論 文 の 内 容 の 要 旨

論文題目　Study of the Global Terrestrial Water Cycle Using a Land Surface Model with Representations of Human Impacts
（人間活動を組み込んだ陸面モデルによる全球陸面水循環に関する研究）

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The evidence is now overwhelming that the growing human dominance of the Earth has resulted in significant negative consequences on the Earth’s regulatory processes over a broad range of scales, and freshwater systems are no exception. The perturbation of freshwater flows and reserves will continue further in the coming decades because of increase in demand for water, and the changes in availability due to anthropogenic climate change. Therefore, as the concerns over global water resources sustainability increase, the importance of monitoring the Earth’s terrestrial water cycle has become increasingly apparent. Moreover, there also remain challenges for agricultural sustainability because significant amounts of additional water will be needed in the future to increase food production for the escalating population in the developing world. Consequently, understanding how the water cycle evolved during the past decades and how it will change in the future under increasing human disturbance and climate variability has become one of the major challenges in hydrology. Adequately addressing such key issues by the accurate predictions of global water resources availability can be achieved only through the development of advanced and integrated assessment models. Therefore, these concerns about global water resources have drawn considerable attention from hydrology and climate research communities in emphasizing the urgent need for developing integrated water resources models which can simulate the impact of anthropogenic activities on the terrestrial water cycle.

Despite numerous advances in the development of land surface models (LSMs) and global terrestrial hydrological models (GHMs), relatively few studies have focused on the impact of anthropogenic activities on the terrestrial water cycle using the framework of LSMs. Comparison of terrestrial water storage anomaly (TWSA) with the Gravity Recovery and Climate Experiment (GRACE) observations reveals that a process based LSM, namely the Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO), outperforms the simple bucket model based GHM H08 in simulating hydrologic variables, particularly in water-limited regions. However, since MATSIRO does not account for the impacts of anthropogenic activities, the anthropogenic water regulation modules derived from H08 are incorporated into MATSIRO. Further, a new irrigation scheme based on the soil moisture deficit is developed. An integrated global water resources assessment model which consists of MATSIRO LSM and human impact modules is thus developed.

Incorporation of anthropogenic water regulation modules significantly improves river discharge simulation in the heavily regulated global river basins. The estimated irrigation water withdrawal for the year 2000 (2462 $km^3\ yr^{-1}$) agrees well with the estimates by the Food and Agriculture Organization (FAO). Results indicate that irrigation significantly affects surface energy balance with increase in latent heat flux (or evapotranspiration) as high as 50 $W\ m^{-2}$ in highly irrigated areas in northwest India and Pakistan. However, increase in latent heat flux averaged over global irrigated areas is rather small (~2%). Moreover, unsustainable anthropogenic water use is estimated to be ~450 $km^3\ yr^{-1}$ for the year 2000, which corresponds closely with documented records of groundwater overdraft, representing an encouraging improvement over the previous modeling studies. Globally, unsustainable water use accounts for ~40% of total blue water used for irrigation. Further, the role of artificial reservoirs on terrestrial water storage (TWS) simulations is also investigated. It is found that representing reservoir storage in the model notably improves TWS simulations, particularly in the highly regulated river basins.

The developed modeling framework is then applied to reconstruct the hydrological cycle during the past half century. Results indicate that human activities have significantly affected TWS and freshwater discharge to the inland seas and global oceans. Summing up the contributions of artificial reservoir water impoundment, unsustainable groundwater use, and climate-driven TWS change, and combining the results for two periods 1951–2000 and 2001–2007, the net effect on global sea level change over the period 1951–2007 is an increase by 0.53 ± 0.08 $mm\ yr^{-1}$. For the period 1961–2003, the net effect is an increase in sea level by ~0.74 $mm\ yr^{-1}$ which of comparable magnitude to the unexplained sea level rise estimated by the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC), while for the period 1993–2003 the estimate of ~1.5 $mm\ yr^{-1}$ is higher than the reported sea level rise. It is also found that the development of large-scale irrigation in the Aral Sea drainage areas reduced the inflow to the sea by ~10 $km^3\ yr^{-1}$.

Furthermore, a fully dynamic groundwater representation and a newly developed pumping scheme are incorporated into the integrated model, thus leading to the development of an integrated model that accounts for Human Impacts and Groundwater representation in MATSIRO LSM (HIGW-MAT). The model simulates global groundwater withdrawal (~630 $km^3\ yr^{-1}$) well as compared to the documented records of global groundwater abstractions.

Simulated groundwater withdrawals for the principal aquifers in the United States compare well with the observations by the United States Geological Survey (USGS). For the High Plains Aquifer simulated total groundwater withdrawal of ~23 km^3 yr^{-1} corresponds closely with ~24 km^3 yr^{-1} estimated by the USGS for the year 2000. Simulated groundwater depletion in the high plains aquifer is also evaluated against the observations from the GRACE satellite mission for the period 2002–2007. Even though the model tends to exaggerate groundwater depletion as compared to GRACE observations, simulated results indicate a decreasing trend of groundwater storage and that corresponds well with USGS observations. It is found that water levels averaged over the entire aquifer area declined by 20 cm yr^{-1} from 2002 to 2007.

Finally, the integrated model is used to assess global water resources; global water scarcity is studied using various water stress indicators, and model application for the estimation of global hydropower potential is also briefly discussed. In consensus with the previously reported estimates, results of this study indicate that ~34% of the global population currently lives under severe water stress conditions. The estimated global theoretical hydropower potential of ~ 49000 TWh yr^{-1} is found to be higher than previously reported.

The consideration of human impacts and explicit representation of groundwater movement and pumping within MATSIRO makes the model a suitable tool for assessing potential anthropogenic impacts on global water resources. In this dissertation, the modeling framework is used for offline simulations. However, since MATSIRO has been developed with a direct linkage to the parent climate model MIROC, the developed framework is ready to be coupled with MIROC to assess potential human impacts on the global climate system and the associated feedbacks.