Active Layer Distortion of Annual Air/Soil Thermal Orbits

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ABSTRACT

A straightforward procedure is proposed as a first order, initial approximation for assessing the character of the heat transfer process in the subsurface. Considering monthly averages of air and soil temperatures as a perpendicular superposition of simple harmonic motions, 'phase-space' figures can be generated to permit a rapid qualitative diagnostic of the subsurface thermal regime. It is found that for subsurface conductive regimes the shape of the interception figures is regular. For sites where an active layer and associated processes are present, the interception figures are highly irregular owing to non-conductive heat transfer. Implications for the prediction of soil temperatures and determination of climatic changes from geothermal data are discussed in this context.

RÉSUMÉ

Une procédure directe est proposée comme une approximation initiale de premier ordre pour estimer le caractère du transfert de la chaleur dans la zone sous superficielle. En considérant les moyennes mensuelles des températures de l'air et du sol comme une superposition perpendiculaire de variables harmoniques simples, des figures de 'phase-espace' peuvent être établies pour permettre un diagnostic du régime thermique sous la surface. Il a été trouvé que pour des régimes des sous-surfaces transférant la chaleur par conduction la forme des figures est régulière. Pour des sites où une couche active et des processus associés sont présents, les figures d'interception sont hautement irrégulières en relation avec un transfert de chaleur par un processus autre que la conduction. Des implications pour la prédiction des températures du sol et la détermination des changements climatiques à partir des données géothermiques sont discutées dans ce contexte.

KEYWORDS: numerical modelling; active layer; soil temperatures

INTRODUCTION

The need to understand the relationship between air and soil temperatures has been a preoccupation of soil scientists for a long time (e.g. Geiger, 1965; Goodrich, 1982; Hinkel and Outcalt, 1993). Such interest has been mostly motivated by applications to agriculture (e.g. de Vries, 1975; Sharrat et al., 1992) and, in the northern latitudes, to the study of the evolution of permafrost and its stability in the context of development and extraction of natural resources (e.g. Hinkel and Outcalt, 1994; Smith, 1975; Goodrich, 1982; Lachenbruch, 1959; Lachenbruch et al., 1988) and...
current attention arising from climate model predictions of high latitude warming.

Recently, because of the general concern about the possible influences of anthropogenic activities on the climate system, a new reason has arisen accentuating the need for understanding the processes governing the air–soil energy exchange mechanisms and factors which influence heat transfer at the air–ground interface. The realization that ground surface temperature variations are recorded in the subsurface as perturbations to the equilibrium geothermal gradient, such that past climatic changes in continental areas can be reconstructed by direct measurement and analysis of temperature–depth profiles, led a number of groups around the world to carry out this type of analysis. The reported results are promising, although there are some restrictions on the resolution of ground temperature changes from these data (see Beltrami and Mareschal, 1995). For reviews see: Pollack and Chapman, 1993; Vasseur and Mareschal, 1993; Beltrami and Chapman, 1994. It remains however, a critical issue that the character of the heat transfer regime in the subsurface be conductive for the validity of the climatic inferences and for the combined analysis of geothermal and proxy (Beltrami and Taylor, 1995; Beltrami et al., 1995).

The number of processes governing the energy transfer between ground and atmosphere is large, and the interrelation between processes is extremely complex (e.g. Goodrich, 1982). Thus instead of attempting to model the air–ground interface in general at each particular location, a first order, initial approximation technique to assess the character of the subsurface heat transfer regime at this interface may be useful.

There have been several attempts to differentiate between conductive and non-conductive heat transfer regimes in soils. These approaches involve Fourier spectral analysis or non-linear dynamics measures from time series of soil temperatures (e.g. Outcalt and Hinkel, 1992; Hinkel and Outcalt, 1993; Outcalt et al., 1992).

In this note I examine, semi-qualitatively, the relationship between air and soil temperature by means of ‘phase-space’ diagrams, and attempt to identify when such a relation corresponds to a conductive regime or whether, at some latitudes, non-conductive active layer processes distort the propagation of the signal of past ground surface temperature variations into the subsurface, making reconstructions of ground temperature histories (GTHs) very difficult or problematic.

THEORETICAL CONSIDERATIONS

As a first order approximation, the air temperature variation can be considered as a sinusoidal oscillation with a period of one year. Similarly, if heat is transferred by conduction, soil temperature generally follow an analogous behaviour, although the amplitudes of oscillation are damped with respect to air temperature as heat diffuses into the ground. It is also well known that soil temperature lags variations of air temperature. From examination of records of air and soil temperature at any location, the decay of the amplitude and the phase lag increase with depth are apparent (Figure 1); this phenomenon has been very well documented (e.g. Geiger, 1965; Smith and Riseborough, 1983 and references therein).

Consider the superposition of two simple harmonic motions (SHMs) in perpendicular directions. This problem can be easily described analytically, as the reader can verify by consulting any elementary physics book (e.g. Joss, 1934).

Assume that air and soil temperature at depth z vary in a perfectly sinusoidal fashion described by:

\[ A_a = A_{a0}\cos(\omega t) \]  
\[ A_s = A_{s0}\cos(\omega t + \delta) \]

Perpendicular superposition of these types of oscillation will yield a curve described by:

\[ A_0 = A_{a0}A_{s0}\cos \delta + A_{a0}\sqrt{1 - \frac{A_{s0}^2}{A_{a0}^2}} \sin \delta, \]

where \( A_{a0} \) and \( A_{s0} \) are the mean amplitudes of air and soil temperatures, \( A_a \) and \( A_s \) are the ‘instantaneous’ soil and air temperatures respectively, and \( \delta \) is the phase lag given by:

\[ \delta = z_s \sqrt{\frac{\pi}{\kappa g T}} \]

where \( z_g \) is ground depth (positive downwards), \( T \) is the period of oscillation and \( \kappa g \) is the thermal diffusivity of the ground. Equation (2) is the equation of an ellipse. If the phase difference is zero then (2) simplifies to the equation of a straight line, and if the phase is 90° it reduces to the parametric representation of the ellipse. In general, the direction of the principal axes of the ellipse depends on the phase difference and a full explanation can be found in Joss (1934).

Evaluation of (2) is straightforward and it can
be used to simulate an idealized case of perpen­
dicular superposition of air and soil temperature
records in the absence of snow cover. As an illus­
tration, examples for some simulated air–soil
temperature interception figures are shown in
Figure 2a, for depths of 50, 100 and 300 cm. Note
the change in the orientation of the ellipses’ prin­
cipal axes with increasing depth.

However, in regions with ground snow cover
during the winter, the situations present different
phase lags for the period without snow ($\delta = z_g \sqrt{\pi/\kappa_g T}$) and with snow ($\delta = z_s \sqrt{\pi/\kappa_s T} + z_g \sqrt{\pi/\kappa_g T}$), where $z_s$ and $\kappa_s$ refer to snow depth and
diffusivity respectively; active layer processes
have been neglected. Thus it would be expected
that, under a conductive regime, a phase-space
plot of air versus soil temperatures would be a
composite of a summer part and a winter part of
two different interception figures, given by:

$$A_s = A_s' \frac{A_g}{A_g'} \cos \left( - z_g \sqrt{\frac{\pi}{\kappa_g T}} - z_s \sqrt{\frac{\pi}{\kappa_s T}} \right) + A_s' \sqrt{1 - \frac{A_g'}{A_g}} \sin \left( - z_s \sqrt{\frac{\pi}{\kappa_s T}} - z_g \sqrt{\frac{\pi}{\kappa_g T}} \right)$$

Strictly speaking, the interception figure should
appear as a half ellipse for the summer and a
time varying ellipse in winter, with the direction
of the principal axes, or eigenvectors, changing
with variations of snow cover.

Figures 2b and 2c show the result of simple
model interception figures for air and soil tem­
perature, at 3 and 0.5 m, in phase space for which
the lag was calculated assuming a summer diffu­sivity of $0.7 \times 10^{-6}$ m²/s, estimated from meteoro­
logical data; for the winter the lag was calculated
assuming a constant snow thermal diffusivity of
$0.3 \times 10^{-6}$ m²/s (Smith, 1975). To simulate year­
to-year monthly average air temperature vari­
bility, white noise was added (SD = 2°C) to a
20°C amplitude air temperature synthetic sinus­
oidal variation. Snow cover was simulated
assuming ground cover to be 0.10, 0.20, 0.30, 1.0,
1.5, 0.5 and 0.25 m, for the months of October
through April respectively, with the rest of the
year remaining snow free. Also, to simulate year
to year variability, noise was added to the
assumed snow cover variation. The background
‘earth’ temperature was set to 0°C for this exam­
ple. The examples in Figures 2b and 2c show 200
months of simulation. The changes in the orien­
tation of the principal axes of these interception
figures vary in time following the changes of the
effective ground depth as expected from equa­
tion (3).

**DATA AND ANALYSIS**

Records of monthly mean air and soil tempera­
tures at several meteorological stations in
Québec and Ontario were obtained from Envi­
rornent Canada to illustrate this application.

Figures 3 and 4 show the 15-year records of
monthly mean air temperature versus monthly
mean soil temperature at depths of 10, 20, 150
and 300 cm at Val d’Or in Québec (48°04’N,
77°47'W) and at depths of 20, 50, 100 and 300 cm for the Elora Research Station in Ontario (43°39'N, 80°25'W).

The deformation of the interception ellipses arises from the insulating effect of snow cover during the winter months at these locations. Snow cover increases the effective depth at which temperature measurements are being made; thus it changes the lag and the shape of the interception ellipse. This can be observed in Figure 5 which shows a three-dimensional plot of monthly means of air, soil temperatures (3 m) and the number of days with snow on the ground for Val d’Or. Comparison of Figure 5 with Figure 3d illustrates that the part of the ellipse corresponding to the winter appears stretched out because of the increasing snow cover (i.e. increasing effective depth) as the season advances.

The ellipse axes vary from summer to winter and their orientation is determined by the phase shift of the different depth records. We also observe in the above figures that, as expected, the amplitudes of temperature oscillation of soil temperatures are damped with respect to the driving air temperature amplitude (Geiger, 1965).

The mean soil temperature in these records differs by several degrees from the mean air temperature; this difference varies with latitude (see Table 1 in Beltrami and Mareschal, 1991) and it is accounted for by the insulating effect of snow cover (e.g. Smith, 1975) and the long-term mean ground temperature. Figure 6 shows the phase-space diagram for air and soil temperature (10 cm) for Gainsville (Florida) and Auburn (Alabama); the absence of snow at these locations preserves the ‘winter’ part of the interception figure, i.e. there is no deformation because there are no effective depth changes during the year, although in this particular case other factors intervene in the air–soil temperature relation. Examination of these figures thus provides strong comparative evidence for the snow cover related distortion of the interception figures in higher latitudes.

From Figures 3 and 4, it is apparent that the ground temperature does not follow air temperature in a straightforward manner. Thus, in most of Canada, ground temperatures respond to the combined effects of air temperature and, mainly, snow cover variations (Goodrich, 1982). From the figures we can see that the snow cover during the time period covered by the data has no
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30
20
10
0
-10
-20
-30

Figure 3 Interception figures (phase-space plots) for monthly averages of air and soil temperatures at Val d’Or (Québec): (a) 10 cm, (b) 50 cm, (c) 100 cm, (d) 300 cm. The records span 15 years.

However, meteorological records of the same type at locations further north show a different story. Figure 7 shows the monthly air temperatures versus soil temperatures at 20, 50, 100 and 150 cm for Kuujjuaq in Quebec (56°06’N, 68°25’W). It is apparent that the interception figures are no longer regular and are dominated by significant variations in winter. Soil temperatures at this location show a large range of values across the freezing point of water. The effect of snow cover insulation, in this case, is partially responsible for the deformations, but at these latitudes the snow cover does not vanish from the ground until spring or early summer, so snow cover variability is probably not responsible for these irregularities. This can be inferred from Figure 7 by noting that the soil temperature remains close to zero for two or three months. Taking into account that these figures were constructed from monthly averages and thus the resolution is rather poor, we interpret the constancy of the autumn soil temperatures and the irregularities in the below freezing side of the figures as

changed drastically as can be inferred from the regularity of the year-to-year interception figures. Indeed, if this relation holds outside the sampling interval, it might be possible to infer the bounds of the soil temperature at a given depth for any month of the year, i.e. the interference figure can be considered as an ‘attractor’ within which the temperature trajectories move about phase-space. It can vary within the bounds of the ellipse, but it cannot lie outside the limits of the figure. In other words the ‘cloud’ of points represents the region in air-soil temperature space with a high probability of finding a particular trajectory. Alternatively, the long-term (decadal) relationship between air and soil temperature can be considered to be deterministic to a large extent, at least when considering monthly averages. Higher resolution data contain higher frequency variability, and this is currently being investigated in this context; for the determination of climatic inferences from deep borehole geothermal data it is this long-term relation between atmosphere and ground which is important.
Figure 4 Interception figures (phase-space plots) for monthly averages of air and soil temperatures at the Elora Research Station (Ontario): (a) 20 cm, (b) 50 cm, (c) 100 cm, (d) 300 cm. The records span 15 years.

'fingerprints' of phase transition processes as the upper 150 cm of soil freeze; i.e. the presence of an active layer.

In the case where the distortion of the phase-space figures is due to snow cover variability only, it would be expected that the subsurface temperatures would be 'well behaved' once the air temperature signal passes through the snow cover. If interception figures of these records are regular, one could assume that the heat transfer into the subsurface can be characterized or modelled as being mainly conductive at the resolution of the data considered here (i.e. monthly thermal diffusivity). To verify this idea, we have plotted the record of monthly soil temperature at 20 cm versus the soil temperatures at 10, 50, 100 and 300 cm for Val d’Or. This is shown in Figure 8. It is clear from these figures that the interception ellipses are regular; thus, at this site, the near surface heat transfer can be thought as being active layer free (soil temperatures remain below 0 °C) or dominated by heat conduction, in agreement with the model assumptions.

To further illustrate the non-conductive character of heat transfer in higher latitudes, Figure 9 shows the 20 cm monthly mean soil temperature versus the temperatures at 50, 100 and 150 cm for Kuujjuaq. From the irregularities of the interception ellipses, for 100 and 150 cm, it can be inferred that the subsurface heat transfer regime at this site is dominated by non-conductive processes.

DISCUSSION AND CONCLUSIONS

A straightforward method has been proposed as a preliminary step to assess the character of the thermal regime of the subsurface. It has been found by examining air–soil temperature phase-space diagrams that, when active layer processes
are present, heat transfer to the ground from air temperature variations is not by conduction, but includes the effects of phase changes and the associated latent heat releases and fluid migration.

The non-conductive character of the heat transfer regime in the subsurface appears as deformations to the interception ellipse such that the analysis presented here can be used as a preliminary diagnostic tool for assessing the relationship between air and soil temperatures and also to assess the stability of permafrost at a given site.

In the context of geothermal data analysis, it is suggested that this simple analysis be carried out, whenever possible, to assess whether the air temperature variations are recorded underground or whether other thermal conditions affect or dominate the thermal regime in the subsurface, before climatic inferences are extracted from geothermal data; seeking a generalized model for the behaviour of air and soil temperatures at each site appears problematic.

Although climatic change determination from geothermal data has proven to be feasible and has a place among other palaeoclimatic indicators (e.g. Hughes and Diaz, 1994), applications of this method of climatic inference might be restricted to latitudes where there exists no active layer or where the active layer is very shallow.

Work is in progress to apply this phase-space methodology in order to map out the areas of conductive and non-conductive regimes of the subsurface across Canada in an attempt to identify areas where temperature–depth profiles might contain useful information in terms of climatic change reconstruction, and in order to assess the spatial distribution of active layer regions in this area.

The approach presented here does not attempt to strictly model the air–soil interface. Detailed measurements of many variables are needed to carry out such work. Furthermore there is no guarantee that such a model would be applicable to other locations. Some detailed observations involving multivariable monitoring are being carried out and the results will be very useful in future detailed studies of the air–soil temperature relationship but this type of monitoring is unlikely to be carried out across spatially extensive regions in the near future.

Figure 5  Relation between air and soil temperature (300 cm) and snow cover at Val d’Or. The plot shown here corresponds to the phase-space diagram in Figure 3d.
Figure 6  Monthly average air and soil (10 cm) temperatures at (a) Gainsville, Florida, and (b) Auburn, Alabama. The lack of snow cover preserves the shape of the interception figures during the winter.

Figure 7  Monthly air versus monthly soil temperature at (a) 20 cm, (b) 50 cm, (c) 100 cm, (d) 150 cm depth for Kuujjuaq (Québec). In this case interception figures are no longer regular, indicating non-conductive heat transfer. The records span for 15 years.
Figure 8  Soil–soil temperature relation below the snow cover for Val d’Or: (a) 20 cm vs 10 cm, (b) 20 cm vs 50 cm, (c) 20 cm vs 100 cm, (d) 20 cm vs 300 cm. Regularity of the interception figures implies a subsurface conductive regime.

Figure 9  Soil–soil temperature relation below the snow cover for Kuujjuarapik: (a) 20 cm vs 50 cm, (b) 20 cm vs 100 cm, (c) 20 cm vs 300 cm. Lack of regularity of the interception figures implies a subsurface dominated by a non-conductive heat transfer regime.
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