Final Report for the NASA LCLUC Project

Regional and Global Climate and Societal Impacts of Land-Use and Land-Cover Change in Northern Eurasia: A Synthesis Study Using Remote Sensing Data and An Integrated Global System Model

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1. Research Objectives

This synthesis proposal is to improve understanding of how the LCLUC, ecosystems and biogeochemical dynamics, climate, and humans have interacted in the region during the last three decades. The improved understanding of established cause-effect relationships among these dynamics will be incorporated into an Integrated Assessment Model (IGSM) to reveal potential data and knowledge gaps and to evaluate how future LCLUC will impact the global climate and socioeconomic systems. The projects research questions will focus on evaluating: 1) changes in the regional LCLU due to both regional and global economic pressures for providing food, fiber and fuel to a growing population and intensified natural processes of fire disturbance and permafrost degradation; and 2) feedbacks of regional LCLUC to the earth system with respect to regional ecosystem and biogeochemical dynamics and the global climate and socioeconomics during the 21st century. The project will undertake 3 tasks:

Task 1: Synthesize the available data on LCLUC and other components of the Earth system with model-data fusion techniques to derive new LCLUC knowledge in the NEESPI region for improving the MIT IGSM;

Task 2: Use the improved MIT IGSM to explore the influence of the global economy and climate on LCLUC in the NEESPI region during the 21st century; and

Task 3: Assess the role of the LCLUC of the NEESPI region in the global socioeconomic and climate systems during the 21st century.

2. Research Findings

2.1. Overview

To address our synthesis research questions, we take advantage of a large amount of in situ and remote sensing data on the NEESPI domain developed over the last three decades and a suite of existing models of land-use and land-cover change and ecosystem and biogeochemistry as well as climate. We have reviewed the status of this past and ongoing work and suggest how future efforts may build upon this work to improve our understanding of how LCLUC interacts with climate change to affect Earth system processes and human activities in the future (Groisman et al. 2017; Monier et al. 2017). We have also accomplished several studies with the data and models towards our research objectives by working with a multi-disciplinary US scientific team including ecosystem scientists, biogeochemical modelers, and economists, reinforced by international collaborators. Using our integrated modeling framework and in situ and satellite data, we addressed the following research questions: 1) We used MIT IGSM model projected climates to drive our biogeochemistry model to examine the impacts of land-use legacies on the carbon budget in Northern Eurasia for the 21st century (Monier et al. 2018); 2) we coupled our modeling framework with the SiBCLiM dynamic vegetation model to examine the impact of climate-induced vegetation shifts on land-use change and associated land carbon fluxes (Kicklighter et al., 2014); 3) we used our modeling framework with data on the distribution of protected areas to examine the potential role of the protected land on carbon sequestration in the region (Kicklighter et al., 2016); 4) we used a LPJ-DGVM driven with MIT IGSM climate
scenarios to examine the permafrost degradation rate and its impacts on climate-induced vegetation shifts and associated ecosystem carbon cycling in the Arctic (Jiang et al., 2016); 5) we used a new version of TEM (TEM 6.0) driven with MIT IGSM climate scenarios to examine the impacts of permafrost degradation on nitrogen availability and associated carbon fluxes in Northern Eurasia (Kicklighter et al., 2018); 6) we used TEM 5.0 to examine the impact of historical climate change on water availability in Northern Eurasia (Liu et al., 2014); and 7) we also used TEM 5.0 to examine the freshwater supply uncertainties in Northern Eurasia (Liu et al., 2015b). Below we summarize our findings during the project.

2.2. Review of past and ongoing studies in Northern Eurasia and their implications for future mitigation and adaptation studies

During the past few decades, the Global Earth System has changed significantly, especially across Northern Eurasia. Changes in the socio-economic conditions of the larger countries in the region have resulted in a variety of regional environmental changes that can have global consequences. The Northern Eurasia Future Initiative (NEFI) has been designed as an essential continuation of the Northern Eurasia Earth Science Partnership Initiative (NEESPI). NEESPI sought to elucidate all aspects of ongoing environmental changes, to inform societies and, thus, to better prepare them for future development. A key principle of NEFI is that this development must now be secured through science-based strategies co-designed with regional decision makers to lead their societies to prosperity in the face of environmental and institutional challenges. NEESPI scientific research, data, models, and knowledge created a solid base to support the NEFI program. Groisman et al. (2017) presents the consensus of the NEFI research vision. It provides the reader with samples of NEESPI accomplishments and formulates new NEFI science questions. They now are: 1. How can we quantify and project ecosystems dynamics in Northern Eurasia when these dynamics may be internally unstable? 2. What are the major drivers of the ongoing and future changes in the regional water cycles? 3. How can the sustainable development of societies of Northern Eurasia be secured in the near future? To address these questions, nine research foci are identified: warming of the Arctic; changing frequency, pattern, and intensity of extreme and inclement environmental conditions; retreat of the cryosphere; changes in terrestrial water cycles; changes in the biosphere; pressures on land-use; changes in infrastructure; societal actions in response to environmental changes; and quantification of Northern Eurasia's role in the Global Earth System. Due to powerful feedbacks between the Earth and Human Systems in Northern Eurasia, we propose to develop Integrated Assessment Models as the final stage of the global change assessment (see Section 2.3). This overarching goal of the NEFI modeling effort will enable evaluation of economic decisions in response to changing environmental conditions and justification of mitigation and adaptation efforts.

2.3. Review of global change modeling for Northern Eurasia

Northern Eurasia is made up of a complex and diverse set of physical, ecological, climatic and human systems, which provide important ecosystem services including the storage of substantial stocks of carbon in its terrestrial ecosystems. At the same time, the region has experienced dramatic climate change, natural disturbances and changes in land management practices over the past century. For these reasons, Northern Eurasia is both a critical region to understand and a complex system with substantial challenges for the modeling community. We have conducted a review to determine the state of past and ongoing efforts of the research
community to understand and model these environmental, socioeconomic, and climatic change (Monier et al. 2017). Modeling efforts have shown that environmental and socioeconomic changes in Northern Eurasia can have major impacts on biodiversity, ecosystems services, environmental sustainability, and the carbon cycle of the region, and beyond. These impacts have the potential to feedback onto and alter the global Earth system. We find that past and ongoing studies have largely focused on specific components of Earth system dynamics and have not systematically examined their feedbacks to the global Earth system and to society. Thus, new approaches are needed to improve our understanding of the role of Northern Eurasia in the coupled human-Earth system. We identify the crucial role of Earth system models in advancing our understanding of feedbacks within the region and with the global system. We further argue for the need for integrated assessment models (IAMs), a suite of models that couple human activity models to Earth system models, which are key to address many emerging issues that require a representation of the coupled human-Earth system.

2.4. Importance of land legacy on future carbon dynamics over Northern Eurasia

Present and future land carbon emissions are strongly dependent on current land carbon stocks, which suffer from large uncertainties driven by difficulties in conducting inventories of carbon stored in soil and vegetation, monitoring the carbon budget using remote sensing, and estimating the amount and lifetime of wood products. A commonly used approach is to simulate the effect of past land-use change and climate on carbon dynamics using historical reconstructions and terrestrial ecosystem models. Unfortunately, major gaps still exist in our capability to reconstruct past land disturbances and climate, which can impact estimates of current carbon stocks. We use TEM along with two scenarios of land-use change and a wide range of climate change projections using MIT IGSM (Figure 1; Monier et al., 2018) that accounts for the uncertainty in greenhouse gases emissions, climate sensitivity and natural variability, to estimate present and future land carbon fluxes from Northern Eurasia. We design a 105-member ensemble of TEM simulations to identify and quantify the role of land legacy, land-use change and climate change and their uncertainties on present and future carbon dynamics across the region. We find that using different historical climate reconstructions simulated under different initial conditions and climate sensitivity leads to a wide range of estimates of present-day terrestrial carbon fluxes over the region. We also show that legacy, related to the recovery from past land-use change and past changes in atmospheric chemistry and climate effects (Figure 2; Monier et al., 2017b), account for a major portion of the future carbon sink potential of Northern Eurasia (19.2 to 26.1 Pg C from 2005 to 2100), with magnitudes (carbon sink of 21.1 to 25.3 Pg C) similar to the effects of future climate change (carbon sink of 10.6 to 18.9 Pg C) and future land-use change (carbon source of 15.8 to 24.4 Pg C). Since legacy effects are generally lumped with land-use change, we argue that current estimates of future land-use change emissions can be misleading and not reflect the true impact of land management decisions. As a result, land-use change reconstructions that account for natural disturbances and the impact of past climate change and variability are required to accurately estimate current land carbon stocks, fluxes, and future carbon dynamics.

2.5. Importance of climate-induced vegetation shifts on land-use change and associated land carbon fluxes

Climate change will alter ecosystem metabolism and may lead to a redistribution of vegetation and changes in fire regimes in Northern Eurasia over the 21st century. Land management decisions will interact with these climate-driven changes to reshape the region’s
In Kicklighter et al. (2014), we present an assessment of the potential consequences of climate change on land use and associated land carbon sink activity for Northern Eurasia in the context of climate induced vegetation shifts. Under a ‘business-as-usual’ scenario, climate-induced vegetation shifts allow expansion of areas devoted to food crop production (15%) and pastures (39%) over the 21st century. Under a climate stabilization scenario, climate-induced vegetation shifts permit expansion of areas devoted to cellulosic biofuel production (25%) and pastures (21%), but reduce the expansion of areas devoted to food crop production by 10%. In both climate scenarios, vegetation shifts further reduce the areas devoted to timber production by 6–8% over this same time period. Fire associated with climate-induced vegetation shifts causes the region to become more of a carbon source than if no vegetation shifts occur. Consideration of the interactions between climate-induced vegetation shifts and human activities through a modeling framework has provided clues to how humans may be able to adapt to a changing world and identified the tradeoffs, including unintended consequences, associated with proposed climate/energy policies.

2.6. The Protected Areas’ Role in Climate-change Mitigation in Northern Eurasia

In Northern Eurasia, about 2.1 million km² of land are currently identified as protected areas, which provide society with many ecosystem services including climate-change mitigation. These areas represent about 14% of the protected areas identified across the globe (Kicklighter et al., 2016; Figure 3).

Combining a global database of protected areas, a reconstruction of global land-use history, and a terrestrial biogeochemistry model, we estimate that protected areas in Northern Eurasia currently sequester 0.05 Pg C annually, which is about one tenth of the carbon sequestered by all land ecosystems annually in this region (0.5 Pg C yr⁻¹) and also about one tenth of the carbon sequestered in all protected areas across the globe.

2.7. Uncertainty of soil thermal regime, climate-induced vegetation shifts and carbon dynamics in the circumpolar north

Permafrost degradation is a major disturbance to boreal ecosystem structure and functioning, thereby affecting carbon dynamics in Northern Eurasia. We incorporated a soil thermal model that couples water and heat transport into a dynamic global vegetation model (LPJ-DGVM) to simulate the soil thermal gradient from surface to 3m depth soil (Figures 4 and 5; Jiang et al., 2016), and its consequent impact on soil organic C (SOC) across different organic horizons, and the ecosystem C budgets during the “spin-up” period, the 20th and 21st centuries, driven by the climate projections simulated with our synthesis tool, the MIT IGSM. The extended model estimates 177, 389, and 844 Pg SOC for the top 30, 100 and 300 cm soil in the circumpolar north, which is in the range of empirical data. Using the simulated soil thermal gradient, the extended model produces ~0.4 Pg C yr⁻¹ lower present-day heterotrophic respiration but ~0.5 Pg C yr⁻¹ higher net primary production than the original LPJ model, both associated with the simulated cooler summer soil temperatures (Figure 6). With explicit estimates of soil temperatures at different depths, the new-thawed permafrost layer under warming climate is simulated to substantially increase the SOC release, thereby leading to a more rapid increase in soil respiration, than that from the original LPJ model. However, except for the extreme warming conditions, concurrent increases in plant photosynthetic rate, due to warming and rising CO₂, overwhelm the enhanced ecosystem respiration such that both boreal forest and arctic tundra ecosystems remain a net C sink over the 21st century. This study highlights the importance of a
valid simulation of soil thermal gradient in determining the C budget in the circumpolar north including Northern Eurasia.

2.8. Permafrost degradation, nitrogen availability and carbon dynamics in the circumpolar north

Enhanced nitrogen availability from warming-induced decomposition of soil organic matter (SOM) associated with permafrost degradation and nitrogen subsidies (atmospheric nitrogen deposition, nitrogen fixation, and the application of nitrogen fertilizers) may influence carbon dynamics in Northern Eurasia. With a new version of TEM (TEM 6.0), we examined how changes in nitrogen availability may influence regional land carbon dynamics during the 21st century for a “business as usual” scenario (Representative Concentration Pathway or RCP 8.5) and a climate stabilization scenario (RCP 4.5) based on climate simulated by the MIT IGSM (Kicklighter et al., 2018). Over the 21st century, nitrogen recycling from net nitrogen mineralization (8.4 to 8.5 Pg N) and nitrogen subsidies (3.5 Pg N for RCP 8.5, 2.9 Pg N for RCP4.5) allow 40.6 Pg C (RCP 8.5) to 53.7 Pg C (RCP 4.5) to be sequestered by Northern Eurasian ecosystems in the absence of wildfires; mostly in trees of boreal forests (Figures 7 and 8; Kicklighter et al., 2017). In forest ecosystems, consideration of enhanced net nitrogen mineralization from permafrost degradation (+1.9 Pg N for both RCP 8.5 and RCP 4.5 scenarios), atmospheric nitrogen deposition (0.2 to 0.3 Pg N), and biological nitrogen fixation (0.3 Pg N) enhanced carbon sequestration estimates in by 132% under the RCP 8.5 scenario and 129% under the RCP 4.5 scenario. Thus, it is critical to consider the influence of soil thermal dynamics and nitrogen subsidies on biome-specific carbon dynamics in Northern Eurasia when assessing responses to future global change.

In a separate study, Hayes et al. (2014) found that permafrost thaw and the subsequent mobilization of carbon (C) stored in previously frozen SOM have the potential to be a strong positive feedback to climate. As the northern permafrost region experiences as much as a doubling of the rate of warming as the rest of the Earth, the vast amount of C in permafrost soils is vulnerable to thaw, decomposition and release as atmospheric greenhouse gases. Diagnostic and predictive estimates of high-latitude terrestrial C fluxes vary widely among different models depending on how dynamics in permafrost, and the seasonally thawed ‘active layer’ above it, are represented. They used TEM 6.0 in a model simulation experiment to assess the net effect of active layer dynamics on this ‘permafrost carbon feedback’ in recent decades, from 1970 to 2006, over the circumpolar domain of continuous and discontinuous permafrost. Over this time period, the model estimates a mean increase of 6.8 cm in active layer thickness across the domain, which exposes a total of 11.6 Pg C of thawed SOM to decomposition. According to our simulation experiment, mobilization of this previously frozen C results in an estimated cumulative net source of 3.7 Pg C to the atmosphere since 1970 directly tied to active layer dynamics. Enhanced decomposition from the newly exposed SOM accounts for the release of both CO$_2$ (4.0 Pg C) and CH$_4$ (0.03 Pg C), but is partially compensated by CO$_2$ uptake (0.3 Pg C) associated with enhanced net primary production of vegetation. This estimated net C transfer to the atmosphere from permafrost thaw represents a significant factor in the overall ecosystem carbon budget of the Pan-Arctic, and a nontrivial additional contribution on top of the combined fossil fuel emissions from the eight Arctic nations over this time period.
2.9. Impact of historical climate change on water availability in Northern Eurasia

In addition to carbon dynamics, we also examined issues related estimating evapotranspiration (ET) and water availability (P–ET, P: precipitation) in Northern Eurasia (NE), which has already experienced dramatic climate changes during the last half of the 20th century. In Liu et al. (2014), we use TEM 5.0, which explicitly considers ET from uplands, wetlands, water bodies and snow cover, to examine temporal and spatial variations in ET, water availability and river discharge in NE for the period 1948–2009. The average ET over NE increased during the study period at a rate of 0.13 mm year\(^{-2}\). Over this time, water availability increased in the western part of the region, but decreased in the eastern part. The consideration of snow sublimation substantially improved the ET estimates and highlighted the importance of snow in the hydrometeorology of NE. We also find that the modified TEM estimates of water availability in NE watersheds are in good agreement with corresponding measurements of historical river discharge before 1970. However, a systematic underestimation of river discharge occurs after 1970 indicates that other water sources or dynamics not considered by the model (e.g., melting glaciers, permafrost thawing and fires) may also be important for the hydrology of the region.

2.10. Uncertainty of freshwater supply in Northern Eurasia: Impact of forcing uncertainties on terrestrial ecosystem model estimates

To assess the uncertainty of freshwater supply in Northern Eurasia, we revised the evapotranspiration (ET) algorithm in our ecosystem model TEM. Using an improved version of TEM, we examined the impact that uncertainties in climate forcing data have on the estimation of ET for the period 1979–2008 (based on five widely used datasets), and explore the dominant climatic drivers of ET in NE. Estimates of regional-average ET vary in the range of 263.5–369.3 mm yr\(^{-1}\) depending on the choice of forcing data, a range of variability that corresponds to as much as 31\% of the mean ET. On the other hand, the long-term average spatial patterns of ET across the region are generally consistent for all forcing datasets. Our ET estimates in NE are largely affected by uncertainties in precipitation (P), air temperature (T), incoming shortwave radiation (R) and vapor pressure deficit (VPD). During the growing season, the correlations between ET and each forcing variable indicate that T is the dominant factor in the North and P in the South. For the non-growing season, the dynamics of ET are mainly explained by R and VPD. Unsurprisingly, the uncertainties in ET-forcings propagate as well to estimates of the volume of water available for runoff (P-ET). Our results indicate that the quality of forcing data remains a major challenge to accurately quantify the regional water balance in NE (Liu et al., 2015).

3. Publications and Manuscripts


Groisman, P., H. Shugart, D. Kicklighter, G. Henebry, N. Tchebakova, S. Maksyutov, E. Monier,


### 4. Conferences and workshops attended


Zhuang, Q., T. Zhang, Modeling wildfire burned area and frequency using statistical approaches, 10th EARSeL Forest Fire Special Interest Group Workshop, Kanika Elias Beach Hotel - Limassol, Cyprus, Nov. 2-5, 2015.

Zhuang, Q., Quantifying Biogeochemical Cycles of CO2 and CH4 over the Land and Aquatic Ecosystems in Northern Eurasia, 2015 AGU Fall Meeting, 14-18 December, San Francisco, California.

Soja, A., including Q. Zhuang, Synthesis of Decades of Change in Northern Eurasian Ecosystems: Current Assessment and Future Projections, 2015 AGU Fall Meeting, 14-18 December, San Francisco, California.


Zhuang, Q., Quantifying the Net Exchanges of Carbon Dioxide and Methane between the Atmosphere and Terrestrial Biosphere in Northern High Latitudes, EGU General Assembly 2015, Vienna, Austria, 12 – 17 April 2015.


Zhuang, Q., D. Kicklighter, Y. Cai, N. Tchebakova, J. Melillo, J. Reilly, A. Sokolov, A. Sirin, S. Makovskyov, and A. Shvidenko, Quantifying the role of land-use and land-cover changes in Northern Eurasia in global greenhouse gas emissions and biomass supply during the 21st century using an earth system modeling approach, AGU Fall Meeting, San Francisco, 12-16 December, 2016.


Zhuang, Q., Quantifying global peatland carbon dynamics using a process-based biogeochemistry model, EGU annual meeting, 8-13, April, 2018, Vienna, Austria.


Zhuang, Q., Impacts of elevated atmospheric CO₂ on global plant productivity through fertilization effects and radiative forcing and physiology-mediated climate...
5. Graduated PhD Students

Qing Zhu (05/2014); Currently employed as Scientist at Lawrence Berkeley National Laboratory.

Xudong Zhu (05/2014); Currently employed as Associate Professor in Xiamen Uni.

Yaling Liu (12/2014); Currently employed as Scientist at Columbia University

Yujie He (12/2014); Currently employed as Scientist at the University of California - Irvine

Zeli Tan (PhD, 12/2015), employed as Post-Doctoral Scientist at the Pacific Northwest National Laboratory (PNNL)

Zhenong Jin (05/2016), employed as Assistant Professor at University of Minnesota

Shaoqing Liu (12/2016), employed as Post-Doctoral Scientist at University of Minnesota

Chang Liao (PhD, 5/2017), employed as Post-Doctoral Scientist at the Pacific Northwest National Laboratory (PNNL)

Peng Zhu (5/2018), employed as Post-doctoral Scientist at University of California at San Diego.

Yang Qu (5/2018), employed as Post-doctoral Scientist at University of Illinois at Urbana-Champaign.
Fig. 1 Northern Eurasia area weighted mean change in surface temperature (°C) and precipitation (%) from the 1981-2000 baseline for the MIT IGSM-CAM ensemble (yellow shading) and the CMIP5 ensemble (grey shading) under the RCP8.5 and RCP4.5 scenarios. The black line represents the CMIP5 ensemble mean, while the red line represented the 5-member ensemble mean of the IGSM-CAM ensemble for the median climate sensitivity. Area (in million km²) covered by each vegetation type (croplands, pastures, young forests, old forests, shrublands, grasslands, tundra, wetlands and others) over Northern Eurasia from 1980 to 2100 under the RCP8.5 and RCP4.5 scenarios (Monier et al., 2016).
Fig. 2 Maps of the cumulative net carbon exchange (in PgC) over Northern Eurasia from 2006 to 2100 for each component (land legacy, land-use change, climate change, total effects and residual) for the RCP8.5 scenario under the median climate sensitivity and averaged over the 5-ensemble members with different representations of natural variability. Maps of young forests cover (%) in 2005, of croplands cover (%) in 2005 and of old forests cover changes (%) from 2005 to 2100. Area weighted, uncentered spatial correlation between the maps of cumulative NCE and associated land cover (or land cover change) are shown for each component of the land carbon fluxes (Monier et al., 2018).
Fig. 3. In Northern Eurasia, about 2.1 million km$^2$ of land are currently identified as protected areas. TEM model estimated that these areas in Northern Eurasia currently sequester 0.05 Pg C annually, which is about one tenth of the carbon sequestered by all land ecosystems annually in this region (0.5 Pg C yr$^{-1}$) and also about one tenth of the carbon sequestered in all protected areas across the globe (Kicklighter et al., 2016). Values represent the area of protected areas (million km$^2$) in each of the 16 EPPA regions (Kicklighter et al., 2016).
Fig. 4. Modeled permafrost distribution and active layer thickness for the period 2091-2100 under six MIT IGSM climate scenarios (Jiang et al, 2016).
Fig. 5. Time series of near surface permafrost extent in the 45°N northward region simulated with LPJ-STM for the historical and projection periods. Near-surface permafrost extent is the integrated area of 0.5° × 0.5° grid cells with the maximum active layer shallower than 3 m (Jiang et al., 2016).
Fig. 6. Difference of modeled annual NEP between LPJ-STM and LPJ of each 0.5° × 0.5° pixel in the 45°N northward region for the period 2091-2100. The purple color indicates that LPJ-STM produces lower annual NEP than LPJ does, and green color indicates the opposite results; white color represents smaller or zero differences (Jiang et al., 2016).
Fig. 7. Cumulative carbon sequestration and loss in Northern Eurasia over the 21st Century under the RCP 8.5 scenario and associated sources of nitrogen including the spatial distribution of carbon sinks and sources (left column), the partitioning of the carbon gains and losses among vegetation, soils, and product pools (middle column), and distribution of nitrogen sources from net N mineralization, biological N fixation, atmospheric N deposition, and N fertilizer application (right column) for all ecosystems (top row), forests (second row), tundra (third row), croplands (fourth row) and other ecosystems (bottom row). Values in the right column represent the total amount of nitrogen provided from the recycling of nitrogen by net N mineralization and nitrogen subsidies (Kicklighter et al., 2018).
Fig. 8. Cumulative carbon sequestration and loss in Northern Eurasia over the 21st Century under the RCP 4.5 scenario and associated sources of nitrogen including the spatial distribution of carbon sinks and sources (left column), the partitioning of the carbon gains and losses among vegetation, soils, and product pools (middle column), and distribution of nitrogen sources from net N mineralization, biological N fixation, atmospheric N deposition, and N fertilizer application (right column) for all ecosystems (top row), forests (second row), tundra (third row), croplands (fourth row) and other ecosystems (bottom row). Values in the right column represent the total amount of nitrogen provided from the recycling of nitrogen by net N mineralization and nitrogen subsidies (Kicklighter et al., 2018).
Fig. 9. Comparison of TEM $P-ET$ estimates driven by the five forcing datasets with the runoff measurements in Peterson et al. [2002] and GRDC in the NE region. Five widely used climate datasets are used to force TEM and estimate $ET$ across NE: (1) the Climate Research Unit (CRU) TS3.1 (with the $P$ dataset being the corrected version v3.10.01) of the University of East Anglia, (2) the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim Reanalysis, (3) the National Aeronautics and Space Administration Modern Era Retrospective-Analysis for Research and Applications (MERRA), (4) the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis, and (5) the Global Meteorological Forcing Dataset for land surface modeling by Princeton University (PU) (Liu et al., 2015).