Impacts of Changes of External Forcings from CMIP5 to CMIP6 on Surface Temperature in FGOALS-g2

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Abstract
External forcings among the different phases of the Coupled Model Intercomparison Project (CMIP) vary considerably, but their impacts have not been extensively investigated yet. This study compares the impacts of CMIP5 and CMIP6 forcings on model stability and the 20th-century global warming and El-Niño Southern Oscillation (ENSO) based on the Pre-Industrial control (PI-control) and historical runs of the Flexible Global Ocean–Atmosphere–Land System Model: Grid-point Version 2 (FGOALS-g2). Results indicate that CMIP6 forcings result in a larger climate drift and a lower climatological global average surface temperature (GAST) than those of CMIP5 in PI-control runs. In historical runs, stronger 20th-century warming trends occur during the periods 1910–1940 and 1970–2005 using CMIP6 forcings, which are closer to the HadCRUT than those of the CMIP5 forcings simulation. A stronger spurious warming trend in the CMIP6 results in an evolution of GAST that is less consistent with the HadCRUT dataset than that in the CMIP5 during 1940–1970. Among all forcings, GHGs and aerosol forcings play the dominant roles in differences in GAST, particularly in the Northern Hemisphere. In both the PI-control and historical runs, a larger ENSO amplitude and smaller seasonality are simulated in CMIP6 than in CMIP5.

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1. Introduction
The Coupled Model Intercomparison Project (CMIP) began in 1995 and has become an important source of multi-model simulation datasets for climate research. During each new phase of the CMIP, the latest versions of climate models are forced by new sets of external forcings [e.g., anthropogenic greenhouse gases (GHGs), solar radiation, volcanic eruptions, and aerosols] based on concurrent observations and current scientific understanding. Hence, for most CMIP data users it is difficult to distinguish the relative contributions of model improvements and changes to external forcings in simulations of specific climate events, such as global warming and internal climate variability. However, such a differentiation is critical to investigations of climate change and related physical mechanisms.

The impact of external forcings is always a hot topic in the climate community. For example, the response of surface temperature to external forcings has been studied extensively, and suggests that the global and regional warming trend since the 1970s can be attributed primarily to anthropogenic GHG and aerosol forcings (e.g., Li et al. 2007; Bindoff et al. 2013; Zhao et al. 2016; Frankignoul et al. 2017). The effects of external forcings on other variables such as precipitation, sea level, and sea ice have also been thoroughly investigated (e.g., Kay et al. 2011; Marvel and Bonfils 2013).

The difference in external forcings among the various CMIP phases can be quite large. For example, in the upcoming CMIP phase 6 (CMIP6), the GHG concentration datasets are latitudinally resolved and include seasonality (Meinshausen et al. 2016, 2017), whereas only global mean concentrations were used in previous CMIP phases in almost all models (Taylor et al. 2009). The solar constants in CMIP6 (Matthes et al. 2017a, b) are generally smaller than those in CMIP5 (http://solarisheppa.geomar.de/cmip5). Anthropogenic aerosols are prescribed as a distribution of aerosol optical and cloud-active properties (a top-down approach) in CMIP6 (Stevens et al. 2017) compared with a distribution of aerosol concentrations (a bottom-up approach) in CMIP5/CMIP3 (Lamarque et al. 2010). It remains to be determined how these changes to external forcings affect surface temperatures. These effects are expected to be closely related to 20th-century global warming and internal climate variabilities.

To investigate these effects, two types of CMIP experiment are performed using the Flexible Global Ocean–Atmosphere–Land System Model: Grid-point Version 2 (FGOALS-g2), one of the CMIP5 models. A pre-Industriual control run (PI-control) is performed to investigate the impact of external forcing changes on model stability (climate drift). The other is a historical run used to examine the response of global average surface temperature (GAST) and internal climate variability (with a focus on the El-Niño Southern Oscillation, hereafter ENSO) to changes in external forcings.

2. Model description and experiment design

2.1 Model description
The FGOALS-g2 was developed in the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) at the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences, Beijing, China (hereafter LASG/IAP/CAS; Li et al. 2013a). It is composed of four main component models: the atmospheric component, GAMIL2 (Grid-point Atmospheric Model of IAP LASG; Li et al. 2013b); the oceanic component, LICOM2 (LASIC/G/IAO Ocean Model; Liu et al. 2004a, b); the sea-ice component, CICE4-LASG (Community Ice Code, improved by LASG; Liu 2010); and the land component, CLM3 (Community Land Model; Oleson et al. 2010). GAMIL2 employs 2.8° × 2.8° horizontal grid and 26 vertical η-layers with the model top at 2.194mb. LICOM2 adopts geographic longitude–latitude grid of 1° × 1° and η-vertical coordinates (30 levels). Resolution of CICE4-LASG is the same as that of LICOM2. CLM3 have the same resolution as GAMIL2. The four components exchange fluxes through the CPL6 coupler (Craig et al. 2005).

2.2 Datasets
Two sets of external forcings (including solar constants,
The evolution of GAST in the PI-control runs forced by the CMIP5 and CMIP6 forcings is shown in Fig. 1. The linear trend during model years 100–550 in the CMIP6 simulation (~0.073°C per 100 years) is larger than that in the CMIP5 simulation (~0.039°C per 100 years), indicating an effect of external forcings on model stability. In addition, the mean GAST value is 13.37°C in the CMIP6 run, lower by ~0.44°C than that in the CMIP5 simulation. This difference is attributed primarily to the smaller solar constants and partly to the stratospheric aerosols in the CMIP6 simulation.

Sea surface temperatures (SSTs) used here are from the monthly 1° × 1° HadISST dataset from 1900 to 2005 (Rayner et al. 2003), and global surface temperature anomalies are from the monthly 5° × 5° HadCRUT dataset from 1850 to 2005 (Morice et al. 2012). Both are used to evaluate the simulations.

3. Results and analysis

The evolution of GAST in the PI-control runs forced by the CMIP5 and CMIP6 forcings is shown in Fig. 1. The linear trend during model years 100–550 in the CMIP6 simulation (~0.073°C per 100 years) is larger than that in the CMIP5 simulation (~0.039°C per 100 years), indicating an effect of external forcings on model stability. In addition, the mean GAST value is 13.37°C in the CMIP6 run, lower by ~0.44°C than that in the CMIP5 simulation. This difference is attributed primarily to the smaller solar constants and partly to the stratospheric aerosols in the CMIP6 simulation.

Figure 2 shows a time series of GAST anomalies and Northern Hemisphere average surface temperature (NAST) anomalies from observations and historical simulations forced by the CMIP5 and CMIP6 forcings. The HadCRUT dataset reveals two warming periods at 1910–1940 and 1970–2005, and a cooling period at 1940–1970. The warming trend is stronger and the average GAST value is greater during the second warming period than during the first. In the historical simulations, the overall evolution of GAST in the CMIP5 simulation is more consistent with observations than that in the CMIP6, in which GAST values are noticeably lower than observations before 1920 and larger than observations after 1920 (Fig. 2a). Table 1 provides values for the trends during the three periods discussed above. In the CMIP5 simulation, the trends during the warming periods are weaker than those from observations, particularly during the first period (1910–1940). The cooling trend during 1940–1970 is not captured by the CMIP5 simulation, which instead shows a spurious warming trend. This poor performance is common to many CMIP models (Hegerl et al. 2007). Offsetting effects between a spurious warming trend during the cooling period and weak warming trends during the two warming periods lead to an overall good simulation of GAST evolution in the CMIP5 simulation. In the CMIP6 simulation, trends during the warming periods are stronger than in the CMIP5 simulation and are closer to observations, but the spurious warming trend during the cooling period is more pronounced. Both experiments with CMIP5 and CMIP6 forcings fail to reproduce the cooling period, which may be related to the underestimation of aerosol/stratospheric aerosols cooling effects and/or internal variability. Meanwhile, intermittent cooling of GAST in the CMIP6 historical runs near year 1885, 1965 and 1992 is caused by stratospheric aerosols cooling effects. GAST in the CMIP6 historical runs are larger than indicated by observations during 1970–2005. Trends of NAST are similar to those of GAST, but with larger variations (Fig. 2b; Table 1).

To further differentiate which types of external forcing contribute to the 20th-century global warming in the CMIP5 and
CMIP6 forcing cases, additional experiments are performed in which each type of external forcing is added separately. It is found that GHGs and aerosols play leading roles in determining surface temperature during the historical runs. As shown in Fig. 3, GHGs promote global warming, whereas aerosols have the opposite effect. The warming from GHGs and the cooling from aerosols are almost balanced during 1850–1970. They gradually become unbalanced as the response of temperature to GHGs increases more quickly than that to aerosols during the period 1970–2005, leading to global warming. The GAST forced by CMIP6 GHGs follows a stronger warming trend than that forced by CMIP5 GHGs, particularly in the Northern Hemisphere, which is consistent with temperature differences between CMIP5 and CMIP6 with full external forcings. There is no significant difference between the responses of GAST to CMIP5 and CMIP6 aerosols before 1970. However, CMIP6 aerosols are more influential than those of CMIP5 to GAST after 1970. In Fig. 3b, the response of NAST to aerosols is stronger because of the spatial distribution and seasonal cycling of GHGs in the Northern Hemisphere (Meinshausen et al. 2011, 2017). The response of NAST to aerosols is similar to that of GAST. Therefore, 20th-century global warming is more significant in the Northern Hemisphere. This could be attributed to the combined effects of latitudinal resolved and seasonality varying CMIP6 GHGs and CMIP6 anthropogenic aerosols. In a word, effects of GHGs and aerosols and their comprehensive impacts are important in deciding whether a cool or a warm NAST and GAST.

Although Li (2013a) shows a good ENSO performance of the CMIP5 historical simulation by FGOALS-g2, to examine the response of ENSO to CMIP5 and CMIP6 external forcings, ENSO-related metrics including amplitude, seasonality, and spectral shape are calculated (Table 2; Guilyardi et al. 2009; Bellenger et al. 2013). ENSO amplitudes are computed as the monthly SST anomaly standard deviation (SSTA Stddev) over the Niño3 (150°W–90°W, 5°S–5°N) and Niño4 (160°E–150°W, 5°S–5°N) regions. Seasonality, which describes the seasonal phase-locking of ENSO, is the ratio of the average Stddev of the Niño3 SST anomaly during years November–January and March–May. Spectral shape, which measures the amplitude of the ENSO biennial component, is the ratio of the Niño3 SST anomaly standard deviation (SSTA Stddev) over the Niño3 (150°W–90°W, 5°S–5°N) and Niño4 (160°E–150°W, 5°S–5°N) regions. Seasonality varying CMIP6 GHGs and CMIP6 anthropogenic aerosols. In a word, effects of GHGs and aerosols and their comprehensive impacts are important in deciding whether a cool or a warm NAST and GAST.

4. Summary and discussion

To investigate the influence of CMIP5 and CMIP6 external forcings on model stability, 20th-century global warming, and ENSO, two types of CMIP simulation, PI-control and historical runs, are performed using FGOALS-g2. Results show that in the PI-control runs the CMIP6 forcing simulation produces a larger

### Table 1. Linear trends of global average surface temperature (GAST) anomalies and Northern Hemisphere average surface temperature (NAST) anomalies during three periods from observations (HadCRUT dataset), and CMIP5 and CMIP6 ensemble average values from historical runs of FGOALS-g2 (units: °C/10 years).

| Period     | Observations | CMIP 5 | CMIP 6 | CMIP 5 | CMIP 6 |
|------------|--------------|--------|--------|--------|--------|
| 1910–1940  | 0.140        | 0.043  | 0.103  |        |        |
| 1940–1970  | −0.026       | 0.025  | 0.067  | −0.032 | 0.007  |
| 1970–2005  | 0.195        | 0.173  | 0.187  | 0.249  | 0.229  |

### Table 2. ENSO-related metrics calculated for observations (HadISST dataset) during years 1900–2005, and for two PI-control runs (during years 1900–2005) and two full-forcing historical runs (during years 1850–2005) of FGOALS-g2 forced by CMIP5 and CMIP6 forcings, respectively. (CMIP5/CMP6 control and CMIP5/CMP6 historical refer to external forcings of CMIP5/CMIP6 in PI-control and historical runs, respectively. Metrics for the two historical simulations are the ensemble mean values.)

| Metric       | Observations | CMIP5 control | CMIP6 control | CMIP5 historical | CMIP6 historical |
|--------------|--------------|---------------|---------------|------------------|------------------|
| Niño3 SSTA Stddev (°C) | 0.78 | 0.70 | 0.75 | 0.77 | 0.81 |
| Niño4 SSTA Stddev (°C) | 0.55 | 0.43 | 0.47 | 0.51 | 0.56 |
| Niño3 Seasonality | 1.52 | 1.49 | 1.41 | 1.43 | 1.38 |
| Niño3 Spectral Shape | 1.15 | 0.93 | 1.34 | 1.21 | 1.02 |
climate drift (~0.073°C per 100 years) and smaller climatological GAST (13.37°C) than that of CMIP5 (~0.039°C per 100 years and 13.81°C). The lower mean GAST can be attributed to the smaller solar constants and stratospheric aerosols in CMIP6. There are two warming periods (1910–1940 and 1970–2005) and a slight cooling period (1940–1970) in the HadCRUT dataset. In the historical runs, positive trends in GAST from the CMIP6 simulations are more consistent with the HadCRUT dataset than the case for CMIP5 during the warming periods. Both experiments with CMIP5 and CMIP6 forcings fail to reproduce the cooling period, and even produce a spurious warming trend during 1940–1970, which could be attributed to the underestimation of aerosol/stratospheric aerosols cooling effects and/or internal variability. However, the overall evolution of GAST in CMIP6 is larger than that in the HadCRUT dataset because of a stronger spurious warming trend from CMIP6 during cooling period. Additional experiments forced by each type of forcing confirm that GHGs and aerosols play leading roles in the differences in evolutions of GAST and NAST between CMIP5 and CMIP6, particularly in the second warming period from 1970 to 2005. These results are consistent with findings of previous studies that GHGs and aerosols are dominant factors in the 20th-century global warming (e.g., Stott et al. 2000; Zhou et al. 2006). ENSO characteristics are also affected by external forcings. Comparing with the case with CMIP5 forcings, CMIP6 forcings produce larger amplitudes and smaller seasonality of ENSO, particularly for time-varying forcings. The spectral shape shows no obvious relationship with the external forcings.

Results presented here, prior to the release of CMIP6 model data, will be useful for CMIP6 data users to differentiate the effects of various CMIP external forcings and to have a better understanding of CMIP6 results. However, further works still need to be done to supplement the investigations presented here. For example, the relationship between the mean state and trends in the PI-control runs will be analyzed in depth. Secondly, only the interannual ENSO variability is analyzed here. The interdecadal variability (e.g., PDO and NAO) and other time-scale oscillations (e.g., MJO) will be taken into consideration in future work. Finally, the physical mechanisms underlying how external forcings affect seasonality and the spectral shape of ENSO will be examined in future work.

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