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Interhemispheric Transfer of Radioactive Pollution from Nuclear Explosions

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Interhemispheric transfer of radioactive pollution from nuclear explosions

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By using a simple model of the atmosphere, having two compartments, it is possible to derive expressions for the fission product reservoirs of the northern and southern hemispheres as functions of the gross rate of exchange between hemispheres, and the fallout rate.

When observed values (1963–6) of the fission products are inserted into the theoretical expressions it is possible to extract approximate estimates of the rate of interhemispheric transfer, and the ratio of northern and southern reservoirs at any time.

Introduction

The radioactive debris from a nuclear weapon consists of fission products, unexpended fissile material such as uranium-235 and plutonium-239, and activation products—the result of the capture of excess neutrons in the weapon material or in the environment of the explosion. This vaporized mixture is forced upwards into the atmosphere by the tremendous release of energy in the explosion. As the cloud rises and cools, the radioactive products condense to form particles of solid debris. It is this particulate material, together perhaps with gaseous tritium (from fusion reactions) and carbon-14 (from the neutron reaction with atmospheric nitrogen), that later constitutes fallout. Nuclear radiations are emitted as the radioactive atoms disintegrate. The lifetime of the many products varies from fractions of a second to many years so that the radioactivity of the mixture decays in a complex manner.

The atmosphere has been polluted for over 20 years by artificial radioactivity from nuclear explosions. At first the explosions were comparatively small so that the nuclear debris was confined zonally, within the troposphere and roughly to the latitudes of the explosion sites. The stratosphere was penetrated for the first time by a thermonuclear device, exploded by the U.S.A. in 1952. Since then there have been many large explosions so that the subsequent dispersal of the debris, controlled by the meteorology of the stratosphere, has been worldwide.

The series of nuclear explosions made by the U.S.A. and the U.S.S.R. during 1961–2 injected massive amounts of fission products into the atmosphere (F.R.C. 1963). These included about 10 MCi of strontium-90 and corresponding quantities of the other fission products. Some of this radioactive debris inserted directly into the troposphere was removed within a few months, chiefly by rain. By far the greater part, inserted in the stratosphere above the tropopause, will have undergone more prolonged mixing and redistribution under the influence of atmospheric motions and gravitation, before passing into the troposphere and falling out.

By using a simple model of the atmosphere and by applying measured values of certain fission products it is possible in general terms to observe the behaviour of the atmosphere and to describe the fate of the pollution from the nuclear explosions in 1961–2 (Peirson & Cambray 1967).

The simple model

The proposed model (figure 1) consists of northern and southern compartments with reservoirs x and y separated by a vertical extension of the equator. The compartments are assumed to have

a fractional rate of exchange per year K: this must be a gross rate that includes the separate mechanisms of the troposphere, the stratosphere and possibly the mesosphere. The fractional rate of deposition per year k is taken to be equal for both hemispheres, although there is no direct evidence available to support the assumption of symmetry.

The justification for choosing a simple two compartment model is that it is doubtful if the observations available have sufficient precision and extent to provide the parameters for more than two compartments. The justification for the separation at the equator is the ability of the

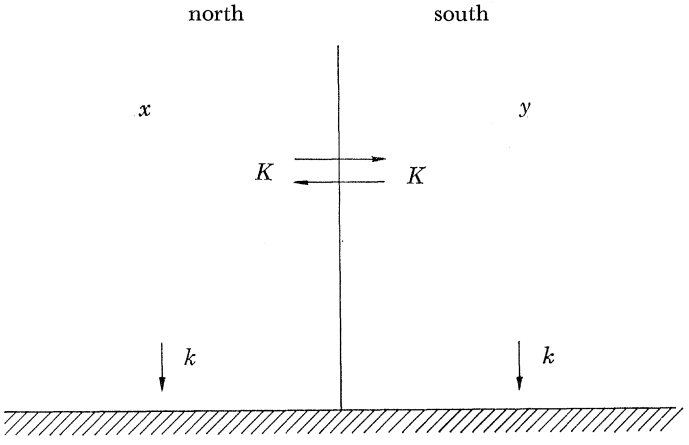

FIGURE 1. The atmospheric model.

hemispheres temporarily to preserve separate identities by (*a*) the preferential deposition in the same hemisphere of debris injected into the northern stratosphere (Peirson & Cambray 1965), and (*b*) the uniform mixture, in age or quality within the hemisphere, of such debris for months after injection, as shown by the fission product ratios (Peirson & Cambray 1965; Lockhart, Patterson, Saunders & Black 1965).

In figure 1 the rate of change of each reservoir is given by the gain from the other hemisphere less the loss to the other hemisphere and the losses by radioactive decay and by deposition.

$$\mathrm{d}x/\mathrm{d}t = Ky - x(K+\lambda+k), \quad \mathrm{d}y/\mathrm{d}t = Kx - y(K+\lambda+k),$$

where λ is the known constant of radioactive disintegration for a particular fission product. Initially it will be convenient to state the solutions of these simultaneous differential equations in the form of the difference and the sum of the reservoirs, thus

$$x - y = (x_0 - y_0) \exp\{-(k+\lambda+2K)\, t\}, \tag{1}$$

$$x + y = (x_0 + y_0) \exp\{-(k+\lambda)\, t\}, \tag{2}$$

where $x = x_0$ and $y = y_0$ when $t = 0$.

Estimates of the rate parameters K and k and of the reservoirs may be obtained by applying these analytical expressions to three sets of experimental results from the stratospheric reservoirs, the worldwide deposition and the ratios of a selected pair of fission products. In each case the period of comparison was chosen to start in the second half of 1963 to allow time for the removal of the direct injection into the lower stratosphere of the debris from the 1962 explosions.

The stratospheric reservoirs

The concentration of strontium-90 (half-life 28 years) in the stratosphere has been sampled (Feely, Biscaye, Davidson & Seitz 1966) from aircraft up to about 22 km and from balloons up to about 35 km. Values for x and y are obtained by integration of these concentrations at various times. In figure 2 these values are fitted in log-linear form to (2) and to the ratio of (1) and (2):

$$\frac{x-y}{x+y} = \frac{r_0-1}{r_0+1}\exp(-2Kt), \tag{3}$$

where $r_0 = x_0/y_0$. Values for the rate of interhemispheric exchange K and the ratio of reservoirs at $t = 0$, r_0 may be simply derived from the slope and intercept of (3). In addition, (2) provides estimates of the rate of deposition k and, using r_0, the northern and southern reservoirs at $t = 0$, x_0 and y_0.

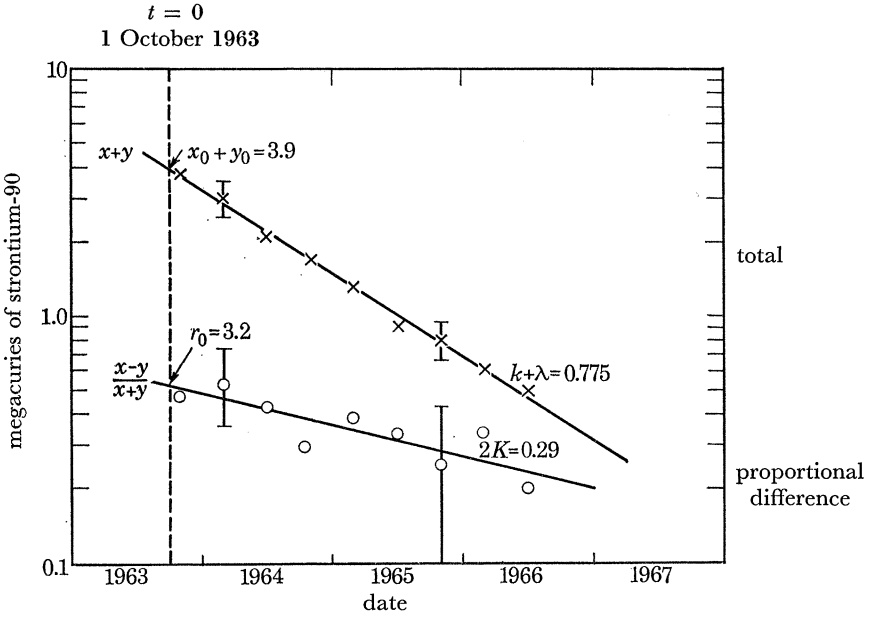

Figure 2. Strontium-90 in the stratospheric reservoirs from 1963 to 1966 (derived from Feely *et al.* 1966).

Worldwide deposition

The deposition in each hemisphere of a fission product such as strontium-90 is given respectively by kx and ky. The total deposition

$$k(x+y) = k(x_0+y_0)\exp\{-(k+\lambda)t\} \tag{4}$$

and the proportional difference is given by equation (3) as before.

Two estimates of the annual global deposition of strontium-90 are available, based upon sampling over networks of stations established by the U.K. (Cambray, Fisher, Brooks & Peirson 1966, 1967) and the U.S.A. (Volchok 1966). Equations (4) and (3) are fitted in figure 3. Estimates of K, r_0 and the other parameters can be extracted as from the reservoir data. The same treatment of the deposition measured by the American network provides alternative estimates of these quantities.

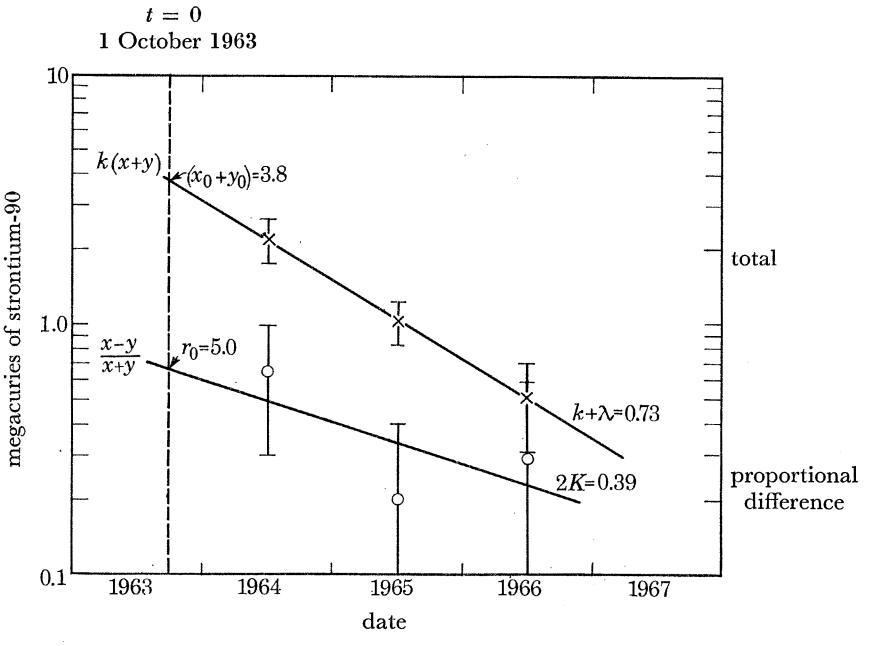

FIGURE 3. The global deposition of strontium-90 from 1963 to 1966 (taken from Cambray *et al.* 1966, 1967).

FISSION PRODUCT RATIOS

The equations (1) and (2) may be rearranged by addition and subtraction to provide solutions for x and y directly. If x_1 be taken as the content of the fission product cerium-144 (285 days) and x_2 as that of caesium-137 (30 years) then the ratio of cerium-144 to caesium-137 in the northern hemisphere is shown to be a function of r_0 and Kt but independent of k (Peirson & Cambray 1967). Thus

$$x_1/x_2 = f(r_0, \tanh Kt), \tag{5}$$

Similarly,

$$y_1/y_2 = g(r_0, \tanh Kt). \tag{6}$$

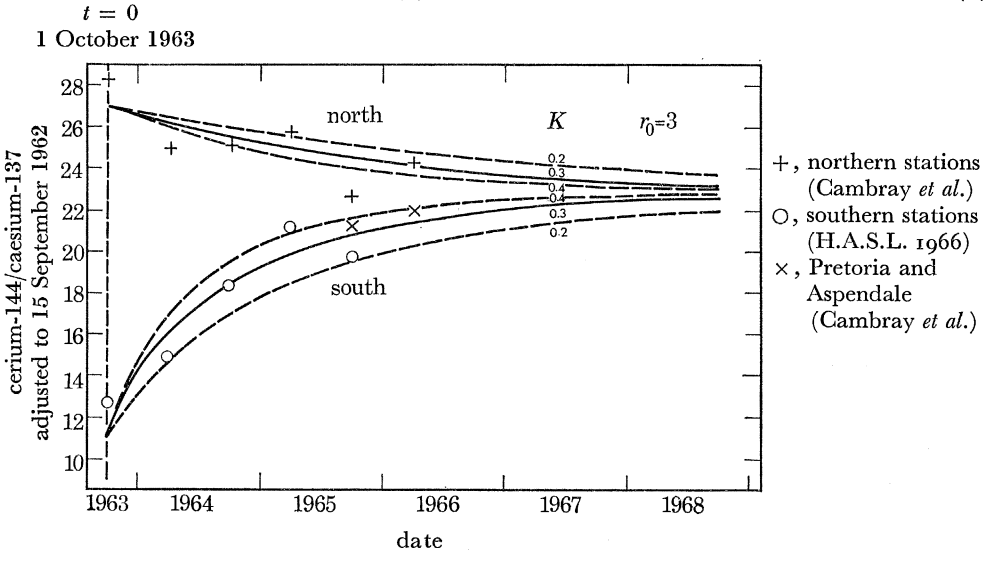

FIGURE 4. Variation of cerium-144/caesium-137 from 1963 to 1966.

In figure 4, equations (5) and (6) are drawn for selected values of K and r_0. Average values of the fission product ratio observed in surface air have been inserted for the northern and southern hemispheres. This implies that the ratio measured near the ground is representative of the whole hemisphere which is assumed to be well mixed, at least as observed from the Earth's surface. The theoretical curves and experimental results have been adjusted to remove the effect of radioactive decay. The experimental data have been derived from Cambray, Fisher, Spicer, Wallace & Webber (1964), Cambray, Fisher, Brooks, Hughes & Spicer (1965) and Cambray *et al.* (1966) in the U.K. and from Volchok (1965), H.A.S.L. (1966) and Krey (1966) in the U.S.A. No stations lying within the latitude range 25° N to 25° S were chosen because of the low values of radioactivity in this region and because of seasonal effects in the troposphere associated with movement of the solar equator. Some (monthly) results were rejected because of interference by tropospheric debris from the small Chinese and French explosions since 1963.

Summary of results

The estimates of the various parameters are summarized in table 1. The uncertainties quoted in the table refer to standard errors derived from the curve fitting by least mean squares. In the cases of the global desposition the strain of fitting to only three points (figure 3) is shown by meaningless values for r_0 and y_0.

Table 1. Summary of rate and reservoir estimates (1963–6)

method	inter-hemispheric transfer rate K/a^{-1}	ratio of reservoirs at 1 October 1963 r_0	deposition rate k/a^{-1}	reservoirs of ^{90}Sr at 1 October 1963		
				total x_0+y_0/MCi	north x_0/MCi	south y_0/MCi
fission product ratio	0.3 (0.2 to 0.4)	3 (2 to 4)	—	—	—	—
stratospheric reservoir	0.15 ± 0.03	3.2 ± 0.4	0.75 ± 0.02	3.9 ± 0.2	3.0 ± 0.4	0.9 ± 0.1
global deposition (U.K.)	0.2 ± 0.2	5 ± 8	0.71 ± 0.02	5.4 ± 0.2	4.5 ± 1.1	0.9 ± 1.1
global deposition (U.S.)	0.44 ± 0.13	-7 ± 14	0.74 ± 0.04	4.7 ± 0.9	5.4 ± 1.8	-0.8 ± 1.8

The values for K are probably in reasonable agreement. If the value obtained by the stratospheric reservoir method is significantly low then it implies that this reservoir is shielded by faster rates outside the stratosphere—above in the mesosphere or below in the upper troposphere. The range of values for K suggests that the mean residence time $(1/K)$ against interhemispheric transfer lies in the range from three to five years.

The ratio of reservoirs r_0 on 1 October 1963 is about 3. The value of this ratio at subsequent times may be readily calculated.

The average value for the deposition rate corresponds to a mean residence time $(1/k)$ of 16 months.

The estimates of the total reservoir x_0+y_0 lie somewhat outside the nominal uncertainties. However, because each estimate requires a vast extrapolation from very small samples to the global scale, the agreement is acceptable.

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