Study on the Influence of Non-orographic Gravity Wave Parameterization Scheme on Prediction in Stratospheric Wind Field

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Abstract. The atmospheric motions of the upper troposphere and the lower stratosphere are affected by the non-orographic gravity waves. In this paper, two parameterization schemes of non-orographic gravity waves, the non-hydrostatic and rotational scheme (WM96 scheme) and the hydrostatic and non-rotational scheme (S02 scheme), are introduced into the global numerical weather prediction model. Study on the influence of the two schemes on the prediction of the stratospheric wind field is carried out in case of the sudden stratospheric warming event in January 2013. The experimental results show that both the WM96 scheme and the S02 scheme can accurately capture the change of the wind fields during the sudden stratospheric warming process. Compared to the Rayleigh friction scheme, the errors of the wind fields 24 hours and 72 hours forecast are significantly reduced when the WM96 scheme or the S02 scheme is used; the prediction of WM96 scheme is closer to the analytic field in some areas of the wind field than the S02 scheme.

1. Introduction

Non-orographic gravity waves mainly have an important influence on the atmospheric motions of the upper troposphere and the lower stratosphere [1]. The formations of zonal wind and temperature structure of the middle atmosphere, comprising the stratosphere and the mesosphere, mainly arise from the balance between radiation and gravity wave drag, in which the non-orographic gravity wave drag plays a major role. The middle atmosphere is dominated by a westerly jet in the winter hemisphere and an easterly jet in the summer hemisphere, and a meridional circulation with upwelling in the tropics and downwelling over the winter pole, referred to as the Brewer-Dobson circulation. The circulation is driven by the momentum of the Rossby wave and small scale non-orographic gravity waves that are breakdown and deposited [2]. Moreover, the non-orographic gravity waves are the main momentum source of the middle atmosphere and an important reason of driving the stratospheric atmospheric circulation, especially for the quasi-biennial oscillation (QBO) and the semi-annual oscillation (SAO). Fritts et al [3] and Alexander et al [4] founded that the non-orographic gravity waves at the top of the troposphere or the bottom of the stratosphere transmit momentum and energy upward to the middle atmosphere, and the momentum accumulates at a certain altitude, thus affected the large-scale circulation. Because the non-orographic gravity waves

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affect the transmission of energy and momentum, the winter westerly jet and summer easterly jet in the upper middle atmosphere are obviously strengthened. Non-orographic gravity waves not only affect the zonal circulation, but also meridional circulation. It is important to maintain the temperature structure of the middle atmosphere due to the meridional circulation caused by the non-orographic gravity waves, especially in the polar regions, because the solar sunshine in the winter is disappeared, which leads to the decrease of the radiation heating in the polar regions, and the dynamic heating caused by the meridional circulation is particularly important. Non-orographic gravity waves caused by convective forcing have important effect on the generation and development of tropical weather systems at low latitudes, such as Typhoons and Inter-tropical Convergence Zone.

Above all, an accurate and effective non-orographic gravity wave parameterization scheme is introduced into the global numerical weather prediction operational model, it may improve the simulation of the momentum transmission and Eliassen-Palm (E-P) flux adjustment caused by the non-orographic gravity waves, and then improve the prediction of temperature and wind field in the middle atmosphere. It has important research and operational value to improve the prediction performance of the numerical weather prediction model.

2. Study on non-orographic gravity wave parametrization scheme

Non-orographic gravity waves are forced by dynamical motions such as convection, frontogenesis, and jet stream activity. The formational mechanism of non-orographic gravity waves is more complex. Because of the strong impact on the large scale circulation, so the non-orographic gravity waves have become one of the parametrization physical processes in model which can't be ignored.

1964, Leovy [5] tried to study the effect of non-orographic gravity waves on the zonal average circulation of the middle atmosphere by using constant Rayleigh friction and Newton cooling coefficients, called the Rayleigh friction scheme. This method has serious systematic deviation in the simulation of the middle atmosphere. The tropical circulation has an unrealistic tendency towards radiation balance and cannot simulate the inter-annually variability of the tropical stratospheric circulation. Most obviously, it can’t accurately describe the QBO and SAO.

1981, Lindzen [6] developed the first gravity wave parameterization scheme based on single wave assumption. He regarded gravity waves as single disturbance that propagates energy upward in the slow-changing background wind, but they don’t interact with each other. An analytic solution can be obtained by using the dispersion relation WKB approximation. This scheme was first applied in a middle atmosphere model [7, 8]. Numerical simulation results showed that the scheme was better than the Rayleigh friction scheme, and it was possible to simulate the zonal wind overturning of the middle atmosphere by using discrete spectrum to the waves with different phase speeds that was unrealizable to Rayleigh friction scheme. In addition, this scheme can simulate the influence of the non-orographic gravity waves generated by air flow on terrain, then reduces the systematic easterly deviation of the zonal wind in the winter hemisphere, and contributes to perfect the simulation of the troposphere jet.

1996, Warner et al [9] regarded the original non-orographic gravity waves of the tropopause or low stratosphere as an upward propagating "launch" spectrum. Warner used 1D spectral equations to study the propagation of gravity waves, the critical-level filtering and some nonlinear diffusion mechanisms were used to solve the wave breakdown caused by the increase of amplitude as a consequence of increasing height and decreasing density, and then he used the wave breakdown and other nonlinear processes to disperse the conservation propagation of the waves. Finally, he used the spectral saturation criterion to constrain the scheme, and the WM96 parameterization scheme of non-orographic gravity waves was obtained. The WM96 scheme used a framework that includes non-hydrostatic and rotational wave dynamics, thus the dispersion relation of gravity waves was more reality. The scheme considered the seasonal variation in the energy function of launch spectrum, so that the calculation of E-P flux and pseudo-momentum flux of gravity waves spectrum was more accurate, and got the more realistic prediction of zonal wind and temperature.

Because the computation cost of the energy spectrum in WM96 scheme is too large to meet the real-time requirement of the numerical weather forecast model. Therefore, Scinocca et al developed a hydrostatic and non-rotational non-orographic gravity waves parameterization operational scheme in 2002 by simplifying the processing of wave energy and momentum flux [10, 11]. The scheme had been successfully used in the global model of the European Centre for Medium-Range Weather Forecast. This scheme was called the S02 scheme.

With the improving of computation power, it is possible to apply the non-hydrostatic and rotational WM96 scheme in operation model that can more really simulate the atmosphere state. In this paper, the WM96 scheme and S02 scheme are introduced into global numerical weather prediction operational model to study the influence of the non-orographic gravity waves parameterization scheme on the prediction of stratospheric wind field.

2.1. Non-hydrostatic and Rotational wave dynamics of WM96 scheme

The WM96 scheme treats the original non-orographic gravity waves as an upward propagating "Launch" spectrum. On this basis, the physical space of the propagation spectrum is defined: $m-\hat{\omega}$ (vertical wave number-inherent frequency) or $k-\omega$ (horizontal wave number-frequency) coordinate structure. It is assumed that the energy spectrum of the non-orographic gravity waves is launched in the lower stratosphere, and the energy of the launch spectrum is a function of the vertical wave number m, the inherent frequency $\hat{\omega}$ and the azimuth φ, so the spectral energy function is obtained through experiential processing:

$$\hat{E}(m,\hat{\omega},\varphi) = \beta A_0(s,t)B_0(p)\phi_0 \frac{m}{m_*^4+m^4} N^2\hat{\omega}^{-p} \tag{1}$$

N is the buoyancy frequencies, β, s, t, m_* are constants, and $A_0(s,t)$ is a constant about s and t. $B_0(p)$ and p are both seasonal variables.

The intrinsic phase speed of gravity waves is the threshold of the amplitude increase of the horizontal perturbation of gravity waves, when the amplitude is close to this threshold, the growth of wave amplitude stops and reaches saturation, and the spectral energy function under saturation condition is:

$$\hat{E}_s(m,\hat{\omega}) = \beta A_0(s,t)B_0(p)\phi_0 N^2\hat{\omega}^{-p}m^{-3} \tag{2}$$

Based on launch spectrum, the WM96 scheme assumes that the composition of the horizontal spectrum is linearly superposed by observing and studying the real background wind field, density and buoyancy frequency profile, so that the launch spectrum produced by the non-orographic gravity waves is conserved propagation process.

The pseudo-momentum flux is finally obtained by using the dispersion relation and Doppler frequency shift:

$$\rho_0\hat{\mathbf{F}}_P(m,\hat{\omega},\varphi) = \rho_0 \frac{\hat{\omega}}{N}\hat{E}(m,\hat{\omega},\varphi)\times\frac{(1-\hat{\omega}^2/N^2)^{1/2}(1-f^2/\hat{\omega}^2)^{3/2}}{(1-f^2/N^2)}\left(\frac{\mathbf{k}_0}{k_0}\right) sign(m) \tag{3}$$

After the non-orographic gravity waves are diffused, the momentum flux generated is used to get the net momentum fluxes toward east and north $\rho\overline{F}_E$ 、 $\rho\overline{F}_N$:

$$\rho\overline{F}_E = \sum_{i=1}^{n_\phi}(\rho\hat{F}(\varphi_i))\cos\varphi_i \quad \rho\overline{F}_N = \sum_{i=1}^{n_\phi}(\rho\hat{F}(\varphi_i))\sin\varphi_i \tag{4}$$

Define the U and V as the meridional and zonal components of wind respectively, then the forced items produced can be obtained from the vertical divergence of the net momentum flux:

$$\frac{\partial U,V}{\partial t} = g\frac{\partial\rho\overline{F}_E,\rho\overline{F}_N}{\partial} \quad \frac{\partial T}{\partial t} = -\frac{1}{c_p}\left(u\frac{\partial u}{\partial t} + v\frac{\partial v}{\partial t}\right) \tag{5}$$

Thus, the wind and temperature fields of the atmosphere are corrected to improve the prediction performance of the model.

2.2. Hydrostatic and Non-rotational scheme of S02 scheme

Based on the WM96 scheme, Scinocca et al [10, 11] developed the hydrostatic and non-rotational non-orographic gravity waves drag scheme in 2002, referred to as S02 scheme.

The S02 scheme replaces the seasonal variable $B_0(p)$ in the launch spectrum energy function by reducing the total launch momentum flux specified at each horizontal azimuth angle. And by reducing the launch of the total E-P flux to simulate the influence of "back-reflection" in the non-hydrostatic and rotational scheme, the energy spectrum is simplified to:

$$\hat{E}(m,\hat{\omega},\varphi) = C\left(\frac{m}{m_*}\right)^s \frac{N^2\hat{\omega}^{-p}}{1-\left(\frac{m}{m_*}\right)^{s+t}} \tag{6}$$

Compared with the WM96 scheme, the S02 scheme uses the hydrostatic and non-rotational dynamic frame, which assumes that the atmospheric motion satisfies the hydrostatic equilibrium and is non-rotational, thus the computation of the frequency $\hat{\omega}$ and the dispersion relation is simplified.

Secondly, the S02 scheme simplifies the E-P flux from $\rho F^H(m,\hat{\omega},\varphi)$ to $\rho F^H(m,\varphi)$ by integrating $\hat{\omega}$, which reduces the calculated amount, and validates that the use of $\rho F^H(m,\hat{\omega},\varphi)$ and $\rho F^H(m,\varphi)$ is consistent in the results when the $\hat{\omega}$ Doppler shift is correctly computed in this integral. Then the $\rho F^H(m,\varphi)$ is transformed in the spectral space, so the momentum flux:

$$\rho\overline{F}(\hat{c},\varphi) = \rho A\frac{\hat{c}-\hat{U}}{N}\left(\frac{\hat{c}-\hat{U}}{\hat{c}}\right)^{2-p}\frac{1}{1+\left(\frac{m_*(\hat{c}-\hat{U})}{N}\right)^{s+3}} \tag{7}$$

$$A = Cm_*^3\left[\frac{N_0^{2-p}-f^{2-p}}{2-p}\right] \quad \hat{U} = U^{(\varphi)} - U_0^{(\varphi)} \quad \hat{c} = c - U_0^{(\varphi)} \quad U^{(\varphi)} = u\cos(\varphi) + v\sin(\varphi) \tag{8}$$

$U^{(\varphi)}$ indicates the velocity in the φ direction, and subscript 0 indicates the velocity at the launch layer. The S02 scheme simplifies the parameterization scheme by simplifying the calculation of launch spectrum energy and momentum flux.

Compared with the WM96 scheme, the S02 scheme, under the condition of hydrostatic and non-rotational, simplifies the processing of wave energy and momentum flux. The parameterization scheme is streamlined, the operation efficiency of the model is improved greatly, and the effective of the wind field and temperature prediction is similar to the WM96 scheme, but the prediction of the middle atmosphere wind field is not stable, and the forecast of the winter warm pole is biased. With the developing of high-performance computer and parallel computing technology, the computation amount of the WM96 scheme is no longer a main obstacle. Therefore, it is possible to consider introducing the WM96 scheme into the numerical model.

3. Experimental results and analysis

Sudden stratospheric warming (SSW) is a characteristic phenomenon of the stratospheric atmosphere circulation in winter, and is often accompanied by deforming or even collapsing of polar vortex [12]. SSW means that in the stratosphere at the 10hPa and below, temperature rises abruptly in a short time, moreover, the gradient of temperature between the mean and pole and the one of geopotential height are reversed in the vicinity of the 60°N zonal circle, the westerly mean jet in the stratosphere is also reversed. In order to test the improving effect of the schemes on the model, YHGSM global spectrum model is used as experimental platform and SSW events from 2012 to 2013 is used as test case in this paper. Rayleigh friction scheme, S02 scheme and WM96 scheme are labeled “scheme A”, “scheme B” and “scheme C”, respectively.

3.1. Wind fields at the Northern Hemisphere 10hPa

Figure 1 is the analysis field of wind at the northern hemisphere 10hPa height obtained from the analysis field from January 1, 2013 to January 9 by using scheme A. It is obviously from the pictures that the zonal wind speed was about 60m/s near 60°N in January 1 and the wind speed reached 80m/s in some areas. In January 3, the zonal westerly wind began to decrease at 60°N north latitude, and the region of 60m/s wind speed decreased. The zonal westerly wind continued to weaken in January 5 and the wind speed was about 20m/s, the negative values of wind speed began to appear in some areas. On January 7, the zonal wind changed into an easterly wind near 60°N, the wind speed was -30m/s, and wind speed was reduced to -50m/s in partial area. From January 1 to 9, the northern hemisphere wind direction changed to the east wind. It means a strong SSW event.

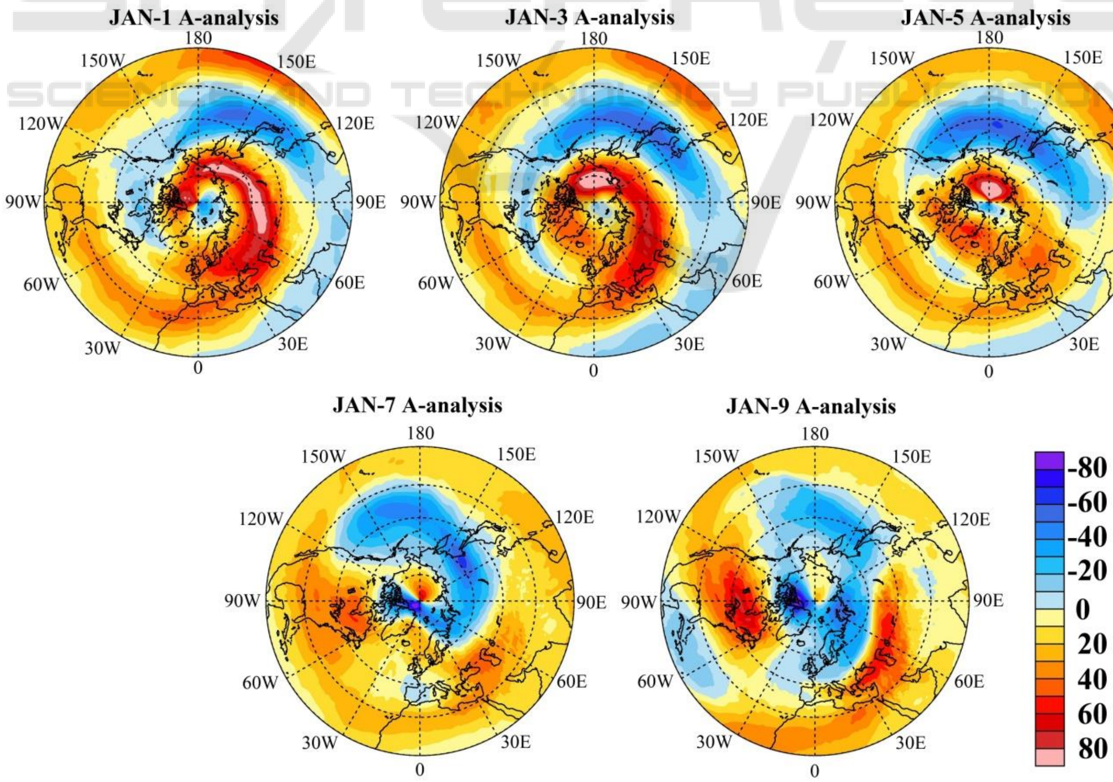

Figure 1. Analysis field of U wind by using scheme A at the Northern Hemisphere 10Pa.

YHGSM T799 model forecasts for ten days by using the analysis field data in January 1 and schemes A, B, C respectively. Figures 2,3 and 4 are the wind field plots from forecast results. We investigate figure 2 to 4, schemes A, B and C have successfully and accurately predicted the reversal of stratospheric wind field in the northern hemisphere during the outbreak of sudden stratospheric warming events. Compared with the scheme A, the schemes B and C are closer to the variation of stratospheric wind field obtained by the analysis field. For the reversal of the wind field, the schemes B and C are closer to the variation of the analytical field than the scheme A. Compare the forecast performance of the schemes A, B and C, it can be seen that the overall results of the three schemes are very close. However, scheme C is closer to the stratospheric wind field derived from the analysis field in some areas.

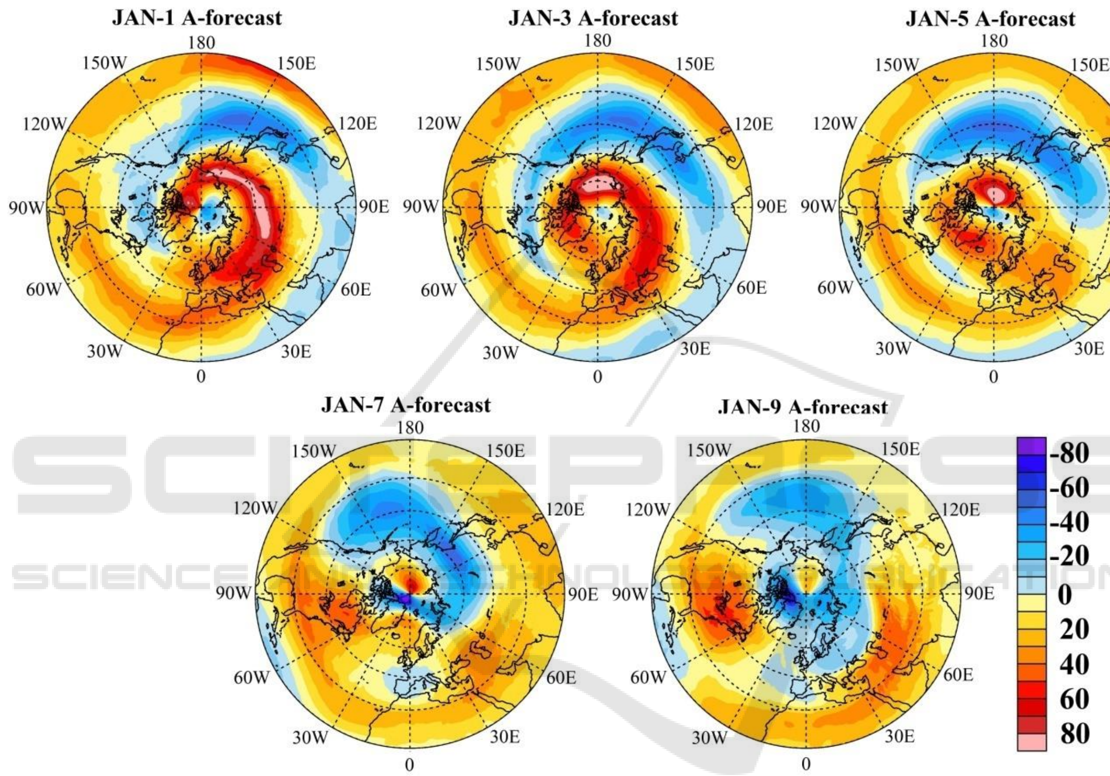

Figure 2. Forecast field of U wind by using scheme A at the Northern Hemisphere 10Pa.

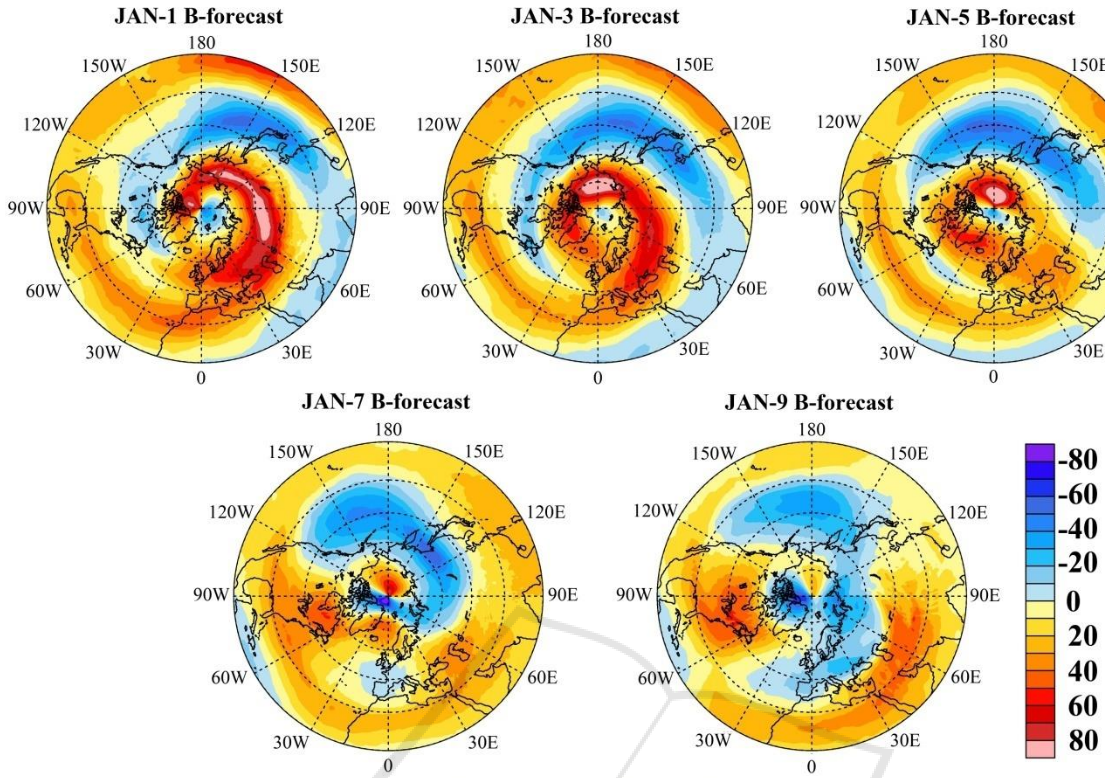

Figure 3. Forecast field of U wind by using scheme B at the Northern Hemisphere 10Pa.

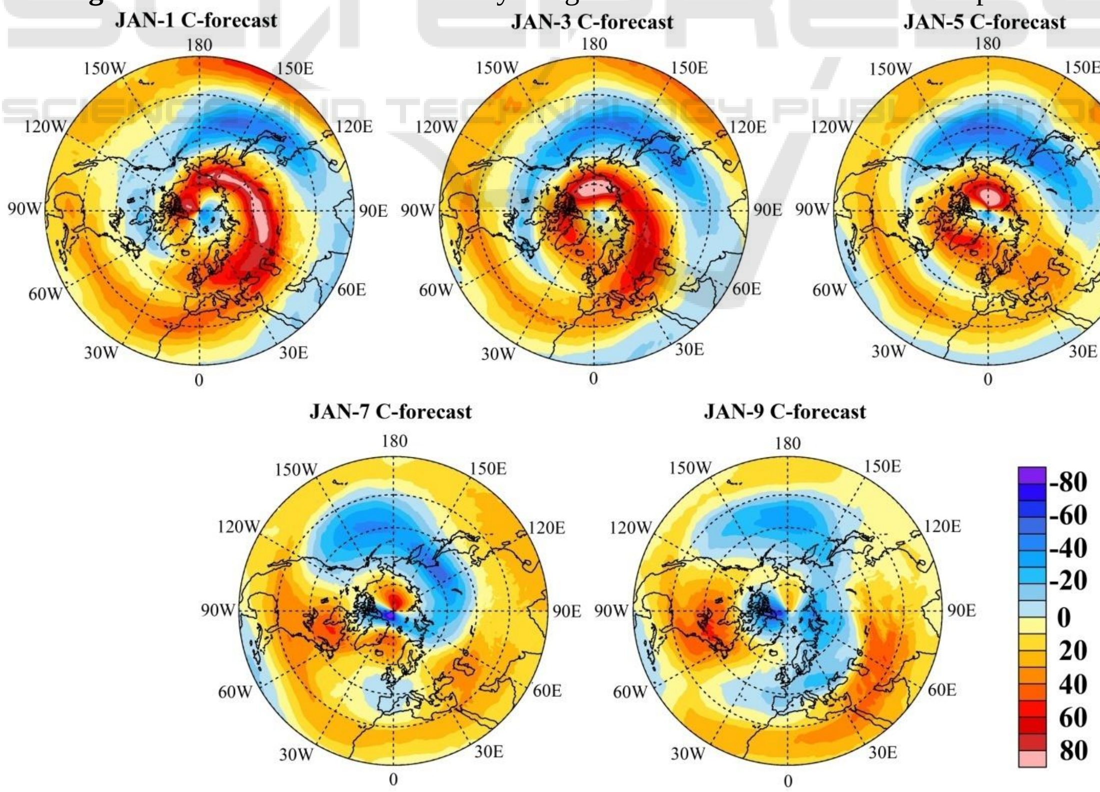

Figure 4. Forecast field of U wind by using scheme C at the Northern Hemisphere 10Pa.

3.2. Global wind forecast deviations at 10hPa

In order to more visually compare the forecast performance between schemes B and C, the 24h and 72h forecasting fields obtained from each scheme are compared with the scheme A analysis field, and the errors of global 24h and 72h wind fields forecasting at 10hPa are obtained.

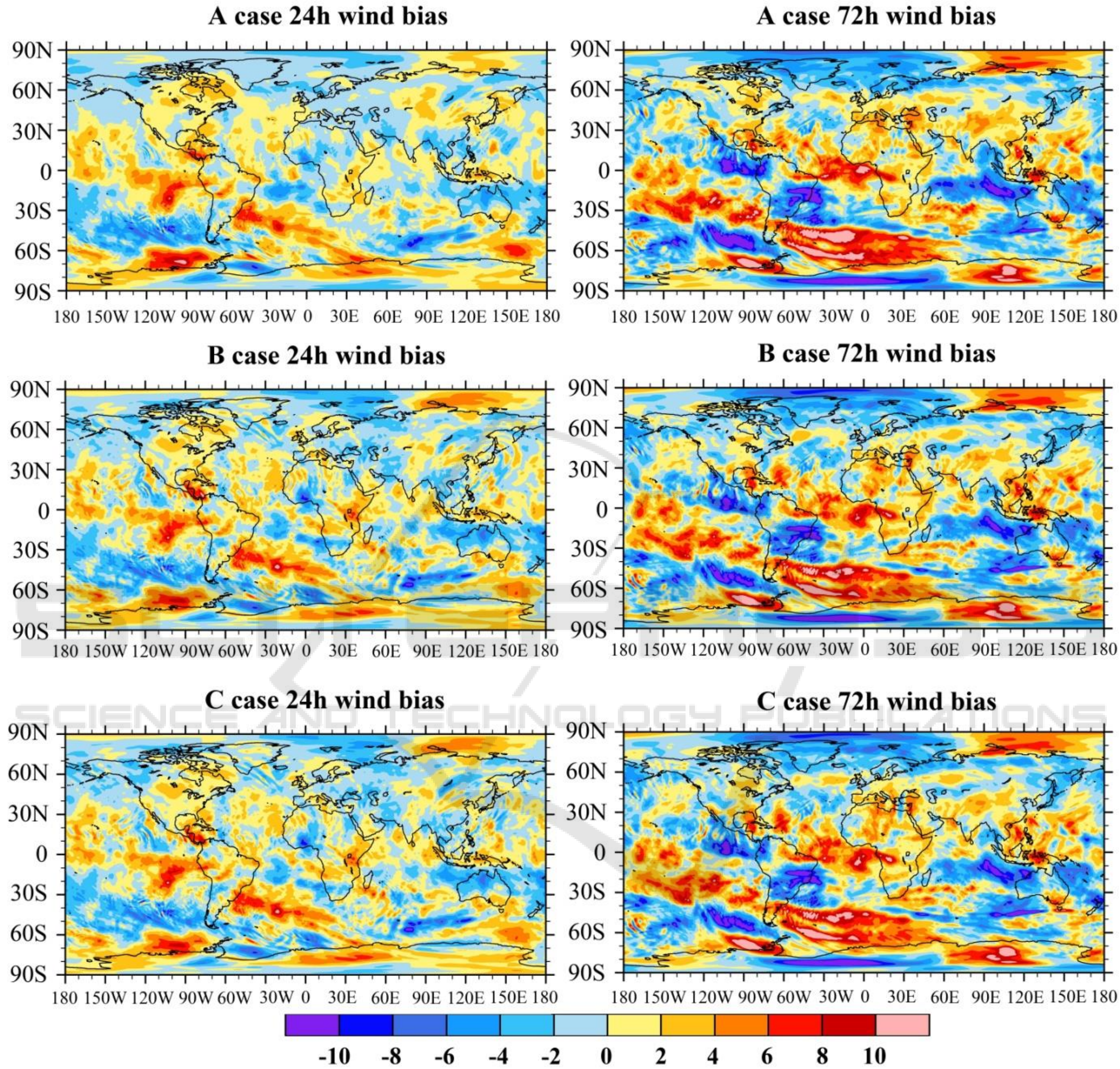

Figure 5. Global 24h and 72h wind fields forecasting deviations at 10hPa pressure level.

Figure 5 shows the global 24h and 72h wind field forecasting deviations at 10hPa pressure level. As shown in the figures, the global distribution situations of wind field forecasting error from three schemes are approximately consistent and mainly distribute from equator to nearby 80°S in the southern hemisphere. The forecast deviations of three schemes are all within the range of -10 to +10. The wind fields forecasting errors of schemes B and C are smaller than scheme A, and the deviation is obviously reduced. For example, the regional error decreases from 90°W to 120°W.

By comparing scheme B (S02) and scheme C (WM96), you can find that the 72h wind field forecasting error is more obviously. Wind field forecasting deviation has no apparent increases in the northern hemisphere, but the forecast error in the southern hemisphere has become larger obviously. The negative deviation -10m/s appears near the 25^{o}S, at the same time, there are positive deviation +10m/s in 60^{o}S region. As can be seen from the diagram, the error region of scheme C reduces compared to the scheme B, and the value of error also decreases.

4. Summary

The SSW event is closely related to the non-orographic gravity waves drag. Therefore, SSW can provide a rigorous test case for the prediction performance of the non-orographic gravity waves parameterization scheme in model. In this paper, a typical SSW event occurred in the northern hemisphere in early January 2013 is selected as a test case, and three experimental schemes are designed to test the prediction performance of the non-orographic gravity waves parameterization scheme in the model. The results show that the WM96 scheme and the S02 scheme can accurately predict the abrupt adjustment process of the stratospheric wind fields. Compared with the S02 scheme, the inversion of the wind fields is closer to the analysis field when the WM96 scheme is used, and the forecast deviation is less and the prediction performance is better.

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