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Estimation of effective roughness length for heat and momentum from FIFE data

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ABSTRACT

Using aircraft and surface data from the 1987 FIFE experiment in Kansas, we estimate the roughness length for momentum to be 0.19 m (with an error range 0.10–0.35 m), and the ratio of roughness length for momentum to that for heat to be about 16 (with an error range of 7–35).

RÉSUMÉ

A l'aide de données collectionées par avion et au sol pendant la campagne FIFE 1987 dans le Kansas, on estime la longueur de rugosité pour la quantité de mouvement à 0,19 m (avec une marge d'erreur de 0,10 à 0,35 m), et le rapport de la longueur de rugosité pour la quantité de mouvement à la longueur de rugosité pour la chaleur à environ 16 (avec une marge d'erreur de 7 à 35).

INTRODUCTION

The parameterization of the land-surface fluxes of sensible and latent heat has become an important research area in both climate and forecast models (Sellers et al., 1986; ECMWF, 1988; Garratt and Pielke, 1989). This note arose out of the intercomparison of time series data from the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE) (Sellers et al., 1988), with the forecast model at the European Centre for Medium Range Weather Forecasting (ECMWF) (Betts et al., 1993). The FIFE experiment took place over a 15×15 km test site of mostly grassland prairie (approximately 39 N, 96.5 W), south of Manhattan, Kansas, during 1987 and 1989. We use data from the 1987 field campaigns. The objective of FIFE was to study land surface processes over grassland throughout the seasonal cycle. Cycle 39 of the ECMWF forecast model contains a 7-cm thick upper soil layer, which has a relatively slow thermal response to the incoming

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solar radiation. An experimental version of the model was developed with a surface skin temperature, which could respond rapidly to the surface energy balance in a manner closer to observations of radiometric skin temperature observed in FIFE. One unresolved issue, however, in the surface flux parameterization is the relationship between the surface roughness for the transfer of momentum (Z_{OM}) and for the transfer of heat (Z_{OH}). Studies have shown that the roughness length for momentum is an order of magnitude larger than the one for heat and moisture (Garratt and Hicks, 1973; Garratt, 1978; Brutsaert, 1982). Beljaars and Holtslag (1991), however, found a ratio as large as 6×10^3 from a study of temperature and wind profiles in Cabauw in The Netherlands. Sugita and Brutsaert (1990a, b) also estimated Z_{OM} and Z_{OH} over the FIFE site. They found a wide range of values for Z_{OH} in the range 10^{-16} to 10 m, with an associated value of Z_{OM} of 1.05 m. Brutsaert and Sugita (1992) and Sugita and Brutsaert (1992) used satellite data (from the AVHRR instrument on NOAA-9 and NOAA-11, and Landsat respectively) to estimate Z_{OH}. They also found a wide range of values for Z_{OH} (from 10^{-2} to 10^{-10} m), depending on the corrections they applied to the data. Kustas et al. (1989) gave an intermediate mean value for Z_{OM}/Z_{OH} of 270 (with a large range) from data over a sparse canopy in Owens Valley, California. The higher this ratio, the higher the surface skin temperature for a given heat flux. Since we wished to reproduce the FIFE surface time series with the experimental surface model, it was of interest to attempt to estimate the ratio of Z_{OM}/Z_{OH} from the FIFE data for inclusion in the model parameterization.

DATA USED

We used three sets of FIFE data. The low level aircraft data from the Canadian Twin Otter (MacPherson, 1988) consisted of averaged data over 15 km runs of mean parameters, and fluxes and their statistics. We used all the runs below 200 m altitude from 30 flights over the FIFE site during July, August and October 1987 to estimate the roughness lengths Z_{OM} and Z_{OH} from the mean wind and temperature and the heat and momentum fluxes using Monin–Obukhov theory (see next section). We also used two sets of FIFE surface data (Betts and Ball, 1992), from the FIFE Information System. The PAM (Portable Automated Mesonet) station time-series data consisted of wind at 5.4 m, and temperature and humidity at 2 m, together with a radiometric measure of the ground surface temperature. No corrections were applied to these radiometric temperatures. Sugita and Brutsaert (1990b) applied corrections for a surface emissivity of 0.98. However the current estimate by the FIFE staff science team (Hall, Goddard Space Flight Center, pers. commun., 1992) is that the surface emissivity over the FIFE area is closer to unity (0.99 ± 0.01). A data set of the mean surface sensible and latent heat fluxes was also used: this was an average over 13 surface flux stations, which made measurements using both eddy correlation and Bowen radio methods. We shall present results from the 4th Intensive Field Campaign (IFC-4) in October. The Twin Otter also carried a downwind looking radiometer, but this data was not used, since its equivalent black-body temperature in July and August was much higher than the surface station data, because of a calibration problem (see Choice of skin temperature).

SURFACE MODEL FORMULATION

We used the surface model formulation as proposed by Beljaars and Holtslag (1991): in the form it is used in an experimental version of the ECMWF model. Data at a height Z are linked to the surface using the Monin–Obukhov profile equations. For wind and momentum flux,

$$\frac{U}{u_*}=\frac{1}{k}\left[\ln\left(\frac{Z}{Z_{OM}}\right)-\psi_M\left[\frac{Z}{L_v}\right)\right] \quad (1)$$

where $k=0.4$ is the Von Karman constant, U is the mean scalar wind at height Z, u_* is the friction velocity related to the stress (τ) and density (ρ) by:

$$\tau/\rho=u_*^2 \quad (2)$$

For the difference of potential temperature off the surface and the heat flux,

$$\frac{\theta-\theta_s}{\theta_*}=\frac{1}{k}\left[\ln\left(\frac{Z}{Z_{OH}}\right)-\psi_H\left(\frac{Z}{L_v}\right)\right] \quad (3)$$

We shall call θ_s the skin temperature. L_v is the Monin–Obukhov length, defined in terms of the fluxes as:

$$L_v=\frac{\theta_v u_*^2}{kg\theta_{v*}} \quad (4)$$

The temperature scale θ_* is defined from the surface sensible heat flux (H_0):

$$H_0=\rho C_p\overline{w'\theta'}=-\rho C_p u_*\theta_* \quad (5)$$

and θ_{v*} is the corresponding scale from the virtual heat flux $\rho C_p\overline{w'\theta'_v}=\rho C_p\overline{w'\theta'}+0.07\,\rho L\overline{w'q'}$.

The two Monin–Obukhov ψ functions were used in the form (Paulson, 1970; Dyer, 1974)

$$\psi_M=2\ln[(1+x)/2]+\ln[(1+x^2)/2]+\frac{\pi}{2}\left(1-\frac{4}{\pi}\tan^{-1}x\right) \quad (6a)$$

$$\psi_H=2\ln[(1+x^2)/2] \quad (6b)$$

where:

$$x=[1-16(Z/L_v)]^{1/4} \tag{6c}$$

In this simple model, we have only one skin temperature, θ_s, which in the Monin–Obukhov model, Eq. (3), is related to the surface sensible heat flux. In the ECMWF model this skin temperature is also used as the surface temperature in the long wave radiation budget, and indeed it is a radiometric temperature for which we have observations. More detailed surface models (such as Sellers et al., 1986) carry, for example, separate temperatures for the ground surface and the vegetation, but we ignore this complexity.

RESULTS

Estimation of Z_{OM} and Z_{OH} from aircraft data

Data used

The data used were from 30 flights over the FIFE area by the Twin Otter research plane of the National Aeronautical Establishment of Canada (now the Institute for Aerospace Research). A total of 393 legs below 200 m were used. The flights are summarized in the Appendix. The archived data was available as run averages, typically 15 km long. We averaged the data from these 30 flights to give mean values for each flight for aircraft altitude Z (determined by onboard radar), pressure p, θ, θ_s(TW), mixing ratio q, U (scalar wind) and the wind components u, v as well as the fluxes of momentum, heat and water vapor. Unfiltered, detrended and filtered fluxes were available.

Correction of aircraft fluxes

Many papers have investigated the relationship between the sensible and latent heat fluxes measured during FIFE by the Twin Otter, flying at typically ≤ 100 m, with those measured at the surface (Betts et al., 1990, 1992; Betts, 1992; Kelly et al., 1992). Typically the aircraft fluxes were 20–40% lower. We corrected the aircraft fluxes based on the error estimates in Betts et al. (1992) to give a best estimate of θ_* and u_*.

There are three ways in which the aircraft flux measurements are typically underestimates of the surface flux. The papers cited above extrapolated the aircraft fluxes to the surface and compared them with the average of the surface station measurements. Betts et al. (1992) concluded that the Twin Otter Sensible and latent heat fluxes were biased low by 18% ± 8% because of high pass filtering of the data (Desjardins et al., 1992) and inadequate sampling of longer wavelengths (the runs were only 15 km long). We shall assume a similar underestimate for the stress measurement for which we have no extensive surface comparison. In addition the aircraft sensible and latent heat fluxes (but not the momentum flux) in July, August and on October 8 were also low by a further 13% (approximately), because the vertical gust velocities were processed using so-called Doppler winds rather than winds from the Litton inertial navigation system (MacPherson, 1990).

TABLE 1

Corrections to Twin Otter fluxes

Date	Stress τ	Sensible heat SH	Latent heat LH
July, August, Oct. 8th	1.30	1.53	1.33
Rest of October	1.30	1.36	1.18

The third reason the fluxes are low is that the aircraft legs are typically ≈ 100 m above the surface. We took the aircraft flight level to be 10% of the boundary layer (BL) height, since we did not have BL height estimates for all flights. We extrapolated the fluxes to the surface as follows. We assumed that at BL top (≈ 1000 m) the momentum flux was zero, and the sensible heat flux was $-0.5\,H_0$ (see Betts et al., 1992). This introduces a further multiplier of 1.1 and 1.15 on the aircraft momentum and sensible heat fluxes to increase them to the surface values. For the latent heat flux, which can increase or decrease with height, we made no further correction. This is not serious because the latent heat flux only plays a small role in the virtual correction to the Monin–Obukhov length L_v in Eq. (4).

The combined corrections to the aircraft fluxes are given in Table 1. As example, the July H_0 flux correction is $1.18\times1.13\times1.15=1.53$, while the stress correction is always 1.1×1.18.

These corrections to the aircraft data are considerable: however these are the only direct flux measurements representative of the FIFE 15×15 km domain. We can use them to estimate the transfer coefficient between the inhomogeneous surface and 100 m on this scale.

Choice of skin temperature

The skin temperature is the measurement which is key to the determination of Z_{OH}. The Twin Otter has a downwind looking radiometer, so we compared this value with the average measurement from the PAM radiometers. We found that during July and August the Twin Otter measurements of skin temperatures tended to be several degrees higher than the PAM temperatures, and this difference increased with increasing skin temperature to values as large as 7 K. According to MacPherson (1988), this was a real error in the Twin Otter measurement due to a calibration problem. The error is much smaller in October 1987, when a different radiometer was used (with different calibration). An improved calibration procedure was used for later experiments. Because of this uncertain error in the Twin Otter radiometer surface temperatures θ_s(TW), we used the PAM surface temperatures for θ_s in Eq. (3), averaged for the time period of each Twin Otter flight.

For each flight we calculated Z_{OM} and Z_{OH}, using the stability dependent formulae Eqs. (1) and (3).

Values for Z_{OM} and Z_{OM}/Z_{OH}

The aircraft wind and stress measurement give an estimate of the roughness length Z_{OM}. Table 2 gives Z_{OM}, derived from averaging all the 300 flights. We averaged values of Z (a radar height above the surface), and $(1/k)\ln(Z/Z_{OM})$ separately and then recomputed Z_{OM} from the averages. The values of $Z_{OM}=0.19$ m is reasonable for this terrain. The range in Z_{OM} from 0.10 to 0.35 m corresponds to one standard deviation in $(1/k)\ln(Z/Z_{OM})$.
To estimate Z_{OH} we rewrite Eq. (3) as

$$\frac{\theta-\theta_{Z_{OM}}}{\theta_*}=\frac{1}{k}\left[\ln\frac{Z}{Z_{OM}}-\psi_H\left(\frac{Z}{L_v}\right)\right] \tag{7a}$$

TABLE 2

Estimate of Z_{OM}, derived from Twin Otter data

No of flights	Z (m)	$[\ln(Z/Z_{OM})/k]$	Z_{OM} (m)
30	106	5.80 ± 1.55	0.19 (0.10–0.35)

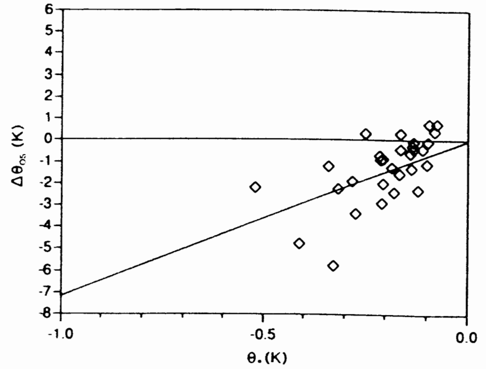

Fig. 1. $\Delta\theta_{OS}$ (the difference between skin temperature and temperature at the roughness height Z_{OM}), against temperature scale, θ_*, calculated from 30 Twin Otter flights during FIFE-1987 [see Eq. (7b)].

and

$$\frac{\Delta\theta_{OS}}{\theta_*}=\frac{\theta_{Z_{OM}}-\theta_s}{\theta_*}=\frac{1}{k}\left(\ln\frac{Z_{OM}}{Z_{OH}}\right) \tag{7b}$$

where $\psi_H(Z_{OM}/L_v)$ has been neglected. When Z_{OM} is known, we can use Eq. (7a) to derive $\theta_{Z_{OM}}$ from θ, θ_* and L_v observed at flight level Z. Equation (7b) can be used now to derive Z_{OM}/Z_{OH}. Figure 1 shows Eq. (7b) in the form of a plot of $\Delta\theta_{OS}=(\theta_{Z_{OM}}-\theta_S)$ against θ_* for the 30 aircraft flights. The ratio of the roughness lengths for momentum and heat is a more sensitive calculation than that for Z_{OM}, because of its dependence on the difference between the skin temperature and flight level temperature. For the 30 flights, linear regression gives a line fit through the origin as shown. Data scattered along the x-axis would correspond to $Z_{OM}\approx Z_{OH}$. The observed slope of 7.2 ± 1.0 gives from Eq. (7b) $Z_{OM}/Z_{OH}=18$ (with an error range from 12–26). This error comes from the linear regression, but it is consistent with an uncertainty in the surface radiometric temperature of order ± 1 K.

Estimation of (Z_{OM}/Z_{OH}) from FIFE October surface data

In October during IFC-4 of FIFE-1987, the surface sensible heat fluxes became largest (≈ 300 Wm^{-2}), because the latent heat fluxes are small (<100 Wm^{-2}) after the vegetation dies. We chose this period to determine (Z_{OM}/Z_{OH}), because the temperature gradients between the surface and 2 m were then large. Given the surface sensible heat flux (from the surface flux measurements), the surface wind and the momentum roughness length ($Z_{OM}=0.2$ m, estimated from the aircraft data), we can calculate L_v and u_* from Eq. (1), as well as θ_*. The surface data time series consisted of 30-min averages over 10 PAM stations of the vector components of the wind. This averaging leads to an underestimate of the mean scalar wind at low wind speeds because of higher frequency convective fluctuations. We calculated a surface free convective velocity scale, w_*, for time-periods with an upward heat flux, again assuming a mean BL depth of $h=1000$ m

$$w_*=\left(\frac{gh(H_0)}{T\rho C_p}\right)^{1/3} \tag{8}$$

We then combined w_* (typically ≈ 1.5 ms^{-1}) with the 30 min mean values of u and v to give

$$U=(u^2+v^2+w_*^2)^{1/2} \tag{9}$$

This w_* correction is only significant at very low wind speeds. For this surface data (wind at 5.4 m and temperature at 2 m), with a surface pressure near

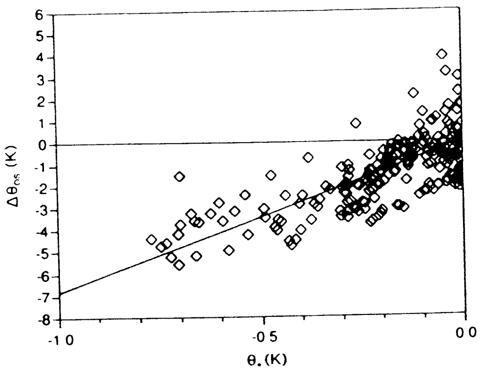

Fig. 2. As. Fig. 1, calculated from mean PAM surface station data during October, 1987.

980 mb, we ignored the difference between temperature and potential temperature.

Figure 2 shows a plot of $\Delta\theta_{OS}=(\theta_{Z_{OM}}-\theta_s)$ against θ_* for IFC-4 of FIFE. The line fit shown through the origin, with a slope of 6.9 ± 0.3, gives [from Eq. (7b)], the ratio $(Z_{OM}/Z_{OH})=15.8\pm2$. This error estimate is again given by the linear regression. However it is not representative of systematic errors in, for example, the skin temperature which may be ± 1 K (giving a similar error of ± 1 in the slope in Fig. 2). The range in the estimate of Z_{OM} directly affects u_* and θ_*, and translates to an error in the slope in Fig. 2 of approximately ± 2, which gives a much wider (and more realistic) range on Z_{OM}/Z_{OH} of (7–35). This value of $Z_{OM}/Z_{OH}=16$ (range 7–35) is comparable to the estimate from the aircraft data of 18 (range 12–26), and similar to the values suggested by Garratt and Hicks (1973) and Garrat (1978). It is clear that (Z_{OM}/Z_{OH}) cannot be determined with great precision, but is also clear that Z_{OH} appears to be at least an order of magnitude smaller than Z_{OM}.

CONCLUSIONS

We have used the Monin–Obukhov formulation to derive estimates of the roughness length for momentum and heat transfer (Z_{OM} and Z_{OH}, respectively) for the FIFE site over the Konza Prairie in Kansas. Our value of $Z_{OM}=0.19$ m (with a range 0.10–0.36 m) derived from aircraft momentum flux measurements is reasonable for this terrain. It agrees quite well with the roughness length for momentum at this grid-point in the ECMWF model of 0.30 m. It is however much smaller than the indirect estimate of $Z_{OM}=1.05$ m derived from rawinsonde profiles by Sugita and Brutsaert (1990a). Their estimates of the friction velocity are however significantly higher than the direct aircraft measurements, even after the latter have been corrected for known underestimates.

The aircraft measurements are representative of the 10 km scale at 100 m above the surface. The scale of representativity of the indirect sonde estimates is unknown. The discrepancy between the two needs further study. Sugita and Brutsaert (1990a) also estimated a displacement height for the rolling terrain of 26.9 m from their profile method. If we introduce this into the calculations using the aircraft data, the impact on our estimates of Z_{OM} (and Z_{OH}), which use direct flux measurements, is small.

The estimation of Z_{OM}/Z_{OH} is less accurate than that of Z_{OM}, since it depends also on the radiometer measurement of skin temperature, as well as the uncertainties in Z_{OM}. The downward looking aircraft radiometer was not well calibrated during FIFE-1987, so we used the average of the skin temperatures measured by downward looking radiometers on the ten PAM surface stations. We used the PAM calibrations in the FIFE Information System archive; as we are using the same data to validate the ECMWF model. We made two estimates of Z_{OM}/Z_{OH}. One used the aircraft winds, temperature and fluxes at a height of about 100 m, together with the PAM skin temperature. This gave $(Z_{OM}/Z_{OH})=18$ (range 12–26). A second estimate from the October PAM data on surface towers gave $Z_{OM}/Z_{OH}=16$ (range 7–35). Both these values are consistent with Garratt and Hicks (1973) and Garratt (1978), but much smaller than the value found by Beljaars and Holtslag (1991). Sugita and Brutsaert (1990b, 1992) and Brutsaert and Sugita (1992) also made estimates of Z_{OH} for the FIFE site. Their values span a wide range. However the mean value in Sugita and Brutsaert (1990b) for a solar zenith angle of 45° is of order 10^{-2} m, rather close to our mean value, although their estimate of Z_{OM} (from Sugita and Brutsaert, 1990a) is significantly larger.

Since our intent was to match the surface diurnal cycle in the ECMWF model to the FIFE surface data time series, it is clear that this requires a value of Z_{OM}/Z_{OH} in a range ≈ 10 to 30. We decided to use the conservative value of $Z_{OM}/Z_{OH}=10$ in our experimental runs of the ECMWF model. The impact of uncertainty in (Z_{OM}/Z_{OH}) in a forecast model can readily be understood if it is translated into an error in the skin temperature. Rewrite Eq. (3) as

$$\frac{\theta-\theta_s}{\theta_*}=\frac{1}{k}\left[\ln\left(\frac{Z}{Z_{OM}}\right)+\ln\left(\frac{Z_{OM}}{Z_{OH}}\right)-\psi_H\left(\frac{Z}{L_v}\right)\right] \qquad (10)$$

For $Z=2$ m, $Z_{OM}=0.2$m, $u_*=0.6$ ms^{-1}, $\theta_*=-0.2$ K (corresponding to a $H_0\approx140$ Wm^{-2}, typical of the summer in FIFE), we get $L_v\approx-140$ m, and the θ difference between surface and 2 m is

$$(\theta_s-\theta_2)=0.2(5.76-0.26)+\frac{0.2}{k}\ln\left(\frac{Z_{OM}}{Z_{OH}}\right)=1.1+\left(\frac{0.2}{k}\right)\ln\left(\frac{Z_{OM}}{Z_{OH}}\right) \qquad (11)$$

For $(Z_{OM}/Z_{OH})=1$, we get $\theta_s-\theta_2=1.1$ K. Each factor of 10 increase in (Z_{OM}/Z_{OH}) increases $(\theta_s-\theta_2)$ by 1.15 K. The error range of less than an order of magnitude in our estmate of (Z_{OM}/Z_{OH}) thus translates into an error of less than ± 0.5 K in the skin temperature for the FIFE area in Kansas during moist periods in the summer, when $H_0 \approx 140$ Wm^{-2}. During dry periods, or periods of low wind speed, this error increases as θ_* increases. Such errors are probably acceptable for a global model. They are certainly within our ability to measure a representative skin temperature on this scale.

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APPENDIX

Table of Twin Otter flights

Date	Flight	Time (UT)	No. of legs	Z (m)	p (mb)	V ms^{-1}	u_* ms^{-1}	θ (K)	θ_s (K)	θ_* (K)
870626	1/2	17.25	12	133	971	5.16	0.47	300.3	302.8	−0.14
870626	2/2	20.36	8	114	971	3.36	0.37	301.8	304.3	−0.18
870628	1/2	19.04	16	119	963	3.82	0.31	304.4	307.6	−0.17
870628	2/2	21.25	8	92	963	3.89	0.33	306.0	307.2	−0.16
870705	1/1	21.56	20	121	962	5.64	0.45	304.1	305.5	−0.13
870706	1/2	17.12	28	109	962	6.63	0.50	305.4	308.5	−0.21
870706	2/2	21.30	16	150	962	9.10	0.59	307.4	307.7	−0.08
870708	1/1	19.31	16	129	965	3.57	0.32	303.4	306.0	−0.20
870709	1/1	16.73	9	99	965	9.55	0.68	303.7	305.6	−0.11
870710	1/1	15.50	14	105	962	12.54	0.80	303.6	304.4	−0.08
870711	1/2	16.85	19	99	961	13.56	0.92	305.2	307.7	−0.10
870711	2/2	20.48	16	100	961	14.21	0.91	307.0	308.5	−0.10
870807	1/2	18.11	13	140	964	9.30	0.58	306.3	310.4	−0.12
870807	2/2	20.85	12	79	964	10.43	0.74	310.4	312.2	−0.13
870809	1/1	21.15	16	131	968	5.27	0.40	303.0	307.7	−0.34
870810	1/1	18.97	14	113	968	4.61	0.54	304.1	311.9	−0.32
870814	1/1	18.54	16	91	959	5.40	0.45	305.7	310.4	−0.28
870815	1/2	16.87	16	100	959	8.67	0.63	307.3	309.6	−0.14
870815	2/2	20.95	16	86	959	11.61	0.76	310.4	310.9	−0.09
870816	1/1	17.91	8	127	960	6.68	0.48	305.7	308.3	−0.25
870817	1/2	18.31	8	95	967	4.63	0.43	305.3	310.2	−0.21
870817	2/2	20.81	8	109	967	8.10	0.59	306.8	308.8	−0.13
870819	1/1	18.35	6	84	969	7.54	0.65	302.7	306.9	−0.18
871006	1/2	18.11	10	84	969	9.98	0.85	292.0	298.3	−0.27
871006	2/2	21.19	8	105	969	11.31	0.80	295.0	297.5	−0.16
871007	1/2	17.61	16	81	973	5.99	0.58	287.0	295.1	−0.41
871007	2/2	20.97	16	75	973	5.34	0.48	290.3	295.4	−0.31
871008	1/1	19.56	10	128	963	11.90	0.80	295.5	300.3	−0.21
871011	2/2	20.60	10	60	980	3.82	0.32	285.9	292.9	−0.52
871013	2/2	18.43	8	111	967	11.77	0.78	296.9	300.7	−0.21

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