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Trends in turbulent heat fluxes over northern Eurasia

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Abstract Recently we developed a method to obtain direct estimates of surface turbulent heat fluxes (latent heat fluxes are estimated only for saturated surfaces, wet and/or snow-covered) using routine meteorological observations. This was possible for the former USSR territory and some other countries, where the standard practice of hourly observations includes measurements of temperature at the atmosphere–land surface boundary and state of the ground. The method has been tested on several observational data sets and is now applied to northern Eurasia. We used the 3-hourly/6-hourly station data for the past several decades to assess the trends of sensible heat fluxes and latent heat fluxes from well saturated surfaces, including snow cover, for the period 1960–1990. Large-scale changes in these fluxes, near-surface temperature inversions and wind speed have been revealed over all of northern Eurasia during the cold season.

INTRODUCTION

Recent studies indicate that changes in the hydrological cycle have already occurred during the past several decades in high latitudes, namely in precipitation, streamflow, sea ice extent, snow cover, snow depth, and potential evaporation (Intergovernmental Panel on Climate Change, 1996). Trends in global radiation, surface air temperature, and evaporation in these latitudes show that the surface heat balance has also been affected (Gilgen *et al.*, 1998; Chapman & Walsh, 1993; Groisman *et al.*, 1997b). A missing link in the comprehensiveness of these assessments is information about the turbulent heat fluxes at the soil surface. These fluxes are not observed (or poorly observed) by existing observational systems. This affects our ability to reliably predict the consequences of climate change on the surface heat balance and the hydrological cycle.

Groisman & Genikhovich (1997) developed a method to obtain direct estimates of surface turbulent heat fluxes (latent heat fluxes are estimated only for saturated surfaces, wet and/or snow-covered) using routine meteorological observations. This was possible for the former USSR territory and some other countries, where the standard practice of hourly observations includes measurements of temperature at the atmosphere–land surface boundary and codes of the surface conditions (wet, dry, snow-covered, etc.). The specifics of these observations restrict the unbiased flux estimation to bare and/or snow-covered soil conditions. Currently, the method is not designed for the estimation of latent heat fluxes from non-saturated soils. The method has been tested on several observational data sets in Russia, The Netherlands, USA, and China and is now applied to northern Eurasia. It provides an unprecedented potential for constructing the climatology and time series of turbulent heat fluxes in thousands of locations during the past several decades.

SUMMARY OF THE TESTING METHOD

The testing has been performed using:

(a) the Cabauw, The Netherlands, boundary layer comprehensive data set with a 30-minute time increment for the entire 1987 year (Beljaars & Bosveld, 1997);

(b) the data of the First International Satellite Land Surface Climatology Project Field Experiment, FIFE, in May–October of 1987 over the tall-grass prairie in Kansas, USA (Sellers *et al.*, 1992);

(c) the data of the Sino-Japanese Cooperative Programme on the Atmosphere–Land Surface Processes Experiment in the Heihe River Basin, 1989–1993, HEIFE (Yamamoto & Guo, 1995);

(d) the data of 12 boundary-layer field experiments carried out by the Russian Main Geophysical Observatory (Orlenko, 1979) and the Institute of Atmospheric Physics (Tsvang, 1985) in summer months over desert, steppe, and forest-steppe climatic zones of the former Soviet Union;

(e) the Russian Heat Balance network data (Main Geophysical Observatory, 1977);

(f) the Russian network of snow evaporation gauges (Leningrad, State Hydrological Institute, 1976).

Additionally, the gridded long-term mean estimates of sensible heat flux over the former Soviet Union have been compared with the maps of the residual term of the equation of the surface heat balance (Budyko, 1956) that is an equivalent estimate of this flux.

Most of the results of this testing have been described by Groisman & Genikhovich (1997) and Groisman *et al.* (1997a). Below we summarize these findings:

- We receive reasonable point estimates of sensible heat flux over bare soil and snow-covered surfaces from measurements similar to routine meteorological observations in the former Soviet Union, China, Mongolia, Romania and some other countries where these observations include measurements of temperature at the atmosphere–land surface boundary. We receive reasonable point estimates of latent heat flux from saturated surfaces at the same locations when the state of the ground is available (e.g. in the former Soviet Union). The above means that the method by Genikhovich & Groisman (1997), when applied to each data set, delivers the flux estimates without significant systematic biases.
- Because originally the routine meteorological observations were not designed for the turbulent flux evaluation, the accuracy of a single flux estimate is marginal (±20%) but it improves substantially with time-averaging.

selected for this presentation. During this period most of the synoptic stations have already been relocated to airports, and their records are almost serially complete.

In 1966 the Soviet Union Hydrometeorological Service switched from 6-hourly (at local standard times) to 3-hourly (coordinated with UTC) routine observations. This made the estimates of mean daily values of all variables more accurate but has altered the times of observation over most time zones of the country and could introduce some inhomogeneity into the mean daily time series of variables with a strong diurnal cycle, e.g. sensible heat fluxes in the warm season. No efforts were made to correct this problem, but we found that in the cold season these changes do not affect the trends presented.

The turbulent flux estimates, as well as the measurements of several other meteorological variables (wind speed at the anemometer height; surface air and ground surface temperature, and total cloud cover), have been area-averaged over the climatic zones shown in Fig. 1. The data from stations located in mountainous regions and in the subtropics (grey-shaded in Fig. 1) have been assessed separately and are not included in the following analyses. Direction from the surface to the atmosphere is considered positive throughout this paper.

RESULTS

When we obtained large-scale changes in both turbulent heat fluxes in the cold season (and in all seasons in the areas north of 55°N) we checked the behaviour of the near-surface temperature gradients, wind speed, and cloud cover to assure ourselves that these changes are realistic and are not a product of changes in observational practice. Figures 2 –5 present our findings for the winter season. Tables 1 and 2 summarize the results of our trend analyses. A short summary of our findings for all seasons is presented below.

- In winter, sensible and latent heat fluxes have decreased during the period from 1960 to 1990 in all climatic zones (Figs 2 and 3). In the desert climatic zone the decrease in latent heat flux cannot be confirmed, because part of this zone in winter does not have a stable snow cover and therefore cannot be considered as a well-saturated surface.
- The above changes in turbulent heat fluxes have been supported by a coordinated decrease in wind speed at the anemometer height (Fig. 4) and by an increase in the

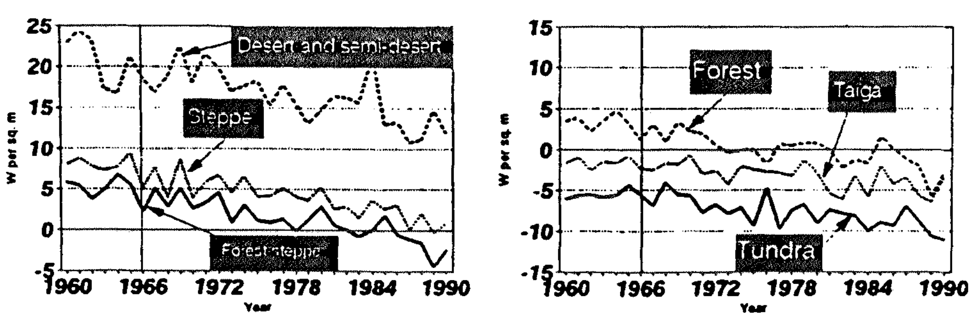

Fig. 2 Winter sensible heat fluxes area-averaged over climatic zones of northern Eurasia. Direction from the surface to the atmosphere is considered positive.

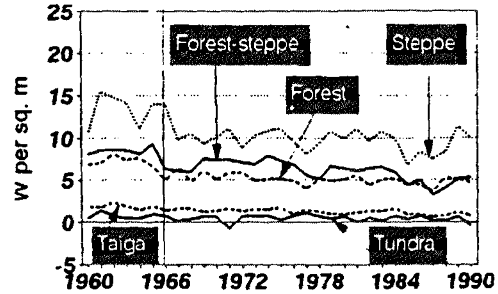

Fig. 3 Winter latent heat fluxes area-averaged over climatic zones of northern Eurasia. Direction from the surface to the atmosphere is considered positive.

near-surface temperature inversions (Fig. 5). These trends in near-surface winds, temperature gradients, and turbulent heat fluxes are not apparently linked to cloud cover variations.

- In tundra, taiga, and forest climatic zones over northern Eurasia, sensible heat fluxes decreased during the period from 1960 to 1990 in all seasons (in summer the decrease in forest and taiga zones can be confirmed only after 1966 due to the data homogeneity problem mentioned above, and in spring, over the forest zone, changes are insignificant).

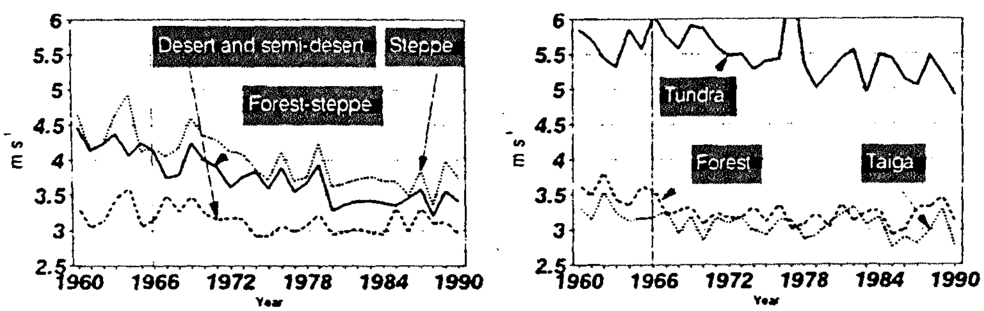

Fig. 4 Winter mean wind speed at the anemometer height (~10 m above the ground), area-averaged over climatic zones of northern Eurasia, m s^{-1}.

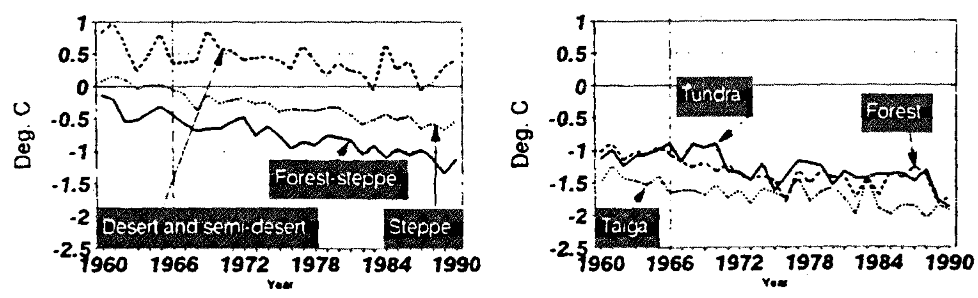

Fig. 5 Near-surface temperature gradient area-averaged over climatic zones of northern Eurasia. Surface air temperature, T_{air}, has always been measured at the fixed height of 2 m above the ground, while the surface temperature, T_{sfc}, is measured at the surface–atmosphere boundary and in winter usually characterizes the snow surface temperature.

Table 1 Estimates of mean daily turbulent heat fluxes area-averaged over climatic zones of northern Eurasia and their linear trends.

(a) Winter. Period 1960–1990. All trends are statistically significant at the 0.01 level (except latent heat flux in tundra, which is significant only at the 0.1 level). Latent heat estimates in desert are representative for snow-covered and/or saturated soils only.

	Winter mean (W m^{-2})	Sensible heat flux linear trend (W m^{-2}/30 years)	Winter mean (W m^{-2})	Latent heat flux linear trend (W m^{-2}/30 years)
Tundra	–7	–5	0	–0.5
Taiga	–3	–4	1	–1
Forest	1	–6	5	–3
Forest-steppe	2	–8	7	–4
Steppe	5	–8	11	–4
Semi-desert and desert	17	–9	45	–23

(b) Sensible heat flux in spring, summer, and autumn. Period 1960–1990 (italicized values represent period 1966–1990).

	Spring mean (W m^{-2})	Spring linear trend (W m^{-2}/30 years)	Summer mean (W m^{-2})	Summer linear trend (W m^{-2}/30 years)	Autumn mean (W m^{-2})	Autumn linear trend (W m^{-2}/30 years)
Tundra	12	–15**	37	–8**	0	–4**
Taiga	13	–4**	*54*	*–4**	6	–3**
Forest	25	–2	*61*	*–9***	12	–3**
Forest-steppe	38	–6	*88*	*–3*	19	–4**
Steppe	49	–8*	*97*	*3*	28	–4**
Semi-desert and desert	76	5	*136*	*–2*	66	–1

* Trend values that are statistically significant at the 0.05 level.

** Trends that are statistically significant at the 0.01 level.

Table 2 Changes in the sign of sensible heat fluxes over northern Eurasia.

Zone	Season	1960s	1980s
Tundra	Autumn	Source	Sink
Forest and forest-steppe	Winter	Source	Sink

– In steppe and forest-steppe climatic zones over northern Eurasia, a decrease in sensible heat fluxes in intermediate seasons (spring and autumn) also occurred.

A decrease in the surface–atmospheric heat exchange, when it is directed from the surface up, and its increase, when it is directed from the atmosphere down, is an important and so far not well understood feature of contemporary climatic change. It implies that we can expect very different rates of temperature changes near the surface compared to those in the troposphere.

REFERENCES

Beljaars, A. C. M. & Bosveld, F. C. (1997) Cabauw data for the validation of land surface parameterization schemes. *J. Climate* **10**, 1172–1193.

Budyko, M. I. (1956) *The Heat Balance of the Earth's Surface* (in Russian; in English in 1958). Gidrometeoizdat, Leningrad.

Chapman, W. L. & Walsh, J. E. (1993) Recent variations of sea ice and air temperature in high latitudes. *Bull. Am. Met. Soc.* **74**, 33–47.

Gilgen, H., Wild, M. & Ohmura, A. (1998) Means and trends of shortwave irradiance at the surface estimated Global Energy Balance Archive data. *J. Climate* **11**, 2042–2061.

Groisman, P. Ya. & Genikhovich, E. L. (1997) Assessing surface–atmosphere interactions using Russian standard meteorological network data. Part 1: Method. *J. Climate* **10**, 2154–2183.

Groisman, P. Ya., Genikhovich, E. L., Bradley, R. S. & Ilyin, B. M. (1997a) Assessing surface–atmosphere interactions using Russian standard meteorological network data. Part 2. Cloud and snow cover effects. *J. Climate* **10**, 2184–2199.

Groisman, P. Ya., Golubev, V. S., Genikhovich, E. L. & Sun B.-M. (1997b) Evaporation from snow cover: an empirical study. In: *Proceedings of the Conference on Polar Processes and Global Climate* (Rosario Resort, Orcas Island, Washington, USA, 3–6 November 1997), 72–73. WMO/ICSU/IOC World Climate Research Programme (WCRP).

Intergovernmental Panel on Climate Change (1996) *Climate Change 1995: The Science of Climate Change. The Second IPCC Scientific Assessment* (ed. by J. T. Houghton, L. G. Meira Filho, B. A. Callendar, N. Harris, A. Kattenberg & K. Maskell). Cambridge University Press, New York.

Leningrad State Hydrological Institute (1976) Materialy nablydenii nad ispareniem s poverhnosti snezhnogo pokrova, 1963–1975 (Open files of observations on evaporation from snow on the ground, 1963–1975). State Hydrological Institute, Leningrad.

Main Geophysical Observatory (1977) *Instructions on Heat Balance Observations* (in Russian). Gidrometeoizdat, Leningrad.

Orlenko, L. R. (1979) *Structure of the Planetary Atmospheric Boundary Layer* (in Russian). Gidrometeoizdat, Leningrad.

Razuvaev, V. N., Apasova, E. B., Martuganov, R. A. & Kaiser, D. P. (1995) Six- and three-hourly meteorological observations From 223 USSR stations. *ORNL/CDIAC-66, NDP-048, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee*, April 1995.

Sellers, P. J., Hall, F. G., Asrar, G., Strebel, D. E. & Murphy, R. E. (1992) An overview of the first international satellite land surface climatology project (ISLSCP) field experiment (FIFE). *J. Geophys. Res.* **97**, 18 345–18 371.

Tsvang, L. R. (1985) Atmospheric-turbulence research at the Tsimlyansk scientific station of the Institute of the Physics of the Atmosphere of the USSR Academy of Science. *Izv., Atmos. And Oceanic Phys.* **21**, 261–267.

Yamamoto, R. & Guo, Ch.-M. (1995) Objective of HEIFE. In: *Proceedings of the International Symposium on HEIFE* (ed. by Y. Mitsuta) (Kyoto University, Japan, 8–11 November 1993), 1–5. Disaster Prevention Research Institute, Kyoto Univ. and Lanzhow Inst. of Plateau Atmos. Phys., CAS.