Numerical Investigation of the Regional Climate Effect of the Lake Nasser

Zhe Xiong
Chinese Academy of Sciences
Ping Wang
Chinese Academy of Meteorological Sciences
Xingang Dai (daixg@tea.ac.cn)
Chinese Academy of Sciences
Mohamed Ramah
National Research Centre
Magdy Abdel Wahab
Cairo University

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Abstract

Lake Nasser is the largest artificial reservoir in the world, with a water area of about 5000–6000 km^2. This study aims to investigate the impact of the Lake on the local or regional climate in Upper Egypt with its surroundings using a high-resolution regional climate model. The numerical experiment is conducted with the RIEMS model with a boundary condition constrained by reanalysis ERA5 for 2010–2012. Two experiments are performed with and without the lake at the surface. The results show that the lake plays a role similar to a smooth, wet, cooling island in the hot desert. The cooling comes from lake water evaporation, which decreases the daily temperature difference resulting from the drop in daily maximal temperature and increase in minimum temperature. The smoothness of the lake water has the surface moisture flow accelerated and has local potential precipitation decreased and increased farther with additional northward moisture flows near the surface induced by the lake. Finally, the mechanism of the lake's impact is explored with the difference in horizontal moisture flux represented by the streamlines, whose pattern approximately coincides with the corresponding precipitation difference during the period. The main finding is that the lake has a significant impact not only on the local climate but also on regional climate, especially regional precipitation. It leads to an additional decrease in precipitation over the lake basin and an increase farther from the basin. This is the first time that a regional climate effect of an artificial lake has been proved by numerical experiment.

Article Highlights

- The numerical experiment reveals a regional climate effect of Lake Nasser in surrounding area in addition to its local climate effect,
- The lake Nasser plays a role as a smooth wet and cooling island leading a decrease in daily temperature difference with decrease in daily maximum and increase in daily minimum.
- The lake has surrounding regional wind field changed leading to a regional anomalous potential rainfall pattern, i.e., less in the lake and surroundings, and more farther from the lake.

1 Introduction

Global and regional climate shows various changes in recent decades, such as increases in torrential rainfall, heat waves, droughts, flooding and cold events against the background of global warming with the augmentation of greenhouse gases (Keeling 1997; IPCC, 2013; Risser and Wehner 2017; Oldenborgh et al. 2017; Williams et al. 2020; Almazroui et al. 2020). Some human activities, such as land use to construct dam reservoirs, can also directly influence local or even regional climate through changes in surface albedo, roughness, or exchanges in heat and water vapor between the atmosphere and surface, in addition to deforestation, overgrazing, urbanization, irrigation works or water conservancy projects (Foley et al. 2005; Tucker et al. 2018; Lambin and Meyfroidt 2011; Best 2019; Spinoni et al. 2021). Climate change is widely known to have a considerable effect on the hydrological setting of rivers, subsequently affecting the dams constructed along these rivers. For instance, more severe rainfall will cause dams to silt up, shortening their usable lives and raising the risk of dam failure and catastrophic flooding, and a more frequent decrease in rainfall will cause drought to the river basin, subsequently making many hydropower projects uneconomic (Zittis et al. 2021).While several studies have been conducted to study the impact of climate change on dam reservoirs on local/regional scales (Christensen et al. 2004; Hamlet and Lettenmaier 1999), the opposite impact of reservoirs on local/regional climate has not been studied to the same extent (Degu et al. 2011).Most often, the impounded reservoirs of dams cause large-scale changes in land cover and land use, and increased humidity results from such regular alterations, which has a considerable impact on mesoscale circulation (Niyogi et al. 2010; Takata et al. 2009). For instance, scientists (Degu et al. 2011) have spatially studied the atmospheric gradient variables associated with precipitation formation around reservoir borders for 92 large dams in North America, and they observed that large dams have the greatest impact on the local climate in Mediterranean and semiarid climates, whereas they have the least impact in humid climates. Additionally, there have been extensive arguments about whether the great artificial lake constructed behind the Chinese Three Gorges Dam (TGD) on the Changjiang River (Yangtze River) brought more rainfall that led to frequent floods in South China due to evaporation since the dam was built across the river in the early 2000s (Zhang et al. 2016).A number of numerical experiments reveal that the reservoir has a limited contribution to the increase in precipitation near the reservoir because the lake water is restricted in the Three Gorges (Wu et al. 2006; Wu et al. 2012). Some scientists indicated that the effect of the TGD on the surrounding climate may be on a regional scale (100 km) rather than a local scale (10 km), as reported in other studies (Wang et al. 2009; Miller et al. 2005), which needs to be examined further by local observations and numerical experiments.

The Nile River is considered the longest river, uniquely crossing several fluctuating climatic zones and hosting a number of dams (Kantoushand Sumi 2013), which include the High Aswan Dam (HAD), Merowe Dam, Khashmel-Girba Dam, Sennar Dam, Roseires Dam, and Grand Ethiopian Renaissance Dam (GERD) (partially completed) on the Blue Nile (see Fig. 1). Lake Nasser has been considered the largest artificial reservoir in the world since HAD was completed across the Nile River on July 21, 1970 (AbdEllah 2020). Lake Nasser is much larger than the Three Gorges Reservoir in area, being approximately 500 km long and 12 km wide on average (Sadek et al. 1997; EL-Mekawy et al. 2018). HAD ended the cycle of flooding from year to year and increased irrigation, leading to more crop land appearing in Egypt, and it generates hydroelectric power for the country. Meanwhile, a series of environmental issues have emerged; for example, water resource losses have occurred, such as large annual evaporation (10–16 billion cubic meters/year) (Elmahdy et al. 2019) and land degradation in the fluvial plain. On the Nile Delta, in the downstream reaches of the Nile, soil salinization and seawater intrusion in the coast belt of the Mediterranean have resulted from the lack of seasonal flooding, which created a grand fertile land for Egyptian settlement before the 1960s (Kim et al. 2002; Monsef et al. 2015; Abdel Wahab et al. 2018). However, the influence of the great Lake Nasser on local climate (such as temperature, evaporation, precipitation, and wind circulation) seems not yet to be addressed in academic publications of climate and hydrological studies. Climate change has exerted various impacts on the Nile (Elshamy et al. 2009; Mostafa and El-Mahdy 2021). The changes in temperature and evaporation amounts of the lake water cause more changes in precipitation patterns (Beyene et al. 2007; Elba et al. 2017), while the rainfall over the Nile basin is considered the most important source for the recharge of the Nile River (Nairobi 1979; Cook and Vizy 2019). This paper presents a numerical experiment on the impacts of Lake Nasser on local temperature, rainfall, humidity, evaporation, and near-surface moisture flux by conducting two simulations with and without the lake.

2 Study Area

Lake Nasser is between latitudes 22° and 24°N and longitudes 31° and 34°E (Fig. 1), with a length of 500 km, and is located in a hot desert area of Upper Egypt in the northeastern part of the Great Sahara Desert, with rare rainfall. The area seemingly belongs to the Mediterranean climate zone, and its rainfall is mostly concentrated during boreal wintertime, in contrast to the southern East African monsoon zone (Dai and Wang 2017). The lake extends southward across the border of Sudan, and the southern part of the lake in Sudan is called Nubia Lake. The total storage capacity of the lake is 162.3BCM of fresh water and renewable at a level of 182 m. The mean width of the lake is approximately 10 km with a maximum value of 60 km, and the mean depth is approximately 25 m with a maximum value of 90 m (Sadek et al. 1997). The annual volume of water supply into the lake and the water released from it control the surface area of Lake Nasser, as the lake surface area could exceed 6276 $km^2$when the HAD is nearly full, with a water level of 180 m (Jeongkon and Mohamed 2002) and a shoreline of more than 7800 km length (Hamdan and Zaki 2016).

3 Data And Model

The data used in this study are Global Precipitation Climate Center (GPCC) monthly precipitation on grids with 0.25°x0.25° (Schneider et al. 2017) and monthly temperature of CRU_Ts4.05 made available by the Climate Research Unit (CRU), University of East Anglia (UEA), United Kingdom (UK) for 1901–2020 with a resolution of 0.5°x0.5° (Harris et al. 2020). In addition, the ERA5 reanalysis datasets at a resolution of 0.1°x0.1° are used as boundary conditions for numerical experiments with a regional climate model to quantitatively estimate the influence of Lake Nasser on the local/regional climate (Hersbach et al. 2020).The regional climate model, named the Regional Integrated Environmental Model System(RIEMS), was developed in RCE-TEA, Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (Xiong et al. 2009; Xiong and Yan 2013; Wang et al. 2015). The latest version of the model (RIEMS 2.0) has a dynamic core of a nonhydrostatic version of Mesoscale Model version 5 (MM5) with a Biosphere-Atmosphere Transfer Scheme (BATS) (Yang and Dickinson 1996) for the description of surface processes and a radiation transfer scheme applied in the Community Climate Model Version 3 (CCM3).

The running model is constrained by initial and lateral boundary conditions of wind, temperature, sea surface temperature (SST), water vapor, and surface pressure, which are all extracted from ERA5 reanalysis data, of which the lateral boundary conditions are provided via an exponential relaxation scheme, and boundary condition data are input at 6 h intervals. The center of the simulation domain is at the point (23°N, 32.5°E) in a horizontal mesh of 199 * 165 grid points, with a grid distance of 3 km. The surface topography data are taken from the USGS high-resolution topographic dataset (https://earthexplorer.usgs.gov/). The high-resolution vegetation data are also taken from the USGS and are reanalyzed for the model based on dominant vegetation type regulation on each grid box.

The experiment is initialized from 0000 UTC 1 January 2010 and runs continuously until 31 December 2012.There two numerical experiments denotedS1 and S2 hereafter.S1 is a normal experiment for the period, while in S2,Lake Nasser is replaced by desert, but other boundary conditions are held the same as those in S1 to assess the lake's climate effect. In addition, there is no cumulus convective parameterization scheme in the experiments owing to the high resolution in the area concerned. In addition, the Lambert projection with standard latitudes on 30°N and 60°N is applied to map the points from spherical coordinates to the projection plane.

4 Results And Discussion

4.1 Regional climate

There is a dry and hot climate in the northeastern part of Africa. Figure 2a shows that the annual temperature in this area is approximately20 ~ 28°C from the northern edge of the area near the Egyptian capital city Cairo through northern Sudan, based on CRU_TS 4.05 (CRU, hereafter) for 2010–2012, in which two hot centers are situated in Sudan and Chad, while relatively low temperatures appear mainly in northeastern Egypt, in addition to a cool tongue extending southward to the joint area of the Egypt, Sudan, Chad and Libya borders. The annual air temperature above the Lake Nasser water is approximately 27 ~ 28°C, which is lower than that of the deserts on its two sides. Such a climate results from the persistent subtropical high in North Africa, which brings a hot and dry climate to the area all year.

Figure 2b shows that Lake Nasser is situated in an extremely dry area between the northern Mediterranean climate zone and southern East Africa monsoon zone, with little precipitation of less than 2 mm for 2010–2012. Clearly, the lake's influence on temperature or precipitation cannot be distinguished from the figures due to their low resolutions (0.5° and 0.25°). Hence, a numerical experiment with a high-resolution model becomes an alternative option for assessing the lake's climate effect.

4.2 Numerical experiments

4.2.1 Temperature

The annual mean temperature in the study area is simulated for 2010–2012 by the regional climate model (RIEMS2.0) with a high resolution of 3 km grid distance under the constraint of boundary conditions induced from the ERA5reanalysis dataset. Figure 3a shows that the simulation can not only produce a pattern of temperature with more details than the CRU or reanalysis ERA5(Fig. 2a, b) but also successfully reveal the impact of Lake Nasser water on the surrounding temperature; i.e., the daily air temperature above the lake water is approximately 25 ~ 26°C versus 27 ~ 28°C above the surrounding land surface (Fig. 3a), close to the CRU value (Fig. 2a). In addition, the maximal air temperature is only approximately30°C above the water, much lower than the temperatures(37 ~ 38°C) in neighboring areas, with a difference of approximately 7 ~ 8°C(Fig. 3b), while the minimum air temperature above the lake is 21 ~ 22°C versus 18 ~ 19°C in surrounding areas with 3 ~ 4°C increments discernible from the pattern of simulated *Tmin* (Fig. 3c). This implies that the impact of the lake on air temperature has clearly been identified from the patterns of the daily temperature and maximum and minimum temperatures simulated with the high-resolution model. As a result, the lake leads to local climate cooling with a decrease in *Tmax* and an increase in *Tmin*, and its influence on the local climate is more significant in daytime than at night resulting from the differences in *Tmax* and *Tmin* (Fig. 3b, c). More quantitative assessment of the lake's impact on regional climate can be directly shown in comparison with the numerical experiment without the lake present at the surface.

Further numerical modeling is performed for 2010–2012 with a surface where Lake Nasser is replaced by the desert surface as the surroundings. The differences in the near-surface temperatures simulated with and without the lake are calculated for quantitative assessment of the lake's contribution to the local or even regional climate. Figure 3d shows that the lake's influence on air temperature is concentrated in the areas that roughly coincide with the lake water, and it contributes a net increment (difference) of the daily air temperature of approximately – 2°C ~ -3°C above the lake and surrounding banks, while the net increment even reaches approximately – 5°C for daily maximal temperature (Fig. 3e), whereas the difference is approximately 3°C for the minimum (Fig. 3f).These results reveal that the appearance of Lake Nasser decreases the daily air temperature difference above the lake with a strong cooling effect during the daytime and warming at nighttime, which implies that the lake water plays a role as a cooling island in the hot desert.

4.2.2 Evaporation

The cooling results from lake water evaporation. The daily water evaporation simulated for 2010–2012 from the surface is low except for Lake Nasser, where evaporation reaches approximately 2 ~ 3 mm/day, which is much greater than that of the surrounding land or desert (Fig. 4a). The net evaporation of the lake water with shorelines, i.e., the difference from the local evaporation simulated without the lake is approximately3 ~ 4 mm/day (Fig. 4b). Evaporation can persistently increase local air humidity; i.e., the lake becomes an important water vapor source to dry Upper Egypt. Evaporation leads to significant water loss from the lake, the water of which supports Egyptian economics and irrigation of the cropland in the country.

4.2.3 Humidity

Figure 5a shows that the specific humidity (*q*) simulated over the lake water is approximately 9 ~ 10 g/kg for 2010–2012, much higher than that for the surrounding lands where *q* is approximately 4 ~ 6 g/kg. The field of the background specific humidity increases from western Egypt to the western bank of the Red Sea, where *q* reaches approximately 7 ~ 8 g/kg. Correspondingly, the net increment of the specific humidity over the lake is approximately 6 ~ 7 g/kg in comparison with the surrounding increment of approximately 1.0 g/kg (Fig. 5b). Hence, the local or even regional climate has become wet since the Lake Nasser was constructed, which may influence local or regional precipitation.

4.2.4 Precipitation

The potential precipitation (simulated precipitation) distribution in the study area can also be identified in the high-resolution simulations for 2010–2012 despite the GPCC analysis, whose resolution is too low to distinguish the influence of Lake Nasser on local precipitation. Figure 6ashowsthat 2010–2012 simulated precipitation is rare in the northwestern part and slightly more in the southeastern part of the area, in which several rainfall centers are located in the position northwest of the High Aswan Dam (HAD), Sudan and the west riverbank of the Red Sea. Figure 6b-d shows that the model successively simulates annual precipitation for 2010,2011 and 2012anddemonstrates a significant difference, i.e., interannual variations year by year; for example, the precipitation amounts in 2011 and 2012 are much less than that in 2010, reflecting the influence of the El Niño-Southern Oscillation (ENSO) cycle on local precipitation. Rainy 2010wasanEl Niño year, while dry 2011 or 2012 is a La Niña year. The ENSO cycle is the dominant signal in inter-annual climate variation, in which the two phases are closely related but produce opposite weather patterns over the Earth (Kenyon and Hegerl 2010). Nevertheless, the influence of the lake on precipitation cannot be distinguished in Fig. 6. Therefore, we calculate the difference in the precipitation simulated with and without the lake to demonstrate the potential impacts of the lake on local precipitation.

The differences in precipitation for the simulations with and without Lake Nasser at the surface show a pattern over the study area, with positive differences in some places and negative differences in others (Fig. 7). The pattern averaged for 2010–2012 shows that the negative differences are concentrated on and around the lake, and the positive differences are concentrated in a farther ring (Fig. 7a). Such a pattern can be more clearly identified in the rainy year 2010 (Fig. 7b), but it is also discernable in 2011 (Fig. 7c) or 2012 (Fig. 7d), although precipitation is rare. The appearance of Lake Nasser influences not only local potential precipitation but also regional precipitation, in which the potential precipitation significantly decreases around the lake and increases farther away despite the significant increase in local humidity. The mechanism of the lake's influence on regional precipitation can be investigated through corresponding moisture circulation changes tied more compactly to local or regional rainfall.

4.2.5 Moisture flow

A decrease or increase in simulated precipitation may be associated with zonal or meridional moisture transport change resulting from the effect of Lak Nasser. The numerical simulation with the lake shows that the westward and southward moisture flows (qu, qv) near the surface become altered over the water surface for 2010–2012; i.e., both the westward and southward moisture transport are intensified, perhaps due to the smoothness of the water surface and increase in humidity (Fig. 8a, b), in addition to the cooling effect of evaporation from the lake water (Fig. 4).The value of qu is approximately − 6 ~ -12 g/S versus − 15 ~ -20 g/S for qv over the lake in comparison with the surroundings, which have values of approximately − 3 g/S for qu and − 6 g/S for qv (Fig. 8a, b). A comparison shows that the differences in the two moisture flux components are – 3 ~ -4 g/S and – 7 ~ -8 g/S over the numerical experiment without the lake (Fig. 8c, d). Evidently, the effect of the lake on thermology and dynamics leads to the westward *qu* not only significantly intensifying above the water but also decreasing in the area west of the lake and increasing in the area east of the lake (Fig. 8c). Similarly, the effect significantly intensifies *qv* southward over the lake and accelerates *qv* northward in most of the study area except for a small one immediately south of the lake (Fig. 8d). However, a study indicated that the change in the climate precipitation rate is mainly tied to meridional moisture transport rather than zonal moisture transport; i.e., the greater the northward moisture flow (transport) is, the higher the local climate precipitation, and vice versa (Dai and Wang 2017). Hence, the major effect of the lake is to reduce potential climate precipitation around it despite the increase in humidity and increase the potential precipitation farther away with additional northward moisture flux.

The correspondence between the difference fields in moisture flux and precipitation can be presented by the streamlines with the components (*qu*, *qv*). Figure 9a shows the streamlines of near-surface moisture flux for 2010–2012, which are all directed from north to south. Such streamline fields usually correspond to an arid climate with rare precipitation according to a study on large-scale climate classification (Dai and Wang 2017). Figure 9b shows the streamline pattern for the moisture fluxes simulated with and without Lake Nasser, in which a divergent belt of streamlines with counterclockwise curvatures appears over the lake and its fringes and mostly corresponds to negative precipitation differences, while the positive precipitation differences in Fig. 7a approximately correspond to the area with northward streamlines. It should be noted that the pattern of the streamlines corresponds merely to the potential precipitation trends in such an extremely arid climate zone, rather than the real or likely real precipitation trends due to the large-scale background of the dry climate over the study area. Thus, the numerical experiments with the regional climate model reveal that Lake Nasser alters the distribution of potential climate precipitation in the area through changes in temperature (cooling), humidity and moisture circulation.

5 Concluding Remarks

The climate impact of Lake Nasser has been explored numerically by the regional climate model (RIEMS). The results demonstrate that the expanded open water area after the lake establishment on the Nile plays a role similar to a wet, cooling and smooth island in the hot and dry desert, leading to a decrease in the daily temperature difference with a significant decrease in the daily maximal temperature and an increase in the minimum. The cooling comes from the evaporation of the lake water, which also causes a significant difference in surface roughness between the lake and surrounding lands, leading to accelerated horizontal moisture flux over the lake water surface; i.e., westward and southward moisture fluxes intensify significantly, with some changes in moisture flow in the rest of the nearby area. The patterns of the changes in climate variables due to the lake provide an additional impact on the regional climate, which decreases the potential precipitation around Lake Nasser and increases farther from the lake in the area with additional northward moisture flux. It seems that the lake's influence on the precipitation pattern also relies on the interannual variation in the precipitation that is connected with the

ENSO cycle; i.e., the influence is strong in the year with an El Niño event in the middle or eastern equatorial Pacific and weak in the years with La Niña events occurring in the eastern equatorial Pacific. In summary, the regional climate effect of the Lake Nasser is associated with its large water extent, which causes significant cooling of the air above the water in comparison with the relatively small water area of the artificial reservoir behind the Three Gorges Dam in the South China mainland, which has an impact on local climate around the dam lake, as reported, especially on temperature and precipitation. Besides, the regional climate effect of Lake Nasser may also result from the north-south-going lake which direction is consistent with surface climate wind direction. The surface wind field would be disturbed significantly by the accelerated wind on the large lake water surface, leading to an anomalous wind pattern that corresponds to anomalous pattern in potential rainfall in the area.

Declarations

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Precipitation Data GPCC at http://gpcc.dwd.de, Reanalysis data ERA5 at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview, CRU TS 4.05 at http://www.cru.uea.ac.uk/data.The GraDS software used for producing the figures of the study was obtained from the Center for Ocean-Land-Atmosphere Studies (COLA, http://cola.gmu.edu/grads/).

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Conflicts of interest/Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval/declaration

The submitted work is original and have not beenpublished elsewhere in any form or language.

Data availability

All the data used in this study are available and please contact the corresponding author (daixg@tea.ac.cn) to get it.

Code availability

All codes used in this study are available and please contact the corresponding author (daixg@tea.ac.cn) to get it.

Authors' contributions

ZX Regional climate simulation, Drawing, Visualization. PW Reanalysis and analysis data calculation, Formal analysis, Drawing, Editing. XD Initiative, Writing, Funding acquisition, Project administration. MR Lake Nasser introduction, Writing, Editing. MAW Initiative, Review and editing, Resources, Funding acquisition, Project administration. All authors reviewed the manuscript.

Author's information

Zhe Xiong

RCE-TEA, Institute of Atmospheric Physics,

Chinese Academy of Sciences,

Beijing 100029

Tel: 86-10-82995217 Email: xzh@tea.ac.cn

Ping Wang

Key Laboratory for Atmospheric Chemistry

Chinese Academy of Meteorological Sciences,

Beijing 100081

Tel: 86-10-58995350, Email: wangp@cma.gov.cn

Xingang Dai: corresponding author,

RCE-TEA, Institute of Atmospheric Physics,

Chinese Academy of Sciences,

Beijing 100029

Tel: 86-10-82995313, Email daixg@tea.ac.cn

Mohamed Ramah:

Department of Geophysical Sciences,

National Research Centre, Giza12622,

Egypt

Tel: +201021003212, Email m.ramah94@gmail.com

Magdy Abdel Wahab:

Astronomy and Meteorology Department

Faculty of Science, Cairo University 12613,

Egypt

Tel: 20-02- 35676844, Email: magdy@sci.cu.edu.eg

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Figures

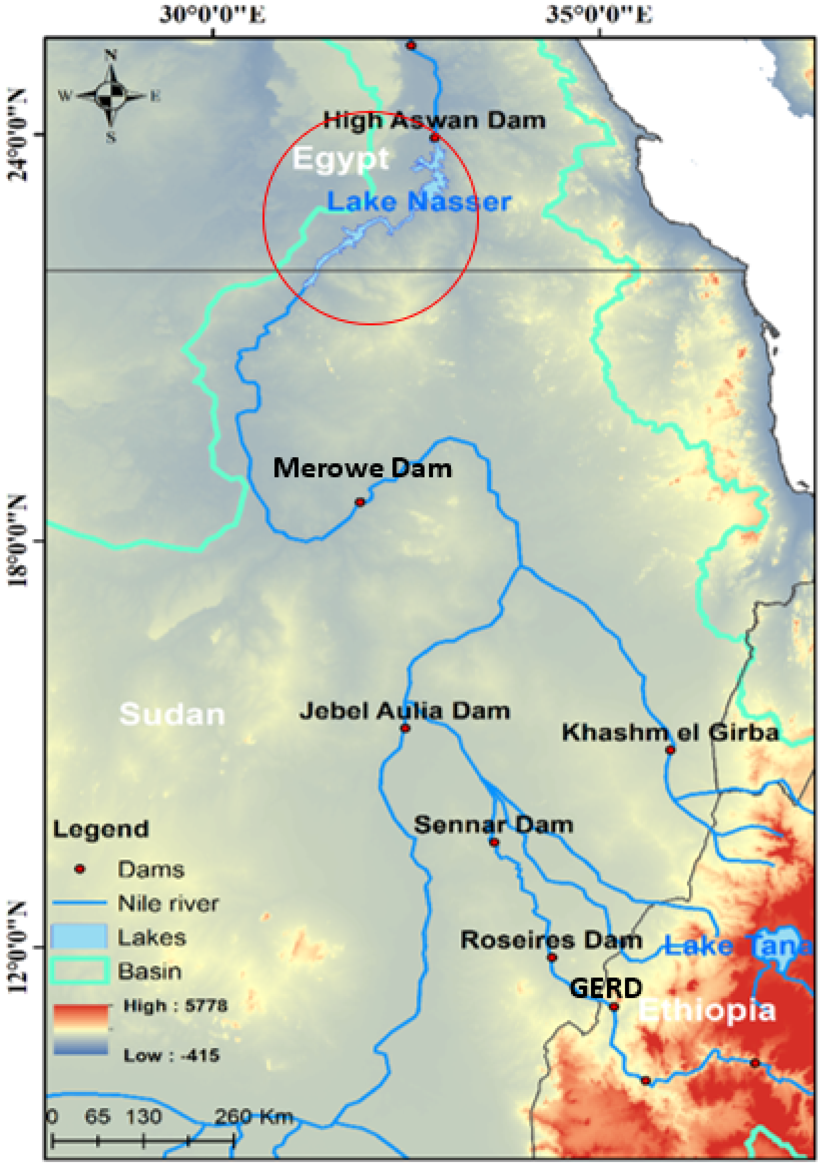

Figure 1

Location map of Lake Nasser in the Nile basin.

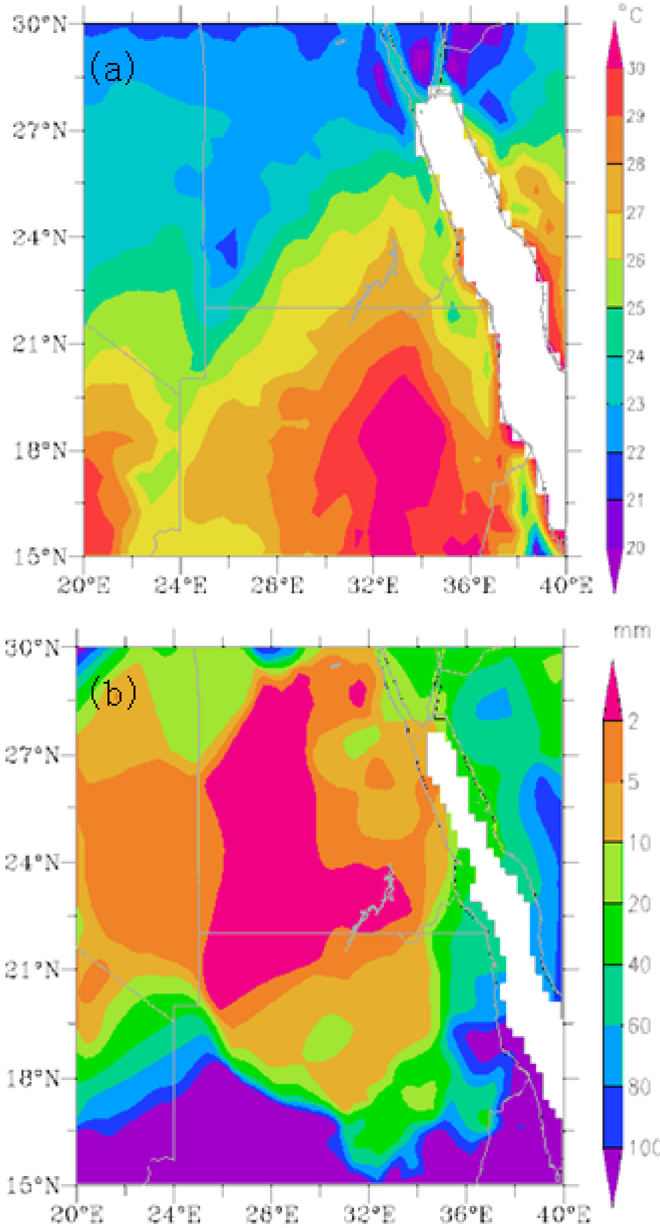

Figure 2

2010-2012 mean temperature (top) and precipitation (bottom),

(a) CRU_TS4.05, (b) GPCC.

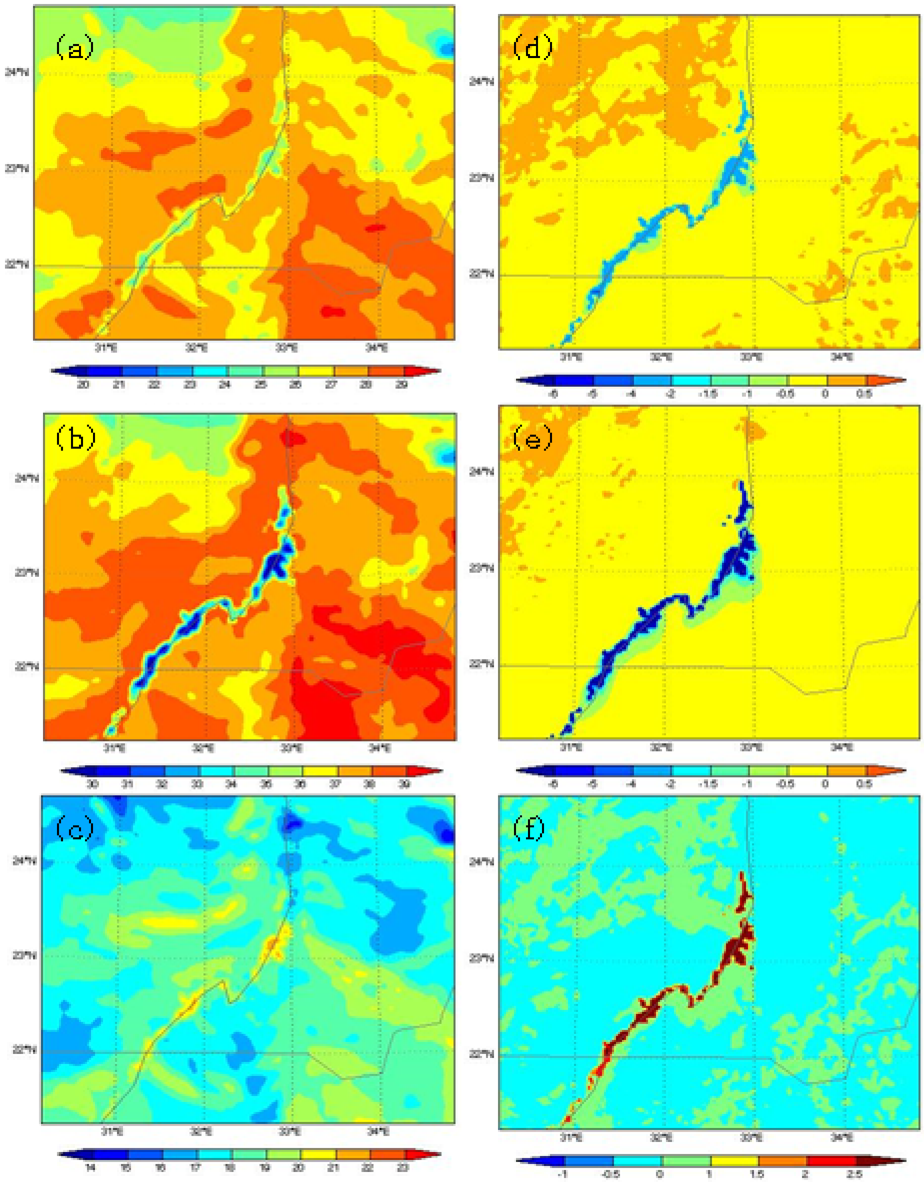

Figure 3

Annual mean simulated temperature and its difference from that without Lake Nasser for 2010-2012, (a, d) daily temperature and difference, (b, e) maximum (*Tmax*) and difference, (c, f) minimum (*Tmin*) and difference.

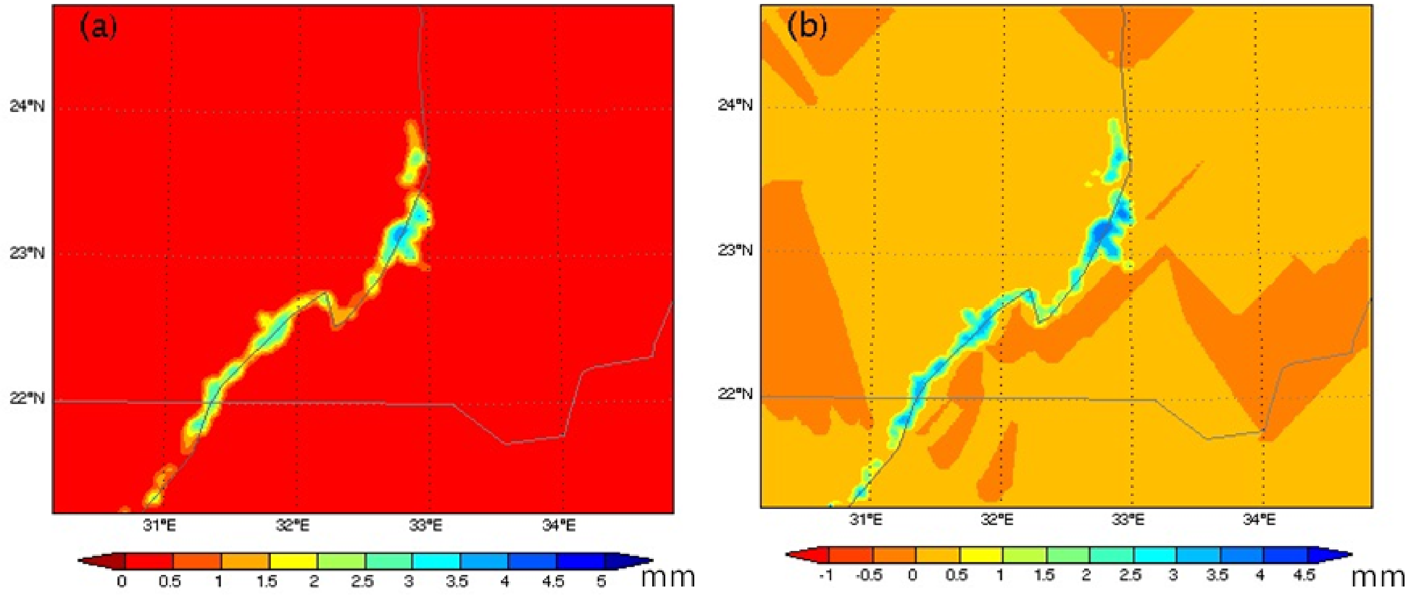

Figure 4

Surface evaporation rate, (a) average for 2010-2012, (b) difference from the simulation without the Lake Nasser, unit: mm/day.

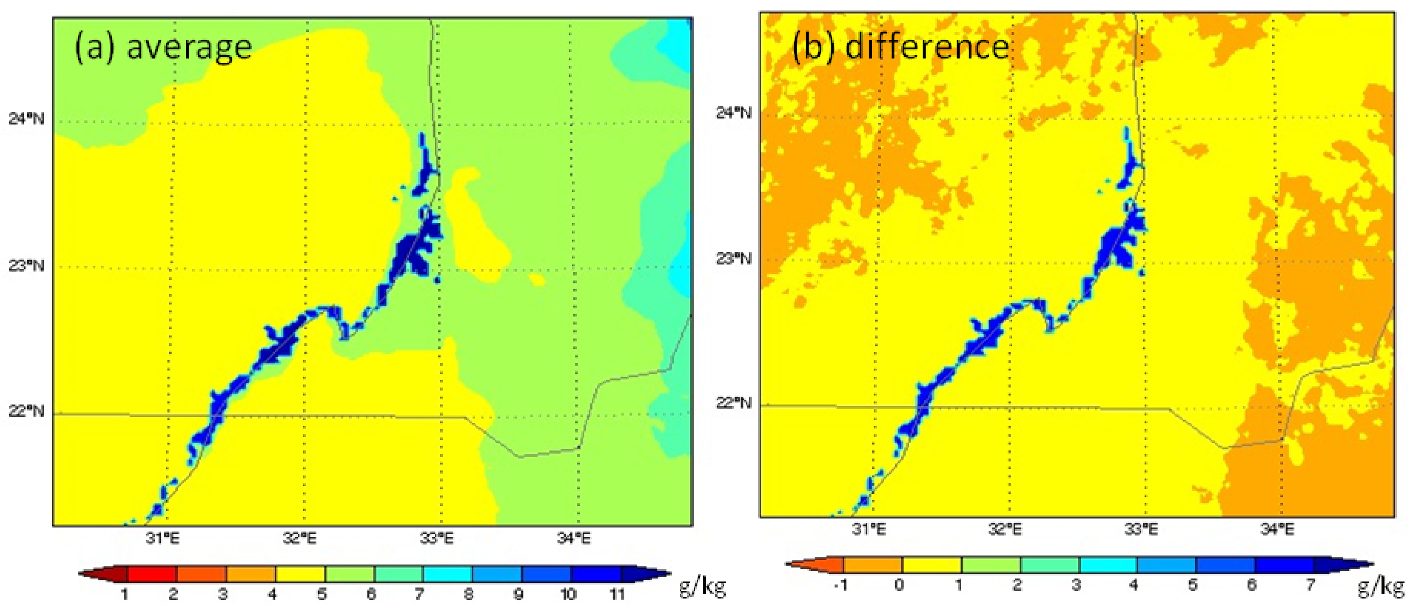

Figure 5

Near-surface specific humidity, (a) average for 2010-2012, (b) difference from the simulation without Lake Nasser, unit: g/kg.

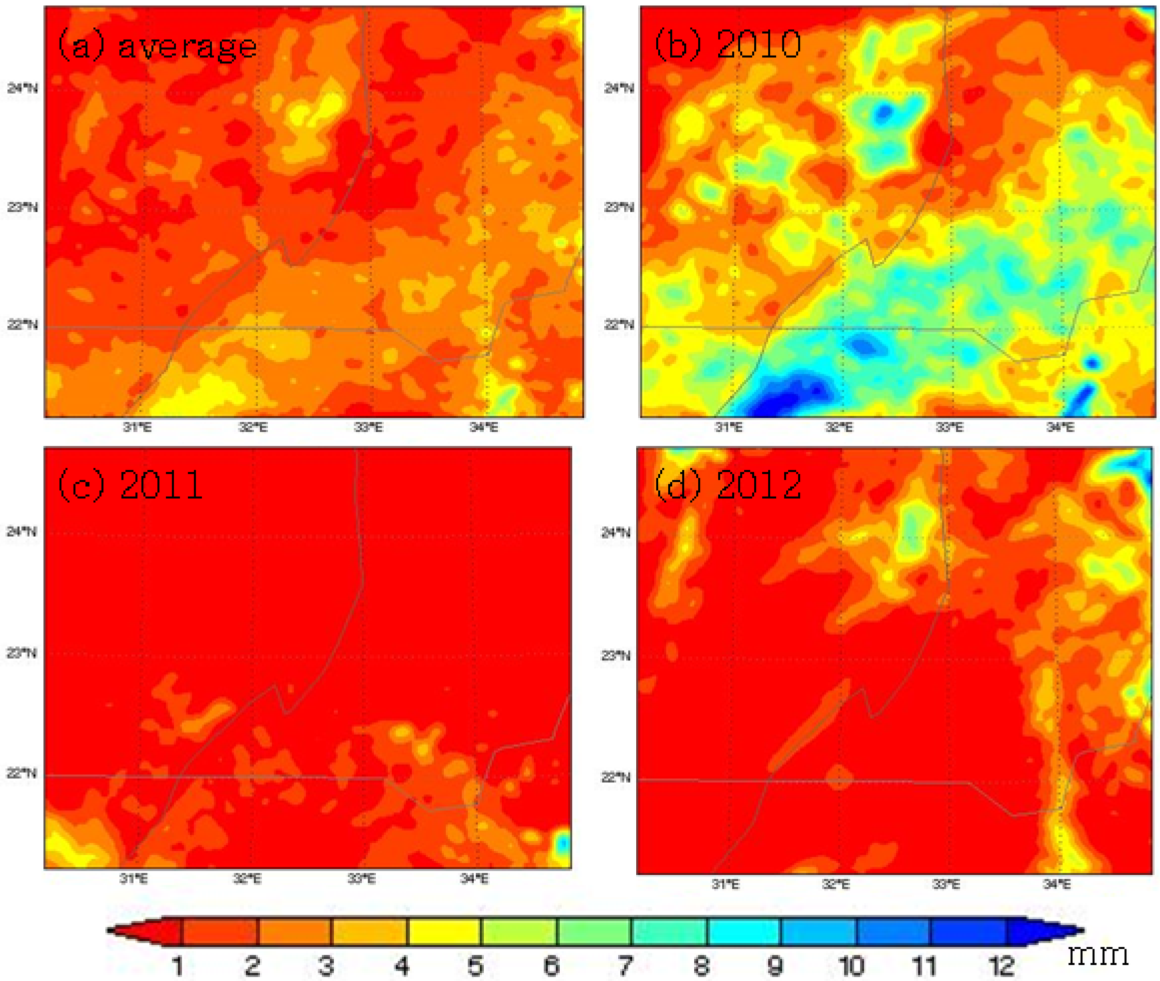

Figure 6

Annual precipitation simulated, (a) 2010-2012 mean, (b) 2010, (c) 2011, (d) 2012, unit: mm.

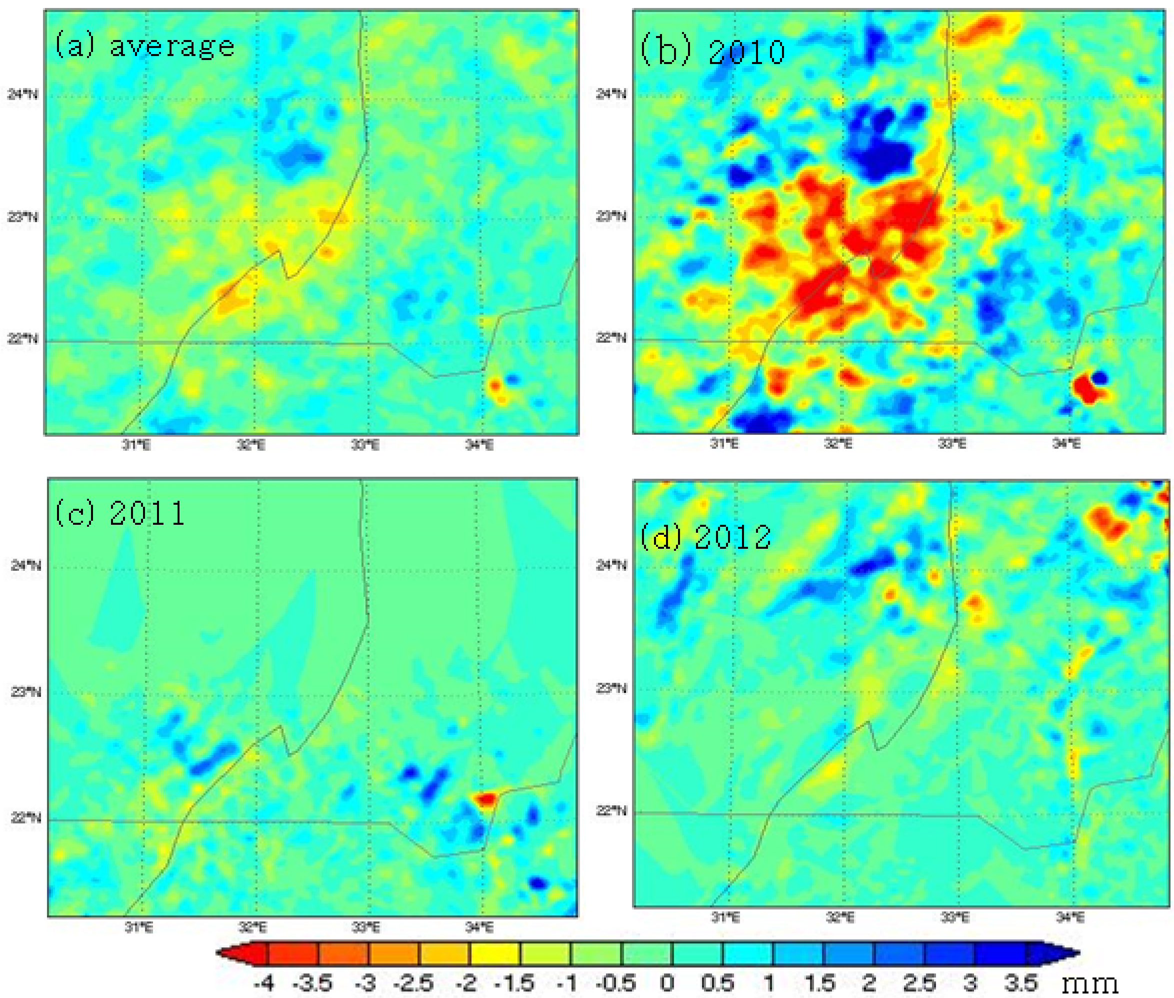

Figure 7

Differences in precipitation simulated by the regional climate model RIEMS with and without Lake Nasser at the surface, (a) 2010-2012 mean, (b) 2010, (c) 2011, (d) 2012, unit: mm.

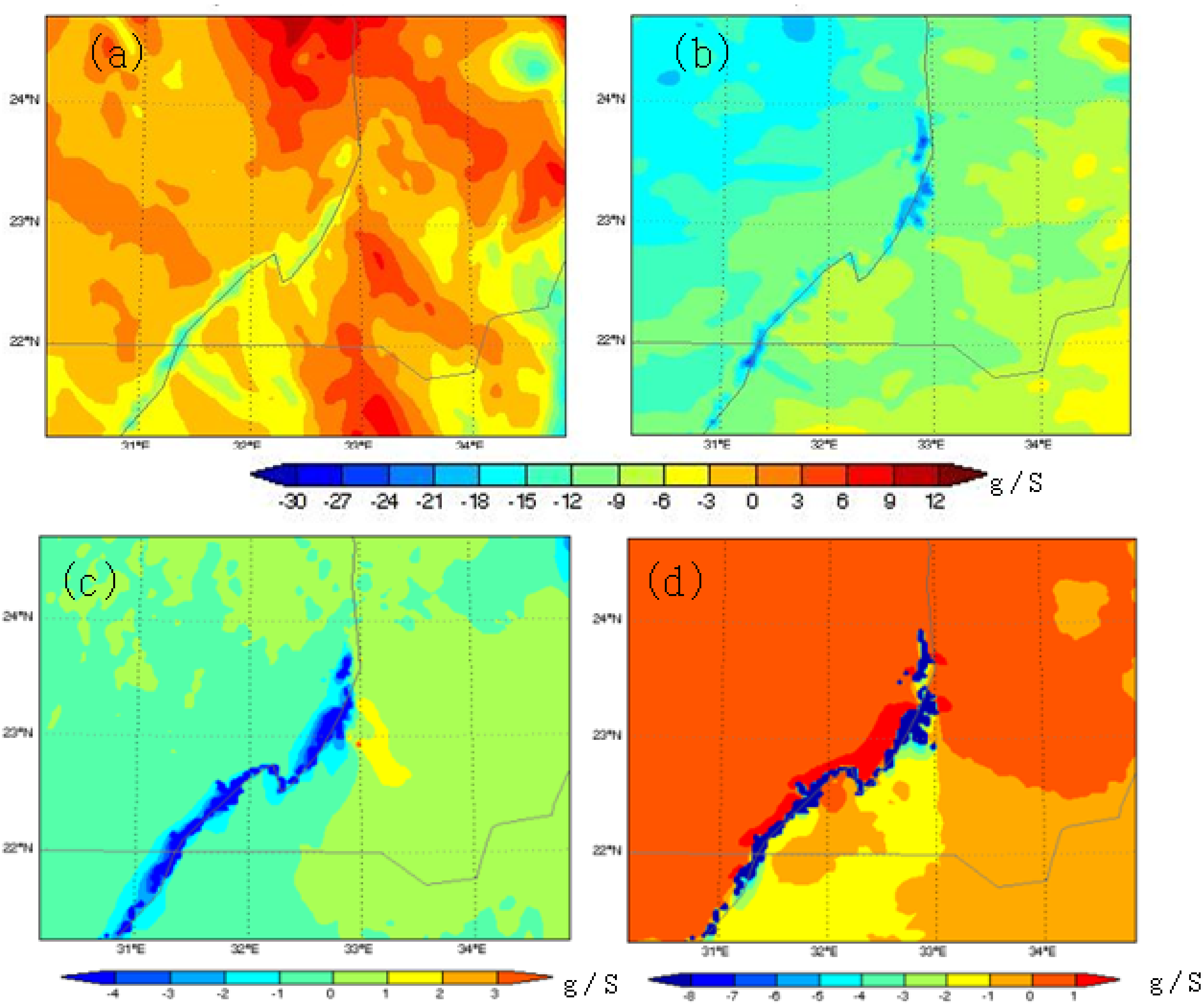

Figure 8

2010-2012 horizontal moisture flux components (*qu*, *qv*) near the surface (s=0.925), (a, b) average, (c, d) differences for the simulations with and without Lake Nasser, unit: g/S.

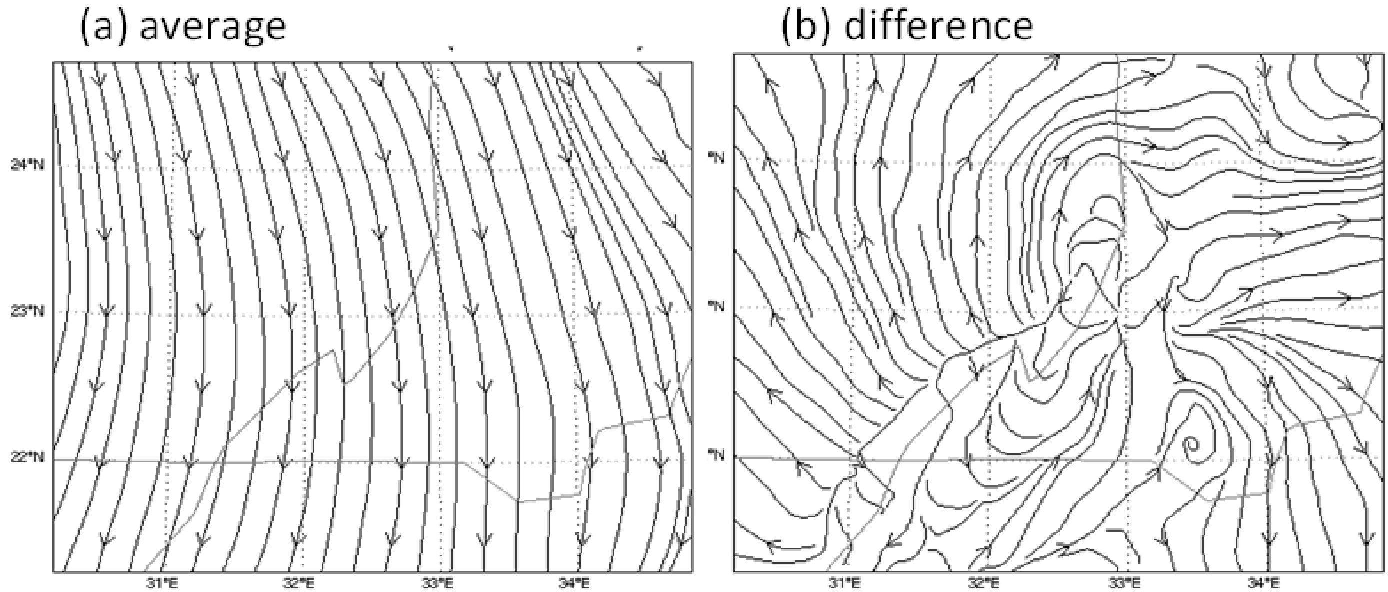

Figure 9

Simulated streamlines of the moisture flux (*qu*, *qv*) near the surface (s=0.925), (a) average for 2010-2012, (b) difference for the simulations with and without Lake Nasser at the surface, unit: g/S.