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Application of ERA5 Reanalysis to the Construction of Initial Conditions for WACCM Simulations

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Abstract This study uses ECMWF fifth-generation reanalysis, ERA5, which extends to the mesopause, to construct the Initial Conditions (IC) for WACCM (Whole Atmosphere Community Climate Model) simulations. Because the biases between ERA5 and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) temperature data are within ± 5 K below the lower mesosphere, ERA5 reanalysis is used to construct IC in the lower atmosphere. Four experiments are performed to simulate a Stratospheric Sudden Warming (SSW) event from 5 to 15 February 2016. The simulation using the WACCM default climatic IC cannot represent the sharp meteorological variation during SSW. In contrast, the 0~4 d forecast results driven by ERA5-constructed IC is consistent with ERA5 reanalysis below the middle mesosphere. Comparing with WACCM climatology ICs scheme, the ICs constructing method based on ERA5 reanalysis can obtain 67%, 40%, 22%, 4% and 6% reduction of temperature forecast RMSE at 10 hPa, 1 hPa, 0.1 hPa, 0.01 hPa and 0.001 hPa respectively. However, such improvement is not shown in the lower thermosphere.

Key words ERA5 reanalysis, SABER, WACCM, Initial Condition, Stratospheric Sudden Warming (SSW)

Classified index P 351

0 Introduction

Comprehensive understanding of the variation of the middle atmosphere is important to accurately simulate weather and climate in the troposphere and ionosphere. Gerber *et al.*^[1] proposed two ways through which the stratosphere is coupled with the above and

below atmospheric layers. An obvious example of coupling with adjacent atmospheric layers is that the jet stream in the troposphere is closely connected with the development of the Antarctic ozone hole in the stratosphere of south pole^[1]. Xie *et al.*^[2] reported that Arctic stratospheric ozone can be connected with El Niño-Southern Oscillation by the combina-

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tion of stratosphere-troposphere path and tropical-subtropical climate teleconnection. Xie *et al.*^[3] argued that the global ozone decrease can cause cooler stratosphere temperature, higher tropopause, lower tropopause temperature and less tropopause vapor entering to the stratosphere. Xie *et al.*^[4] proposed that El Niño Modoki leads stronger and colder south polar vortex but weaker and warmer north polar vortex in the stratosphere, its effect is contrary to that of typical El Niño. Zhang *et al.*^[5] find that Arctic polar vortex has shifted towards Eurasia continent and away from North American in the past 30 years, and the shifting can offset tropical warming owing to climate change. In addition, the amplitude of the gravity wave from lower atmosphere increases with altitude due to the decrease of atmosphere density, saturates and breaks in the middle and high atmosphere leading to strong disturbances in this region, which has been verified by high resolution numerical simulations based on WACCM^[6]. Because of the importance of coupling between different atmospheric layers, some numerical models of the middle-high atmosphere, including NOGAPS-ALPHA^[7,8], WAM^[9], and WACCM^[10,11] have been developed.

Among these models, WACCM is one of the most popular middle-high atmospheric numerical models which include full atmospheric dynamics and chemistry. The vertical levels of WACCM extend from the earth's surface to the lower thermosphere (approximately 140 km). At present, the research hotspots based on WACCM include the response of the atmosphere to solar variability and high-energetic particle flux^[12,13], the response of stratosphere to El Niño-Southern Oscillation^[14], and numerical simulation of stratospheric sudden warming events^[15]. When users perform numerical experiments using WACCM without custom Initial Conditions (IC), WACCM uses climatic IC automatically. Although such climatic IC may be effective for climate research, they cannot accurately represent the initial state of the atmosphere in numerical simulations that involve strong variability in the middle and upper atmosphere, as

in SSW events. Custom IC are typically obtained from reanalysis or analysis data. However, among all atmospheric grid database, only NOGAPS-ALPHA (Navy's Operational Global Atmospheric Prediction System-Advance Level Physics High Altitude) analysis reaches to the lower thermosphere (approximately 100 km). Sassi *et al.*^[16] combined NAVDAS analysis (middle-high level), MERRA reanalysis (low level), and SD-WACCM-X climatology (thermosphere) to specify dynamical fields for SD-WACCM-X. NAVDAS analysis is still not available to the public. In November 2016, ECMWF released its fifth-generation reanalysis dataset, ERA5^[17]. ERA5 reanalysis extends from the surface to the top of the mesosphere (approximately 80 km, 0.01 hPa). It is the first open-access reanalysis data that includes the troposphere, stratosphere, and mesosphere.

This study uses ERA5 reanalysis to construct IC for WACCM. Firstly, the reliability of ERA5 in near space by comparing the ERA5 and SABER temperature data is verified. Secondly, IC for WACCM using ERA5 reanalysis is constructed and numerical experiments are performed to simulate a recent SSW event from 5 to 15, February 2016. Finally, SABER and ERA5 temperature data are used to evaluate and compare the forecasting effect of experiments based on the ERA5-constructed IC and climatic IC.

1 Data and Methods

The recently released ECMWF fifth-generation reanalysis ERA5 is a product of IFS (Integrated Forecasting System)^[17]. ERA5 involves 137 levels (Figure 1b) between the surface and top level at 0.01 hPa (about 80 km). Its horizontal and temporal resolutions are 31 km and 1 h, respectively. ERA5 includes deterministic and probabilistic products with 10 ensemble members. The deterministic product is employed in this study.

SABER is a sensor carried on NASA's TIMED (Thermosphere Ionosphere Mesosphere Energetic and Dynamic) satellite. Based on the emissions in diffe-

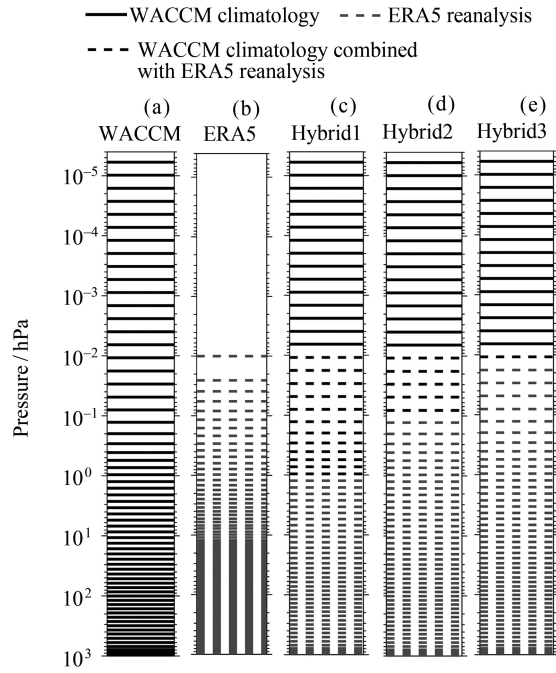


Fig. 1 Levels of WACCM (a), ERA5 reanalysis (b), Hybrid1 (c), Hybrid2 (d), and Hybrid3 (e) scheme for constructing ICs

rent channels and a non-local thermodynamic equilibrium algorithm, SABER products, including profiles of temperature, ozone, and other tracer concentrations, are produced at heights from 20 to 120 km. In this study, the SABER-V2.0 temperature product is used, which has notable algorithm improvements relative to SABER-V1.7^[18,19].

WACCM is a version of NCAR's Community Climate Model that extends to near space and the lower thermosphere. WACCM is also a branch of the Community Earth Simulation Model. WACCM supports Finite-Volume (FV) and Spectral-Element (SE) cores. In this work, we choose FV core and set the horizontal resolution to 1.9° (latitude) $\times 2.5^\circ$ (longitude). There are 66 pressure levels (Figure 1a) between the surface and the lower thermosphere (5.96×10^{-6} hPa, 140 km). WACCM's vertical resolution is approximately 1.1~1.7 km below the stratosphere and 3.5 km in the mesosphere^[10,11,20]. The component set of WACCM used here is F_2000_WACCM^[21], in which atmospheric model is active (dynamic). So the performed ex-

periments here are not the "nudging" one requiring no specified dynamics at each model time step^[22-24].

According to Sassi's method of specifying dynamical fields for SD-WACCM-X^[16], to use ERA5 reanalysis to construct IC for WACCM. For the lower layer, the model states below the Initial Hybrid Height (IHH) come from ERA5 reanalysis. For the middle layer, the model state from IHH to 0.01 hPa is the linear-weighted hybrid of ERA5 and WACCM climatology, and the weighting coefficient of ERA5 decreases linearly from 1 to 0 with height, whereas that of WACCM climatology has the opposite trend. This hybrid method eliminates abnormal breaks at the nearby levels of ERA5's upper boundary. Above 0.01 hPa, the model states are specified by WACCM climatology. To compare the effects of the IC constructed with different IHHs, we construct three hybrid schemes: Hybrid1, Hybrid2, and Hybrid3. The IHH values of the above three schemes are 1, 0.1, and 0.01 hPa, respectively. Hybrid3 is the extreme hybrid scheme as it has only one mixing level (0.01 hPa). Figure 1 shows the levels of WACCM (a), ERA5 reanalysis (b), and the three hybrid schemes (c)~(e). We perform four numerical experiments, one control experiment using WACCM climatology and the other three experiments using the hybrid schemes to simulate the third SSW event, which occurred from 5 February 2016 (00:00 UT) to 15 February 2016 (18:00 UT). To examine the forecasting effect and use the following three statistical indexes: mean bias, standard bias and correlation coefficient between forecast and observation (or reanalysis).

2 Results

2.1 Comparison of Temperature between ERA5 Reanalysis and SABER Observations

Before using ERA5 to construct IC for WACCM, it is necessary to compare the ERA5 and SABER temperature data to evaluate the applicability of ERA5 reanalysis in near space. The vertical distributions

of global mean bias and standard bias between the two sets of data are shown in Figure 2. The ERA5 temperatures in the mesosphere and the middle-lower stratosphere are lower than the SABER temperatures. The maximal cold bias of ERA5 is at 0.3 hPa, where the maximum mean bias reaches -7.5 K. In the middle-lower stratosphere, the cold bias of ERA5 relative to SABER is within -2.5 K. In the upper stratosphere, the warm bias of ERA5 relative to SABER is also less than 2.5 K. According to Figure 2(b), the standard bias decreases with height and the minimum is only 1.67 K below 10 hPa, while the standard bias increases with height and reaches 12.8 K at the mesopause above 10 hPa. In total, the ERA5 and SABER temperatures show good agreement throughout the stratosphere and the lower mesosphere, where the bias is within ± 5 K. Thus, ERA5 reanalysis is used to construct the IC for WACCM below the lower mesosphere.

2.2 Applying ERA5-constructed IC in WACCM Simulations

Figure 3 shows the variation of zonal mean temperature and zonal wind in near space presented by ERA5 reanalysis, SABER data and simulated by three hy-

brid experiments. According to Figures 3(a) and (b), the variation in vertical thermal structure described by ERA5 and SABER are similar. During this stratospheric sudden warming event, the stratopause descended from 1 to 5 hPa. After the direction of zonal wind reversed on 7 February, the east wind layer dropped to the middle stratosphere (about 10 hPa) as the stratopause descended. The SABER data indicate that the mesosphere became cooler than the normal state, and the mesopause dropped during the warming period. In addition, an obvious double mesopause appeared at 0.01 and 0.0005 hPa according to the ERA5 and SABER data. All states began to recover to normal after 10 February.

The simulated temperature of the four experiments (Figure 3d, e, h, i) indicates that the mesopause descended during SSW. However, the control experiment did not generate the double-mesopause structure on 10 February. Moreover, the warming layers simulated by the control experiment (WACCM climatology) were only located at the stratopause and the lower mesosphere but not the entire stratosphere. In addition, the descent of the stratopause is not indicated in the results of the control experiment, and the simulated temperature of the control experiment at the middle-lower stratosphere is warmer than that of ERA5 reanalysis. All hybrid experiments indicate that the wind direction changed from west to east (Figure 3f, g, j, and k). However, the results of the control experiment are quite different from the results of the ERA5 reanalysis in terms of the time at which the wind direction changed from west to east and the speed of the east wind. During the warming period, the east wind speed simulated by the control experiment is larger than that of the ERA5 and hybrid experiments. During the period of stratopause recovery, the east wind reverses gradually to the west wind for the ERA5 and hybrid experiments. In contrast, the east wind does not change for the control experiment. The above shortcomings of the control experiment are greatly improved in the hybrid experiments.

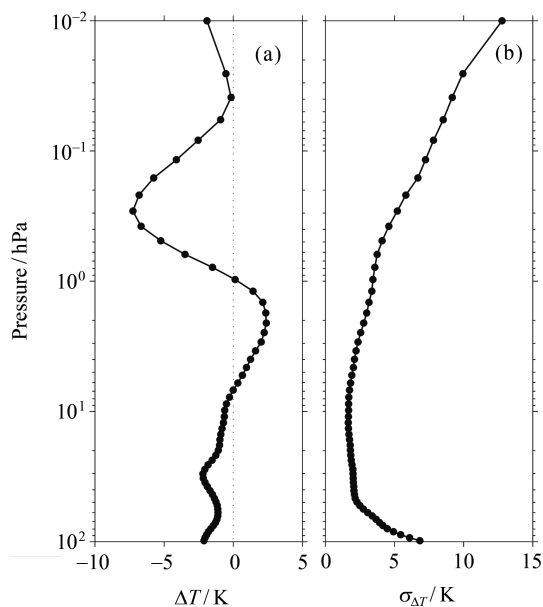


Fig. 2 Profiles of ERA5-SABER global mean temperature bias (a) and standard bias (b). The data are obtained from 1 January to 29 February 2016

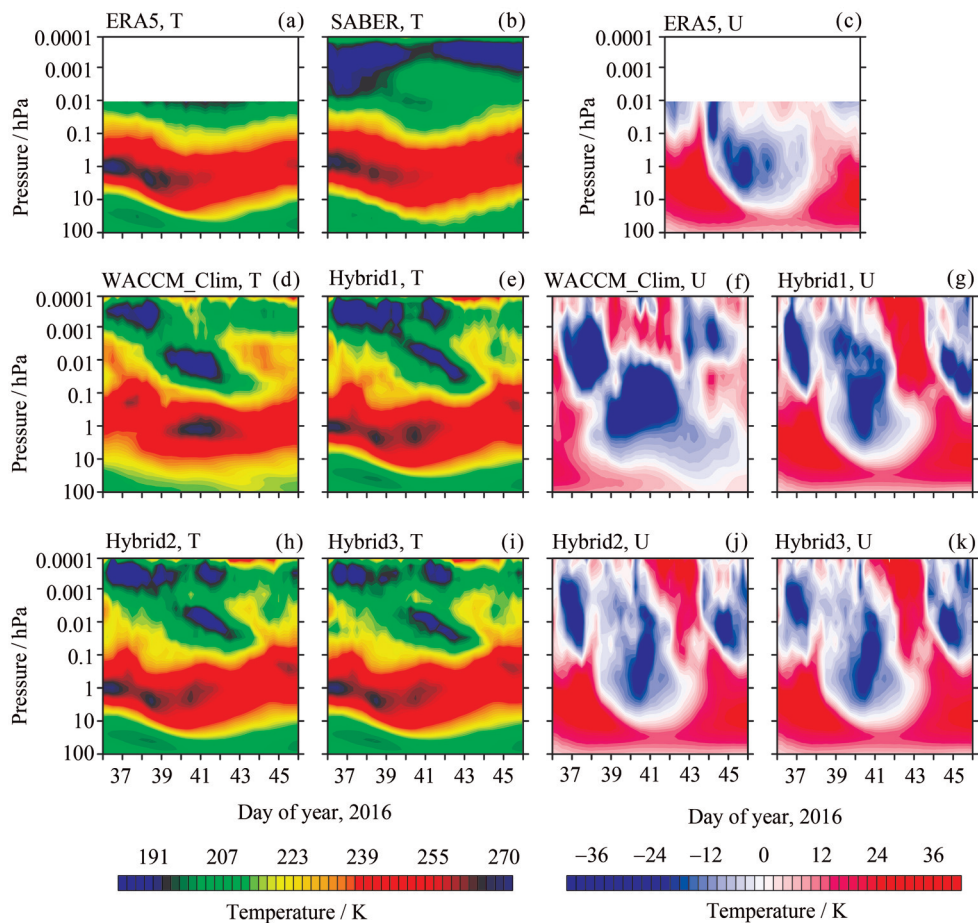


Fig. 3 Profiles of zonal mean temperature (a, b, d, e, h, and i) and zonal wind (c, f, g, j, and k) averaged between 70°N and 82.75°N from 5 to 15 February 2016

2.3 Forecast Verification

The forecast verifying results of the four experiments based on ERA5 temperature are shown in Figure 4. All experiments, including the control, produce similar vertical distributions of mean bias. Compared to the ERA5 reanalysis, all experiments produce warmer temperatures in the middle and lower layer of both stratosphere and mesosphere, but colder temperatures in the upper layer of both stratosphere and mesosphere. The largest bias in the simulated results relative to ERA5 appears in the lower mesosphere. Figure 4(a), (b), (c), and (d) show that 0~4 d forecast biases of three hybrid experiments are lower than that of the control experiment (WACCM climatology) at any levels. In the upper mesosphere ($0.1\sim 0.01$ hPa), the 0~3 d forecast of temperature based on Hybrid3 scheme shows least difference with ERA5 reanalysis

among three hybrid IC-constructing schemes. The maximum standard bias of the control experiment is 20 K in the mesopause (Figure 4e). The standard biases of three Hybrid experiments increase with height and time and are lower than 3 K, 7 K, and 10 K below 10 hPa, 1 hPa, and 0.1 hPa, respectively. This might be attributed to the larger bias of WACCM at higher levels. Pedatella *et al.*^[15] reported that the bias of WACCM is much larger than observational error. According to Figure 4(i), temperature field of control experiment shows low correlation with ERA5 reanalysis at most levels and time. However, correlation coefficients of hybrid experiments are higher than 0.9 at most levels and time (Figure 4j, k, and l).

For making independent test, SABER temperature observations are used to verifying the advantage of IC constructing schemes. Figure 5 shows the fore-

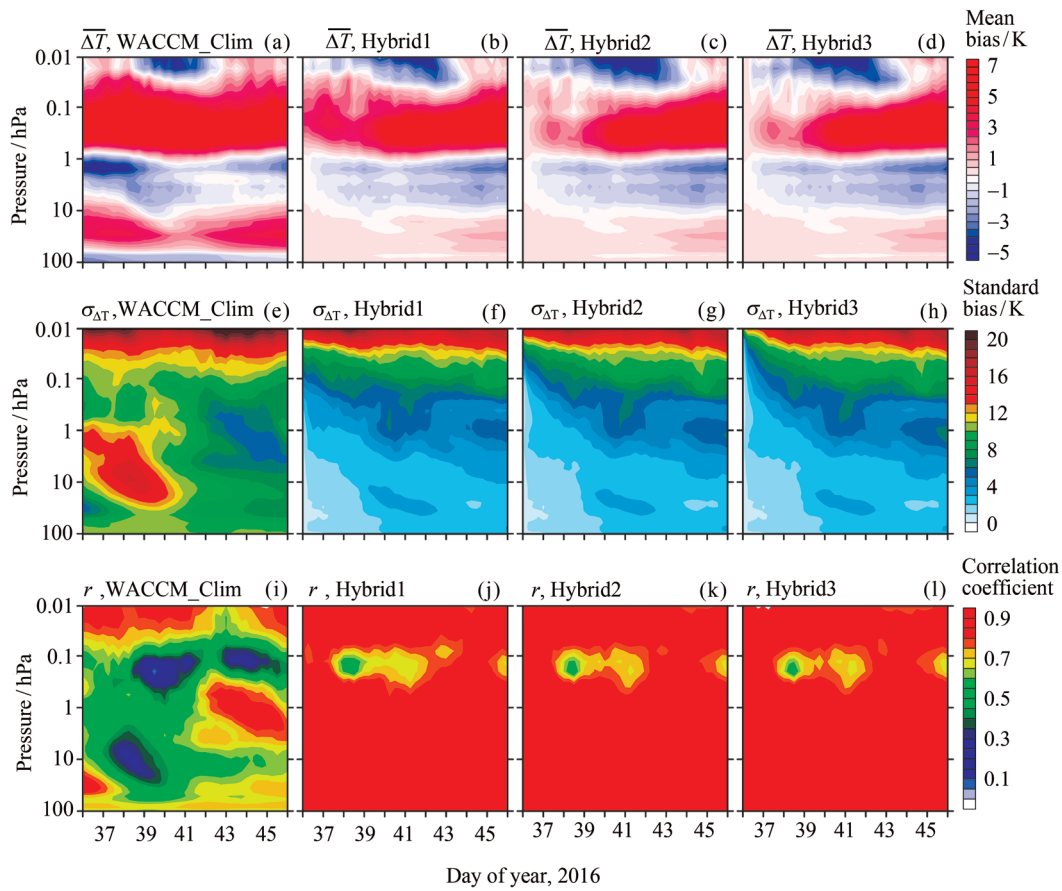


Fig. 4 Profiles of global forecast mean bias (a, b, c, and d), standard bias (e, f, g, and h) and correlation coefficient (i, j, k, and l) of four experiments relative to ERA5 temperature products from 5 to 15 February 2016

cast verifying results based on SABER temperature data. According to the distribution of biases (Figure 5 a, b, c, and d), simulated temperature by all experiments is rather warmer below the mesopause but colder in the lower thermosphere relative to SABER observations. The biases in three hybrid experiments are slightly smaller than that of the control experiment (WACCM climatology) in the lower thermosphere. This may be because WACCM IC constructed by ERA5 reanalysis can represent more real lower atmospheric waves, whose upward propagation is supposed to improve the simulation of the lower thermosphere.

Ren *et al.*^[25] and Xu *et al.*^[26] reported that gravity wave drag could send effective atmospheric signals from the lower atmosphere to the middle-high atmosphere, and assimilating observations in the lower atmosphere can simulate the state of the mesosphere better. Figure 5(e), (f), (g), and (h) show that

the standard biases of three hybrid experiments increase with height and are within 10 K below 0.1 hPa. In terms of the control experiment, the maximum of the standard bias below 0.1 hPa reaches 20 K. Based on the distributions of correlation coefficients in Figure 5(i), (j), (k), and (l) in the developing phase of SSW (before February 10), the results of the control experiment have a low negative correlation with SABER data. The correlations between the hybrid experiments and SABER data are larger than that between the control experiment and the SABER data, especially in the stratosphere and lower mesosphere. However, the results of both the control and hybrid experiments show weak positive correlations with SABER temperature in the lower thermosphere.

To making point-to-point comparison, Figure 6(a) shows profiles of global mean 0~10 d temperature forecast RMSE of different experiments. RMSE profiles behave increasing trend with height.

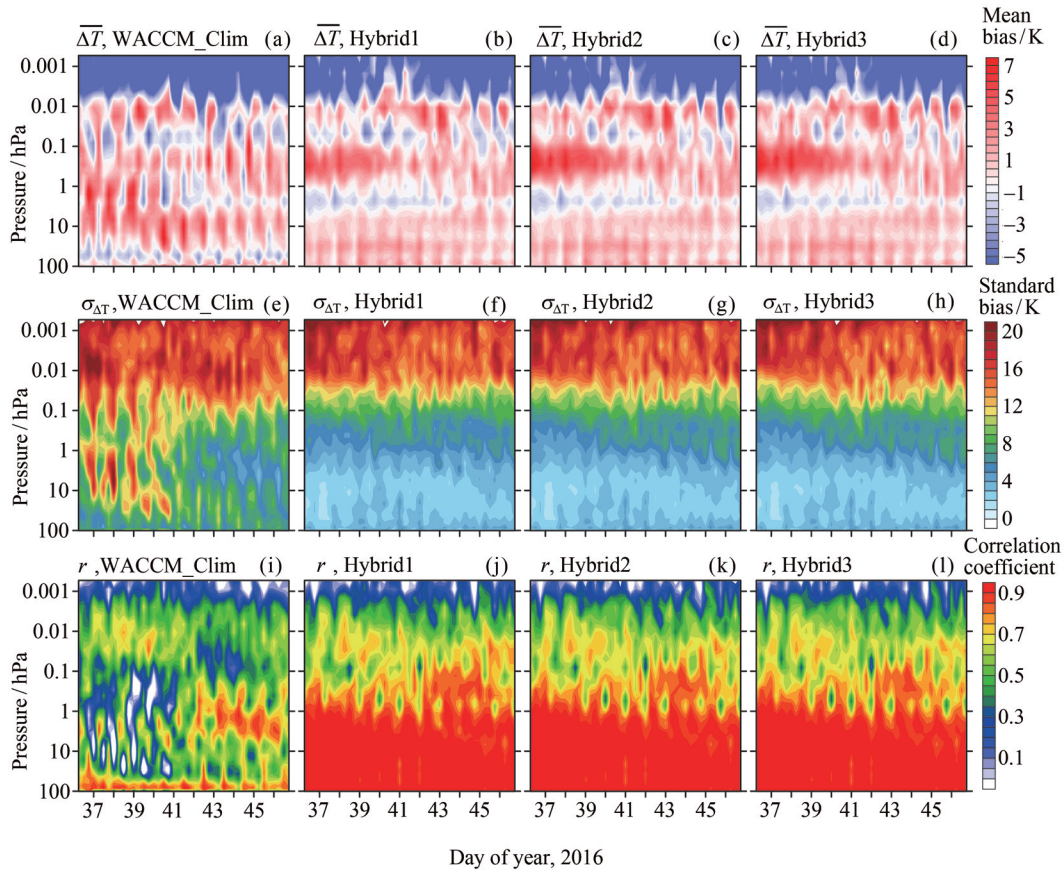


Fig. 5 Profiles of global forecast mean bias (a, b, c, and d), standard bias (e, f, g, and h), and correlation coefficient (i, j, k, and l) of four experiments relative to SABER temperature from 5 to 15 February 2016

RMSE of three hybrid experiments is always lower than that of control experiment (WACCM climatology) even in the layer where ERA5 reanalysis does not cover (< 0.01 hPa). Figure 6(b) shows that hybrid IC constructing schemes lead to 67%, 40%, 22%, 4% and 6% reduction of RMSE at 10 hPa, 1 hPa, 0.1 hPa, 0.01 hPa and 0.001 hPa respectively relative to WACCM climatology experiment. The variation of RMSE of three Hybrid experiments presents the similar vertical distribution, but only a little difference between 1~0.1 hPa which may be explained by significant bias between SABER observation and ERA5 reanalysis in those layer shown in Figure 2(a).

3 Conclusions

ECMWF fifth-generation reanalysis, ERA5, which extends to the mesopause, are used to construct IC for

WACCM. Because the biases between ERA5 and SABER temperatures are within ± 5 K, ERA5 reanalysis is used to constrain the ICs for WACCM in the lower atmosphere. We use the ERA5-constructed IC and WACCM default climatic IC to perform simulations of a SSW event in 2016. The results indicate that the WACCM climatology-based ICs cannot accurately represent sharp variation of zonal wind and temperature in near space during SSW. The numerical simulation results derived by the ERA5-constructed ICs are consistent with the ERA5 reanalysis in terms of representing the evolution of zonal wind and temperature below the middle mesosphere within future 0~4 d. The independent forecast verifying results reveal that, comparing with that of WACCM climatology ICs scheme, the construction of ICs including ERA5 reanalysis leads to 67%, 40%, 22%, 4% and 6% reduction of temperature forecast RMSE at 10 hPa,

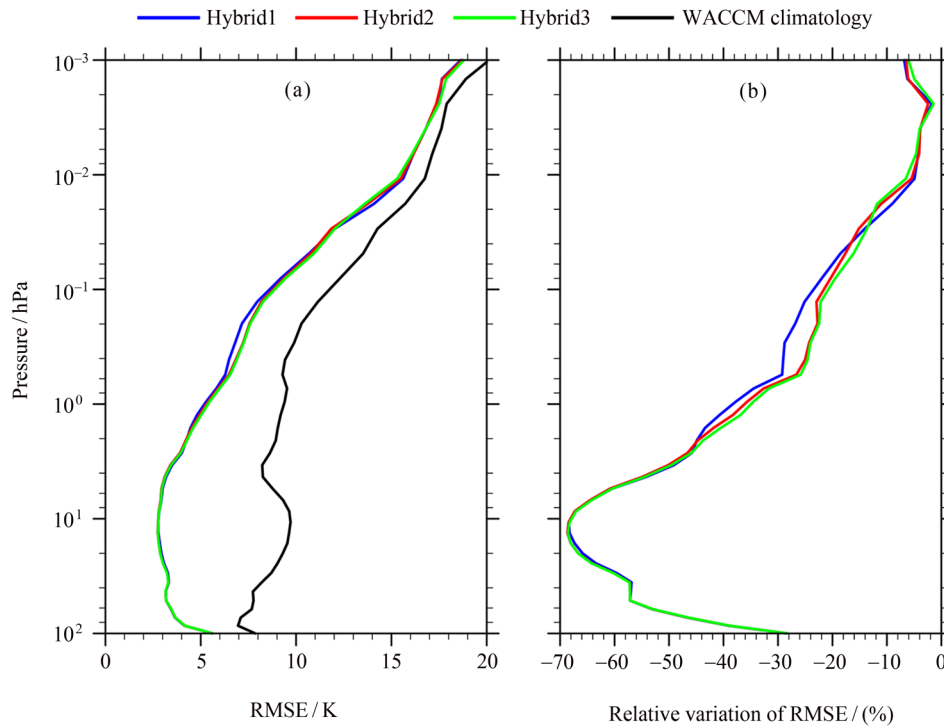


Fig. 6 Profiles of global mean RMSE of 0~10 d temperature forecast and RMSE relative variation of temperature forecast relative to its RMSE from WACCM climatology experiments calculated by SABER observations from 5 to 15 February 2016

1 hPa, 0.1 hPa, 0.01 hPa and 0.001 hPa respectively. However, the improvement is not obvious in the lower thermosphere.

This work verifies the usefulness of ERA5 in constructing ICs for near-space numerical simulations. Even though the application of ERA5 results in better forecasting ability than using WACCM climatology ICs, the large model error still leads to large state variable errors after several days of numerical integration. To improve the forecasting precision of the middle-high atmospheric model, more work should focus on assimilating diverse observations in near space and then the ICs can be better adjusted.

Acknowledgments WACCM's source code is available from <http://www.cesm.ucar.edu>. ERA5 reanalysis is downloaded from <http://apps.ecmwf.int>. SABER-V2.0 is available from <http://saber.gats-inc.com>. The authors thank Hanli Liu from NCAR/HAO, Kelvin Reader from NCAR/DAReS, Dr. SUN Weiyang from CSSR/ NSSC and two anonymous reviewers for their helpful advice.

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