorized into three according to what to predict.

First, a general circulation model (GCM) simulates the global changes of the ocean and atmospheric conditions in the troposphere and lower stratosphere. Korean Meteorology Administration (KMA) runs 40 or 25 km GCM for the extended-range forecast (〉10 days) and seasonal forecasts (〉 1 month).

A regional prediction model is most widely used for weather prediction of specific regions such as East Asia. For the regional prediction model in KMA, the horizontal resolution is about 12 km and the lead time is 72 hours. Regional forecast requires forecast information outside the region simulated by the GCMs.



General circulation model

- 25km horizontal resolution
- 70 vertical levels (80km)
- 12 days forecast
- 4DVAR

Regional prediction model

- 12km horizontal resolution
- 70 vertical levels (80km)
- 87 hours forecast
- 4DVAR

Local prediction model

- 1.5km horizontal resolution
- 70 vertical levels (40km)
- 36 hours forecast
- 3DVAR

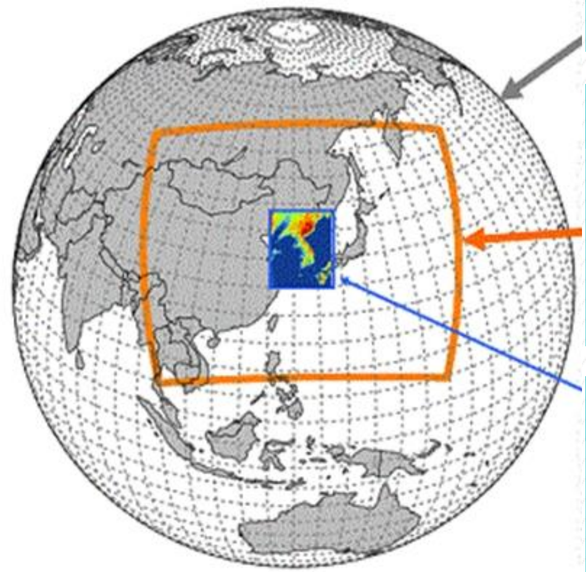
Learning Activities

1. Numerical weather prediction (NWP) model

2) Types of NWP models

A local prediction model is used to predict local and detailed weather variations, which are particularly affected by terrain. The model used in KMA has 1.5 km horizontal resolution and produces 36 hours prediction. For the information outside the specific area, it uses the prediction output from the regional prediction model.

Also, there are some models that are purpose-tailored, such as models for predicting ocean waves, fog, and aerosol.



General circulation model

- 25km horizontal resolution
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Regional prediction model

- 12km horizontal resolution
- 70 vertical levels (80km)
- 87 hours forecast
- 4DVAR

Local prediction model

- 1.5km horizontal resolution
- 70 vertical levels (40km)
- 36 hours forecast
- 3DVAR

Learning Activities

2. Principles of NWP model

For numerical forecasting, the atmospheric motion must be structured for computer program processes. To achieve this goal, the meteorological variables should be divided into grid boxes, and representation of the atmospheric properties in each grid box should be as realistic as observed.

The atmospheric motion on a grid point is driven by the sum of all the forces acting on it, and the values of state variables in a grid point, such as temperature, pressure, and humidity, indicate the averaged value which changes over time.

Learning Activities

2. Principles of NWP model

By constructing a system of equations governing the atmosphere and expressing it numerically for computation, we can predict the future on the basis of three-dimensional data.

Equation of motion	$\frac{\partial \boldsymbol{V}}{\partial t} = -\boldsymbol{V} \cdot \nabla \boldsymbol{V} - \omega \frac{\partial \boldsymbol{V}}{\partial p} + f\boldsymbol{k} \times \boldsymbol{V} - \nabla \Phi + D_M$
Thermodynamic equation	$\frac{\partial T}{\partial t} =- -\boldsymbol{V} \cdot \nabla T + \omega \left(\frac{kT}{p} - \frac{\partial T}{\partial p} \right) + \frac{\overline{Q_{rad}}}{c_p} + \frac{\overline{Q_{con}}}{c_p} + D_H$
Moisture budget equation	$\frac{\partial q}{\partial t} = -\boldsymbol{V} \cdot \nabla q - \omega \frac{\partial q}{\partial p} + E - C + D_q$
Continuity equation	$\frac{\partial \omega}{\partial p} = -\nabla \cdot \boldsymbol{V}$
Hydrostatic equation	$\frac{\partial \Phi}{\partial p} = -\frac{RT}{p}$

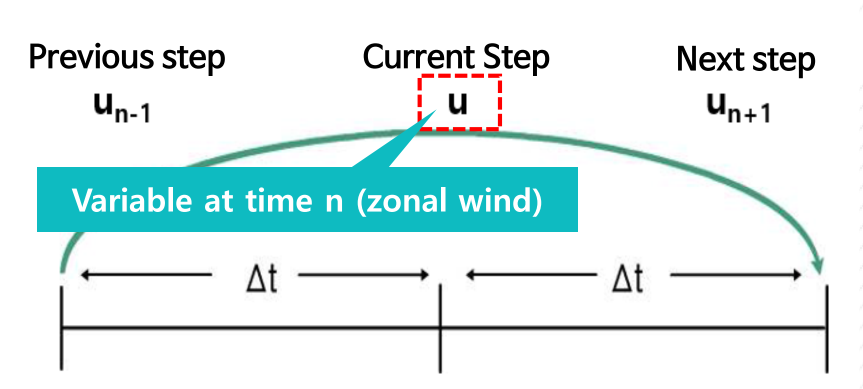
Physical processes related to convection, radiation, precipitation, turbulent mixing

Learning Activities

2. Principles of NWP model

1) Governing equation set

The equations governing the atmosphere are called "primitive equations", which include equations of motion, thermodynamic equation, moisture equation, continuity equation and ideal gas law. The terms Q, E, and C on the right side are related to physical processes such as convection, radiation, precipitation, turbulent mixing, etc. These terms are calculated using physical parameterization.



How can we use these differential equations to predict future values? Let's assume a variable u (zonal wind) at time n. We will predict the u from one step back (n−1) to the current (u) and to one step forward (n + 1).

Learning Activities

2. Principles of NWP model

1) Governing equation set

This problem can be easily solved by the following process. ⊿t is the time interval, for example, 20 minutes, 10 minutes. The tendency of u (rate of change of u) is needed to predict u_{n+1}. This can be calculated from the equation of motion of the primitive equations. The x−momentum equation can be simplified by assuming the geostrophic balance.

$$u_{n+1} + u_{n-1} + 2\Delta t\left(\frac{\partial u}{\partial t}\right)_n$$

Tendency of u

Zonal wind (u) at time n+1

Δt time interval (example : 20 min, 10 min)

Momentum equation

$$\frac{\partial V}{\partial t} = -V\cdot\nabla V - \omega\frac{\partial V}{\partial p} + fk\times V - \nabla\Phi + D_M$$

Simplified x-momentum equation

$$\frac{\partial u}{\partial t} = fv - \frac{1}{\rho}\frac{\partial p}{\partial x}$$

Coriolis force

The meridional wind (v), density of air (ρ), and pressure gradient at time n.

f constant

Tendency of u

Pressure gradient force

Learning Activities

2. Principles of NWP model

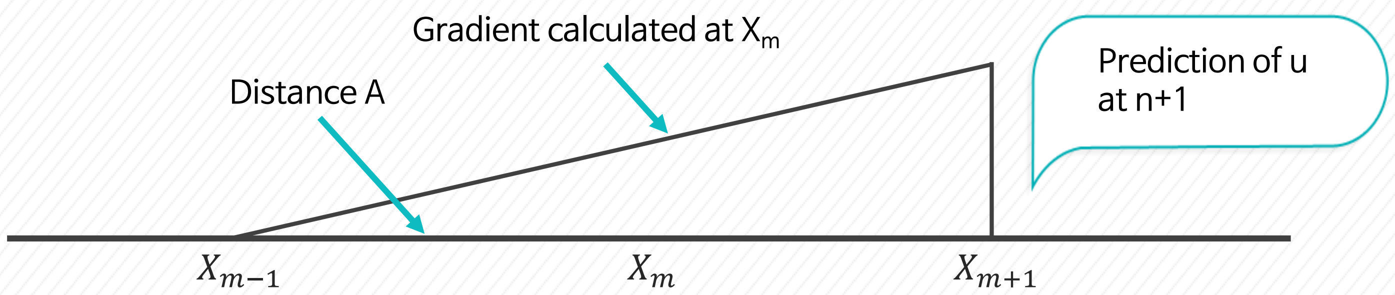
1) Governing equation set

In this equation, the left hand side is the rate of change u that we need to calculate. The first term on the right hand side is the Coriolis force, and the second term is the pressure gradient force. Since f is a constant, we can obtain the tendency of u if we have the values of meridional wind (v), air density (ρ), and pressure gradient at time n. Then, the wind (u) at time n+1 can finally be calculated.

Calculation of the pressure gradient by spatial distribution of pressure

Pressure gradient at grid point xm with grid spacing Δx(example: 40km, 10km)

$$\left(\frac{\partial p}{\partial x}\right)_m = \frac{p_{m+1} - p_{m-1}}{2\Delta x}$$



⟨Discretization in space⟩

Learning Activities

2. Principles of NWP model

1) Governing equation set

Next, we will calculate the pressure gradient from the pressure distribution. For example, the pressure gradient at point x_m with interval ⊿x (40km, 10km) can be approximated as shown in the figure. Using the observed pressure at point X_{m-1}, X_m, X_{m+1}, the pressure gradient at X_m can be obtained and used in the x-momentum equation to derive the acceleration term. Finally, we get u at the n+1 time step and further.

Learning Activities

2. Principles of NWP model

2) Model resolution

The atmospheric motions ranges from molecular to planetary scales. Due to the limited computing resources and observation, small processes cannot be explicitly represented in the models.

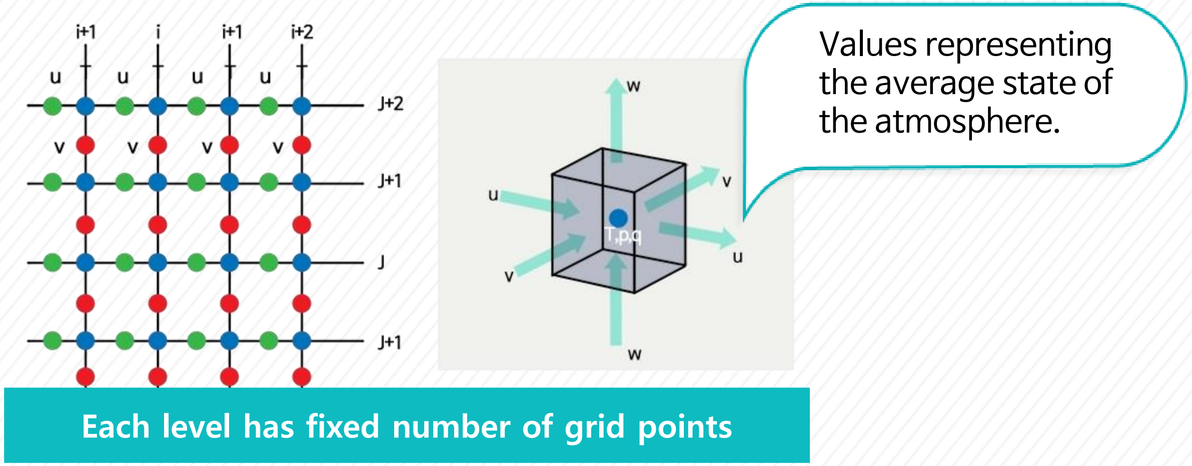
Horizontal resolution is the distance between grid points. The higher the spatial resolution, the smaller the meteorological phenomena that the numerical model can simulate.

In general, the resolution of a model is determined by the performance of the computer, the domain size, and the size of the smallest meteorological phenomenon the model attempts to simulate. The model resolution can increase with better computer performance, smaller domain, and smaller phenomenon.

Learning Activities

2. Principles of NWP model

2) Model resolution



〈Grid points and grid boxes〉

The models have vertical levels. Each vertical level has a fixed number of grid points relative to the Earth's surface. The number of vertical levels determines the vertical resolution of the model. Each grid point has values representing the average state of the atmosphere.

By calculating each term of the primitive equation from the current state, we can predict the future state. As the time intervals are shorter, such as 10 minutes or 30 seconds, more stable and detailed results can be obtained. However, if the model is integrated for a longer time, the calculation will take too long. If this time interval is large, stability problems can lead to inaccurate and unstable results. These time intervals are referred to as temporal resolution.

Learning Activities

2. Principles of NWP model

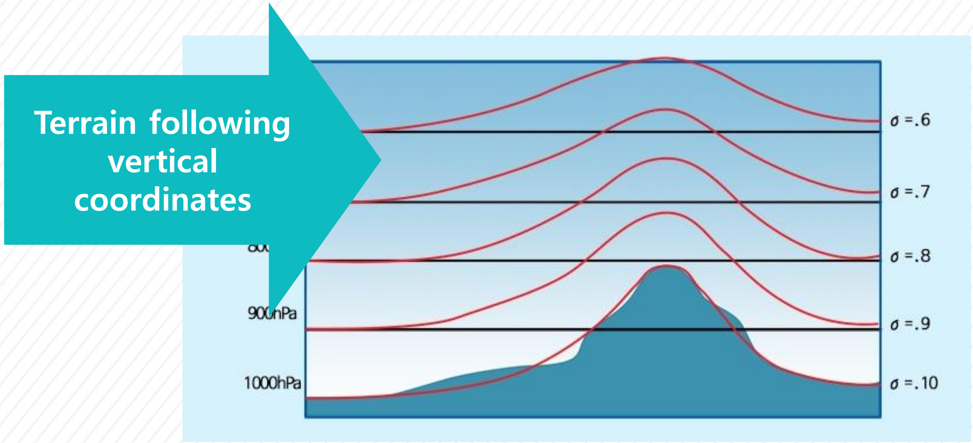
3) Coordinate system

The observations are made at regular time intervals in 3D space. The vertical coordinate system used in models are terrain following vertical coordinate systems instead of the commonly used z and p coordinate systems.

The main reason for not adopting either z or p coordinate systems for the vertical coordinate system is because the Earth is not flat. The model cannot calculate the spatial derivative consecutively in the region with mountains.

To solve this discontinuity problem on vertical coordinates, Phillips developed a terrain following sigma coordinate system. It is a vertical coordinate for atmospheric models defined as pressure normalized by its surface value, which allows for continuous fields to be represented smoothly at the lower layers in the model.

The sigma coordinate or a slightly modified η-coordinate are used in most of numerical models in KMA. η-coordinates use a sigma coordinate system near the ground, and use a z-coordinate system above a certain altitude.



⟨Sigma coordinate⟩

Learning Activities

3. Numerical forecasting process

3) Coordinate system

If we use the governing equations programmed into a computer, this becomes what we call a "numerical model". Let's take a closer look at the process of producing forecasts with the numerical model.

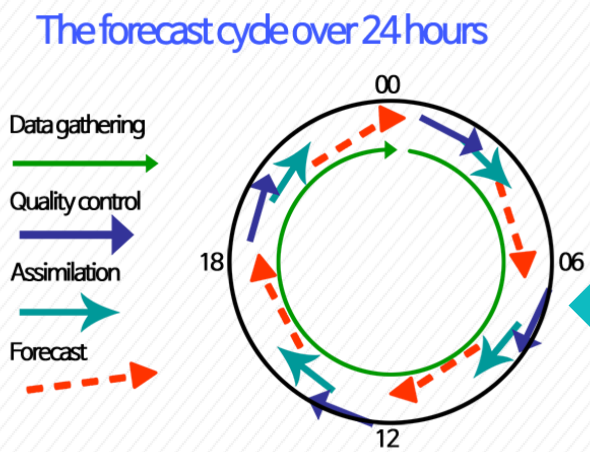
The first step of producing forecasts includes the collection, quality control, and data assimilation of observational data. We convert meteorological data collected from a large number of sources in real time to the grid system of the model. Data obtained from various sources are first subjected to quality control process. Then, they are finally assimilated, taking into account errors and physical balances between variables.

Missing values can be replaced by interpolation or extrapolation with the surrounding values. Data assimilation is a process of creating model initial conditions from observations and the predicted field (first guess field).

Learning Activities

3. Numerical forecasting process

3) Coordinate system



Numerical forecasting process

This figure shows a cycle of numerical forecasting processes that are repeated throughout the day. Data collection, quality control, data assimilation, and forecasting are carried out sequentially.

The huge size of predicted three-dimensional variables is finally transmitted to the forecaster.

However, the predictions are not perfect. There are errors in the observational data, data assimilation process, and numerical models. Therefore, the forecaster produces a final forecast based on his/her experience and statistics when interpreting the results from the numerical model.

Summary

1. Numerical forecasting model

- NWP is a series of processes that numerically integrate the governing equations for the dynamical and physical principles of the atmospheric phenomena using a computer and analyze the present state and ultimately predict the future weather conditions quantitatively.
- NWP models currently used for operations in KMA can be classified into general circulation model, regional prediction model, and local prediction model, according to the phenomena to be dealt with.
- The general circulation model simulates the global changes of the ocean and atmospheric conditions in the troposphere and lower stratosphere.
- The regional prediction model is the most widely used model for weather prediction
- Local prediction model is used to predict local and detailed weather variations, which are particularly affected by terrain.

Summary

2. Principles of numerical weather prediction model

- For numerical forecasting, the atmospheric motion must be structured to be processed by a computer program.
- The higher the spatial resolution, the smaller the meteorological phenomena that the numerical model can simulate.
- Besides the z and p coordinate systems, there are terrain following, sigma coordinate, eta coordinate, and hybrid coordinate systems.

Summary

3. Numerical forecasting process

- The initial condition is made through the process of data collection, quality control, and data assimilation.
- The initial condition is used as the starting point for the model integration.
- The forecaster makes a final forecast based on experience and statistics when interpreting the results from the numerical model.