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## CAS FGOALS-f3-L model dataset descriptions for CMIP6 DECK experiments

HE Bian<sup>a,b,c</sup>, YU Yongqiang<sup>a,c,d</sup>, BAO Qing<sup>a</sup>, LIN Pengfei<sup>a,c</sup>, LIU Hailong<sup>a,c,d</sup>, LI Jinxiao<sup>a,c</sup>, WANG Lei<sup>a,c</sup>, LIU Yimin<sup>a,b,c</sup>, WU Guoxiong<sup>a,b,c</sup>, CHEN Kangjun<sup>a</sup>, GUO Yuyang<sup>a,c</sup>, ZHAO Shuwen<sup>a,c</sup>, ZHANG Xiaoqi<sup>a,e</sup>, SONG Mirong<sup>a</sup> and XIE Jinbo<sup>a</sup>

<sup>a</sup>State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences, Beijing, China; <sup>b</sup>CAS Center for Excellence in Tibetan Plateau Earth Sciences, Institute of Tibetan Plateau Earth Sciences, Beijing, China; <sup>c</sup>College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, China; <sup>d</sup>Center for Ocean Mega-Science, Chinese Academy of Sciences, Qingdao, China; <sup>e</sup>School of Atmospheric Sciences, Nanjing University of Information Science and Technology, Nanjing, China

### ABSTRACT

The datasets of the Chinese Academy of Sciences (CAS) Flexible Global Ocean–Atmosphere–Land System (FGOALS-f3-L) model for the baseline experiment of the fully coupled runs in the Diagnostic, Evaluation and Characterization of Klima (DECK) common experiments of phase 6 of the Coupled Model Intercomparison Project (CMIP6) are described in this study. The CAS FGOALS-f3-L model team submitted the piControl run with a near equilibrium ocean state for 561 model years, and 160-year integrations for three ensemble members of abrupt-4× CO<sub>2</sub> and 1pctCO<sub>2</sub>, respectively. The ensemble members restart from the 600, 650 and 700 model years in the piControl run, respectively. The baseline performances of the model are validated in this article. The preliminary evaluation suggests that the CAS FGOALS-f3-L model can preserve the long-term stability well for a mean net radiation flux of 0.31 W m<sup>-2</sup> at the top of the atmosphere, and a limited decreasing trend of -0.03 W m<sup>-2</sup>/100 yr. The global annual mean SST is 16.45°C for the 561-year mean, with an increase of 0.03°C/100 yr. The model captures the basic spatial patterns of climate-mean SST and precipitation, but still underestimates the SST over the warm pool. The coupled model mitigates the precipitation bias in the ITCZ compared with the results from CMIP5. Moreover, the model's climate sensitivity represented by the equilibrium climate sensitivity has been reduced from 4.5°C in CMIP5 to 3.0°C in CMIP6. All these datasets contribute to the benchmark of model behaviors for the desired continuity of CMIP.

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CMIP6; DECK; FGOALS-f3-L; piControl; abrupt-4×CO<sub>2</sub>; 1pctCO<sub>2</sub>; climate sensitivity

### 关键词

第六届国际耦合模式比较计划; DECK; FGOALS-f3-L; 工业革命前试验; 4倍二氧化碳试验; 1%每年二氧化碳试验; 气候敏感度

## CAS FGOALS-f3-L 参加CMIP6 DECK 试验数据介绍

### 摘要

本文介绍了CAS FGOALS-f3-L参加CMIP6 DECK耦合试验数据。主要包括piControl, abrupt-4×CO<sub>2</sub>和1pctCO<sub>2</sub>的试验设计, 模式设置以及初步结果评估。piControl提供了561年的模拟结果, abrupt-4×CO<sub>2</sub>和1pctCO<sub>2</sub>分别提供了三组集成员, 每个成员包括160年的积分。初步评估结果表明, piControl试验中, 耦合模式可以保证长期稳定积分。在气候态降水模拟上, piControl试验可以合理的再现全球海表温度和降水的基本分布型, 相比上一代耦合模式, 在ITCZ地区的降水有所改进。另一方面耦合模式的气候敏感度约为3.0°C, 相比上一代的耦合模式更为合理。

## 1. Introduction

The identification of a handful of common experiments—the Diagnostic, Evaluation, and Characterization of Klima (DECK) experiments (klima is Greek for ‘climate’)—was proposed as the fundamental experiments in phase 6 of the Coupled Model Intercomparison Project (CMIP6) (Eyring et al. 2016). The DECK experiments are used to establish model characteristics and serve as the entry card for a model to participate in one of CMIP's phases. DECK contains four baseline experiments: (a) a historical Atmospheric Model Intercomparison Project (amip) simulation; (b) a pre-industrial control simulation (piControl or

esm-piControl); (c) a simulation forced by an abrupt quadrupling of CO<sub>2</sub> (abrupt-4×CO<sub>2</sub>); and (d) a simulation forced by a 1% yr<sup>-1</sup> CO<sub>2</sub> increase (1pctCO<sub>2</sub>). The amip experiment is forced by observed sea surface temperature (SST) and sea ice, while the other three experiments are the coupling of the atmospheric and oceanic circulation simulations. The goal of DECK is to make it possible to track changes in the performance and response of models and CMIP phases for consistency.

The Chinese Academy of Sciences (CAS) Flexible Global Ocean–Atmosphere–Land System model, finite-volume version 3 (CAS FGOALS-f3-L) (the ‘L’ denotes a low

horizontal resolution of 100 km), climate system model was developed at the LASG (State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics), Institute of Atmospheric Physics (IAP), CAS (Bao and Li 2020). The model group recently completed the DECK simulations (in late 2019), and the model outputs have been released after a series of postprocesses on the Earth System Grid (ESG) node at the IAP. For the amip simulations, the datasets have already been published (in early 2019), and dataset descriptions are documented in He et al. (2019). The other three experiments—piControl, abrupt-4× CO<sub>2</sub> and 1pctCO<sub>2</sub>—are to be introduced in this paper, since the model configurations are the same. The piControl simulation is performed under conditions of 1850, which is representative of the period before global industrialization. This simulation is an attempt to produce a stable quasi-equilibrium climate state under 1850 conditions for the other experiments, such as the historical simulation, abrupt-4×CO<sub>2</sub>, 1pctCO<sub>2</sub>, etc. It can also be used to study the unforced internal variability of the climate system. The abrupt-4×CO<sub>2</sub> experiment is designed to understand the global surface temperature feedback responses to CO<sub>2</sub> forcing (Gregory et al. 2004), while the 1pctCO<sub>2</sub> experiment is designed for studying model responses under simplified but somewhat more realistic forcing than abrupt-4×CO<sub>2</sub> (Meehl et al. 2000).

The CAS FGOALS-f3-L model group has completed the above simulations and provides a description of the DECK experiment outputs—specifically, those of piControl, abrupt-4×CO<sub>2</sub> and 1pctCO<sub>2</sub>—and the relevant essential model configurations and experimental methods for a variety of users in this paper. Section 2 describes the model and experimental design. Section 3 addresses the technical validation of the outputs from the CAS FGOALS-f3-L experiments. Section 4 provides usage notes, and section 5 presents a short summary.

## 2. Model and experiments

### 2.1 Introduction to the model

CAS FGOALS-f3-L is a climate system model. The model configuration is briefly listed in Table 1. The coupled model is composed of five components:

- (1) The Finite-volume Atmospheric Model (FAMIL), which has been updated from version 1 (Zhou et al. 2015) to version 2.2 (Li et al. 2019; Bao et al. 2019; Bao and Li 2020). The model dynamic core, physics packages, and baseline performance of the amip experiments are addressed in He et al. (2019).

**Table 1.** Model configurations of CAS FGOALS-f3-L.

Model configuration	FGOALS-f3-L
Atmosphere	FAMILv2.2 Resolution: C96 (1° × 1°) L32 (Zhou et al. 2015; Bao et al. 2019; He et al. 2019; Li et al. 2019)
Ocean	LICOM3 Resolution: Triple grid (1° × 1°) L30 (Liu et al. 2012; Li et al. 2017)
Land	CLM4.0 Resolution: 1° × 1° (Lawrence et al. 2011)
Sea ice	CICE4.0 Resolution: 1° × 1° (Hunke et al. 2010)
Coupler	NCAR Coupler7 (Craig, Vertenstein, and Jacob 2011)

- (2) Version 3 of the LASG/IAP Climate System Ocean Model (LICOM3) (Liu et al. 2012; Li et al. 2017). The updates from LICOM2 and the baseline performance of the model for the historical runs are presented in Guo et al. (2020)
- (3) Version 4.0 of the Community Land Model (CLM4) (Oleson et al. 2010).
- (4) Version 4 of the Los Alamos Sea Ice Model (CICE4) (Hunke et al. 2010).
- (5) Version 7 of the coupler from the National Center for Atmospheric Research (NCAR) (Craig, Vertenstein, and Jacob 2011).

### 2.2 Descriptions of experiments

The experiment settings of piControl, abrupt-4× CO<sub>2</sub> and 1pctCO<sub>2</sub> are introduced here. The basic configurations of these three simulations are summarized in Table 2. For piControl, the external forcings are prescribed as their values in 1850 (Table 3). The global annual mean greenhouse gas (GHG) concentrations are from Meinshausen et al. (2017). The solar irradiance is fixed at 1360.8 W m<sup>-2</sup> (Matthes et al. 2017). The 3D ozone concentrations are from <http://blogs.reading.ac.uk/ccmi/forcing-databases-in-support-of-cmip6/>. The aerosol mass concentrations are also prescribed and taken from the NCAR Community Atmosphere Model with Chemistry (CAM-Chem) (Lamarque et al. 2012), including sulfates, sea salt, black carbon, organic carbon, and dust. The piControl experiment runs for 1160 model years, with the first 599 years used as spin-up time. The model outputs from model-year 600 to 1160 are submitted as the quasi-equilibrium state for the fully coupled model.

The abrupt-4×CO<sub>2</sub> experiments run for 160 years. The external forcings are the same as in piControl except that the CO<sub>2</sub> concentration is four times that of piControl. The time-lag method is used to realize the three perturbations

**Table 2.** Experiment designs.

experiment_id	Variant_label	Restart time	Years of integration	Experiment design	DOI for experiment_id
piControl	r1i1p1f1	600	561	Free coupled model run with all the external forcings fixed as their values in 1850. The first 599 years of integration are taken as the spin-up time and the model outputs after 600 model years are submitted.	<a href="http://doi.10.22033/ESGF/CMIP6.3447">http://doi.10.22033/ESGF/CMIP6.3447</a>
abrupt-4xCO2	r1i1p1f1	600	160	Restart run from 1 January in model-year 600 of piControl. CO <sub>2</sub> prescribed as four times that in piControl. All other external forcings identical to piControl.	<a href="http://doi.10.22033/ESGF/CMIP6.3176">http://doi.10.22033/ESGF/CMIP6.3176</a>
	r2i1p1f1	650	160	Same as r1i1p1f1 but with a restart from 1 January in model-year 650 of piControl.	
	r3i1p1f1	700	160	Same as r1i1p1f1 but with a restart from 1 January in model-year 700 of piControl.	
1pctCO2	r1i1p1f1	600	160	Restart run from 1 January in model-year 600 of piControl. CO <sub>2</sub> prescribed to increase 1% yr <sup>-1</sup> . All other external forcings identical to piControl.	<a href="http://doi.10.22033/ESGF/CMIP6.3054">http://doi.10.22033/ESGF/CMIP6.3054</a>
	r2i1p1f1	650	160	As in r1i1p1f1 but with a restart from 1 January in model-year 650 of piControl.	
	r3i1p1f1	700	160	As in r1i1p1f1 but with a restart from 1 January in model-year 700 of piControl.	

**Table 3.** External forcing settings in piControl, abrupt-4xCO2, and 1pctCO2.

External forcing	Description
GHGs	Fixed as their global mean values in 1850: CO <sub>2</sub> : 284.3 ppm in piControl 1137.2 ppm in abrupt-4xCO2 1% yr <sup>-1</sup> increase from 284.3 ppm in 1pctCO2 CH <sub>4</sub> : 808.2 ppb N <sub>2</sub> O: 273.0 ppb CFC-11 equivalent: 0.032 ppb CFC-12 equivalent: 0.016 ppb
Solar irradiance	1360.8 W m <sup>-2</sup>
Aerosols	Three-dimensional distributions prescribed as their values in 1850, including sulfates, sea salt, black carbon, organic carbon, and dust (Lamarque et al. 2012)
Ozone	Three-dimensional distributions prescribed as their values in 1850 ( <a href="http://blogs.reading.ac.uk/ccmi/forcing-databases-in-support-of-cmip6/">http://blogs.reading.ac.uk/ccmi/forcing-databases-in-support-of-cmip6/</a> )

that are identified by the variant\_label: r1i1p1f1, r2i1p1f1, and r3i1p1f1. The characteristics in r1i1p1f1 denote the realization\_index, initialization\_index, physics\_index, and forcing\_index. The first experiment (r1i1p1f1) restarts from 1 January in model-year 600 of piControl. The second experiment (r2i1p1f1) is the same as r1i1p1f1 except that the integration restart date is 1 January in model-year 650. Similarly, the start date is 1 January in model-year 700 in the third experiment (r3i1p1f1).

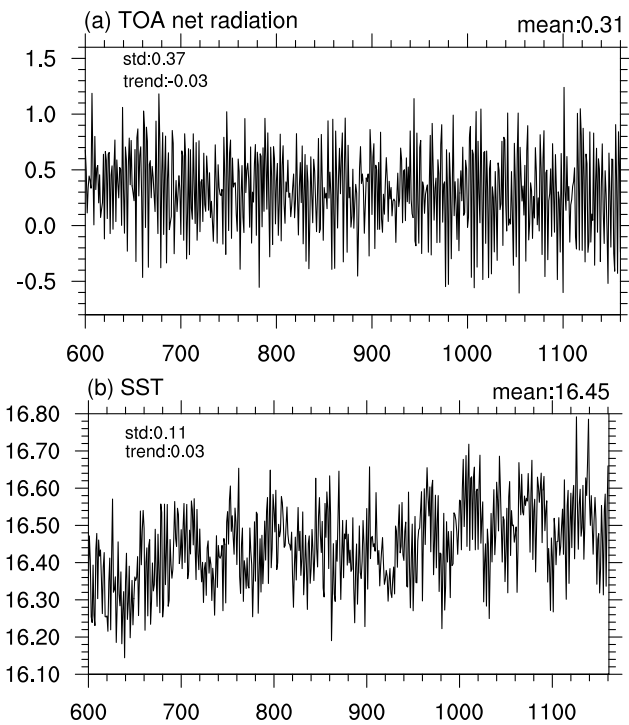
The 1pctCO2 experiments are also integrated for 160 years. The external forcings are the same as in piControl except that the CO<sub>2</sub> concentration is increasing at 1% yr<sup>-1</sup>. The ensemble method is the same as in abrupt-4xCO2, with restart dates for r1i1p1f1, r2i1p1f1 and r3i1p1f1 of 1 January in model-years 600, 650, and 700 in piControl, respectively. All of the DECK experiments documented in this paper have been officially published at the ESG node and the DOIs (digital object identifiers) for the experiment\_id are listed in Table 2.

### 3. Basic performance of model results

The basic performances of the model simulations are evaluated in this section. As the external forcings are prescribed and held constant in the piControl experiment,

the simulation mainly shows an internal climate variability for global climate. This simulation aims to provide a near-equilibrium ocean state and to serve as the control run for the other experiments. We show the global annual mean net radiation at top of the atmosphere (TOA) from model-years 600 to 1160 in Figure 1(a) to investigate the model's stability. The result shows that the TOA net radiation is quite stable during the long-term integration, with a mean value of 0.31 W m<sup>-2</sup>. The climate trend of the radiation is -0.03 W m<sup>-2</sup>/100 yr and the standard deviation is 0.37 W m<sup>-2</sup>, which is also reasonable. In response to the TOA net radiation, the global annual mean SST shows a slight increasing climate trend of 0.03°C/100 yr (Figure 1(b)). The time series of SST is also quite stable, with a standard deviation of 0.11°C and mean value of 16.45, which are within the ranges of the CMIP5 climate models (Gupta et al. 2013). All these results suggest that the climate drift of CAS FGOALS-f3-L is small and the 561-year near-equilibrium ocean state in piControl is stable.

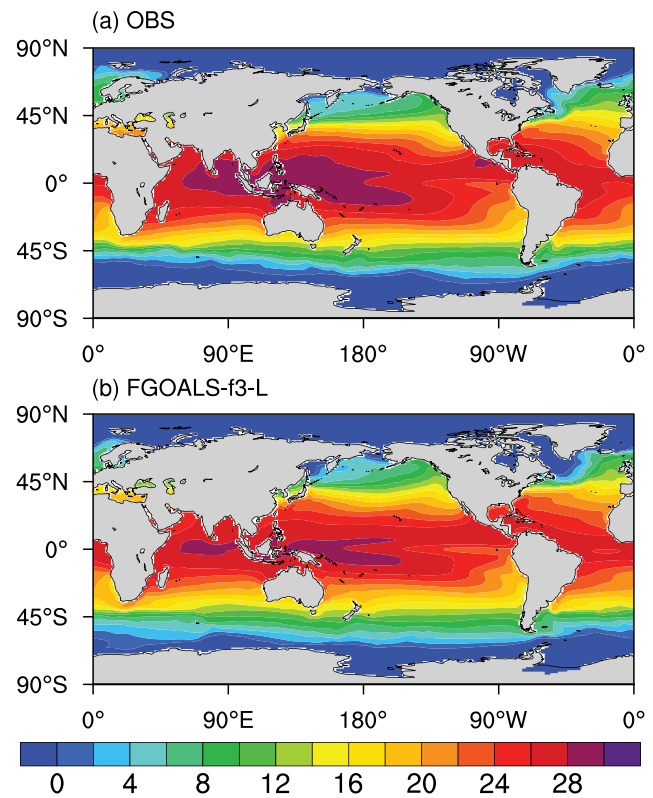
The basic spatial characteristics of the climate-mean SST and precipitation for piControl are also examined, in Figure 2. Compared to the observed (Taylor, Williamson, and Zwiers, 2000) climate-mean (1871–1900) SST distribution (Figure 2(a)), CAS FGOALS-f3-L (Figure 2(b)) captures the large-scale pattern for the global meridional



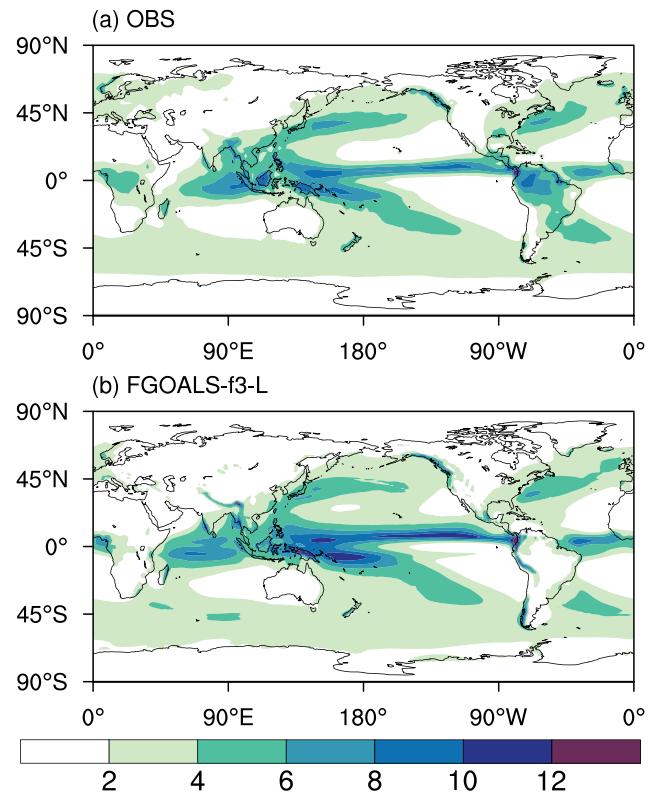
**Figure 1.** (a) Time series of global mean TOA net radiation (units:  $\text{W m}^{-2}$ ) for piControl from model-year 600 to 1160 with a global mean value of  $0.31 \text{ W m}^{-2}$ , standard deviation of  $0.37 \text{ W m}^{-2}$  and climate trend of  $-0.03 \text{ W m}^{-2}/100 \text{ yr}$ . (b) Time series of global mean SST for piControl from model-year 600 to 1160 with a global mean value of  $16.45^\circ\text{C}$ , standard deviation of  $0.11^\circ\text{C}$  and climate trend of  $0.03^\circ\text{C}/100 \text{ yr}$ .

variations well. However, for the  $28^\circ\text{C}$  isothermal line, the model underestimates the SST, mainly over the western Pacific regions. This systematic bias persists from the previous version (see Figure 1 in Bao et al. (2013)). The simulated climate-mean precipitation is shown in Figure 3. Compared to the observation (Figure 2(a)) derived from Global Precipitation Climatology Project (Adler et al. 2003), the model reproduces the basic pattern both in the tropical and subtropical ocean regions. The most striking improvement is that the model largely overcomes the double ITCZ problem that existed in the previous version, characterized as the dry area ( $< 4 \text{ mm d}^{-1}$ ) over the equator close to the date line in FGOALS-f3-L (Figure 3(b)), but extending west to the Maritime Continent in the previous version (see Figure 5 in Bao et al. (2013)). However, the model still overestimates the precipitation over ocean regions while underestimating the precipitation over land. In particular, the precipitation over South American land is missing (Figure 3(b)). This bias also exists in the amip simulation (He et al. 2019), which implies that the land–air interactions are important for reproducing this pattern.

The abrupt- $4\times\text{CO}_2$  and 1pct $\text{CO}_2$  experiments are designed to understand the climate feedback and to

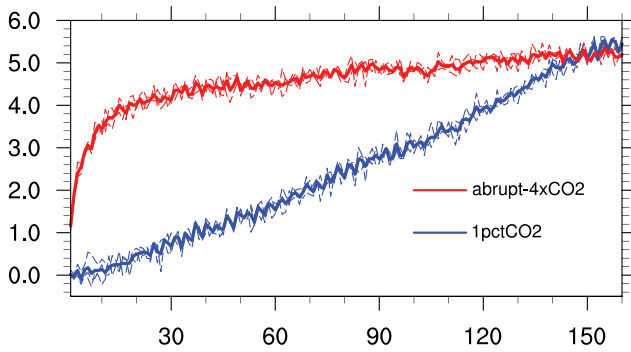


**Figure 2.** Climate mean distribution of SST (units:  $^\circ\text{C}$ ): (a) observation (1871–1900 mean); (b) FGOALS-f3-L (600–1160 mean).



**Figure 3.** Climate mean distribution of precipitation (units:  $\text{mm d}^{-1}$ ): (a) observation (1979–2014); (b) FGOALS-f3-L (600–1160 mean).

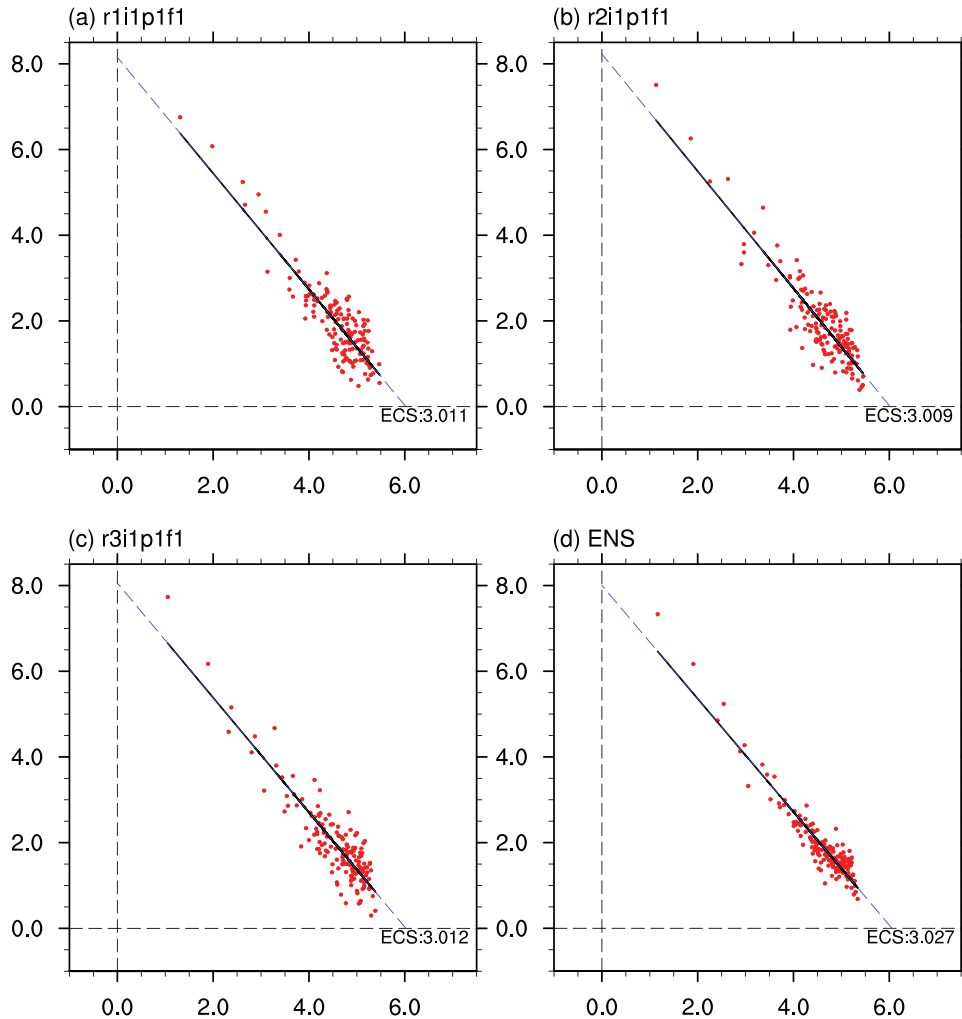




**Figure 4.** Time series of global mean surface air temperature anomalies (units:  $^{\circ}\text{C}$ ; relative to piControl) for ensemble means of abrupt-4 $\times$ CO<sub>2</sub> and 1pctCO<sub>2</sub>, respectively. The dashed lines are the three ensemble members, respectively.

quantitatively estimate the model climate sensitivity. In general, the feedback response is measured by the global surface temperature change under imposed CO<sub>2</sub>

forcing. In 1pctCO<sub>2</sub>, the CO<sub>2</sub> increases at a rate of 1% yr<sup>-1</sup>, starting from its 1850 value that is prescribed in piControl. The model responses to this forcing would be more realistic than in abrupt-4 $\times$ CO<sub>2</sub> (Meehl et al. 2000). For abrupt-4 $\times$ CO<sub>2</sub>, the CO<sub>2</sub> concentration is quadrupled from its prescribed level in piControl and held fixed. In this experiment, the climate system subsequently evolves to a new equilibrium, and the net radiation flux at the TOA and the associated changes in surface air temperature (SAT) can be used to measure the model's effective equilibrium climate sensitivity (ECS) (Gregory et al. 2004). We show the time series of the global annual mean SAT anomalies (relative to piControl) for both abrupt-4 $\times$ CO<sub>2</sub> and 1pctCO<sub>2</sub> in Figure 4. The results from the ensemble members are shown as dashed lines while the ensemble means are shown as the thick solid lines. It is clear that the SAT increases gradually from 0 to 5.09 $^{\circ}\text{C}$  in 1pctCO<sub>2</sub> for the



**Figure 5.** Climate sensitivity of CAS FGOALS-f3-L estimated from the 160-year integrations from abrupt-4 $\times$ CO<sub>2</sub> and associated piControl simulations. The abscissa is the surface air temperature anomaly (units:  $^{\circ}\text{C}$ ) and the vertical axis is the TOA net radiation anomaly (units:  $\text{W m}^{-2}$ ). The blue dashed lines are the extension lines of the regression lines. (a) r1i1p1f1; (b) r2i1p1f1; (c) r3i1p1f1; (d) ensemble mean.

**Table 4.** Surface air temperature responses to abrupt quadrupling of CO<sub>2</sub> and 1% yr<sup>-1</sup> CO<sub>2</sub> increase at 150 model years.

SAT responses (°C) at 150 model years	abrupt-4×CO <sub>2</sub>	1pctCO <sub>2</sub>
Ensemble mean	5.07	5.09
r1i1p1f1	5.20	5.16
r2i1p1f1	4.98	5.18
r3i1p1f1	5.04	4.95

150 years (Table 4). On the other hand, the SAT increases rapidly in abrupt-4×CO<sub>2</sub> for the first 20 years to almost 4° C, reaching a near equilibrium state after 20 years and 5.07°C after 150 years of integration (Table 4). This result suggests the model's climate sensitivity is lower than in its last version, as documented in Chen, Zhou, and Guo (2014), for the SAT increases to almost 6°C in both simulations. Following Gregory et al. (2004), the ECS of CAS FGOALS-f3-L is estimated in Figure 5. It shows that the results within the three ensemble members are close to each other and the ensemble mean ECS appears at 3.03° C, which is lower than in the previous version (4.5°C) as documented in Chen, Zhou, and Guo (2014). This improvement is mainly due to the changes in the radiation and microphysics schemes in the atmospheric model, such that the unrealistic greenhouse effect over the upper tropical troposphere can be reasonably handled (He 2016). The model's reasonable climate sensitivity also contributes to the realistic simulations of the historical run as documented in Guo et al. (2020).

#### 4. Usage notes

The original atmospheric model grid is in the cube-sphere grid system with a resolution of C96, which has six tiles and is irregular in the horizontal direction. We merged and interpolated the tiles to a nominal resolution of 1° on a global latitude–longitude grid, scaled by one-order conservation interpolation, for public use.

The format of datasets is version 4 of the Network Common Data Form (NetCDF), which can be easily read and written by common professional software such as Climate Data Operators ([https://www.unidata.ucar.edu/software/netcdf/workshops/2012/third\\_party/CDO.html](https://www.unidata.ucar.edu/software/netcdf/workshops/2012/third_party/CDO.html)), netCDF Operator (<http://nco.sourceforge.net>), NCAR Command Language (<http://www.ncl.ucar.edu>), and Python (<https://www.python.org>).

#### 5. Summary

The CAS FGOALS-f3-L model team has completed integrations of the CMIP6 DECK experiments including the piControl run with a near equilibrium ocean state for 561 model years, and 160-year integrations for three ensemble members of abrupt-4× CO<sub>2</sub> and 1pctCO<sub>2</sub>,

respectively. The climate trend of TOA net radiation fluxes in piControl is  $-0.03^{\circ} \text{ W m}^{-2}/100 \text{ yr}$  and the SST trend is  $0.03^{\circ}\text{C}/100 \text{ yr}$ . The global annual mean SST is  $16.45^{\circ}\text{C}$  for the 561-year mean, with an increase of  $0.03^{\circ}\text{C}/100 \text{ yr}$ . The estimated ECS for CAS FGOALS-f3-L is  $3.0^{\circ}\text{C}$ .

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#### Data availability statement

The data that support the findings of this study are available from <https://esgf-node.llnl.gov/projects/cmip6/>

#### Disclosure statement

No potential conflict of interest was reported by the authors.

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