Development of a Long-term Daily Gridded Temperature Dataset and Its Application to Rain/Snow Discrimination of Daily Precipitation

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Abstract

We created a daily mean gridded temperature dataset of monsoon Asia (15˚S-55˚N, 60˚E-155˚E) for the period of 1973-2007, with a 0.50 x 0.50 degree grid. We analyzed this dataset based on station observations collected and a quality control and interpolation system developed through the activities of the Asian Precipitation – Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) project (Yatagai *et al.*, 2009, 2012). The number of stations is up to 1.5-3 times the number of stations based on the Global Telecommunication System (GTS), which have been used to obtain other gridded temperature products. The monthly means and climatology of our product are comparable to the monthly means of those products. This is the only product in Asia that has high resolution both temporally and spatially as the APHRODITE precipitation product is known for.

The ability to discriminate between rain and snow is added to the APHRODITE daily precipitation product by using daily mean temperature and relative humidity (RH). Relative humidity is derived from a reanalysis product, because RH observation data are collected insufficiently for interpolation. We found use of the temperature product of this study and the RH derived from the reanalysis product to be adequate for determining whether precipitation was rain or snow. Our estimated solid precipitation amount using rain/snow discrimination for late fall to early spring (October to March) is consistent with satellite observations.

This dataset is available on the APHRODITE website <http://www.chikyu.ac.jp/precip>. The combination of daily mean temperature, precipitation and rain/snow information in this high- resolution gridded format would be useful as input to river-flow models, crop models and many other situations where water resources must be estimated.

Key words: climate change, daily temperature, quality control, rain/snow discrimination

1. Introduction

Many temperature datasets based on surface observations have been developed to estimate recent increases in surface temperature and to assess the impact of global warming. Changes in temperature affect vegetation, agriculture, the spread of infectious diseases and many other aspects of human life. Moreover, it has been pointed out that global warming will bring heavier rainfall or drought, or changes of snowfall into rainfall. Whether the precipitation is solid or liquid is critical for those who live in mountainous areas or the subarctic zone because rain may damage permafrost ground, mountain glaciers or perpetual snow by causing them to melt.

Surface temperatures simulated in climate models are dependent on the complexity of physical processes such as the solar radiation balance, fluxes, surface topography and weather. Moreover, the resolution of climate models has been developing rapidly recently. Therefore, a surface temperature dataset which is highly resolved both spatially and temporally, based on surface observations is needed for validation of the output data of high-resolution climate models.

Currently a number of gridded temperature datasets based on surface observations are available. A monthly time series of gridded terrestrial air temperatures has been released from the University of Delaware (UDel) (Legates and Willmott, 1990; Willmott and Robeson, 1995). HadCRUT3 (Brohan *et al.*, 2006) is a monthly gridded temperature dataset created by the Hadley Centre, UK Met Office, in collaboration with the Climate Research Unit (CRU) of the University of East Anglia. The CRU has also released a high-resolution monthly temperature dataset, CRU_TS2.1 (Mitchell *et al.*, 2004;

Mitchell and Jones, 2005). The E-OBS dataset has been released by the EU-FP6 project ENSEMBLES (Haylock *et al.*, 2008) for European daily gridded temperatures. The Hadley Centre and US National Climatic Data Center (NCDC) have created the HadGHCND daily gridded temperature dataset based upon maximum and minimum temperature observations (Caesar *et al.*, 2006). Table 1 gives detailed information such as spatial and temporal resolution and data periods for each dataset.

The APHRODITE project has released a high-resolution daily gridded precipitation dataset covering nearly the whole Eurasian continent (Yatagai *et al.*, 2009). Since 2006, we have made continuous efforts to collect rain-gauge data, build good relationships with many Asian countries and improve our quality control and interpolation in the project (Yatagai *et al.*, 2011, 2012. In this study, we have developed a high-resolution gridded daily mean temperature product for Asia by making use of APHRODITE project achievements.

2. Data and Analysis Procedures

2.1 Station data sources

Station daily air temperature data were compiled from the following kinds of sources,

1) GTS-based datasets,
 - Global Summary of the Day (GSOD) (data are available at the NCDC FTP site <ftp://ftp.ncdc.noaa.gov/pub/data/gsod> [last accessed on 20 June 2011])
 - Global Historical Climatology Network (GHCN2), (Peterson and Vose, 1997)

2) Pre-compiled datasets from the following organizations or groups,
 - Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment (GAME) Tropics <http://hydro.iis.u-tokyo.ac.jp/GAME-T> [last accessed on 20 June 2011]
 - Association of Southeast Asian Nations (ASEAN) Compendium of Climatic Statistics project

Table 1 List of gridded temperature datasets based on station observations. Spatial resolution denotes resolution in (longitude) × (latitude). All datasets consist of terrestrial surface air temperatures. The reference paper for each dataset is presented in Section 2.

Dataset	Region	Variable(s)	Resolution (spatial)	(temporal)	Period
CRU_TS2.1	Global	Tmx/mn/ave	0.5deg × 0.5deg	Monthly	1901-2002
HadCRUT3	Global	Tave(anomaly)	5.0deg × 5.0deg	Monthly	1850-present
UDel	Global	Tave	0.5deg × 0.5deg	Monthly	1900-2008
E-OBS	Europe	Tmx/mn/ave	0.5deg × 0.5deg 0.25deg × 0.25deg	Daily	1950-present
HadGHCND	Global	Tmx/mn	3.75deg × 2.5deg	Daily	1950-2007
APHRODITE	Asia	Tave	0.5deg × 0.5deg	Daily	1973-2007

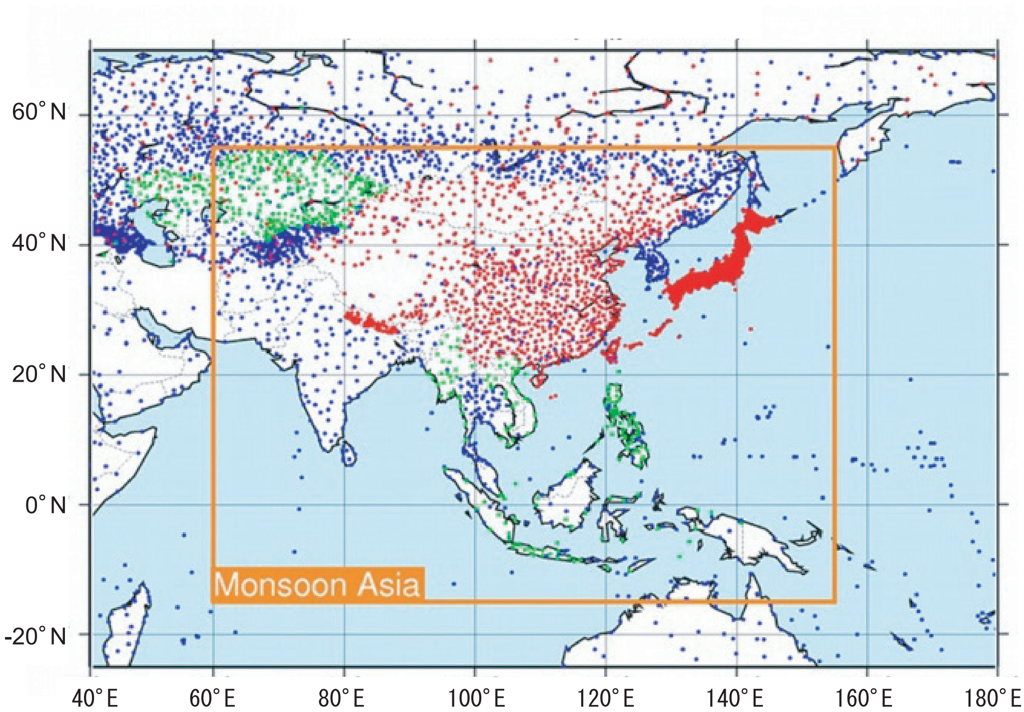

Fig. 1 Distribution of observation stations which passed our QC system for the year 1987. Blue: GTS based datasets. Green: pre-compiled datasets. Red: individual collections by the APHRODITE project. The orange boundary indicates the area of the Monsoon Asia gridded dataset, corresponding to the APHRO_MA precipitation dataset.

3) Individual collection by the APHRODITE project,
- Archives of national meteorological and hydrological services (NMHs) or individuals in Japan, China, Mongolia, Russia, Taiwan and Nepal.

GHCN and Nepal country data consist of daily maximum and minimum temperatures. We estimated daily mean temperature using Equation (1),

$$\text{Tmean} = (\text{Tmax} + \text{Tmin})/2 \quad (1),$$

where Tmin/max/mean are the daily minimum/maximum/mean temperature, respectively. Estimated daily mean temperature data are also used in the product and treated the same as daily mean temperature.

Figure 1 shows the distribution of temperature observations for 1987, in which a large number of daily reports were collected. The region analyzed was 60°E-155°E, 15°S-55°N, corresponding to APRHO_MA (Monsoon Asia) of the APHRODITE gridded daily precipitation product. Observations are dense, especially in Japan, Nepal and Taiwan. We collected 1.5 to 3 times the amount of data compared to GTS-based reports, upon which most available gridded temperature datasets are based. A time series of the number of observation records is shown in Fig. 2. The number of reports varies among years and seasons. It is constant from April to October, and then gradually decreases to a minimum in December and January since some stations are closed due to severe winter weather during that season. The number of reports is no more than half that of the warm seasons. It was smaller in 1951-1972 than in recent years. Reports in India before 1973 are found to be missing entirely. In this study, interpolation is applied to 1973-2007.

2.2 Quality control of observation data

A number of erroneous data have been found in collected observation datasets. Detection of errors is essential to the accuracy of the gridded product. We developed an automated quality control (QC) system for observed precipitation (Yatagai *et al.*, 2009, 2010; Hamada *et al.*, 2011). The system has been modified to detect erroneous temperature data. We did not apply comparison of time series of nearby stations, in our processes for detecting errors, since differences arising from elevation of the stations could be detected. Our QC process, modified from Hamada *et al.* (2011) is as follows.

1) Detection of outliers

Temperature outliers are removed by identifying days on which temperature exceeded six standard deviations from the mean with reference to all days within seven days of that calendar day over all available years. For example, to test the observation on 12 January 1975, we calculate the mean and standard deviation using observations from 5 January to 19 January for all available years. This method is based on the application by Haylock *et al.* (2008) to the observation data archive of Europe (E-OBS). They detected temperature outliers using five standard deviations from the mean within five days of daily temperatures in Europe. We used six standard deviations from the mean within seven days to detect temperature outliers because quite a few values in the tropics would be misjudged as temperature outliers when using the same parameters as Haylock *et al.* (2008).

2) Detection of constant values

We detected repetition of constant values, including zero, by five times or more. In cases where temperatures were recorded in 0.5 degree centigrade increments or the Fahrenheit scale, repetition by five times was frequently detected. We could not distinguish which of these may have been erroneous.

2.3 Interpolation of daily mean temperature

Our interpolation algorithm was based on the procedure for gridding observed precipitation used by Yatagai *et al.* (2009). As for temperature, since we did not collect monthly means or high resolution climate data, we tried to interpolate based on raw observed temperatures. The interpolation processes modified from Yatagai *et al.* (2009) is described below.

1) Temperature correction to mean sea level with a temperature lapse rate 6.0°C/km.
2) Interpolation of the corrected temperature onto 0.05 degree grids using a distance-weighting function based on Spheremap (Willmott *et al.*, 1985) with 100 km of effective radius. The number of observations is also calculated.
3) Temperature correction to GTOPO30 elevation (U.S. Geological Survey EROS Data Center, 1998) with a temperature lapse rate 6.0°C/km.
4) Regridding of the 0.05 degree data into a 0.50 degree grid product using area-weighted means.

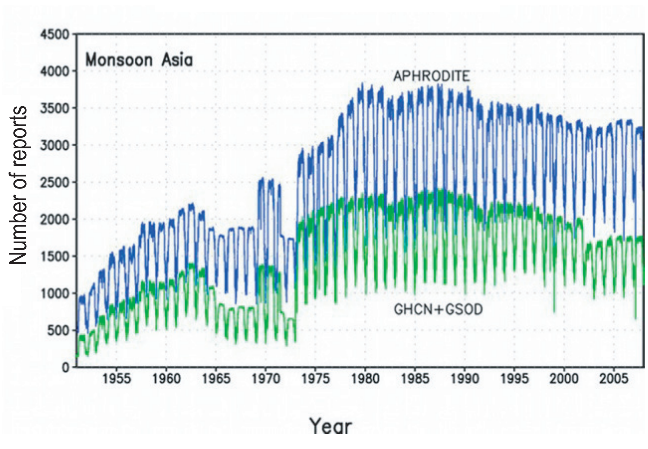

Fig. 2 Time series of the number of valid daily reports for the Monsoon Asia region (60°E-155°E, 15°S-55°N). Blue: number of all valid reports used in the APHRODITE gridded dataset. Green: number of valid reports from the GTS network. The GTS reports are included among the valid APHRODITE reports.

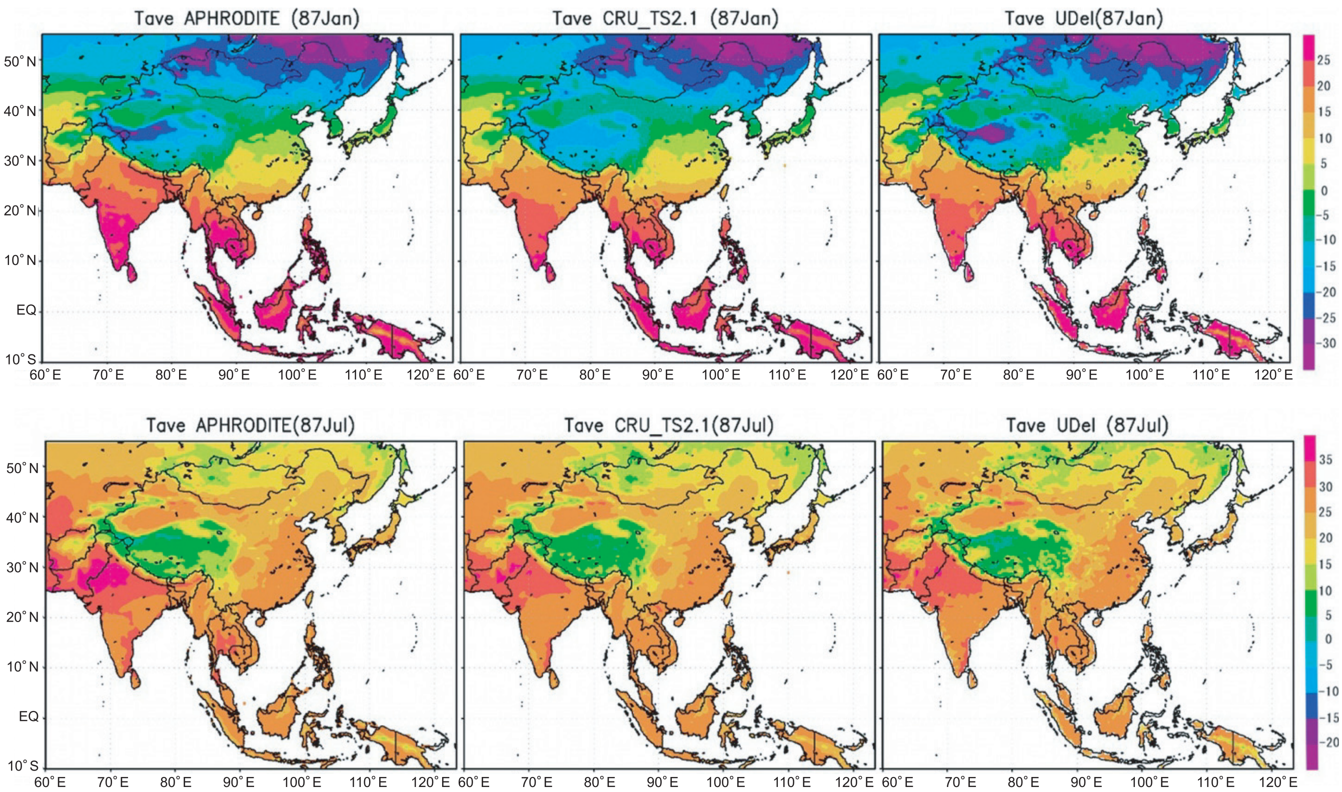

Fig 3 Monthly mean temperatures of January (upper panels) and July (lower panels) 1987, using the gridded datasets of APHRODITE (left) CRU_TS2.1 (center) and UDel (right). Unit: degrees centigrade.

3. Analyses of Gridded Daily Mean Temperature

3.1 Climatology

We derived climatology data and monthly means of daily mean temperature. The monthly mean daily mean temperatures of January and July 1987 derived from the datasets of APHRODITE (this study), CRU_TS2.1 and UDel are shown in Fig. 3. Differences between APHRODITE and the other datasets are within 3°C in most of the grids (figure not shown). The APHRODITE daily mean gridded temperature is comparable to those products based on monthly mean observations. The distribution of temperatures over the Himalayas and Tibetan Plateau resembles that of UDel. On the other hand, our temperature data are higher than those of the UDel and CRU_TS2.1 datasets in India for both winter and summer. Those differences may have resulted from differences in density of the input data. Original temperature data of Nepal and ASEAN were collected by the APHRODITE project whereas the observation data from NMHs of India were limited to precipitation.

3.2 Linear trends of maximum daily mean temperature over Monsoon Asia

Daily gridded products are useful for analyzing extremes such as the maximum/minimum daily mean temperature of the year or the number of summer days. Figure 4 shows linear trends of the average of the highest five daily mean temperatures each year for the period 1978-2007. A large positive trend is seen around Mongolia. It can be seen that the highest temperature of the year has been rising recently, especially in inland regions. The increasing trend in Mongolia is also seen in HadEX, a set of extreme indices released by the Hadley Centre (Alexander *et al.*, 2006). The relationship between the trend over Mongolia and changes in precipitation is an issue for future studies.

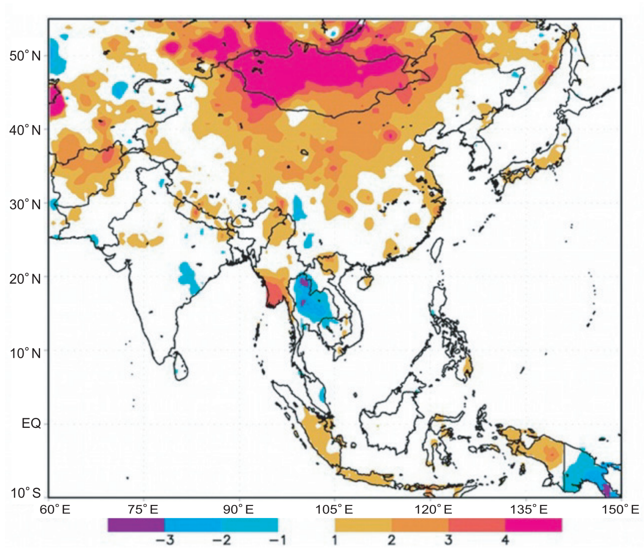

Fig. 4 Linear trends (°C/30yr) of averages of the five highest daily mean temperatures each year for the period 1978-2007.

4. Rain/Snow Discrimination Using APHRODITE Daily Gridded Precipitation Products

In managing water resources, especially in mountainous regions, it is essential, to judge whether precipitation is liquid or solid. Solid precipitation accumulates during winter and melts in spring. Accumulated precipitation melts and flows down in spring and the water is used by many people. Heavy rainfall in spring may cause floods. Since APHRODITE gridded precipitation is daily, the resulting highly resolved product with good representation of precipitation in Himalayas, together with rain/snow discrimination meet the needs of NMHs and hydrological model users.

4.1 Analysis procedure

Whether precipitation is melting or not depends on humidity as well as surface temperature. Matsuo and Sasyo (1981a, 1981b) found through observation and numerical modeling that melting of snowflakes follows a linear function of temperature and relative humidity. Melting versus non-melting condition is judged using the following equation,

$$RHcri = 92.5 - 7.5T \quad (2),$$

where RHcri is the critical relative humidity (%) and T is surface air temperature (°C). A line graph of Eq. (2) is shown in Fig. 5. Below the critical humidity threshold, precipitation is all snow and above it, it is rain, a mixture of snow and rain or sleet, according to conditions. Here, sleet is classified as melting. Rain/snow discrimination is made in accordance with the melting or non-melting condition of precipitation. It can be seen that precipitation at as much as 10°C above freezing level might not be melting under dry conditions.

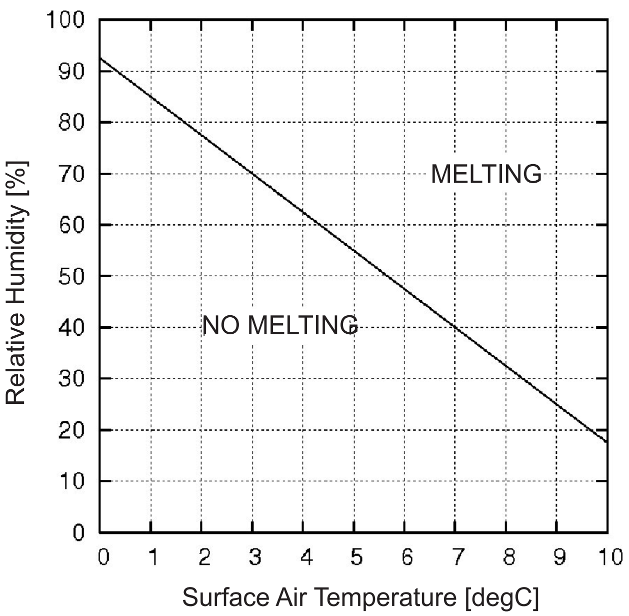

Fig. 5 Rain (melting)/snow (not melting) discrimination following Equation (2).

Most of the collected gauge data lack humidity information. Though some gauge data have humidity observations on the surface, the number of humidity records is too small to calculate surface humidity through the analyzed area. Therefore, we substituted relative humidity derived from a reanalysis product (2-m temperature, specific humidity at the surface and surface pressure) for observations in order to discriminate rain from snow. In this study we used reanalysis data derived from the European Centre for Medium-range Weather Forecast (ECMWF) Reanalysis product for the period of 1957 to 2002 (ERA40; Uppala *et al.*, 2005) and the Interim product for the period of 2002 to 2007 (ERA-Interim; Dee *et al.*, 2011). Variables such as 2-meter temperature and specific humidity were used for the period of 1973-2007, with a horizontal resolution of 1.5 degrees. Two-meter temperatures from the model surface were corrected to mean sea level, interpolated into a 0.05 degree grid and adjusted to GTOPO30 elevation. RH was also interpolated into the 0.05 degree grid.

Judging from Eq. (2), the value of 1 is given in cases where the temperature and RH of each 0.05 degree grid satisfy the condition of snowing. The ratio of 0.05 degree grid boxes judged as in a snowing condition for each 0.5 degree grid was then calculated, corresponding to the daily precipitation dataset.

4.2 Total solid precipitation amounts over Asia

To validate our rain/snow discrimination based on reanalysis of RH and daily mean temperature, we calculated the total solid precipitation amount (TSP) for the extended winter season (October to March) and compared it with satellite snow cover observations. TSP is defined as the total amount of precipitation proportional to the snowing ratio. Melting of snow during the winter and distribution of perpetual snow or mountain glaciers are not taken into account. Snow cover data are derived from Northern Hemisphere EASE-Grid Weekly Snow Cover and Sea-Ice Extent data which combine AVHRR, GOES and other visible-band satellite data, and passive microwave brightness temperature data of SSMR and SSM/I (Robinson *et al.*, 1993). We used the monthly and 1-degree grid interpolated version for the period of 1971-1995 edited by the Physical Sciences Division, Earth System Research Laboratory, US National Ocean and Atmosphere Agency (NOAA/ESRL PSD) [downloaded from http://www.esrl.noaa.gov/psd/data/gridded/data.snowcover.html]. Figure 6 displays TSP and snow cover observed by satellites in the extended winter of 1985/86. The TSP derived from observed temperatures is comparable to the snow cover observed by satellites in the regions where temperatures in the extended winter stay continuously below freezing. The distribution of TSP reproduces the extent of snow cover in Tibet and the Himalayas very well. The rain/snow discrimination based on our temperature product is a good indicator for monitoring solid precipitation in mountainous regions. On the other hand, it underestimates solid precipitation in

Siberia and Mongolia because the dry monsoon prevents solid precipitation from being caught by rain gauges. TSP is likewise overestimated in the extratropics such as Japan and South Korea, where it snows and rains (and melts) repeatedly during wintertime.

RH is derived from the temperature, specific humidity and surface pressure of ERA-40 and ERA-Interim. Figure 6 (c) displays TSP calculations based on rain/snow discrimination using reanalysis data, including daily mean temperature, in terms of consistency. In comparison with Fig. 6 (a), it is clear that TSP based on ERA-40 and -Interim is overestimated, that is, the reanalysis surface temperatures are lower than the observed ones.

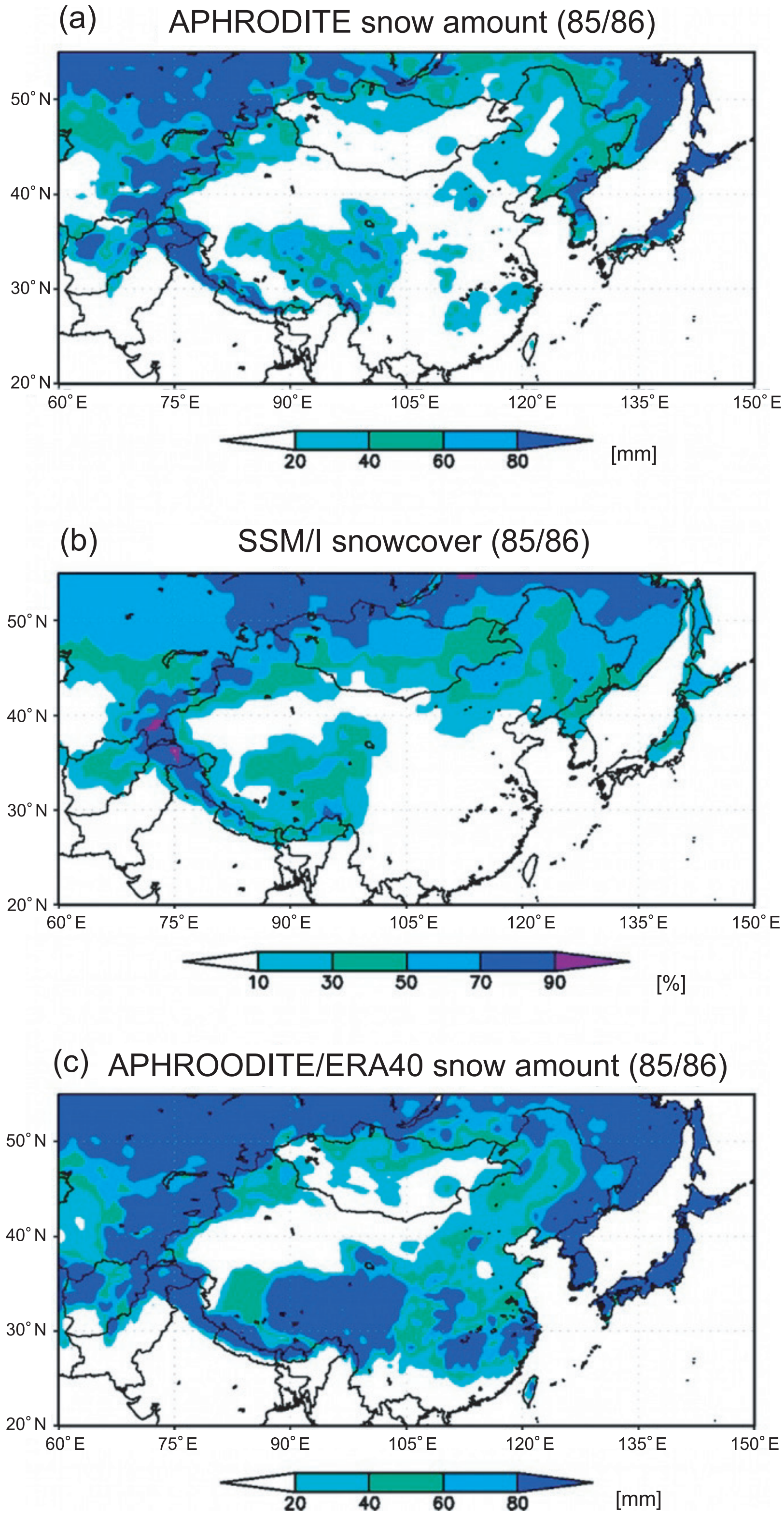

Fig 6 (a), (c) Total solid precipitation (TSP) amount (mm) (b) satellite-observed snow cover extent (%) averaged from October 1985 to March 1986. TSP has been calculated from APHRODITE (a) and ERA40 reanalysis daily mean temperature with APHRO_MA daily precipitation and snowing ratio (c).

5. Concluding Remarks

In this study we created a daily mean gridded temperature dataset of high resolution. The input data, QC and interpolation system developed for the APHRODITE precipitation product work properly with some modifications. The climatology data and monthly means of the product are comparable to those of other monthly mean gridded temperature datasets. This dataset is useful not only for improved evaluation of daily series of reanalysis data, satellite data and model outputs, but also monitoring of long-term change and statistical analysis of extreme weather.

Rain/snow discrimination is added to precipitation data as a ratio of 0.05 degree grids in a snowing condition in each 0.50 degree grid. The TSP amount for the extended winter season is derived for estimating the validity of the discrimination. It can be seen that the TSP amount reproduces the snow cover extent observed from satellites well. The rain/snow information is necessary for the accurate estimation of precipitation amounts observed from satellites, since microwave reflections from rainfall and snowfall differ. It also offers new applications to many research fields such as water resource management as use as an input in flow models.

The data periods of gridded temperature datasets might be too short for analyzing global changes. Station observations in East Asia (*e.g.*, Japan, China and Taiwan) are available for the period of 1951-2007. There is room to extend the analysis, currently limited to East Asia, and the data period. On the other hand, evaluation from a statistical point of view is insufficient. This will be an issue for future studies.

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