Parameterization of an intra-seasonal variation in the thermo-insulation effect of snow cover on soil temperatures and energy balance

Sergey A. Sokratov, Roger G. Barry

National Snow and Ice Data Center / Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder, Boulder, CO 80309-0449

We present results of the analysis of an observed variation in the energy balance of a soil surface in Barrow, Alaska, in 1993–1998. When combined with data on snow depth, the data allowed several stages to be distinguished in the intra-seasonal variation of the snow cover effect on the temperature regime and energy balance of the underlying soil. Each stage corresponds to specific snow cover thermo-insulation effects in terms energy-balance dependence of the soil-surface on snow depth. Stages in the intra-seasonal surface-balance variation can be used as an alternative incorporating detailed snow-physics in modeling the soil freezing/thawing phenomenon and modeling the distributed energy balance of snow-covered landscapes. Preliminary ideas are presented on applying the parameterization based on seasonal stages for non-permafrost regions.

Introduction

Recent studies of climatic change in cold regions [*Beniston et al.*, 1997; *Serreze et al.*, 2000] indicate considerable complexity in the interrelationships between various components of the cryosphere. Long-term air temperature trends in cold regions differ geographically and seasonally [*Lee et al.*, 2000; *Serreze et al.*, 2000; *Zhang et al.*, 2000b]. Many cryospheric phenomena allied with winter conditions were also found varying geographically, but in general show changes paralleling hemispheric/global air temperature trends [*Dyurgerov and Meier*, 2000; *Hartley and Robinson*, 2000; *Magnuson et al.*, 2000; *Schwartz and Reiter*, 2000; *Smith*, 2000; *Ye*, 2000; *Zhang et al.*, 2000a]. However, analysis of such an obvious proxy of climate variation as soil temperature data illustrates serious problems in understanding climate trends in the near-surface interface processes.

High spatial variability of "soil climate" has been noted at different scales and in different regions [*Ménard et al.*, 1998; *Miller et al.*, 1998; *Nelson et al.*, 1998; *Zabolotnik*, 1998]. This indicates high spatial variability in soil response to climate variation. While reconstructions from borehole temperatures show continental-scale warming of soils, especially pronounced during the last century [*Pollack and Huang*, 2000], in central Yakutia, for instance, the long-term air temperature increase did not result in increase of the maximal thaw depths [*Skryabin et al.*, 1999]. Moreover, the positive long-term temperature trends estimated for this region [*Serreze et al.*, 2000, Figures 1 and 2] are accompanied by wide spatial variability of the observed long-term temperatures trends in soils, varying from positive to negative [*Vasil'ev*, 1999]. In addition, long-term soil temperature trends in selected sites, when estimated separately for different months and seasons, vary greatly and may even be of opposite sign [*Gilichinsky et al.*, 1998; *Gilichinsky et al.*, 2000].

This phenomenon may be explained by two main factors that can affect the soil temperature more or less independently of air temperature variations: namely, the effects of winter snow cover and of soil moisture content on the conductive properties of soil [*Mühll et al.*, 1998; *Zhang et al.*, 2001; *Zhang et al.*, 1997]. In cold regions the latter has an obvious relationship to the snow cover water equivalent.

Snow cover parameterization

A number of publications provide analyses of the spatial and temporal variation of snow cover response to climate variations [*Clark et al.*, 1999; *Fallot et al.*, 1997; *Krenke et al.*, 1998; *Ye et al.*, 1998; *Zhang et al.*, 2000b]. Recently published datasets on soil temperature [*NSIDC,* 1998, version 2 in preparation], soil moisture [*Robock et al.*, 2000] and snow cover depth [*CPEOD*, 2000; *EWG*, 2000; *NCDC*, 1998; *NSIDC*, 1999], provide a basis for examining in detail the relationships between global climate change in cold regions and soil responses. Analysis of such data must be accompanied by surface energy balance modeling.

Spatial heterogeneity of the surface parameters and variability of microclimate conditions on the one hand, and difference in scales between the available in situ data and the requirements of distributed models on the other hand, oblige investigators to strike a balance between spatial averaging of climate parameters used in energy balance modeling and consideration of spatial heterogeneity, affecting the accuracy of the modeled results [*Delage et al.*, 1999; *Ducharne et al.*, 2000; *Koster et al.*, 2000]. In the case of snow cover, its spatial representation can be taken into account through a snow cover classification [*Sturm et al.*, 1995]. However, in addition to spatial variability of snow (and underlying soil) parameters, there is a temporal dimension to their variability, related to the intra-seasonal evolution of a snow cover.

Based on the results of observations, it was reported that the daily frost depth in the ground depends much more on the temperature profile inside a snow cover (determined by time/depth variation of the effective heat conductivity of snow), than on soil water content (at least when the latter was more than 0.1) or on vegetation [*Yamazaki et al.*, 1998]. When the effective heat conductivity of the snow cover was incorporated in the model through the depth fractions of snow layers with different structure, the results showed that a change of the depth hoar fraction in the snow cover from 0 to 0.6 could reduce the seasonal freezing depth by up to 80% [*Zhang et al.*, 1996]. Neglecting the change of the snow cover effective heat conductivity with snow aging in the model may explain the 1–4 weeks residual delay in the modeled spring snow-melt [*Sud and Mocko*, 1999].

Uncertainties in the expected results of a spatially-distributed model, based on point-simulated snow physics, makes the incorporation of complex physical models of snow cover evolution (i.e. [*Brun et al.*, 1992; *Lehning et al.*, 1999]) in modeling temperature field and freezing/thawing in soils of questionable value. In consequence, the approach usually adopted is the following: When observational data are available, the effective heat conductivity of snow cover is related to the snow density (as in [*Sturm et al.*, 1997]), while the snow density is determined by snow depth, varying regionally [*Keller and Gubler*, 1993; *Osokin et al.*, 2000]. A more detailed description is sometimes involved, but the accepted key for estimation of the temporally-varying effect of snow cover on the energy balance of an underlying soil is through a representation of intra-seasonal snow depth variations in a coupled snow-ground model [*Romanovsky et al.*, 1997].

Thermo-insulation effect of a snow cover

Basically, the thermo-insulation effect of snow cover is expected to increase with snow depth (up to some limiting value, beyond the 0.4–0.5 m range of snow depth considered here [*Maksimova et al.*, 1977]). Analysis of snow thermo-insulation effects in terms of the ratio between the monthly-mean changes in air temperature and 0.2 m depth soil temperature, made with 30-years observational data from Irkutsk, Russia [*Sokratov et al.*, 2001] showed such a relationship only for the February–March time-interval. In other months, the calculated ratio did not correlate with the observed snow depths.

The idea that heat-flux from the soil to the atmosphere at the beginning of a winter season is unaffected by air temperature fluctuations cannot explain many years when the sign of the temperature change in the air is opposite to that in the soil (Figure 1). The cause of such unexpected results appears to be in the timing of changes in the intra-seasonal surface energy balance. However, the monthly-mean temperature data obscures shorter time intervals when there is variation in the relative weight of the snow cover's thermo-insulation effects on the energy balance of the soil surface. This question is now addressed using daily time-scale observations.

Intra-seasonal variation of the thermo-insulation properties of snow cover

Soil temperature data from Barrow, Alaska, compiled by K.M. Hinkel, University of Cincinnati, combined with the corresponding snow depth and air temperature data from the National Weather Service allowed analysis with daily-mean-resolution of the intra-seasonal variation of the snow cover effect on the energy balance of an underlying soil at a permafrost site. The analyzed data represent soil temperatures collected from late summer 1993 to late spring 1998 at Barrow, Alaska. A Grant Instruments Squirrel 1204 data logger was utilized in temperature measurements. Eight channels were connected to thermistors, reporting hourly temperatures at 0.01, 0.08, 0.15, 0.22, 0.29 0.50, 0.75, and 1 m depth. It was suggested by K.M. Hinkel that "owing to thermal disturbance during probe installation, the first couple of weeks of data should be considered suspect and eliminated from any analysis". The temperature measurements had a precision of 0.015°C at the ice point. The logging system had a lower limit of –22°C, which was reached on several occasions in winter. At the site, the surface organics are underlain by silt at a depth of approximately 0.3 m. In the present analysis, data at 0.01, 0.08, 0.75, and 1 m are used for heat-fluxes calculations. Heat conductivity of the corresponding soils under frozen and thaw conditions was taken from *Romanovsky and Osterkamp* [2000]. For the present parameterization we omit consideration of the soil-freezing-temperature difference from 0°C and the dependence of the soil heat conductivity on soil moisture. The latter may be responsible for scatter in the results shown below.

The soil-surface (0.01 m depth) temperature allows division of each year into summer and winter seasons, with surface temperatures above or below 0°C respectively. Transitions normally take place in one day and very few summer days experienced soil-surface temperatures below 0°C. At daily time-resolution, the start of the winter season always agreed with a change in the direction of near-surface heat-flux from energy gain by the soil to energy losses. A combination of heat-fluxes and temperature variation also allows division of each winter season into four stages. An example of the intra-seasonal variation of the soil surface energy balance based on these stages is shown in Figure 2.

Numbering the stages from the beginning of a winter season, stage I is characterized by the heat-fluxes near the soil surface and in the permafrost being in opposite directions. The thaw layer is freezing from the top, surface temperature is decreasing with quite a pronounced zero-curtain effect [*Outcalt et al.*, 1990] at the Barrow site, and heat-flux from the surface reaches its maximum for the year, while the temperature and the heat-flux in the underlying permafrost show little change. However, almost exactly on the day when all the thawed soil layer temperatures become negative, the situation changes.

Stage II starting from this moment differs greatly from stage I. During this stage the difference between the heat-fluxes at the surface and at depth is decreasing. The heat-flux in the permafrost changes direction and heat-losses from soil finally take place throughout the whole layer where temperatures were measured.

After the heat-fluxes at the surface and at depth become equal, the fluxes vary almost in parallel to one another. This is stage III, when the heat-flux from the soil surface is slowly decreasing, mainly because of the gradual cooling of the deep soil layers with relatively small temperature fluctuations at the soil surface under the snow cover. Eventually, the heat-fluxes at depth and at the surface become zero.

The start of stage IV corresponds to energy gain by the soil with temperatures still below 0°C. The heat-fluxes are still almost parallel although the temperature difference between those at the soil surface and those at some depth is noticeably increasing. The end of this stage corresponds to the start of soil thaw from the surface.

Although no snow remain at the soil surface during the last stage (V), the summer energy balance of soil at Barrow can be affected by heat "injection" due to melt water. The beginning of stage V corresponds to maximal heat-flux into the soil, both at the surface and in the permafrost. The heat-flux in permafrost gradually decreases until the next winter season. The near-surface heat-flux variation is more likely related to the summer precipitation, but the general trend is still a gradual decrease to zero, corresponding to the start of soil freezing in the next winter season.

The generalized pattern of the intra-seasonal soil energy balance variation during the winter stages (I–IV) shows the influence of snow cover. However, the snow cover effect, as was suggested based on the analysis of monthly data for Irkutsk, has different relative weights at different stages. Figure 3 presents the available summarized energy balances of the soil surface in Barrow during stages I–III. The last two stages show a reasonable in terms of the "classical" explanation dependence of the energy losses from the soil, with deeper snow cover giving smaller losses. However, the energy balance during stage I does not show such dependence.

Plotting the time-length of each year's stage I against snow depth (Figure 4) allows us to relate the snow depth to the energy balance and explains the apparent "independence" of these two parameters found for non-permafrost conditions at Irkutsk (Figure 1). In stage I, the heat losses by the soil correspond to energy gained over the previous summer season. The more snow is on the ground, the longer it takes to lose this accumulated heat. However, the final result will always be the same—completely frozen soil. In non-permafrost regions the process is more complex, because there is always a thaw layer beneath. In terms of the stages presented here a considerable part of the winter season is represented by a combination of stages I and III. Thus, the snow cover depth should first affect the timing of balance between the heat-fluxes at the surface and at the depth, and only then the amount of the heat losses.

In the last stage of winter (IV), the data from Barrow suggest that the driving force of soil warming is the air temperature. Only four years' data were available for analysis, but these give a reasonable description of the snow cover effect (Figure 5). For snow cover of similar depth, the higher the air temperature, the more heat the soil can gain. However, interpolating the data to similar air temperatures, the more snow is on the ground at the beginning of this stage, the less heat will be gained by the soil.

Conclusions

Division of the intra-seasonal variation of snow cover influence on the soil surface energy balance into stages can have various applications:

The results of the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) illustrate that a more detailed representation of snow physics allows a more accurate outcome from climate models [*Slater et al.*, 2000]. However, incorporation of a complex description of the snow cover properties in spatially-distributed models is not always possible [*Slater et al.*, 1998; *Yang et al.*, 1997]. The intra-seasonal parameterization suggested here allows the snow effect on the soil conditions to be described in terms of the variation in timing of a certain stage, distributed over a region of study. During each stage, the effective thermo-physical properties of snow cover can still be represented by simple empirical relationships. Accepting spatially-distributed differences in the length of each stage, depending on variability of the initial soil conditions and snow depth changes with time, more accurate results should be obtained from a distributed soil freezing model or a Landscape Surface Scheme (LSS) without greatly increased the model complexity.

The results of our analysis show that at Barrow, snow depth has a direct effect on the soil-surface energy balance only during stages II and III. In stage I it affects the time-length of the stage. Snow depth is secondary to the air temperature during stage IV.

Comparison of inter-annual variations in the snow cover effects can also be made using a seasonal division into stages. An example of a multi-year energy balance at the soil surface, based on the data for Barrow, is presented in Figure 6. It can be seen that the timing and the amount of heat gained or lost by soil during each stage varies considerably from year to year (Figure 6a). The snow cover role in this variation was shown in Figures 3–5. However, similar estimation can be done for other factors responsible for the soil surface energy balance (soil moisture, summer precipitation, microclimatic variations), providing a simple and effective way to involve these parameters in understanding the relationships between climate variability and “soil-climate”.

The energy-balance-years differ in length, and do not agree with calendar years. While the mean-annual temperatures of soil at Barrow were increasing in 1993–1998, and this can be considered as an evidence of warming, summarization of soil-surface energy balance by seasons (Figure 6b) can be a more accurate representation of the year-to-year variability than using mean-annual, season-mean, or monthly-mean temperatures. The data presented in Figure 6b shows that a correlation exists between the energy balance of a winter and the following summer seasons, but not for the pairs summer–next-winter. Hence, the dominant season for the soil freezing/thaw cycles at Barrow is winter. This also explains the negative energy balances to the end of each energy-balance-year. The high positive number for 1993–1994 is the result of the much smaller energy balance of stage I than in other years, likely caused by proximity to the date of installation of the equipment.

Acknowledgements

The presented data analysis was made possible by financial support of the Innovative Research Program of the Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder.

References

Beniston, M., H.F. Diaz, and R.S. Bradley, Climatic change at high elevation sites: An overview, *Climatic Change*, *36*(3/4), 233–251, 1997.

Brun, E., P. David, M. Sudul, and G. Brunot, A numerical model to simulate snow-cover stratigraphy for operational avalanche forecasting, *Journal of Glaciology*, *38*(128), 13–22, 1992.

Clark, M.P., M.C. Serreze, and D.A. Robinson, Atmospheric controls on Eurasian snow extent, *International Journal of Climatology*, *19*(1), 27–40, 1999.

CPEOD (Climate Processes and Earth Observation Division—Meteorological Service of Canada), *Canadian snow data, daily snow depth and snow water equivalent*, CPEOD, Downsview, Ontario, Canada, 2000. (CD–ROM)

Delage, Y., L. Wen, and J.M. Bélanger, Aggregation of parameters for the Land Surface Model CLASS, *Atmosphere–Ocean*, *37*(2), 157–178, 1999.

Ducharne, A., R.D. Koster, M.J. Suarez, M. Stieglitz, and P. Kumar, A catchment-based approach to modeling land surface processes in a general circulation model. 2. Parameter estimation and model demonstration, *Journal of Geophysical Research*, *105*(D20), 24,823–24,838, 2000.

Dyurgerov, M.B. and M.F. Meier, Twentieth century climate change: Evidence from small glaciers, *Proceedings of the National Academy of Sciences of the United States of America*, *97*(4), 1406–1411, 2000.

EWG (Environmental Working Group—Joint US–Russian Arctic Atlas), *The Arctic Climatology Project Arctic Meteorology and Climate Atlas—Version 1.0*, NSIDC/CIRES, Boulder, Colorado, 2000. (CD–ROM)

Fallot, J.–M., R.G. Barry, and D. Hoogstrate, Variations of mean cold season temperature, precipitation and snow depths during the last 100 years in the former Soviet Union (FSU), *Hydrological Sciences Journal*, *42*(3), 301–327, 1997.

Gilichinsky, D.A., R.G. Barry, S.S. Bykhovets, V.A. Sorokovikov, T. Zhang, S.L. Zudin, and D.G. Fedorov–Davydov, A century of temperature observations of soil climate: Methods of analysis and long-term trends, in *Permafrost, Seventh International Conference*, edited by A.G. Lewkowicz, and M. Allard, pp. 313–317, Centre d'Études Nordiques, Université Laval, Yellowknife, Canada, 1998.

Gilichinsky, D.A., S.S. Bykhovets, V.A. Sorokovikov, D.G. Fedorov–Davydov, R.G. Barry, T. Zhang, M.K. Gavrilova, and O.I. Alexeeva, Ispol'zovanie dannykh meteorologicheskikh stantsii dlya otsenki tendentsii mnogoletnikh izmenenii temperatury pochv na territorii sezonnoi i mnogoletnei kriolitozony Rossii [Use of the data of hydrometeorological survey for century history of soil temperature trends in the seasonally frozen and permafrost areas of Russia], *Kriosfera Zemli*, *4*(3), 59–66, 2000. (in Russian, summary in English)

Hartley, S. and D.A. Robinson, A shift in winter season timing in the northern plains of the USA as indicated by temporal analysis of heating degree days, *International Journal of Climatology*, *20*(3), 365–379, 2000.

Keller, F. and H. Gubler, Interaction between snow cover and high mountain permafrost Murtèl/Corvatsch, Swiss Alps, in *Permafrost. Sixth International Conference*, edited by J. Brown and others, pp. 332–337, South China University of Technology Press, Beijing, China, 1993.

Koster, R.D., M.J. Suarez, A. Ducharne, M. Stieglitz, and P. Kumar, A catchment-based approach to modeling land surface processes in a general circulation model. 1. Model structure, *Journal of Geophysical Research*, *105*(D20), 24,809–24,822, 2000.

Krenke, A., L. Kitaev, T. Kadomtseva, R.G. Barry, and C. Haggerty, Interannual variations of the snow cover distribution over the Northern Eurasia in relation to the climate changes, in *Second International Conference on Climate and Water*, edited by R. Lemmelä, and N. Helenius, pp. 1165–1171, Helsinki, Edita, Espoo, Finland, 1998.

Lee, S.E., M.C. Press, and J.A. Lee, Observed climate variations during the last 100 years in Lapland, Northern Finland, *International Journal of Climatology*, *20*(3), 329–346, 2000.

Lehning, M., P. Bartelt, R. Brown, T. Russi, U. Stöckli, and M. Zimmerli, SNOWPACK model calculations for avalanche warning based upon a new network of weather and snow stations, *Cold Regions Science and Technology*, *30*(1–3), 145–157, 1999.

Magnuson, J.J., D.M. Robertson, B.J. Benson, R.H. Wynne, D.M. Livingstone, T. Arai, R.A. Assel, R.G. Barry, V. Card, E. Kuusisto, N.G. Granin, T.D. Prowse, K.M. Stewart, and V.S. Vuglinski, Historical trends in lake and river ice in the Northern Hemisphere, *Science*, *289*(5485), 1743–1746, 2000.

Maksimova, L.N., A.B. Chizhov, V.G. Melamed, A.V. Medvedev, V.A. Dubrovin, and E.N. Dunaeva, Otsenka vliyaniya snezhnogo pokrova na temperturnyi rezhim i sezonnoe promerzanie porod (s primeneniem EVM) [Estimation of the snow cover influence on temperature regime and seasonal freezing of grounds (with usage of computer)], in *Merzlye porody i snezhnyi pokrov [Frozen rocks and snow cover]*, edited by K.F. Voitkovskii, pp. 127–135, Nauka, Moscow, 1977. (in Russian)

Ménard, É., M. Allard, and Y. Michaud, Monitoring of ground surface temperatures in various biophysical micro-environments near umiujaq, eastern Hudson Bay, Canada, in *Permafrost. Seventh International Conference*, edited by A.G. Lewkowicz and M. Allard, pp. 723–729, Centre d'Études Nordiques, Université Laval, Yellowknife, Canada, 1998.

Miller, L.L., K.M. Hinkel, F.E. Nelson, R.F. Paetzold, and S.I. Outcalt, Spatial and temporal patterns of soil moisture and thaw depth at Barrow, Alaska U.S.A., in *Permafrost. Seventh International Conference*, edited by A.G. Lewkowicz and M. Allard, pp. 731–737, Centre d'Études Nordiques, Université Laval, Yellowknife, Canada, 1998.

Mühll, D.V., T. Stucki, and W. Haeberli, Borehole temperatures in alpine permafrost: A ten year series, in *Permafrost. Seventh International Conference*, edited by A.G. Lewkowicz and M. Allard, pp. 1089–1095, Centre d'Études Nordiques, Université Laval, Yellowknife, Canada, 1998.

NCDC (National Climatic Data Center), *United States Snow Climatology—Version 1.0*, vol. 1–3, NCDC–NOAA, Asheville, North Carolina, 1998. (CD–ROM)

Nelson, F.E., S.I. Outcalt, J. Brown, N.I. Shiklomanov, and K.M. Hinkel, Spatial and temporal attributes of the active-layer thickness record, Barrow, Alaska, U.S.A., in *Permafrost. Seventh International Conference*, edited by A.G. Lewkowicz and M. Allard, pp. 797–802, Centre d'Études Nordiques, Université Laval, Yellowknife, Canada, 1998.

NSIDC (National Snow and Ice Data Center), *CAPS, Circumpolar Active-layer Permafrost System—Version 1.0*, NSIDC/CIRES, Boulder, Colorado, 1998. (CD–ROM)

NSIDC (National Snow and Ice Data Center), *Historical Soviet Daily Snow Depth—Version 2.0*, NSIDC/CIRES, Boulder, Colorado, 1999. (CD–ROM)

Osokin, N.I., R.S. Samoilov, A.V. Sosnovskii, S.A. Sokratov, and V.A. Zhidkov, Model of the snow cover influence on soil freezing, *Annals of Glaciology*, *31*, 417–421, 2000.

Outcalt, S.I., F.E. Nelson, and K.M. Hinkel, The zero-curtain effect: Heat and mass transfer across an isothermal region in freezing soil, *Water Resources Research*, *26*(7), 1509–1516, 1990.

Pollack, H.N. and S. Huang, Climate reconstruction from subsurface temperatures, *Annual Review of Earth and Planetary Sciences*, *28*, 339–365, 2000.

Robock, A., K.Ya. Vinnikov, G. Srinivasan, J.K. Entin, S.E. Hollinger, N.A. Speranskaya, S. Liu, and A. Namkhai, The global soil moisture data bank, *Bulletin of the American Meteorological Society*, *81*(6), 1281–1299, 2000.

Romanovsky, V.E. and T.E. Osterkamp, Effects of unfrozen water on heat and mass transport processes in the active layer and permafrost, *Permafrost and Periglacial Processes*, *11*(3), 219–139, 2000.

Romanovsky, V.E., T.E. Osterkamp, and N.S. Duxbury, An evaluation of three numerical models used in simulations of the active layer and permafrost temperature regimes, *Cold Regions Science and Technology*, *26*(3), 195–203, 1997.

Schwartz, M.D. and B.E. Reiter, Changes in North American spring, *International Journal of Climatology*, *20*(8), 929–932, 2000.

Serreze, M.C., J.E. Walsh, F.S. Chapin III, T. Osterkamp, M. Dyurgerov, V. Romanovsky, W.C. Oechel, J. Morison, T. Zhang, and R.G. Barry, Observational evidence of recent change in the northern high-latitude environment, *Climatic Change*, *46*(1/2), 159–207, 2000.

Skryabin, P.N., Y.B. Skachkov, and S.P. Varlamov, Poteplenie klimata i izmenenie termicheskogo sostoyaniya gruntov v Tsentral'noi Yakutii [Climate warming and thermal state of ground in central Yakutia], *Kriosfera Zemli*, *3*(3), 32–40, 1999. (in Russian with English summary)

Slater, A.G., A.J. Pitman, and C.E. Desborough, The validation of a snow parameterization designed for use in General Circulation Models, *International Journal of Climatology*, *18*(6), 595–617, 1998.

Slater, A.G., C.A. Schlosser, C.E. Desborough, A.J. Pitman, A. Henderson–Sellers, A. Robock, K.Ya. Vinnikov, K. Mitchell, A. Boone, H. Braden, F. Chen, P.M. Cox, P. de Rosnay, R.E. Dickinson, Q.Y. Duan, P. Etchevers, N. Gedney, and Y.M. Gusev, The representation of snow in Land Surface Schemes; Results from PILPS 2(d), *Journal of Hydrometeorology*, (in press), 2000.

Smith, L.C., Trends in Russian Arctic river-ice formation and breakup, 1917 to 1994, *Physical Geography*, *21*(1), 46–56, 2000.

Sokratov, S.A., V.N. Golubev, and R.G. Barry, Svyaz' protsessov teplo- i masso-perenosa v snezhnom pokrove s izmeneniem klimata [The relation of the heat- and mass-transfer processes in snow with climate change], *Kriosfera Zemli*, *5*(2), (in press), 2001. (in Russian with English summary)

Sturm, M., J. Holmgren, M. König, and K. Morris, The thermal conductivity of seasonal snow, *Journal of Glaciology*, *43*(143), 26–41, 1997.

Sturm, M., J. Holmgren, and G.E. Liston, A seasonal snow cover classification system for local to global applications, *Journal of Climate*, *8*(5), 1261–1283, 1995.

Sud, Y.C. and D.M. Mocko, New snow-physics to complement SSiB Part I: Design and evaluation with ISLSCP initiative I datasets, *Journal of the Meteorological Society of Japan*, *77*(1B), 335–348, 1999.

Vasil’ev, I.S., Reaktsiya termicheskogo rezhima pochvogruntov Yakutii na sovremennye izmeneniya klimata [Response of thermal soil regime of Yakutia to present-day climate change], *Meteorologiya i Gidrologiya*, (2), 98–104, 1999. (in Russian)

Yamazaki, T., A. Nishida, and J. Kondo, [Seasonal frost depth of grounds with the bare surface, snow cover and vegetation], *Seppyo, Journal of Japanese Society of Snow and Ice*, *60*(3), 213–224, 1998. (in Japanese with English summary)

Yang, Z.L., R.E. Dickinson, A. Robock, and K.Ya. Vinnikov, Validation of the snow submodel of the biosphere–atmosphere transfer scheme with Russian snow cover and meteorological observational data, *Journal of Climate*, *10*(2), 353–373, 1997.

Ye, H., Decadal variability of Russian winter snow accumulation and its associations with Atlantic sea surface temperature anomalies, *International Journal of Climatology, 20*(14), 1709–1728, 2000.

Ye, H., H.R. Cho, and P.E. Gustafson, The changes in Russian winter snow accumulation during 1936–83 and its spatial patterns, *Journal of Climate, 11*(5), 856–863, 1998.

Zabolotnik, S.I., Latitudinal and altitudinal trends of seasonal soil thaw in Yakutia, in *Permafrost. Seventh International Conference*, edited by A.G. Lewkowicz and M. Allard, pp. 1187–1191, Centre d’Études Nordiques, Université Laval, Yellowknife, Canada, 1998.

Zhang, J., D. Rothrock, and M. Steele, Recent changes in Arctic sea ice: The interplay between ice dynamics and thermodynamics, *Journal of Climate, 13*(17), 3099–3114, 2000a.

Zhang, T., R.G. Barry, D. Gilichinsky, S.S. Bykhovets, V.A. Sorokovikov, and J. Ye, An amplified signal of climatic change in soil temperatures during the last century at Irkutsk, Russia, *Climatic Change*, (in press), 2001.

Zhang, T., T.E. Osterkamp, and K. Stamnes, Influence of the depth hoar layer of the seasonal snow cover on the ground thermal regime, *Water Resources Research*, *32*(7), 2075–2086, 1996.

Zhang, T., T.E. Osterkamp, and K. Stamnes, Effects of climate on the active layer and permafrost on the north slope of Alaska, U.S.A., *Permafrost and Periglacial Processes*, *8*(1), 45–67, 1997.

Zhang, X., L.A. Vincent, W.D. Hogg, and A. Niitsoo, Temperature and precipitation trends in Canada during the 20th century, *Atmosphere–Ocean*, *38*(3), 395–429, 2000b.

Figures captions

Figure 1 Illustration of the "independence" of the ratio between temperature change in air to the soil temperature change at 0.2 m depth from snow depth at Irkutsk (1953–1995) for monthly-mean data. T is temperature, subscripts a and s correspond to air and soil respectively, superscripts D and J to December and January respectively [*Sokratov et al.*, 2001].

Figure 2 Example for Barrow, Alaska (1996–1997) of the intra-seasonal variation of: (a) temperatures: in air (dashed line), at 0.01 m soil depth (seasonally thaw peat, gray line), at 1 m soil depth (permafrost, silt, solid line); (b) heat fluxes between: 0.01–0.08 m depths (seasonally thaw peat, gray line), 0.75–1 m depths (permafrost, silt, solid line); (c) snow depth. The roman numerals shows the separate stages of the intra-seasonal variation of the soil surface energy balance, determined from temperatures and heat fluxes (see text).

Figure 3 Relationship between the energy balance of the surface layer of soil (0.01–0.08 m) at different stages (see Figure 1) of the intra-seasonal variation of the soil surface energy balance, and the average snow depths for the corresponding time-intervals (Barrow, Alaska): I (1993–1997, ■), II (1993–1997, ○) and III (1993–1998, △).

Figure 4 Relationship between the time-length of stage I of the intra-seasonal variation of the soil surface energy balance and average snow depths for the corresponding time-intervals (1993–1997, Barrow, Alaska)

Figure 5 Relationship between the energy balance of the surface layer of soil (0.01–0.08 m) during stage IV of the intra-seasonal variation of the soil surface energy balance and the average air temperatures for the corresponding time-intervals (1994–1997, Barrow, Alaska). Roman numerals show the maximal snow depth during stage IV.

Figure 6 Summarized energy balance: (a) by intra-seasonal stages, (b) by seasons. Numbers at the bottom of (b) show the end of year energy balance (1993–1998, Barrow, Alaska)

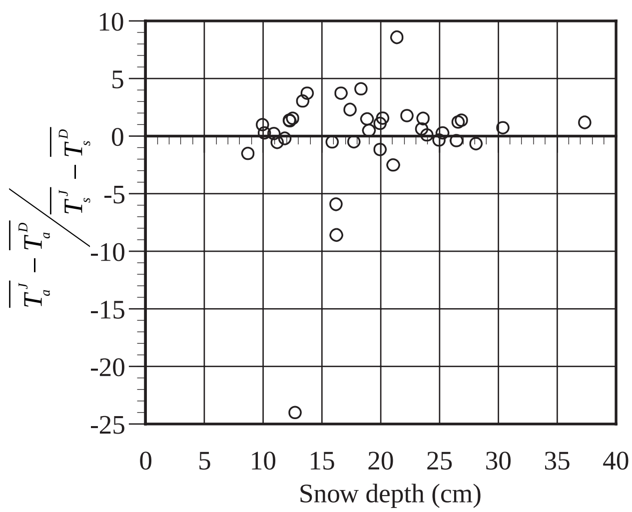
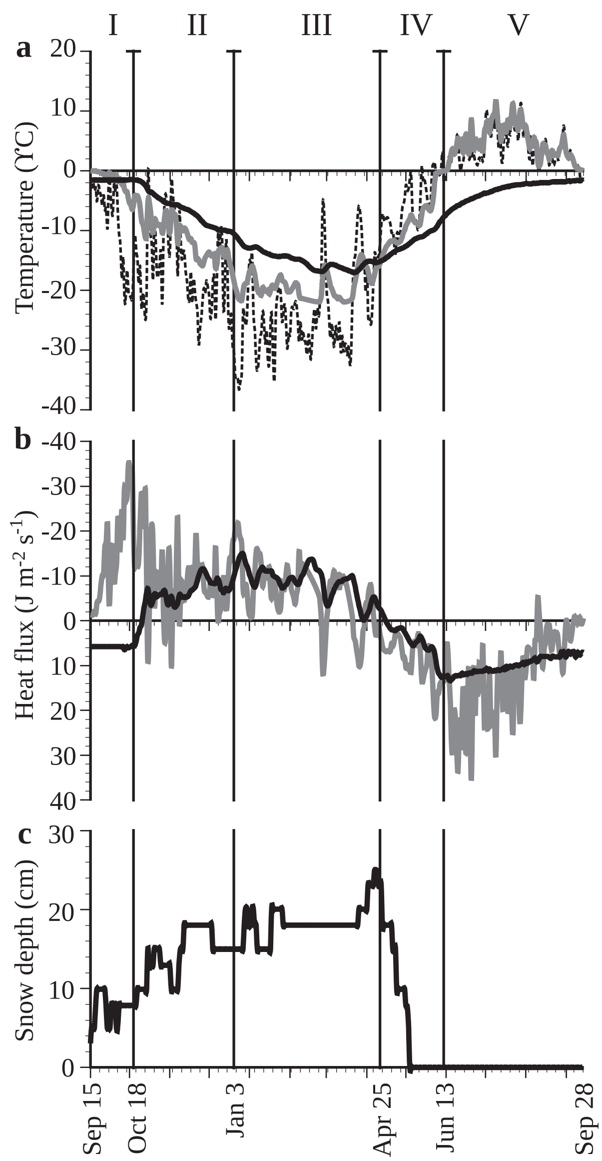


Figure 1.



I
II
III
IV
V
a
20
10
0
-10
-20
-30
-40
Temperature (°C)
b
-40
-30
-20
-10
0
10
20
30
40
Heat flux (J m-2 s-1)
c
30
20
10
0
Snow depth (cm)
Sep 15
Oct 18
Jan 3
Apr 25
Jun 13
Sep 28

Figure 2

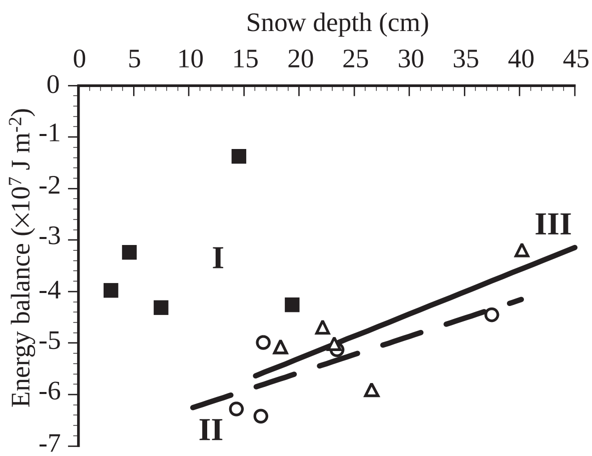
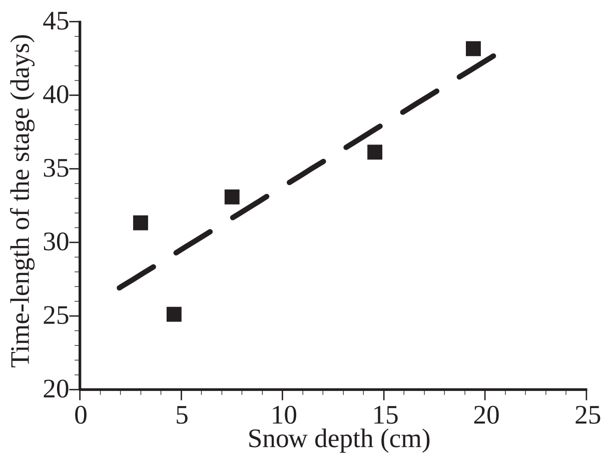
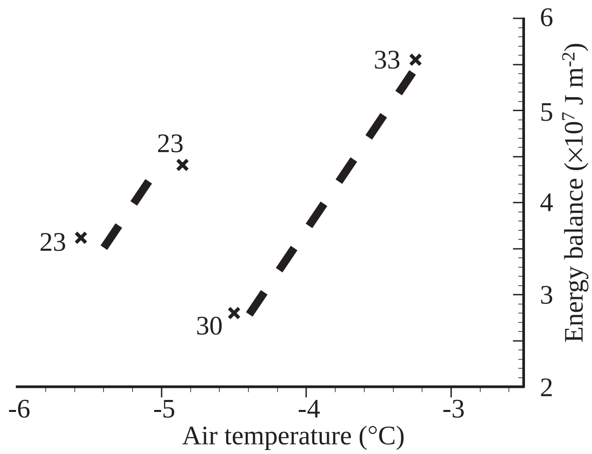

Snow depth (cm)
0
5
10
15
20
25
30
35
40
45
0
-1
-2
-3
-4
-5
-6
-7
Energy balance (×10^7 J m^-2)
I
II
III

Figure 3



45
40
35
30
25
20
0
5
10
15
20
25
Time-length of the stage (days)
Snow depth (cm)

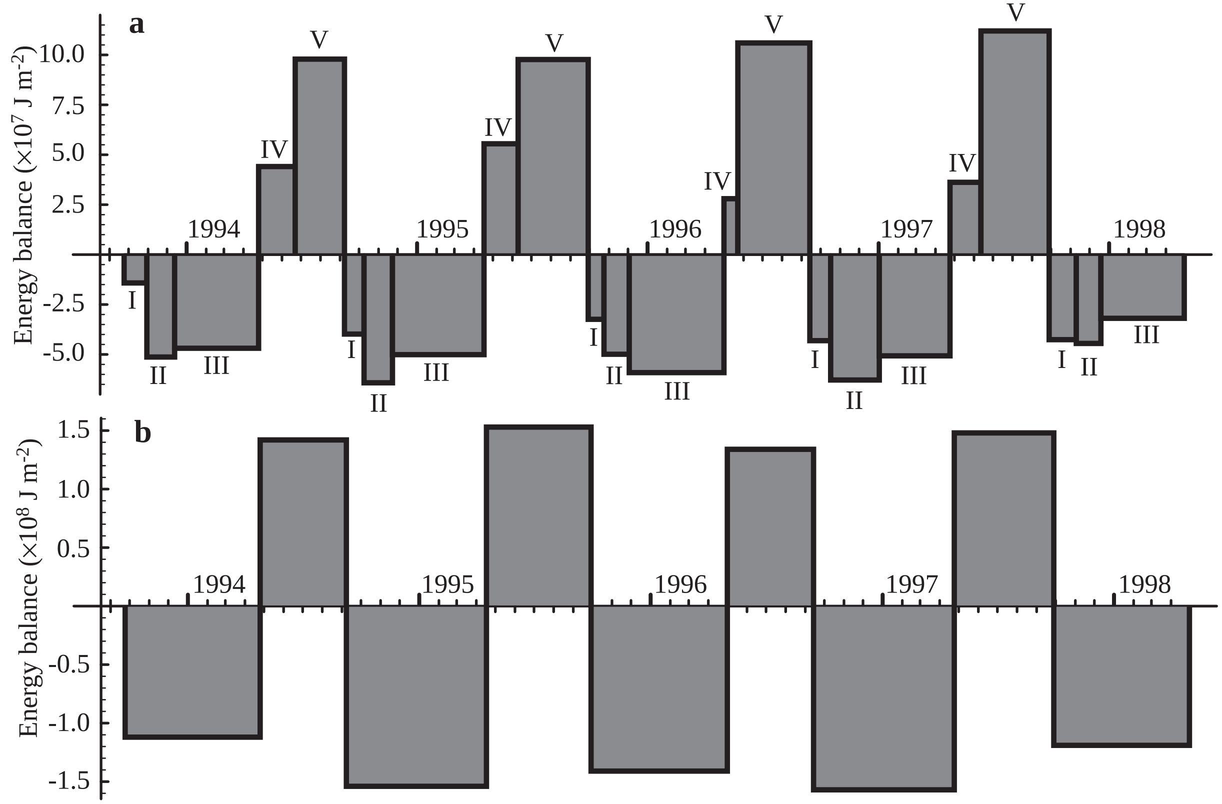
Figure 4



6
5
4
3
2
33
23
23
30
-6
-5
-4
-3
Air temperature (°C)
Energy balance (×10^7 J m^-2)

Figure 5

Figure 6



End of “energy-balance-year” ($\times 10^6$ J m^{-2}): 29.7 -0.956 -7.51 -8.84