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研究課題名（和文）衛星観測を活用したデータ駆動型の水文季節予報手法の開発

研究課題名（英文）Data-driven Seasonal Hydrologic Prediction Using Earth Observing Satellites

研究代表者
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研究成果の概要（和文）：河川流量の推定について、大河川における流量データの構築を目指した。具体的には、観測が定期的に広域・高頻度で行われている、衛星高度計による河川の水位データを用いて流量を推定した。全球の河川流量の長期的な変動性を推定し、気候モード（例：ENSO）がそれをどのように調整するかを調査した。Pekelの全球表面水データとHydroLAKESデータを組み合わせて140万の全球湖沼の過去34年間の長期月別変動を分析した。データ駆動型の陸面モデルを開発し、それを用いて長期的な全球陸域水貯留量の変化に対する人間の影響を検出した。樹木年輪に基づく気候再構築を行い、内陸東アジアの水文気候の転換点を検出した。

研究成果の学術的意義や社会的意義
人工衛星は地球の広範な領域をリアルタイムで観測し、アクセスが困難な地域でも情報を提供することができる。これは地上観測が難しい地域でも洪水や干ばつ予測に必要なデータを提供できることを意味し、迅速かつ正確な予測を可能にする。本研究を通じて、NASAなどとの国際的な共同研究を通じて、多様な人工衛星とデータ駆動型モデリングに関する研究成果を積み上げることができた。特に水循環を含む多様な分野でデータ駆動型モデルを開発し、それらを活用した研究は世界的に評価の高い学術誌で出版された。これは災害、食料、保健などのさまざまな社会部門での被害を減らし、持続可能な発展の促進に貢献するものである。

研究成果の概要（英文）：Regarding the estimation of river discharge, this study aimed to enhance discharge data for large rivers. Specifically, discharge was estimated using river water level data obtained from satellite altimeters, which are observed regularly, extensively, and at high frequency. The long-term variability of global river discharge was estimated, and the study investigated how climate modes (e.g., ENSO) modulate it. By combining Pekel's global surface water data with HydroLAKES data, the long-term monthly variability of 1.4 million global lakes over the past 34 years was analyzed. A data-driven land surface model was developed and used to detect human impacts on long-term global water storage changes. Climate reconstructions based on tree rings were applied to detect turning points in the hydroclimate of inland East Asia.

研究分野：水文学

キーワード：水文季節予測　衛星リモートセンシング　データ駆動型モデル

１．研究開始当初の背景

Flood and drought are hydrological states of excessive and lack of water, and they damage lives and cause significant economic loss. In Japan, approximately 220 billion yen in damage occurs annually due to pluvial and fluvial flood, and inland flooding claims 133 lives and $4 billion in property losses in an average year in the U.S. In 2014, California had the statewide economic loss as much as $2.2 billion, with a total loss of 17,100 agricultural jobs. In general, they are understood to have completely distinguished dynamics in terms of scales in space and time, as flood has a rather concentered damage footprint, and drought impacts in a larger and persistent way. However, it should be noted that flood extents a similar spatial scale in its development stage, as it is a consequence of aggregated 'over-filling' in upstream area.

２．研究の目的

Timely prediction of flood and drought could greatly minimize the related losses but requires 1) to understand linkages among associated climate, weather and terrestrial processes across various spatiotemporal scales and 2) accurate information on the hydrologic state of an entire river basin, including its storages of snow, surface water, soil moisture and groundwater, i.e., its total water storage (TWS). Unfortunately, our knowledge is still not enough to describe all the physical processes and to completely represent their interactions in numerical simulation, and comprehensive observations of all the relevant hydrological variables are not currently available with existing in-situ networks. In the proposed project, we will build and test a data-driven inference framework to answer the science question, “How can earth observing satellites benefit seasonal prediction of hydrological disasters?”. We aim to build a data-driven framework for predicting regional hydrological outlook at lead times from 6 months to the present, and the broader goals include to combine predicted hydrologic extremes on socio-economic data, geophysical models and in-situ data sets for assessing vulnerabilities to flood and drought. Preferentially, river stage level (H) will be predicted as a proxy of flood and drought, and GRACE measured total TWS and global sea surface temperature (SST) will be used as a local and a global external forcing, respectively (Fig. 1). A unified data interface will be developed to integrate multiple satellite observations across various orbits and spatiotemporal resolutions. A common architecture for database will be designed with careful review and discussions on the current data distribution systems and potential extensions of the application.

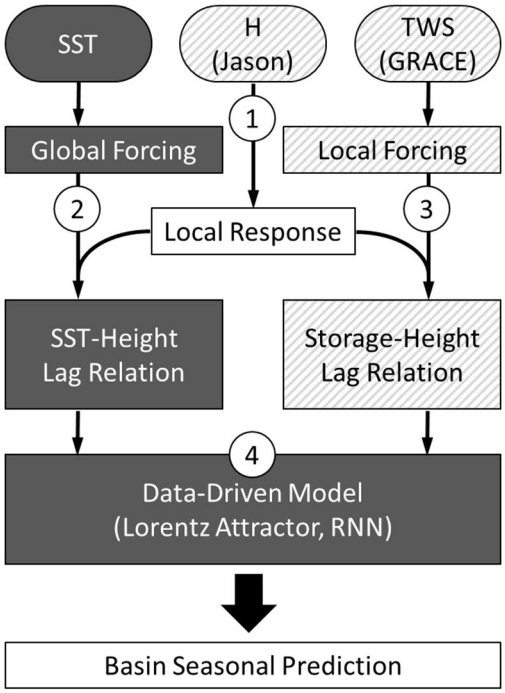

Figure 1. Overall structure of proposed project. Gray-filled and hatched pattern indicate main leading role by Japan and US team, respectively. Tasks in white box require equal contributions from both parties. Numbers correspond to the subsections in the proposal.

３．研究の方法

(1) *Global River Water Height Monitoring*

Since the Topex/Poseidon mission (1992-2006), satellite radar altimetry has built 25+ years continuous records of water surface height observation, and they have been actively utilized for sea level monitoring. Although the Surface Water and Ocean Topography (SWOT, to be launched in 2021) is expected to largely contribute to measure terrestrial water surface dynamics, data from previous and ongoing missions have not been widely used. A Co-I (N. Utsumi), during visiting Rader Science and Engineering Group of JPL (2017-present), will work closely with an OJR (J.T. Reager) to develop a waveform retracker and to produce standard monitoring product applying tropospheric/ionospheric and crustal vertical motion corrections. Such data process sequence will be developed and tested for Jason missions (2001-present) and will be updated with the SWOT satellite observation become available.

(2) *Teleconnections between Global Sea Surface Temperature and Regional Hydrologic Cycle*

The applicant (H. Kim) has investigated to find teleconnection patterns between SST and river discharge as a feasibility study of the proposed idea. Idealized multi-model climate experiments organized by US CLIVAR Drought Working Group have been utilized to quantify distinguished impacts of Pacific and Atlantic Oceans. In the pilot study, it has been found that intensity and phase lag of teleconnection between SSTs and river discharge differs by each river, and their dynamics are asymmetric. Based on this finding, empirical models for each basin will be developed based on the relationships between remote SST forcing and local hydrologic response variability.

(3) *Regional Flood Potential and Drought Assessment from GRACE*

In previous researches of OJRs (J. Reager and J. Famiglietti) (e.g., Reager et al. 2014), terrestrial gravity anomalies from NASA's Gravity Recovery and Climate Experiment (GRACE) mission were applied at the regional scale to show the usefulness of a remotely sensed, water storage-based flood potential method. The spatial and temporal changes in the Earth's gravity field are assumed proportional to changes in water storage at certain spatial scales. Like a bucket that reaches a full capacity, saturation periods indicate the potential for a region to transition to a flood-prone situation. The method works extremely well and could provide several months of early warning for the largest events. Similarly, GRACE TWS and Jason river water height relation curve will be determined for global basins to model the impact of local forcing variability.

(4) *Data-Driven Prediction Using Ensemble Lorentz Attractor and Recurrent Neural Network*

The proposed study will develop an ensemble-based Lorentz Attractor model to empirically describe non-linear dynamics between remote/local forcings and river water height response. Based on the Takens's embedding theorem, ensemble of reconstructed attractors with combinations of forcings (i.e., SST and GRACE) and delayed coordinates will be produced for each river basin. Bayesian model averaging will be used to gain further skill of ensemble prediction and to estimate prediction uncertainty. In the ongoing pilot study by the applicant (H. Kim), it is found the Lorentz attractor modeling outperforms traditional data-driven approach (e.g., multivariate regression) in conversion of river water stage to discharge.

Deep Learning approach will be another approach in the proposed seasonal prediction framework. The applicant developed an adaptive sequential deep learning algorithm based on Recurrent Neural Network (RNN) with Long-Short Term Memory (LSTM). In the case study, in Kinu river basin during the Kanto-Tohoku heavy rainfall in September 2015, the application of the new algorithm efficiently reduces error in extending lead time up to 24 hours. In the proposed study, this method will be applied to incorporate global and local forcings retrieved from various satellite observations.

４．研究成果

Regarding the estimation of river discharge, this study aimed to enhance discharge data for large rivers. Specifically, discharge was estimated using river water level data obtained from satellite altimeters, which are observed regularly, extensively, and at high frequency. The long-term variability of global river discharge was estimated, and the study investigated how climate modes (e.g., ENSO) modulate it. (Fig. 2; Kim, 2020)

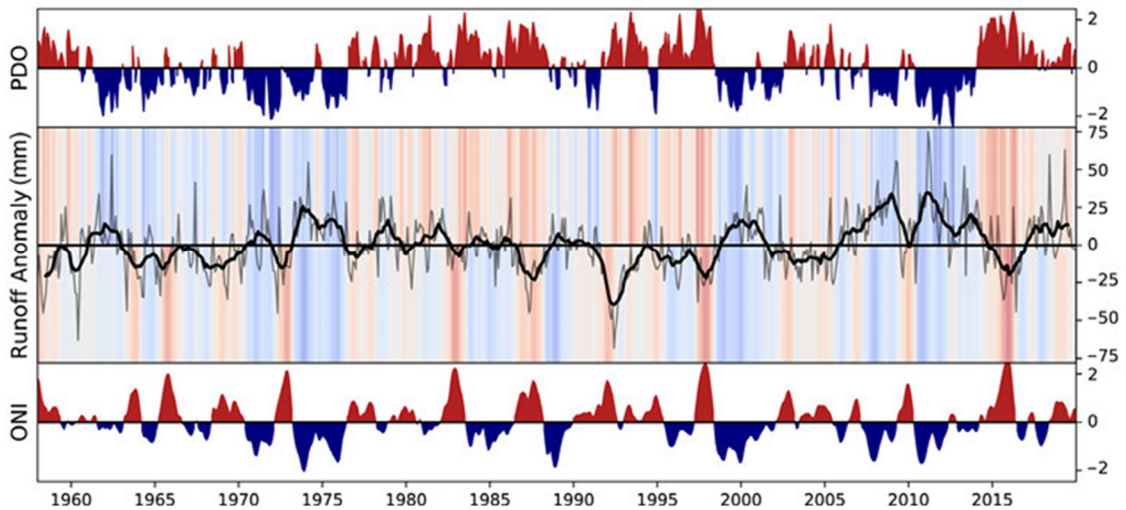

Figure 2. Interannual variability of ONI (lower), PDO (upper), and global runoff (middle; mm; thick line is 12-month moving average). ONI and PDO are shared red (positive phase) or blue (negative phase). Shading above and below the zero-line of global runoff is proportional to PDO and ONI, respectively.

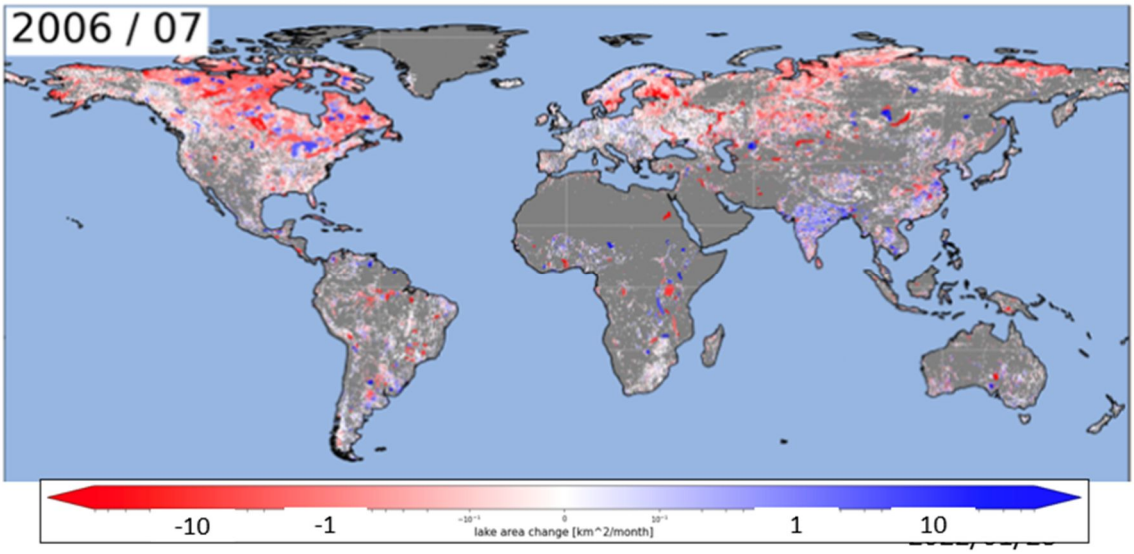

Figure 3. Satellite-based monitoring for long-term variabilities of 1,426,112 global lakes' surface.

By combining Pekel's global surface water data with HydroLAKES data, the long-term monthly variability of 1.4 million global lakes over the past 34 years was analyzed (Fig. 3). Accurate monitoring of lake water surface area is essential for understanding and managing global water resources. This study presents an improved methodology for estimating the monthly water surface area of over 1.4 million global lakes (including reservoirs) using long-term satellite observation data from the Landsat series. Our approach introduces two significant enhancements: (1) estimating the buffer length to define the region of interest (ROI) individually for each lake, and (2) complementing and modifying the Landsat data using time series information. By comparing our results with existing datasets and performing experiments with synthetic data, we demonstrate the effectiveness of these improvements in increasing estimation accuracy and data quantity. Furthermore, our final dataset, named Adaptive Buffer and Corrected water pixel Distribution Global Lake Area Dataset (ABCD-GLAD), includes intermediate information from the development process as quality indicators, providing valuable insights for future research. Our methodology aligns with a specific database, such as HydroLAKES, promoting consistency and fostering collaboration within the research community. This study offers a valuable reference for enhancing the post-processing of Landsat data and contributes to the ongoing efforts to monitor and manage global lake water resources.

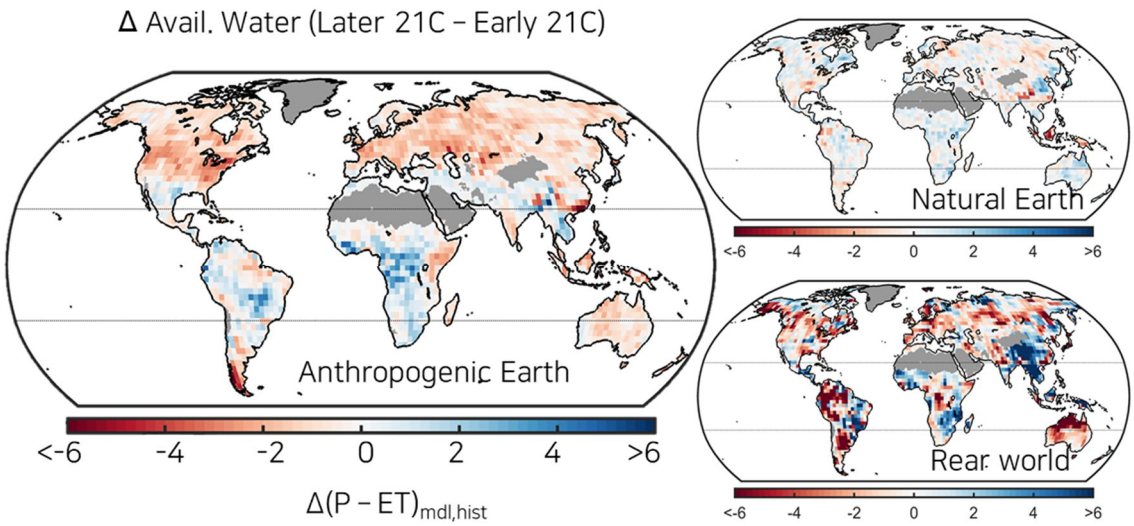

Figure 4. Comparison between "Anthropogenic Earth", data-driven model (left), "Natural Earth", climate model without anthropogenic forcings (top right), "Real World", observation (bottom right)

A data-driven land surface model was developed and used to detect human impacts on long-term global water storage changes (Fig. 4; Padron et al. 2020). Human-induced climate change impacts the hydrological cycle and thus the availability of water resources. However, previous assessments of observed warming-induced changes in dryness have not excluded natural climate variability and

show conflicting results due to uncertainties in our understanding of the response of evapotranspiration. The global pattern from the data-driven model is consistent with climate model estimates that account for anthropogenic effects, and it is not expected from natural climate variability, supporting human-induced climate change as the cause. There is regional evidence of drier dry seasons predominantly in extratropical latitudes and including Europe, western North America, northern Asia, southern South America, Australia and eastern Africa. We also find that the intensification of the dry season is generally a consequence of increasing evapotranspiration rather than decreasing precipitation.

Climate reconstructions based on tree rings were applied to detect turning points in the hydroclimate of inland East Asia (Fig. 5; Zhang et al. 2020). Unprecedented heatwave-drought concurrences in the past two decades have been reported over inner East Asia. Tree-ring–based reconstructions of heatwaves and soil moisture for the past 260 years reveal an abrupt shift to hotter and drier climate over this region. Enhanced land-atmosphere coupling, associated with persistent soil moisture deficit, appears to intensify surface warming and anticyclonic circulation anomalies, fueling heatwaves that exacerbate soil drying. Our analysis demonstrates that the magnitude of the warm and dry anomalies compounding in the recent two decades is unprecedented over the quarter of a millennium, and this trend clearly exceeds the natural variability range. The "hockey stick"–like change warns that the warming and drying concurrence is potentially irreversible beyond a tipping point in the East Asian climate system.

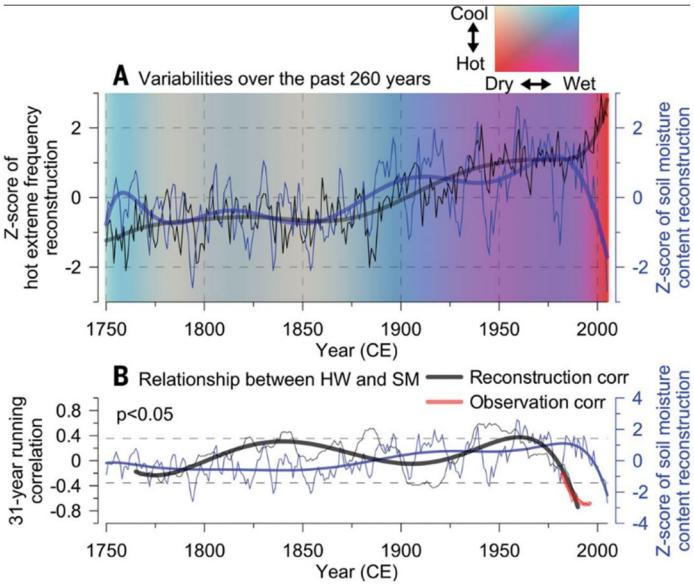

Figure 5. Shown is a comparison between the July-August mean extremely hot day frequency variability and soil moisture variability in inner East Asia over the past 260 years. (A) Variability of the reconstructed extremely hot day frequency (black) and soil moisture content (blue) and their low-frequency variations over the past 260 years. (B) Thirty-one-year running correlation between hot extreme frequency and soil moisture over 1750–2005 based on the reconstructions (black curves) and over 1967–2011 based on reanalysis and JULES-Sheffield data (red curve), where the light dashed lines indicate the $P < 0.05$ significance level. The blue curves are the soil moisture reconstruction; bold curves are their low-frequency variations.

To improve the performance of neural network-based prediction, a loss function considering data which is not uniformly distributed (Koo and Kim, 2021). In regression analysis under artificial neural networks, the prediction performance depends on determining the appropriate weights between layers. As randomly initialized weights are updated during back-propagation using the gradient descent procedure under a given loss function, the loss function structure can affect the performance significantly. In this study, we considered the distribution error, i.e., the inconsistency of two distributions (those of the predicted values and label), as the prediction error, and proposed weighted empirical stretching (WES) as a novel loss function to increase the overlap area of the two distributions. The function depends on the distribution of a given label, thus, it is applicable to any distribution shape. Moreover, it contains a scaling hyperparameter (β) such that the appropriate parameter value maximizes the common section of the two distributions. To test the function capability, we generated ideal distributed curves (unimodal, skewed unimodal, bimodal, and skewed bimodal) as the labels, and used the Fourier-extracted input data from the curves under a feedforward neural network. In general, WES outperformed loss functions in wide use, and the performance was robust to the various noise levels. The improved results in RMSE for the extreme domain (i.e., both tail regions of the distribution) are expected to be utilized for prediction of abnormal events in non-linear complex systems such as natural disaster and financial crisis.

５．主な発表論文等

〔雑誌論文〕　計19件（うち査読付論文　13件／うち国際共著　13件／うちオープンアクセス　11件）

１．著者名 Bannai Takumi、Xu Haoyang、Utsumi Nobuyuki、Koo Eunho、Lu Keming、Kim Hyungjun	４．巻 50
２．論文標題 Multi‐Task Learning for Simultaneous Retrievals of Passive Microwave Precipitation Estimates and Rain/No‐Rain Classification	５．発行年 2023年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1029/2022GL102283	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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２．論文標題 Calibrating global hydrological models with GRACE TWS: does river storage matter?	５．発行年 2023年
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３．雑誌名 Science Advances	６．最初と最後の頁 -
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2．論文標題 Abrupt shift to hotter and drier climate over inner East Asia beyond the tipping point	5．発行年 2020年
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2．論文標題 [Global Climate] River Discharge and Runoff [in "State of the Climate in 2018"]	5．発行年 2019年
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６．研究組織

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７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
米国	Jet Propulsion Laboratory / NASA			
カナダ	University of Saskatchewan			
韓国	KAIST			