Hydrological Research Letters **6**, 87–91 (2012)
Published online in J-STAGE (www.jstage.jst.go.jp/browse/HRL). doi: 10.3178/HRL.6.87

Is snowmelt runoff timing in the Japanese Alps region shifting toward earlier in the year?

Tsutomu Yamanaka[1], Yoshifumi Wakiyama[1] and Keisuke Suzuki[2]
[1]*Terrestrial Environment Research Center, University of Tsukuba, Japan*
[2]*Institute of Mountain Science, Shinshu University, Japan*

Abstract:

Inter-annual variations of snowmelt runoff timing in 15 basins across central Japan were analyzed across 30 years, from 1980–2009, to determine if mountain hydrology has been affected by global warming. Observed daily river discharge was utilized to calculate center time (CT) of mass of flow. CT was found to be occurring significantly earlier in the year at two northern basins, with a rate of change of around five days per decade. While decreasing trends in CT in the other basins were not significant, negative correlations between CT and winter temperature was significant except for the central to northeastern basins. The effect of winter warming on snowmelt runoff was more significant in northern basins on the Sea of Japan side, where CT also correlated with the flowering date of cherry trees. Positive correlations between precipitation and discharge were stronger in southern basins, disturbing winter warming effect on spring discharge. These findings support the notion that winter warming accelerates snowmelt runoff, although year-to-year fluctuations were more pronounced than progressive warming over the three decades. Our results highlight inter-basin differences in hydrological response to climatic change, serving to validate down-scaling of climate simulations over the Japanese Alps region.

KEYWORDS snowmelt runoff; global warming; inter-annual variation; mountain hydrology; Japanese Alps

INTRODUCTION

Mountains are often referred to as natural “water towers”, which provide freshwater for populations not only within their foothills but also in downstream lowlands (Viviroli *et al.*, 2007). Mountainous areas are characterized by greater amount of precipitation and lower temperatures sometimes associated with less evapotranspiration than in low-lying areas, as well as temporary water storage in the form of snow and ice, resulting in a delay in runoff (Zierl and Bugmann, 2005). A hydrological response to global warming in snow-dominated regions is a substantial shift in streamflow seasonality (Barnett *et al.*, 2005; Parry *et al.*, 2007). Alpine environments are among the most sensitive to such climatic changes, providing opportunities for early detection of their signals (Diaz *et al.*, 2003; Beniston, 2003).

In the western United States, including the Sierra Nevada and the Rocky Mountains, a shift in the timing of snowmelt runoff toward earlier in the year has been detected using observational records of river discharge (Aguado *et al.*, 1992; Dettinger and Cayan, 1995; Stewart *et al.*, 2004, 2005; McCabe and Clark, 2005). The shift can be mainly attributed to warming in winter (Dettinger and Cayan, 1995), spring (Stewart *et al.*, 2004) or both (Stewart *et al.*, 2005), rather than precipitation variability. Similar changes due to global warming were projected for the European Alps using numerical models of regional climate and catchment hydrology (Middelkoop *et al.*, 2001; Etchevers *et al.*, 2002; Zierl and Bugmann, 2005). These hydrological changes in mountains may increase flood risk in lowlands during winter-spring seasons and/or decrease summer streamflow, potentially reducing water availability for domestic, industrial and agricultural purposes (Middelkoop *et al.*, 2001).

The Japanese Alps are a series of mountain ranges (i.e., Northern, Central and Southern Alps) across central Japan, with more than 20 peaks over 3,000 meters. Mountains in this region store large amounts of snow during winter, and serve adjacent areas with water in succeeding seasons (Suzuki, 2008). Wada *et al.* (2004) reported significant increases in both winter runoff and winter temperature at the upper Kurobe River basin situated in the northern edge of Northern Alps. For the same basin Shinohara *et al.* (2009) adopted a simplified hydrological model to show that winter warming increases spring runoff and decreases summer runoff. While these studies offered valuable insights into consequences of global warming in a part of the Japanese Alps region, little is known about the other basins within the region.

The present study addresses inter-annual variations in the timing of snowmelt runoff at diverse basins in Japanese Alps region. The primary objective of this study is to examine whether global warming has already induced a forward shift in runoff timing toward earlier in the year in this region. Furthermore, we attempt to clarify how changes in temperature and precipitation affect river discharge in specific months, and to compare hydrological response among the basins.

MATERIALS AND METHODS

Data set

Fifteen river basins covering Japanese Alps and adjacent mountain ranges were selected for the analysis (Figure 1, Table SI). We utilized daily data of river discharge observed by the Ministry of Land, Infrastructure and Transport, Japan

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Correspondence to: Tsutomu Yamanaka, Terrestrial Environment Research Center, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8577, Japan. E-mail: tyam@suiri.tsukuba.ac.jp

Received 17 July, 2012
Accepted 13 September, 2012

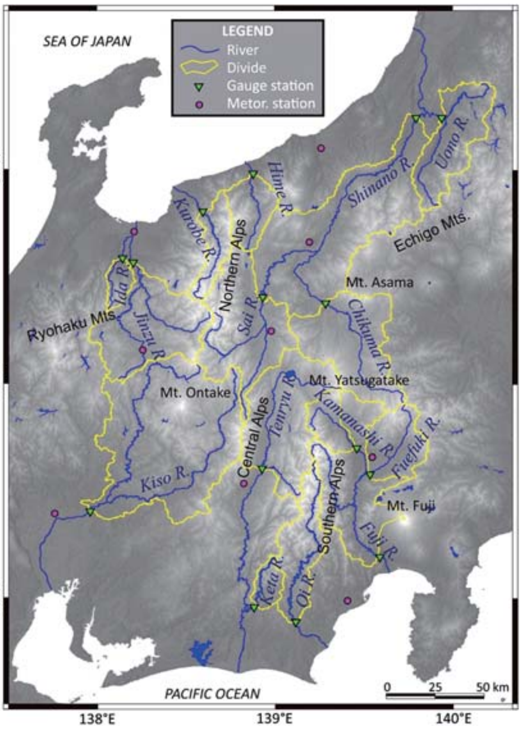

Figure 1. Map of the Japanese Alps region and study basins.

(MLIT). Data sets are available from Annual Records of Rainfall and Discharge Database (Japan River Association, 2007) or MLIT Water Information System (http://www1.river.go.jp/). In the present study, we focused on a recent 30-year period from 1980–2009.

For comparison we utilized monthly meteorological data (air temperature and precipitation) and phenology data (flowering date of cherry; FDC) observed at Japan Meteorological Agency (JMA) surface stations within or close to the selected basins (Figure 1). While these data may not always reflect average or representative conditions within each basin, we judged such a problem to be minor because of high, spatial coherence of their inter-annual variations (e.g., correlation coefficient for nearest neighbors, $r_{nn} > 0.93$ for January temperature and 0.87 for FDC). However, spatial representativeness of precipitation data was relatively low (e.g., $r_{nn} > 0.59$ for April precipitation). Although there are Automatic Meteorological Data Acquisition Systems (AMeDAS), we utilized only data from manned stations (some of which were changed to unmanned ones recently), since phenology data are available and long-term meteorological records are expected to be more reliable at the manned stations.

Measure of snowmelt runoff timing

Previous studies have used several measures of snowmelt runoff timing: monthly or seasonal fraction of annual streamflow (Aguado *et al.*, 1992; Dettinger and Cayan, 1995; Stewart *et al.*, 2005), spring streamflow pulse or spring pulse onset (Cayan *et al.*, 2001; Stewart *et al.*, 2005), center time (CT) of mass of flow (Stewart *et al.*, 2004, 2005), and center mass date (CMD; McCabe and Clark, 2005). The CT has good correlation with spring pulse onset, with less noise, and provides a time-integrated perspective of snowmelt runoff (Stewart *et al.*, 2005), so that we adopted this measure.

The CT is the flow-weighted mean of date, calculated as

$$CT = \Sigma(t_i Q_i)/\Sigma Q_i \qquad (1)$$

where t_i is the time in days from the beginning of the water year, and Q_i is the corresponding river-discharge for *i*-th day. In the present study, January 1 was assumed to be the beginning of the water year, since minimum monthly discharge usually occurred in January for most of the selected stations; therefore, CT is represented as day-of-year (DOY). A problem with the use of CT is that this measure is affected by runoff during not only snowmelt season, but also by runoff during the rainy seasons. This is not a serious problem for western North American basins, where relative importance of streamflow during the snowmelt season is very high (50–80%; Stewart *et al.*, 2005). In case of the Japanese Alps region, however, runoff in warm seasons is comparable to or greater than snowmelt runoff, and thus year-to-year variation of rainfall, especially due to Bai-u front and/or typhoon activities, may introduce apparent change in CT. For this reason, in the present study, calculation of CT was performed for the period from January 1 to May 31. Runoff during this period contains a snowmelt and rainfall component. It should be noted that CT provides an indirect measure rather than exact timing of snowmelt.

Statistical analysis

Two statistical approaches were applied to test for presence of long-term trend of CT: linear regression analysis and the Mann-Kendall trend test (Westmacott and Burn, 1997). Statistical significance of obtained slope values in the linear regression model was examined by *t*-test. The Mann-Kendall trend test is a non-parametric test for identifying a monotonic trend and is insensitive to outliers and missing data (Dettinger and Cayan, 1995).

Linear regression analysis was also applied to confirm whether CT or monthly discharge correlated with temperature and precipitation. Statistical significance of correlation coefficients were examined by *t*-test.

RESULTS

Long-term trend

Mean values of calculated CT in each basin for the study period range from DOY83 (March 24) in Fuefuki basin to DOY111 (April 21) in Hime basin (Table I). The CT varied inter-annually and the maximum and minimum values were DOY68 (March 9) and DOY125 (May 5), respectively.

Two river basins covering the northern part of Northern Alps, Jinzu and Kurobe, showed significant decreasing trends of CT, suggesting a shift in snowmelt runoff timing toward earlier in the year in more recent decades. This result is consistent with that from previous studies (Wada *et al.*, 2004; Shinohara *et al.*, 2009). The trends indicate that snowmelt runoff tends to occur 4.6 and 6.3 days earlier per decade in Jinzu and Kurobe basins, respectively. Decreasing trends were also observed in most of the other basins, although not statistically significant ($p > 0.05$).

Increasing trends of annual mean air temperature were significant at all the meteorological stations in the study

Table I. Mean and trend of the center time (CT) for the 30-year period (1980–2009). Correlation coefficients between CT and monthly mean temperature (T_1–T_5) or monthly total precipitation (P_1–P_5) for January to May or the flowering date of cherry (FDC) are also shown.

River basin	Mean (DOY)	Trend (d decade^{-1})	Correlation coefficient, *r*										
			T_1	T_2	T_3	T_4	T_5	P_1	P_2	P_3	P_4	P_5	FDC
Ida	85.9	−1.9	−0.68***	−0.70***	−0.61***	−0.48*	−0.39*	0.24	0.08	0.08	0.14	0.01	0.71***
Jinzu	96.6	−4.6*†	−0.52**	−0.63***	−0.40*	−0.26	0.00	−0.22	−0.21	−0.20	0.33	0.35	0.57***
Kurobe	107.6	−6.3*†	−0.60***	−0.44*	−0.30	−0.18	−0.04	0.37	−0.32	−0.53**	0.22	0.33	0.29
Hime	110.8	0.0	−0.41*	−0.63***	−0.67***	−0.30	0.13	−0.20	−0.07	−0.43*	−0.26	0.06	0.70***
Sai$^{\#}$	94.3	0.7	−0.12	0.16	0.08	0.21	0.15	0.02	0.14	0.15	0.34	0.45*	0.07
Chikuma$^{\#}$	85.4	−1.5	−0.08	−0.17	0.00	0.15	0.02	−0.31	0.04	−0.05	0.35	0.52**	0.13
Shinano$^{\#}$	100.4	−3.2	−0.42*	−0.51**	−0.44*	−0.16	0.07	−0.24	−0.06	−0.25	0.10	0.45*	0.57***
Uono	93.0	−2.5	−0.62***	−0.79***	−0.81***	−0.63***	−0.33	0.52**	0.36*	0.31	−0.10	0.11	0.88***
Kiso	89.9	−1.7	−0.39*	−0.23	−0.04	0.06	0.08	−0.26	−0.40**	0.24	0.65***	0.56**	0.27
Tenryu	90.5	0.2	−0.41*	−0.11	0.02	0.33	0.25	−0.12	−0.37	−0.05	0.67***	0.62***	0.16
Keta	94.8	−0.7	−0.43*	−0.27	0.14	0.19	0.14	−0.40*	−0.43*	0.02	0.43*	0.45*	0.20
Oi	101.0	−1.1	−0.47*	−0.46*	−0.09	0.23	0.10	−0.27	−0.47*	0.11	0.34	0.31	0.24
Kamanashi$^{\$}$	84.4	−0.5	−0.31	0.03	0.00	0.24	0.25	−0.04	−0.07	0.14	0.33	0.56**	−0.04
Fuefuki$^{\$}$	82.9	−1.2	−0.06	−0.33	−0.05	−0.03	−0.09	−0.13	0.10	0.32	0.44*	0.33	0.22
Fuji$^{\$}$	93.0	−4.3	−0.32	−0.36	−0.20	0.01	0.15	−0.40*	−0.18	0.11	0.37*	0.58**	0.30

Significance level: * for $p < 0.05$, ** for $p < 0.01$, *** for $p < 0.001$ in *t*-test, and † for $p < 0.05$ in Mann-Kendall trend test.

$^{\#}$ Shinano basin includes Sai and Chikuma basins.

$^{\$}$ Fuji basin includes Kamanashi and Fuefuki basins.

area ($p < 0.001$ in *t*-test, and $p < 0.01$ in the Mann-Kendall test). Rates of the temperature increase ranged from 0.394 to 0.598℃ decade^{-1}. These values are considerably higher than the linear trend in annual global mean temperature of 0.177 (± 0.052) ℃ decade^{-1} for the period of 1981–2005 (Solomon *et al.*, 2007). However, the increasing trend in winter temperatures were not significant except at Toyama station to the north of Jinzu basin; that is, year-to-year variation in winter temperatures are greater than the progressive increase.

Correlation of CT with meteorological and phenological variables

Inter-annual variations of CT significantly negatively correlated with temperature during winter (i.e., January and February) to early-spring (i.e., March) in Ida, Jinzu, Kurobe, Hime, Shinano and Uono basins (Table I; $p < 0.01$). All of these basins are situated at around Northern Alps and adjacent mountain ranges facing to the Sea of Japan. Negative correlations with lower significance ($0.01 < p < 0.05$) were also found in Kiso, Tenryu, Keta and Oi basins, which partly cover western or southern parts of Central Alps and Southern Alps. On the other hand, no significant correlation was observed between CT and temperature in the upper reaches of Shinano river (i.e., Sai and Chikuma), or the Fuji basin and its upper reaches (i.e., Kamanashi and Fuefuki).

CT significantly positively correlated with precipitation in mid- to late-spring (i.e., April to May) for river basins of Sai, Chikuma and Shinano, as well as in southern basins (i.e., Kiso, Tenryu, Keta, Kamanashi, Fuefuki and Fuji). Such a relationship was not clear in northern basins (i.e., Ida, Jinzu, Kurobe, Hime and Uono). CT and winter precipitation positively correlated in Uono basin, but negatively correlated in the southern basins, Keta and Fuji. In the northern basins, Kurobe and Hime, significant negative correlations between CT and early spring precipitation in March were observed.

Positive correlations between CT and FDC were highly significant in the northern basins ($p < 0.001$), except for Kurobe basin. CT and FDC showed very good agreement, especially in Uono basin which had the highest correlation coefficient of 0.88 (Figure S1).

Dependence of river discharge on temperature and precipitation

In addition to CT, inter-annual variation of river discharge in a specific month often correlated with air temperature or precipitation amount in the same or preceding month. In all basins except Kurobe basin, significant positive correlations were found between monthly total discharge and monthly mean temperature in February (Figure 2a). Positive correlations between discharge and precipitation were also found, although they were not significant in Ida, Kurobe, Shinano and Uono basins and tended to be clearer in southwestern study regions (Figure 2b).

In Ida, Jinzu, Hime, Shinano, Uono and Kamanashi basins, negative correlations were significant between April discharge and preceding January temperature (Figure 2c). On the other hand, positive correlations were significant between April discharge and April precipitation in most of the basins, other than Ida, Jinzu, Hime and Uono basins; and correlation coefficients were generally greater in southern study regions (Figure 2d).

DISCUSSION

Cayan *et al.* (2001) analyzed changes in the onset of spring season over inter-annual to inter-decadal time scales and found that fluctuation in the flowering dates of lilac and honeysuckle significantly correlated with the spring snowmelt pulse. The present study confirmed excellent correlation between CT and FDC in northern basins close

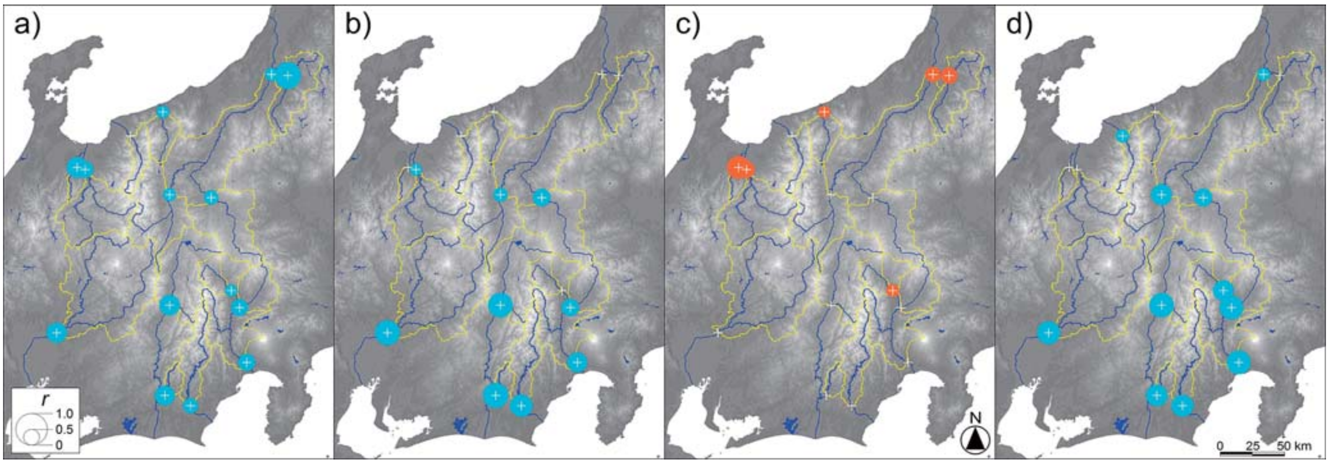

Figure 2. Spatial distribution of correlation coefficients, *r*, between a) February discharge and February temperature, b) February discharge and February precipitation, c) April discharge and January temperature, and d) April discharge and April precipitation. Blue circles represent positive correlation and red circles negative, and their size is proportional to absolute value of correlation coefficient; only significant correlations ($p < 0.05$) are shown. White crosses indicate the location of gauge stations.

to the Sea of Japan. This demonstrates high performance of CT as an indicator of snowmelt runoff timing and implies that spring onset in hydrological and biological phenomena are similarly modulated by winter temperature.

Both linear regression analysis and the Mann-Kendall trend test indicated that in the last 30 years since 1980, CT occurred earlier in Jinzu and Kurobe basins. A shift toward earlier CT, indicating earlier snowmelt, corresponded with winter warming in recent decades – with significantly increasing winter temperatures measured at a meteorological station near these basins. For the other basins, such a trend was not always significant for both CT and winter temperature. However, significant negative correlations between CT and winter temperature was observed in most basins studied, other than the upper Shinano basins and the whole of Fuji basin. Thus, it can be concluded that changes in winter temperature has substantially affected the timing of snowmelt runoff in the Japanese Alps region.

According to numerical projections by Ma *et al.* (2010) and Whitaker and Yoshimura (2012), global warming will induce increased winter discharge and decreased spring discharge over areas to the northeast of the Japanese Alps. Indeed, winter temperature positively correlated with winter discharge over a large extent of the region. However, significant negative correlations between winter temperature and spring discharge are concentrated in the northern part of Northern Alps and adjacent mountain ranges (i.e., Ryohaku mountains and Echigo mountains) facing to the Sea of Japan. Areas facing the Sea of Japan are strongly influenced by cold air masses from Siberia in winter, and depth of snow cover reaches up to more than one meter (Figure S2). The findings of the present study suggest that in such snow-dominated areas, temperature fluctuations rather than precipitation variability affect river discharge more strongly during snowmelt season. However, it remains unclear whether this is due to temperature dependence of the snowfall : rainfall ratio, or the snowmelt rate.

On the other hand, in the Fuji basin and the upper reaches of the Shinano River, influence of precipitation variability (especially in spring) overcame effects of winter temperature on snowmelt runoff timing. In these rain-dominated areas, future change in precipitation, rather than temperature, would have greater impact on flow regime.

In southwestern study regions (i.e., Kiso, Tenryu, Keta and Oi basins), where winter precipitation is greater than in upper Shinano and Fuji basins, CT correlated negatively with both winter temperature and winter precipitation. Although a positive correlation between temperature and precipitation can be found in February, it was not the case in January. In addition, CT had a stronger correlation with temperature than with precipitation in January. These facts suggest that temperature effect upon river discharge through snowmelt is independent of precipitation effect in January, and is important even in these southern basins.

Apart from climatic factors, inter-annual changes in vegetation and/or water use potentially affect hydrological cycles. For instance, construction or operation of dams may affect runoff timing and weaken the relationship between CT or river discharge and meteorological variables. In fact, there are dams at upstream areas in most cases for the study region. Nevertheless, our analysis found significant correlations between them, suggesting high impacts of climatic conditions on mountain hydrology.

CONCLUSIONS

Is snowmelt runoff timing in the Japanese Alps region shifting toward earlier in the year? The answer to this question is partially “yes”, while it differs with river basins; they are classified into three sub-regions. First, in the northern basins on the north of Northern Alps and adjacent mountains near to the Sea of Japan (i.e., Ida, Jinzu, Kurobe, Hime, Shinano and Uono), snowmelt runoff timing is sensitive to temperature change in winter and highly correlates with flowering date of cherry. Especially in Jinzu and Kurobe basins, forward shift of snowmelt runoff timing is significant with slopes of 4.6 and 6.3 days per decade, respectively. However, in the other basins in this sub-region, year-to-year variation of winter temperature rather than its progressive increase controls snowmelt runoff more significantly; warmer (colder) winter introduces greater (less) winter discharge and less (greater) spring discharge. Secondly, in the central to southeastern basins on the east of Northern and Southern Alps (i.e., Sai, Chikuma, Kamanashi, Fuefuki and Fuji), winter temperature change hardly affects runoff seasonality, while precipitation variation has greater impacts. Thirdly, in southwestern basins on the west to south of Northern, Central and Southern Alps (i.e., Kiso, Tenryu, Keta and Oi), precipitation variation primarily controls river discharge, while winter temperature also has non-negligible impacts on snowmelt runoff. This geographical contrast would be useful information for validating the down-scaling of climate simulation results and hydrological response in Japanese Alps region.

ACKNOWLEDGEMENTS

This study has been supported in part by the Research and Education Funding for Japanese Alps Inter-Universities Cooperative Project, Ministry of Education, Culture, Sports, Science and Technology, Japan. The authors are grateful for the helpful comments from the anonymous reviewers.

SUPPLEMENTS

Supplement: This includes Figures S1, S2 and Table SI.

Figure S1. Inter-annual variations of the center time (CT) of mass of flow and the flowering date of cherry (FDC) at Uono basin, as the highest correlation case.

Figure S2. Spatial distribution of annual maximum snow depth (Mesh Climatic Data 2000; Japan Meteorological Agency, 2002).

Table SI. Summary of study basins.

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