A Summary Report of the GAME-Tibet Synthesis

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1. Introduction

The GAME-Tibet project is an international land-atmosphere interaction field experiment implemented in the Tibetan Plateau both at the plateau scale and a meso-scale under the framework of the World Climate Research Programme (WCRP) / Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment (GAME). The overall goal of GAME-Tibet is to clarify the interactions between the land surface and the atmosphere over the Tibetan Plateau in the context of the Asian Monsoon system. To achieve this goal, the scientific objectives of GAME-Tibet are to improve the quantitative understanding of land-atmosphere interactions over the Tibetan Plateau, to develop process models and methods for applying them over large spatial scales, and to develop and validate satellite-based retrieval methods. GAME-Tibet is an inter-disciplinary, coordinated effort by filed scientists, modelers and remote sensing scientists in meteorology and hydrology to address these objectives.

GAME-Tibet started in 1996 progressed rapidly through two experimental phases, the pre-phase observation period (POP) in 1997 and the intensive observation period (IOP) in 1998. It contributed to international research activities in the related science fields by providing the all obtained data through the GAME-Tibet Data Information System (DIS) in 2000. It has now moved on to the most rewarding part of project efforts for the analysis of results and the testing of new theories, models and algorithms.

This summary report is intended to introduce the reader to GAME-Tibet briefly and to summarize some of the significant findings of the science teams of GAME-Tibet, emphasize scientific gains in reference to the GAME-Tibet objectives, and outline some future research directions.

2. Experiment Design

The process-, modeling-, and satellite-based studies were carried out in cooperation with the Chinese national Tibetan Plateau Experiment (TIPEX) and the China-Japan Cooperative Study on Asian Monsoon Mechanisms (JEXAM) under the framework of the Joint Coordination Committee (JCC). Taking into account the importance of seasonal variations in key processes, the experiments at two different scales, the plateau-scale experiment and the meso-scale experiment, were implemented. To understand one-dimensional land surface-atmosphere interaction processes with spatial and seasonal variations, and to develop and validate sophisticated models, the plateau-scale experiment was carried out basically using the automatic weather station (AWS) and radiosonde networks. The meso-scale experiment was implemented in the central plateau, corresponding to the upper reaches of the Nujian basin, by using two- and three-dimensional intensive observing systems. The characteristics of frozen ground vary over a wide range, from continuous permafrost in the north to seasonal permafrost in the south. The details of the experiment design is provided in "GAME implementation Plan" (GAME International Science Panel, 1998).

GAME-Tibet covered the north to south transect observation of the plateau-scale experiment and the whole meso-scale one. The following measurements were done during the IOP by the efforts of GAME-Tibet:

1) Land surface-atmosphere interaction
- Boundary Layer measurements by using the AWSs at the 14 stations, the PBL tower at Amdo, and the turbulent flux measurement at Amdo and BJ site.
- Intensive radiosonde observation at Amdo on selected days to investigate diurnal variations of the PBL in June, July and August.
- Barometer network for local circulation measurement.

2) Precipitation and cloud studies
- 3-D Doppler radar observation about 10 km south of Naqu from the end of May to the middle of September.
- Ground-based precipitation measurement using the rain gauge network in the mesoscale area.
- A snow particle measurement system and a microwave radiometer for measurement of total water vapor and cloud liquid water content at Naqu.
- A GPS receiver for water vapor measurement at Amdo.

3) Land surface monitoring by satellite remote sensing.
- Ground truth data collection of spectral reflectance, soil moisture, surface temperature and surface roughness along the north-south transect and in the west part of the Tibet.

4) Cold region hydrology including permafrost study
- Soil moisture and temperature measurements along the north-south and east-west transects.
- River discharge and evaporation measurements in the meso-scale area.

5) Isotope study on precipitation and surface water
- Isotope sampling for study on the origin of precipitation and its recycling along the north-south and east-west transects.
- Isotope sampling for understanding formation processes of stable isotopic composition in the meso-scale experimental field.

67 scientists, including 37 Japanese, 25 Chinese and 3 Korean, organized the 5 expedition teams for the 5 months IOP from May to September in 1998. Each team covered one month observation by staying in Naqu or Amdo for 35 day including the 5 days overlapping with the next team. The AWSs in the west Tibet were maintained by JEXAM.

3. GAME-Tibet Data Information System (DIS)

According to the GAME-Tibet data policy, "final validated datasets obtained during the POP and IOP will be open to the international science community by June, 2000", a data information system that could serve not only the GAME-Tibet investigators but also wider research communities was generated as a tool for archiving and distributing the complex datasets after the data collection efforts (Tamagawa *et al.*, 2001).

The level 2 data (quality checked and uniformly reformatted physical data associated with the detail information on site location, sensors, and observers) were transferred from the raw data obtained during the POP and IOP by the observers. All level 2 data were archived at the GAME-Tibet GIS and are opened through the user-friendly interface of WWW (http://monsoon.t.u-tokyo.ac.jp/tibet/index.html). Several pictures of the site and sensors and figures for the data quick view are also attached with the level 2 data at each site and its documentation for users' convenience.

4. Summary of Results

In this section, the results of the four science groups that were loosely arranged along disciplinary lines: atmospheric boundary layer, hydrology, modeling and remote sensing will be described.

4.1 Atmospheric Boundary Layer

The exchange of sensible and latent heat at the interface of atmosphere and the land surface was directly measured by eddy correlation method based on the measurement of atmospheric turbulence. Four flux sites, Amdo, MS3478, BJ (Naqu) and MS3637, were set up and the measurements were conducted during the IOP. In these sites the radiation budget, soil surface temperature, soil temperature profile, soil moisture profile and soil heat flux were also measured. These measured results serve as a consistent database to study land surface-atmosphere interaction.

With these results both diurnal and seasonal changes of the sensible and latent heat flux were clearly detected at Amdo where the longest and continuous data were obtained. Before the monsoon, the ground surface was very dry and the diurnal change of the surface temperature was as large as 50 degrees Celsius. The latent heat flux was very small and the sensible heat flux was dominant. As the ground surface became wet after the onset of monsoon, the latent heat flux increased and the sensible heat flux decreased. This change was in harmony with the decease of the ground surface temperature. Typical diurnal change of fluxes was also obtained for pre-monsoon, mid-monsoon and late-monsoon periods (Ishikawa *et al.*, 1999). Tsukamoto *et al.* (2001) compared the flux observation at four sites. They also showed that the sensible heat flux controls the development of the depth of mixing layer.

At these flux sites, Tanaka *et al.* (2001a, 2001c), Miyazaki *et al.* (2001), Wang (2001) and Kim *et al.* (2001) reported 'flux imbalance'. They suggest that many factors are responsible for the imbalance. They also stress the importance of mean vertical motion of air mass which may be induced by small scale organized disturbances. Tanaka *et al.* (2001c) gave a discussion on the measurement of soil heat flux. They roughly estimated the surface soil heat flux needed to melt the permafrost and to heat the soil layer from April to June using the soil moisture and temperature data. The required surface heat flux was about 30 W/m^2 on average, which was greater than that measured by soil heat plate. Tanaka *et al.* (2001b) examined the performance of a heat plate numerically and suggested that some correction is necessary to the soil heat flux. The surface imbalance problem has not yet been resolved. This severely limits the usefulness of the observed flux data.

The western Tibet is a region where the distribution of meteorological station is very sparse. Two automated meteorological stations were set up at Gaize and Shichuanhe and the continuous measurements of surface boundary layer and some soil variables have been conducted. Haginoya (2001) reported the surface meteorology and fluxes estimated by the

Bowen ratio method at these sites. Xu and Haginoya (2001) estimated the monthly averaged surface fluxes at fourteen Tibetan sites using conventional surface observation data. At Amdo site PBL tower observation has been continued after the IOP. Tanaka *et al.* (2001d) compute the bulk transfer coefficient for the sensible heat flux at the site by comparing the tower data with turbulent flux during IOP. The coefficient is obtained as a function of the bulk Richardson number. With this coefficient and the continued tower observation data they computed the sensible heat flux until July 2000. The data suggests the strong interannual variation, even the tower observation failed in Spring, when the sensible heat flux is largest in the year.

4.2 Hydrological Processes

The seasonal march in the Tibetan Plateau is characterized clearly by the rainy period and the dry one. During the rainy season, the active convection associated with a big amount of diabatic heat release plays an important role in the Asian summer Monsoon system. To understand and model the seasonal and interannual variability of the Asian summer Monsoon, it is important to address the hydrological processes, especially the origin and circulation of water vapor at large scale, the precipitation fields, and the land surface hydrological processes in the permafrost in the Tibetan Plateau.

4.2.1 Water vapor transport and water cycle in and around the plateau

Two approaches, the stable isotope study and the observation and modeling of the local circulation were introduced to understand the origin and transport of water vapor.The results of precipitation sample analysis for stable isotope study show the similar temporal variation of $\delta^{18}O$ in daily precipitation at the six sites in the meso-scale experiment field, the very low value of $\delta^{18}O$ in precipitation under the strong monsoon, and the higher $\delta^{18}O$ value associated with the convective precipitation (Tian *et al.,* 1999). The two characteristic feature of d-excess, which is often used for estimating the origin of the water, were found from the data obtained at Amdo (Numaguti *et al.,* 1999). One is an increasing trend of d-excess during continuous precipitation periods. The value is about 10 at the beginning phase of each precipitation event and over 20 in later stage. The other is an overall large value of d-excess, about 20, especially under a large-scale disturbance which embarked water vapor from south rather than from west. To explain this phenomena physically, a global isotope circulation model, which does not include fractionation process, was introduced. It suggests the importance of cloud process for high d-excess value.

Kuwagata *et al.* (2001) pointed out an important role of the mountain-valley circulation with the very typical diurnal variation in the water vapor transport in the Tibetan Plateau. Based on the radiosonde observation, the precipitable water decreased in the daytime at the valley area, while that increased during daytime over the mountain range. The magnitude of the diurnal variation ranged from 2 to 6 mm, which varied with time and space. The ECMWF 4DDA product also shows significant daytime decrease of precipitable water appeared in the valley regions around Naqu. Analysis of the GMS-5 water vapor channel image also indicated overall daytime increase of water vapor over the Plateau, but with some valley regions of daytime decrease. This diurnal variation of water vapor was also quantitatively simulated by a two-dimensional numerical model.

4.2.2 Precipitation fields

The intra-seasonal variation of the convective activity at the plateau-scale depends deeply on the variations of mid-latitude baroclinicity and the Tibetan anti-cyclone, while the spatial and diurnal variations of the convection are closely related with the mountain-valley topography in the plateau (Ueno, 1998; Kurosaki and Kimura, 2001). There are three types of meso-scale disturbances: the convective echo structure in daytime associated with vortex generation mechaaanisms, the stratified echo in nightime, and the combined system with frequent weak rainfall (Uyeda *et al.,* 2001; Shimizu *et al.,* 2001).

4.2.3 Land surface hydrological processes in the permafrost

The hydrological variability of permafrost was investigated both in the plateau- and meso- scales in the Tibetan Plateau. The plateau scale soil moisture distribution and its seasonal and interannual variations were observed by the space-based passive microwave remote sensing data. The thawing and freezing processes and their spatial and interannual variations were studied in the plateau scale by using the ground-based soil moisture and temperature profiles and atmospheric forcing data. The satellite synthetic aperture radar (SAR) data is used for detecting the surface soil moisture heterogeneity in the meso scale. A wide range of the meso-scale distribution of soil moisture in the permafrost region was examined by the observed data at several flat areas and on a slope (Koike *et al.,* 2001b).

The SSM/I surface soil moisture product shows the seasonal march of the soil moisture distribution in the Tibetan Plateau. The north-east and center parts of the plateau become wet in June while the other part is still dry. The wet area expands to north and west in July and to south in August. The center part keeps wet during the summer. Regarding to the spatial and temporal variation of soil moisture and temperature profiles along the Qinghai-Xizang highway, very clear spatial variability was identified, that is, the dryer and colder north and the wetter and warmer south, while any clear interannual variation between in 1997-1998 and 1998-1999 was not seen (Koike *et al.,* 2001b). The seasonal march of the soil moisture and temperature profile variation at the experimental slope suggested that the wide range of the soil moisture distribution along the slope, that is, wet valley and dry hilltop, was caused by the permafrost hydrological processes on the slope associated with the surface and sub-surface water flow along the slope and the surface energy budget differences due to the soil moisture distribution (Ishidaira *et al.,* 1999). In addition, the wide range of soil moisture distribution and its significant seasonal variation were also observed even at the flat areas. The wetter area appeared in the concaves, while the dryer in the convexes. Hirose *et al.* (2000) pointed out the importance of the interactive processes between the micro-topography and soil moisture in the permafrost region. The detention in the concaves keeps the active layer shallow due to the larger thermal capacity of soil and the larger amount of latent heat flux in the wetter area while the active layer grows more rapidly in the convexes due to the larger amount of soil heat flux.

Intensive observation of pressure head by using tensiometers in subsurface water and sampling of subsurface water at multiple depths were performed to investigate subsurface flow process in monsoon season, 1998. The pressure head of subsurface water ranged from -10 to -100 cmH_2O and zero flux plane was often observed above the depth of 30 cm. The groundwater recharge was very active during this period, thus the groundwater table rose up to the depth of 55 cm in the beginning of September. The δD and $\delta^{18}O$ of shallow subsurface water varied markedly with precipitation and evaporation, whereas those of groundwater were stable. The mean $\delta^{18}O$ of groundwater was 3.4 ‰ higher than the volume weighted mean $\delta^{18}O$ of precipitation. The difference of $\delta^{18}O$ between the groundwater and the precipitation would be caused by isotopic enrichment along with evaporation from the soil surface, and 27 % of precipitation might be lost by evaporation from the soil surface (Tsujimura *et al.*, 2001).

4.3 Modeling

Field observations under a wide range of meteorological and hydrological conditions motivated the development and testing of key process models describing soil moisture and temperature profiles, flux exchange at the surface-atmosphere interface, boundary layer flux profiles, radiative transfer, cloud formation and rainfall. In addition to one-dimensional modeling of land-atmosphere interaction, meso-scale and regional-scale modeling, and methods for scaling up land surface process were investigated.

4.3.1 One-dimensional modeling of land-atmosphere interactions

A new frozen soil parameterization in the land surface scheme was developed by incorporated a modified approximation Stefan solution in the framework of the land surface model - SiB2 to calculate the frost/thaw depth over time, and to estimate the soil moisture and temperature profiles during the freeze-thaw cycle. The structure of the soil model in SiB2 is kept but the governing equations of water balance and surface heat balance are modified to account for soil freezing/thawing. The model was calibrated and validated using the GAME-Tibet observations (Li and Koike, 2001). The new model estimates the frost depth more precisely, predicts the soil temperature reasonably and phase transition time more realistically than original SiB2.

An one-dimensional heat and water flow model was developed to simulate soil moisture and temperature profiles and surface fluxes in detail (Ishidaira *et al.*, 1998). Regarding to heat flow, thermal diffusion in soil is calculated with fine vertical resolution by introducing the thermal conductivity and the heat capacity which are considered as the function of volumetric water content. The ground surface temperature is calculated by surface heat balance and is used as the upper boundary condition. The water transport is expressed by a 5-layer soil model, in which the water budget is calculated by using the change of liquid water in the layer, the amount of water transport between layers, the change of liquid water content associated with thawing and freezing of permafrost and the deifference of the hydraulic conductivity and in the soil matrix potential.

To consider the soil moisture – micro-topography interaction, a detention storage component, which affects on the surface energy budget, was added into the one-dimensional model (Hirose *et al.,* 2000). The performance check of the soil moisture-microtopography interaction component was done, and indicated the variability of surface soil moisture that is consistent to the observed one.

4.3.2 Two- and three- dimensional meso- and regional- scale modeling

To simulate the seasonal variation of the diurnal cycle of the cloud activities over and around the plateau derived by GMS, Regional Atmospheric Modeling System (RAMS) developed at Colorado States University (CSU-RAMS) was applied in two dimensions domain with north-south direction (17N-42N, 90E) (Kurosaki and Kimura, 2001). The characteristic diurnal cycles of cloud, less or no cloud in the morning of the pre-monsoon period and low-level cloud in the morning of the monsoon over the Tibetan Plateau, and frequent low-level cloud over the southern slope of Himalayas, were simulated well.

Yoshikane *et al.* (2001) conducted numerical experiments to investigate the mechanism of the Baiu front by using CSU-RAMS. The location of the Baiu front is speculated to be quite sensitive to the zonal mean flow. The Baiu front accompanied by the low level jet was also represented by numerical experiments without topography, which suggests that the Baiu front could be reproduced by two factors alone, the zonal mean field and the land/sea contrast. The orography, including the Tibetan Plateau, intensifies the precipitation of the Baiu front, especially when the upper-level jet is weak and located northword.

4.3.3 Development of methods for scaling up land surface process models

Due to the non-linear relationship between evaporation and soil moisture, calculated evaporation by using spatially averaged soil moisture is smaller than actual one under dry condition and larger under wet condition. The effects of the wide range of the soil moisture distribution due to the presence of detention storage in the Tibetan Plateau is expressed by a linear function of the standard deviation of soil moisture (Hirose *et al.,* 2000). This result suggests a method for scaling up heterogeneous land surface processes.

4.4 Remote Sensing

Due to the dynamics and constantly changing behavior of the parameters inherent to energy and water cycle processes, and because of the relatively few ground observation stations over the Tibetan Plateau, efficient monitoring and continuity in space and time sampling over the complete plateau are only possible by satellite remote sensing. In turn, the field observations and process studies help to serve as sources of ground-truth information for satellite-based retrieval algorithms. To meet the objectives of the process and modeling studies reported above, GAME-Tibet focused on the development and validation of satellite algorithms for precipitation, radiation budget, surface fluxes, soil moisture and snow.

4.4.1 Precipitation

Quantitative estimation of spatial distribution of precipitation in the Tibetan Plateau is one of the important aspects for understanding the function of water cycle processes and estimation of water resources. Ueno *et al.* (2001) developed an SSM/I algorithm for rainfall by introducing a new scattering index into the existing scattering algorithm detect the weak intensity of precipitation in the plateau. The accumulated monsoon precipitation distribution in 1998 obtained by the new algorithm shows better agreement with the GMS estimated precipitation in the plateau area without screening of the surface condition.

A new algorithm for precipitation over land by deriving the optical thickness from the brightness temperature of the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) (Fujii and Koike, 2001). The effect of land surface controlled by soil moisture emissivity on radiation transfer is taken into account in this algorithm. This means that soil moisture can be estimated at the same time in addition to precipitation. Based on a microwave radiative transfer equation, two indices, *Index of Soil Wetness* (ISW) and *Polarization Index* (PI), which remove the effect of land surface physical temperature, are introduced into the algorithm. Surface roughness effects on land surface emissivity are included by using the polarization mixing ratio and the surface roughness. As the results of the algorithm application to the GAME-Tibet meso-scale experimental field, the estimated optical thickness and soil moisture are in good agreement with the patterns of precipitation observed by the 3D Doppler radar, and the observed soil moisture at 4 cm in depth, respectively. A unique relationship between the optical thickness and the observed precipitation by rain gauges can not be seen due to the emission from precipitation layer, the temporal sampling of TMI observation, and the profiles of hydrometeors. A reasonable relationship between the estimated optical thickness, and observed precipitation by rain gauges is obtained after 10 days of longer temporal averaging.

We can produce the diurnal cycle of rainfall because the TRMM satellite has a non-sun-synchronous orbit. Area-averaged rain rate, averaged storm height, proportion of convective rain to all rain in the rectangular area, and the rain area to the rectangular area were calculated from the TRMM Precipitation Radar (PR) data. This rectangular area almost covers the overlapping area of the Naqu hydrological basin and Doppler radar coverage. Totally 87 snapshots of rainfall events were obtained by TRMM PR during the IOP. The results indicate that precipitation with a high storm height developed in the afternoon while the rain area was not large. In contrast, large startiform precipitation developed in the evening and night and the largest amount of rainfall appeared in the night (Shimizu *et al.,* 2001).

4.4.2 Radiation budget and surface fluxes

Estimation of the energy exchange distribution between the land and atmosphere is one of key issues of the GAME-Tibet project. The fluxes of radiation, soil heat, sensible heat and latent heat were estimated by combining the in-situ data, NOAA14 Advanced Very High Resolution Radiometer (AVHRR) data and the radiation transfer model, MORTRAN (Ma *et al.,* 2001). The results show that 1) the very wide range of fluxes due to the complex surface conditions, 2) the estimated components of energy budget are in good agreement with the observed ones except the latent heat flux at one site, 3) the large value of the net radiation due to the high elevation and the land cover condition.

4.4.3 Soil moisture

A new algorithm based on microwave radiative transfer theory was developed for soil moisture using passive microwave sensors (Koike *et al.,* 2001a). It was applied to the data from the TMI and evaluated by using the field data obtained during the IOP (Koike *et al.,* 2001b). The estimated soil moisture corresponds reasonably to the soil moisture observed by the TDR sensor at 4 cm in depth. Just after the heavy rainfall, the satellite derived soil moisture is greater than the ground observations because the TMI only detects the surface moisture, which is much wetter than the observations at 4 cm depth. Conversely, during dryer periods the algorithm underestimates because the soil surface dries more rapidly. The monthly averaged diurnal cycle of the land surface physical temperature calculated by the proposed algorithm shows the same pattern as the ground observations, however with several K bias. The estimated water content of the vegetation also corresponds well to the observations, with an accuracy of 10% or less.

A time series data from the Japanese Earth Resources Satetlite-1 (JERS-1) Synthetic Aperture Radar (SAR) at L-band was used an algorithm for surface soil wetness at fine spatial resolution by using surface roughness measurements during the POP and a microwave backscattering model (Tadono *et al.,* 2000). A surface roughness map was generated by the JERS-1 SAR winter data by applying the scattering model and the relationship between two surface parameters under the perfectly dry condition. A soil moisture distribution in summer was estimated by applying the scattering model and the surface roughness map to a summer SAR data. The estimated distributions of soil moisture in the Tibetan plateau qualitatively correspond to those obtained by field measurement.

4.4.4 Snow

An algorithm for snow was developed by a relationship between the land surface radiation and snow properties derived from the radiative-transfer theory on a scattering dielectric layer over a homogeneous half-space. The total land surface brightness temperature is the sum of the direct component and diffuse component, which corresponds to the reflected sky radiation and the thermal radio emission from the snowpack and soil, and the radiation scattered from the direct and diffuse fields, respectively. By assuming snow grain size, snow density, and radiation from the soil-snow interface, brightness temperatures at two different frequencies, 19 and 37 GHz, were calculated by inputting snow depth and physical temperature. This algorithm was applied to the data from the

TMI and evaluated by using the field data obtained in the winter of 1997-1998 (Koike *et al.,* 2001a).The estimated snow physical temperature is in good agreement with ground observations made with infrared thermometers. Snow depth was not validated because of the lack of adequate ground observations.

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