Research on lightning numerical prediction

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Abstract. In this paper, the numerical lightning prediction G model (abbreviated as LNP-G1) established by the cumulus electric field model breaks through the traditional statistical prediction model of experience plus linear extrapolation, and adopts the dynamic model based on the objective development law of cumulus cloud for the first time, thus realizing the lightning prediction in the real sense. It is certain that with the application of LNP-G in business, it will provide timely and advanced lightning objective numerical forecast for marine ships, aerospace, rocket launch, forest fire prevention and other industries, so as to avoid or reduce the major harm caused by lightning.

1. Introduction

Lightning (lightning) is a long-distance instantaneous discharge phenomenon in thunderstorm weather [1]. The physical effects of lightning, such as large peak current, high peak power, extreme high temperature, strong electromagnetic radiation and shock wave, especially cloud to ground lightning, will damage ground buildings, forests, power and electronic equipment, navigation, aerospace, communications, and even threaten human life. Therefore, it is of great significance to provide accurate and efficient lightning forecast in time, so as to protect the possible disasters caused by lightning in advance, and guarantee the development of national economy.

At present, most of the lightning alerts are based on the lightning location data, linear extrapolation by superimposing radar data, and search for the statistical correlation of meteorological elements related to lightning, Takahashi [2] (1974) added the relationship between volume charge and precipitation particles in one-dimensional time-varying cumulus model. Rawlins [3] (1982) for the first time added the non-inductive electrification parameterization formula to the three-dimensional cloud model.

Yair et al. [4] (2010) and Lynn et al. [5] (2012) proposed a dynamic lightning prediction method. The method is based on the generation rate of potential electric energy in convective and stratiform clouds. Every time the electric energy exceeds the threshold, a lighting event will occur, and then it will be accumulated for each model time step. The charge dissipation caused by turbulence and the change caused by horizontal transmission are also considered.

In China, Chen pointed out that the positive and negative electric fields in cumulus are closely related to the phase transition of particles in cloud[6]. Zhai et al[7], proposed that lightning intensity is closely related to wind shear. Yamuhong et al [8] (1996) established a two-dimensional time-varying axisymmetric model for the development of cumulus dynamics and electricity. Zhang et al [9] (1999) introduced the parametric discharge scheme into the two-dimensional axisymmetric dynamic electric
coupling mode. Sun[10] established a three-dimensional numerical model of thunderstorm dynamic electric coupling.

In conclusion, seldom numerical prediction of lightning has been. At present, linear extrapolation based on lightning location data and radar data, as well as finding statistical correlation of meteorological elements related to lightning, so as to achieve early warning of lightning. This paper will establish the lightning numerical prediction g1 model (abbreviated as lnp-g1) based on the dynamic model of the objective development law of cumulus cloud, so as to break through the traditional statistical prediction model of experience plus linear extrapolation and realize the real lightning objective prediction.

2. Establishment of dynamic equations

(1) Set up g equations based on the g model of lightning dynamics

a. Navier Stokes equation of motion [11]

\[
\begin{align*}
\nabla \cdot V &= 0 \\
\frac{\partial V}{\partial t} + (V \cdot \nabla)V &= -\frac{1}{\rho} \nabla P + \frac{1}{\rho} \nabla \cdot \tau
\end{align*}
\]

(1)

Among them, \( P \) is Pressure, \( \tau \) is a viscous stress vector.

b. Thermodynamic equation [12]

\[
\frac{d \ln \theta}{dt} = \frac{\dot{Q}}{C_p T}
\]

(2)

among \( \theta \) is a potential temperature, \( \dot{Q} \) is the heating rate of the air mass, \( T \) is the temperature.

C. Air pressure equation [13]

Then there are the following pressure prediction equations:

\[
\frac{d \pi'}{dt} + \frac{C^2}{C_p \rho \theta_x} \frac{\partial \rho \theta_x u_j}{\partial x_j} = - \frac{R_d}{C_v} \pi' \frac{\partial u_j}{\partial x_j} + \frac{C^2}{C_p \theta_x} \frac{d \theta_x}{dt} + D_{\pi'}
\]

(3)

Here, \( \pi' \) is the dimensionless pressure disturbance momentum, where \( C \) is the adiabatic sound velocity, \( D_{\pi'} \) is a sub grid scale term.

d. Conservation equation of water matter:

Water substances are divided into seven categories: water vapor, cloud water, rain water, ice crystal, snow, graupel and hail. There are 12 water matter prediction equations in the model, namely, the specific water content equation of water vapor, cloud water, rain water, ice crystal, snow, graupel and hail, and the specific concentration equation of rain water, ice crystal, snow, graupel and hail

\[
\frac{d Q'_x}{dt} = S_{Q'_x} + D_{Q'_x} + \frac{1}{\rho} \frac{\partial}{\partial z} \left( \rho Q'_x V'_x \right)
\]

(4)

\[
\frac{d N'_x}{dt} = S_{N'_x} + D_{N'_x} + \frac{1}{\rho} \frac{\partial}{\partial z} \left( \rho N'_x V'_x \right)
\]

(5)

The first term on the right side of the above equation is the source sink term of the microphysical electrification process, the second term is the Reynolds average turbulent flux, the third term is the rate of gravity settlement and displacement of precipitation aquatic products, \( V'_x \) is the final falling velocity of rain, ice crystal, snow, graupel and hail.
e. The electric field g equation of cumulus cloud is established. The contribution radius of cloud particles is defined as:

\[ r_{gi} = \frac{\pi \rho_i N_{oi}}{\rho_{oi}} \]  

(6)

\[ \gamma_E = 16\pi r_{gi}^{0.75} \left\{ 2Z + 1.5 \ln Q_i \right\} \]  

(7)

Among them of \( Q_i, \rho_i, \rho_{oi}, N_{oi} \) (\( i = 1, 2, 3, 4, \ldots \)) Represents cloud droplets, water droplets, ice crystals, graupel) are the mixing ratio, air density, particle density and number density of each particle in the cloud (here, the constant is approximately taken, and the integral number density is approximately used).

Based on the understanding of the nature of charge [14], the G equation of fluid electric field is established through the experiment of dripping electricity, and the G equation of cumulus electric field is obtained through mathematical derivation [15].

The left side of the above formula \( \gamma_E = \frac{E}{E} \) is the relative change rate of electric field, the right side, \( \dddot{Z} \) and \( \dot{Z} \) is respectively the acceleration and collision speed of particles in the cloud, and \( \ln Q_i \) is the logarithmic change rate of mixing ratio of particles in the cloud (water drop, ice crystal, graupel, hail). \( \dddot{Z} \ln Q_i \) is defined as the mixed specific charge rate, it reflects the speed of phase transition charge from a microscopic point of view.

The electric field g equation of convective cloud is obtained by convective

\[ \gamma_E = 16\pi r_{gi}^{0.75} \left\{ 2\left[ -\frac{\partial p'}{\rho_0 c^2} + \left( \frac{T'}{T_0} - \frac{p'}{p_0} + 0.61 q' - q_i \right) g + F_z \right] + 1.5 \dddot{Z} \ln Q_i \right\} + \alpha \]  

(8)

In the above formula, P is the air pressure, \( p_0, T_0, \rho_0 \) is the basic state physical quantity, \( p', T', q' \) respectively is the disturbance pressure, disturbance temperature and disturbance water vapor caused by cumulus convection, Z is the vertical height, G is the acceleration of gravity, \( q_i \) is the specific humidity, \( q_i \) is the specific water content, \( F_z \) is the turbulent viscosity force in the vertical direction.

The left side of the above formula is the relative rate of change of electric field. The first item in the right bracket (in the bracket) mainly reflects the magnitude of convective intensity (acceleration), which is the contribution of cloud particle's macro motion to the relative rate of change of electric field in the cloud. The second item in the right bracket mainly reflects the contribution of the logarithmic rate of change of mixing ratio of particles in the cloud and the collision speed of cloud particles to the charge of cloud particles. It reflects the contribution of microphysical process to the relative change rate of electric field in the cloud; the last item on the right is the interaction between the atmospheric electric field and the electric field in the cloud. The third effect is negligible. Therefore, the charge of thundercloud is closely related to the first two items.

3. Establishment of lightning objective numerical prediction g model

On the basis of the g model of lightning dynamics based on experiments, the output products of wrf numerical prediction are screened, and then the difference equation of lightning dynamics is established, and then the relevant elements are processed by programming language, so as to establish the lightning numerical prediction g model (abbreviated as LNP-G) in Figure 1.
4. Comparison of lightning numerical prediction model G products with the actual situation

Forecast by LNP-G mode: 2019.8.1 15:00 (07:00 in the world) in northwest Inner Mongolia, northeast Heilongjiang, eastern Jilin lightning. The result is in good agreement with the reality (Figure 2a yellow part).

Figure 1. Technical roadmap of lightning numerical prediction

Figure 2. The yellow (two slashes) in 2a is the lightning sign, and the red dot in 2b is the predicted lightning area.
Through LNP-G forecast: at 16:00 on August 2, 2019 (at 08:00 world time), there are lightning pictures Figure 3b in Daxinganling area in the north of Heilongjiang, Jiamusi Sanjiang Plain Area and Eastern Liaoning, which are in good agreement with the actual situation (yellow part of Figure 3a).

![Figure 3a](image1.png) ![Figure 3b](image2.png)

**Figure 3.** The yellow (two slashes) in 3a is the lightning sign, and the red dot in 3b is the predicted lightning area.

According to the lnp_g forecast, at 4:00 on August 3, 2019 (06:00 world time), lightning pictures 4B shows that in Heihe area in the north of Heilongjiang Province and the north of Inner Mongolia, which are in good agreement with the actual situation (yellow part of Figure 4a).

![Figure 4](image3.png)

**Figure 4.** The yellow (two slashes) in 4a is the lightning sign, and the red dot in 4B is the predicted lightning area.
According to the LNP-G forecast, at 23:00 on August 5, 2019 (15:00 world time), lightning pictures 5B shows that in Heihe area in the north of Heilongjiang Province and the north of Inner Mongolia, which are in good agreement with the actual situation (yellow part of Figure 5a).

![Figure 5](image1.png)

**Figure 5.** The yellow (two slashes) in 5a is the lightning sign, and the red dot in 5b is the predicted lightning area.

LNP_G1 was used to forecast lightning (Figure 6b) in the northern area of Greater Khingan Mountains at 13:00 (05:00 UTC) on May 21, 2020, which fits well with the actual situation (Figure 6a).

![Figure 6](image2.png)

**Figure 6.** The yellow (two slashes) in 6a is the lightning sign, and the red dot in 6b is the predicted lightning area.

LNP_G1 was used to forecast lightning (Figure 7b) in the northern part of The Greater Khingan Mountains at 17:00 (9:00 UTC) on May 21, 2020, which fitted well with the actual situation (Figure 7a).
Figure 7. The yellow (two slashes) in 7a is the lightning sign, and the red dot in 7B is the predicted lightning area.

LNP_G1 was used to forecast lightning (Figure 8b) in northeast Heilongjiang province at 15:00 (07 UTC) on May 27, 2020, which fits well with the actual situation (Figure 8a)

Figure 8. The yellow (two slashes) in 8a is the lightning sign, and the red dot in 8b is the predicted lightning area.

LNP_G1 was used to forecast lightning (Figure 9b) in northeast Heilongjiang province at 16:00 (08 UTC) on May 27, 2020, which fits well with the actual situation (Figure 9a)
Figure 9. The yellow (two slashes) in 9a is the lightning sign, and the red dot in 9b is the predicted lightning area.

LNP-G1 was used to forecast lightning (Figure 10b) in the western Greater Khingan Mountains and eastern Inner Mongolia at 15:00 (0700 UTC), on May 30, 2020 which fits well with the actual situation (Figure 10a).

Figure 10. The yellow (two slashes) in 10a is the lightning sign, and the red dot in 10b is the predicted lightning area.
LNP_G1 was used to forecast lightning (Figure 11b) in the western Greater Khingan Mountains and eastern Inner Mongolia at 17:00 (09 UTC) on May 30, 2020, which fitted well with the actual situation (Figure 11a).

Figure 11. The yellow (two slashes) in 11a is the lightning sign, and the red dot in 11b is the predicted lightning area.

5. Conclusion
1. The prediction products of LNP_G1 mode fit well with the actual thunderstorm.
2. It is proved that the cumulus electric field G model is correct and scientific and can reflect the objective law of electric field development in cumulus clouds.
3. Based on the Cumulus electric field G model, the objective prediction of lightning can be realized through reasonable difference method. It is certain that with the application of LNP-G in business, it will provide timely and advanced lightning objective numerical forecast for marine ships, aerospace, rocket launch, forest fire prevention and other industries, so as to avoid or reduce the major harm caused by lightning.

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