Coupling of the CAS-LSM Land-Surface Model With the CAS-FGOALS-g3 Climate System Model

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Abstract The land-surface model of the Chinese Academy of Sciences (CAS-LSM), which includes lateral flow, water use, nitrogen discharge and river transport, soil freeze-thaw front dynamics, and urban planning, was implemented in the Flexible Global Ocean-Atmosphere-Land System model, grid-point version 3 (CAS-FGOALS-g3) to investigate the climatic effects of eco-hydrological processes and human activities. Simulations were conducted using the land-atmospheric component setup of CAS-FGOALS-g3 with given sea-surface temperatures and sea-ice distributions to assess its new capabilities. It was shown that anthropogenic groundwater use led to increased latent heat flux of about 20 W∙m⁻² in three groundwater overexploitation areas: North India, northern China, and central United States. The groundwater lateral flow accompanied by this exploitation has led to deepening water table depth in these regions. The derived permafrost extent from the soil freeze-thaw front (FTF) was comparable to observations, and the inclusion of FTF dynamics enabled simulations of seasonal variations in freeze-thaw processes and related eco-hydrological effects. Inclusion of riverine nitrogen transport and its joint implementation with the human activity scheme showed large dissolved inorganic nitrogen concentrations in major rivers around the globe, including western Europe, eastern China, and the U.S. Midwest, which were affected by nitrogen retention and surface water use during transport. The results suggest that the model is a useful tool for studying the effects of land-surface processes on global climate, especially those influenced by human interventions.

Plain Language Summary The land-surface model of the Chinese Academy of Sciences (CAS-LSM) was implemented in the Flexible Global Ocean-Atmosphere-Land System model, grid-point version 3 (CAS-FGOALS-g3) to investigate climatic effects of hydro-thermal processes and human activities. Besides obtaining a reasonable simulation of the land-surface variables, the new capabilities of the model were also assessed. The new modules were shown to have a significant impact on the land-surface hydrothermal cycle and climate. The results suggested the model’s potential capabilities for studying the climate effects of eco-hydrological processes and human interventions.

1. Introduction Eco-hydrological processes play an important role in land-atmosphere interactions, and human activities including CO₂ emissions and land and water resource management have been shown to influence the climate at a local and global scale (Pielke & Avissar 1990; Solomon et al., 2007). Agricultural activities including water withdrawal and irrigation human water use (HWR) can significantly cool the surface, enhance evapotranspiration, and consume local water resources (Lobell et al., 2006; Zeng et al., 2017). Extraction and consumption of water resource is also complicated by groundwater lateral flow (GLF) from the surrounding areas that offsets the loss of locally stored water and hence affects the climate (Maxwell et al., 2007; Z.,
Xie et al., 2012; Zeng et al., 2016b). Regulation of surface water and groundwater greatly affects nitrogen transport in rivers through processes such as soil nitrogen leaching, while dams can detain considerable nutrients that would otherwise be carried by rivers to oceans (Liu et al., 2019; Maavara et al., 2015; Woli et al., 2016). Another human activity, urbanization, can also alter climate by changing the anthropogenic heat release (AHR) due to energy consumption, urban water usage (UWU), and urban height variability (UHV) of structures (Block et al., 2004; D. J. Sailor 2011; Sailor et al., 2004). These extensive human activities have significant potential for altering the climate (Bonan, 1997; Yu et al., 2014; Zeng et al., 2017). Another process that is closely related to the human activities mentioned above and to soil eco-hydrological processes is soil freezing and thawing in frozen ground, including changes in freezing and thawing fronts, which has a significant influence on ground hydrothermal characteristics of the terrestrial carbon cycle (Schuur et al., 2008, 2009; Zimov et al., 2006). Understanding and reasonably representing the effects of eco-hydrological processes and human activities in land-surface and climate system models is very important for providing insights into weather and climate impacts of societally relevant quantities, such as climate and environmental prediction and water availability (Tian et al., 2016; Wood et al., 2011; Z. Xie et al., 2016).

A number of studies have discussed the representation of eco-hydrological processes and human activities in land-surface models, including the HWR and the associated GLF (Xie et al., 2012, 2018; Zeng et al., 2016a, 2016b, 2017), urbanization models, including anthropogenic heat (ANT), UWU, and UHV (Block et al., 2004; Hendel et al., 2016; Ketterer et al., 2017), riverine dissolved inorganic nitrogen (DIN) transport (Liu et al. 2019; Y. Wang et al., 2020a), and FTFs (Gao et al., 2016, 2019). Eco-hydrological processes and human activities were not well represented in the climate models that participated in the recent Coupled Model Intercomparison Project Phase 6 (CMIP6) (Eyring et al., 2016). CMIP was proposed by the World Climate Research Program to provide a better understanding of the responses of the Earth system to external forcing changes and to promote climate system model development (Eyring et al., 2016; Taylor et al., 2012). The Community Earth System Model, version 2 (CESM2, Danabasoglu et al., 2020) and the Energy Exascale Earth System Model (E3SM, Golaz et al., 2019) were among the models included, and the corresponding land components CLM 5.0 (Community Land Model version 5, D. M. Lawrence et al., 2019) and the E3SM Land Model (Zhu et al., 2019) considered the effects of irrigation and nitrogen transport (D. M. Lawrence et al., 2019; Zhou et al., 2020). However, they did not simultaneously consider these processes and human activities, which makes it difficult to fully quantify the degree to which human activities affect the eco-hydrological system and global climate.

Recently, the Chinese Academy of Sciences (CAS-LSM) land-surface model was developed based on CLM 4.5 (Oleson, 2013), which includes groundwater lateral flow, human water regulation, soil freeze-thaw front dynamics, riverine dissolved inorganic nitrogen transport, anthropologic heat release, urban water usage, and urban planning (Gao et al., 2019; Wang et al., 2020b, 2020a, 2020c; Z. Xie et al., 2018). CAS-LSM has been included in the evaluation project of the Land Surface, Snow and Soil Moisture Model Intercomparison Project (LS3MIP; van den Hurk et al., 2016). In this study, CAS-LSM is coupled into the Flexible Global Ocean-Atmosphere-Land System model, grid-point version 3 (CAS-FGOALS-g3) to investigate the climatic effects of eco-hydrological processes and human activities. CAS-FGOALS-g3 was developed by the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences (Li et al., 2020a, 2020b). It contributes to CMIP6 by providing historical, Diagnostic, Evaluation, and Characterization of Klima (DECK) simulations and other CMIP-endorsed model intercomparison projects, and serving as a platform for evaluating climate response to anthropogenic forcing. The updated CAS-FGOALS-g3 expands the range of feasible studies, which makes it possible to further assess the impact of the interaction between anthropogenic activities and the eco-hydrologic system, and, hence, weather and climate.

The remainder of this paper is organized as follows. Section 2 describes model development, and Section 3 provides the data and the experimental design. Section 4 describes the validation of land-surface climate simulations using the new CAS-FGOALS-g3 with a focus on the hydro-thermal cycle, as well as an assessment of the new features of CAS-FGOALS-g3 with the CAS-LSM implementation. Section 5 presents a discussion and summary.
2. Model Development

2.1. CAS-LSM

Detailed descriptions of the model improvements and the performance of CAS-LSM in the offline mode (i.e., forced with observed meteorology) were provided by Z. Xie et al. (2018, 2020). For reference, a schematic diagram is included that depicts the additional processes and functionality that exist within CAS-LSM (Figure 1). The schemes for GLF, human water use, FTFs, anthropogenic nitrogen discharge, and urban planning (UPS, including AHR, urban human water, and UHV) were implemented in CLM4.5 (Oleson, 2013) to produce CAS-LSM, which now contains these processes. CLM4.5 was developed by the National Center for Atmospheric Research. The model included bio-geophysical and bio-geochemical mechanisms and energy and mass fluxes from the land to the atmosphere and was the land-surface component of the Community Earth System Model 1.2.0 (Hurrell et al., 2013). The bio-geophysical processes included solar and longwave radiation interactions with vegetation canopies and soil, momentum and turbulent fluxes from the canopies and from soil, heat transfer in soil and snow, hydrology of canopies, soil, and snow, and stomatal physiology and photosynthesis. The bio-geochemical processes included vegetation photosynthesis, phenology, the carbon and nitrogen cycles, decomposition, and wildfires (Lindsay et al., 2014). Also contained in CLM4.5 was an interactive crop-management model, which simulated crop growth and its effect on land processes. A sub-gridded hierarchy of land units, soil profiles, and plant-function types was used in CLM4.5 to describe the heterogeneity within each grid cell. Different land uses, such as varieties of vegetation, lakes, urban areas, and glaciers, were addressed separately even if they coexisted in a grid cell. CAS-LSM, building upon CLM4.5, coupled GLF, HWR, FTFs, UPS, and DIN as optional configurations, with the target being more complete land-surface modeling. Apart from the DIN modules that have been implemented in the bio-geochemical sector of the land-surface model, the other processes (GLF, HWR, FTFs, and UPS) are implement-
ed in the bio-geophysical sector. For the simulations in CAS-FGOALS-g3, the horizontal resolution in CAS-LSM follows that of the atmospheric grid, that is, the 2 × 2° latitude-longitude grid (Li et al., 2020a, 2020b).

The following subsection (2.1.1) introduces the HWR scheme. A description of GLF follows (2.1.2) because groundwater lateral flow is accompanied by HWR. Section 2.1.3 discusses freeze-thaw fronts (FTFs), and Section 2.1.4 addresses nitrogen transport and human water use because changes in FTFs are related to HWR and soil eco-hydrological processes, alter hydrothermal characteristics, and affect the terrestrial carbon cycle. Another human activity, urbanization, can also alter climate. An urban planning scheme is described in Section 2.1.5.

2.1.1. Human Water Use (HWR)

The HWR scheme was incorporated into CAS-LSM as a sub-model (Zeng et al., 2017; Zou et al., 2015). The HWR sub-model mainly considered withdrawal due to groundwater pumping, in which the estimated groundwater pumping rate from aquifers was apportioned among agricultural, industrial, and domestic users. The industrial and domestic consumptions had two components, where the wastewater produced by industry and human daily life was treated as a discharge into local rivers and the net water consumption was treated as evaporation to the atmosphere. The aquifer recharge rate was updated by subtracting the groundwater (GW) extraction rate from the original aquifer recharge rate; for irrigation consumption, the net water input rate was timed as the ratio of the agricultural consumption rate and added to the top of the soil surface. The pumping rate and the other ratios were determined by forcing data combined from three data sources, including the Food and Agriculture Organization of the United Nations (FAO) global water information system (http://www.fao.org/nr/water/aquastat/main/index.stm), the Global Map of Irrigation Areas, version 5.0 (Siebert et al., 2005, 2013), and the historical monthly soil moisture and saturated soil moisture simulated by CLM4.5 offline using the atmospheric forcing data set described by Qian et al. (2006) for 1965–2000.

2.1.2. Groundwater Lateral Flow (GLF)

A two-dimensional GW movement equation based on Darcy’s Law and the Dupuit approximation (Bear, 1972) was used to realize GW exchange between grid cells. The numerical formulation of this equation assumed an equal chance of a cell exchanging water with its horizontal neighboring cells from eight directions. The vertical flux between the soil column and aquifer \( q_{\text{recharge}} \) calculated by the CAS-LSM on a coarse grid (e.g., a 2 × 2° latitude-longitude grid) was sent to the GLF module as the upper boundary, and the GLF fluxes were calculated in a 1-km cell based on the water table gradients between itself and its neighboring cells. The groundwater table depth on the 1-km cell was then updated based on the calculated GLF fluxes and the vertical water flux obtained from CAS-LSM on the coarse grid. Meanwhile, the calculated GLF flux on the 1-km cell was sent back to CAS-LSM to adjust the water table depth on the coarse grid. A simple resolution conversion method based on the LSM sub-grid structure (Zeng et al., 2018) was used to link CAS-LSM and the GLF module at different resolutions – the \( q_{\text{recharge}} \) calculated for each plant functional type of a CAS-LSM 2 × 2° grid cell is transferred to a number of 1-km cells that are occupied by the same type of land cover and belong to the CAS-LSM grid cell, while lateral fluxes at each 1-km grid cell are averaged over all members within a 2 × 2° grid cell and set back to CAS-LSM. For the depth-to-bedrock, which describes the distance between the ground surface and the less permeable bedrock layers, the global data set of depths-to-bedrock at 1-km resolution presented by Shangguan et al. (2017) was used.

2.1.3. Freeze-Thaw Fronts (FTFs)

For the FTFs, Stefan’s equation (Gao et al., 2016, 2019; Jumikis, 1978; Lunardini, 1981; Woo et al., 2004; Xie et al., 2013; Zhang & Wu 2012) provided a basis for computing one-directional freezing and thawing in a soil column (Jumikis, 1978), which was based on heat conduction and assumed that all heat that reached the freezing or thawing front was used for water freezing or melting. This method is frequently used by permafrost scientists to predict frost depth and to simulate heat transfer during water phase transitions in frozen soil when little site-specific information is available. It could also be used to calculate one-directional FTFs in a soil profile (Gao et al., 2016; C. Xie & Gough 2013). The FTFs were implemented in CAS-LSM in this study following Gao et al. (2019).
2.1.4. Nitrogen Transport and Human Water Use

For nitrogen processes, the schemes of human activities (including nitrogen discharge and water regulation) and riverine DIN transport were incorporated into CAS-LSM through coupling with the RTM. For nitrogen discharge, nitrogen fertilizer data were updated using the scheme of Lu and Tian (2017), and the point source pollution was updated using the data merged by Morée et al. (2013). For water regulation, the surface water included the scheme of Hanasaki et al. (2006), and the groundwater scheme followed that of Zou et al. (2015) and Zeng et al. (2016a). For surface water and groundwater, the data were determined from several source data sets, including the Food and Agricultural Organization (FAO) water-use data set (http://www.fao.org/nr/water/aquastat/data/query/index.html), the Global Map of Irrigation Areas, version 5.0 (Siebert et al., 2013), the historical monthly soil moisture levels and saturated soil moisture levels simulated by CLM4.5 offline for 1965–2000 (Zeng et al., 2017), and the FAO water information system for 2010 (http://www.fao.org/nr/water/aquastat/main/index.stm). During DIN transport, a proportion of DIN will be affected by surface and groundwater regulation based on the mean DIN concentration and the withdrawal rate for surface and groundwater (Liu et al., 2019). For nitrogen river transport, based on the water transport framework in CAS-LSM, the DIN inputs, including soil DIN runoff and leaching, nitrogen deposition, and point source nitrogen discharge, were used as tracers in the nitrogen transport module, along with a DIN retention module during transport (Nevison et al., 2016). Because nitrogen transport is associated with water temperature, this variable was also considered in CAS-LSM following the scheme of Van Vliet et al. (2012). Anthropogenic heat discharge from thermoelectric power plants was also considered in CAS-LSM (Liu et al., 2019, 2020), where the input data for the emitted heat came from Raptis and Pfister (2016).

2.1.5. Urban Planning

Urban planning is concerned with the design and development of urban environments, including population control, transport management, and building distribution. Energy consumption, water usage, and building construction in a city are closely related to urban planning, which has important effects on weather and climate by affecting energy, the water cycle, and urban meteorology. In CAS-LSM, AHR, UWU, and urban roughness height (and height variation) schemes were incorporated to consider the effects of these processes.

AHR was treated as part of the sensible heat flux that affected the energy balance equation. AHR can be divided into four components: AHR from vehicles, the building sector, industry, and human metabolism (D. J. Sailor & Lu, 2004), representing the major sources of waste heat in the urban environment. Because anthropogenic heat is closely tied to energy consumption (D. J. Sailor, 2011), the AHR from vehicles, buildings, and industry can be estimated by listing all kinds of energy consumption (including coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, natural gas, and electric power). For UWU, a simple UWU scheme, including urban irrigation and road sprinkling, was incorporated into the CAS-LSM model based on the scheme described by Zeng et al. (2017). In this context, ecological and farmland irrigation were both treated as urban irrigation, and the road sprinkling scheme was activated at night during the summer when water was applied to the impervious road layer to accelerate evaporation. As for the urban roughness height, this parameter is affected by building construction and the spatial distribution of urban building heights, which can affect the heat and momentum variables. The scheme used here was based on the work of Millward-Hopkins et al. (2011). It is worth noting that because urban planning is currently used only in the regional setup, it was set as an option in the model and was not used in the global coupled simulations.

2.2. Coupling CAS-LSM with CAS-FGOALS-g3

CAS-FGOALS-g3 is a global climate model consisting of atmosphere (L. J. Li et al., 2020a), land (Z. Xie et al., 2018), oceans (LICOM), and a sea-ice model (Holland et al., 2012). A general overview of CAS-FGOALS-g3 has been provided by L. J. Li et al. (2020a). The land component of CAS-FGOALS-g3 was CAS-LSM (Z. Xie et al., 2018), which included the processes mentioned earlier, including GLF (Z. Xie et al., 2012; Zeng et al., 2016a, 2016b, 2018), human water exploitation (Zou et al., 2014, 2015; Zeng et al., 2016b, 2017), FTFs (Gao et al., 2016, 2019), river nitrogen transport and human water use (Liu et al., 2019), and urban planning. Additional input land-use data sets were also included in CAS-LSM, and human water use, urban water use and AHR, and anthropogenic nitrogen discharge were treated as forcing input data in the model.
The coupling of CAS-LSM into CAS-FGOALS-g3 (Figure 1) was based on the version 7 coupler (CPL7) developed at the National Center for Atmospheric Research (NCAR) (Craig et al., 2012). Compared with the previous version of the coupler CPL6 (Craig et al., 2005), where all components were constrained to run as separate executables on unique processor sets, the CPL7 infrastructure is a significant advance. CPL7 possesses a top-level driver that runs on every computer processor and controls time sequencing, processor concurrency, and exchange of state information and fluxes between components. This makes it possible to run the components to achieve the model component layout that optimizes overall model performance and efficiency. In addition, the improved memory and performance scaling of CPL7 can support much higher-resolution configurations. Moreover, the sophisticated computing resource control and the single executable design provide more flexibility while simplifying hardware requirements for running the model. The land component communicates both state information and fluxes with the atmosphere component through the coupler at every atmospheric time step (e.g., 600 s). The output of CAS-LSM to the atmospheric model includes surface albedo (direct beam and diffuse for visible and near-infrared wave bands), upward longwave radiation, sensible heat, latent heat, water vapor flux, absorbed solar radiation, radiative temperature, 2-m temperature and specific humidity, surface wind stress, snow water equivalent, and others. The input from the atmospheric model to the CAS-LSM includes incident solar radiation (direct beam and diffuse for visible and near-infrared wave bands), incident longwave radiation, reference height and horizontal wind, specific humidity, pressure, temperature at the reference height, CO₂ concentration, aerosol and nitrogen deposition rates, and lightning frequency. The new functionalities mentioned above were implemented as input forcing in the CAS-LSM and affect the atmosphere by exchange between the land state and the atmospheric component through the coupler during every coupling interval.

3. **Experimental Design and Data**

To assess the model and its new functionalities, a set of experiments and the validation data are introduced in this section.

3.1. **Experimental Design**

The main simulations presented here were the five members from the Atmospheric Model Inter-Comparison Project (AMIP) protocol simulation (for 1979–2014), three groups of online (land-atmosphere coupled) simulations called CTL, GC, and LGC (corresponding to the use of the FTF, FTF and HWR, FTF, HWR, and GLF modules), and two groups of offline (atmospheric data driven-land) simulations called CTL-off, GC-off, and an additional single member online simulation with biogeochemistry module opened, called NP (Table 1). The AMIP simulations were used to perform basic validation of the model, whereas the other experiments served to demonstrate the new functionalities. The AMIP simulations were performed using the time-varying external forcing recommended by CMIP6 (https://esgf-node.llnl.gov/search/input4mips/). The atmosphere and land resolution was 2° × 2° in latitude and longitude in these simulations, and the monthly observations of sea surface temperatures (SSTs) and sea ice concentration from the HadISST data set (Rayner et al., 2003) were used for prescribing ocean surface conditions. The forcing for the AMIP runs included the monthly mean total solar irradiance (TSI) (Matthes, 2017), greenhouse gas (GHG) concentrations, including latitudinal changes and seasonality (Meinshausen et al., 2017), ozone concentrations, anthropogenic aerosol optical properties and the associated Twomey effect (Stevens, 2017), land-use changes (Land Use Harmonization v2, http://luh.umd.edu/), and historical stratospheric aerosols. In addition, anthropogenic groundwater exploitation forcing data from 1965 to 2014 were added (Zeng et al., 2017).

For the AMIP runs, the five members shared the same setup, but with different initial conditions. The simulation period for the AMIP runs was 1979–2014. As for the CTL, GC, and LGC simulations, they generally followed a similar setup to the AMIP runs, except that the simulation period for these runs was for a 41-years duration from 1976 to 2010 (using the period 1970–1975 for spinup). To reduce internal noise and enhance the forced signal caused by HWR and GLF, ensemble averages were used here, where each group of experiments contained three ensemble simulations using different initial conditions, the results of which were then averaged over the ensemble for evaluation (Koster et al., 2002, 2006). In the current study, three individual simulations, typically differing only in their initial atmospheric and land-surface conditions, made up each ensemble (CTL, GC, or LGC). Simulations with corresponding ensemble members in the
three sets of simulations typically shared the same initial conditions (for instance, CTL1, LC1, and LGC1 shared the same initial conditions). The offline simulations using CTL-off and GC-off shared the same initial condition with the online simulations, and the CRUNCEP forcing data set was used to run the offline model (Harris et al., 2014). The NP transport simulation generally followed a similar setup to the AMIP runs, except that the bio-geochemical module and nitrogen transport module were opened to obtain the nitrogen transport-related variables. The simulation period was 1960–2014.

3.2. Validation Data

The 2-m temperature data consisted of the 0.5 × 0.5° land temperature data compiled by Cort Willmott and Kenji Matsuura of the University of Delaware from a large number of stations of the Global Historical Climate Network and the archive of Legates and Willmott (Willmott & Matsuura, 2001). The precipitation observations were obtained from CPC Merged Analysis of Precipitation and came from the Climate Prediction Center (CPC) Merged Analysis of Precipitation 1979–2009 monthly time series, which have a resolution of 2.5 × 2.5° (P. P. Xie & Arkin, 1997). For the latent heat flux, the global latent heat estimate data were obtained from FLUXNET-MTE (Jung et al., 2009, 2010). The FLUXNET-MTE data came from the FLUXNET network of eddy covariance towers and were upscaled to monthly data on a 0.5 × 0.5° grid (Jung et al., 2010) using the model tree ensemble (MTE) approach described by Jung et al. (2009) (1982–2004 average). For soil moisture, the Global Land Data Assimilation System version 2 (GLDAS 2) data were used (Rodell et al., 2004). The Moderate Resolution Imaging Spectroradiometer (MODIS) all-sky albedos were derived from the black-sky (direct) and white-sky (diffuse) near-infrared and visible wave band albedos by weighting them according to the empirical partitioning functions of solar radiation into these components (e.g., direct to diffuse radiation for near-infrared and visible solar radiation) derived from atmospheric model simulations following Lawrence et al. (2011). The MODIS data came from collection 4, which contained the climatological averages for 2001–2003. The Northern Hemisphere Equal-Area Scalable Earth (EASE)-Grid Snow Cover and Sea Ice Extent (Brodzik & Armstrong, 2013) was used as a comparison for snow cover.

4. Simulations

4.1. Validation

This section describes an assessment of the new model’s basic simulation capability for land-surface climate using the AMIP simulations and the validation data with a focus on the hydro-thermal cycle. The variables included surface air temperature, precipitation, latent heat flux, soil content and runoff, surface albedo, and snow cover.

4.1.1. Surface Air Temperature, Precipitation, and Latent Heat Flux

The ensemble mean climatological annual cycle of surface air temperature and precipitation for nine representative high latitude, mid-latitude, and tropical regions for CAS-FGOALS-g3 and the observational estimates for both variables are shown in Figures 2a–2f. For the G3 temperature simulations, the overall results showed that the annual G3 simulation cycle in the nine regions generally mimicked the observations, al-
though there was an overall cold bias for almost all the regions in January-February-March and October-November-December, with the highest bias in the 5°–8°C range. For April-May-June and JAS, on the other hand, the simulated temperatures were close to the observed values. The only exception was in the Amazon (Figure 2c), where there was minor overestimation in the JAS cycle. Specifically, the bias meant that the high latitude and mid-latitude values (Figures 2a and 2b) were similar despite the wider seasonal cycle in high-latitude regions. For the tropics (Figure 2c), however, the bias tended to be smaller, with the largest values in the Sahel region.
Unlike the temperature case, comparison of regionally averaged seasonal precipitation cycles with observations tended to show a larger bias in the tropics, where larger seasonal precipitation cycles occur (Figures 2d–2f). At high latitudes, the cycle generally followed that of the observations with minor bias, although this was not apparent because of the small amplitude in seasonal cycles (Figure 2d). In the mid-latitudes, despite the overall correspondence of the seasonal cycles, underestimates were seen in China, the eastern United States, and Europe, especially in summer June-July-August (JJA) (Figure 2e). In the tropics, where the seasonal precipitation cycle is the largest, apparent underestimates occurred in the Amazon, Sahel, and Indian regions (Figure 2f). The bias in the Amazon was about 3–4 mm/day, or nearly 50% of the annual cycle, which is quite large. Compared to the Amazon, the bias in the Indian region was up to 2–3 mm/day, or approximately 20%–30% of total precipitation in the summer monsoon season. In the Sahel, on the other hand, the simulated rain peak was earlier than the observations, with a peak in May, whereas the observed peak occurred in August. Overall, the precipitation bias in the tropics was greater at higher latitudes, and bias in these regions could add up to 20%–50% of total precipitation.

For variables other than temperature and precipitation, the annual cycle for the same nine representative regions is shown in Figures 2g–2i. Unlike those of the first two variables, the seasonal cycle of the regional average latent heat flux showed an overall underestimation compared with the MTE estimate, especially for the peak. This underestimation occurred regardless of latitude and was similar for high and mid-latitude regions from April to September (Figures 2g and 2h), but later for the tropics (Figure 2i) in summer, with a bias range between the model and data estimated peaks of about 20–40 W/m². The only exception was in the Amazon region, where the underestimates continued all year round.

4.1.2. Soil Water Content and Runoff

The differences in mean soil water content for MAM and SON between the model simulation and GLDAS2 (Rodell et al., 2009) are shown in Figure 3. Although the simulations agreed well with observations in general (Figures 3a and 3b), the magnitudes of the simulated values were smaller than those of GLDAS2 in regions of the Amazon, southern and central Africa, North America, southern and eastern Asia, and Australia. This indicated weaker seasonal variation in the simulated soil water content.

River discharge to oceans in the CAS-LSM simulations was calculated using the RTM (Branstetter & Famiglietti, 1999), which transported grid-cell runoff to oceans by pathways that approximated the paths of the real global river network. Overall, the total simulated river discharge into oceans was scattered around the observations (Figure 4), with underestimates at some stations, especially in those with lower annual discharge. Because the total discharge into the world’s oceans was directly related to land precipitation minus evapotranspiration, these underestimations may have been due to precipitation bias in the model. In the simulations, the most poorly simulated large rivers were the Congo and Orinoco Rivers, where far too much discharge was simulated for the Congo River (over 100% more discharge than observed) and far too little discharge from the Orinoco River (less than 50% of the observed discharge).

4.1.3. Surface Albedo and Snow Cover Extent

Figure 5 compares the global all-sky snow-free surface albedo to the MODIS albedo estimates. The MODIS all-sky albedos were derived from the black-sky (direct) and white-sky (diffuse) near-infrared and visible waveband albedos by weighting them according to the partitioning of solar radiation into these components. The MODIS data came from collection four and consisted of the climatological averages for 2001–2003. Overall, the simulated values were very much like the MODIS values, except for certain mountain regions like the Tibetan Plateau, the Rocky Mountains, and some northern high-latitude regions like Siberia.
and Alaska. The Tibetan Plateau was the region with the highest bias (about 0.2), whereas in other regions, the bias ranged from 0.1 to 0.15.

The Northern Hemisphere snow cover extent was also compared with the Northern Hemisphere EASE-Grid Snow Cover and Sea Ice Extent data, as displayed in Figure 6. Clearly, the CAS-LSM simulation was a good overall match to the NH snow cover extent, except for an overestimate on the Tibetan Plateau and minor underestimates in parts of Europe and near-polar regions in North America. The Tibetan Plateau had the highest bias (about 60%), whereas in other regions, the bias ranged from 10% to 30%.

4.2. New Features in CAS-FGOALS-g3

This section assesses the model's new functionality using the simulations of CTL, GC, LGC, CTL-off, GC-off, and NP. The assessment focuses on the impact of GLF and HWR on water table and regional climate, the simulation of the freeze-thaw front, and the impact of anthropogenic nitrogen discharge on DIN transport in global rivers.

4.2.1. Impact of Anthropogenic Groundwater Exploitation on Regional Climates

Global water demand is rapidly increasing because of economic development and population growth (Alvarez et al., 2012; Devic et al., 2014; Rodell et al., 2009; Shi et al., 2013). Groundwater is widely used to supplement human demands for freshwater due to its convenience of extraction and good quality. However, the continuous overextraction of groundwater resources for consumption not only reduces groundwater table levels, but also changes the regional, and even global, environment and climate (X. Chen & Hu, 2004; Pokhrel et al., 2012). Implementation of anthropogenic groundwater exploitation in the CAS-FGOALS...
model was done using a groundwater exploitation extraction forcing data set. Figure 7 shows the simulated annual and summer (JJA) temperature and latent heat flux with and without anthropogenic groundwater exploitation (GC and CTL, respectively). It is apparent that adding anthropogenic groundwater exploitation has caused a significant surface cooling in representative overextraction regions such as North India, North China, and the central United States. The greatest cooling occurred in North India, which is widely known for its extensive water extraction (Kumar & Singh, 2008), with a cooling of around 1°C (Figure 7a). This
cooling develops an even larger amplitude of over 2°C in summer (JJA) (Figure 7b), which is in the growing season when irrigation water demand tends to be highest. The North China and the central United States also experience this effect, although cooling in the North China Plain is part of a larger and wider cooling effect of close to 1.5°C, whereas a smaller cooling pattern occurs in the central United States. Along with surface cooling, surface evaporation is also affected by groundwater exploitation. It has been shown that in the three representative overextraction regions of North India, North China, and the central regions of the United States, groundwater withdrawal tends to increase latent heat flux by almost 30 W·m⁻² in the North India and North China plains, along with a near 10 W·m⁻² in the central United States (Figure 7c). This increase is more intense in summer, reaching values of over 40 W·m⁻² in the North India and North China plains and a greater than 10 W·m⁻² increase in the central United States. According to Dirmeyer et al. (2013), evapotranspiration in these three places was more restricted by water availability than in other regions. Thus, when a greater supply of water was available, the latent heat of evaporation was also greater. It was also shown that this effect of anthropogenic groundwater exploitation is stronger under coupled (GC-CTL) than uncoupled simulation (Figure 8)-enhanced annual and summer cooling of as high as 0.5°C.
and 1°C in North China, and near 0.5°C and over 2°C in North India region, respectively (Figures 8a and 8b), while increased latent heat flux occur in North India and North China (Figures 8c and 8d), with North India experiencing over 30 W/m² increase in summer. The indirect response of the climate to groundwater exploitation through land-atmosphere coupling may be partly responsible for this enhanced effect. These results argued for the explicit representation of anthropogenic groundwater exploitation within coupled climate models for better assessment of climate impact.

4.2.2. Impact of GLF on the Water Table

Changes in groundwater heads due to activities such as overexploitation can lead to a decline of the groundwater table and depression cones near wells (Chen et al., 2003, 2011). These can cause changes in the lateral flow that naturally transports groundwater from surrounding areas to local groundwater depressions. This process plays a critical role in offsetting the loss of locally stored water and in relieving the negative effects of overexploitation on the eco-hydrological system. The addition to the model of the GLF procedure enabled consideration of this lateral flow, which has been shown to be an important process, especially for simulating hydrological variables. Figure 9 shows the simulated equilibrium water table depth with and without GLF (LGC and CTL, respectively), and their difference, for 1980–2008. Apparent modification to the groundwater by the GLF module can be seen in these figures; the water tables in North Africa, the Arabian Peninsula, parts of central Asia, and southern Australia have deepened. Among these, the largest drop can be seen in North Africa; small parts of northern India also showed similar deepening phenomena. In other regions, such as the western coasts of North America and Australia, the deepening rate was less. This increased spatial variability of the modeled groundwater table depth in the LGC run may result in differences in the bio-geophysical and bio-geochemical aspects of the land surface (e.g., land-atmospheric coupling, water extraction by vegetation, etc.) and may thus have potential effects on the climate process under climate warming.

4.2.3. Freeze-Thaw Fronts

Freeze-thaw processes in soils, including changes in FTFs, are extremely sensitive to warming. However, the latest climate models do not predict changes in FTFs directly. Implementation of the FTF module in CAS-FGOALS generally followed the prescription of Gao et al. (2019). The maximum thaw depth in permafrost regions was used as the active layer depth; its spatial distribution is shown in Figure 10a. Although a direct comparison with observations was difficult because no subgrid-scale permafrost representation was
used, the spatial distribution of the model simulation was still comparable with the maps provided by the International Permafrost Association (IPA; Brown et al., 1998; Figures 10a and 10b).

Figure 9. Global equilibrium groundwater table depth patterns (m) from the (a) LGC simulation, (b) GC simulation, and (c) their difference (LGC-GC) for 1980–2008.
Figure 11 shows the climatological spatial distribution of FTFs in February and August and the seasonal cycle for two regions (one in seasonally frozen ground, and another in a permafrost region) for 1979–2008. The thaw depth was usually shallowest in February and deepest in August. The simulated thaw depths in February were therefore all near the surface, except for a few places near the borders of seasonally frozen ground and permafrost (Figures 11a). In August, the simulated thaw depths presented a decreasing trend as the latitude increased (Figures 11b). The simulated frost depths, on the other hand, showed an opposite trend to the thaw depths. The frost depth extended to the south in February and retreated north in August (Figures 11c and 11d, respectively). Figures 11e and 11f show the weight-averaged FTF seasonal cycle of two regions (seasonally frozen ground and permafrost, respectively). In seasonally frozen ground (Figures 11e), the frost went deeper in winter and gradually became shallower as time advanced to summer. The thaw depth, on the other hand, started to move down in spring and went deeper in May until both the frost and thaw depths met; then the thaw depth became shallower again from summer to fall. In the permafrost region (Figures 11f), because the frost below is basically frozen all the time, only the thaw depth is defined. The thaw depth started to move downward in spring, went deeper through the summer, and then became shallower until winter, when the thaw depth was essentially zero. Overall, the FTFs tended to simulate the seasonal variations of the freeze-thaw process, and the FTF-derived permafrost extent was comparable to observations. Hence, the inclusion of FTF was appropriate for simulating the seasonal freeze-thaw process in seasonally frozen ground and in permafrost regions.

4.2.4. Anthropogenic Nitrogen Discharge and DIN Transport in Global Rivers

Excess nutrients from pollution discharge, and regulated outflow through rivers from lands to oceans can seriously impact coastal ecosystems. A reasonable representation of these processes in LSMS and RTMs is important for understanding human-environment interactions. The implementation of the nitrogen transport module in CAS-FGOALS (Figure 1) was much like the coupling process shown in Figure 1 in Liu et al. (2019). Note that currently the process of N transport to the ocean is not included in the model and merits future work. Figure 12 shows the forcing of point-source N and its transport in global rivers as simulated by CAS-FGOALS-g3 for 1970–2010. It is evident that several large point sources of N exist around the globe, with three centers including the central and east United States (Mississippi River), western Europe, and northern China (Yellow and Yangtze Rivers). The annual forcing rate of source N ranges from 50 to 600 mg N m⁻² year⁻¹. Corresponding to this forcing, it was apparent that almost all large rivers in the world have been affected by widespread human activities (Figure 12b). The rivers in western Europe and eastern China were the most polluted, with an annual DIN increase of over 30 Gg N year⁻¹. The nitrogen discharge
Figure 11. Climatological distribution of February and August (a)–(b) thaw depth, (c)–(d) frost depth, and (e)–(f) seasonal cycle of two regions (in seasonally frozen ground and permafrost respectively) for 1979–2008. The blue and red lines in (e)–(f) represent the freeze and thaw fronts, respectively.
by both runoff N and point sources could directly and markedly augment the amount of DIN in most rivers across the world and was hence an important factor related to riverine environmental problems. Undoubtedly, the Mississippi River Basin, Yellow River Basin, Yangtze River Basin, and western Europe are the most affected regions.

The process of N transport within a river is also important. Because the reaction of the N transported in the river is affected by river temperature, the river temperature distribution is first shown in Figure 13a. The river temperatures generally changed with latitude, where the temperature decreased as the geographical position moved northward. Another significant feature was change with altitude, meaning that river temperatures in mountain regions like the Tibetan Plateau or the Andes Mountains are lower than those in surrounding regions. DIN retention in rivers is affected by river temperature and transport reactions and is shown in Figure 13b. Most DIN retention occurred in western Europe, North China, the central United States, and the south-eastern parts of Australia and South America. This retention ranges between around 100 mg-N·m⁻²·year⁻¹ except for the central and east USA, where the magnitude is about 200–400 mg-N·m⁻²·year⁻¹. In addition to N retention, N transport was also impacted by surface water regulation (Figure 13c), which tended to withdraw DIN at rivers. The withdrawn DIN, corresponding to large water-use activities such as in northern India, North China, and parts of the United States, is shown in Figure 13d. The effect of this withdraw DIN is generally smaller than that of the retention, with the magnitude of 10–30 mg-N·m⁻²·year⁻¹. In general, the results of this study suggest that incorporating schemes related to riverine nitrogen transport and human activities into the model could be an effective way to monitor global river water quality and evaluate the performance of global land-surface modeling. In future work, the
model developed in this study will be coupled with atmospheric and ocean models to simulate and project the global nitrogen cycle.

5. Summary and Discussion

In this study, the CAS-LSM land-surface model has been implemented in the CAS-FGOALS-g3 climate system model to investigate the climatic effects of eco-hydrological processes and human activities. The updated model includes representations of lateral flow, water use, nitrogen discharge and river transport, soil freeze-thaw front dynamics, and urban planning. To assess the model’s new capabilities, simulations were conducted using the land-atmospheric component setup of CAS-FGOALS-g3 with given sea-surface temperatures and sea-ice distributions. When compared against observations, the CAS-FGOALS-g3 surface climate simulations showed reasonable distributions of land-surface variables, including 2-m temperature, precipitation, latent heat flux, river ocean discharge, soil moisture, snow fraction, and surface albedo. The seasonal temperature cycles in high latitude and mid-latitude regions were closer to observations than those in tropical regions, whereas comparison of the regionally averaged seasonal precipitation cycles with observations did not show obvious trends with latitude. The other variables generally presented an overall reasonable result as well. Note that due to the scarcity of global data for some land variables, the reanalysis or estimated data have been used as a reference (e.g., latent heat flux and soil moisture). This is principally a question about FLUXNET-MTE because these variables may be hard to measure reliably, especially over land. However, the current data used are mostly for global reference, and a more comprehensive comparison using other products such as that from LandFlux of the GEWEX Data and Analysis Panel Integrated Product (McCabe et al., 2016) may merit future work.

The new capabilities include simulations of HWR, GLF, FTFs, nitrogen transport, and urban planning. Anthropogenic groundwater use led to increased latent heat flux of about 20 W·m⁻² in the three groundwater over-exploitation areas of North India, the central United States, and northern China. Groundwater lateral flow accompanied by exploitation has led to increasing water table depth in these regions. Inclusion of HWR and GLF makes it possible to model potential effects on climate HWR. The derived permafrost extent from the soil freeze-thaw front (FTF) was comparable to observations, and the inclusion of FTF dynamics enabled simulation of seasonal variations in freeze-thaw processes and related eco-hydrological effects. Aside from FTFs, incorporating schemes related to riverine nitrogen transport and human activities into the model was shown to be an effective way to monitor global river water quality and evaluate the performance of global land-surface modeling. The overall results of the new scheme suggested that the model is a potentially useful tool for studying the effects of land-surface processes on global climate, especially those that experience human interventions.

Figure 13. Global climatological distribution of river temperature (°C), retained DIN (mg·N·m⁻²·year⁻¹), surface water withdrawal (mm·year⁻¹), and withdrawn DIN (mg·N·m⁻²·year⁻¹) for 1970–2010.
Data Availability Statement

The AMIP run data are archived at the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, and are available for research purposes through ESGF-node (https://esgf-node.llnl.gov/projects/cmi6/); data for other figures were obtained online (http://data.lasg.ac.cn/xjb/land/).

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