Geophys. J. Int. (1992) **109**, 488–500

Atmospheric pressure and gravity

J. B. Merriam
Department of Geological Sciences, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 0W0

Accepted 1991 November 30. Received 1991 November 15

SUMMARY

Gravity Green's functions for a column load of a model atmosphere on a spherical, elastic Earth are presented and they are used to evaluate the contribution of global atmospheric pressure variations to local gravity. The Green's functions are found to be relatively insensitive to the details of the model atmosphere, but they are dependent on the temperature at the base of the column, and on the relative height difference between the base of the column and the gravity station. The total signal that global pressure systems contribute to gravity is about 30 μgal, of which about 90 per cent is produced by the atmosphere within 50 km of the gravity station. A zone between 50 and 1000 km from the gravity station contributes a couple of μgal, as does the remainder of the globe. This pattern, the coherence scale of pressure fluctuations, the time and spatial scales appropriate to the hydrostatic approximation, and the distance of the gravity station from the oceans, suggest a division of the globe into local, regional, and global zones. Data requirements, processing details, and the reliability of the computed signal are different in each zone. The local zone is within about 50 km of the gravity station. Within this zone pressure changes rapidly in time, but is spatially coherent, so that hourly observations of pressure and temperature at the gravity site alone are sufficient to compute an accurate correction, except when a front is passing through. The regional zone extends from the edge of the local zone to between several hundred and a thousand kilometres. The signal from this zone is small and is only weakly coherent with the signal from the central zone, so that a rather sparse array of hourly samples of pressure and temperature are required. The gravity signal from the global zone can reach about a μgal. It varies on a time-scale of days, and is influenced by the response of the oceans to pressure variations. Previously reported observations that the admittance between local pressure and gravity residuals depends on epoch, frequency, or site, are most probably due to incorrect modelling. A proper local, regional, temperature, and global correction can adequately account for the gravity signal from the atmosphere to within a few tens of ngal in the diurnal band, and about 100 ngal in the days to seasonal band, except during extreme weather conditions. The application of the local correction lowers the power spectral density of the gravity residuals in every band from seasonal to hourly. The regional, global, and temperature corrections lower the residual noise in the seasonal and synoptic bands, but are not consistently effective at periods less than about half a day.

Key words: atmospheric pressure, gravity, Green's functions.

INTRODUCTION

The purpose of this paper is to show how to correct properly for the atmospheric pressure signal in gravity, and to assess how well the correction can be performed. The sampling requirements in time and space of the meteorological data are also demonstrated. Several contradictions in previously published results are resolved.

Gravity (measured positive down) and local atmospheric pressure are known to correlate with an admittance of about $-0.3\ \mu$gal mbar^{-1} (Warburton & Goodkind 1977; Merriam 1981; Spratt 1982; Müller & Zürn 1983; Rabbel & Zschau 1985; Niebauer 1988). Assuming a 50 mbar pressure disturbance, this can cause gravity to vary by about 20 μgal. Indeed, Warburton & Goodkind demonstrated that the residual noise on a superconducting gravimeter record (after removal of the Earth tide) is dominated by the atmospheric pressure signal. This signal is broad-band, from hours to years, and must be very carefully removed before one can take full advantage of the sensitivity (~1 ngal) of this instrument. The sensitivity of the gravimeter, and the approximate value of the admittance between local pressure and gravity, suggest the gravimeter will respond to atmospheric pressure changes of a few μbar. It also suggests that the gravimeter will respond not just to local pressure, but to pressure changes over a very broad area. Indeed, I have found that the global pressure system must be taken into account in order to correct for the effect to even the μgal level. To date the atmospheric pressure correction is routinely applied with a single valued admittance only, a process that leaves long-period residuals of a few μgal, and short-period (less than a day) residuals of about a μgal. The long-period residuals are due to the neglect of very distant pressure systems and the unmodelled effect of variations in local temperature. The short-period residuals are due to changes in the horizontal scale of local pressure systems.

Warburton & Goodkind (1977) presented the first analysis of the relation between atmospheric pressure and gravity. They used a standard atmosphere applied as a column load centred on the gravimeter, a half-space approximation for the Newtonian attraction, and a spherical, elastic Earth for the load-induced deformation. The result showed that the admittance between pressure and gravity depended on the lateral scale of the pressure cell, and varied from $-0.43\,\mu\text{gal mbar}^{-1}$ for large cells of radius several hundred km or more, to about $-0.35\,\mu\text{gal mbar}^{-1}$, for cells of several tens of km radius. They also showed that the direct Newtonian attraction of the atmospheric mass was much larger and of opposite sign to the change in gravity produced by the elastic deformation of the Earth by the load of the atmosphere. They also pointed out that, at tidal frequencies, admittances between observed gravity and pressure were biased by the effect of ocean tides on gravity, and that therefore the effective admittance (one determined by a regression between gravity and local pressure) would not be reliable near tidal frequencies.

Merriam (1981), in a study of a long gravity tide record at Alice Springs, derived an admittance based on a spherical Earth model with a thin atmosphere, and found that the admittance ranged between $-0.37\,\mu\text{gal mbar}^{-1}$ for loads of a few hundred km extent, to $-0.28\,\mu\text{gal mbar}^{-1}$ for loads of more than a thousand km in lateral extent. While this is in rough agreement with the result of Warburton & Goodkind in the magnitude of the effect, note that the influence of scale size is opposite. A simple fit of an admittance between pressure and residual gravity at Alice Springs yielded an admittance of $-0.34\,\mu\text{gal mbar}^{-1}$. Merriam also suggested using the rate of change of local pressure as a proxy for a regional array of barometers.

Spratt (1982) used a similar model and found admittances in agreement with Merriam's. Spratt also examined the gravity signal from regional and global pressure variations, and suggested that a ring of barometers 16.5° from the gravity site would yield a further reduction in residuals (from those of a single valued admittance) by about 50 per cent. The results presented here suggest that a single ring of barometers at any distance would be of very little advantage, and that what is really required is a global array of barometers, with denser coverage near the gravimeter.

Müller & Zürn (1983) in the study of the passage of a cold front over a gravimeter found an admittance of about $-0.4\,\mu\text{gal mbar}^{-1}$, when the front was at some distance, and a rather complex behaviour as the front approached and receded from the gravimeter. They used an isothermal atmosphere on both sides of the front, and various models for the shape of the front.

Rabbel & Zschau (1985) presented results for two hypothetical weather systems of radii 160 and 1000 km in a model atmosphere of thickness 8.4 km (about one scale height). The pressure cells loaded a spherical elastic Earth, but the larger Newtonian attraction was apparently modelled on a half-space. Admittances varied from $-0.3\,\mu\text{gal mbar}^{-1}$ for the smaller cell, to $-0.4\,\mu\text{gal mbar}^{-1}$ for the larger cell (the same pattern found by Warburton & Goodkind, and opposite to that found by Merriam and Spratt). They also suggested the use of a two part admittance using the pressure at the gravimeter, and an average pressure in the surrounding area. My results indicate that the use of a local pressure and a regional average would be of little advantage.

Van Dam & Wahr (1987), in a study primarily aimed at predicting surface displacements, correctly observed that global atmospheric pressure is important, contributing a few μgal to the total gravity in the days to seasonal band. This is confirmed here, and an effective rational for determining the necessary distribution of barometers (and hence what should be considered local atmosphere and what should be considered global atmosphere) is presented. The gravity Green's functions used here are markedly different from the functions used by Van Dam & Wahr at distances less than several tens of degrees of the gravimeter.

Niebauer (1988) has appreciated the geometric effects of scale height in the atmosphere and curvature of the Earth, and his conclusions regarding the consequence to the gravity signal are confirmed here. His isothermal atmosphere is replaced here with a more realistic structure, and elastic loading effects are included.

The dependence of the admittance on the lateral scale of the weather systems presumably explains, at least in part, why an admittance calculated by a least-squares fit of pressure to gravity varies from station to station and time to time; the effective lateral scale of the pressure system changes with time. For example, I find that least-squares fitting an admittance between pressure and residual gravity at the Cantley, Quebec installation of the superconducting gravimeter GWR12, results in values in the range −0.30 to $-0.37\,\mu\text{gal mbar}^{-1}$ depending on epoch. However, it is clear from the above that there remains some disagreement on how the lateral scale actually effects the admittance. Merriam and Spratt find larger admittances (in absolute value) as the scale size decreases, while Warburton & Goodkind and Rabbel & Zschau find the opposite. The reason for this difference is that Merriam and Spratt compute the Newtonian attraction on a spherical Earth, while Warburton & Goodkind and Rabbel & Zschau use a half-space.

The scale height of the atmosphere, the curvature of the Earth, and the relative contributions of Newtonian attraction and elastic loading, combine in a complex way within a few degrees of the gravity site to produce a broad zone surrounding the instrument from which there is no net signal. In this zone the centre of mass of a column of atmosphere is roughly on the gravimeters horizon. I find that 90 per cent of the gravity signal of a regional weather system 1000 km in diameter comes from the area within 50 km of the gravimeter, almost no signal arises from the area between 50 and 250 km of the instrument, and about 10 per cent comes from the zone between 250 and 500 km of the instrument. Furthermore, while pressure correlates positively throughout the weather system, local gravity and distant pressure correlate strongly and negatively from 0 to 50 km, weakly and positively from 250 to 500 km, and not at all from 50 to 250 km. This pattern is extremely important in deciding on the distribution of pressure observations that are required to make an adequate gravity correction. Weather systems throughout the remainder of the globe can contribute about a μgal to local gravity, but global pressure does not correlate with local pressure, except perhaps at subharmonics of the S_2 tide (Spratt 1982), and so the signal from the rest of the atmosphere can only be reliably obtained by a global integration.

Ultimately the goal is to derive an atmospheric correction that matches the sensitivity of the superconducting gravimeter ~1 ngal. However, this goal seems unachievable for the near future. A practical goal is a gravity correction good to perhaps 100 μngal. I show in subsequent sections that the Green's functions presented here allow a correction for atmospheric pressure good to a few tens of ngal in the diurnal band, and 100 ngal in the days to seasonal band, except under extreme weather conditions.

METHOD

Near the gravimeter, the entire troposphere, and much of the stratosphere, contribute to the Newtonian attaction, so that atmospheric densities are nominally required through a substantial height of the atmosphere. However, I find that densities at altitude can be adequately computed with a hydrostatic assumption and prescribed vertical temperature gradients. Thus, surface level observations of temperature and pressure are sufficient to compute the Newtonian component of gravity of a column of air to about the 1 per cent level, except in extreme weather conditions.

If the atmosphere is in hydrostatic equilibrium (an excellent approximation for time scales of several hours and longer) then changes in pressure at the base of a column of air are directly related to the change in mass per unit area of the column. Furthermore, if the temperature structure is known as well, the change in pressure at any level in the column, and the resulting change in density, can be immediately obtained using the ideal gas law. I show in subsequent sections that changes in surface temperature provide enough information on changes in temperature aloft to permit densities to be calculated well enough to estimate the Newtonian attraction of a large regional air mass to about 1 per cent. The Newtonian attraction of a column of air thus depends only on the pressure and temperature at its base, so that the attraction of a thin column can be interpreted as a Green's function. To distinguish these column load Green's functions from the more familiar point mass load Green's functions of Farrell (1972), I call them atmospheric load gravity Green's functions. The integration of these atmospheric load gravity Green's functions over the observed surface pressure and temperature fields then gives the gravity signal from the atmosphere above this area.

The Newtonian gravitational attraction of a column of air at some distance changes as the pressure at the base of the column changes (because mass moves into and out of the column) and as the temperature at the base of the column changes (because the centre of mass of the column rises and falls with temperature). The mass effect is by far the larger of the two, but the thermal expansion and contraction of the atmosphere can change gravity by nearly a μgal.

ATMOSPHERIC LOAD GRAVITY GREEN'S FUNCTIONS

A mass load on the Earth's surface changes gravity by direct Newtonian attraction, and by deforming the Earth. Farrell (1972) has derived gravity Green's functions for the elastic part, but when the load is distributed throughout a considerable height, as is the case with the atmosphere, rather than as a thin veneer, as is approximately the case for the ocean tide load, the Newtonian part requires some special care. The lowest part of the atmosphere is responsible for most of the Newtonian attraction, but I have found that even heights to 60 km can contribute at about the 1 per cent level, depending on the distance between the base of the column and the gravimeter. To appreciate the distinction between a mass load concentrated at the surface of the Earth, and a distributed load, consider a column of air at 2.7° from a gravimeter. The centre of mass of the column (about 5.5 km height) is on the instrument's horizon, with the net result that the (radial) attraction at the gravimeter nearly vanishes. For a column nearer to the gravimeter the attraction is dominantly upwards, and further from the gravimeter the attraction is dominantly downwards. When elastic effects are included there is a broad region, extending from about 50 km from the gravimeter to about 250 km from the gravimeter, where the total gravity is small, partly because most of the atmosphere is so close to the horizon, and partly because of cancellation of positive and negative contributions from the elastic and Newtonian components respectively.

A column of air of area dA, and density $\rho(z)$, at distance ϕ, has a radial Newtonian attraction (postive down)

$$g(\phi) = -\int_0^{z_{\max}} \frac{G\rho(z)\sin\alpha}{r^2}\, dA\, dz \tag{1}$$

where z is the vertical height in the column, r is the vector disance between a volume of air $(dA\, dz)$ and the gravimeter, and α is the angle between the vector distance and the local horizon at the gravimeter.

Pressure and density are related by the ideal gas law

$$\rho = \frac{\hat{m}P}{R^*T} = \frac{P}{RT}$$

where R^* is the ideal gas constant, $\hat{m}$ is the mean molecular weight, and T the temperature in degrees K. The mean molecular weight for dry air is 0.028966 kg mol^{-1}, which gives 287.05 J kg^{-1} °K^{-1} for the specific gas constant R. Assuming hydrostatic equilibrium, and a temperature structure, the variation of density and pressure with height can be calculated. For example, an isothermal atmosphere has

$$\rho(z) = \rho_0 e^{-z/H}, \qquad P(z) = P_0 e^{-z/H}$$

where the factor

$$H = \frac{RT}{g}$$

is the scale height of the atmosphere, which depends on the specific gas constant, temperature and gravity. If the atmosphere is not isothermal then the hydrostatic equation, with the observed temperature profile, must be integrated over height, but the above equations are approximately correct for any height interval, if T is the average temperature in the interval. Typically, H varies from about 8 km near the surface to about 7 km in the stratosphere. I have adopted a temperature structure that is close to that of the COSPAR standard atmosphere for mid-latitudes, that is, a surface temperature of 15 °C, a lapse rate of 6.5 °C km^{-1} in the troposphere, an isothermal stratosphere at 58 °C, and a lapse rate of −2.5 °C km^{-1} from 25 to 60 km.

The mean molecular weight for dry air is practically constant to 60 km, but water vapour content is extremely variable, so that in principle, some allowance for water vapour must be made in the equation of state. Since an increase in water vapour content decreases density, as does an increase in temperature, meteorologists commonly handle the inertial aspects of water vapour by using a virtual temperature in the equation of state. The virtual temperature is the temperature at which dry air would have the same density as moist air. It is defined by

$$T^* = \frac{1 + 1.609w}{1 + w} T$$

where w is the mixing ratio (mass m of water vapour per unit mass of dry air). The virtual temperature never exceeds the actual temperature by more than 7 °C, and usually by less than 1 °C, so that, the maximum effect on density is only about 2 per cent, and the maximum effect on gravity is only 100 ngal.

Using the ideal gas law in (1) this becomes

$$g(\phi) = -\frac{GP_0\, dA}{RT_0} \int_0^{z_{max}} \frac{T_0 P(z)}{T(z) P_0} \frac{\sin \alpha}{r^2} dz.$$

Here, and elsewhere, the subscript 0 indicates a surface level value. The specific gas constant R is nearly constant throughout the height that most of the gravity signal comes from.

Expressing the angle α as a function of height in the column and radial distance from the gravimeter,

$$g(\phi) = \frac{G\, dA P_0}{RT_0} \int_0^{z_{max}} \frac{T_0 P(z)}{T(z) P_0} \times \frac{a - (a + z)\cos \phi}{[(a + z)^2 + a^2 - 2a(a + z)\cos \phi]^{3/2}} dz.$$

The integrand in the above equation goes nearly as the inverse of $2a^2\phi$, at least in a thin atmosphere approximation, so it is convenient to scale the above equation by this factor, so that

$$g(\phi) = \frac{Gd\,AP_0 2a^2\phi}{2a^2\phi\; RT_0} \int_0^{z_{max}} \frac{T_0 P(z)}{T(z) P_0} \times \frac{a - (a + z)\cos \phi}{[(a + z)^2 + a^2 - 2a(a + z)\cos \phi]^{3/2}} dz. \tag{2}$$

The term inside the square brackets is roughly $z_{max}/g_0 H_0$, again in a thin atmosphere approximation. Evaluating the constant outside the brackets, absorbing it into the bracketed term and labelling this $GN(\phi)$, yields

$$g(\phi) = \frac{P_0}{10^5 \phi} GN(\phi)\ \mu\text{gal mbar}^{-1} \tag{3}$$

where the absorbed constant term includes the area of a spherical cap with radius 1°. This choice is merely numerically convenient, and of course the above formula should only be used with an infinitesimally small area. The constant has also been evaluated using mean sea level gravity, and so there is a slight latitude effect in the constant, of less than 1 per cent, that has been neglected. Note that in (2) the temperature and pressure structures in the integrand are normalized with respect to their surface values, so that the integrand is nominally independent of surface temperature and pressure. Thus in (3), $g(\phi)$ is directly proportional to surface pressure through $GN(\phi)$, but $GN(\phi)$ also has an implicit dependence on temperature structure, $T(z)$. Despite the fact that the gradients in $T(z)$ are defined, $T(z)$ also depends on T_0, because the defined thickness of the troposphere, and the isothermal part of the stratosphere, depend on T_0. As a result, $GN(\phi)$ has a weak dependence on T_0.

Table 1 shows GN as a function of ϕ from 0.00001° to 180°. This was computed by integrating (2) over a thin column from height $z = 0$ to height $z = 60$ km. This height (several scale heights) has been found to be necessary to compute $GN(\phi)$ to better than 1 per cent at all ϕ. Beyond about 20 per cent from the column load, the thickness of the atmosphere is no longer important, so the column load Newtonian Green's function approaches that for a thin atmosphere,

$$GN(\phi) = 1.629 \frac{\phi}{\sin(\phi/2)}$$

but this does not happen until the separation between the gravity station and the base of the column is several tens of degrees.

In (2) GN has been integrated with a model atmosphere that is very close to the COSPAR standard atmosphere. Pressure and density in the column of air depend on temperature, and since these are generally only available at the surface, I have adopted a model in which the temperature gradients are defined, and temperatures are controlled by temperature at the surface. That is, the surface temperature is 15 °C, the lapse rate in the troposphere is 6.5° km^{-1}, the stratosphere to a height of 25 km is isothermal at 58 °C, and the lapse rate above this is −2.5° km^{-1}. To allow for variation in temperature, a derivative of GN with respect to temperature at the base of the column was computed (Table 1). Because temperatures at height in the model are controlled by surface temperature

Table 1. The atmospheric load gravity Green's functions.

ϕ	GN	$\frac{\partial GN}{\partial T}$	$\frac{\partial GN}{\partial z}$	$\frac{\partial^2 GN}{\partial z^2}$	GE
deg	$\frac{\mu gal}{mb}$	$\frac{\mu gal}{mb\,^{\circ}C}$	$\frac{\mu gal}{mb\,km}$	$\frac{\mu gal}{mb}$	$\frac{\mu gal}{mb}$
0.00001	-4938.0	17.1	0.00	0.0024	61.50
0.00005	-4896.0	16.9	-0.12		61.48
0.0001	-4879.0	16.8	-0.25		61.47
0.0005	-4772.0	16.2	-0.35		61.28
0.001	-4664.0	15.5	-0.50		61.16
0.0025	-4407.0	14.0	-0.75		60.36
0.005	-4074.0	12.1	-1.00		59.57
0.0075	-3805.0	10.6	-1.10		58.78
0.01	-3576.0	9.38	-1.20		57.99
0.015	-3197.0	7.46	-1.25		56.31
0.02	-2889.0	6.00	-1.30		54.57
0.025	-2632.0	4.84	-1.35		52.95
0.03	-2411.0	3.91	-1.39		51.33
0.04	-2052.0	2.50	-1.45		48.33
0.05	-1770.0	1.52	-1.50		45.74
0.06	-1544.0	0.829	-1.53		43.14
0.07	-1358.0	0.337	-1.53		41.05
0.08	-1203.0	-0.014	-1.52		38.97
0.09	-1073.0	-0.262	-1.50		37.36
0.10	-962.3	-0.436	-1.46	0.0025	35.75
0.11	-867.3	-0.555	-1.29		34.79
0.12	-785.2	-0.662	-1.16		33.84
0.13	-713.9	-0.684	-1.04		32.88
0.14	-651.5	-0.713	-0.94		31.92
0.15	-596.6	-0.726	-0.86		30.97
0.16	-548.1	-0.727	-0.79		30.46
0.175	-485.3	-0.715	-0.72		29.99
0.180	-466.7	-0.708	-0.70		29.67
0.190	-432.2	-0.691	-0.67		29.35
0.20	-401.5	-0.673	-0.65		29.02
0.225	-336.9	-0.619	-0.60		28.52
0.25	-286.2	-0.563	-0.55		28.01
0.275	-245.8	-0.511	-0.51		27.01
0.30	-213.0	-0.462	-0.49		26.01
0.325	-186.2	-0.419	-0.47		24.84
0.35	-163.9	-0.380	-0.46		23.66
0.375	-145.3	-0.345	-0.45		22.65
0.40	-129.5	-0.314	-0.45		21.64
0.425	-116.1	-0.287	-0.45		21.13
0.450	-104.6	-0.263	-0.44		20.28
0.475	-94.59	-0.241	-0.44		19.96
0.50	-85.91	-0.222	-0.43		19.60

Table 1. (*Continued*)

ϕ	GN	$\frac{\partial GN}{\partial T}$	$\frac{\partial GN}{\partial z}$	$\frac{\partial^2 GN}{\partial z^2}$	GE
deg	$\frac{\mu gal}{mb}$	$\frac{\mu gal}{mb\,°C}$	$\frac{\mu gal}{mbkm}$	$\frac{\mu gal}{mb}$	$\frac{\mu gal}{mb}$
0.55	-71.64	-0.190	-0.42		19.65
0.60	-60.49	-0.164	-0.41		19.70
0.65	-51.63	-0.142	-0.41		19.72
0.70	-44.47	-0.125	-0.41		19.73
0.75	-38.61	-0.110	-0.41		19.74
0.80	-33.76	-0.0980	-0.40		19.75
0.85	-29.69	-0.0876	-0.40		19.44
0.90	-26.26	-0.0788	-0.40		19.12
0.95	-23.33	-0.0712	-0.40		18.81
1.00	-20.81	-0.0647	-0.40	0.0026	18.50
1.10	-16.73	-0.0540	-0.40		18.05
1.25	-12.31	-0.0423	-0.40		17.09
1.30	-11.15	-0.0392	-0.40		16.67
1.40	-9.198	-0.0339	-0.39		16.04
1.50	-7.613	-0.0297	-0.39		15.60
1.60	-6.312	-0.0262	-0.39		15.16
1.75	-4.756	-0.0220	-0.39		14.60
1.80	-4.321	-0.0208	-0.39		14.41
1.90	-3.550	-0.0187	-0.39		14.04
2.00	-2.891	-0.0169	-0.39	0.0035	13.68
2.50	-0.6851	-0.0109	-0.39		11.83
2.75	-0.0020	-0.00899	-0.39		11.18
3.00	0.5183	-0.00756	-0.39		10.54
4.00	1.719	-0.00425	-0.39		8.500
5.00	2.276	-0.00272	-0.39	0.0062	7.171
6.00	2.579	-0.00189	-0.39	0.0089	6.268
7.00	2.762	-0.00138	-0.39	0.012	5.624
8.00	2.882	-0.00105	-0.39	0.016	5.264
9.00	2.964	-0.000828	-0.39	0.020	4.904
10.00	3.023	-0.000667	-0.39	0.025	4.543
15.00	3.166	-0.000286	-0.39	0.056	3.809
20.00	3.221	-0.000152	-0.39	0.10	3.075
25.00	3.253	-0.000091	-0.39	0.15	2.488
30.00	3.277	-0.000057	-0.39	0.22	1.902
40.00	3.319	-0.000023	-0.39	0.40	0.622
50.00	3.363	-0.000008	-0.40	0.62	0.416
60.00	3.414	-0.000001	-0.41	0.85	-0.099
70.00	3.474	0.000006	-0.42	1.2	-0.318
80.00	3.544	0.000010	-0.42	1.6	-0.113
90.00	3.625	0.000013	-0.43	2.0	0.265
120.00	3.948	0.000018	-0.47	3.6	1.377
150.00	4.426	0.000022	-0.52	8.4	2.331
180.00	5.130	0.000026	-0.61	12.0	2.897

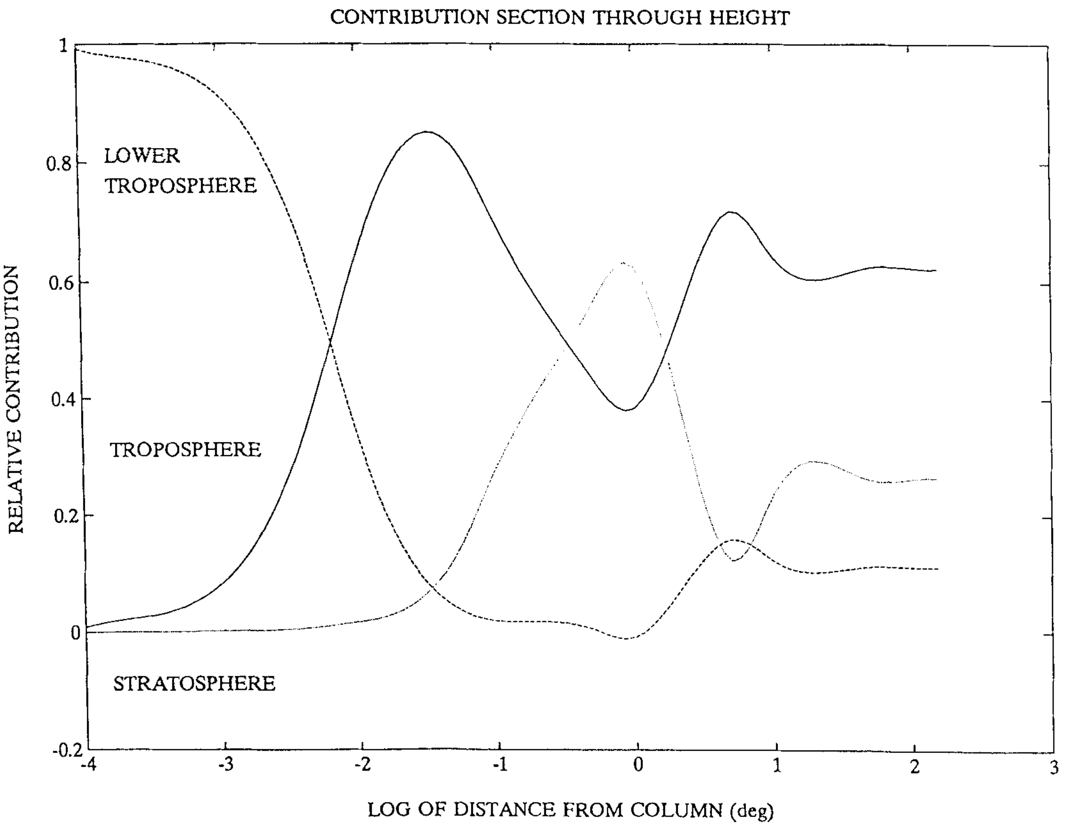

Figure 1. A Newtonian gravity contribution section through an atmospheric column as a function of distance from the base of the column. At small distances <0.1°, only the troposphere is important, and relatively large errors in model densities in the stratosphere can be tolerated. At intermediate distances (0.1°–3°) the stratosphere is relatively important, but on an absolute scale the signal from this zone is very small. At large distances the stratosphere contributes about 20 per cent of the signal, but only because it has 20 per cent of the mass; the details of the mass distribution are unimportant.

and the defined gradients, the derivative with respect to surface temperature implicitly includes a derivative with respect to temperature at height.

Fig. 1 shows a contribution section through a column of atmosphere, relative to the total attraction of the column. At small distances, most of the attraction comes from the lower troposphere (<1 km in height). At intermediate distances, the troposphere and stratosphere are contributing in roughly equal amounts, but in absolute terms the attraction from this zone is small. At greater distances, the troposphere contributes nearly 80 per cent of the total, but the total mass in the column (obtained directly from the pressure) is the only important factor at these large distances, and not how it is distributed. Thus, although the integration extends to great heights, conditions in the stratosphere are relatively unimportant in determining the attraction of a column of air. Effectively, this means that relatively large errors in model temperature in the upper troposphere and stratosphere are relatively inconsequential to gravity. This conclusion will be reinforced in a latter section.

Topography affects GN geometrically, in that the angle α is a function of both ϕ and the height difference between the gravity station and the base of the column, and with regard to mass, in that more of the atmospheric column must be integrated if the base of the column is below the height of the gravity station. Therefore, Table 1 also contains the first and second derivatives of GN with respect to the height difference between the gravity station and the base of the column of air. At small ϕ the effect is mostly geometric, and the second derivative dominates. At greater distances the effect is mostly one of mass, and the first derivative dominates. The apparent sensitivity to height at small distances is misleading, in that large height differences at small distances are unlikely. Topography is a relatively minor consideration. Variations in height of a kilometre within a few hundred km of the gravimeter alter the pressure correction by only a few hundred ngal.

Including both temperature and topographic effects, the tabular expression for GN is modified in the following way:

$$GN(\phi) = GN(\phi)_{\text{table}} + \frac{\partial GN}{\partial T}(T_0 - 15\,°\text{C}) + \frac{\partial GN}{\partial z}h + \frac{\partial^2 GN}{\partial z^2}\left(\frac{h}{a\phi(\text{rad})}\right)^2$$

where T_0 is the temperature at the base of the column, in °C, h is the height of the base of the column, in kilometres, above the gravity station, and a is the radius of the Earth in kilometres. In (2) P_0 is the pressure at the height of the gravimeter. When height-corrected Green's functions are used, the pressure to be used is the pressure at the height of the gravimeter, so that, station level pressure must first be corrected to the level of the instrument, and this pressure used with the height-corrected Green's functions.

The loading effect of the atmospheric column on the elastic Earth is generally smaller than the direct Newtonian attraction, at least near the load, and can be computed following Farrell (1972). Scaling the elastic part in the same way as the Newtonian part it is

$$g(\phi)=\frac{P_0}{10^5\phi}GE(\phi)\ \mu\text{gal mbar}^{-1}$$

where $GE(\phi)$ is the Green's function for the contribution of elastic deformation to the gravity signal (Table 1). *GE* has been computed on a PREM model Earth (Dziewonski & Anderson 1981), but the elastic effects are generally so much smaller than Newtonian effects, that the details of the Earth model are unimportant. For example, if *GE* is uncertain by a few per cent due to uncertainty in the Earth model, then the resulting error in gravity is only a few tens of ngal. Anomalous local conditions, for example the response of an aquifer to atmospheric pressure, present special problems that are not considered here.

Gravity at angular distance ϕ from the base of a column of atmosphere with area *A* in steradians is to be computed as follows from the tabulated values of *GN* and *GE*:

$$g(\phi)=\frac{GN(\phi)+GE(\phi)}{10^5\phi(\text{rad})}\frac{A}{2\pi[1-\cos(1°)]}\ \mu\text{gal mbar}^{-1}$$

and tabulated values of *GN* should be corrected for temperature and topography beforehand.

GN has a zero at about 2.7°, and the sum of *GE* and *GN* has a zero near 1.1, with the result that there is a rather broad band a few degrees from the gravity station from which the model atmosphere makes no net contribution to gravity. This is an important result, because it suggests a division of the globe into three zones, which contribute to gravity in different proportions, on different time-scales, and from which the gravity contribution can be calculated with varying reliability.

The local zone is from the gravity station out to 50 km. In this zone the Green's functions are large, and loading effects are only about 1 per cent of the Newtonian attraction. The coherence scale of atmospheric pressure under normal conditions is large compared to the size of this zone, so that a single barometer at the gravity site is sufficient to permit gravity to be computed to within a few tens of ngal, except during the passage of a front through the zone, or when a strong low-level inversion has developed. If topography within the zone fluctuates by no more than a km, then topographic effects on gravity are probably less than 50 ngal. Integrating the Green's functions from 0 to 0.5°, the admittance between gravity at the centre of the local zone, and pressure in the zone, is

LOCAL ADMITTANCE $= -0.356\ \mu$gal mbar^{-1}.

The regional zone extends from 0.5° to perhaps 10°, or more, from the gravity station. This is on the order of the synoptic scale of weather systems, so that pressure will generally correlate throughout this zone, but the correlation will weaken as distances increase. In the vicinity of Ottawa, the standard deviation between barometer records increases as 0.01 mbar km^{-1}. This means that while a single barometer at the gravity station is not sufficient to compute the gravity from this zone, a very tight network of stations is not required either. If pressure correlates exactly throughout this zone (and for this example only the regional zone is from 0.5°–10°), then the regional admittance is + 0.078 μgal mbar^{-1}.

The local and regional admittances are practically independent of epoch. However, because regional pressures deviate significantly from local pressure, an effective admittance (one determined by a regression between local pressure and gravity), can vary by as much as the regional admittance itself. This means that the effective admittance (of the local and regional zones together) can be anywhere in the range −0.27 to −0.43 μgal mbar^{-1}. Observations that a local admittance depends on epoch (e.g. Merriam 1981), are thus explained as variable conditions in the regional zone, and temperature effects in both the local and regional zones. Similar contentions that the effective admittance is a function of frequency are due to variations in the effective scale size of local weather systems. If proper local and regional corrections are performed there is no need to consider a frequency-dependent, or epoch-dependent admittance. Experience with the superconducting gravimeter GWR12 at Cantley, Quebec, suggests that, at most superconducting gravimeter sites, the local meteorological network will have sufficient stations in the regional zone to permit an adequate correction. In contrast with the local zone, the loading effects of the atmosphere are important in this zone. Topography is of more importance in the regional zone than it is in the local zone. It can vary the gravity signal from the regional zone by as much as 400 ngal per km of elevation.

While 0.5° is a useful definition for the local zone surrounding any site, the definition of the regional zone is site-dependent. This is because the regional zone should not include any oceanic areas, as these will involve an inverse barometer correction which cannot be properly performed on anything but a global integration over the oceans. A 500 km radius would be a minimum size for the regional zone, and the maximum is limited only by continental scales, and considerations of the temporal spectrum of gravity changes.

Fig. 2(a) shows a contribution section through the local zone, divided into seven bands. About half of the total signal from the local zone comes from a narrow band between 1 and 10 km from the gravity station. The standard deviation in the pressure difference between two stations in eastern Canada (adjusted for differences in height) goes as 0.01 mbar km^{-1}. Integrating this with the partial admittances in Fig. 2(a) then suggests that the 1σ error in the gravity correction for the local zone, resulting from the use of a single barometer instead of an array of barometers, is only about 35 ngal. When a front is passing through the local zone, the error may be much larger than this, in which case Fig. 2(a) suggests that the zone from 1 to 10 km of the gravity station is a critical area from which to have additional pressure data. Fig. 1 indicates that the stratosphere makes little contribution in this innermost band, so that any errors in the stratospheric densities of the assumed model atmosphere are not very important in the local zone correction.

Fig. 2(b) is a contribution section through a regional zone extending from the edge of the local zone out to 10° from the gravimeter. Repeating the previous exercise, the use of a single barometer at the gravimeter, instead of an

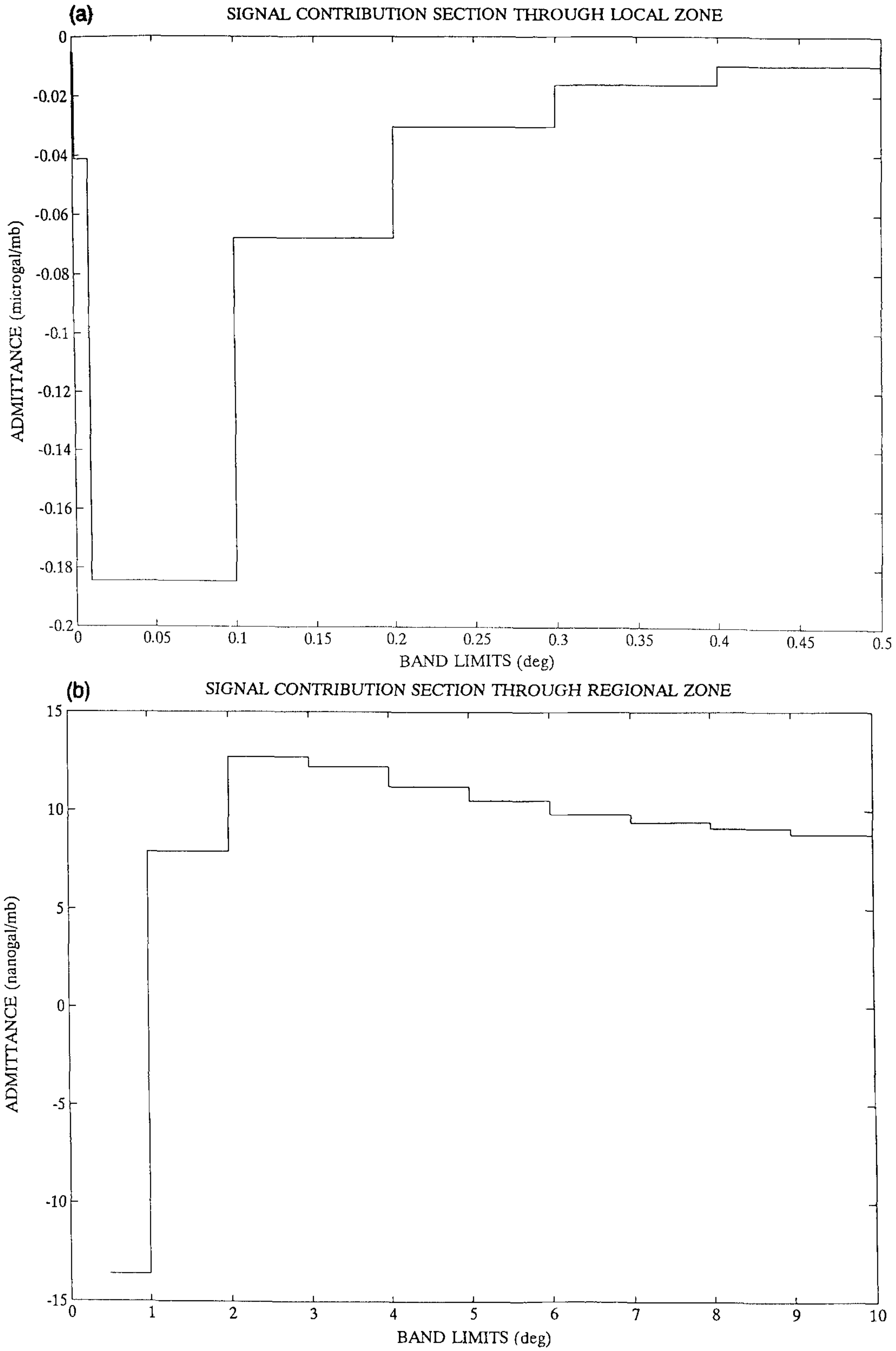

Figure 2. (a) A signal contribution section through the local zone. A circular local zone has been divided into five bands 0.1° wide, and two smaller bands. The y axis is the partial admittance of each band. The band from 0.01° to 0.1° accounts for half of the total admittance of the local zone. This band is therefore a critical area from which to have additional information on the pressure when a front is passing through the local zone. (b) A signal contribution section through the regional zone. A circular regional zone has been divided into nine bands 1° wide, and one smaller band. The y axis is the partial admittance for each band. Note that the band from 0.5° to 2.7° has no net contribution to gravity, and that the rest of the regional zone contributes in roughly equal weight to the total admittance. A roughly uniform distribution of barometers in the regional zone, with a mean separation of a few hundred kilometres, is required to adequately model the gravity signal from this zone.

extensive array of barometers in the regional zone, results in a 1σ error in the regional zone correction of over half a μgal. Similarly, if an array of barometers with mean separation of a few hundred km is used in the regional zone, then the 1σ error drops to less than 100 μgal.

There is a small temperature dependence of gravity from both the local and regional zones arising from the expansion and contraction of the atmosphere (unattended by pressure changes) as the temperature rises and falls. As the atmosphere warms, the centre of mass of the local column of air moves further from the gravimeter, and the upwards attraction of the column diminishes. Thus the temperature admittance for the local zone is positive. Most of the regional zone is below the instrument horizon so its Newtonian attraction is positive and again diminishes as the centre of mass ascends. The regional zone temperature admittance is therefore negative, and partially cancels that of the local zone. Because the effect is small in any case, spatial variations of temperature within the local and regional zones can be ignored, and it is convenient to combine the effect from both zones:

TEMPERATURE ADMITTANCE
$= +0.013(T_c - 15°)\ \mu\text{gal}\ °\text{C}^{-1}$.

The global zone is the rest of the globe outside of the local and regional zones. The gravity signal from this zone is surprisingly large, about a μgal, but most of the power is at periods of several days to seasonal. The zone is mostly oceanic, and so some sort of inverse barometer response of the oceans to atmospheric pressure is required. At periods of several days, where the power spectrum of this zone peaks, a hydrostatic inverse barometer is probably adequate, but at periods of a day or less, the reliability of such a model is uncertain. Wunsch (1972) in a study of Bermuda sea level concluded that at periods between 40 and 400 hr, the sea surface response to air pressure is as an inverse barometer, and that there appears to be no excitation of oceanic normal modes by atmospheric pressure at periods less than 300 hr. Since the spectrum of the gravity signal from the global zone is dominated by longer periods, a twice per day sampling, on a coarse global grid, is adequate. In this zone the total mass in a column of air is the only important factor, and not how that mass is distributed throughout a column of air, so that temperature and topographic effects are unimportant.

DISCUSSION

The Green's functions derived here are based on the ideal gas law, the hydrostatic assumption, and a temperature model of the atmosphere which agrees with the COSPAR mid-latitude standard to within a few per cent. At any time environmental temperatures may disagree with those defined by the model by several tens of degrees. This would seem to suggest that the Newtonian Green's functions, and computed gravity, could be in error by 10 per cent as well. However, the Newtonian attraction of a column of air is not very sensitive to the temperature structure of the atmosphere. The reason for this is that any reasonable temperature structure will result in densities which integrate to the same total mass; temperature affects the distribution of density within the column, but not the total mass. In other words, the mass per unit area of a column of air in the adopted model is P_0/g_0, the same as it would be for *any* column of air in hydrostatic equilibrium, *regardless of temperature structure*. As a result, temperature structure in the column of air influences gravity only to the extent of raising or lowering the centre of mass, without altering the total mass.

In the global zone, only the total mass is important, not how it is distributed throughout the column, and so the Green's functions in this zone are relatively insensitive to the adopted model of the atmosphere. In the local zone the centre of mass of the 100 km diameter column of air may move up and down as the temperature structure changes (about 18 m °C^{-1}), but this is so small compared to the diameter of the column that gravity at the centre of the base changes very little. In the regional zone, the location of the centre of mass is more important, because it may lie above or below the instrument's horizon. However, in absolute terms, the net attraction from the regional zone is small, so the overall effect is not very important.

To test the sensitivity of the local and regional admittances to the adopted temperature structure of the model atmosphere, the tropospheric lapse rate was varied between the dry adiabatic lapse rate 10 °C km^{-1}, and a moist adiabatic lapse rate of about 3 °C km^{-1}. Temperatures at height were then found to differ by as much as 70 °C from the adopted standard, but the local admittance only differed by about a half a per cent, and the regional admittance by about 3 per cent (but recall that gravity from the regional zone is only a few μgal). In addition, several observed temperature soundings in the atmosphere were used in place of the adopted model in the computation of the Green's functions. These were: a typical winter sounding (with a strong frontal inversion), a typical summer sounding, and a sounding during extremely unstable atmospheric conditions. The two typical soundings produced Green's functions, and admittances, that varied from the model values by less than a per cent, while the extreme weather sounding produced admittances which differed by only 2 per cent from the model. In terms of gravity, this means that errors in the adopted temperature structure result in errors in computed gravity of less than 100 ngal during normal conditions, and no more than 400 ngal during extreme weather conditions.

The validity of the hydrostatic assumption is of some concern as well. Surface level pressure does not immediately supply the mass per unit area in the column of air if the column is not in hydrostatic equilibrium, so that relative errors in densities imply relative errors of similar magnitude in gravity. However, departures from hydrostatic equilibrium are relatively small; in the synoptic scale vertical accelerations are no more than 10^{-7} times gravity, so that hydrodynamic pressures are less than a microbar, and the error in the gravity correction arising from the adoption of the hydrostatic approximation is less than a ngal. In the mesoscale, the hydrostatic assumption begins to weaken. However, even in severe local storms hydrodynamic pressures only reach ~2 mbar (Atkinson 1981), or the equivalent of 0.7 μgal error in the gravity correction.

When the atmosphere is not in hydrostatic equilibrium, when there are temperature inversions, and when fronts are passing through the local or regional zones, actual conditions will differ from the standard model and the computed correction may be in error by more than a per cent (only a few hundred ngal).

A typical meteorological classification of weather scales is into synoptic (macro-), meso-, and microscales (Atkinson 1981). The synoptic scale has characteristic dimensions and wavelengths of greater than 500 km, and periods greater than 48 hr. It is in quasi-geostrophic balance, and hydrostatic equilibrium. The mesoscale has characteristic scales and wavelengths between 20 and 500 km, periods between 1 and 48 hr, non-geostrophic motion, and is in hydrostatic equilibrium. The microscale has characteristic scales less than 20 km, periods less than an hour and is neither in geostrophic balance, nor hydrostatic equilibrium. Thus the meteorological classification is in convenient harmony with the classification into local, regional, and global zones. The global zone is responding to synoptic scale variations only, while mesoscale and microscale anomalies are largely averaged out. The regional zone is responding to synoptic scale variations, but is sensitive to mesoscale variations as well. The local zone is sensitive to micro- and mesoscale motions, although these have not been considered here.

The same conditions that are a problem in the local zone can result in a poor correction for the regional zone. Microscale variations within the regional zone are relatively unimportant, because they will be averaged out to some degree. Anomalous conditions within a frontal zone are of little importance because of the relatively small area occupied by the front. The regional zone admittance (0.078 μgal mb^{-1}), and the coherence scale of atmospheric pressure fluctuations (~0.01 per km of station separation) suggests that a mean separation of 200 or 300 km between meteorological stations in the regional zone is all that is required. The gravity correction for this zone should be good to much better than 100 ngal.

The global zone is quite different from either the local or regional zones. It is so large that pressure variations on all scales are averaged and the gravity signal varies on time-scales of days rather than hours. Departures from hydrostatic equilibrium are relatively unimportant, partly because the net effect from this zone is an order of magnitude smaller than that from the local zone to begin with, and partly through averaging. The global zone has its own unique problem, in that 70 per cent of it is oceanic, and therefore some allowance must be made for the response of the oceans to the global pressure. At periods greater than a few days, the response should be largely an inverse barometer, which can be calculated reasonably well (Wunsch 1972; Merriam 1981; Chelton & Enfield 1986). At periods shorter than a few days, particularly in the semi-diurnal–diurnal band, the ocean response to atmospheric pressure may be dynamic, and a proper correction cannot as yet be done. Uncertainty in the response of the oceans means that the net correction for this zone is probably only good to a few hundred ngal level for gravity stations near coats, and perhaps a hundred ngal for inland stations.

Table 2 shows the approximate spectral amplitudes of the local regional, global and temperature corrections in the synoptic (days to seasonal), diurnal, semi-diurnal, ter-diurnal, quart-diurnal and intertidal bands. Each correction

Table 2. The approximate amplitude of atmospheric pressure corrections to gravity (in ngal) in tidal and intertidal bands. These corrections are certainly good to 10 per cent at all times, and probably better than 1 per cent during typical weather conditions.

		1 DAY		1/2 DAY		1/3 DAY		1/4 DAY
LOCAL	1000	100	10	100	8	50	2	10
REGIONAL	100	10	1	10	< 1	5	< 1	1
GLOBAL	100	10	-	-	-	-	-	-
TEMPERATURE	50	20	1	5	< 1	2	< 1	1

is certainly good to 10 per cent, even under extreme weather conditions, so that dividing each table entry by 10 gives an approximate upper bound on the error in the correction in that band. That is, about 100 ngal in the synoptic band and less than 10 ngal in every other band. If the corrections are good to about the 1 per cent level, which is true except during extreme weather conditions, then dividing each table entry by 100 gives the error in that correction in that band. Under normal weather conditions therefore, the above corrections should be good to about 10 ngal.

When an admittance between gravity residuals and pressure is fitted by least squares, some of the regional correction is accommodated, because pressure in the regional zone correlates somewhat with pressure at the gravimeter site. To test how well this procedure could account for the regional correction, I computed a pseudo-regional correction by using the pressure at the gravimeter, instead of observed pressure in the regional zone. The pseudo-regional correction differed from the regional correction by as much as 800 ngal, and predictably, the largest differences occurred when pressure was changing most rapidly, for example when a front was passing through.

To see how successful the local, regional, global and temperature corrections were in reducing noise levels in superconducting gravimeter data, I used a 420 day long hourly registration from the superconducting gravimeter GWR12 at Cantley, Quebec. The instrument was calibrated to about half a per cent by running it side by side with an absolute instrument for about three months in early 1990 (Bower *et al.* 1991). The record was corrected for Earth tides and drift and tares were removed to yield a residual composed of calibration errors, errors, errors in the ocean tide correction, the air pressure signal, and other sources of noise. The effectiveness of the correction for each zone was then assessed by looking at the decrease in power spectral density in separate frequency bands, as a result of performing the correction. The local correction lowered noise levels in all bands from seasonal to the Nyquist at 0.5 cy hr^{-1}. The regional, global and temperature corrections lowered noise levels in the seasonal and synoptic bands, but were not consistently effective at periods shorter than about half a day.

Local pressure and gravity residuals (corrected for tides, temperature, global pressure and regional pressure) were strongly coherent in all the intertidal bands down to periods of about three hours. Fig. 3 shows a portion of the

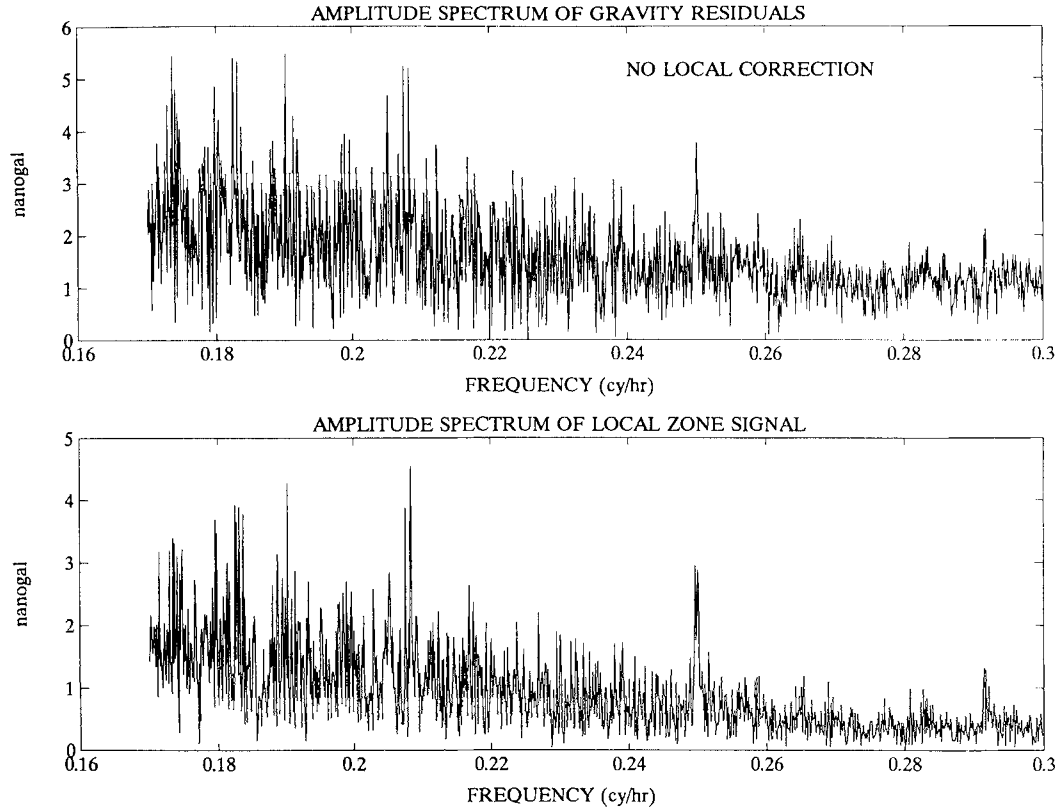

Figure 3. The amplitude spectrum of gravity residuals corrected for regional, global and temperature effects, but not local zone effects (top), and the computed gravity signal from pressure in the local zone (bottom). The response of the gravimeter to the few ngal signal due to atmospheric mass in the local zone is clearly evident.

amplitude spectrum of gravity residuals (top, corrected for everything but local zone effects), and the gravity signal from the local zone (bottom). At periods this short, the amplitude of gravity residuals is less than 10 ngal, and pressure is only a few μbar, so that both the gravimeter and the barometer are operating near their limits. Nevertheless, the known signal from the local atmosphere is clearly expressed in the gravity residuals. The transfer function between gravity residuals and local pressure in this band is nearly the expected value of 0.3–0.4 μgal mb^{-1} with a phase of approximatly 180°, so that the gravimeter is responding to and faithfully tracking atmospheric pressure signals at near the ngal level and at periods of several hours. There is some evidence that at periods shorter than a half day the amplitude of the transfer function is more like 0.4 μgal mbar^{-1} and the gravity signal may lead or lag the local pressure by about 10°.

I computed an effective admittance between local pressure and gravity residuals (corrected for tides, regional pressure, global pressure, and temperature) in the long-period intertidal band, in order to get an effective admittance for the local zone. The result was in agreement with the theoretical result for the local correction to within about 1 per cent. The usual way of computing an admittance (that is, without doing the regional correction separately) yielded -0.326 ± 0.012 μgal mbar^{-1}. Most of the difference between the gravity signal computed from local and regional integration, and the gravity signal computed using an effective admittance, occurs when a front is passing through the regional zone. During these brief times the error may reach a μgal.

CONCLUSIONS

Atmospheric pressure influences local gravity at about the 20 μgal level. I have shown that most of the signal comes from within 50 km of the gravimeter. Within this local zone atmospheric pressure is essentially uniform, so that a single barometer at the gravimeter site characterizes the gravity signal from this zone very well. The admittance between gravity and local zone pressure is -0.356 μgal mbar^{-1}, so that a good barometer ($\sim$10 μbar accuracy or better) is needed in the local zone. I have found that local pressure and gravity residuals correlate with an admittance near -0.3 μgal mbar^{-1} at periods down to three hours. The amplitude of gravity residuals is less than 10 μgal at periods as short as this, so the gravimeter is responding to the gravity signal from the atmosphere at near its sensitivity. Except during extreme atmospheric conditions, the local zone admittance should be good to better than 1 per cent. This means a maximum error in the gravity correction of about 100 ngal, and probably less than 10 ngal in amplitude in any band above the diurnal in frequency.

The regional zone has a pressure field which usually correlates with the local pressure, but can sometimes be quite different. For this reason, an effective admittance (a least-squares fit of gravity residuals to local pressure) can sometimes give very good results, but will also sometimes over- or undercorrect by up to a μgal. To adequately characterize the gravity signal from the regional zone requires an array of barometers. An average pressure in the regional zone, or a ring of barometers surrounding the gravimeter at some distance is not sufficient to calculate an appropriate correction. I have found that a mean separation of a few hundred kilometres between barometers in the regional zone is sufficient. Given the suggested size of the regional zone, anywhere from a few hundred to a thousand kilometres in radius, this calls for a dozen or so barometer stations. An important feature of the gravity effect of the atmosphere which is described here is that while the atmosphere nearest the gravimeter has the greatest effect on gravity, there is a zone very near the gravimeter from which the atmosphere makes no net contribution to gravity; this in fact defines the boundary between the local and regional zones.

The atmosphere in the local and the regional zones expands and contracts with temperature without any accompanying change in pressure. There is however an effect on gravity because the centre of mass of the local plus regional atmosphere moves nearer to and farther from the gravimeter. This correction is less than a μgal, but its use really only lowers the residual noise levels in the synoptic band.

Thus correction derived from the rest of the globe can contribute a few μgal, mostly at periods of several days and longer. It is subject to a poorly known oceanic response to pressure, but most of the power is at long periods where the inverse barometer response is more likely to be valid. More work is required to establish the reliability of the global zone correction, but it is probably good to a few per cent, or perhaps 100 ngal.

Many of the observations of a site, epoch, or frequency-dependent gravity–pressure admittance are simply due to a lack of appreciation for the importance of coherence scale in the atmosphere, the temperature effect, and the geometry of scale height and Earth curvature. Variable conditions in the regional zone alone can cause an effective admittance to vary by up to $\pm 0.05\ \mu\mathrm{gal\ mbar^{-1}}$. A proper correction, as outlined here, accounts for the variable conditions in the regional zone. The gravity signal from the local zone has been defined by a single barometer at the gravimeter site. This is adequate under most conditions, but when there are larger horizontal pressure gradients in the local zone (that is, greater than $0.01\ \mathrm{mbar\ km^{-1}}$) more information on pressure is required.

ACKNOWLEDGMENTS

This work was supported through a Natural Sciences and Engineering Research Council of Canada Operating Grant. Don Bower and Nicholas Courtier, of the Geophysics Division of the Geological Survey of Canada, supplied the gravity data and provided helpful information on the details of the data collection and processing. Ron Miksha verified much of the numerical work, and computed the regional correction for the CSGI. The pressure data for the global correction were obtained from NCAR and the author is indebted to Dennis Joseph and Ray Jenne for helpful discussions. Mike Webb of the Canadian Climate Center supplied for pressure data for the regional correction.

REFERENCES

Atkinson, B. W., 1981. *Meso-Scale Atmospheric Circulations*, Academic Press, London.

Bower, D. R., Liard, J., Crossley, D. J. & Bastien, R., 1991. Preliminary calibration and drift assessment of the superconducting gravimeter GWR12 through comparison with the absolute gravimeter JILA2, *Cahiers du Centre Européan de Géodynamique et de Séismologie*, **3**, 192–142.

Chelton, D. B. & Enfield, D. B., 1986. Ocean signals in tide gauge records, *J. geophys. Res.*, **91**, 9081–9098.

Dziewonski, A. M. & Anderson, D. L., 1981. Preliminary reference Earth model, *Phys. Earth planet. Inter.*, **25**, 297–356.

Farrell, W. E., 1972. Deformation of the Earth by surface loads, *Rev. Geophys. Space Phys.*, **10**, 761–797.

Merriam, J. B., 1981. An investigation of dispersive effects on tidal gravity measurements at Alice Springs, *Phys. Earth planet. Inter.*, **27**, 187–193.

Müller, T. & Zürn, W., 1983. Observation of gravity changes during the passage of cold fronts, *J. Geophys.*, **53**, 155–162.

Niebauer, T. M., 1988. Correcting gravity measurements for the effects of local air pressure, *J. geophys. Res.*, **93**, 7989–7991.

Rabbel, W. & Zschau, J., 1985. Static deformations and gravity changes at the Earth's surface due to atmospheric loading, *J. Geophys.*, **56**, 81–99.

Spratt, R. S., 1982. Modelling the effect of atmospheric pressure variations on gravity, *Geophys. J. R. astr. Soc.*, **71**, 173–186.

Van Dam, T. M. & Wahr, J. M., 1987. Displacements of the Earth's surface due to atmospheric loading: effects on gravity and baseline measurements, *J. geophys. Res.*, **92**, 1281–1286.

Warburton, R. J. & Goodkind, J. M., 1977. The influence of barometric pressure variations on gravity, *Geophys. J. R. astr. Soc.*, **48**, 281–292.

Wunsch, C., 1972. Bermuda sea level in relation to tides, weather and baroclinic fluctuations, *Rev. Geophys.*, **10**, 1–49.