

Review Article

Overview of the Application of Orographic Data in Numerical Weather Prediction in Complex Orographic Areas

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Complex orography is still a big challenge for all numerical weather prediction (NWP) models. Orography is an important factor that affects the NWP results. The orography in NWP mainly affects the main accuracy of the results through two aspects: orographic representation in models dynamics and orography-related parameterization schemes in the physical processes. To ensure the accuracy of NWP results, it is necessary to have a comprehensive understanding of the application of orographic data in NWP. This paper summarized the influence of orography on weather, the influence of orographic representation on prediction accuracy, and the parametrization of orography-related drag in NWP models. Finally, this paper elaborates the problems of the application of orographic data in NWP and looks forward to future directions in this field, hoping to improve the performance of NWP in complex orographic areas and provide a reference for better application in NWP.

1. Introduction

Orography plays an important role in atmospheric motion at different scales, and it also has an important influence on the movement and evolution of a weather system. When air flows through uneven mountains, the orography causes the airflow to climb and go around orography, and this affects the atmosphere's energy transmission and budget through its thermal action. Currently, numerical weather prediction (NWP) models are widely used with the development of computer technology. However, various NWP and climate models still have a typical problem; that is, they cannot accurately predict the intensity and structure of the zonal flow in complex orographic areas. Orography is one of the key factors affecting the prediction accuracy of NWP models [1, 2].

The NWP in complex terrain has always been a research hotspot because of its inaccurate predictions. For example, Moya-Álvarez et al. [3] studied the simulation of rainfall under complex orographic conditions such as the central Andes of Peru by the Weather Research and Forecasting

Model (WRF). In normal simulations, the model over-estimated the amount of precipitation, but in extreme precipitation and hail weather, the model underestimated the amount of precipitation. It can be seen that there is still a lot of room for improvement in the numerical prediction in complex orographic areas. Inappropriate representation of the current land, especially the inappropriate description of orography and biophysical parameters in specific spatial areas, has led to the uncertainty of simulation from local to regional scales in the NWP model [4]. Caccamo et al. [5] used different grid resolutions and orographic data to simulate the impact of heavy rainfall event in Sicily when studying weather prediction performances for complex orographic areas. It is found that it was still a challenge to provide accurate and timely prediction of extreme rainfall in complex orographic areas. However, if appropriate high spatial resolution models are used, the forecast performance can be effectively improved. Mass et al. [6] also found that in coastal areas with complex orography, high-resolution NWP models can improve forecasting skills. Besides, Alpert et al. [7] also found that the high-resolution NWP models have

better performance in capturing precipitation in high-altitude areas. One of the main reasons is that the representation of orography can be improved at high resolution.

Around the 1950s, there was no orographic data in the various digitized versions that are now available. The first orographic data used in NWP models was read from aeronautical orographic charts (Figure 1) [8]. At that time, orographic heights were averaged by eye over one-degree squares, and aeronautical charts were not complete, so there was an urgent need to develop a set of orographic datasets with high quality and high global coverage. However, with the development of satellite and remote sensing technology, various global datasets with different resolutions have been developed, such as ETOPO5, GTOPO30, Shuttle Radar Topography Mission data (SRTM), and ASTER GDEM [9–11]. Later, these orographic datasets started to be applied to various global and regional NWP models and greatly improved the model performance [4, 5, 12–15]. In addition, orographic data of various regions were generated, such as the high-resolution orographic dataset of the Heihe River Basin [16]. Different resolutions of orographic data represent different orographic characteristics. As a result, different meteorological features and different weather phenomena will be obtained if different orographic data are utilized. Nunalee and Horváth [17] compared the prediction results from orographic data with different resolutions and confirmed that different orographic data can generate completely different orographic wake mechanics, such as whether or not vortex shedding exists. Vortex shedding means that when the wind hits a mountain and flows along its surface, the airflow will change, and a circulating vortex will be generated at the end of the airflow. He et al. [18] compared the simulation results from various orographic data, including the Shuttle Radar Topography Mission (SRTM), and found that orographic data had a much higher impact on temperature than precipitation.

Complex orography is still a big challenge for all NWP models [19]. Orography is the key factor in the inaccuracy of NWP results in complex orographic areas. The orography in NWP mainly affects the accuracy of the results through two aspects: orographic representation in models dynamics and orography-related parameterization schemes in the physical processes (Figure 2). Hence, to predict the weather more accurately in complex orographic areas, it is essential to have a comprehensive understanding of the application of orographic data in NWP. As shown in Figure 2, this paper reviewed recent developments from several aspects, including the influences of orography on weather, the influence of orographic representation on prediction accuracy and the parametrization of orography-related drag in NWP models, hoping to provide references for future studies and operations.

2. The Effect of Orography on Weather

When Dimri [20] simulated rainfall caused by an active western disturbance in India, it was found that the distribution and rate of rainfall were highly sensitive to orography. It can be seen that orography is an important factor

affecting rainfall. However, the basic mechanisms of orographic rainfall had not yet been fully resolved. The large number of physical processes involved and interactions between different processes make the quantitative prediction of rainfall in complex orography a difficult task [21]. The influence of orography on rainfall has been a hot topic since ancient times. For example, Oikonomou et al. [22] utilized the regional climate model, RegCM3.1, to set up two simulation experiments. One retained the land cover data but removed the orographic height in the study area to become a flat orography. This was termed the “flat experiment.” The other preserved the original orography to study the relationship between the Greek orography and prolonged drought. It was found that due to the effect of orography, there was a significant precipitation system between the Greek mainland and Crete Island. When the orographic height was removed, the duration of extreme drought was significantly extended. This indicated that the orography had a very important impact on the distribution of local extreme drought. Alpert et al. [7] also found that there is a significant relationship between seasonal precipitation and orographic altitude. Sethunadh et al. [23] simulated a rainstorm event over the city of Chennai using the high-resolution regional National Center for Medium Range Weather Forecast (NCMRWF) Unified Model (UM). After improving the orographic representation, it was found that the local details of the rainfall distribution were better simulated. The possible reason is that after improving the orographic representation, the detailed orographic features that affect rainfall have been more realistically represented. Torma and Giorgi [24] studied the rainfall in the Carpathians Mountains and found that the elevation, size, and orientation of the mountains in the complex orography play a key role in the occurrence and changes of rainfall. Besides, many scholars have also studied the relationship and mechanisms between orography and rainfall [17, 25, 26]. It can be seen that orography plays an important role in the generation and development of rainfall. In the global distribution of heavy rain (Figure 3(a)), most of the rainstorm centers were located near complex orographic areas, such as the Qinghai-Tibet Plateau, Cordillera Mountains, Appalachian Mountains, Andes Mountains, and so on [27]. In the average number of rainstorm days in eastern China (Figure 3(b)), the areas with the most rainstorm days were mostly located on the southeast windward slope of mountains, such as Taihang Mountains, Funiu Mountains, Dabie Mountains, Wuyi Mountains, and Nanling Mountains. When a rainfall weather system moves closer to a mountainous area, orography can make the original weather system without precipitation begin to show precipitation, and the distribution of rainfall in the weather system with precipitation becomes very uneven. As a result, in some parts of the mountain, there will be more rainfall, and the duration of the rainfall will also be prolonged. These effects are called the orographic effect of increasing rainfall [28]. Although the movement of weather systems with water vapor to mountains areas is an important factor in rainfall, the Mesoscale Alpine Project (MAP) in 1999 showed that change of orography on airflow was a crucial factor affecting the

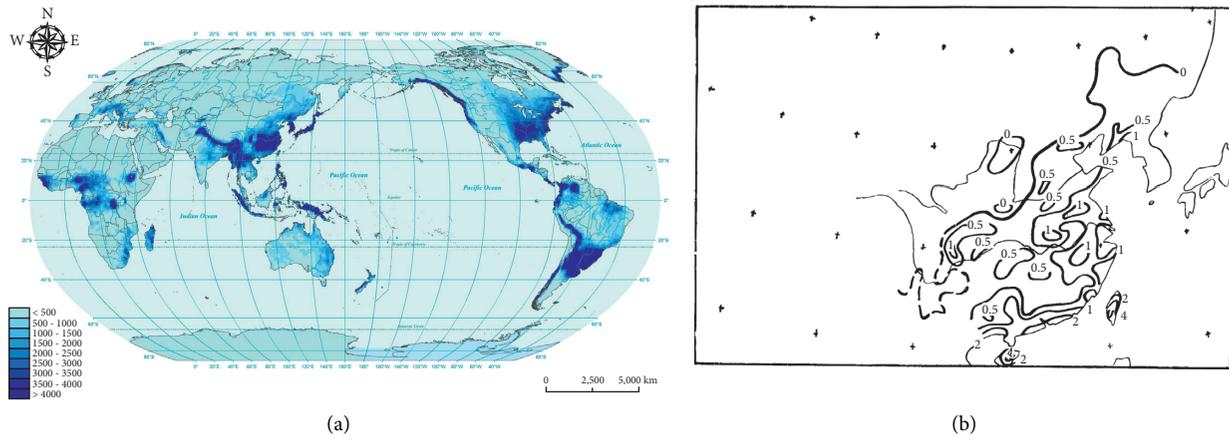


FIGURE 3: The spatial distribution of heavy rainfall. (a) The global average annual heavy rainfall over land from 1991 to 2000 (units: $\text{mm} \cdot 10a^{-1}$) [27]. (b) Average number of days with heavy rain in eastern China (daily rainfall ≥ 100 mm) [28].

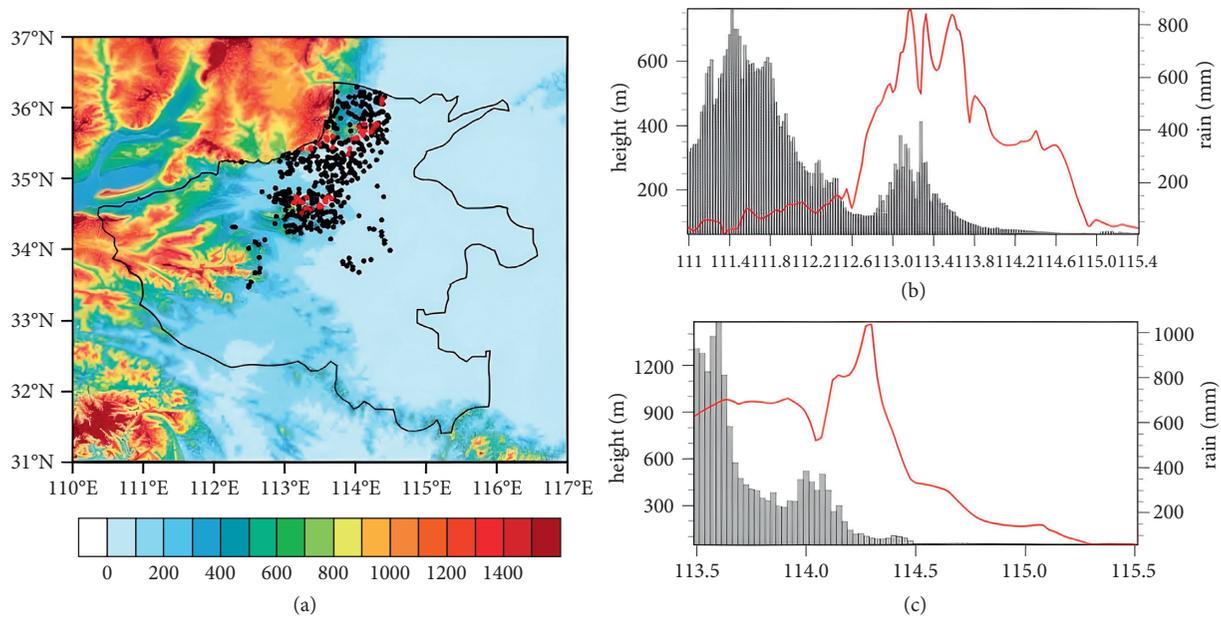


FIGURE 4: The heavy rainstorm from 08:00 on 17th of July to 08:00 on 23rd of July, 2021, in Zhengzhou, China. (a) The site distribution of process accumulated rainfall larger than 400 mm and less than 800 mm (black dots) and larger than 800 mm (red dots) (filled color represents altitude, units: m). (b) The variation curves of altitude (columnar shadow) and process accumulated rainfall over the Zhengzhou station 34.7°N and (c) the station 35.77°N [32].

The orography not only has a great influence on rainfall, but also has a great influence on other weather systems and meteorological elements. For example, Renault et al. [33] found that the vortex stretching and the surface drag related to turbulent momentum flux divergence caused by orography enhanced the drag coefficient on land and caused a significant decrease in wind speed. Obermann-Hellhund and Ahrens [34] simulated Mistral and tramontane using orography of different resolutions and also found that the reduction of orographic details (low-resolution orography) would lead to a change in wind pattern change and a reduction in wind speed. Huang and Wu [35] studied the effect of ideal orography on upstream tropical cyclone track. It was found that when the tropical cyclone was still far away from

the orography, the changes in the background flow caused by the orography firstly caused large-scale steering current to push the tropical cyclone to the southward. When the tropical cyclone approached the ideal orography, the role of inner-core dynamics became very important and the channel effect generated by orography caused tropical cyclone to deflect further south. In addition, the subgrid scale orography also has a great influence on various weather processes and climate. It is discussed in detail in Section 4 of the article. The steepness of the orography is also very sensitive to different meteorological models and vertical coordinates. Yudin [36] applied two nonhydrostatic numerical models, a finite-difference model and a finite-element model, to predict gravity wave propagation. The finite-

difference model is suitable for smooth orography, and the finite-element model is suitable for steep orography. Gallus [37] used the National Center for Environmental Prediction (NCEP) regional Eta model, and used the Eta vertical coordinate and stepwise treatment of orography to replace the terrain-following sigma vertical coordinate, to study the influence of the stepped orography on the flow near the mountains. It was found that the stepped orography caused a significantly underestimate of wind speeds at leeward side of mountains during the storm and stepped orography caused weaker mountain waves than generated when the sigma vertical coordinate was used.

Most of these studies use sensitivity experiments to study the impact of orography on the weather. By changing the orographic conditions in NWP models, people can better understand its impact and improve the accuracy of NWP. Sensitivity tests can clearly explain the influence of orography on weather and provide a quantitative measure of the impact of orography, and this has become a research hotspot. However, sensitivity tests have primarily been confined to specific phenomena, specific parts of the world, or to specific parameterization schemes. This has no universal practicality to the regional NWP and does not improve the accuracy of operational NWP models. As a result, we should develop quantitative methods in future studies to improve the practicality and universality.

3. Orographic Representation in NWP Models

With the wide application of various NWP models, the accuracy of weather prediction results has greatly improved [38, 39]. However, if in a complex orographic area, the prediction of the value of meteorological elements, such as precipitation and wind, would still be inaccurate. This is primarily because of the uncertainty of the orography representation and orographic drag parametrization [39]. Chapter 3 will mainly discuss the representation of orography, and the parameterization of orographic drag will be discussed in Chapter 4. To ensure the accuracy of NWP results, we need not only to understand the general influence of a regional orography on weather, but also to choose a set of orographic data and orography processing schemes suitable for NWP. This would be of great benefit to improve and optimize future NWP operations.

3.1. What Kind of Orographic Data Is Better? The main challenge of NWP models in complex orographic areas is that it is difficult to accurately represent the orography. In NWP models, when orographic height is represented by the discrete numerical grid, the value of each grid point represents the average orographic height in this grid, but it cannot represent the change of orographic height within the unit grid. Therefore, at a certain resolution of the NWP model, the grid values of the model implicitly smooth the orographic height, which reduces the actual orographic height, causing the model to underestimate the blocking effect of mountains [40]. When the NWP model uses a higher resolution, the numerical grid area of the model will

be smaller, which means that the representation of orographic height may be more accurate. Then, does a higher resolution lead to a better result?

For orographic dataset, the orographic resolution includes the resolution of the original orographic data and the resolution of the orographic data after interpolation. Some scholars have noted that high-resolution orographic data in climate models are essential to improve the accuracy of precipitation prediction results in mountainous regions [24]. Gao et al. [41] used the regional climate model, RegCM2, to predict the precipitation of East Asia. They used "actual orography" made by the National Center for Atmospheric Research (NCAR). This means that the orographic height was the original data and had not been interpolated and processed, and they used very smooth model orography that refers to the original orographic data after processing. Then, they interpolated these two orographic data into different resolutions. Finally, they compared the simulated precipitation results. They found that the prediction accuracy of rainfall in East Asia depended on the resolution of the orographic data. The higher the resolution, the better the accuracy. However, if the resolution was the same, the simulation of the "actual orographic" data was better than that of using the smoothed orographic data. For the high-resolution orographic data with a resolution of 30 m produced by the Chinese Academy of Sciences and Global 30" orographic data produced by the United States Geological Survey (USGS) in the Black River Basin, Liu et al. [16] used these two datasets to predict the meteorological fields by the Mesoscale Model 5 (MM5) in the Black River Basin. The results showed that the higher-resolution data had a better capability to predict temperature and wind than the USGS data, but the improvement in the precipitation prediction was not obvious. This was different from the results of Gao et al. [41] who believed that the resolution of orography can greatly affect precipitation predictions. This might have been caused by the fact that the precipitation prediction is not only affected by orography, but also by many other factors including the performance of NWP models, differences in research areas, divergence of the orographic data, and other factors.

The SRTM and ASTER GDEM orography data have been widely used in weather prediction research because of its high resolution. Many scholars have conducted different studies on what is the best orographic dataset. For example, Zhang and Yin [12] predicted and compared the characteristics of meteorological features of atmospheric boundary layer in Huangshan and the surrounding areas of Anhui Province by replacing GTOPO30 (approximately 1 km resolution) orographic data produced by USGS with SRTM3 (approximately 90 m resolution) orographic data produced by the National Aeronautics and Space Administration (NASA) into the model WRF. This was combined with four boundary layer parametrization schemes. It was found that when the SRTM3 orographic data were used, the meteorological fields of the atmospheric boundary layer predicted from various boundary layer schemes were better than those from GTOPO30. In a word, the SRTM3 orographic data were better than GTOPO30 in the WRF. Caccamo et al. [5]

used the ASTER GDEM V2 orographic data (an approximate 1 arcsec resolution) produced by the Japanese Ministry of Economy, Trade and Industry (METI) and the NASA to replace the GTOPO30 orographic data (an approximate 30 arcsec resolution) produced by the USGS. Finally, they directly compared the observation data and the model prediction results and found that using the higher original resolution orographic data was key factors for accurate model prediction, especially for complex orography. Kirthiga and Patel [4] used SRTM orographic data to update the surface information and simulated micrometeorological and near-surface weather by the WRF model. In the modified run, it was found that the model better simulated the temporal changes in surface temperature, surface pressure, solar radiation, wind speed, and relative humidity. For these near-surface weather variables, the improvement in 24-hour forecast ranges from 15% to 30%. De Meij and Vinuesa [13] and De Meij et al. [14] simulated the effects of TOPO30 and SRTM orographic data on the 2 m temperature, the 10 m wind speed and rainfall by the WRF model and found that the result with SRTM orographic data was closer to reality. In addition, the prediction accuracy of the precipitation event was also increased. These studies showed that orography with high-resolution data, such as SRTM, could improve the accuracy of prediction results compared with the low-resolution data. The possible reason is that higher-resolution orographic data can reflect more realistic orographic conditions and represent smaller-scale orographic effect. Therefore, orography can be more resolved by NWP model, and the negative impact caused by the uncertainty of orographic representation is reduced.

3.2. The Processing of Orographic Data. Sometimes introducing high-resolution orographic data to a model may cause false disturbances, such as sudden abnormal increases or decreases in the value of meteorological elements, especially excessive wind speeds at some grid points. These problems have a significant impact on the performance and robustness of NWP models. Zhu et al. [42] studied the effect of high-resolution orographic data in a new-generation Global/Regional Assimilation Prediction System (GRAPES), developed by the China Meteorological Administration for the prediction of near-ground features (e.g., temperature and wind) in southern China. They found the 2 m temperature at 06Z to be a false oscillation; that is, its value had a sudden change that was possibly due to a lack of smooth orographic height in the model. Although high-resolution orographic data can improve NWP models accuracy, it should be recognized that a large number of experiments are still needed to study which orographic processing technology reduces the impact of high-resolution orographic “noise” on the dynamic calculation process to improve the stability and accuracy of NWP models. These studies show that filtering and smoothing the orographic field is effective to solve these problems.

Orographic processing began to appear and develop a long time ago. Davies and Brown [43] argued that an orographic filtering scheme should be used in grid point

models under neutral and stable stratified flow regimes within the context of the nonlinear three-dimensional Blasius model [44, 45]. Research results show that orographic features with a length of more than or equal to six grid lengths were fully resolved, and orographic features less than two grid lengths could not be resolved but often actually harm the overall fidelity of NWP models. Therefore, an orographic smoothing scheme was needed here. These researches provided helpful information to later scholars. Webster et al. [46] applied the filter given by Raymond [47] to the UM as a scheme to filter orographic data. It was found that this filter can improve or eliminate excessive wind speed at some grid points. Later, Rutt et al. [48] proposed a novel, very flexible variational approach to orographic smoothing and studied its effects in the numerical model. It was found that new orographic smoothing scheme could reproduce the results of the schemes of Raymond [47] and Webster et al. [46]. Tu et al. [49] and He et al. [50] studied the impact of high-resolution orographic smoothing schemes on ground fields, such as the precipitation, in the GRAPES and WRF models using the Chebyshev polynomial filtering method. The results showed that the smoothed orographic data had a positive effect on the precipitation prediction under the complex orographic conditions on the eastern side of the plateau. Chen et al. [51] studied the effect of different orographic smoothing methods on precipitation forecasts using the WRF model. It was found that different orographic smoothing schemes could have different effects on the precipitation intensity and spatial distribution, and orography should not only be close to the actual orography as much as possible, but also reach a certain degree of smoothness. These studies have shown that that it is important to select better orographic smoothing schemes when using high-resolution orographic data.

4. The Orography-Related Drag Parameterization

As we all know, it is extremely important and necessary to represent orographic effects as accurately as possible in NWP models. However, due to the limitation of model resolution, small-scale orography cannot be resolved by models. The unresolved orography is called subgrid orography. When the orography is complex, current models cannot describe some features of small-scale orography well, such as slope and ridge direction. But subgrid orography plays an extremely important role in the model atmosphere in both the heat and motion aspects. In addition, it is usually difficult for model dynamics to deal with this problem with reasonable mathematical methods at current NWP models' resolution because the wavelength of the gravity wave excited by the subgrid orography is too small. Therefore, parametrization scheme to describe the effect of orographic drag on the weather system is currently a good method.

The orography-related drag parameterizations mainly include turbulent orographic form drag (TOFD) and orographic gravity wave drag (OGWD). In most NWP models, the orographic gravity wave drag parameterization scheme includes two parts, one is the orographic gravity wave drag,

and the other is the low-level blocking drag. The orographic workshop of the European Center for Medium-Range Weather Forecasts (ECMWF) made a suggestion that the orographic gravity wave and low-level blocking are parameterized at subgrid scales above 5 km, and the TOFD are parameterized at scales below 5 km [52]. Since it is generally believed that on smaller horizontal scales, vertical propagation of orographic gravity waves becomes less likely and 5 km is considered to be a reasonable limit. Of course, 5 km is not an exact value, but an approximate number. Davoli [53] considered this limit value to be 6 km.

4.1. Turbulent Orographic Form Drag (TOFD). In the last century, Fiedler and Panofsky [54] proposed the concept of effective roughness length. They defined the effective roughness length. The effective roughness length of the complex orographic area is equal to the roughness length of the area with uniform orography, the same surface stress. For a long time thereafter, the effective roughness method was used in NWP models to consider the effects of turbulent orographic drag and performance of NWP models had also been effectively improved [55–58]. This method believes that under neutral conditions of the atmosphere, when turbulent air flows through undulating orography, it still follows the logarithmic law within a certain vertical range. Numerical experiments [45, 59] and a series of observations [60–62] found and confirmed that above a certain altitude in the undulating orography, the wind profile approximately follows the logarithmic law.

Although the effective roughness method greatly improves the performance of NWP models, it also has some shortcomings. For example, it causes the effective roughness to be overestimated in the region where the orographic height varies greatly, resulting in greater surface stress and thus falsely low wind speeds near the ground. Given these shortcomings, Wood et al. [63] represented drag of turbulent orography by a well-defined stress profile. However, this scheme did not address the characterization of complex orographic areas involving multiple scales, which is crucial for large-scale NWP models. Based on Wood et al. [63], Beljaars et al. [64] developed a turbulent orographic drag parameterization scheme for large-scale models. To obtain the contributions of all scales of orography, it integrated over the orographic spectrum and it took the wind forcing layer as part of the orographic wavenumber spectrum integration to solve the convergence problem. This parameterization scheme made turbulent orographic drag parameterization a big step forward from the traditional effective roughness concept and was applied to the ECMWF. Xue et al. [65] compared the effective roughness method of turbulent orography with the direct parameterization method. It is found that the direct parameterization method could drag the wind on the vertical ridge and deflected the wind in the direction parallel to the ridge with a certain vertical attenuation thickness. The direct parameterization method treated turbulent orographic drag as a single item, which made the application and improvement of the scheme extremely convenient, and the physical meaning was clearer.

Richter et al. [66] and Lindvall et al. [67] also added turbulent orographic form drag parameterization into the Community Atmosphere Model (CAM5). CAM5 cut off all turbulence at high stabilities and instead used a strong orographic surface stress parameterization, which was referred to here as turbulent mountain stress (TMS). TMS increased the surface stress based on the effective roughness length method. It was only used for the atmospheric part and not the land model where the vegetation roughness length was used instead. TMS was mostly good for the large-scale circulation because it can improve sea level pressure, zonal wind speeds, and zonal anomalies of the 500 hPa stream function, but its beneficial effects on boundary layer flow were not always obvious [68]. The TMS surface stress τ is calculated as

$$\tau = \rho C_d |V|V, \quad (1)$$

where ρ and V are the air density and the wind vector at the lowest model level and C_d is a drag coefficient given by

$$C_d = \frac{f(R_i)k^2}{\ln^2[(z + z_0)/z_0]}, \quad (2)$$

where R_i is the Richardson number and $f(R_i)$ is the function of it, as follows:

$$\begin{aligned} f(R_i) &= 1 \text{ if } R_i < 0, \\ f(R_i) &= 0 \text{ if } R_i > 1, \\ f(R_i) &= 1 - R_i \text{ if } 0 < R_i < 1, \end{aligned} \quad (3)$$

where $k = 0.4$ is the Von Kàrmàn constant, z is the altitude of the model mean orography, and z_0 is an effective roughness length, representing the idealized size of the perturbing (turbulent-eddies-generating) surface elements due to the unresolved orography. In fact,

$$Z_0 = \min(\text{tms_z0fac} * \sigma, 100 \text{ m}), \quad (4)$$

where σ is the standard deviation of unresolved orography (measured in meters) on scales smaller than 6 km and assuming that the maximum vertical extent of the unresolved orographic roughness elements is order of 100 m. `tms_z0fac` is a numerical parameter affecting the minimum roughness length seen by the model, and its value is generally 0.075.

Under the background of increasing model horizontal resolution, Davoli et al. [53] believe that it is necessary to retune some physical parameters of the atmospheric model to reduce model bias. After repeated tuning, they tuned the parameter value of `tms_z0fac` in formula (4) from 0.075 to 0.1875. The results show a significant improvement compared to before the adjustment, especially in the European atmospheric circulation in winter. However, this work painted an only partial picture of the effects of such a partial model physics retuning effort and therefore suffered from a number of shortcomings and limitations. In order to more accurately represent the orographic drag effect, it is necessary to carry out a large number of NWP experiments and perform fine-scale simulations of different complex orographic areas to calibrate parameters in NWP models.

4.2. Orographic Gravity Wave Drag (OGWD). The study of orographic waves began a long time ago, and the development of mathematical theories has explained many aspects of the generation and evolution of orographic waves [69]. These works have contributed to the development of parameterization scheme for orographic gravity wave drag. When a stably stratified flow crosses a mountain, the subgrid orography may excite orographic gravity waves, and these can transmit horizontal momentum to areas where fluctuations are absorbed or dissipated. The dissipation of this fluctuating flux is called orographic gravity wave drag. The gravity wave drag can affect not only high-altitude winds, but also clouds and precipitation. It plays a very important role in maintaining the conservation of atmospheric circulation energy [70]. In the 1970s and 1980s, NWP systems could only resolve Rossby waves and some midlatitude cyclones. With improvements in the spatial resolution, the predicted motion became too strong, and later scholars found that the predicted wind speed deviation was primarily due to the lack of a clear simulation of the subgrid gravity wave drag [71–73]. In 1984, Boer et al. [74] considered the subgrid orographic gravity wave drag in the Canadian Climate Center atmospheric general circulation model. They introduced the climatology of this model and compared it with the observations. In atmosphere climatology, they found that the model was generally successful in reproducing the mean observations, such as the tropospheric circulation. In 1986, based on Lindzen’s saturation hypothesis theory [72], Palmer et al. [75] developed a gravity wave drag parameterization scheme. This scheme primarily considered the effect of wave fragmentation in the low-level stratosphere on the gravity wave drag. The results showed that the problem of a strong westerly jet in the troposphere was reduced by the use of the parameterization scheme. In 1987, Mcfarlane [70] added the parameterization scheme of the gravity wave drag to the climate model and found that the momentum sank due to the breaking of gravity waves that were excited by orography and played a decisive role in the structure of the flow between the troposphere and the lower stratosphere. So far, the first-generation OGWD parameterization methods for the large-scale NWP models with relatively low model tops were developed had been basically formed. Shortly thereafter, Wu [76] explained the orographic gravity wave drag parameterization systematically, further enhancing people’s understanding of orographic drag. These schemes reduced the overall size of jets to separate the stratospheric jet from the tropospheric jet and produced a large easterly wind shear in the upper troposphere. They have a great influence on the stratospheric drag at mid-latitudes, directly affecting the jet in the stratospheric and indirectly affecting the westerly winds on the surface through the secondary circulation caused by stratospheric drag. This indirect effect can improve cold pole problems and decrease westerly bias.

During the same period, the NWP community conducted research on “severe downslope windstorms” found in the lower reaches of mountains, such as the Boulder storm in the lower Rocky Mountains [77–79]. However, there was some debate about the exact physical mechanism of this

phenomenon, but most agreed that the orographic gravity wave drag associated with mountain storms may be excessive [78, 80, 81]. While these phenomena did not occur all the time, the drag generated each time may be greater than the drag created by breakup of stratospheric orographic wave. In the boundary layer, similar resonance breaking and drag may also be important [82]. Therefore, these processes may play a large role in the break-even of large-scale atmospheric momentum.

These studies promoted the continuous development of OGWD parameterization. There was an increasing need to increase low-level drag in the model. Some scholars have begun to express these orographic effects by enhancing OGWD in the lower troposphere [83]. Iwasaki et al. [84] studied “linearly trapped” nonhydrostatic waves in the lower reaches of mountains and parameterized its effect in a special way and found that improved prediction results. Kim and Arakawa [85] studied the influence of “nonlinear trapped” waves due to wave breaking in the lower troposphere. They systematically parameterized its effect to enhance low-level drag in lower reaches regions where nonlinearities are strong, but not in weak nonlinear regions. Later, this parameterization scheme was introduced into NWP models and improved the performance of models [81]. This way of enhancing low-level drag separates the lower reaches’ wave breaking zone from the upstream blocking zone. They are respectively related to the strength and weakness of the vertical divergence of the horizontal momentum flux. In 1997, Lott and Miller [86] proposed a new OGWD parameterization scheme to develop and improve these and other low-level drag and orographic specifications. This parameterization scheme could deal explicitly with the low-level flow that was “blocked” when height of the subgrid scale orography was sufficiently high. The prediction results of the new subgrid scale orographic gravity wave drag parameterization scheme were closer to actual observations. Soon after, this orographic gravity drag scheme was applied to ECMWF. The basic principles of the orographic gravity wave drag scheme are as follows:

$$H_n = \frac{NH}{|V|}, \quad (5)$$

where H_n is the dimensionless height of the mountain. N , H , and V are the Brunt–Väisälä frequency, maximum height of the obstacle, and velocity. When H_n is small, all airflow currents can climb over mountains and gravity wave is excited by vertical movement of airflow. Assuming that the mountain is oval, the surface stress generated by the gravity wave is

$$\tau_w = \rho_0 b G B(\gamma) N U H^2, \quad (6)$$

where ρ_0 , b , and G are low-level density, tuning coefficient, and mountain shape function. $B(\gamma)$ is the function of mountain anisotropy. When H_n is large, vertical movement is restricted. Part of the low-level airflow will be blocked or form a bypass.

$$Z_b = H \frac{(H_n - H_{nc})}{H_n}, \quad (7)$$

where H_{nc} is a critical value. Z_b is the height of airflow can climb over the mountain. Airflow below this height will bypass this mountain. At this time, all drag is

$$\tau \approx \tau_w \left(1 + \frac{\pi C_d}{2GB(\gamma)} \frac{H_n - H_{nc}}{H_n^2} \right), \quad (8)$$

where C_d is the drag coefficient.

In 2003, Webster et al. [46] improved orographic representation in the UM and used a new orographic gravity wave drag scheme based on [86]. They considered the friction and rotation of the airflow in the new scheme and divided the total drag into two parts: the blocking flow and the gravity wave drag. The results showed that the introduction of the new scheme obviously improved the prediction results for the northern hemisphere and tropical regions. Gao and Ran [87] made improvements to Mcfarlane's scheme [70] that did not consider the problem of the gravity wave breaking and obtained a more complete parametrization scheme that described the drag impact of stationary gravity wave breaking on the zonal mean atmospheric circulation. This scheme not only considered the drag effect of the remaining momentum on zonal mean atmospheric circulation after the gravity wave is broken, but also considered the impact of momentum loss caused by the dissipation of the broken gravity wave on the zonal mean atmospheric circulation. In 2007, Andrew [88] modified orographic gravity drag scheme based on [86] and considered the blocked flow drag. He modified the subgrid orography height to the effective orographic height, which is the maximum height that the blocked layer depth can reach minus the blocking layer height. That is, modify H in formula (6) to H_{eff} .

$$H_{eff} = 3\mu - Z_b, \quad (9)$$

where μ is the standard deviation of the subgrid orographic height. Finally, the modified scheme was evaluated, and it was found that when calculating the gravity wave drag, it could reduce the excessive deceleration of motion in areas with complex orography.

Since then, orographic gravity wave drags parametrization schemes had been applied to various numerical models, and predictive capabilities of various NWP models have been improved and optimized. For example, Xu et al. [89] introduced the OGWD parametrization scheme of ECMWF based on [86] into the GRAPES model, filling the gap in the description of this type of physical processes in the GRAPES global medium-term numerical prediction system. The results indicated that with the introduction of the OGWD process, the distribution of the predicted fields was closer to that of the real atmosphere. Liu et al. [90] studied the occurrence mechanism of heavy rain in southern China by WRF model with the OGWD parametrization scheme based on Kim and Arakawa [85]; it was found that the parametrization scheme could predict the central position and the intensity of the heavy rain well. In addition, it was found that the gravity wave could strengthen the vertical upward motion. In 2017, Wang and Xi [91] introduced the OGWD scheme of the WRF model in the GRAPES-MESO

model (GRAPES-MESO is the regional system version of GRAPES) and combined with the low-level airflow blocking parametrization proposed by Lott and Miller [86]. They divided the subgrid orographic drag into the OGWD and blocking drag to study the distribution of OGWD in the Qinghai-Tibet Plateau. Finally, it was found that the model had a more accurate description for low-level and high-level orographic gravity wave breaking.

The convoluted interaction between different processes related to orography is a difficult problem in NWP [21]. However, in recent years, there are few studies on the interaction between resolved orographic drag and parameterized orographic drag. Vosper et al. [92] described the resolved and unresolved orographic drag by predicting the flow of South Georgia and New Zealand Island. They found that the parameterized orographic drags increased when the model grid length decreased. When the characteristic island wavelength was about eight grid lengths, the resolved and parameterized orographic drag were approximately the same size. When wavelengths were shorter than 8–10 grid lengths, the parameterized orographic drag was very large. However, when the island scale changes, the resolved part of the orographic drag and the parameterized part of the orographic drag cannot be completely balanced. Van Niekerk et al. [93] studied the resolved and parameterized orographic drag in eleven different modes from eight major operational modeling centers, such as ECMWF's Integrated Forecasting System (IFS), Met Office's UM model, and Global Spectral Model 1705 (GSM1705) of Japan Meteorological Agency (JMA). They found that the parameterized gravity wave drag in most of NWP models was underestimated to varying degrees. Hence, the parameterized orographic drag introduced was slightly larger, and this may improve the results of the NWP prediction. Some studies have also found that the resolved orographic drag changes were not precisely balanced by the parameterized orographic drag changes in the numerical models [1, 92, 94, 95], so it cannot ensure that NWP models remain robust between different resolutions. This reveals that there are still some problems in the handling of orographic drag in NWP models, and more researches are needed to solve the division of orographic drag in the model dynamics and physical parameterization and division between different physical parameterization schemes.

5. Conclusion and Discussion

This paper reviewed recent developments from several aspects, including the influences of orography on weather, the influence of orographic representation on prediction accuracy, and the parametrization of orography-related drag in NWP models. The primary conclusions are shown as follows:

- (1) Sensitivity analysis tests were used to study the influence of orography on weather. It was found that orography has a great influence on different scale systems and meteorological elements, such as near-surface wind, temperature, rainfall and heavy rain

systems, long-term droughts, mesoscale wind fields, tropical cyclones, and so on.

- (2) In general, the higher the resolution of the orographic data in NWP models, the more accurate the model forecast results, and this is primarily reflected in elements such as precipitation and wind. In addition, it is important to process the original orographic dataset prior to application, including performing filtering, smoothing, and other schemes, to make prediction results nearer to the actual weather, and to ensure the accuracy of the NWP model prediction.
- (3) The introduction of the orographic drag parameterization scheme greatly improves the prediction performance of NWP models. However, the intricate interaction between different parameterization schemes and between parameterization and resolved orographic drag also bring uncertainty to the numerical model, so lots of researches are still needed.

Finding an appropriate resolution, suitable orographic data, and the optimal orographic processing scheme to obtain a better orography representation requires great many numerical experiments, and the amount of calculation is very high. Hence, we must select a model with high accuracy and good stability. Because today's computers do not have enough computing power to deal with small enough space and time resolution problems, the parameterization of the subgrid scale orographic drag in NWP models will be necessary. However, parameterization relies heavily on simplified assumptions that are primarily based on linear theory and ideal peaks, and it does not describe the non-linear effects imposed on complex orography well. As a result, parameterization becomes a source of uncertainty and deviations. How numerical models are designed to cross areas where models cannot identify to reduce or eliminate these uncertainties and deviations is critical for applications of NWP, wind resource prediction, and numerical model modeling in complex orography [40]. With the improvement of computer performance, the NWP model resolution is getting finer and finer. Can the NWP model dynamics completely resolve orographic drag and eliminate the parameterization schemes? This is an open topic and there is no definite answer. In 2006, Smith et al. [96] utilized seven examples to explore the sensitivity of the horizontal resolution of numerical model to OGWD. The result indicated that in most cases, even if the horizontal resolution were raised to finer than 4 km, the impact of the gravity wave drag in the model still could not be fully resolved. Kim et al. [97] predicted the model resolution needed to eliminate gravity wave drag parameterization and found that the horizontal resolution required to achieve this goal was still much higher than the highest resolution achieved up to now. Probably in the recent period, parameterized schemes are still mainly used to represent effect of unresolved orographic drag in NWP models. However, with the rapid development of artificial intelligence, machine learning algorithms that are automatically improved through data learning and do not

require explicit programming provide great opportunities for NWP. There are already some scholars doing this work. For example, Matsuoka et al. [98] proposed a deep learning method to predict the gravity wave drag. After training and testing, the model produced better estimates of the fine-scale momentum flux distribution of the gravity waves. It can be seen that in future research, there is great potential to use the parameterization schemes based on machine learning algorithms to couple into a higher-precision NWP model to extract key features of the data with higher efficiency and make accurate predictions.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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