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Snow temperature measurements at Vostok station from an autonomous recording system (TAUTO): preliminary results from the first year operation

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Temperature gradients in the upper layers of the snow pack are of importance for studying the emissivity properties of the snow surface with respect to microwaves used in remote sensing as well as for the heat and mass transfer in snow thickness. Gradients drive the initial snow microstructure metamorphisms that probably influence the firn properties in regard to air molecules fractionation and the air bubble enclosure process at close-off depths. As a contribution to investigation of these problems and following J.-M. Barnola initiative, we developed an autonomous recording system to monitor the temperature of the upper layers of the snow pack. The instrument was built to be autonomous and to be continuously operating within environmental conditions of the Antarctic plateau and the polar night. The apparatus which monitors temperature from the first 10 m of snow by 15 sensors of a «temperature grape» was set at Vostok station during 55th Russian Antarctic Expedition within the frame of the French Russian collaboration (GDRI Vostok). From the available hourly measurements over the first year, we present preliminary results on the thermal diffusive properties of the snow pack as well as some character of the temperature variations on the Antarctic plateau.

Introduction

Polar ice core provide a wealth of information on climate and on its dynamics over period of time encompassing by now the last 0.8 million years [6]. The most salient result from the ice core studies is the close correlation between temperature and greenhouse gases (CO_2, methane) firstly observed from the Vostok ice core over one then four climate cycles [2, 17]. This correlation is now extended over the last 0.8 million years [13, 21], and the information that present-day greenhouse gas levels are unprecedented high had a large impact on several IPCC assessments on Global Climate Change [10].

While climate proxies (e.g. water isotopes, chemical elements, dust...) are imprinting the upper snow layers at a given time, gases are entrapped in air bubbles 50 to 120 m below surface at the close off depth and within layers 1000 to 6000 year older. The depth and age difference estimations are very challenging as they depend on densification processes which are variable with site temperature and accumulation [9, 15, 19] but also from various factors. Among observations, the ice core records of O_2/N_2 ratio and the air volume contains signal variability at orbital frequencies [3, 18] suggesting the firn properties in depth may keep memory from solar radiation in initial stage of metamorphosis of upper snow layers [12]. Surface snow layers are very porous and are subject to metamorphosis due to combined effects of solar radiation, weather conditions and strong daily temperature gradients. Transfers of heat, water vapor and gases are intense and they contribute to firn ageing and post-depositional effects with fractionation of water isotopes [4, 5, 11], the photolysis of chemical elements as nitrates within the very upper layers [7], and the gravitational fractionation of gases in depth [20].

Temperature and properties of the upper snow layers are also of importance with respect to the remote sensing observations of Polar Regions, for interpreting the brightness temperature time-series which are acquired routinely by passive microwave [16]. Of interest is the 19 GHz brightness temperature which is sensitive to snow temperature at depth, up to a few meters [22] but also from the microwave penetration depth which is unknown. In this respect, in-situ temperature measurements for the upper layers at a site represent a «field truth» and will help for modeling the emissive properties of the snow pack.

As a contribution to these problems, and following a project promoted by J.-M. Barnola (deceased 2009); we developed an autonomous system for continuous recording the temperature variations of the upper layers of the snow pack to be deployed at some selected sites in Antarctica. One instrument was deployed at Vostok station in the frame of the Russian French collaboration (GDRI Vostok). Here we present the data from the first year of operation along with preliminary values for thermal diffusivity and some character of the temperature variations during winter.

Fig. 1. TAUTO recording system and its setting in the field.
Top – insulated box containing the central electronic unit, and details of the electronic cards with low energy consuming microprocessor; bottom – setting the instrument in a pit at Vostok station during summer 2010 (RAE 55) and data downloading operation during summer season (RAE 56)
Рис. 1. Автономная регистрирующая система TAUTO и её установка в полевых условиях.
Вверху – термоизолированный бокс, вмещающий основной электронный блок и элементы электронной карты с энергосберегающим микропроцессором; внизу – установка системы в шурфе на станции Восток летом 2010 г. (55-я РАЭ) и скачивание накопленных данных в летний полевой сезон 56-й РАЭ

Methods and results

The TAUTO recording system. Autonomous and automatic digital recording system was built at Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE) and customized for operating within the low temperature environment of the Antarctic plateau. The «Temperature AUTOmatic (TAUTO)» recording system uses a low power consummation microcontroller which scrutinizes voltage drop from up to 64 platinum resistances (PT100). It has capability for data storage for years on flash disk and for transmitting the data to ARGOS communication system satellite. The electronic hardware is composed from three main cards: the central unit, the memory and the transmitter (Fig. 1). All is fitted for operating by −40 °C, and placed in a sealed insulated box buried in snow. Miniaturized heating systems allow pre-heating of the most temperature sensitive electronic chips during a programmed short time before the cycle of measurements. The power supply is given by two 10 watts solar panels set at surface and six 60 Ah buffer batteries buried in snow to prevent the very low temperature during winter. The system is fitted to operate in full autonomy of energy during 4 months and to overcome the polar night.

Attention was paid to configure the temperature probes. The manufactured Platinum Resistance Temperature (PRT) detectors have been chosen for both the relative small size and the accuracy (IEC751 (1983), 1/10 DIN) of $\pm(0.03 + 0.0005 \cdot |T|)$ °C. This DIN standard interchangeability for Pt resistance temperature detector is only for the uncounted sensor, and is higher for mounted probes (Pt sensor with metallic sheath, 4 lead wires, and a connector). So, we measured the effective relative accuracy of the mounted PRT probes: ±0.15 °C on the range of our measurements (−20 °C to −90 °C).

Each of the 15 sensors was connected to a small diameter (1.5 mm diameter) 4 wires Teflon® line (white color) of various lengths (up to 15 m) and assembled together to make a so-called «temperature grape». The grape is connected to the main unit.

Improvements of sensor calibration were conducted at LGGE in order to reduce the interchangeability of the PT100. For this relative inter-calibration, the 15-sensors from the grape were measured all together with one reference temperature sensor (accuracy of ±0.05 °C with respect to absolute temperature) at 3 different temperatures (~−30, −45 and

−58 °C). To a given stable condition, the 15-sensors mean resistance value was calculated. A correction factor was applied to each resistor in order to provide a resistance value closest to the mean stack value. A tabulated version of the Callendar-Van Dusen equation is used to calculate temperatures from resistances. This calibration stage between all sensors resulted after corrections with a relative accuracy of ±0.05 °C and an absolute precision better than ±0.1 °C (comparison with our calibrated reference probe).

Each hour the system wake-up automatically from a real time clock (RTC), and after 2 mn of warm-up, a new cycle of measurements starts. Time is tuned from a GPS receiver. A low excitation current (1 mA) is applied to PT100 through (2 wires) for minimizing self-heating of sensor while the voltage drop across the sensor is measured on the 2 other wires by a high impedance amplifier. The 4 wires resistance readings are multiplexed one by one during 1 sec. The analogic signal is converted to digital values then to resistance value (and temperature). The data are stored in an 8 Mo flash memory and transmitted to satellite (ARGOS system). ARGOS data are weekly downloaded to LGGE and to AARI from the reception center in Toulouse (France). The power consumption is 60 mW as background, then 100 mW during 2 mn every hour to scan sensors for temperature measurements, then 30 mW for 2 mn twice a day for a GPS receiver used for the time synchronization, and finally 250 mW during 2 sec every 200 sec of the emission to ARGOS. The redundancy of emission is 2 or 3 times and reduces download errors.

The whole system has been set in 2010 (55^{th} Russian Antarctic expedition) within the clean sector of Vostok station. A 3 m deep pit was dug for burring the electronic unit and batteries and setting the sensors (see Fig. 1). From surface to 200 cm depth, each sensor was introduced in undisturbed snow layer from the pit wall by using a long needle pushed horizontally up to 30 cm inside the wall. The pit was then carefully filled with soft snow. Deeper sensors have been lowered into a nearby drill hole. The sensors have been set at following depth: closest to surface (~0 cm), then at 5, 10, 15, 20, 30, 40, 50, 60, 80, 90, 140, 200, 500 and 1000 cm. Transmission of hourly data started to operate efficiently soon after the setting and 99% of the data were transmitted. For each hour the system generate, store and transmit in 57 octets: the time, the temperature from the 15 sensors, the signal from a resistor having a low sensitivity to temperature (3 ppm per °C change) and temperature inside the box. However, during winter (June and July) satellite transmission stopped likely because the very low temperature or the accumulation of hoarfrost on the solar panels. The full record was however downloaded manually from flash memory following summer season (RAE 56) and almost 100% of the data have been recovered.

Temperature records. The temperature records (raw data) are shown on Fig. 2 for different depths. The surface temperature record is dominated by the large (~50 °C) amplitude of the seasonal cycle (minimum −76 °C, maximum −28 °C) while the amplitude attenuates with depth. Reliability of the data set is good and only few errors affect some lines. The errors appear as wiggles values in the data (see Fig. 2) and noise, which can be detected and corrected for the smooth records (e.g. sensors buried in snow). During summer period (see Fig. 2, B) the very upper sensors of the first ~30 cm record the daily oscillations paced by the sun. During winter (April to September), daily oscillation vanishes, the upper layers temperatures drop below ~−70 °C, while rather rapid changes by up to 20 °C appear within a few days or week (see Fig. 2, A) before returning to cold conditions. This phenomenon is repeated several times during the winter suggesting a pseudo periodic «weekly» component (hereafter weekly wave), while atmospheric and weather changes are generally chaotic instead periodic. This salient variation is recorded in depth down to 140 cm.

Signal analysis. Indeed the firn temperatures follow the weather conditions at surface and the records are irregular. As a preliminary approach, signals in depth are assumed to be a mixture of different quasi-periodic oscillations. Amongst them we selected the most prominent ones (daily, weekly, annual waves) by using a Gaussian filter from the «Analyseries software» [14]. To do so, after removing the few errors in data set, the hourly values were re-sampled to a step of 10 values per day. We then applied filters with a passing band expressed in cycle per day: 0.0033 cpd ±0.0005 cpd for the annual component, 1 cpd ±0.25 cpd for the daily component which is well present during the summer season, and 0.12 cpd ±0.06 cpd for the weekly component which is mostly present during winter.

The records of the daily and quasi-weekly component are shown on Fig. 3 for several sensors, displaying the progressive attenuation of signal amplitude as well as an increasing phase-lag with depth. For the daily component recorded during the summer season, amplitude become negligible below ~40 cm depth. For the quasi-weekly wave, depth penetration is 140 cm. For the annual wave (not shown), the amplitude of the filtered component at 140 cm depth is about 10 °C and already the half of extreme temperature amplitude signal recorded between winter and summer in surface. Amplitude becomes 8.5 °C at 2 m, 2.2 °C at 5 m, and 0.4 °C at 10 m and therefore still significant at this depth. The propagation in solid of a sine temperature signal $A(0, t)$ with amplitude A_0 and a period T, applied over an infinite surface is attenuated and delayed with depth (x). The solution $A(x, t)$, is given by the Fourier heat transfer equation:

$$A(0, t) = A_0 \sin(\omega t); \quad (1)$$

$$A(x, t) = A_0 \exp(-\alpha x) \cdot \sin(\omega t + \alpha x), \quad (2)$$

where $\omega = 2\pi/T$; $\alpha = (\omega/2\varkappa)^{0.5}$; $\varkappa$ is the bulk thermal diffusivity expressed in m^2s^{-1} or in $cm^{-2}s^{-1}$, and it writes

$$\varkappa = 0.5\omega/\alpha^2, \quad (3)$$

$\varkappa$ is linked to the thermal conductivity (λ) by the relationship:

$$\varkappa = \lambda/\rho C_p, \quad (4)$$

where λ is the thermal conductivity (in $Wm^{-1}K^{-1}$), ρ the mass density ($kg \cdot m^{-3}$) and C_p the ice heat capacity

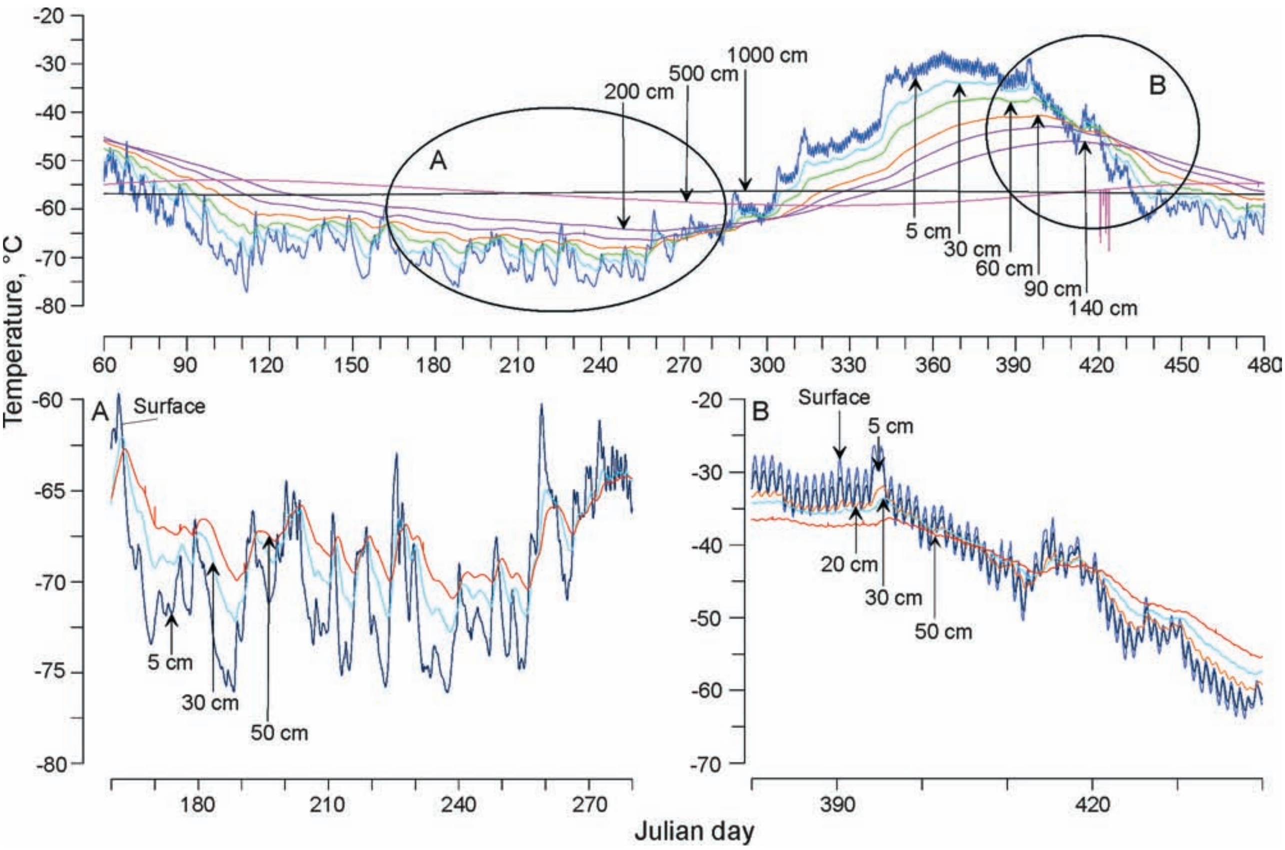

Fig. 2. Firn temperature recorded at different depths from February 2010 to February 2011 (raw data), and zooms for winter period (A) and summer period (B).

Depths of sensor are 5, 30, 60, 90, 140, 200, 500 and 1000 cm (top figure); 0, 5, 30, 50 cm (zoom A); 0, 5, 20, 30, 50 cm (zoom B) respectively. January 1st 2010, 00H:00 is taken as origin of the date. A few outliers occur in the records and are likely digit bugs from the TAUTO recording system

Рис. 2. Температура снега, зарегистрированная на различных глубинах в период с февраля 2010 г. по февраль 2011 г. и увеличенные участки записи, соответствующие зимнему (A) и летнему (B) периодам.

Верхний рисунок показывает данные датчиков, расположенных на глубинах 5, 30, 60, 90, 140, 200, 500 и 1000 см, рис. A – 0, 5, 30 и 50 см, рис. B – 0, 5, 20, 30 и 50 см. За начало отсчёта времени выбрано 00:00 1 января 2010 г. Отскакивающие значения, которые иногда появляются в записи, скорее всего, ошибки регистрирующей цифровой системы TAUTO

($Jkg^{-1}K^{-1}$); $\varkappa$ is ~1 to $10\cdot10^{-3}$ $cm^2\cdot s^{-1}$ (or $1–10\cdot10^{-7}$ m^2s^{-1}) for snow, and λ ~0.015–0.1 $Wm^{-1}K^{-1}$ for snow mass density of 300 $kg\cdot m^{-3}$. From the temperature records, values for $\varkappa$ are deduced from the spectral analysis (cross correlation) of two records, and phase lag versus signal period is calculated. Alternatively, a mean value of diffusivity for a given period could be evaluated from equation (3) from attenuation factor (α). For a given layer located between two sensors at depth x_1 and x_2, the correlation plot between two sensors lead to the amplitude ratio. This latter can be also deduced for a selected time duration from the ratio of standard deviations of two signals (σ_{A1}/σ_{A2}) and α writes:

$$\alpha = \mathrm{Ln}(\sigma_{A1}/\sigma_{A2})/(x_2–x_1). \quad (5)$$

Signal attenuation and thermal properties. The phase lag and the diffusion coefficient could be deduced from correlation between the records from two adjacent sensors (Fig. 4). The displays (Lissajous curves) are ellipses with width and orientation in quadrant depending on phase lag between the two signals. For 5 cm and surface sensors, the two signals are almost synchronous (narrow ellipse) and the amplitude ratio of daily wave is 0.97 during the first 20 days after launching the instrument, then ratio reduces to 0.65. This evolution is likely due to the burring by snow fall or wind drift or the change of the environment of the first sensor. Between 10 and 5 cm sensors, the amplitude ratio is 0.54, between 20 and 15 cm, the ratio is 0.74. Between 30 and 20 cm, amplitude ratio is 0.15 only and the apparent figure indicates the two signals are in quadrature ($\pi/2$ phase lag for daily wave corresponding to a time lag of 0.25 days or 6 hours).

For deeper layer, the same approach was applied by using the quasi-weekly wave which penetrates deeper. The bulk diffusivity is shown on Fig. 5. It varies from 2 to $15\cdot10^{-3}$ cm^2s^{-1}. For deeper layer, one have to use longer wavelength (annual) but the available record is

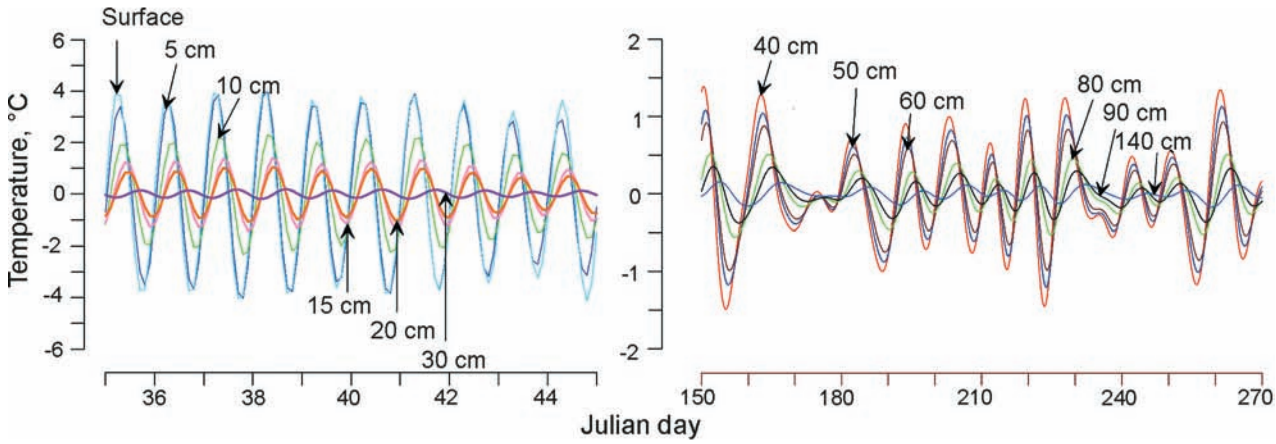

Fig. 3. Gaussian filtered component of temperature records.
Left – daily signal component for layer from 5, 10, 15, 20, 30 cm depth; right – quasi-weekly (8 days) signal component from 40, 50, 60, 80, 90 and 140 cm depth

Рис. 3. Компоненты спектра температурного временного ряда, выделенные с помощью гауссовского фильтра.
Слева – суточный компонент вариаций температуры на глубинах 5, 10, 15, 20, 30 см; справа – квазинедельный (8 дней) компонент вариаций температуры на глубинах 40, 50, 60, 80, 90 и 140 см

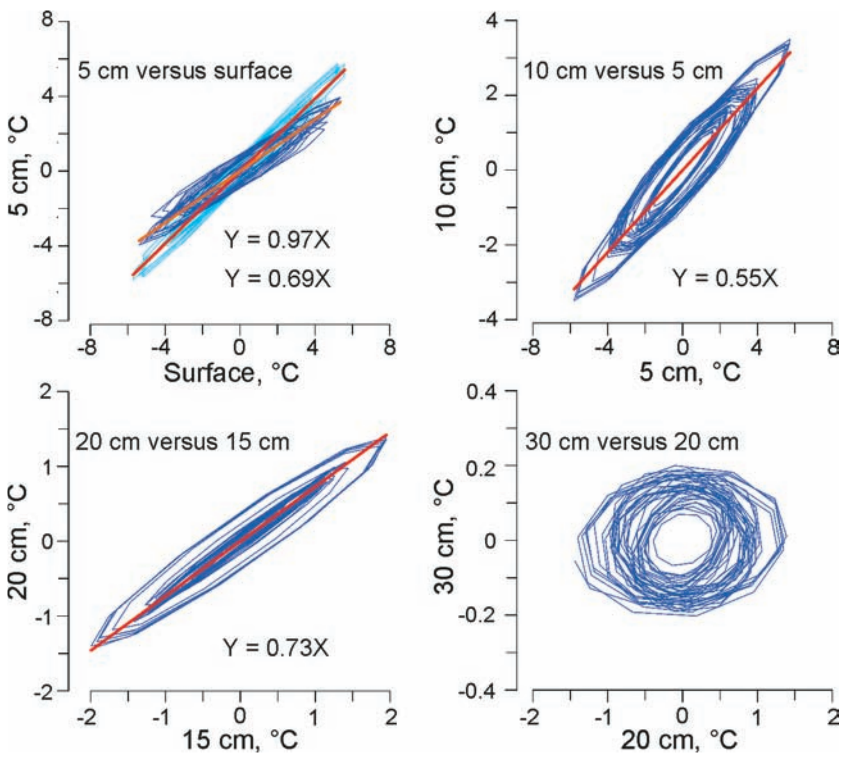

Fig. 4. Correlation plots between temperature signals (filtered daily component) for different depths: 5 cm surface versus; 10 cm versus 5 cm; 20 cm versus 15 cm; 30 cm versus 20 cm.
Regression lines and equations are also shown. For surface-5cm couple a change occurred after 20 days of operation due to a snow fall event.

Рис. 4. Графики корреляции между отфильтрованными суточными изменениями температуры на глубинах: 0 и 5 см; 5 и 10 см; 15 и 20 см; 20 и 30 см.
На графиках показаны линии регрессии и приведены их уравнения. Изменение наклона линии регрессии для глубин 0 и 5 см произошло спустя 20 дней после установки системы в результате аккумуляции снега над верхним датчиком

still too short for accurate calculations. On Fig. 6, is shown the thermal diffusion coefficient record with respect to time for the upper layers of snow pack. For each wave component, diffusivity coefficient was deduced from the ratio of standard deviation around the mean signal calculated over 10 days. For surface layer, the evolution which is observed for the 0–5 cm layer likely reflects snow accumulation events that affect the sensor which is slowly buried. In snow pack diffusivity values are within one order of magnitude (e.g. ~3 to $30 \cdot 10^{-3} cm^2 s^{-1}$), while most extreme values are given by two adjacent layers: 80 to 90 cm (for the less diffusive) and 90 to 140 cm layer (for the highest) respectively. With respect to stratigraphy the 80 to 90 cm layer is found below a very hard and 2 cm thick layer at 70 cm depth which likely causes a different evolution and property. More work is needed for linking such differences to the firn observations.

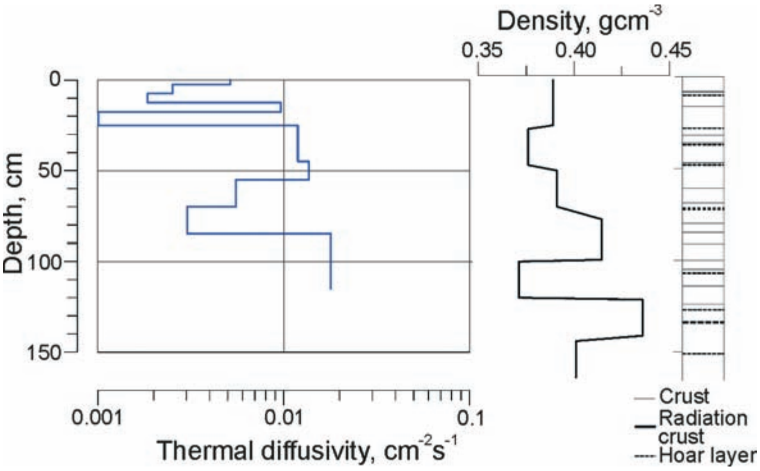

Fig. 5. Thermo physical properties of snow pack at Vostok.
Left – mean thermal diffusivity for the first 1.4 m of snow from daily and quasi-weekly filtered components; middle – snow density profile; right – snow pit stratigraphy

Рис. 5. Термофизические свойства снега на станции Восток.
Слева – средние коэффициенты термической диффузии в пределах верхних 1,4 м снежной толщи, полученные на основе анализа суточных и недельных колебаний температуры; в центре – профиль плотности снега в шурфе; справа – стратиграфическая колонка снежной толщи

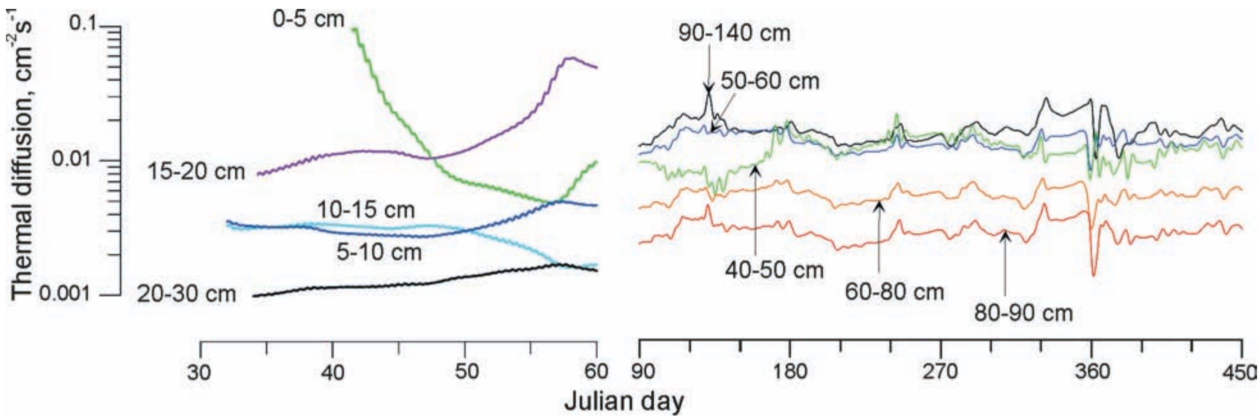

Fig. 6. Snow thermal diffusivity with respect to time (moving average over 10 days).
Left – for the uppermost layers of snow pack as deduced from the filtered (daily) component; right – for layers from 40 to 140 cm depth and deduced from the filtered (weekly) component

Рис. 6. Изменение коэффициентов термической диффузии во времени (скользящее среднее по 10 дням).
Слева – для верхних слоёв снежной толщи по результатам анализа отфильтрованных суточных колебаний температуры; справа – для слоёв в интервале глубин 80–140 см по результатам анализа отфильтрованных недельных колебаний температуры

Discussion and perspectives

The autonomous recording system for monitoring temperature of the upper layers of the snow pack which was deployed at Vostok station fulfilled almost completely the assigned technical task. Data recovery from the 15 sensors set in the snow pack is so far very good. The system had a break in ARGOS data transmission during two months in winter and few errors of readings. The technical reasons of these drawbacks are actually unknown while they have so far a negligible influence.

During the first year of operations, the records captured the very large amplitude of the seasonal cycle along with the small daily undulations of temperature during summertime and its rapid attenuation in depth. The records also revealed several rapid warming (up to 20 °C) during winter time occurring within a few days before returning to cold conditions. This is not specific to Vostok station as this phenomenon was already observed in Dome C region from AWS data and simulated by using atmospheric general circulation models [8]. While the temperature signal is not periodic, we have considered in this preliminary study that the warming gives to the winter temperature an apparent variability within a band of frequencies at about 1 per 1–2 weeks suggesting a kind of pseudo-periodic reorganization of the atmospheric system at synoptic scale over Antarctica. These apparent weekly waves penetrated deeper in the snow pack down to 140 cm. Much work has to be done in this field and the Vostok data will provide new data set to be integrated in the existing network. This can be used variously and amongst application are the comparison with records from other sites, the comparison with the weather reanalysis along with the results from simulations at regional scale from atmospheric general circulation modeling. In this respect, a network of instruments is currently operating with a second TAUTO system deployed at Concordia station and a third instrument has been set in 2012, at a site location 300 km from Vostok station along the route to Concordia station. In future, this network data will be worth for the simulation of atmospheric circulation in a similar way to what was done for the Dome C region [e.g. 8].

With respect to our preliminary approach to deduce thermal properties of firn, data analysis need to be reduced in a more accurate manner, e.g. by using spectral analysis, and compared in more details with available observation on firn stratigraphy, density and grain size. This will be useful for modeling the thermal properties of the firn with respect to microwaves emission from the surface. Continuation of the temperature monitoring for several years will allow investigating thermal properties of deeper layer down to 10 m. The TAUTO data are complementary to the long temperature grape («Termokosa») deployed at Vostok by RAE down to 100 m depth aiming at monitoring the long term evolution of Antarctic temperature, and to the earlier obtained data on snow temperature at Vostok [1].

This temperature monitoring network which is currently under deployment in this region of the Antarctic plateau through the Russian-French collaboration is of importance as it will provide in the coming years unique and pertinent data of in-situ temperatures which will be used in several fields of research in atmospheric and climate sciences.

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Температура снежной толщи на станции Восток по данным автоматической станции TAUTO: предварительные результаты первого года наблюдений

Точные измерения температурных градиентов в верхнем слое снега в Антарктиде необходимы для исследования излучения снежной поверхности в микроволновом диапазоне, которое используется в дистанционных наблюдениях, а также для изучения процессов тепло- и массопереноса в снежной толще. Градиент температуры – важнейший фактор, контролирующий метаморфизм снега, в ходе которого закладываются первоначальные структурные особенности снежных слоёв, влияющие на последующее уплотнение снега и фирна, захват атмосферного воздуха в ходе превращения фирна в лёд и фракционирование этого воздуха по газовому составу. С целью изучения этих процессов и в развитие инициатив Ж.-М. Барнола разработана автоматическая система мониторинга температуры верхних слоёв снежной толщи. Созданная авторами станция предназначена для многолетней непрерывной работы в автономном режиме в суровых условиях полярной ночи на высокогорном антарктическом плато. Система, обеспечивающая мониторинг температуры с помощью высокоточных датчиков, расположенных на 15 горизонтах в пределах верхних 10 м снежной толщи, была установлена совместно французскими и российскими специалистами на станции Восток в сезон работы 55-й Российской антарктической экспедиции. Исследования выполнялись в рамках российско-французского Европейского научно-исследовательского объединения (ЕНИО) «Восток». Анализ результатов ежечасных автоматических измерений температуры, полученных с помощью станции в течение первого года наблюдений, позволил получить данные об изменениях температуры снега на различных глубинах и сделать предварительные выводы о теплофизических свойствах верхней части снежной толщи в этом районе Центральной Антарктиды.

Вариации коэффициента термической диффузии снежной толщи по глубине и во времени оценивались на основе анализа запаздывания и затухания с глубиной суточных и недельных вариаций температуры. Установлено, что значения этого коэффициента изменяются от 3 до $30 \cdot 10^{-3}$ см^{2}с$^{-1}$, отражая пространственно-временны́е изменения физических и структурных свойств снега. Помимо высокоамплитудных сезонных и суточных колебаний температуры (последние наблюдаются только в летний период), для зимнего времени характерны квазипериодические изменения с периодом около одной недели, которые начинаются с быстрого повышения температуры на 10–20 °C, после чего следует медленный возврат к обычным зимним температурам. Подобные зимние потепления, которые ранее были зарегистрированы автоматической метеостанцией на Куполе С, по-видимому, связаны с периодической перестройкой атмосферной циркуляции в Антарктиде синоптического масштаба.