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# Application of the Indirect Effect on Regional Gravity Fields in the North Atlantic Ocean

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# 北大西洋 重力場에 적용한 Indirect Effect

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*Abstract*

Gravity measurements at sea are considered to be made on the geoid. The free-air anomalies are then determined by subtracting the theoretical gravity values predicted on a reference ellipsoid from the observed values. The gravity effect due to the height difference between the geoid and reference ellipsoid and the mass between them is known as the 'indirect effect'. The result of applying the indirect effect to surface ship derived gravity anomalies in the North Atlantic Ocean demonstrates the importance of its inclusion for regional studies involving mantle processes.

**요약** : 바다에서의 중력관측은 지오이드上에서 측정된 것으로 간주되고 Free-air 이상치는 지오이드上의 관측치로부터 표준타원지구면 위에서 예상되는 중력치를 감함으로 결정된다. 표준타원지구면과 지오이드면의 고저差 및 두 面 사이의 질량差에 따른 중력효과를 "Indirect Effect" 라고 하는데 이 "Indirect Effect"를 북대서양 해수면上에서 관측된 중력이상치에 고려해 본 결과 이 "Indirect Effect"를 바다에서의 중력관측치에 포함시키는 것이 맨틀운동을 포함한 지구의 광역 연구조사에 중요함이 밝혀졌다.

## INTRODUCTION

The earth's geoid, an equipotential surface normal to the gravity force, is approximated by the mean sea level surface. Thus gravity measurements collected at sea aboard research vessels are considered to be made on the earth's geoid. The free-air gravity anomalies are obtained by subtracting the theoretically predicted gravity values on a reference ellipsoid from the observed gravity values on the geoid. However, the geoid itself undulates with respect to the reference ellipsoid. The gravity effect due to height differences btween the reference ellipsoid and the geoid is not taken into account in the reduction procedure of the free-air gravity anomalies. This is known as the 'indirect effect' in geodesical problems (Heiskanen and Moritz, 1967; Bomford, 1980), but generally neglected in marine geophysical studies. Though the indirect effect may not be important in local studies (gravity anomalies with wavelength < 500 km), it becomes significant for regional studies in which the long wavelength ($\lambda > 500$ km) components of gravity are analyzed (Chapman and Bodine, 1979). In this paper we apply the indirect effect in order to derive a new corrected regional gravity field for the North Atlantic Ocean.

## COMPUTATION OF INDIRECT EFFECTS

In order to compute the indirect effect, two factors should be considered as discussed by Chapman and Bodine (1979). The first factor is a free-air correction which accounts for the height difference between the geoid and the reference ellipsoid, denoted by N in Figure 1. The magnitude of this correction is obtained by taking the first derivative of normal gravity in radial direction times the geoid undulation in meters, N. This correction factor is about 0.3086 mgal/m and is always positive for positive geoid undulations, N, and negative for negative geoid undulations. (The geoid undulation is positive upward from the reference ellipsoid.) The second factor is the gravitational attraction of the mass between the goeid and the reference ellipsoid. This may be approximated as a simple Bouguer slab whose magnitude is $2\pi G_p N$, (where G is gravitational constant, $6.67 \times 10^{-8}$g cm$^3$ sec$^{-2}$, $p$ is water density, 1.03 g cm$^{-3}$, and the geoid undulation, N in meters). This correction is approximately 0.043 mgal/m. Since the reference ellipsoid assumes no mass outside the reference surface and no lateral density variation, the Bouguer correction term to the indirect effect is negative where the geoid undulation, N, is positive and vice versa. By combining the two correction terms, we have the indirect effect 0.2656 mgal/m (Chapman and Bodine, 1979).

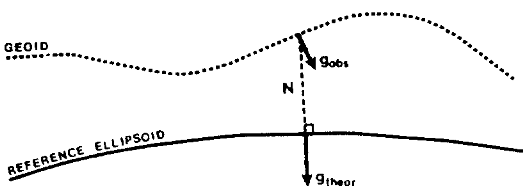


Fig. 1. Gravity measurements at sea are made on the geoid which undulates with respect to the reference ellipsoid. Free-air anomalies are determined by subtracting the theoretical gravity values ($g_{theor}$) on a reference ellipsoid from the observed gravity values ($g_{obs}$) on the geoid. The gravity effects due to the height differences (N) and the mass between the two reference surfaces are called the indirect effect.

## AVERAGED SURFACE SHIP GRAVITY ANOMALIES

We obtained 1° × 1° averaged gravity values from a detailed free-air anomaly map of the North Atlantic Ocean (Jung and Rabinowitz, in press). The gravity measurements utilized to construct the free-air gravity contour map were referred to the International Gravity Formula 1930 (IGF 1930). The 1° × 1° averaged gravity values after being converted to the Geodetic Reference System 1967 (Bomford, 1980) are presented in Figure 2. In order to determine the 1° × 1° averaged values, we subdivided every 1° × 1° block on the gravity map into 9 or 36 smaller blocks, depending on the steepness or gradients of the gravity contours within each of the 1° × 1° blocks. The free-air anomalies at the center of the subdivided blocks were then determined through interpolation and/or extrapolation, and the averages of the 1° × 1° blocks were computed.

The general trends of the 1° × 1° surface ship gravity map (Figure 2) are very similar to the detailed free-air anomaly map (Jung and Rabinowitz, in press) with somewhat subdued local peaks and troughs. The most prominent features of Figure 2 are the broad positive anomalies over the Mid-Atlantic Ridge area and negative anomalies over the adjacent oceanic basins. The positive values over the Mid-Atlantic Ridge show a rather distinct change near 32°N. North of 32°N, the 1° × 1° surface ship gravity is more positive than to the south with values in the north, in places, more positive than 40 mgal.

The 1° × 1° surface ship gravity values over the western basin are more negative than those over the eastern basin. The largest negative values, more negative than −60 mgal, are observed over the Hatteras Abyssal Plain. From the Hatteras Abyssal Plain toward the Mid-Atlantic Ridge the gravity values gradually increase to near zero at the ridge crest. Over

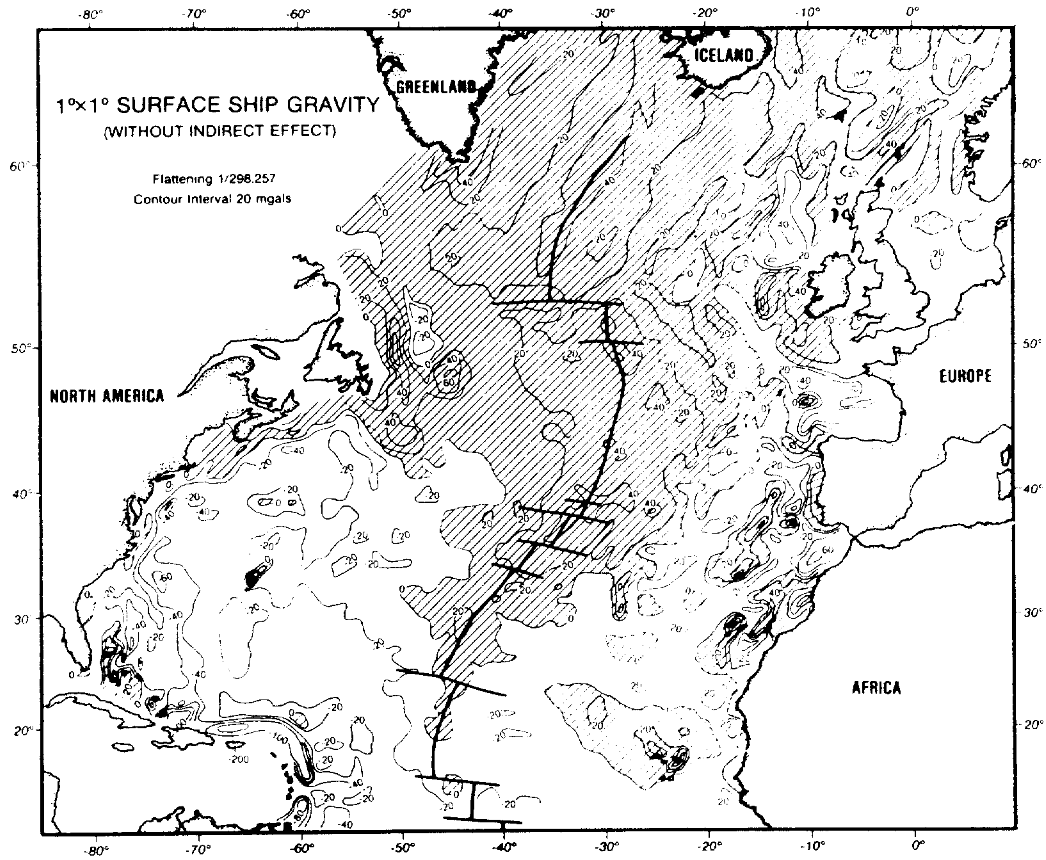


Fig. 2. Map of the 1° × 1° averaged free-air gravity anomalies determined from the detailed gravity map of and Jung and Rabiniwitz (in press). This map was constructed based on the 1° × 1° averaged values at the center of 1° × 1° blocks.

the eastern basin, the gravity values show values near −20 mgal. The locations of extensive volcanic activity away from the Mid-Atlantic Ridge, such as the Bermuda, Cape Verde, Canary, and Madeira Islands, are all associated with relative regional free-air gravity highs with values about 20 mgal. The largest negative surface anomalies in the North Atlantic, more negative than −200 mgal, are observed along the Puerto Rico Trench.

## APPLICATION OF THE INDIRECT EFFECT TO THE AVERAGED SURFACE SHIP GRAVITY ANOMALIES

In order to compute the indirect effect, we assume the geoid undulations of the North Atlantic Ocean are that of GEM10C standard earth model which is complete up to degree and order of 20 (figure 3a). We compute the indirect effect on the centers of 1° × 1° blocks employing the relationship, 0.2656 mgal/m, and present the result in Figure 3b. By adding the values of computed indirect effect (Figure 3b) to the 1° × 1° averaged free-air anomalies of the North Atlantic Ocean (Figure 2), we have the 1° × 1° averaged free-air gravity anomalies of the North Atlantic Ocean with the indirect effect shown in Figure 4.

The result of including the indirect effect to the surface ship gravity anomalies in the North Atlantic ocean does not basically change the trends in the long wavelength component of the gravity field. The most significant observation

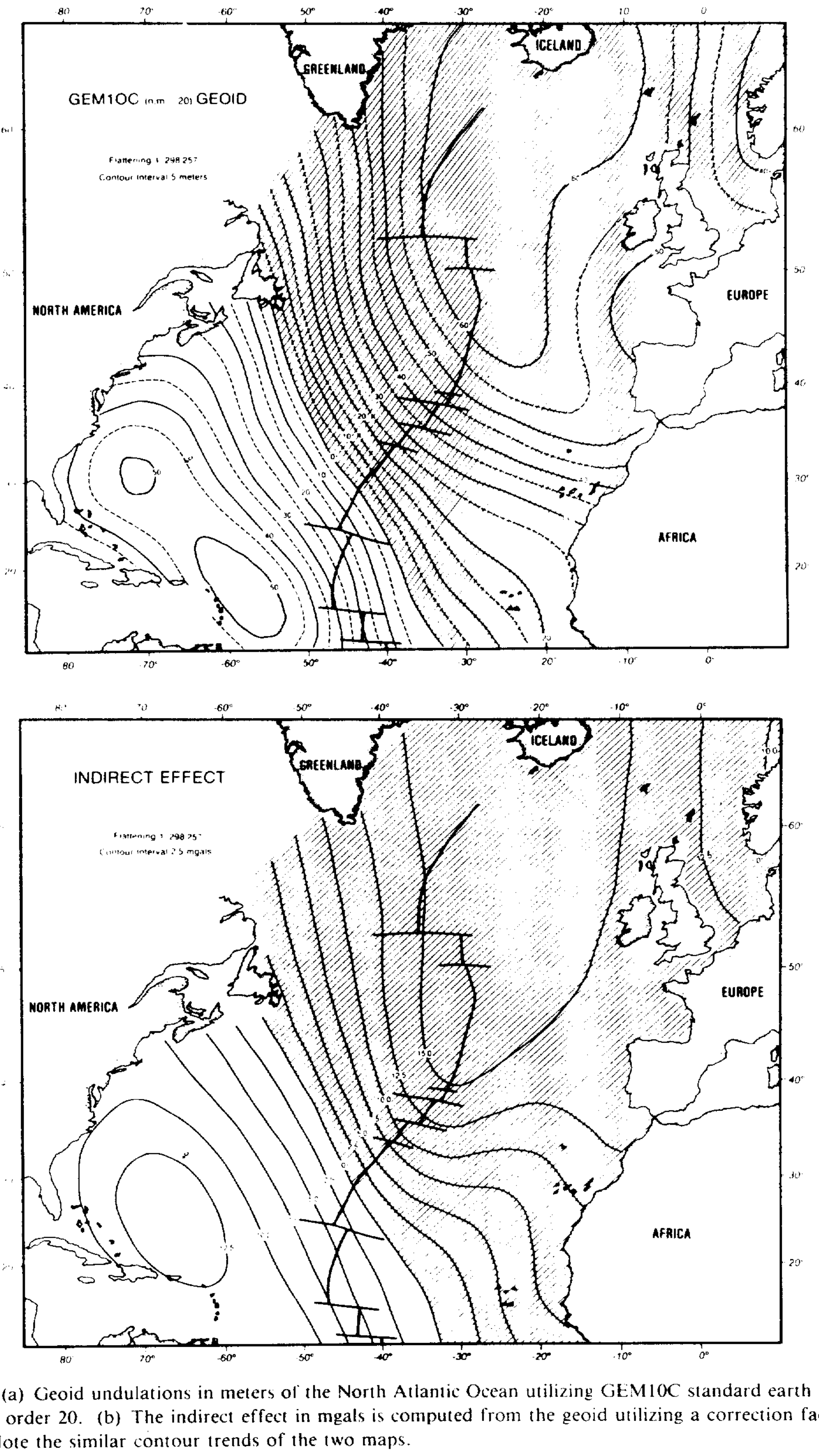


Fig. 3. (a) Geoid undulations in meters of the North Atlantic Ocean utilizing GEM10C standard earth model with degree and order 20. (b) The indirect effect in mgals is computed from the geoid utilizing a correction factor 0.2656 mgal/m. Note the similar contour trends of the two maps.

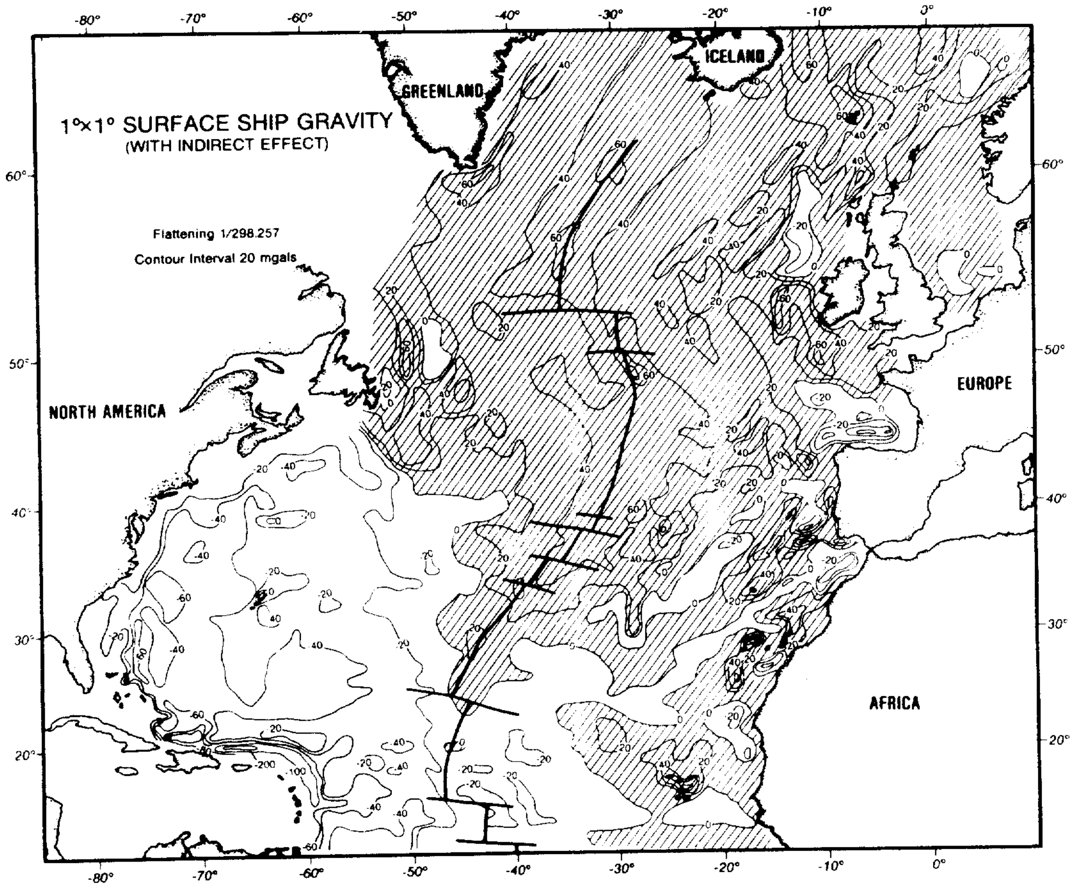


Fig. 4. The 1° × 1° averaged free-air gravity anomalies with indirect effect included are obtained by adding Figure 3b to Figure 2. Note the inclusion of the indirect effect does not alter the basic long wavelength features, but accentuates the asymmetry of the North Atlantic Ocean gravity fields.

of Figure 4 is that the inclusion of the indirect effect accentuates the asymmetric features discussed in previous section. Positive values in the north become more positive and negative values over the western basin become more negative. An approximate 50% change in amplitude is observed over the Reykjanes Ridge and the western basin areas. Further, the many patches of negative anomalies observed in the eastern basins approach zero or became positive.

## CONCLUDING REMARKS

The consideration of the indirect effect is very important for the regional geophysical studies to understand deep mantle processes. For example, Talwani and Le Pichon (1969) noted that a considerable part of the isostatic anomalies in the North Atlantic Ocean can be due to non-isostatic origin — possibly mantle convections. The application of the indirect effect substantiates their conclusions and suggests further non-isostatic mechanisms to explain even larger isostatic anomalies. Cochran and Talwani (1978) conclude that in order to account for the gravity anomalies in the shallow ridge area to the north of 32°N, a portion of compensation must be distributed to depths of several hundred km (within the asthenosphere); the more local features within this region are compensated at much shallower depths within the lithosphere. The application of the indirect effect also further substantiates their conclusions indicating that the gravity anomalies would show that the ridge is either more uncompensated (less mass deficiency) and/or deeper compensation.

In conclusion, as noted by Chapman and Bodine (1979) the consideration of the indirect effect should be included in regional studies. We have included this effect to the most recent surface ship derived gravity map of the North Atlantic Ocean. The important north-south and east-west asymmetries observed in the regional gravity field of the North Atlantic are seen to be further accentuated when the indirect effect is applied.

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