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Doctoral Dissertation

Estimation of Snowmelt Distribution using
Numerical Snowpack Model based on
Long-term Snow Observation

長期積雪観測に基づいた積雪変質モデルによる
融雪分布の推定

Yoko Taniguchi

谷口 陽子

Division of Earth and Planetary Dynamics, Department of Natural History Sciences,

Graduate School of Science, Hokkaido University

北海道大学大学院理学院自然史科学専攻

地球惑星ダイナミクス講座

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Abstract

Early spring snowmelt in snowy and cold regions has a significant impact on flood control during the snowmelt season and on water resource management throughout the year. However, it is difficult to understand the snowmelt phenomenon itself, which is caused by the ever-changing weather conditions outside the snowpack and the snow quality transformation inside the snowpack. Estimating the spatial distribution of snow water equivalent (hereafter referred to as SWE) as basic information on snowmelt in mountainous areas remains one of the unsolved problems in snow hydrology. In order to challenge resolving this problem, this doctoral thesis aims to show the spatial distribution of snowmelt volume and its temporal variation in the Jozankei Dam and Hoheikyo Dam basins, by collecting as many observational data as possible and performing snowpack simulation.

In the first half of Chapter 3, the snowpack transformation model SNOWPACK was verified at a station located in the driftwood disposal facility of the Jozankei Dam (hereafter referred to as J-Site 1). We collected continuous meteorological data with an hourly interval, intermittent snow pit observations, and other by manual measurements. These observations have been conducted from the winter of 2005 to the spring of 2018. We then validated the SNOWPACK during the eight winter seasons, when sufficient observation data were available. The results showed that the SNOWPACK reproduced the observed data well in terms of snow depth, snow quality, and SWE when forced by Radar/Rain Gauge-Analyzed (R/A) Precipitation data.

In the latter half of Chapter 3, the SNOWPACK simulation was extended to the entire Jozankei dam basin, and the distribution of the snowmelt environment was mapped

to show seasonal changes within the basin during the snowmelt season. The results showed that the snowmelt rate increased: the average is about 10% on March 31, 42% on April 15, and 83% on April 30. This rapid snowmelt in April can be explained by the increase in the basin mean temperature from -5°C to 2°C . However, on April 30, the minimum snowmelt rate was still 45% at the upstream sites, and more than half of the snowmelt volume was still maintained at some sites. The accumulated snowpack layer was completely covered with melt form in May, but there was a long period of snow cover in the upper reaches during April, indicating that the snow melted unevenly in the watershed from March to May.

To further investigate the non-uniformity of the snowmelt rate within the watershed, we compared the average timing of snowmelt over eight winters at the site at the downstreammost point of the Jozankei Dam basin (J-Site 2), the midstream site of J-Site 1, and the Haruka-yama rainfall station in the upstream (J-Site 3). The results showed that there was a 27-day difference in snowmelt dates between J-Site 2 and J-Site 3. The timing of the maximum inflow at Jozankei Dam in the eight-winter average was within the range of 36 to 40 days after the cumulative melt form rate reached 50%. This indicates that the accumulated melt form ratio is a new indicator for predicting the timing of snowmelt inflow into dams.

A similar validation was conducted in the Hoheikyo Dam basin, by continuous snow observations at the Hoheikyo Dam site (hereafter referred to as H-Site 1). As a result, it was found that the observed values of snow depth, snow quality, and snow equivalent water volume were also reproduced at H-Site 1 by using R/A precipitation as the input value of precipitation. However, when deployed to the basin, we could not achieve the verification because the observation in the basin was done only for snow

depth once in one winter. Therefore, reliable and continuous snow depth observations at multiple points are required for an accurate estimate of snowmelt in the Hoheikyo Dam basin.

Finally, we discussed the remaining issues to be addressed in evaluating the snowmelt environment in mountainous areas. As the consequence of this dissertation, the accuracy of the input precipitation is most critical. For example, the snow depth was often underestimated even with R/A Precipitation. The representativeness of the snow depth should be also considered in snowmelt, and higher resolution snow depth observations are desired for a more accurate estimate of snowmelt.

日本語要旨

積雪寒冷地における春先の融雪は、融雪期の治水や年間を通じた水資源管理に大きな影響を及ぼす。一方で、積雪外部の気象条件や積雪内部の雪質変態が時々刻々と変化して発生する融雪はその現象自体を把握することが難しい。そのため、山岳地帯の雪解けに関する基本的な情報である積雪相当水量（SWE）の空間分布を推定することは、積雪水文学における未解明の問題の一つとなっている。本博士論文では、この問題の解決に向けて、定山溪ダムと豊平峡ダム流域においてできる限りの観測データを収集し積雪変質モデルの計算を行うことで、融雪量やその時間経過について空間分布で示すことを目的とした。

第3章の前半では、札幌市の定山溪ダム流域内の観測点（定山溪流木処理場、以下 J-Site 1 と記す）において、積雪変質モデル SNOWPACK の再現性を調査した。J-Site 1 は、積雪観測が継続的に行われている貴重な観測点である。観測項目は連続気象データ（時間単位）と積雪断面観測であり、自動計測機による観測を手動観測で補っている。これらの観測は2005年冬季から2018年春季まで行われており、本研究では観測データが十分にそろっている2010年冬季から2018年春季までの8冬季間において検証を行った。その結果、積雪変質モデル SNOWPACK は、降水量の入力値にレーダーアメダス解析雨量を用いることで、積雪深、雪質、積雪相当水量の項目において、観測値をよく再現することが分かった。

第3章の後半では、積雪変質モデル SNOWPACK の適用範囲をダム流域全体に広げ、融雪環境の分布をマッピングし、融雪期の流域内の季節変化を示した。定山溪ダム流域での2010年冬季から2018年春季までの8冬季間の平均値を定量的に示した結果、融雪率は流域平均で3月31日には約10%であるのが、4月15日には42%、4月30日には83%と増加し、4月中に急速に融雪が進むことを明らかにした。4月のこの急速な融雪は、流域平均気温が -5°C から 2°C に上昇したことで説明できる。ただし、4月30日の時点でも最低融雪率は上流域地点で45%であり、いくつかの地点ではまだ融雪量の半分以上が維持されていた。また、積算ざらめ化率では、3月1日に下流で50%を超えたが、上流では10%未満にとどまった。5月には流域全体の積雪層がざらめ雪

で完全に覆われたが、4 月中は上流域でしまり雪の期間が長く、3 月から 5 月にかけて流域で雪が不均一に溶けたことを示した。

流域内での融雪速度の不均一をさらに調べるため、定山溪ダム流域の最下流地点である定山溪ダム地点（以下、J-Site 2）、中流域地点である J-Site 1、上流域地点である春香山雨量観測所（以下、J-Site 3）にて、8 冬季平均の融雪のタイミングを比較した。その結果、最下流地点 J-Site 2 と上流域地点 J-Site 3 では消雪日に 27 日の差が発生していた。一方で、積算ざらめ化率が 50%に達するタイミングは 3 地点で 5 日の差に留まっており、消雪日より下流上流によるバラつきは小さいことが分かった。8 冬季平均の定山溪ダムの最大流入量のタイミングは、積算ざらめ化率が 50%に達してから 36 日から 40 日の範囲に収まっていた。これより、積算ざらめ化率は融雪がダムに流入するタイミングを予測する上で新たな指標になることを示した。

同様な検討を豊平峡ダム流域でも行い、SNOWPACK による融雪の流域分布を示した。豊平峡ダム流域では、積雪観測を連続して行っている地点が豊平峡ダム地点のみであるため、モデルの精度検証は豊平峡ダム地点（以下、H-Site 1）で行った。その結果、H-Site 1 でも J-Site 1 と同様に降水量の入力値にレーダーアメダス解析雨量を用いることで、積雪深、雪質、積雪相当水量の項目において、観測値をよく再現することが分かった。ただし、流域へ展開した際には、流域内の観測値が 1 冬季に 1 回の積雪深のみのため十分な検証を行うことができなかった。信頼できる連続した積雪深の観測値を複数点入手することは豊平峡ダム流域における大きな課題である。

最後に、山岳地帯の融雪環境を評価する上で取り組むべき残りの問題について議論した。この論文の結論として、入力降水量の精度は最も考慮されなければならない。たとえば、R/A 降水量を使用しても積雪深は過小評価されることがあった。融雪では積雪深の代表性も考慮する必要がある。より正確な融雪の推定には、より高解像度の積雪深観測が望まれる。

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Chapter 1. Introduction

Snow is the most important water resource in the regions where a lot of snow falls in the cold season. Snow accumulated in the catchment areas melts during spring and summer and supplies river water and groundwater. The snowmelt water is often of high quality and is used as domestic, agricultural and industrial water by human activities in the downstream. Estimates of water resource recharge from snow in mountainous areas are therefore important in terms of water use and flood control. Generally, due to the nonuniform distribution of precipitation and temperature, the distribution of snowfall and melting is nonuniform throughout the basin, making it difficult to represent them in a certain area accurately. Additionally, the rate of melting is greatly dependent on the metamorphism within the snowpack (Kojima 1967). However, because, in severely cold winter, frequent meteorological observations and snow-pit surveys are rarely conducted, we could not accurately understand the distribution of snowfall and snowmelt. Therefore, estimating the spatial distribution of SWE, which is considered fundamental information for snowmelt in mountainous areas, remains one of the unveiled problems in snow hydrology (Dozier et al. 2016).

One of the possible ways to estimate mountainous snow melting in real-time is remote sensing. Synthetic Aperture Radar can observe the snow cover area without the influence of clouds, which offers a hint for the spatial distribution of snowmelt in the basin (Fatima et al. 2021). The observed snow disappearance date estimated from satellite observations and melting calculations reconstructed daily SWE with 500 m horizontal resolution back to the maximum accumulation date (Slater et al. 2009). Although, as above, remote sensing may effectively estimate snow cover over the mountainous

catchment areas, it cannot observe the snow conditions inside the snowpack. Therefore, by remote sensing solely, we cannot provide an accurate snowmelt potential and its temporal variation in the map of catchment areas.

Another possible way to mitigate the problem is snowmelt modeling that accurately computes snow properties, at least SWE, with some optimal parameters (Fayad et al. 2017). There are four types of snowmelt model: statistical runoff model for snowmelt water (Stewart et al. 2005), degree-day model (Null et al. 2010), energy balance model (Herrero et. al. 2009; Sensoy et al. 2006; Mernild et al. 2016), and multi-layer snowpack model (Bartelt and Lehning 2002; Brun et al. 1992; Jordan 1991; Niwano et al. 2012). The obstacles to modeling approaches are obtaining meteorological data of the required resolution and validating the models. The former problem mainly stems from precipitation observations during the severe winter in mountainous areas, where gauge measurements largely miss snowfall in windy environments (Buisan et al. 2016; Smith et al. 2016; Pan et al. 2016), with errors ranging from 20% to 50% (Rasmussen et al. 2012). The missing rate depends on not only wind speed but snowflake characteristics (Thériault et al. 2012) and turbulence around the instrument (Colli et al. 2015). Moreover, for a continuous observation, the regular maintenance of observation equipment is necessary. However, in mountainous regions, it is extremely difficult to find accessible sites suitable to the observation. The use of meteorological radar data can mitigate the problem, but it often suffers from the shadow of clouds and mountains in the scanning range. The latter problem is attributed to the difficulty of snow observation in the mountainous region. Some simpler approaches tried to make a statistical relation to diagnose SWE from temperature, precipitation, radiation, and other terrain factors (Elder et al. 1998; Molotch and Meromy 2014). However, as a special campaign offers snow data in a few seasons,

the statistical model cannot be used for general use due to the missing of interannual variability (Fayad et al. 2017). On the other hand, the validation of the snowpack model needs at least snow depth or SWE observations. Despite that multiple sampling within $O(10\text{-m})$ area ensures the representativeness of snow observation at a single site (Rice and Bales 2010; López-Moreno et al. 2011, Watson et al. 2006; Jost et al. 2007), the spatial distribution of snow depth or SWE for a broader catchment area is hardly captured (Bales et al. 2006; Gottardi et al. 2012; Raleigh et al. 2016). Moreover, another snow properties like snow type are much more difficult to do because of labor in snow-pit observation.

Reviewing the difficulty in the snow and rainfall observation in the mountainous catchment areas, we emphasized the importance of continuous observations to validate snow model and accurate, high-resolution precipitation observation that force the snow model. This is because, if a snowpack model and input meteorological data were validated by as much observation as possible, the snow melting distribution could be mapped in the basin. The map would be helpful to estimate the temporal variation of snow melting water into the dam and downstream. This kind of observations has been performed for the dam control and river administration, just behind the dense-populated residential area. The dam and river basin behind Sapporo City, with the most populated city under the snowy climate in the world is one of the good examples. Moreover, there are many experiences that a snowpack model is applied to Hokkaido region (Katsuyama et al. 2017; Katsuyama et al. 2020). However, there are no researches using long-term observational data to show the temporal variation of snowmelt distribution in the dam basin. This motivated us to make a detailed map of snowmelt with a moderate number of continuous data that can be collected, which has not been attempted yet.

This study aims to map the timing and amount of snowmelt in the basin of Jozankei and Hoheikyo Dams (Fig. 2-1), which undertakes a reservoir role for Sapporo City. The basin was hence paid attention to hydrological researchers by estimating the snowmelt from the heat balance and the dam inflow by a runoff model (Usutani et al. 2007; Nishihara et al. 2014) and contributed to daily dam inflow forecast (Usutani and Nakatsugawa 2008), though their analyses unveiled the snow type distribution and the explicit time evolution. With an aid of radar/gauge precipitation observation, we perform the snowpack simulation for each grid point in the dam basin. We extensively validate a snowpack model and input precipitation for 8-winter seasons by all available observation data. This enabled us to map a basin distribution of snowmelt, which contains snow types with some caution on a usage limitation.

This dissertation is organized as follows: Chapter 2 contained the detailed description of observed data and snowpack model. We mainly documented the results based on the analysis for the Jozankei Dam basin in Chapter 3 and then checked the method applicability and the result generality by the analysis for the Hoheikyo Dam basin in Chapter 4. Chapter 5 made discussions related to the results. Chapter 6 concluded the dissertation.

Chapter 2. Data and Method

2.1. Observation Data within the Jozankei Dam basin

J-Site 1 is located at 43.0313°N , 141.1286°E aside of the driftwood disposal facility of the Jozankei Dam (yellow star in Figs. 2-1b, 2-2a). Meteorological and snow observations have been operated by Civil Engineering Research Institute for Cold Region (CERI) during the winter seasons. It provided wind speed by an anemometer at 6.5 m height, temperature, and relative humidity by a thermo-hygrometer at 3.0 m height, snow depth by a lightwave sensor, incoming shortwave and longwave radiations by a

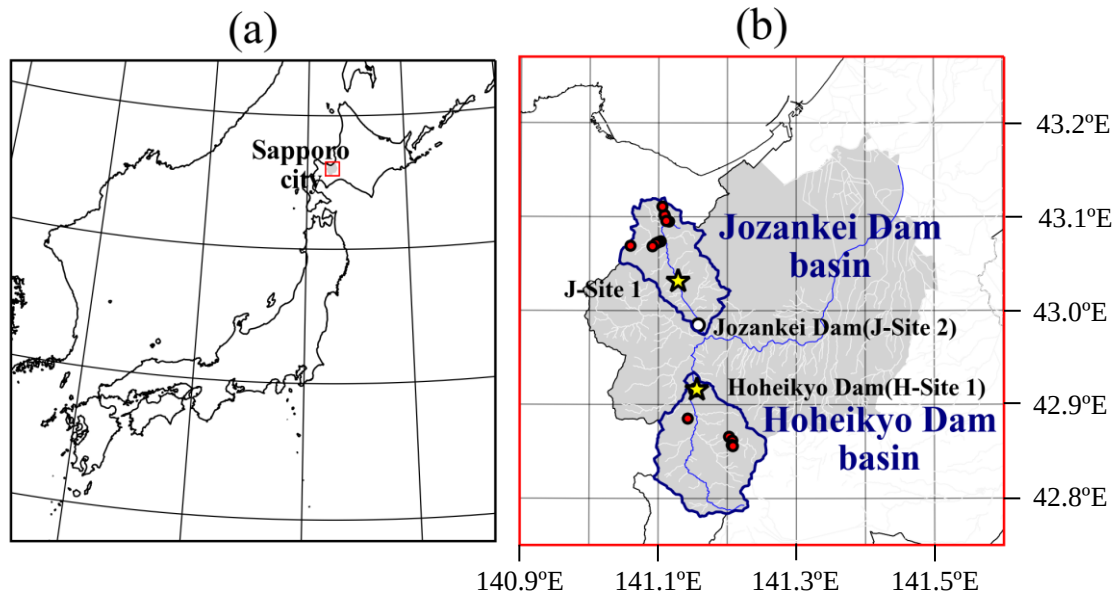


Figure 2-1: (a) Map of the study area and (b) a zoom-in map. Sapporo City area is shaded. The Jozankei and Hoheikyo dam basins are enclosed by blue line. White circles denote dam point. Star marks and red circles are observation points within the basin.

radiometer, SWE by snow weight gauge¹, and precipitation by an automated rain gauge with a minimum amount of 0.5 mm. The precipitation data can be corrected to compensate for insufficient capture by the wind data (Yokoyama et al. 2003). We used the hourly dataset for 8-winter seasons from 2010/11 to 2017/18. We moreover used the snow-pit observation data, in which the snow grain type was manually determined through the snowpack layers at selected dates.

J-Site 2 (42.985°N, 141.1542°E) serving as the terminal point of Jozankei Dam (white circle in Figs. 2-1b, 2-2a) has been operated by Ministry of Land, Infrastructure, Transport and Tourism (MLIT). We used annual precipitation data based on an automated

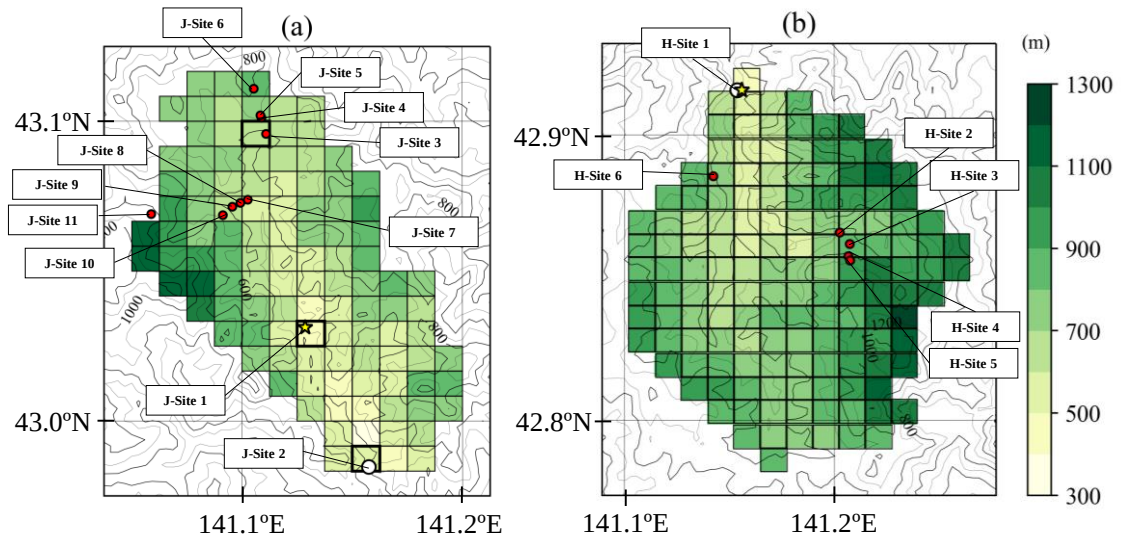


Figure 2-2: Elevation maps (1km-mesh) of the (a) Jozankei and (b) Hoheikyo dam basins. The open circles are dam sites. Star marks and red circles are the observation

¹ Its improper installment resulted in a systematic error caused by the horizontal influx. When compared to the intermittent snow sampler observations from 2008/09 to 2015/16, it was found that the gauge data should be multiplied by 0.806 for correction. We utilized the corrected value in this study.

rain gauge observation. We also used the inflow data into the Dam (Fig. 2-3a). J-Sites 3 to 10 (red circles in Figs. 2-1b, 2-2a) have been operated by MLIT. The snow depth was measured by a snow depth gauge. J-Site 11 (red circle in Figs. 2-1b, 2-2a) is snow depth data at the highest point in the Jozankei dam basin. This was observed by the managers of Sapporo Kokusai Ski Resort, and we received their cooperation in providing us with the original data. The location information of the observation points and the observation items are detailed in Table 2-1.

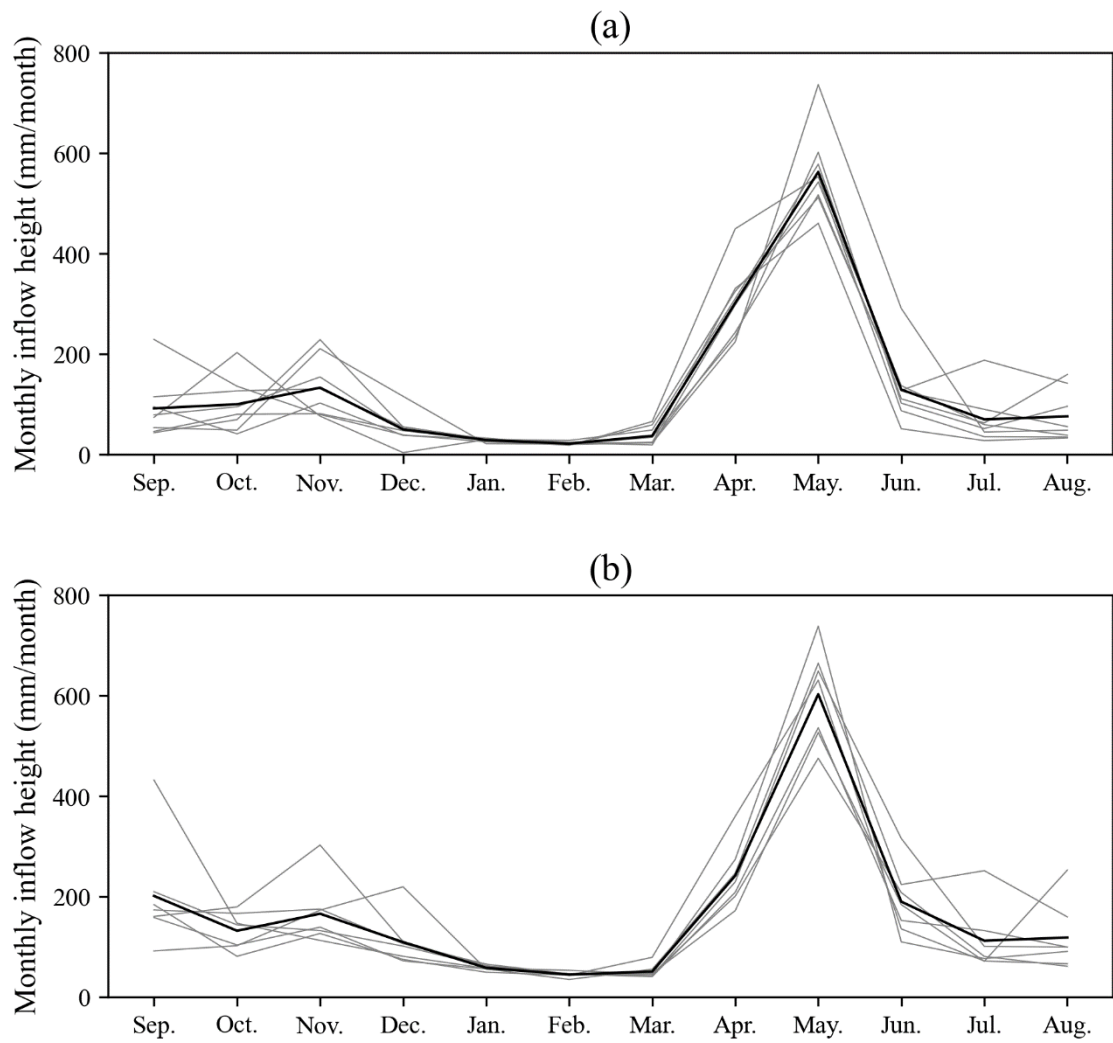


Figure 2-3: Monthly inflow height of (a) Jozankei and (b) Hoheikyo Dams from September 2010 to August 2018. Gray lines denote the data each year and the black line is the average over the periods. Data from September 2015 to August 2016 were missed for (b).

Table 2-1: Location information and observation items of observation points within the (a) Jozankei and (b) Hoheikyo Dam basins.

(a) Observation points within the Jozankei Dam basin

SiteNo.	Observation item	Location name	Latitude	Longitude	Altitude (m)
J-Site1	Meteorological and Snow-pit observation point	The driftwood disposal facility of the Jozankei Dam	43.0313°N	141.1286°E	397
J-Site2	Hydrological observation points	Jozankei Dam	42.9850°N	141.1542°E	390
J-Site3	Snow depth observation point	Mt. Haruka course No1	43.0958°N	141.1108°E	550
J-Site4	Snow depth observation point	Mt. Haruka course No2	43.1087°N	141.1012°E	680
J-Site5	Snow depth observation point	Mt. Haruka course No3	43.1021°N	141.1083°E	710
J-Site6	Snow depth observation point	Mt. Haruka course No4	43.1109°N	141.1052°E	850
J-Site7	Snow depth observation point	Mt. Shirai course No1	43.0738°N	141.1026°E	530
J-Site8	Snow depth observation point	Mt. Shirai course No2	43.0728°N	141.0991°E	560
J-Site9	Snow depth observation point	Mt. Shirai course No3	43.0715°N	141.0954°E	600
J-Site10	Snow depth observation point	Mt. Shirai course No4	43.0687°N	141.0912°E	700
J-Site11	Snow depth observation point	The summit of Sapporo Kokusai Ski Resort	43.0691°N	141.0587°E	1087

(b) Observation points within the Hoheikyo Dam basin

SiteNo.	Observation item	Location name	Latitude	Longitude	Altitude (m)
H-Site1	Meteorological, Snow-pit and Hydrological observation point	Hoheikyo Dam	42.9157°N	141.1556°E	509
H-Site2	Snow depth observation point	Soranuma swamp course No1	42.8658°N	141.2024°E	700
H-Site3	Snow depth observation point	Soranuma swamp course No2	42.8619°N	141.2072°E	750
H-Site4	Snow depth observation point	Soranuma swamp course No3	42.8575°N	141.2066°E	850
H-Site5	Snow depth observation point	Soranuma swamp course No4	42.8560°N	141.2074°E	900
H-Site6	Snow depth observation point	Near National Highway	42.8856°N	141.1422°E	850

2.2. Observation Data within the Hoheikyo Dam basin

H-Site 1 (42.985°N, 141.1542°E) serving as the terminal point of Hoheikyo Dam (white circle and yellow star in Figs. 2-1b, 2-2b) has been operated by MLIT and CERI. We used annual precipitation data based on an automated rain gauge observation. We also used the inflow data into the Dam (Fig. 2-3b).

Meteorological and snow observations in H-Site 1 have been operated by CERI during the winter seasons same as J-Site 1. It is noted that precipitation by an automated rain gauge, temperature, and relative humidity was not installed in this site. For these data, we used the data measured by the Hoheikyo Dam Management Office of MLIT. H-Sites

2 to 6 have been operated by MLIT. Snow surveys are conducted in these observation points about once a year in March, almost corresponding to the snow melting season.

2.3. Radar/Rain Gauge-Analyzed Precipitation

The precipitation data covering the entire river basin were obtained from the Radar/Rain Gauge-Analyzed Precipitation (R/A) dataset, in which the C-band radar data by the Japan Meteorological Agency (JMA) and MLIT were combined with the rain gauge data obtained by the JMA and others. The R/A data were provided as hourly accumulation at 1-km horizontal resolution. In this way, the R/A precipitation is more suitable to comprehensively understand the basin rainfall than the rain gauge data with low observation density.

On the other hand, R/A precipitation still needs improvement to measure snowfall in winter. Ito et al. (2020) examined the accuracy of the R/A precipitation through water balance analysis in the Tedoru River basin. They found that if the basin evapotranspiration and basin runoff are correct, the annual water balance difference is about 607 mm (a difference ratio of -17.2% against the basin area rainfall), indicating that the basin area rainfall estimated by the analyzed rainfall was underestimated. However, in late June to mid-October, when snowfall, snow accumulation, and snowmelt are less influenced, the balance difference was about 49 mm (4.7%), showing high estimation accuracy. From this, they concluded that the analyzed rainfall can accurately estimate the basin area rainfall excluding winter.

2.4. Water Balance Method and Evapotranspiration Data

Accurate input of snowfall is essential for estimating snowmelt. However, due to measurement errors in observed snowfall and the sparse distribution of observation points, the accuracy of the input precipitation is confirmed from the water balance of the entire watershed. In general, water balance is equal to the total annual precipitation combined with the total runoff and evapotranspiration. Since the inflow (m^3/s) is measured every hour at the dam site, this data is converted to runoff (mm/h) for use.

For 11 years from 2000 to 2010, Usutani et al. (2014) estimated hydrological quantities (rainfall, snowfall, snow accumulation, snowmelt, evapotranspiration) for each mesh of approximately 1 km-mesh using the LoHAS model (Kuchizawa et al. 2002) based on the two-layer model proposed by Kondo et al. (1994) with snow accumulation and snowmelt processes added, for river basins in Hokkaido. The outline of this heat budget model is shown in Fig. 2-4.

Next, the rainfall, snowmelt, and evapotranspiration were input into a runoff model consisting of the tank model to calculate the runoff. The slope runoff of the mesh was calculated using the tank model, and the river channel was traced to an arbitrary point using the kinematic wave formula. As a result, the ratio of the river flow estimated by this method to the observed flow was in the range of 0.86 to 1.03, and it is considered that the hydrological quantities are estimated satisfactorily in terms of water balance.

Taniguchi et al. (2016) used this method to input the current climate (for 20 years from September 1984 to August 2004) from MRI-NHRCM20, a regional climate model of the Japan Meteorological Agency that applies the IPCC-AR5 RCP8.5 scenario, to estimate evapotranspiration in the Jozankei Dam and the Hoheikyo Dam basins. The results showed that the 20-year average was 557 mm per year in the Jozankei Dam basin

and 507 mm in the Hoheikyo Dam basin. Therefore, these values were used as the annual evapotranspiration in this study.

Water and Heat Budget Model:

LoHAS (Long-term Hydrologic Assessment model considering Snow process)

This model represents heat exchanges using equations, and estimates of evapotranspiration and snowmelt amounts.

$$\text{Vegetation layer} \quad \underbrace{(1-f_v)(R\downarrow + \varepsilon\sigma T_g^4)}_{\text{Heat entering the vegetation layer}} = \underbrace{2(1-f_v)\sigma T_v^4 + H_v + l(E_v + I)}_{\text{Heat leaving the vegetation layer}}$$

$$\text{Ground surface} \quad \underbrace{f_v R\downarrow + (1-f_v)\sigma T_v^4 - Q_G + Q_R}_{\text{Heat entering the ground surface}} = \underbrace{\varepsilon\sigma T_g^4 + H_g + lH_g}_{\text{Heat leaving the ground surface}}$$

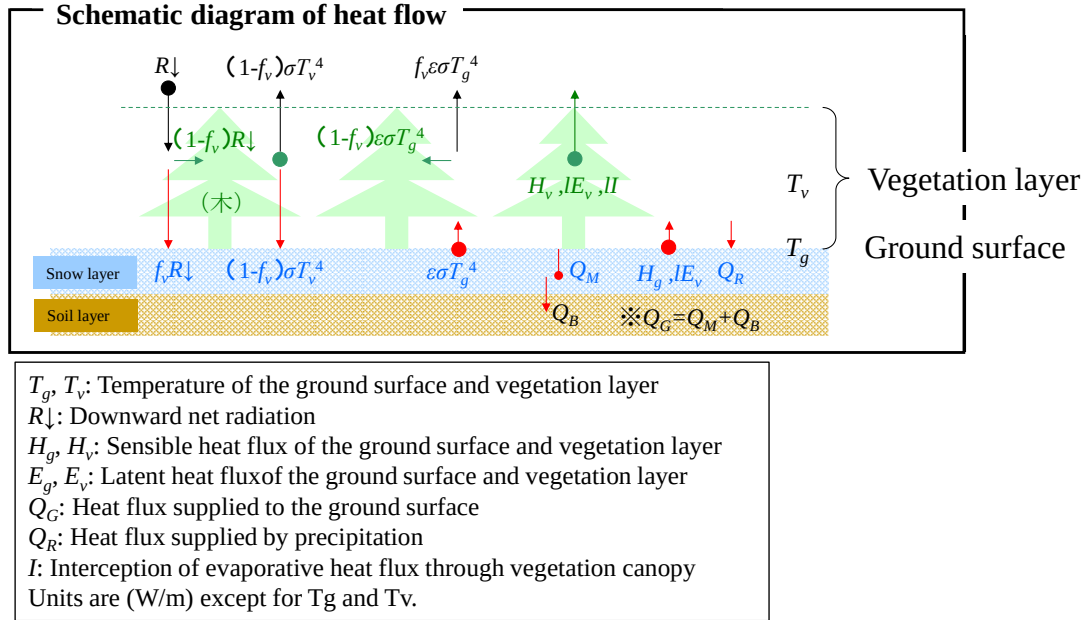


Figure 2-4: Overview of LoHAS (Long-term Hydrologic Assessment model considering Snow process) model used to estimate evapotranspiration.

2.5. Model and Experiments

We used version 3.6.0 of the SNOWPACK model (Bartelt and Lehning 2002), which contains the solver of mass and energy exchanges between adjacent snowpack and soil layers and snow surface processes on radiation, precipitation, and heat flux (Michlmayr et al. 2008), with snowpack metamorphosis in compressible layers as the National Research Institute for Earth Science and Disaster Resilience (NIED) scheme (Hirashima et al. 2004). The model outputs the vertical position, primary and secondary snow grain types, temperature, density, and depth of snowpack layers in an hourly interval. The model also provides SWE and snow depth of the vertical column, which were used as the index of accumulated snow amount.

The snow grain type in the SNOWPACK model was classified into precipitation particles, decomposing and fragmented precipitation particles, rounded grains, faceted crystals, depth hoar, surface hoar, and melt forms (Lehning et al. 2002b). We evaluated the snow melting timing by the cumulative melt forms ratio, defined as the ratio of the thickness of melt forms to the total. Neither horizontal transport nor avalanches were assumed because of their smaller horizontal scale than the mesh size here.

The SNOWPACK model was first forced by meteorological data at J-Site 1 that was updated every hour for 8-winter seasons from 2010/11 to 2017/18. The input data were air temperature, relative humidity, wind speed above the snow surface, incoming shortwave and longwave radiation, precipitation, and soil temperature. The precipitation was identified as liquid if the air temperature ($^{\circ}\text{C}$) exceeded the critical temperature ($^{\circ}\text{C}$) empirically estimated as $7.7 - 6.6 \text{ RH}$, where RH denotes relative humidity, and otherwise solid (Kondo 1994). The soil temperature was asymptotic to the initially given

value of the annual mean air temperature ($10\text{ }^{\circ}\text{C}^2$) plus $2.3\text{ }^{\circ}\text{C}$ (Hirota et al. 1995). We added a model experiment by replacing the gauge data with the R/A data at the nearest point to the observation site.

The SNOWPACK model next ran for every 111 grid points set in the Jozankei Dam basin or every 142 grid points set in the Hoheikyo Dam basin meshed at $1/120^{\circ}$ in latitude by $1/80^{\circ}$ in longitude. Due to no direct meteorological observation at almost all points, the input data were the same as those at H-Site 1 uniformly given to the entire basin except for precipitation, temperature, and incoming shortwave radiation³. The R/A dataset was used for the precipitation, and the temperature at H-Site 1 was corrected according to the lapse rate of 6.5 K km^{-1} . The incoming shortwave radiation was used after a correction of slope inclination based on topography data under the assumption of no scattering lights. We remark that the assumption of uniform wind in the basin may not hold near the top of mountains where stronger wind likely blows snow particles farther.

² The annual mean temperature at Sapporo was substituted due to no continuous observations around the Jozankei Dam basin.

³ The assumption that wind was given uniformly over the basin can be supported by the insensitivity of sensible and latent heat flux to wind speed below $5\text{ }^{\circ}\text{C}$ (Kondo and Yamazaki 1987). It is also applied for a warmer season because the snow melting was reasonably simulated at J-Site 3 forced by wind data at J-Site 1 (Fig. 3-4).

Chapter 3. Results for Jozankei Dam basin

3.1. Snow observation at J-Site 1

We validated the SNOWPACK model by various observations at J-Site 1 and chose reasonable precipitation data. Figures 3-1 and 3-2 show the snow-pit observation and the simulation results of the SNOWPACK model from 2010 to 2017. The simulation with the gauge precipitation data underestimated the observed snow depth almost by half through the season (blue dotted line in Figs. 3-1, 3-2). The correction by wind speed data alleviated the problem, but the result still suffered from the significant underestimation of the observed snow depth (blue line in Figs. 3-1, 3-2). In contrast, the simulation with the R/A precipitation data reproduced the observed snow depth in the accumulation period (color in Figs. 3-1, 3-2).

The SWE simulated with the R/A precipitation was in moderate agreement with the observation by the snow sampler (circles) (Fig. 3-3). The snowmelt day was delayed only 4 days on average over the eight-winters, in the simulation with the R/A precipitation. In contrast, it was earlier by > 2 weeks in the simulation with the rain-gauge precipitation (Figs. 3-1, 3-2). In addition, the snow type in the simulation with the R/A precipitation was consistent with the intermittent snow-pit observations: the faceted crystals in the upper layer on 12 January; the precipitation particles on the thick rounded gains in February and March; and the dominance of the melt forms on 13 April (Figs. 3-1a, b).

Therefore, the SNOWPACK model can be validated by various observations of the snow environment at J-Site 1 in 2010/2011. The results did not change substantially for 2011/12 and 2012/13 (Figs. 3-1c-f, Table 3-1), except for slightly less snow accumulation and earlier melting by about a week in the simulation after 2013/2014 (Figs.

3-1g,h; Table 3-1). These may be related to the underestimation of R/A precipitation (Section 3.2). However, we now chose the R/A precipitation as reasonable input data to the model and hereafter regard this simulation as a reference.

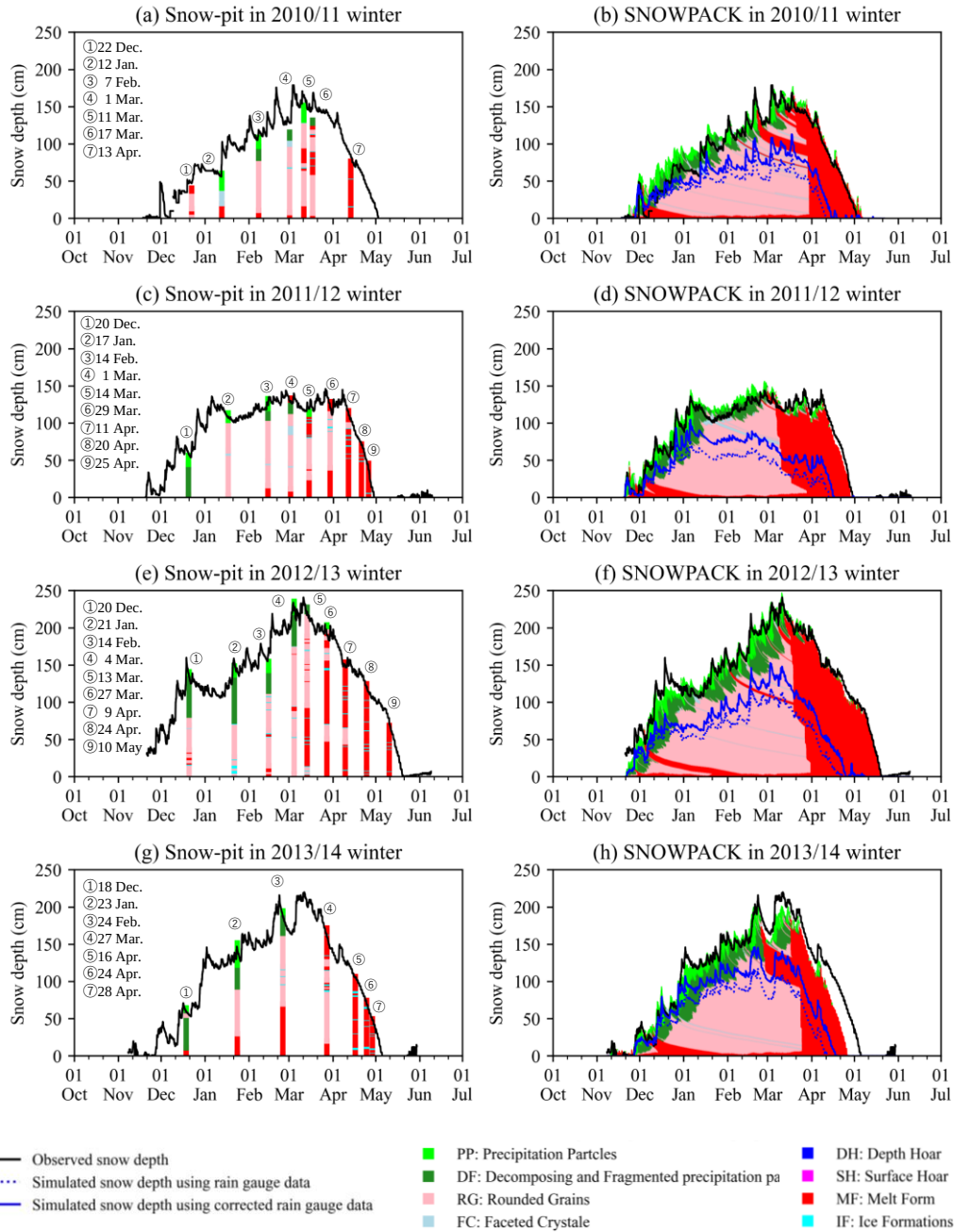


Figure 3-1: (a, c, e, g) Snow depth (cm) and (color) snow types in the snowpack observed at J-Site 1 from 2010/11 to 2013/14 winters. Snow types are color-coded as legend below according to Fierz et al. (2009). (b, d, f, h) Snow depth at J-Site 1 in the SNOWPACK model simulation driven by (upper edge of color shade) R/A precipitation, (blue dashed line) rain-gauge precipitation, and (blue line) corrected one. Color shading denotes snow types in the simulation with R/A precipitation.

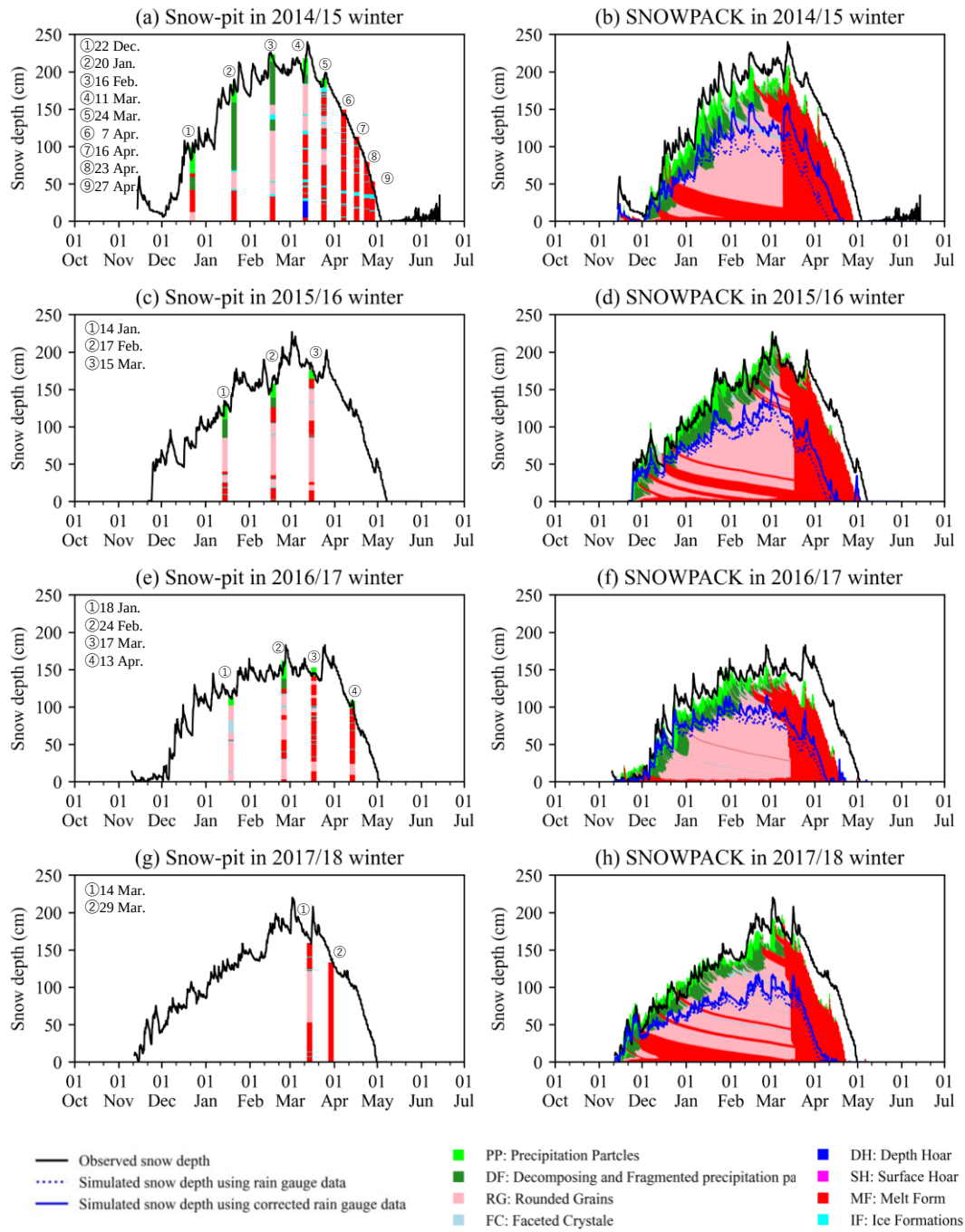


Figure 3-2: Same as Fig. 3-1, but for the 2014/15 to 2017/18 winters.

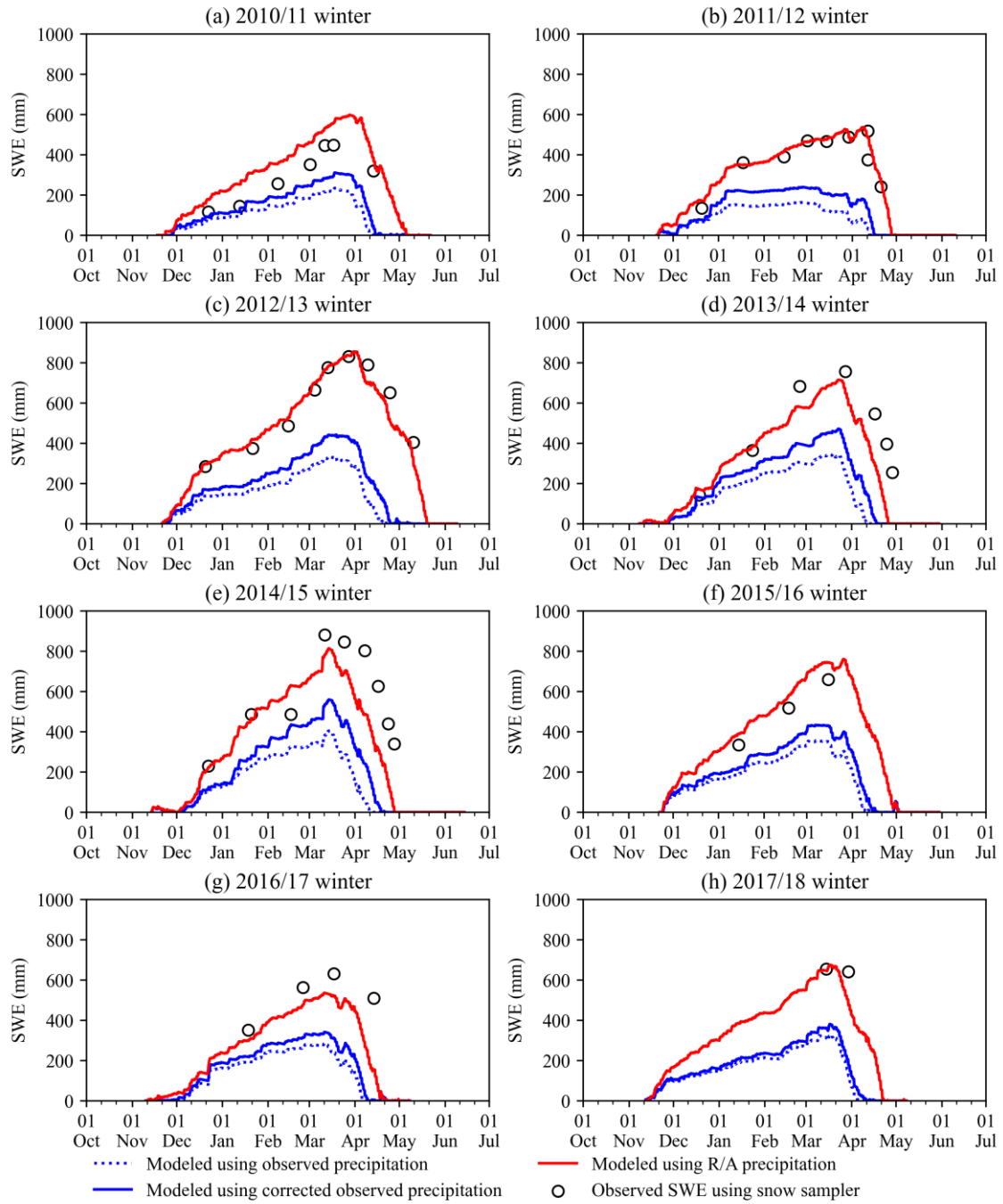


Figure 3-3: Snow water equivalent (SWE; mm) at J-Site 1 in the simulation with (red) R/A precipitation, (blue dotted) rain-gauge precipitation, and (blue) corrected one from 2010/11 to 2017/18 winters. Circles denote the SWE estimated from snow sampler data at J-Site 1.

Table 3-1: Calculation period and comparison between SNOWPACK calculation and observation for peak snow depth and the date, and snow melt date.

	Calculation period	Peak snow depth (cm)		Date of peak snow depth		Date of snow melt	
		observation	calculation	observation	calculation	observation	calculation
1	18 Nov. 2010 - 21 May 2011	179	177	03 Mar.	18 Mar.	02 May	06 May
2	20 Nov. 2011 - 09 Jun. 2012	146	156	26 Mar.	27 Feb.	29 Apr.	28 Apr.
3	21 Nov. 2012 - 08 Jun. 2013	241	247	11 Mar.	10 Mar.	20 May	21 May
4	08 Nov. 2013 - 29 May 2014	220	203	11 Mar.	21 Feb.	05 May	26 Apr.
5	14 Nov. 2014 - 13 Jun. 2015	240	209	13 Mar.	13 Mar.	03 May	28 Apr.
6	22 Nov. 2015 - 29 May 2016	227	225	01 Mar.	01 Mar.	07 May	03 May
7	10 Nov. 2016 - 07 May 2017	183	158	25 Feb.	25 Feb.	02 May	23 Apr.
8	12 Nov. 2017 - 07 May 2018	220	197	02 Mar.	09 Mar.	30 Apr.	23 Apr.

3.2. Other observations in the basin

We next validated the SNOWPACK model and precipitation data by using other observations in the basin. The snow depth at J-Site 3 mostly attained 300 cm at the peak of the season (Fig. 3-4). However, the simulation with the R/A precipitation could not reproduce the snow depth there; the difference is a factor of 1.55 on average over the eight-winters (Fig. 3-4). Moreover, compared to the satellite images in Nishihara and Tanise (2019), the snow melting around J-Site 3 occurred too early in the simulation even with the R/A precipitation (not shown).

Indirect evidence of the underestimation of R/A precipitation was provided by a rough estimate of the water budget in the basin (Table 3-2). We assume that the precipitation over the basin roughly equals to evapotranspiration and the dam inflow. Assuming evapotranspiration at 557 mm/yr every year (Kuchizawa and Nakatsugawa 2002; Taniguchi et al. 2016; Sawano et al. 2015), the R/A precipitation over the basin is about 90% of the estimate from the basin's water budget (Table 3-2).

Figure 3-5 shows the basin distribution of R/A precipitation divided into annual, snowy, and rainy seasons. Compared to the elevation distribution in Fig. 2-2a, the area around J-Site 11 has the highest elevation and is expected to have high rainfall and snowfall, but both values are smaller than the surrounding grids. In addition, in the northern part of the basin, both rainfall and snowfall are equivalent to those of J-Site 2 (Jozankei Dam point), the most downstream point, suggesting that the R/A precipitation is underestimated.

Therefore, it is considered that the R/A precipitation was insufficient in the northern area around J-Site 3. The R/A precipitation seemed slightly underestimated even in the whole basin domain. However, consistency with the various snow observations at

J-Site 1 (Figs. 3-1, 3-2) and the agreement with satellite images in most areas (not shown) allowed us to analyze the results of the reference experiment, with caution of an earlier bias in the snow melting by about a week in the downstream and more in the northern area.

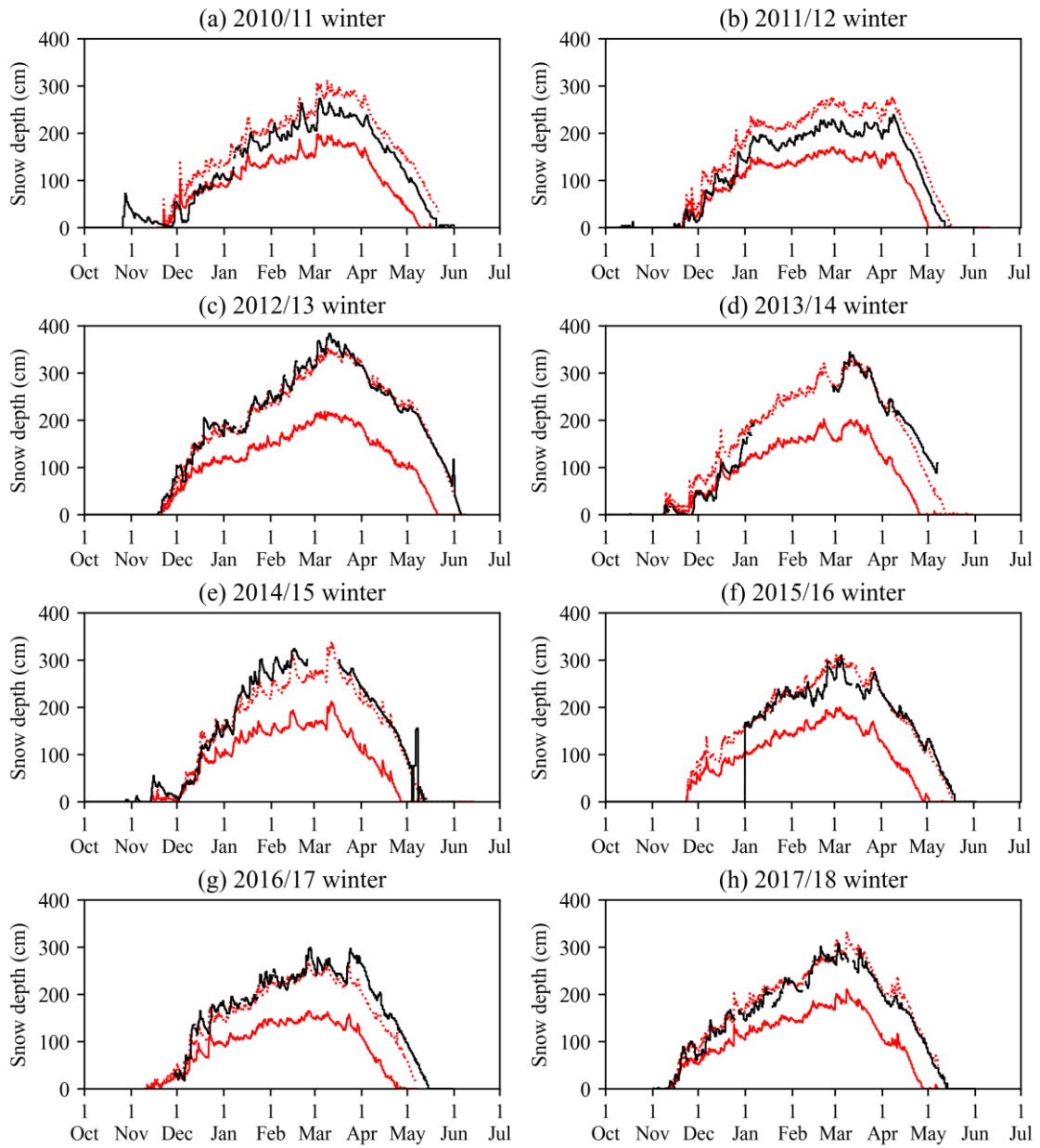


Figure 3-4: Snow depth (black) observed by snow gauge and (red) simulated with the (solid line) original and (dashed) corrected R/A precipitation data at J-Site 3 from (a) 2010/11 through (h) 2017/18 winter. The correction was done by multiplication by a factor of 1.55.

Table 3-2: Comparison of annual precipitation calculated by the water balance method and R/A precipitation in the Jozankei Dam basin.

	Period	a Observed Runoff (mm/yr) at Jozankei Dam	b Evapotranspiration (mm/yr)	c = a + b Annual precipitation estimated by water balance (mm/yr)	d Annual R/A precipitation (mm/yr)	e = d / c Ratio of R/A precipitation to estimated precipitation
1	1 Sep. 2010 - 31 Aug. 2011	1524	557	2081	1860	0.89
2	1 Sep. 2011 - 31 Aug. 2012	1451	557	2008	1811	0.90
3	1 Sep. 2012 - 31 Aug. 2013	1814	557	2371	2109	0.89
4	1 Sep. 2013 - 31 Aug. 2014	1595	557	2152	1982	0.92
5	1 Sep. 2014 - 31 Aug. 2015	1524	557	2081	1815	0.87
6	1 Sep. 2015 - 31 Aug. 2016	1681	557	2238	2156	0.96
7	1 Sep. 2016 - 31 Aug. 2017	1421	557	1978	1665	0.84
8	1 Sep. 2017 - 31 Aug. 2018	1776	557	2333	2060	0.88
	Average	1598	557	2155	1932	0.90

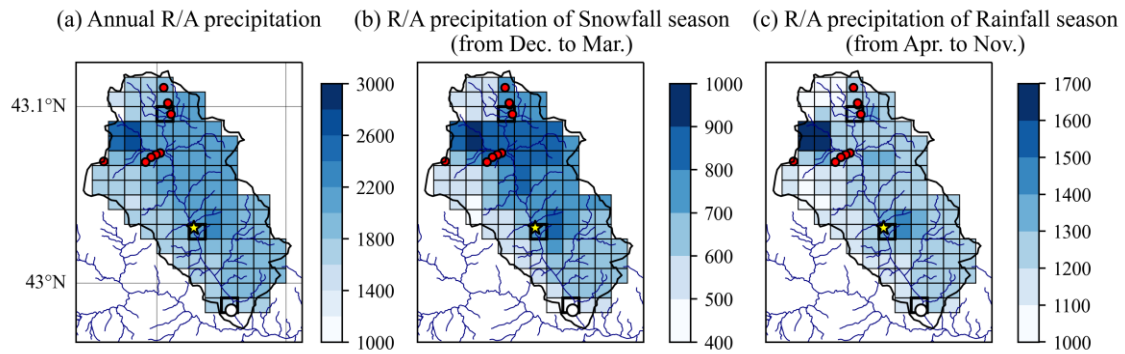


Figure 3-5: (a) Basin distribution of annual R/A precipitation averaged from September 2010 to August 2018 (mm/yr). The blue lines denote rivers in the basin and the Jozankei Dam basin is enclosed by the black line. Observation points are indicated with the same legend as in Fig. 2-2. (b) Basin distribution of snowfall season R/A precipitation averaged from September 2010 to August 2018 (mm/yr). (c) Basin distribution of rainfall season R/A precipitation averaged from September 2010 to August 2018 (mm/yr).

3.3. Snowmelt mapping

Figure 3-6 shows the map of snow depth and cumulated melt forms ratio averaged over 8 winters in the melting season in the Jozankei Dam basin. Because the elevation ranges from 396 m to 1,197 m in the basin (Fig. 2-2a), the snow melting and the change to melt forms were nonuniform over the basin. On 1 March, the snow depth exceeded 230 cm upstream but was near 90 cm downstream, because of the difference in the snowfall amount in the winter season (Fig. 3-6a). On 1 May, the snow depth was less than 50 cm in the downstream, while it remained up to 203 cm in the upstream (Fig. 3-6c). This was mainly caused by temperature difference in the basin (Figs. 3-7e,f).

Similarly, the cumulated melt forms ratio increased faster on the downstream side (Figs. 3-6d-f). On 1 March, melt forms exceeded 50% in downstream but remained at less than 10% upstream (Fig. 3-6d). On 1 April, the snowpack layer was mostly filled with melt forms downstream, but the snowpack still had the rounded grains upstream (Fig. 3-6e). The snowpack fully covered with the melt forms over the basin in May (Fig. 3-6f). The results above indicated the nonuniform snow melting in the basin from March to May.

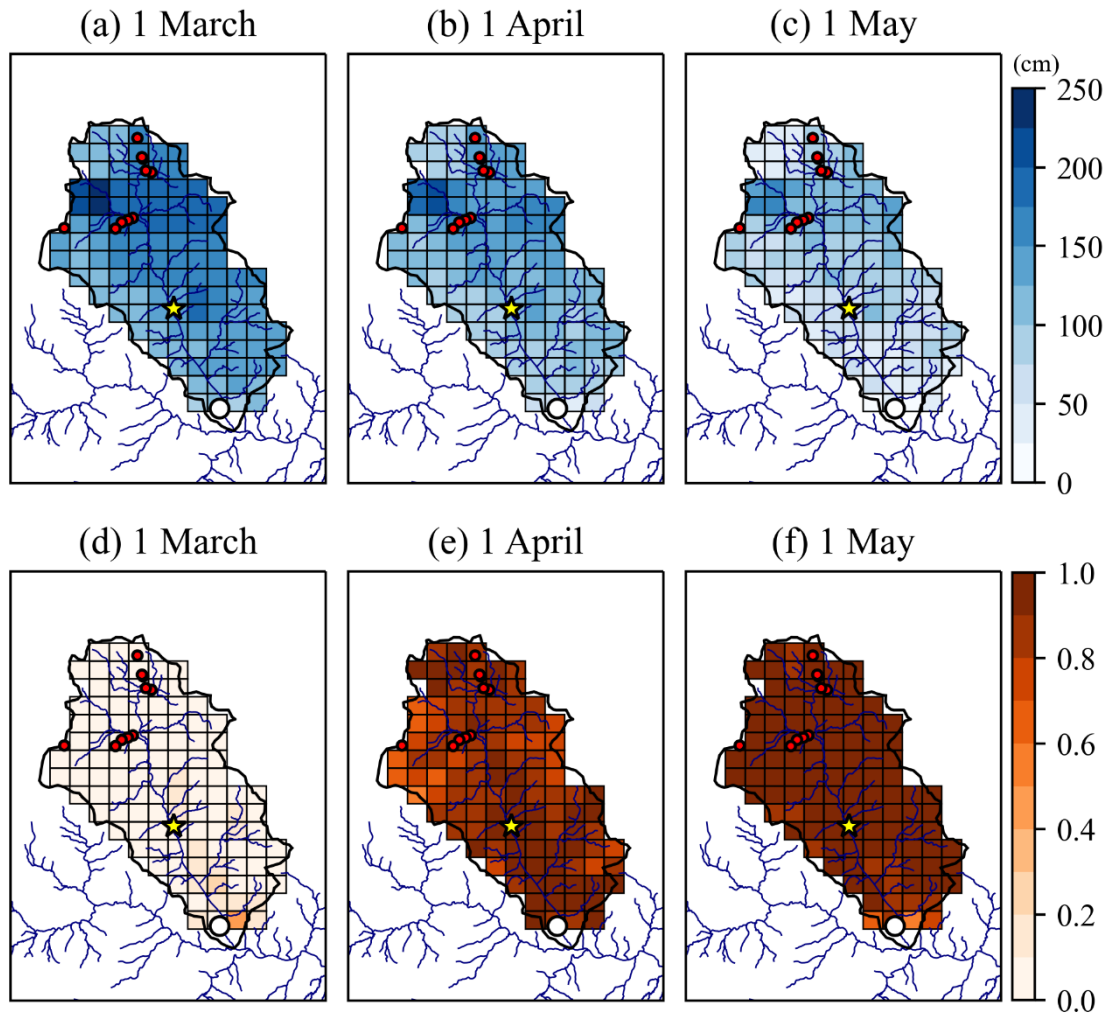


Figure 3-6: (a-c) Snow depth (cm) in the Jozankei Dam basin on (a) 1 March, (b) 1 April, and (c) 1 May, with the color shading as in the right, averaged over 8-winter simulations. Navy line shows the river and black line shows the Jozankei Dam basin. (d-f) Same as (a-c), but for melt forms ratio. The open circle denotes Jozankei Dam point, the star marks are the observation J-Site 1 and the red circle is the other observations.

Figures 3-7a-c show the snowmelt rate defined as the SWE divided into its maximum value in the season. The snowmelt rate averaged over the basin was about 10% on 31 March (Fig. 3-7a) and 42% on 15 April (Fig. 3-7b). On 30 April, the average snowmelt rate in the basin was 83%, but the lowest rate was 45% in the upstream area, and more than half of the snowmelt amount was still maintained at some points (Fig. 3-7c). This rapid snow melting in April was explained by the basin-average temperature increase from -5°C to 2°C (Figs. 3-7d,f). The temperature crossed the freezing point around 15 April (Fig. 3-7e). Since the altitude exceeds 1,000 m at the mountaintop in the basin and is below 400 m at the dam point (Fig. 2-2a), the temperature deviation from the basin average ranged $\pm 2\text{ K}$ according to the lapse rate. This range caused the snow melting timing difference between the upstream and downstream of the basin.

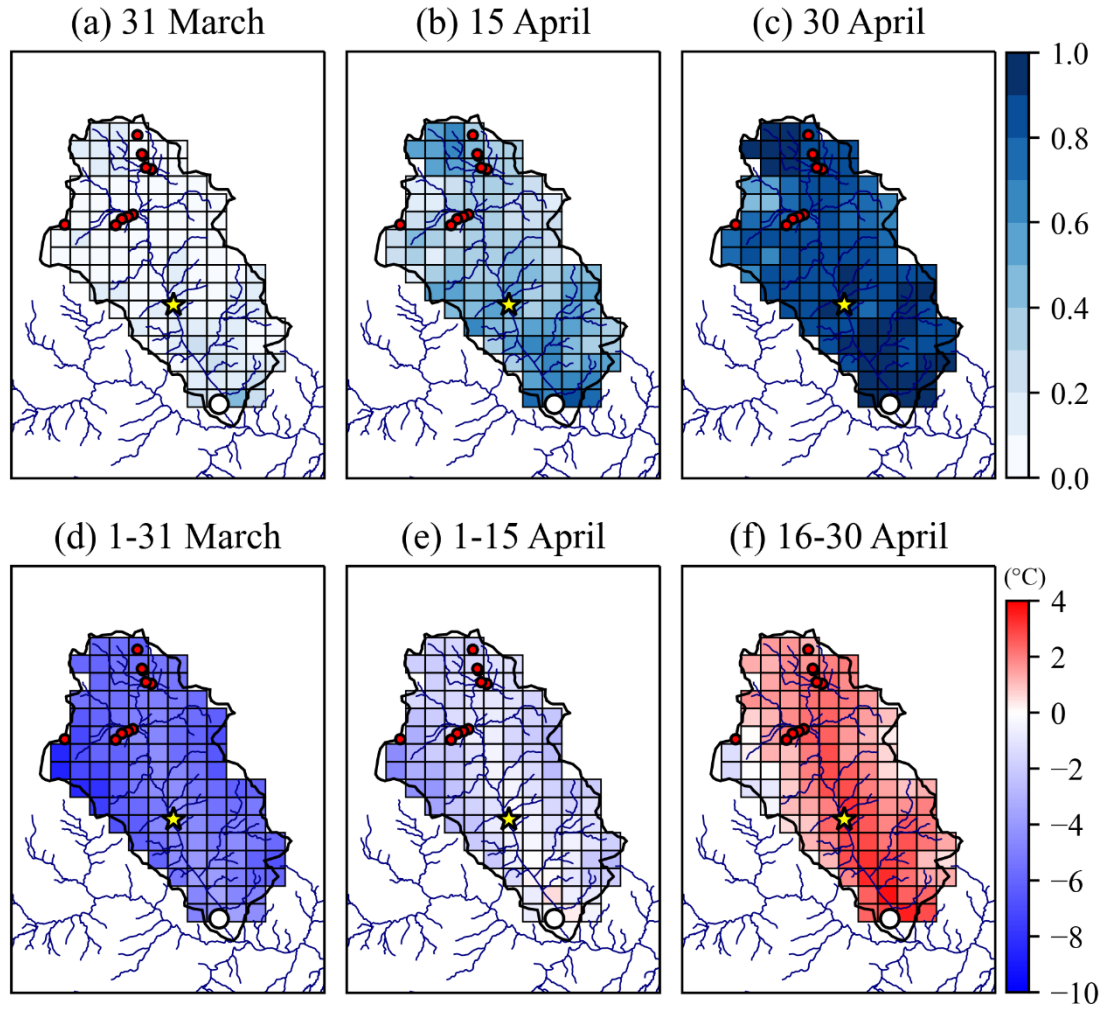


Figure 3-7: (a-c) Snowmelt rate in the Jozankei Dam basin on (a) 31 March, (b) 15 April, and (c) 30 April averaged over 8 winter simulations. (d-f) Eight-year mean surface air temperature (°C) (d) in March and in the (e) first and (f) latter halves of April, estimated by an altitude correction for the observed temperature at the J-Site 1 marked by the yellow star. The red circles indicate other observation sites.

Figure 3-8a shows the seasonal march of snow depth for 8 years at J-Sites 1-3 (Considering the noticeable bias in the R/A precipitation, the simulation for J-Site 3 was redone with the corrected data multiplied by 1.55). In spite of no significant difference in the timing of the maximum snow depth among the three sites, the day when the snow melts completely was different: the snowmelt day at J-Site 3 lagged behind the day at J-Site 1 by about two weeks (Fig. 3-8b) and the day at J-Site 1 lagged behind the day at J-Site 2 by about a week as well (Fig. 3-8c), in terms of an 8-year average in the simulation. The peak inflow occurred 8 days after the snow disappeared at J-Site 2 and occurred 19 days before at J-Site 3. Hence, the difference in snow melting between upstream and downstream points was 27 days.

In contrast, the timing when melt forms exceeded 50% is 20 March in J-Site 1, 25 March in J-Site 3, and 21 March in J-Site 2 (Figs. 3-8b,c) for an 8-year average. This timing difference in the basin was much smaller than the difference in snow melting. Moreover, the dam inflow peaked at 36 days after the timing of melt form dominance at J-Site 3 and at 40 days at J-Site 2. This timing lag has little interannual variation. Hence, the number of days after the cumulative melt forms ratio exceeded 50% could be a leading measure of snow melting.

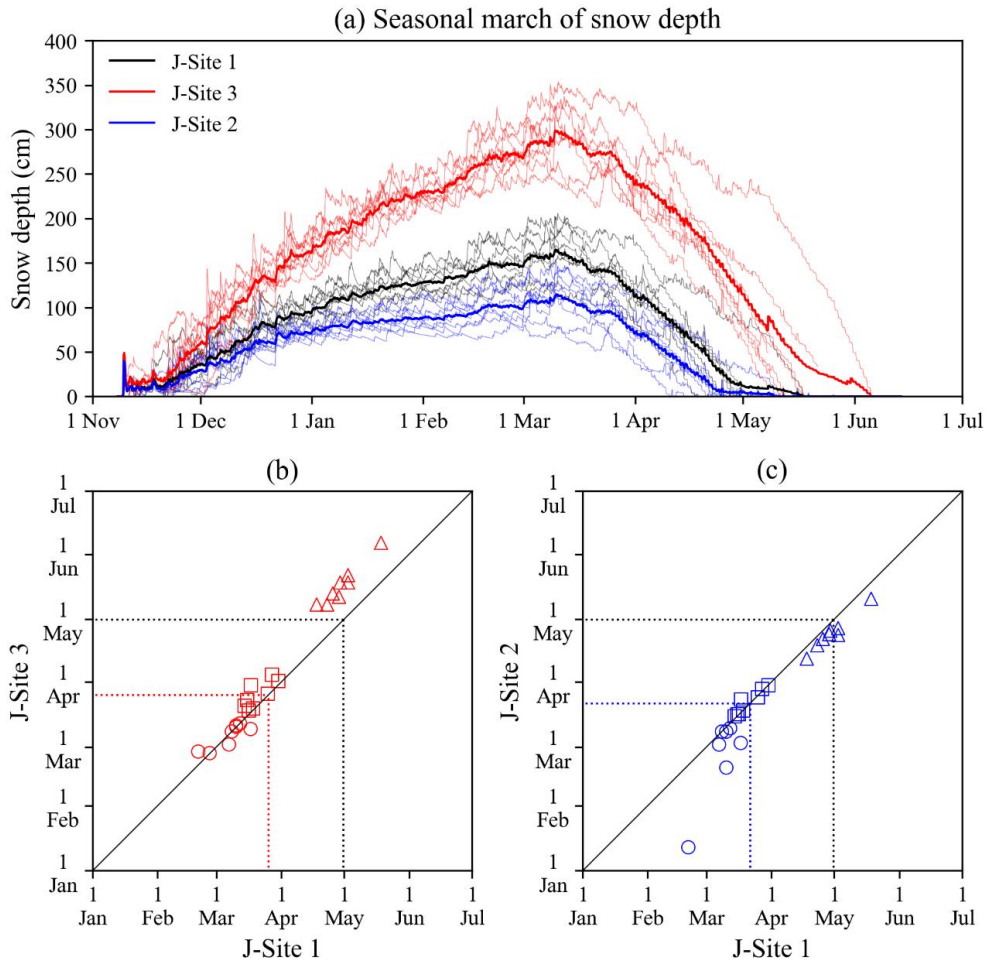


Figure 3-8: (a; thin lines) Seasonal marches and (thick line) their average of snow depth (cm) at (black) J-Site 1, (red) J-Site 3, and (blue) J-Site 2 in the simulation. The snowpack simulation in J-Site 2 was driven by R/A precipitation data multiplied by 1.55. (b; circle) Peak date of snow depth, (square) the snowmelt date when snow completely disappears, and (triangle) the first date when the melt forms rate crosses 50% in the graph of J-Site 1 versus J-Site 3. Each mark denotes the simulation result in 8 winters from 2010/11 to 2017/18. Black and red dotted lines denote 29 April and 25 March, when the dam-inflow attains the peak and when about 50% of the snow layer turns to melt forms at J-Site 3 in average over eight years. (c) Same as (b), but for the graph of J-Site 1 versus J-Site 2. Blue dotted line denotes 21 March, when about 50% of the snow layer turns to melt forms at J-Site 2 in average over 8 years.

Chapter 4. Results for Hoheikyo Dam basin

4.1. Snow observation at H-Site 1

We first checked the applicability of the SNOWPACK model simulation to H-Site 1 (Hoheikyo Dam point). Figures 4-1 and 4-2 show the observation data of the snow-pit and simulation results of the SNOWPACK model from 2010 to 2017. The SNOWPACK simulation forced by observed precipitation at H-Site 1 (Figs. 4-1, 4-2; blue dotted line) underestimated the observed snow depth for all eight winters, like J-Site 1. On the other hand, SNOWPACK simulation results forced by corrected observed precipitation showed significant improvements over the results with uncorrected observed precipitation in many years (Figs. 4-1, 4-2; blue line). The exception is 2014/2015, in which the snow disappearance date fell within the error range of 15 days from observation. The observed precipitation was corrected by the formula of Yokoyama et al. (2003) considering the capture rate by wind speed, but this correction did better work in H-Site 1 than in J-Site 1. This is because the wind speed at H-Site 1 is on average 2.5 m/s, stronger than at J-Site 1 on average 0.8 m/s. In the case of 2014/2015, the observed snow depth was overestimated by the corrected observed precipitation. The snow disappearance day had an error within 8 days when forced by the R/A precipitation, and the error was reduced to 7 cm from the maximum snow depth that was overestimated by 40 cm (Fig. 4-2b). Although the R/A precipitation was slightly underestimated in 2016 and 2017, the SNOWPACK simulation well reproduced the maximum snow depth and the snow disappearance date throughout the eight-winters (Table 4-1). However, it should be noted that the simulation results using the R/A precipitation data show an underestimation of SWE except for the 2010/11 winter (Fig. 4-3).

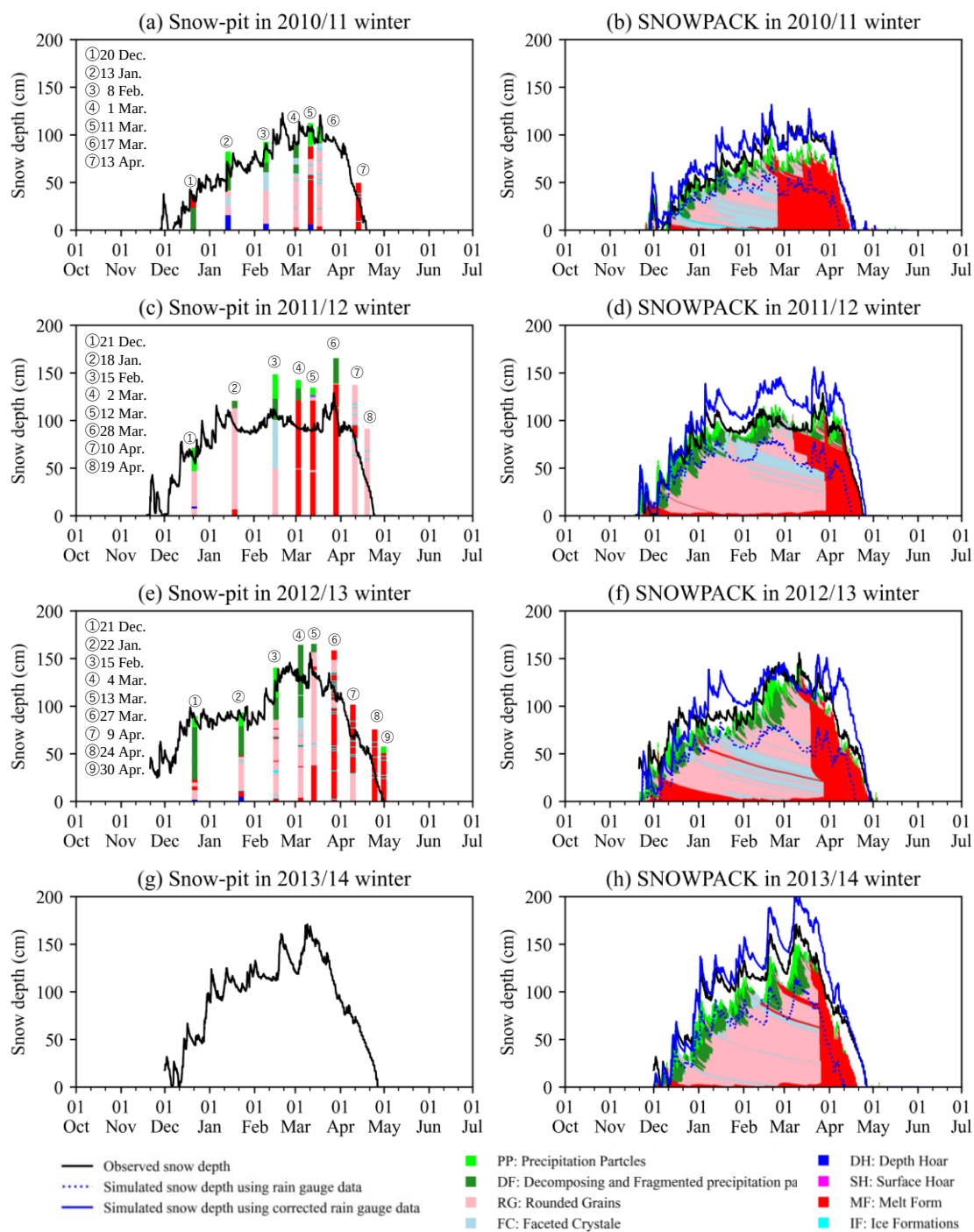


Figure 4-1: Same as Fig. 3-1, but for H-Site 1.

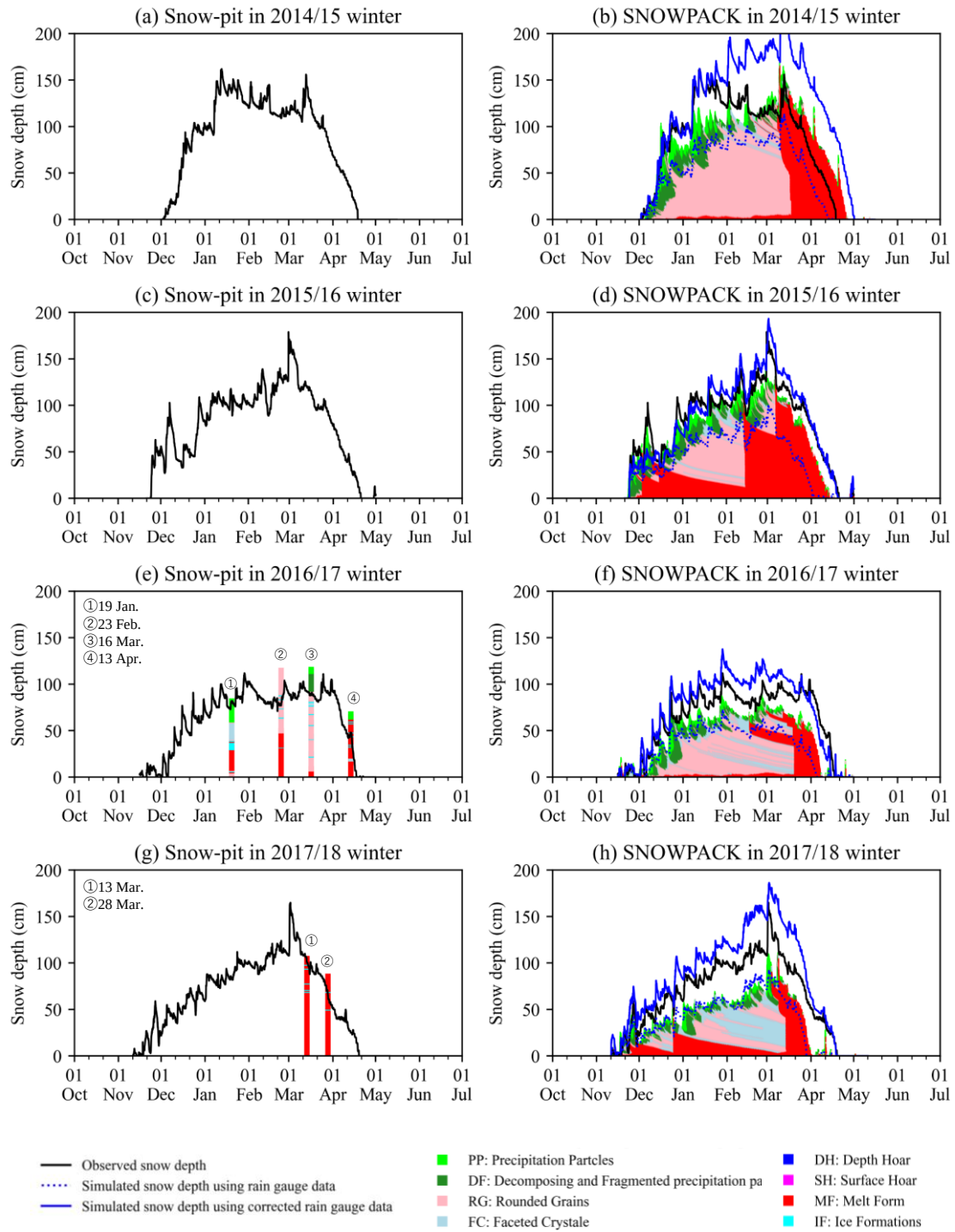


Figure 4-2: Same as Fig. 3-2, but for H-Site 1.

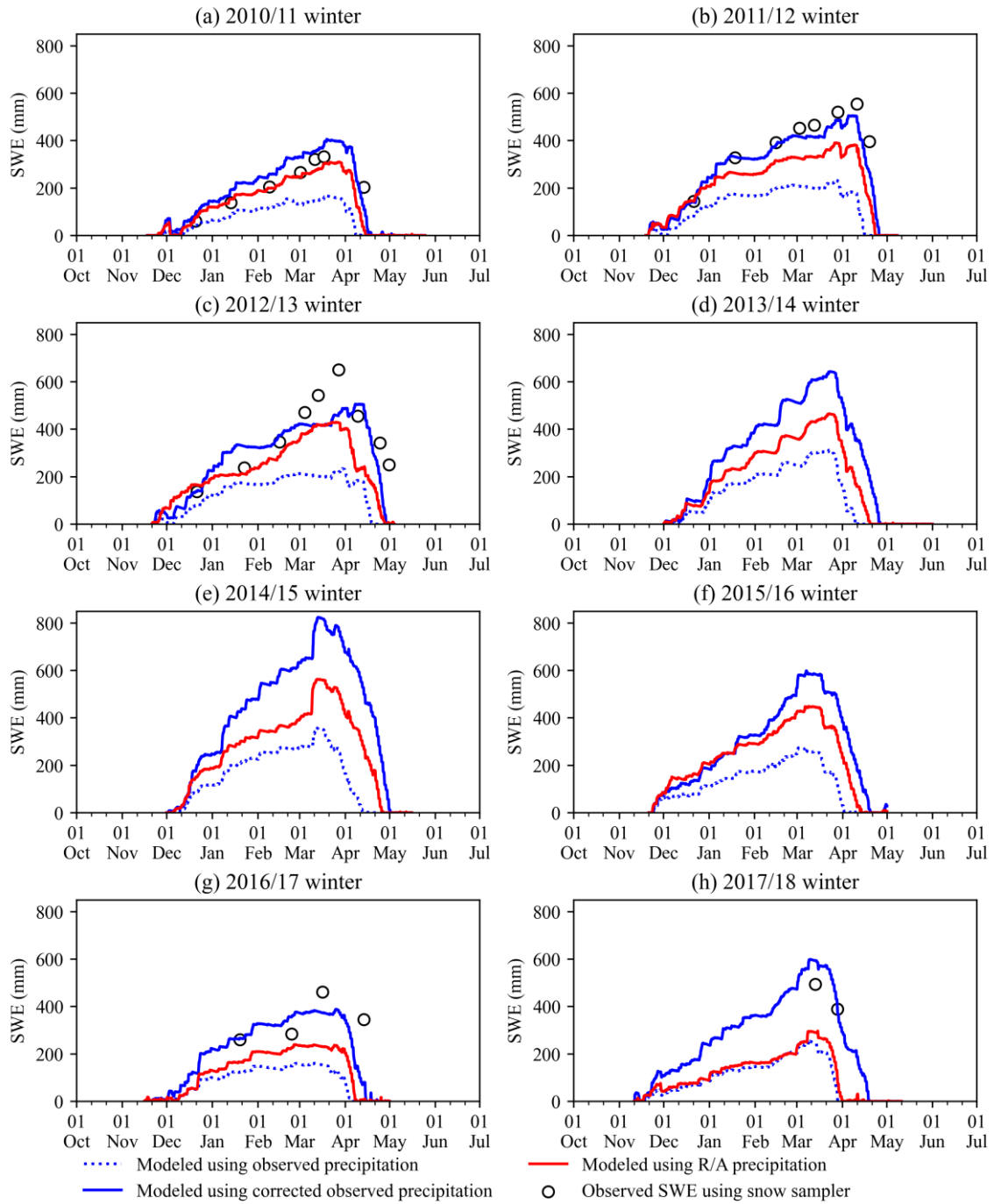


Figure 4-3: Same as Fig. 3-3, but for H-Site 1.

Table 4-1: Same as Table 3-1, but for H-Site 1.

	Calculation period	Peak snow depth (cm)		Date of peak snow depth		Date of snow melt	
		observation	calculation	observation	calculation	observation	calculation
1	18 Nov. 2010 - 24 May 2011	123	103	20 Feb.	19 Feb.	18 Apr.	15 Apr.
2	19 Nov. 2011 - 07 May 2012	129	126	27 Mar.	26 Mar.	24 Apr.	23 Apr.
3	21 Nov. 2012 - 03 May 2013	156	144	11 Mar.	09 Mar.	30 Apr.	27 Apr.
4	01 Dec. 2013 - 31 May 2014	171	150	09 Mar.	08 Mar.	26 Apr.	20 Apr.
5	01 Dec. 2014 - 15 May 2015	162	169	12 Jan.	09 Mar.	18 Apr.	26 Apr.
6	21 Nov. 2015 - 30 Apr. 2016	179	140	29 Feb.	28 Feb.	20 Apr.	13 Apr.
7	16 Nov. 2016 - 30 Apr. 2017	112	94	28 Jan.	22 Dec.	17 Apr.	09 Apr.
8	11 Nov. 2017 - 10 May 2018	165	112	02 Mar.	08 Mar.	19 Apr.	02 Apr.

4.2. Water balance of the Hoheikyo Dam basin

Even though the R/A precipitation was likely accurate at H-Site 1, the accuracy was not necessarily uniform across all areas in the Hoheikyo Dam basin. Conducting the same water balance analysis as in Chapter 3, the R/A precipitation over the basin is about 68% of the estimate from the basin's water budget (Table 4-2). This is a piece of indirect evidence of the underestimation of R/A precipitation in Hoheikyo Dam basin.

In addition, the amount of precipitation during the snowy season from 1 December to 31 March was extracted from the annual R/A precipitation, and the basin distribution was shown (Fig. 4-4b). Similarly, the distribution of precipitation during the rainy season (1 September to 30 November and 1 April to 31 August) is shown in Fig. 4-4c. In the Hoheikyo Dam basin, the areas where precipitation is concentrated change between the snowy season and the rainy season. The amount of precipitation during the rainy season follows the elevation distribution of the basin (Fig. 2-2b). As shown in Section 2.3, the accuracy of the rainy season of the R/A precipitation has been confirmed in previous studies. Therefore, the decrease in annual R/A precipitation at Hoheikyo Dam is thought to be mainly due to snowfall.

In the Hoheikyo Dam basin, there are no points where snow depth is continuously observed, so verification at each point will not be performed.

Table 4-2: Same as Table 3-2, but for the Hoheikyo Dam basin

	Period	a Observed Runoff (mm/yr) at Hoheikyo Dam	b Evapotranspiration (mm/yr)	c = a + b Annual precipitation estimated by water balance (mm/yr)	d Annual R/A precipitation (mm/yr)	e = d / c Ratio of R/A precipitation to estimated precipitation
1	1 Sep. 2010 - 31 Aug. 2011	1852	507	2359	1607	0.68
2	1 Sep. 2011 - 31 Aug. 2012	2210	507	2717	1774	0.65
3	1 Sep. 2012 - 31 Aug. 2013	2292	507	2799	2024	0.72
4	1 Sep. 2013 - 31 Aug. 2014	1980	507	2487	1774	0.71
5	1 Sep. 2014 - 31 Aug. 2015	2030	507	2537	1792	0.71
6	1 Sep. 2015 - 31 Aug. 2016	1626	507	2133	1335	0.63
7	1 Sep. 2016 - 31 Aug. 2017	2160	507	2667	1718	0.64
8	1 Sep. 2017 - 31 Aug. 2018	2021	507	2528	1718	0.68
	Average	2021	507	2528	1718	0.68

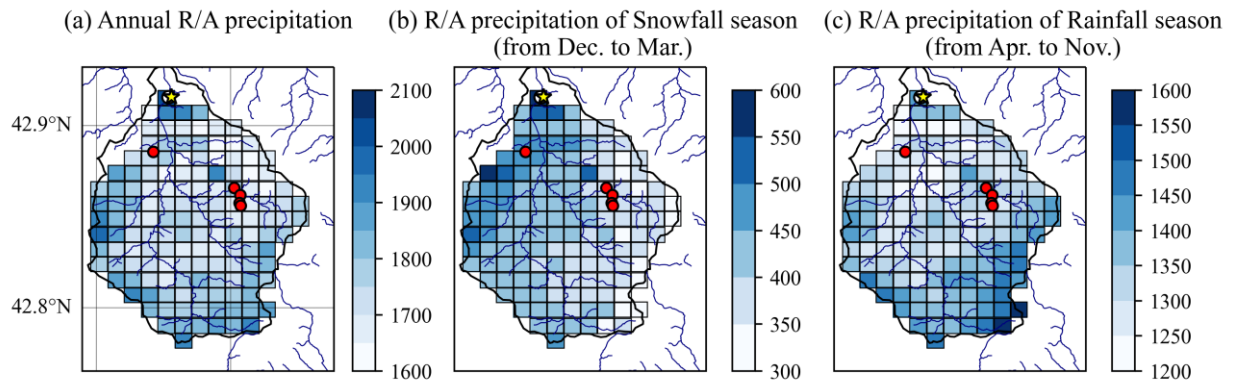


Figure 4-4: Same as Fig. 3-4, but for the Hoheikyo Dam basin.

4.3. Snowmelt mapping

Although the previous section indicated that the R/A precipitation was not uniformly accurate across the basin, we assume uniform accuracy for the purpose of assessing the applicability of snowmelt mapping. This is to reduce the uncertainty of the simulation. It is necessary to show the corrected distribution of R/A precipitation, but since this is difficult at the present stage due to the small number of observations, this will be the next study. Figure 4-5 shows the map of snow depth and cumulated melt forms ratio averaged over 8 winters in the melting season in the Hoheikyo Dam basin. Because the elevation ranges from 496 m to 1,226 m in the basin (Fig. 2-2b), the snow melting and the change to melt forms were nonuniform over the basin. On 1 March, the snow depth exceeded 113 cm upstream but was near 62 cm downstream, because of the difference in the snowfall amount in the winter season (Fig. 4-5a). On 1 May, the snow depth was less than 9 cm in the downstream, while it remained up to 82 cm in the upstream (Fig. 4-5c). This was mainly caused by temperature difference in the basin (Figs. 4-6e,f).

Similarly, the cumulated melt forms ratio increased faster on the downstream side (Figs. 4-5d-f). On 1 March, melt forms exceeded 34% in downstream but remained at less than 5% upstream (Fig. 4-6d). On 1 April, the snowpack layer was mostly filled with melt forms downstream, but the snowpack still had the rounded grains upstream (Fig. 4-5e). The snowpack fully covered with the melt forms over the basin in May (Fig. 4-5f).

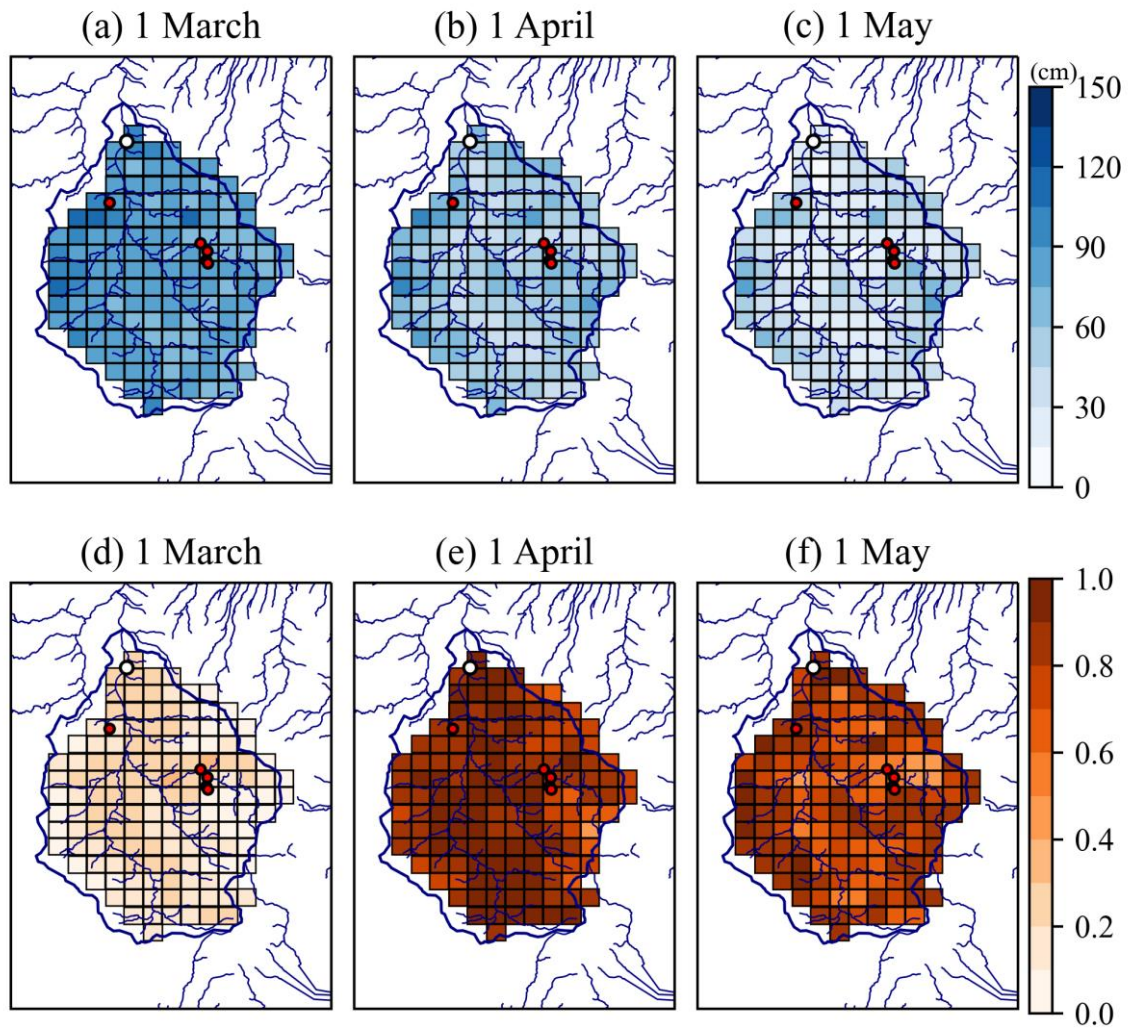


Figure 4-5: Same as Fig. 3-6, but for Hoheikyo Dam basin.

Figures 4-6a-c show the snowmelt rate defined as the SWE divided into its maximum value in the season. The snowmelt rate averaged over the basin was about 17% on 31 March (Fig. 4-6a) and 53% on 15 April (Fig. 4-6b). On 30 April, the average snowmelt rate in the basin was 88%, but the lowest rate was 56% in the upstream area, and more than half of the snowmelt amount was still maintained at some points (Fig. 4-6c). This rapid snow melting in April was explained by the basin-average temperature increase from -6°C to 2°C (Figs. 4-6d,f). The temperature crossed the freezing point around 15 April (Fig. 4-6e). Since the altitude exceeds 1,000 m at the mountaintop in the basin and is below 500 m at the dam point (Fig. 2-2b), the temperature deviation from the basin average ranged $\pm 4\text{ K}$ according to the lapse rate. This range caused the snow melting timing difference between the upstream and downstream of the basin. Though being aware of the accuracy of input precipitation to SNOWPACK model, the above results indicated that the snow melting were quite sensitive to surface height, say surface temperatures, as in the Jozankei Dam basin.

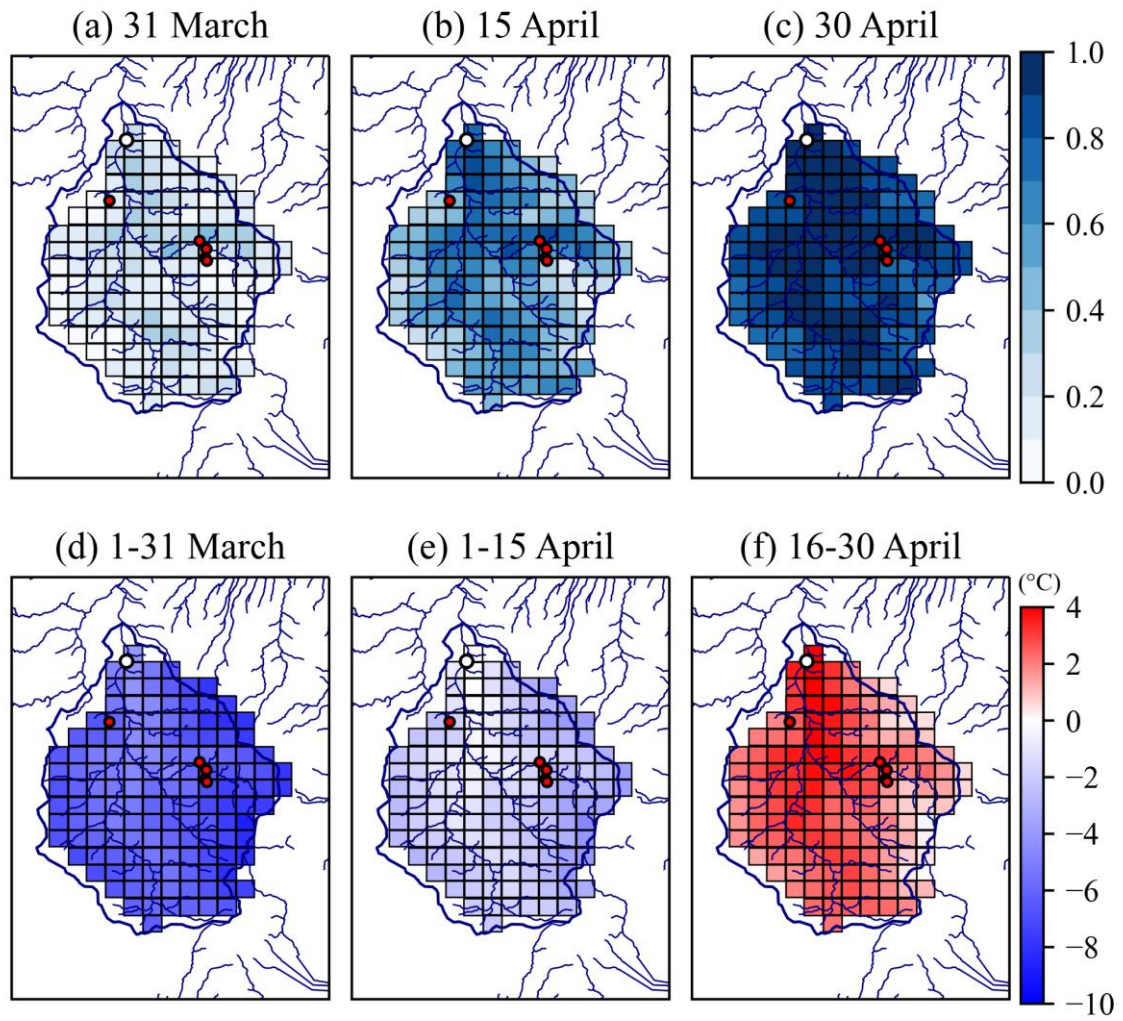


Figure 4-6: Same as Fig. 3-7, but for Hoheikyo Dam basin.

Chapter 5. Discussion

We here discuss two problems commonly faced in the snowpack and snowmelt analysis in this dissertation. The largest problem that we should address is the accuracy of input precipitation data, which is known as one of snow hydrological problems as in Introduction. We mainly used the R/A precipitation because it brought a better performance in the model validation for a specific site than the rain gauge data, which were much underestimated due to missing by strong wind or sublimation by electric heater (Rasmussen et al. 2012; Buisan et al. 2016; Smith et al. 2016; Pan et al. 2016; Figs. 3-1, 3-2, 3-3) and were not always adjusted well by a correction formula (Yokoyama et al. 2003; Figs. 4-1, 4-2, 4-3). However, even the R/A precipitation data likely had an underestimate bias across the target dam basins. This was suggested by not only a rough estimate by water budget with an evapotranspiration amount assumed after the literature but the snow depth comparison between observation and simulation in several points scattered over the basins. The R/A precipitation data in the basin were mostly compiled by the C-band radar data. It was generally known that the radar had much difficulty in observing solid precipitation in the cold environment (Ito et al. 2020). For example, even if the radar were directed horizontally, it could not detect distant particles in low-level snow clouds due to the curvature of the Earth. Moreover, the Z-R relation was not uniformly applied to the non-spherical solid precipitation. There is the possibility that some areas are in the shadow zone behind the mountain observed from the Sapporo Radar located near the basin (Figs. 5-1, 5-2, 5-3). In this case, because the R/A data were dependent on the C-band radar almost 200 km far south of the basin, the data should be significantly underestimated.

The water balance method for the dam basin showed that the R/A precipitation in the entire basin may be underestimated (Tables 3-2, 4-2, Figs. 3-5, 4-4). It was found that the corrected value of the R/A precipitation in the basin is not uniform and may have different values depending on the point. This is because it is difficult to verify the corrected value of the R/A precipitation if there is only one observation value of snow depth in one winter, as shown in Figs. 5-2 and 5-3. The well-estimated snowmelt in the basin will improve the accuracy of the runoff analysis of snowmelt water and the timing of its flow into the dam. For the verification, we again emphasize that the snow depth observation should be sufficiently provided in terms of sampling frequency and sampling points over the basin. Since the snowpack simulation is highly sensitive to input precipitation, we must be vigilant about precipitation accuracy. The best-effort validation in snow depth observations in this dissertation was intended to be one of the methods employed.

Given the difficulty in precipitation observation in snowy environments, one might find that measuring snow depth provides comparatively more accurate data in a less challenging manner than precipitation observations. Because the snow depth has been certainly observed by a simple instrument measuring distance like ultrasonic wave reflection or vertically fixed ruler (Lee et al., 2015), the observation error was likely small. However, the snow depth is extremely non-uniform because light snow particles were drifted by wind and accumulated around obstacles (Lundquist et al. 2015). For example, in H-Site 1 snow depth and snow-pit observations were provided albeit in slightly different locations. Despite that the horizontal distance is only 200 m in an almost level plain, the difference in snow depth is at most 30 cm (Fig. 4-1c). This means that the representativeness of snow depth cannot be ensured without the resolution of snow terrain,

which may be at the order of 10 m. The drone technology that could be applied to accurate snow depth observation (Walter et al. 2020) may resolve this problem. In another way, the highly efficient large eddy simulation for drift snow (Tanji et al. 2023) could help evaluate if the observation site is representative of the surrounding area.

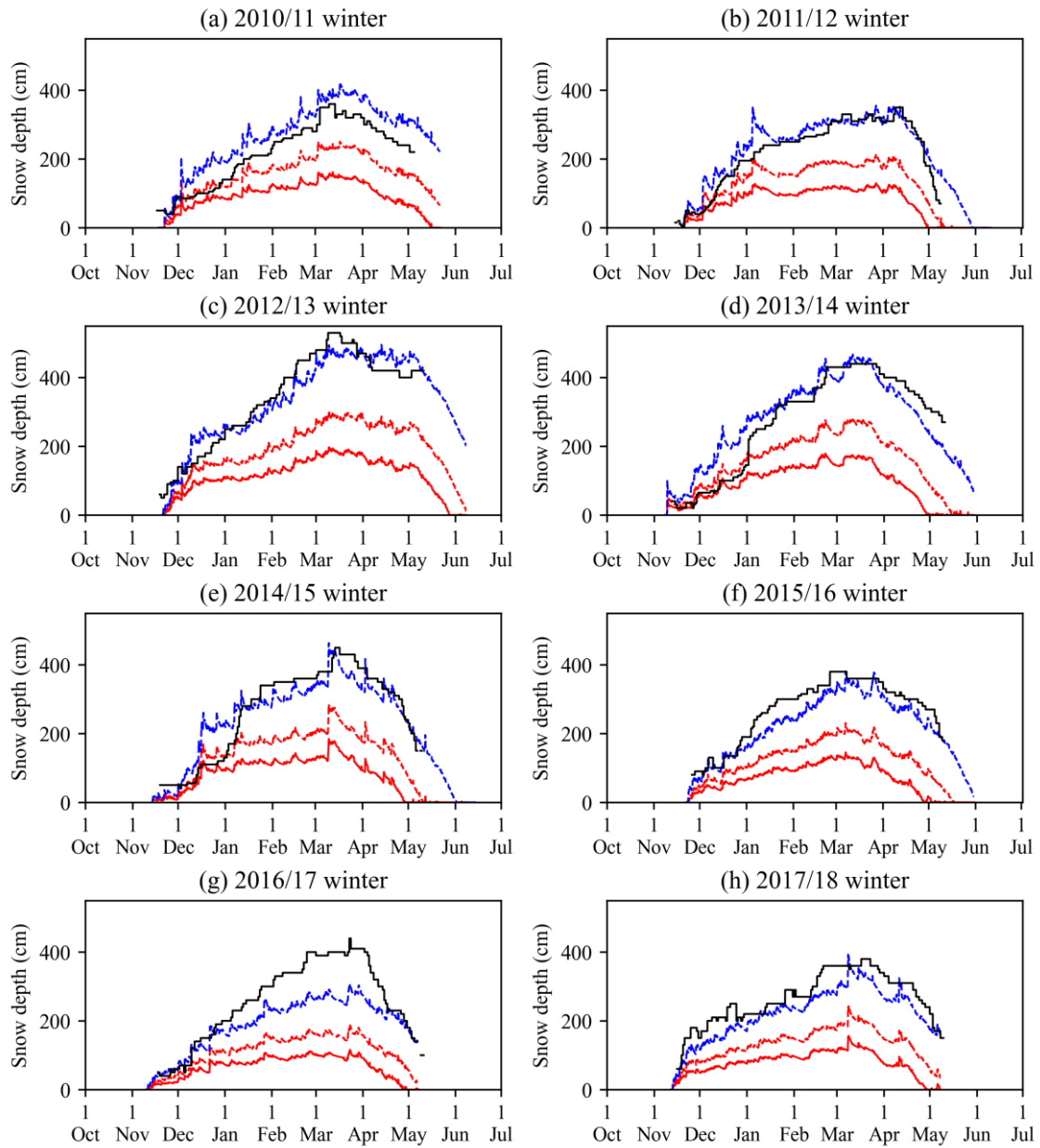


Figure 5-1: Same as Fig. 3-4, but for J-Site 11. (blue dashed line) simulated with corrected R/A precipitation data at J-Site 11 from (a) 2010/11 through (h) 2017/18 winters. The correction of blue was done by multiplication by a factor of 3.

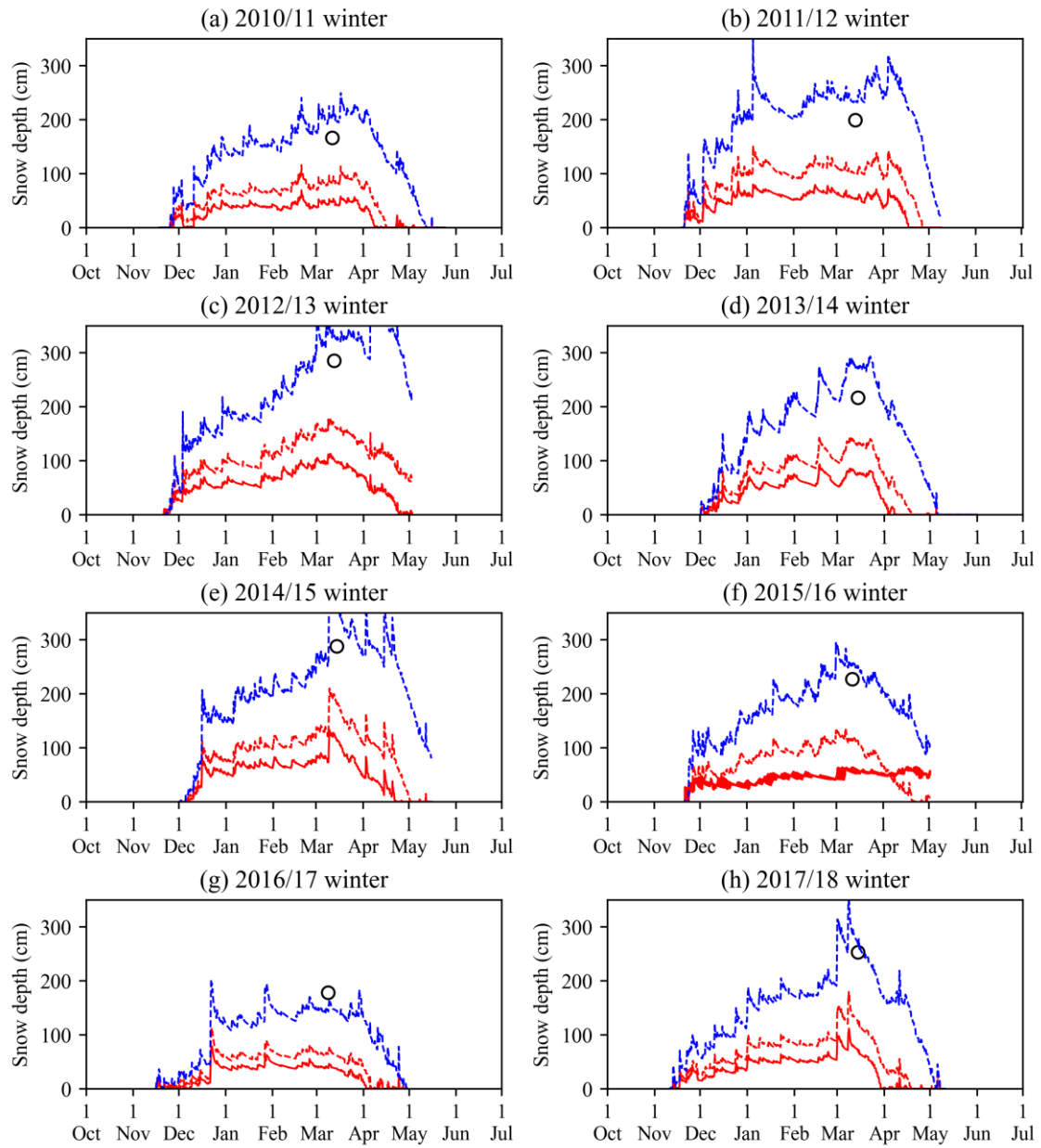


Figure 5-2: Same as Fig. 5-1, but for H-Site 2. The open circles are observation data.

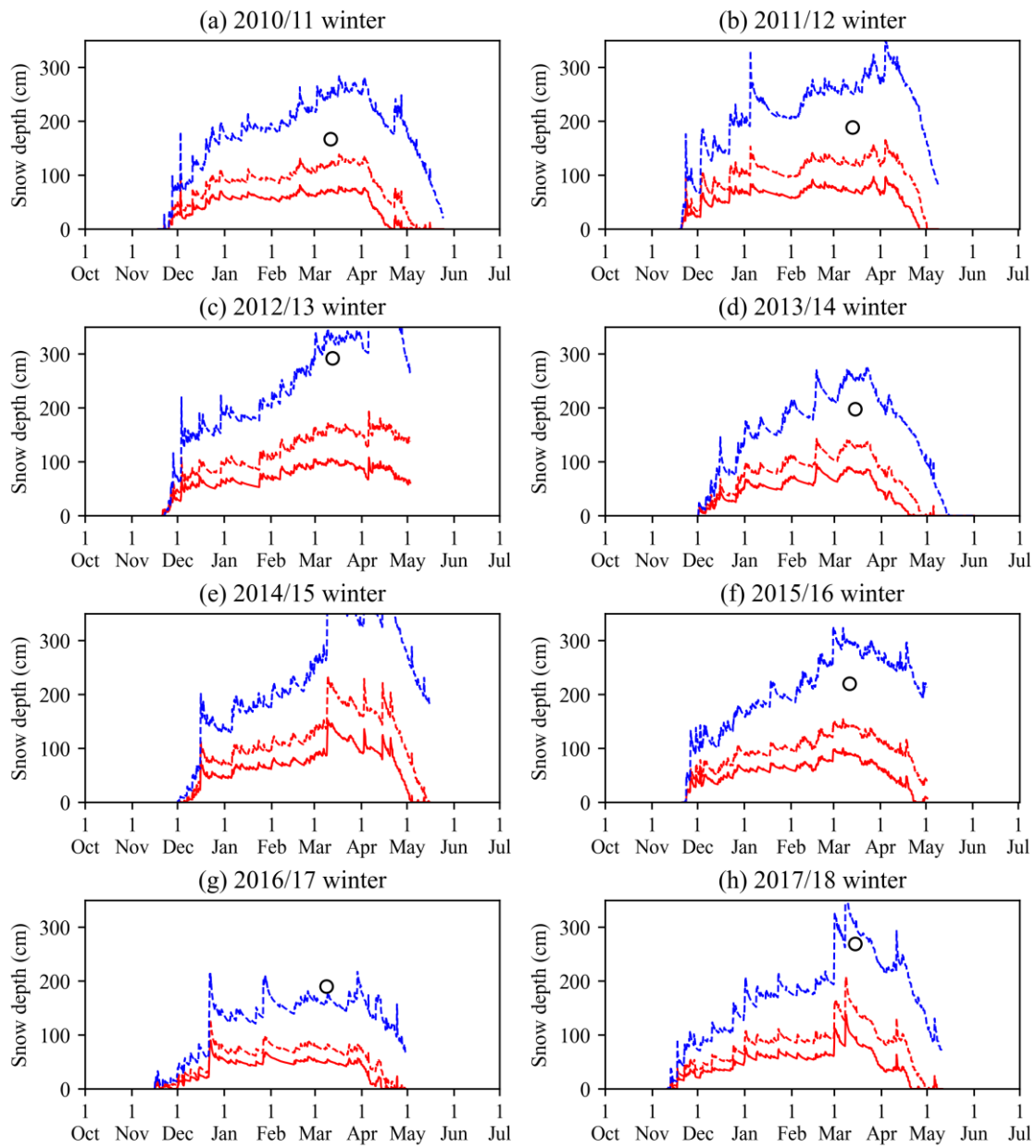


Figure 5-3: Same as Fig. 5-2, but for H-Site 5.

Chapter 6. Conclusion

We mapped the snow melting distribution in the Jozankei Dam basin by a physical snowpack model forced by high-resolution radar precipitation and other climatic variables observed at the single site. First, the snowpack model and input precipitation data were validated by various observations at J-Site 1, snow depth observation at J-Site 3, water budget estimation based on the dam inflow, and snow melting timing in the literature of Nishihara and Tanise (2019; Figs. 3-1, 3-2). Consequently, it was found that we may reasonably use the SNOWPACK model driven by the R/A precipitation in the basin, with caution of an earlier bias in the melting timing by about a week in the downstream and more in the northern area. Second, the mapping of simulation results indicated the difference in snowmelt timing mainly depending on the surface elevation (Figs. 3-6, 3-7). The additional snowpack simulation with the corrected R/A precipitation at J-Site 3 suggested that the snowmelt at J-Site 2 occurred 27 days earlier than at J-Site 3 (Fig. 3-8). We obtained consistent results by the Hoheikyo Dam basin analysis (Figs. 4-1, 4-2, 4-5, 4-6). Because errors in the snowpack simulation seemed largely due to the problem in snowfall, an enhanced observation network for snow depth deployed over the basin using Snow Analysis and Forecasts by the JMA, and X-band multi-parameter radar may contribute to a more accurate simulation of the snow environment of the basin.

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References

- Bales, R., N. Molotch, T. Painter, M. Dettinger, R. Rice, and J. Dozier, 2006: Mountain hydrology of the western United States. *Water Resource Research*, 42, W08432.
- Bartelt, P., and M. Lehning, 2002: A physical SNOWPACK model for the Swiss avalanche warning: Part I: Numerical model. *Cold Regions Science and Technology*, 35, 123–145.
- Brun, E., P. David, M. Sudul, and G. Brunot, 1992: A numerical-model to simulate snow cover stratigraphy for operational avalanche forecasting. *Journal of Glaciology*, 38, 13–22.
- Buisan, S., M. Earle, J. Collado, J. Kochendorfer, J. Alastrué, M. Wolff, C. Smith, and J. López-Moreno, 2016: Assessment of the underestimation of snowfall accumulation by tipping bucket gauges used operationally by the Spanish national weather service. *Atmospheric Measurement Techniques Discussions*, 1–22.
- Colli, M., L. Lanza, R. Rasmussen, and J. M. Thériault, 2015: The collection efficiency of shielded and unshielded precipitation gauges. Part I: CFD airflow modeling. *J. Hydrometeor.* 17, 231–243.
- Dozier, J., E. H. Bair and R. E. Davis, 2016: Estimating the spatial distribution of snow water equivalent in the world's mountains. *Wiley Interdisciplinary Reviews Water*, 3, 461–471.
- Elder, K., W. Rosenthal, and R. Davis, 1998: Estimating the spatial distribution of snow

water equivalence in a montane watershed. *Hydrological Process*, 12, 1793–1808.

Fatima, K., G. Veyssiere, C. Coleus, A. Dufour, I. D. Gouttevin, P. Durand, S. Gascoin, and M. Grizonnet, 2021: Monitoring wet snow over an Alpine region using Sentinel-1 observations. *Remote sensing*, 13, 381.

Fayad, A., A. Gascoin, G. Faour, J. I. Lopez-Moreno, L. Drapeau, M. L. Page, and R. Escadafal, 2017: Snow hydrology in Mediterranean mountain regions: A review. *Journal of Hydrology*, 551, 374–396.

Fierz, C., R. L. Armstrong, Y. Durand, P. Etchevers, E. Greene, D. M. McClung, K. Nishimura, P. K. Satyawali, and S. A. Sokratov, 2009: The International Classification for Seasonal Snow on the Ground, IHP-VII Technical Documents in Hydrology, Vol. 83, Paris: UNESCO, pp. 80.

Gottardi, F., C. Obled, J. Gailhard, and E. Paquet, 2012: Statistical reanalysis of precipitation fields based on ground network data and weather patterns: Application over French mountains. *Journal of Hydrology*, 432–433, 154–167.

Herrero, J., M. J. Polo, A. Moñino, and M. A. Losada, 2009: An energy balance snowmelt model in a Mediterranean site. *Journal of Hydrology*, 371, 98–107.

Hirashima, H., K. Nishimura, E. Baba, A. Hachikubo, and M. Lehning, 2004: SNOWPACK model simulations for snow in Hokkaido, Japan. *Annals of Glaciology*, 38, 123–129.

Hirota, T., M. Fukumoto, R. Shiroyaka, and K. Muramatsu, 1995: Simple method of estimating daily mean soil temperature by using force-restore model. *Journal*

of Agricultural Meteorology, 53, 269–277.

Ito K., S. Fujii, and T. Maruyama, 2020: Accuracy check of Radar AMeDAS precipitation by water balance analysis of the Tedoru River mountainous basin. Journal of the Japanese Society of Irrigation, Drainage and Rural Engineering (IDRE), **311**, pp.I_185-I_191, written in Japanese.

Jordan, R., 1991: A one-dimensional temperature model for a snow cover. Technical Documentation for SNTHERM.89. Special Report 657. U.S. Army Cold Regions Research and Engineering Laboratory, 64 pp.

Jost, G., M. Weiler, D. Gluns, and Y. Alila, 2007: The influence of forest and topography on snow accumulation and melt at the watershed-scale. Journal of Hydrology, 347, 101–115.

Katsuyama, Y., M. Inatsu, K. Nakamura, and S. Matoba, 2017: Global warming response of snowpack at mountain range in northern Japan estimated using multiple dynamically downscaled data. Cold Regions Science and Technology, 136, 62–71.

Katsuyama, Y., M. Inatsu, and T. Shirakawa, 2020: Response of snowpack to +2 °C global warming in Hokkaido, Japan. Journal of Glaciology, 66, 83–96.

Kojima, K., 1967: Comparison between the melting rates of brown snow and white snow. Low Temperature Science Series A, 25, 221–224.

Kondo, J., 1994: Meteorology of the water environment-water and heat balance of the Earth's Surface. Asakura Shoten Press, 348pp, written in Japanese.

Kondo J., and T., Yamazaki, 1987: Estimates of snowmelt by a heat balance method,

Seppyo, 49, 181–191, written in Japanese.

Kuchizawa, H., and M. Nakatsugawa, 2002: Estimations of snow peak condition and evapotranspiration based on water and heat balances in watersheds. Monthly report of Civil Engineering Research Institute, 588, 20–38, written in Japanese.

Lee, J.-E., G. W. Lee, M. Earle, and R. Nitu, 2015: Uncertainty analysis for evaluating the accuracy of snow depth measurements. *Hydrology and Earth System Sciences*, 12, 4157–4190.

Lehning, M., P. Bartelt, B. Brown, C. Fierz, and P. Satyawali, 2002a: A physical SNOWPACK model for the Swiss avalanche warning: Part II: Snow microstructure. *Cold Regions Science and Technology*, 35, 147–167.

Lehning, M., P. Bartelt, B. Brown, and C. Fierz, 2002b: A physical SNOWPACK model for the Swiss avalanche warning: Part III: Meteorological forcing, thin layer formation and evaluation. *Cold Regions Science and Technology*, 35, 169–184.

López-Moreno, J. I., S. R. Fassnacht, S. Beguería, and J. Latron, 2011: Variability of snow depth at the plot scale: implications for mean depth estimation and sampling strategies. *Cryosphere*, 5, 617–629.

Lundquist, J., M. Hughes, B. Henn, E. Gutman, B. Livneh, J. Dozier, and P. Neiman, 2015: High-elevation precipitation patterns: Using snow measurements to assess daily gridded datasets across the Sierra Nevada, California. *Journal of Hydrometeorol*, 16, 1773–1792.

Mernild, S., G. Liston, C. Hiemstra, J. Malmros, J. Yde, and J. McPhee, 2016: The Andes Cordillera. Part I: snow distribution, properties, and trends (1979–2014).

International Journal of Climatology, 37, 1680–1698.

Michlmayr, G., M. Lehning, G. Koboltschnig, H. Holzmann, M. Zappa, R. Mott, and W. Schonher, 2008: Application of the Alpine 3D model for glacier mass balance and glacier runoff studies at Goldbergkees, Austria. *Hydrological Processes*, 22, 3941–3949.

Molotch, N. and L. Meromy, 2014: Physiographic and climatic controls on snow cover persistence in the Sierra Nevada Mountains. *Hydrological Process*, 28, 4573–4586.

Nishihara, T., M. Nakatsugawa, and T. Usutani, 2014: Development of snowmelt runoff model incorporating the characteristics of snow distribution in forest and non-forest range. *Advances in river engineering (Japan Society of Civil Engineers)*, 20, 449-454, written in Japanese.

Nishihara, T., and A. Tanise, 2019: A study on a method for how to utilize snow cover information extracted from satellite images for dam operation during the snowmelt period. *Journal of The Remote Sensing Society of Japan*, 39, 299–306, written in Japanese.

Niwano, M., T. Aoki, K. Kuchiki, M. Hosaka, and Y. Kodama, 2012: Snow Metamorphism and Albedo Process (SMAP) model for climate studies: Model validation using meteorological and snow impurity data measured at Sapporo, Japan. *Journal of Geophysical Research*, 117, F03008.

Null, S., J. H. Viers, and J. F. Mount, 2010: Hydrologic response and watershed sensitivity to climate warming in California's Sierra Nevada. *PLoS ONE*, 5, e9932.

- Pan, X., D. Yang, Y. Li, A. Barr, W. Helgason, M. Hayashi, P. Marsh, J. Pomeroy, and R.J. Janowicz, 2016: Bias corrections of precipitation measurements across experimental sites in different ecoclimatic regions of western Canada. *Cryosphere*, 10, 2347–2360.
- Raleigh, M., B. Livneh, K. Lapo, and J. Lundquist, 2016: How does availability of meteorological forcing data impact physically based snowpack simulations? *Journal of Hydrometeorology*, 17, 99–120.
- Rasmussen, R., B. Baker, J. Kochendorfer, T. Meyers, S. Landolt, A. P. Fischer, J. Black, J. M. Theriault, P. Kucera, D. Gochis, C. Smith, R. Nitu, M. Hall, K. Ikeda, and E. Gutmann, 2012: How well are we measuring snow: The NOAA/FAA/NCAR winter precipitation test bed. *Bulletin of American Meteorological Society*, 93, 811-829.
- Rice, R. and R. Bales, 2010: Embedded-sensor network design for snow cover measurements around snow pillow and snow course sites in the Sierra Nevada of California. *Water Resour. Res.*, 46, W03537.
- Sawano, S., N. Hotta, N. Tanaka, Y. Tsuboyama, and M. Suzuki, 2015: Development of a simple forest evapotranspiration model using a process-oriented model as a reference to parameterize data from a wide range of environmental conditions. *Ecological Modelling*, 309–310, 93–109.
- Sensoy, A., A. Sorman, A. E. Tekeli, Ü. Sorman, and D. C. Garen, 2006: Point-scale energy and mass balance snowpack simulations in the upper Karasu basin, Turkey. *Hydrological Process*, 20, 899–922.
- Slater, A. G., M. P. Clark, and A. P. Barrett, 2009: Comment on "Estimating the

distribution of snow water equivalent using remotely sensed snow cover data and a spatially distributed snowmelt model: A multi-resolution, multi-sensor comparison" by Noah P. Molotch and Steven A. Margulis. *Advances in Water Resources*, 32, 1680–1684.

Smith, C., A. Kontu, R. Laffin, and J. Pomeroy, 2016: An assessment of two automated snow water equivalent instruments during the WMO Solid Precipitation Intercomparison Experiment. *Cryosphere Discussions*, 1–31.

Stewart, I., D. R. Cayan, and M. D. Dettinger, 2005: Changes toward earlier streamflow timing across western North America. *Journal of Climate*, 18, 1136–1155.

Tanji, S., M. Inatsu, and Y. Harada, 2023: Comparison of the LBM snowdrift model output with observation results. *Progress in Earth and Planetary Science*, 8, 57.

Taniguchi, Y., M. Nakatsugawa, and K. Kudo, 2016: Study on effect of quantitative and qualitative changes of snow cover from the future climate change. *Journal of Japan Society of Civil Engineers, Ser. G (Environmental Research)*, 72, I_205–I_211, written in Japanese.

Thériault, J., R. Rasmussen, K. Ikeda, and S. Landolt, 2012: Dependence of snow gauge collection efficiency on snowflake characteristics. *Journal of Applied Meteorology and Climatology*, 51, 745–762.

Usutani, T., M. Nakatsugawa, and K. Hoshi, 2007: Development of practical snowmelt runoff model with water flow through snowpack. *Journal of Japan Society of Hydrology and Water Resources*, 20, 93-105, written in Japanese.

Usutani, T., and M. Nakatsugawa, 2008: Accuracy of snowmelt runoff forecast based on

weather forecast. *Advances in river engineering* (Japan Society of Civil Engineers), 14, 41-46, written in Japanese.

Usutani, T., M. Nakatsugwa, and N. Matsuoka, 2014: Generalization of model parameters for evaluating basin-scale soil moisture content. *Journal of Japan Society of Civil Engineers. Ser. B1, Hydraulic engineering*, 70, I_355–I_360, written in Japanese.

Yokoyama, K., H. Ohno, Y. Kominami, S. Inoue, and T. Kawakata, 2003: Performance of Japanese precipitation gauges in winter. *Seppyo*, 65, 303-316, written in Japanese.

Walter, B., H. Huwald, J. Gehring, Y. Bühler, and M. Lehning, 2020: Radar measurements of blowing snow off a mountain ridge. *The Cryosphere*, 14, 1779–1794.

Watson, F., T. Anderson, W. Newman, S. Alexander, and R. Garrott, 2006: Optimal sampling schemes for estimating mean snow water equivalents in stratified heterogeneous landscapes. *Journal of Hydrology*, 328, 432–452.