Hydrological models and satellite observations have been widely used to study the variations in the Earth’s hydrology and climate over multitude of scales. Yet, both satellite products and model results suffer from inherent uncertainties, calling for the need to improve the representation of critical processes in the models. Irrigation and groundwater—two major hydrologic processes with complex reciprocal interplay—in large-scale hydrological models are rather poorly parameterized and heavily simplified, hindering our ability to realistically simulate groundwater-human-climate interactions. This dissertation advances the physical basis for irrigation and groundwater parameterizations in global land surface models, leveraging the potential of emerging satellite data toward a more realistic quantification of the impacts of human activities on the hydrological cycle. A comprehensive global analysis is developed to examine the historical spatial patterns and long-term temporal response, i.e., the terrestrial water storage (TWS), of two models to natural and human-induced drivers. Human-induced changes in TWS are then quantified in the highly managed global regions to identify the uncertainties arising from a simplistic representation of irrigation and groundwater. The potential of improving irrigation representation in the CLM4.5 is then investigated by assimilating the soil moisture data from SMAP satellite mission using 1-D Kalman Filter assimilation approach. Next, a new prognostic groundwater module is implemented in CLM5 to account for lateral groundwater flow, pumping, and conjunctive water use for irrigation. In particular, an explicit parameterization for the steady-state well equation is introduced for the first time in large-scale hydrological modeling. Finally, the impacts of climate change on global TWS variabilities and the implications on sea level change are examined for the entire 21st century using multi-model hydrological simulations. The key findings and conclusions are: (1) in terms of TWS, notable differences exist not only between simulations of hydrological models and GRACE but also among different GRACE products, therefore, TWS variations from a single model cannot be reliably used for global analyses; (2) these differences significantly increase in projections of TWS under climate change, however, models agree in sign of change for most global areas; (3) TWS is expected to decline in many regions in southern hemisphere, but increase in northern high latitudes, projected to accelerate sea level rise by the mid- and late-21st century. (4) constraining the target soil moisture in CLM4.5 using SMAP data assimilation with
1-D Kalman Filter reduces the bias in the simulated irrigation water, improving irrigation and soil moisture simulations in CLM4.5; (5) the new groundwater model significantly improves the simulation of groundwater level change and promisingly captures most of the hotspots of groundwater depletion across the U.S. overexploited aquifers; and (6) the simulation with the lateral groundwater flow substantially enhances the TWS trends relative to the default CLM5. These results and findings could provide a basis for improved large-scale irrigation and groundwater modeling and improve our understanding of hydrology-human-climate interactions.