COMMONWEALTH DEPARTMENT OF HEALTH

Australian Radiation Laboratory

Radioactive Fallout In The Southern Hemisphere From Nuclear Weapons Tests

by

J.R. Moroney

Invited paper presented to the International Symposium on Environmental Radiation at the 1979 Meeting of the Radiation Research Society of Japan, November 1979.

ARL/TR013
ISSN 0157—1400

NOVEMBER 1979

AUSTRALIAN RADIATION LABORATORY
LOWER PLENTY ROAD
YALLAMBIE VICTORIA 3085
TELEPHONE: 433 2211

AUSTRALIAN RADIATION LABORATORY

RADIOACTIVE FALLOUT IN THE SOUTHERN HEMISPHERE FROM NUCLEAR WEAPONS TESTS

by

J.R. Moroney

Invited paper presented to the International Symposium on Environmental Radiation at the 1979 Meeting of the Radiation Research Society of Japan, November 1979.

ARL/TR013
ISSN 0157-1400
NOVEMBER 1979

LOWER PLENTY ROAD,
YALLAMBIE, VIC, 3085.
TELEPHONE: 433 2211

ABSTRACT

Fallout in the southern hemisphere, and its origins in the national programs of atmospheric nuclear weapons testing in both hemispheres, are reviewed.

Of the 390 nuclear tests conducted in the atmosphere to date, 53 were carried out in the southern hemisphere and it is the second phase of these, between 1966 and 1974, that is seen to have been responsible for the main fallout of short-lived fission products in the southern hemisphere.

In contrast to this, the programs of atmospheric nuclear testing in the northern hemisphere up to 1962 are shown to have been the main source of long-lived fission products in fallout in the southern hemisphere. The course followed by this contamination through the environment of the southern hemisphere is traced for the national programs of nuclear testing after 1962 taken separately (France, China) and for the earlier national programs taken together (U.S.S.R., U.S.A. and U.K.).

The impact on populations in the southern hemisphere of fallout from atmospheric nuclear weapons tests to date is assessed.

INTRODUCTION

During the first six years of the development of nuclear weapons, all nuclear explosions were of low yield and were carried out in the northern hemisphere (Carter & Moghissi (1977)). Fallout was confined to the troposphere and little of the debris penetrated beyond latitude 10^{o}S. Thus the southern hemisphere was virtually excluded from the effects of these early explosions.

Fallout was introduced into the southern hemisphere on 2 October 1952 when a nuclear device was exploded in Australia as part of the British program for developing nuclear weapons. Later that month, on 31 October 1952, the United States tested a 10 Mt experimental thermonuclear device at Eniwetok, in the Marshall Islands; this was the first high yield nuclear explosion and the first release of fallout to be distributed globally.

The nature and distribution of fallout in the southern hemisphere from these nuclear tests, and from those that followed, were determined by a set of interacting factors, the most important of which were

- the time sequence of the tests, their yields and geographical locations and the altitudes at which debris was injected into the atmosphere,
- the atmospheric transport processes affecting the fallout particulate and
- the nature and radionuclide composition of the debris;

and the subsequent impact of this material on the population of the southern hemisphere depended on the properties of the radionuclides themselves, including the pathways taken to irradiate organs and tissues.

Each of these factors has received considerable attention and comprehensive reviews of available information have been made from time-to-time by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR (1958), (1962), (1964), (1966), (1969), (1972) and (1977)) in deriving dose commitments for the world population to assess impact on public health. Therefore, in the present paper, the factors will be discussed only briefly and with emphasis on the implications to fallout in the southern hemisphere.

The reviews by UNSCEAR continue to confirm the over-riding importance to the dose commitments of the contributions made by the short-lived and long-lived fission product components of fallout. It is the purpose of this paper, therefore, to identify the main features of both these components of fallout in the southern hemisphere and to trace them to their origins in the nuclear weapons testing programs carried out in the atmosphere by the nuclear powers.

ATMOSPHERIC NUCLEAR EXPLOSIONS

A sequence of periods of nuclear weapons testing in the atmosphere can be identified and the information on tests to date, summarised in Table 1, is arrayed accordingly. The data on number of tests, total and fission yields, and releases of fission products to the atmosphere of both hemispheres, are drawn from the available literature sources (Bennett (1978); Carter & Moghissi (1977); Carter (1979); Krey & Krajewski (1971b) and (1972); Krey et al (1973) and (1975); Leifer et al (1976); U.S. Federal Radiation Council (1963)).

TABLE 1 : Summary of yield data for atmospheric nuclear weapons tests

Period	National program			Total yield (Mt)	Fission yield (Mt)	Release of fission products to the atmosphere (Mt)			
						Northern hemisphere		Southern hemisphere	
	Country	Number of announced explosions	Location			troposphere (1)	stratosphere	troposphere (1)	stratosphere
1945–51	USA USSR	22 3	several USSR	<1	<1	<1	-	-	-
1952–54	Britain USA " USSR	3 19 8 3	Australia Central Pacific Ocean USA USSR	60	37	- 1	- 18	<<1 -	- -
1955–56	Britain USA " USSR	6 13 14 11	Australia Central Pacific Ocean USA USSR	31	14	- 1	- 8	<<1 -	- -
1957–58	Britain " USA " USSR "	3 9 27 46 14 24	Australia Central Pacific Ocean Central Pacific Ocean USA USSR Arctic	81	40	5	30	<<1	-
1959–60	France	3	North Africa	<<1	<<1	<<1	-	-	-
1961–62	France USA " USSR "	1 3 30 13 53	North Africa USA Central Pacific Ocean USSR Arctic	<<1 <<1 37 302	<<1 <<1 16 85	<<1 <<1 5 3	- - 11 82	- - - -	- - - -
1963–65	China India	2 1	China India	<<1 <<1	<<1 <<1	<<1 <<1	- -	- -	- -
1966–70	China France	8 21	China South Pacific Ocean	13 8	8 7	1 -	7 -	- 1	- 6
1971–74	China France	5 20	China South Pacific Ocean	3 3	>2 >2	<1 -	2 -	- <1	- 2
1975–79	China	5	China	4	2	<<1	2	-	-
TOTAL	-	390	-	543	215	18	160	2	8

(1) excludes local fallout

Of the total release to date of 188 Mt of fission products to the atmosphere (excluding local fallout), 160 Mt went into the stratosphere of the northern hemisphere and 18 Mt into the northern troposphere. The corresponding releases to the atmosphere of the southern hemisphere were 8 Mt and 2 Mt, respectively.

..../3

The main periods of nuclear testing in the northern hemisphere were 1957-58 and 1961-62, when 13 Mt of fission products were released to the troposphere and 123 Mt were injected into the stratosphere. For the southern hemisphere, all injections into the stratosphere, and most of the total release to the troposphere, occurred in the two periods 1966-70 and 1971-74.

The national programs of atmospheric nuclear testing in the northern hemisphere up to 1962 were characterised by extended series of low yield explosions in continental USA (Nevada : 37^{o}N, 116^{o}W) and in USSR (Semipalitinsk : 52^{o}N, 78^{o}E) with a few low yield tests by Britain in the Central Pacific Ocean (Christmas Island : 2^{o}N, 157^{o}W) and by France in North Africa (Reggan : 27^{o}N, 0^{o}); and by extended series of high yield explosions by USA in the Central Pacific Ocean (Eniwetok : 11^{o}N, 162^{o}E; Bikini : 11^{o}N, 165^{o}E; Johnston Island : 17^{o}N, 169^{o}W; Christmas Island : 2^{o}N, 157^{o}W) and by USSR in the Arctic (Novaya Zemlya : 75^{o}N, 55^{o}E) with one limited series by Britain in the Central Pacific Ocean (Christmas Island : 2^{o}N, 157^{o}W). Most stratospheric injections from the high yield explosions were into the lower stratosphere, either in equatorial or polar regions. However, a few explosions in the period 1952-1954 in the Central Pacific Ocean, and a few in 1961-62 in the Arctic, injected material into the upper stratosphere. In 1961-62, four of these explosions, of 20 to 60 Mt total yield, carried material into the polar mesosphere and the very high altitude of these injections strongly influenced subsequent southward exchange of the debris and its deposition as fallout in the southern hemisphere (Peterson (1970)).

After 1962, nuclear weapons testing in the atmosphere of the northern hemisphere was carried out exclusively by China in a program of low and high yield explosions (Lop Nor, Sinkiang Province : 40^{o}N, 90^{o}E). The main releases of debris from these explosions were into the troposphere and the low temperate stratosphere.

In the southern hemisphere, atmospheric nuclear tests were carried out in two national programs. In the first of these, Britain conducted 12 low yield explosions in Australia from 1952 to 1957 (Monte Bello Islands : 20^{o}S, 115^{o}E; Emu : 29^{o}S, 132^{o}E; Maralinga : 30^{o}S, 131^{o}E); and, in the second, France executed a total of 41 nuclear tests in the South Pacific Ocean in the two periods 1966-70 and 1971-74 (Tuamotu Archipelago : 22^{o}S, 139^{o}W). The firings in Polynesia ranged in yield up to several megatons, with releases of debris to the troposphere and to the low temperate stratosphere.

In all, some 16 sites were employed for atmospheric nuclear testing and their locations are shown on the map of Figure 1.

ATMOSPHERIC TRANSPORT PROCESSES

Particulate material released to the troposphere is subjected to strong mixing by eddy diffusion and convection processes and, at temperate latitudes, to rapid eastward transport, completing a circuit of the Earth in two weeks (Angell (1959); Devlin et al (1971)). These processes extend debris throughout the hemisphere of release at reduced concentrations. However, with a mean residence time of about 30 days if released to the upper layers of the troposphere, but only five days if in the lower, rain-bearing layers (Machta et al (1970)), tropospheric debris tends to be deposited to ground predominantly in the latitude band of its release.

Exchange of tropospheric debris between hemispheres is inhibited by strongly established circulation cells located on both sides of the equator. Penetration of debris into the troposphere of the opposite hemisphere is usually sharply limited in extent (Lockhart et al (1963)). Interhemispheric transfer times average about 1.5 years but preferred regions of less leisurely exchange have been noted (Rangarajan et al (1970); Trefry (1975)). Thus, fallout particulate released into the troposphere or reaching the troposphere from the stratosphere, tends to be deposited rapidly to ground, remaining in the same hemisphere.

The stratosphere is characterised by rapid zonal transfer processes and slow vertical and meridional circulations. Debris injected into the lower stratosphere is uniformly mixed throughout the latitude band within a few weeks, if in temperate or polar regions, and within a few months, if in the tropics (Bolin (1965)). By comparison, vertical and meridional transfer times are of the order of months to years.

Meridional circulation and mixing processes in the stratosphere have been studied extensively by several techniques including the use, as tracers, of fission products and other radionuclides released in nuclear weapons tests. In a series of papers, List & Telegadas ((1964), (1966) and (1969)) were able to develop a model from the tracer data to account for the large scale processes known to occur in the stratosphere below 40 km altitude. The model is represented in Figure 2 which is taken from their work. Briefly, they conclude that there is a net flow of stratospheric air from the summer hemisphere to the winter hemisphere above 37 km, with a mean descending motion in the winter stratosphere between 25^{o} and 70^{o} latitude. Mixing processes predominate throughout the summer stratosphere and, below 25 km, extend into the winter hemisphere to 25^{o} latitude. An upward and poleward flow occurs across the equatorial tropopause.

The immediate movement experienced by debris injected into the stratosphere depends, therefore, on the season and on the latitude and altitude of injection. Interhemispheric transfer occurs by mixing in the equatorial stratosphere, whereas,

for high altitude injections, there is rapid transfer from the summer to the winter hemisphere. Whichever of the several alternative transport paths is involved, however, they lead, directly or indirectly, to the tropopause breaks, at the temperate zone jet streams, at which the main transfer occurs to the troposphere.

Mean residence times for debris in the stratosphere, at altitudes between 15 and 25 km, range from .3 to 2 yr. depending on the altitude and latitude of injection (Reiter (1974)). For debris released into the lower stratosphere at mid northern latitudes, the mean residence time varies systematically, with the season, from .7 to 1.2 yr. (Telegadas (1974), (1976) and (1979)).

The transfer of debris from the lower stratosphere into the troposphere at temperate and higher latitudes has a pronounced winter maximum, leading to the strong spring maximum observed in fallout at these latitudes. (Karol (1970)).

The transfer rate for exchange of stratospheric debris between hemispheres has been observed to be seasonally dependent, with a mean value of .14 yr^{-1} (Krey & Krajewski (1969) and (1971a)). Closer study, however, suggested a regular six-monthly change in transfer rate, between .17 yr^{-1} and .29 yr^{-1} (Wise (1979)). Taken with a mean residence time of 1.2 yr, these rates reflect a long term transfer to the opposite hemisphere totalling 12% to 17% of the debris released to the stratosphere in a particular nuclear explosion. The magnitude of transfer to the southern hemisphere, of debris from nuclear weapons tests in the northern hemisphere, is indicated by application of the residence times and transfer factors to the yield data summarised in Table 1. The releases, transfers and net fission product burdens of each hemisphere are given in Table 2. The projected net burdens of the two hemispheres are in agreement with the integrated deposits of ^{90}Sr observed up to 1978, 12.3 and 3.9 MCi (Feely & Toonkel (1979)), expressed as Mt of fission by the quotent .109 MCi ^{90}Sr/Mt of fission (Harley et al (1965)).

TABLE 2 : Release of fission products to the atmosphere and their exchange between hemispheres.

northern hemisphere				southern hemisphere			
troposphere (Mt)	stratosphere (Mt)			troposphere (Mt)	stratosphere (Mt)		
	released in hemisphere	transferred to southern hemisphere	transferred from southern hemisphere		released in hemisphere	transferred to northern hemisphere	transferred from northern hemisphere
16	160	19 to 27	1	2	8	1	19 to 27
18	134 to 142			2	26 to 34		

(1) data on yield of fission products are taken from the summary of Table 1

As shown in Table 2, in the long term, some 75% of fallout deposit in the southern hemisphere can be expected to have come from nuclear tests in the northern hemisphere.

RADIONUCLIDES AND PATHWAYS

The main radionuclides which have reached the population of the southern hemisphere from nuclear explosions in the atmosphere are listed in Table 3, together with the critical pathways followed through the environment, from explosion to man, and the specific organs at risk. Table 4 reproduces the summary of dose commitments derived by UNSCEAR in their most recent assessment of the impact on the world population of radioactive contamination from nuclear weapons tests (UNSCEAR (1977)).

TABLE 3 : Main radicactive contaminants of the environment from nuclear tests

Radio-nuclide	Half-life[1]	Radiation emitted	Origin	Principal organ at risk	Pathway	Atmospheric route
^{3}H	12.3 yr.	β	thermonuclear explosions	whole body	ingestion	stratosphere
^{14}C	5730 yr.	β	activation	whole body	ingestion	stratosphere
^{89}Sr	50.5 d.	β	fission product	bone	ingestion	troposphere
^{90}Sr	28.5 yr.	β	fission product	bone	ingestion	stratosphere
^{95}Zr	65.0 d.	β,γ	fission product	whole body	external irradiation	troposphere
^{103}Ru	39.7 d.	β,γ	fission product	whole body	external irradiation	troposphere
^{106}Ru	365 d.	β(γ:deug.)	fission product	lung	inhalation	troposphere & stratosphere
^{131}I	8.0 d.	β,γ	fission product	thyroid	ingestion	troposphere
^{137}Cs	30 yr.	β(γ:deug.)	fission product	whole body	external irradiation & ingestion	stratosphere
^{140}Ba	12.8 d.	β,γ	fission product	whole body	external irradiation	troposphere
^{141}Ce	32.6 d.	β,γ	fission product	whole body	external irradiation	troposphere
^{144}Ce	285 d.	β,γ	fission product	lung	inhalation	troposphere & stratosphere
^{239}Pu	24400 yr.	α	weapons material and activation	lung and bone	inhalation	stratosphere
^{240}Pu	6540 yr.	α				
^{241}Pu	14.4 yr.	β				
^{241}Am	433 yr.	α,γ			inhalation & ingestion	

(1) Kocher (1977)

Of all radionuclides generated in nuclear explosions, ^{14}C is destined to give the greatest integrated radiation dose to man, in both hemispheres, albeit to be delivered over some 8300 yr.

Short-lived fission products, which predominate in tropospheric fallout, occurred widely in the southern hemisphere. As shown in Tables 3 & 4, ^{95}Zr, ^{103}Ru, ^{140}Ba and ^{141}Ce are major sources of external γ-radiation from fallout deposit. ^{89}Sr & ^{131}I are important internal radiation sources following ingestion of contaminated foodstuffs and especially when tropospheric fallout reaches dairy pastures. Data for several centres in the southern hemisphere are discussed below.

TABLE 4 : Summary of dose commitment in mrad from radionuclides produced in all nuclear tests carried out before 1976 (UNSCEAR (1977)).

Source of radiation	Northern temperate zone				Southern temperate zone				World population			
	Gonads	Bone marrow	Bone lining cells	Lung	Gonads	Bone marrow	Bone lining cells	Lung	Gonads	Bone marrow	Bone lining cells	Lung
External												
Short-lived nuclides	48	48	48	48	11	11	11	11	30	30	30	30
^{137}Cs	62	62	62	62	18	18	18	18	38	38	38	38
Internal												
^{3}H	2	2	2	2	0.2	0.2	0.2	0.2	2	2	2	2
$^{14}C^{a}$	7	32	29	9	7	32	29	9	7	32	29	9
^{54}Mn				1								1
^{59}Fe	1	0.6	1	1	0.3	0.2	0.3	0.3	0.7	0.4	0.7	0.7
^{90}Sr		84	120			24	33			52	71	
^{89}Sr		0.4								0.3		
^{106}Ru				41				10				24
^{137}Cs	27	27	27	27	8	8	8	8	17	17	17	17
^{144}Ce				65				15				38
$^{239}Pu^{b}$			1	1			0.3	0.3			0.9	0.9
Total[c]	150	260	290	260	45	93	100	72	94	170	190	160

Notes: 1. The dose commitments for ^{85}Kr, ^{134}Cs and ^{140}Ba, although discussed in the text, are not shown in this table because they are negligible compared with the values included.

2. For internal irradiation, where body activities have been measured, uncertainties are probably within a factor of 2. For external irradiation and for lung-dose estimates, where the models used were not checked by direct measurement, the uncertainties are probably within a factor of 5.

[a] Dose accumulated up to the year 2000. The total dose commitment to gonads and lung is about 120 mrad, to bone lining cells 414 mrad and to bone marrow 455 mrad, delivered over some 8300 y.

[b] These dose commitments appear to be the same in different organs because of rounding. Only inhalation contributions are shown; for discussion on the ingestion pathway see chapter II, section N.

[c] Rounded to two significant figures.

The two long-lived fission products in fallout, ^{90}Sr & ^{137}Cs have long been regarded as posing the main threat to health from nuclear weapons tests - ^{90}Sr by irradiation of bone tissue and ^{137}Cs by irradiation of all body tissues as an internal, or an external, source. More attention has been given to ^{90}Sr than to ^{137}Cs. Indeed, ^{90}Sr remains the focal point of many fallout studies and more is known of its behaviour in the environment than for any other radioactive contaminant. This emphasis may now change as the principles of ICRP26 (ICRP (1977)), and effective equivalent dose commitments, in particular, become more widely adopted by those dealing with problems of aged fission products in the environment. Notwithstanding this possibility, however, because of the abundance of data available for it, ^{90}Sr remains the radionuclide of choice in the discussion given below of long-lived fallout in the southern hemisphere.

^{106}Ru and ^{144}Ce have half-lives long enough for the nuclides to reach ground level air in both hemispheres after injection into the lower stratosphere in a nuclear explosion. ^{144}Ce, in particular, was included in several fallout monitoring programs and was observed throughout the southern hemisphere. For neither of the two radionuclides, however, are there adequate data for the southern hemisphere. The dose commitments entered for them in Table 4 (UNSCEAR(1977)) were estimated drawing heavily on the ^{90}Sr data.

With an inhalation pathway, plutonium in fallout reaches man only when it is present in ground level air; that is, during active periods of nuclear weapons testing. This limitation is reflected in the dose commitments of 1 mrad or less given for ^{239}Pu in Table 4. From the analyses made by Bennett (1974a & b;1976), and their subsequent extension by UNSCEAR (1977), it may be concluded that the ingestion pathway to man for Pu will continue to be unimportant as long as the contaminant remains unavailable for uptake by plants. No studies for the southern hemisphere have been made of Pu in the environment.

The southern hemisphere encompasses a diversity of inhabited environments, few of which have been studied in sufficient depth to enable the environmental transfer processes, of the radionuclides of interest, to be characterised. The main bodies of data on fallout for the southern hemisphere derive from national programs mounted by Argentina, Australia and New Zealand (Beninson (1973); Menossi et al (1975); Moroney & Stevens (1975); N.Z. National Radiation Laboratory (1978)), from the multination survey in the South Pacific and South America supported by France (France (1967) & (1977)) and the world-wide monitoring being carried out by USA and Britain (Toonkel (1979); Feely et al (1979); Cambray et al (1979)).

The major fallout studies in the southern hemisphere have been for countries in the temperate zone, supporting western cultures and western-type diets. There appear to be few data for the tropical and subtropical regions of high population density, such as Melanesia, Indonesia and southern Africa (other than South Africa). The surveys made in Polynesia do not appear to be directed towards characterising the radionuclide transfer processes for that environment. The few definitive data that are available, however, such as ^{90}Sr in bone, are consistent with the main bodies of information for the hemisphere (Harley (1971), (1974) & (1975)).

SHORT-LIVED FISSION PRODUCTS IN TROPOSPHERIC FALLOUT

Fission products were released directly to the troposphere of the southern hemisphere in the five series of nuclear tests carried out by Britain in Australia between 1952 and 1957 and in the eight series conducted by France in Polynesia from 1966 to 1974.

The major periods of nuclear testing in the northern hemisphere also contributed tropospheric debris to the southern hemisphere, although much reduced in proportion to yield due to the constraints of the interhemispheric exchange processes.

The tropospheric transport and distribution of fallout in the southern hemisphere were reported and discussed for particular series of nuclear tests (Butement et al (1957) & (1958); Dwyer et al (1959); Trefry & Callus (1968); France (1967)) and reviews were made of the phenomena involved (Trefry (1975)). Figures 3(a) & 3(b), reproduced from Trefry's paper, depict representative debris trajectories for nuclear tests by the US over the Central Pacific Ocean and for tests by France in Polynesia. Although main trajectories are shown to be dominant in both Figures, secondary trajectories have been of great importance to some regions; for example, the westward moving material from the Tuamotu Archipelago has reached islands in Polynesia to the west and north-west of the test site in only a few days (N.Z. National Radiation Laboratory (1974)).

In Figure 4 is plotted the average ratio of ^{89}Sr to ^{90}Sr recorded in monthly fallout deposits between 1961 and 1968 for sites within ten degree latitude bands of the southern hemisphere (Hardy (1968)). In 1962 and 1963, following the US nuclear tests at Christmas Island, and in 1966 and 1967 following the tests by France in Polynesia, the deposition of fresh debris in the southern hemisphere occurred mainly between latitudes $20^{o}S$ and $40^{o}S$. More than 70% of the associated ^{90}Sr deposited at the time can be attributed to one or other of the test series by these measurements (Hardy(1970)). Therefore, whichever of the two sources generated the tropospheric debris, deposition was predominantly at temperate latitudes.

Tropospheric fallout from the nuclear tests in the Arctic by USSR in 1961 is reflected in Figure 4 in the broad peak in the ratio of ^{89}Sr to ^{90}Sr in the 0^{o} to $10^{o}S$ latitude band at the close of 1961. There is no evidence, however, of substantial penetration beyond latitude $10^{o}S$. This does not preclude extended interhemispheric penetration on a reduced scale and reports have been made of tropospheric fallout from tests in the Arctic reaching New Zealand (McNaughton & Woodward (1961)) and of debris from Polynesia being detected in Japan (Sotobayashi et al (1969)).

The ^{89}Sr data for latitudes $20^{o}S$ to $40^{o}S$, extended to 1969 (Hardy (1970)), are presented in Figure 5 as average monthly fallout deposit. Also included in Figure 5 are results for ^{95}Zr in ground level air for Santiago ($33^{o}S$, $70^{o}W$) and Pretoria ($26^{o}S$, $28^{o}E$) (Feely et al (1979); Cambray et al (1979 etc.). The peaks in each of these three sets of data after 1963 coincide with the execution of

..../10

series of nuclear tests by France in Polynesia. Similar patterns are found in the observations of short-lived fission products in fallout for all of the major programs which monitored fallout in the southern hemisphere following these tests.

By employing radionuclide ratio techniques, or other suitable methods, it has become common practice to estimate time of origin of tropospheric fallout and thus to attribute the debris to one or more announced nuclear explosions (for example : Cambray et al (1979); de Geer et al (1978)). Rarely have these procedures produced other than the expected conclusion, especially when more active debris has been under study.

For short-lived fission products, the age of the debris at deposition can have an important bearing on radiation exposure of populations in the path of tropospheric fallout. Elapsed times between explosion and fallout deposition - transit times - have been observed for French nuclear tests to range from a few days for the westward curling trajectory discussed above, to about five days to South America (France (1969)) and ten to twenty days to reach Australia (Devlin et al (1971)).

Debris injected into the troposphere tends to be deposited to ground long before atmospheric mixing has advanced far towards achieving uniform concentrations. Strong geographical variation, on both latitudinal and longitudinal scales, is to be expected, therefore, in the occurrence of short-lived fission products in fallout at ground level. Such variation is reflected in the two sets of results in Figure 5 on ^{95}Zr in ground level air for Santiago and Pretoria and in the integrated concentrations of ^{131}I in milk supplies shown in Figure 6 for Argentina and Australia (Menossi et al (1975 etc.); Bullock et al (1975 b etc.)). The Australian milk producing areas alone range from latitude $17^{o}S$ to $42^{o}S$ and from longitude $116^{o}E$ to $153^{o}E$ and show systematic differences of more than five-fold in ^{131}I contamination.

The γ-emitting radionuclides, ^{95}Zr, ^{103}Ru, ^{140}Ba & ^{141}Ce, together, are responsible for some 90% of the total external γ-radiation dose to body tissues, in a year, from all fission products deposited to ground as tropospheric fallout. The dose calculations, summarised in Table 5 for fission neutrons on ^{239}Pu, were made from published data on chain yields and decay systematics (Meek & Rider (1972)) and dose rates at 1 m. above a uniformly contaminated plane (Crocker et al (1966)), with no account taken of possible fractionation effects or shielding.

Regular monitoring of these radionuclides in tropospheric fallout deposit would enable determination of external radiation dose by direct calculation. However,

..../11

there is no substantial body of data for any of the four radionuclides for the southern hemisphere; only for Buenos Aires have regular measurements been made (UNSCEAR (1977)). In view of their importance, therefore, it can only be concluded that it was due to the technical problems entailed in their measurement at low activity that prevented more attention being given to their systematic monitoring in fallout deposit in the southern hemisphere.

TABLE 5 : Contributions to the incomplete dose in μrad from external γ-radiation emitted from short-lived fission products in fallout deposit (1)

Radionuclide	Dose from t to t + 1y. (t: time after fission in days)					
	14d.	21d.	30d.	60d.	90d.	120d.
^{95}Zr + ^{95}Nb	2.8	4.2	5.9	10.3	12.8	13.8
^{103}Ru + ^{103m}Rh	.4	.6	.7	.9	.9	.7
^{140}Ba + ^{140}La	2.6	2.8	2.5	1.1	.3	.1
^{141}Ce	.1	.2	.2	.3	.2	.2
All other fission products	.8	.7	.6	.7	.9	1.2
Total $\frac{\mu rad}{1nCi\ \beta/m^2}$	6.7	8.4	10.0	13.3	15.1	16.0
% from ^{95}Zr, ^{103}Ru, ^{140}Ba & ^{141}Ce	88%	92%	94%	95%	94%	86%

(1) surface density of 1 nCi/m^2 of β activity at the time of deposition from fission of ^{239}Pu.

Indirect methods for estimating external γ-radiation dose, based on determination of β-activity of the fallout deposit and use of conversion factors such as those summarised in Table 5, were employed in some country-wide surveys. These methods are less than satisfactory but a considerable body of data was obtained with them. Population-weighted external γ-radiation doses from tropospheric fallout in Australia, for the years 1956 to 1974, estimated by such methods, are plotted in Figure 7 (Bullock et al (1975 b etc.)). They include provision for shielding (UNSCEAR (1977)) and suggest a total dose of some 4 mrad to the population from tropospheric fallout.

The importance of milk supplies, as a pathway for ^{131}I to follow from fallout to thyroid, was first recognised in time for regular monitoring to be enforced on the resumption of nuclear weapons testing in the atmosphere in 1961. No measurement of ^{131}I in milk supplies of the southern hemisphere was made before 1961. The set of population-weighted thyroid doses for Australia (Bullock et al (1975 b etc.)), included in Figure 7, suffers from this deficiency.

O'Brien (1977) estimated the dose commitments to the population of the northern temperate zone from ^{89}Sr, ^{131}I, ^{136}Cs & ^{140}Ba in milk supplies following deposition of the radionuclides in tropospheric fallout. Lack of sufficient data

for the southern hemisphere would appear to preclude a comparable analysis being made for the southern temperate zone.

Estimated radiation doses of a type similar to those in Figure 7 could have been derived for Argentina or New Zealand with like results. Insufficient information is available, however, for a country-by-country appraisal for the southern hemisphere. The estimates in Figure 7 should be taken only as an indication of radiation doses from tropospheric fallout in countries of the subtropical and temperate zones using western-type diets.

Radiation doses to the population of the southern hemisphere from short-lived fission products have derived largely from

- British nuclear tests in Australia, and US tests in the Central Pacific Ocean, between 1952 and 1958,
- US nuclear tests at Christmas Island in 1962 and
- French nuclear tests in Polynesia from 1966 to 1974,

with little contribution from the nuclear weapons testing programs of USSR and China.

LONG-LIVED FISSION PRODUCTS IN STRATOSPHERIC FALLOUT

The major releases of ^{90}Sr to the atmosphere were in the three periods of intensive testing of high yield nuclear weapons in the northern hemisphere, given in Table 1 as 1952-54, 1957-58 and 1961-62. At the close of 1962, the ^{90}Sr content of the stratosphere in the northern hemisphere reached its maximum value of some 5.7 MCi and, a year later, it peaked at 1.2 MCi in the stratosphere of the southern hemisphere (Machta et al (1964)). Figure 8 describes the subsequent changes in measured ^{90}Sr inventories of the stratosphere in the two hemispheres (Krey & Krajewski (1971b), (1971c) and (1972); Krey et al (1969), (1970), (1973), (1974) and (1975); Leifer & Toonkel (1978); Leifer et al (1976) and (1979); Stebbins (1961); Telegadas (1969)).

Equilibrium between the ^{90}Sr content of the stratosphere in the two hemispheres was reached in late - 1966. In the ensuing months, the depletion rate of the ^{90}Sr inventory of the stratosphere of the southern hemisphere reflected a mean residence time of 1.2 y.

Equilibrium was broken, first in the northern hemisphere, by the commencement of high yield nuclear testing by China in June 1967 and then, in the southern hemisphere, by the high yield explosion by France in August 1968. Estimates of the release of ^{90}Sr to the stratosphere in these tests, and in those that followed, were made from the measured stratospheric inventories and reported values are summarised in Table 6. The effect of these series of injections on the ^{90}Sr content of the stratosphere is indicated in Figure 8.

..../13

TABLE 6 : ^{90}Sr injections into the stratosphere from nuclear weapons tests by China and by France

Date	Country	^{90}Sr injection into stratosphere kCi	Reference
17 Jun '67	China	170	Krey et al (1969)
27 Dec '68	"	110	" " " (1970)
29 Sep '69	"	150	Krey & Krajewski (1971b)
14 Oct '70	"	198	" " " (1972)
26 Jun '73	"	170	Krey et al (1975)
17 Jun '74	"	45	Leifer et al (1976)
17 Nov '76	"	260	" " " (1979)
24 Aug '68	France	230	Krey et al (1970)
31 May '70	"	241	Krey & Krajewski (1972)
4 Jul '70	"		
12 Jun '71	"	44	" " " "
14 Aug '71	"	130	Krey et al (1973)
14 Sep '74	"	35 (estimated)	

Models of large scale transport of debris in the atmosphere were developed from the tracer studies mentioned above. Several approaches were followed but all were aimed at broad description of the global distribution of fallout following a single injection of debris into the stratosphere (Davidson et al (1966); Hunt & Manabe (1968); Krey & Krajewski (1969), (1970) and (1971a); Peirson & Cambray (1967); Peterson (1970); Seitz et al (1968)). Three of these models have been examined in relation to deposition of ^{90}Sr fallout in Australia from the nuclear tests by China and France and the HASL Box Model was found to give useful results. The Box Model employs first order kinetics to represent transport between atmospheric compartments, as shown in Figure 9 (Krey & Krajewski (1969)). Taking the equilibrium content of ^{90}Sr in the stratosphere of each hemisphere as 160 kCi at December 1966, and applying the subsequent injections of ^{90}Sr listed in Table 6, the stratospheric burden of ^{90}Sr in the southern hemisphere, given by the Box Model, is displayed in Figure 10(a), together with the measured inventories.

The latitudinal variation of ^{90}Sr deposition in the southern hemisphere is shown in Figure 11 where the mean annual deposit in 10^{o} bands of latitude is plotted for the period 1958 to 1978, together with the integrated deposit for the same period (Volchok & Kleinman (1971); Feely & Toonkel (1979 etc.)). Deposition was mainly between latitudes 20^{o} and $60^{o}S$ with the highest annual deposits occurring between 30^{o} and $50^{o}S$. The latitudinal distribution of ^{90}Sr is determined largely by the mid-latitudinal location of the breaks in the tropopause - at the temperate zone jet streams - at which the main transfer of debris takes place between the stratosphere and the troposphere.

Regional variability of ^{90}Sr deposition within latitude bands is reflected in Figure 12 which compares four independent sets of data on mean annual deposit - for Argentine, Australia (major dairying areas), New Zealand and the latitude band 20^{o} to $40^{o}S$ - over the period 1958 to 1978 (Health and Safety Laboratory (1977); Bullock et al (1975a etc.); N.Z. National Radiation Laboratory (1978)). Estimated

values are included for Australia to extend coverage to the commencement of ^{90}Sr fallout in the southern hemisphere in 1953. The results for Argentina are distinctive. While Argentina is at a latitude similar to New Zealand, ^{90}Sr deposition was uniformly lower; moreover, the highest annual deposit recorded for Argentina was well below that for the other data sets and occurred a year later. By contrast, the results for the Australian dairying areas correlate closely with the annual averages for the latitude band 20^{o} to $40^{o}S$, lying 18% higher ($r^2 = .99$). Regional variation of ^{90}Sr deposition within a latitude band derives from long-term differences in the efficiency of tropospheric scavenging processes bringing the ^{90}Sr to ground.

Both Figures 11 & 12 show that the highest annual deposits of ^{90}Sr in the southern hemisphere generally occurred in 1964 and 1965. They derived from transfer, through the upper atmosphere, of debris released in the nuclear explosions carried out in the northern hemisphere in 1961 and 1962, with Peterson's analysis attributing an important fraction to mesospheric transfer from the very high yield explosions in the Arctic (Peterson (1970)). The effect of the direct releases of ^{90}Sr to the atmosphere of the southern hemisphere was most evident in tropospheric fallout from the French nuclear tests (Cambray et al (1979 etc.)) and in the subsequent deposition from the stratosphere recorded from 1969 to 1972.

The annual deposit of ^{90}Sr predicted by the HASL Box Model for the latitude band 20^{o} to $40^{o}S$ is displayed in Figure 10(b) together with the measurement results.

Transfer of ^{90}Sr from fallout deposit to diet received much attention in the years following the major series of nuclear tests of 1957-58 and 1961-62 and was studied systematically at several laboratories (Scott Russell et al (1966)). Simplified modelling of features of the overall transfer process evolved from this work (UNSCEAR (1962) and (1977)) and the transfer function for ^{90}Sr between fallout deposit and diet, now in general use (UNSCEAR (1977)), is

$$C_{dj}(i) = b_1^j f(i) + b_2^j f(i-1) + b_3^j \sum_{m=1}^{\infty} e^{-\mu m} f(i-m)$$

Where $C_{dj}(i)$, pCi/gCa, is the concentration of ^{90}Sr in foodstuff j in year i, $f(i)$, mCi/km^2, is the annual deposit of ^{90}Sr in year i and μ^{-1} yr. is the effective mean life of ^{90}Sr in its availability for plant uptake, including radioactive decay.

The contribution of foodstuff j to the total transfer factor P_{23} from fallout to diet is

$$W_j P_{23}^j = W_j \left(b_1 + b_2 + b_3 \cdot \frac{e^{-\mu}}{1-e^{-\mu}}\right)$$

Where W_j is the fractional contribution of foodstuff j to the total Ca intake.

..../15

TABLE 7 : Parameters of the transfer function for ^{90}Sr between fallout deposit and diet

parameter	milk products	vegetables & fruit	root vegetables	grain products	miscellaneous foods	Total diet
	ARGENTINA					
P_0	1.2	1.4	.2	6.7	1.6	2.3
P_1	1.1	.9	0	6.4	1.8	1.3
P_2	.2	.2	.4	.3	.07	.1
P_3	.19	.13	.26	.04	.02	.09
f_j	3.3	3.6	1.5	19	6.8	4.9
R_{23}^j	.57	.13	.13	.10	.07	1.00
$f_j R_{23}^j$	1.9	.5	.2	1.9	.5	4.9
$\sum f_j R_{23}^j$	5.0					
	AUSTRALIA					
P_0	1.8	.6	no data	8.4	no data	2.0
P_1	.9	0	"	0	"	1.0
P_2	.3	2.2	"	.9	"	.3
P_3	.07	.25	"	.10	"	.07
f_j	6.9	8.3	"	17	"	7.5
R_{23}^j	.79	.08	.01	.05	.07	1.00
$f_j R_{23}^j$	5.4	.7	(.2)	.9	(.2)	7.5
$\sum f_j R_{23}^j$	7.4					
	NEW ZEALAND					
P_0	2.2	no data	no data	no data	no data	no data
P_1	.1	"	"	"	"	"
P_2	1.0	"	"	"	"	"
P_3	.30	"	"	"	"	"
f_j	5.1	"	"	"	"	"
R_{23}^j						"
$\sum f_j R_{23}^j$						
	DENMARK					
P_0	1.0	2.6(1)	10(2)	.9	1.9	1.1
P_1	.5	0	.5	2.5	.4	1.2
P_2	.2	.9	.5	.03	.3	.2
P_3	.13	.06	.02	.02	.15	.08
f_j	3.1	17	33	4.7	4.2	4.4
R_{23}^j	.4	.05	.01	.48	.02	1.00
$f_j R_{23}^j$	1.4	.9	.3	2.2	.1	4.4
$\sum f_j R_{23}^j$	4.9					

(1) all vegetables; (2) fruit

Parameters of the transfer functions for the main components of diet, derived by regression analysis of measurement data for ^{90}Sr in deposition and diet, are given in Table 7 for Argentina, Australia and New Zealand (Beninson (1973 etc.); Bullock et al (1975a etc.); N.Z. National Radiation Laboratory (1978)). Results for Denmark are included for comparison. The measurement data for Argentina and Australia, together with the fitted transfer functions, are plotted in Figure 13.

The contributions, $W_j P_{23}^j$, to the transfer factor, P_{23}, and the magnitude of the transfer factor itself, differ between countries. For Argentina and Denmark, milk products and grain products are the most important contributors to the intake of ^{90}Sr by the population. For Australia, milk products predominate and it is their contribution that leads to P_{23} for Australia being some 50% or more greater than for Argentina and Denmark. New Zealand, too, has a high value of P_{23}^j for milk.

The relatively high uptake of ^{90}Sr into foodstuffs in the southern hemisphere has long been recognised (Bryant et al (1959); Kulp et al (1959)) but it has not been the subject of specific study.

Transfer of ^{90}Sr from diet to bone can be described by a transfer function, the parameters of which are age dependent (Bennett (1972)). For transfer of ^{90}Sr to adult bone, the expression in general use (UNSCEAR (1977)) is

$$C_b(i) = cC_d(i) + g \sum_{m=0}^{i} C_d(i-m)\, e^{-\nu m}$$

Where $C_b(i)$, pCi/gCa, is the concentration of ^{90}Sr in adult bone in year i and ν^{-1} yr. is the effective mean life of ^{90}Sr in bone, including radioactive decay.

TABLE 8 : Parameters of the transfer function for ^{90}Sr between diet and adult bone tissue

parameter	Australia	Northern hemisphere
c	0	.023
g	.028	.031
ν	.20	.25
p_{34}	.15	.16

The transfer factor for ^{90}Sr from diet to bone is

$$p_{34} = c + \frac{g}{1-e^{-\nu}}$$

Parameters of the transfer function for Australia, derived by regression analysis of the measurement data for diet and bone, are given in Table 8. Values obtained by UNSCEAR (1977), representative of countries in the northern hemisphere, are included for comparison. As expected, the two sets of parameters show no important difference. The measurement data for Australia, together with the fitted transfer function, are shown in Figure 13.

The transfer functions for ^{90}Sr from deposition to diet to bone were assembled with the HASL Box Model to enable description of the fate, in the Australian environment, of ^{90}Sr injected into the stratosphere in the nuclear tests by France and China. The starting point for this analysis was taken as the first high yield nuclear explosion by China, in June 1967. The ^{90}Sr released in that, and subsequent, explosions was superimposed on the contamination already present in the environment from earlier nuclear tests, mainly by USSR and USA. The undistributed residue from the earlier tests comprised the ^{90}Sr content of the stratosphere at December 1966, in equilibrium between the two hemispheres.

The outcome of the calculation is displayed in Figure 14 where the contributions made by the national programs of nuclear testing by France and China are shown separately from those made by the earlier programs of USSR, USA and Britain.

..../17

The measurement data on ^{90}Sr in deposit, diet and bone for Australia are included for comparison. Dose commitments from ^{90}Sr, and current dose rates to bone tissue of Australian adults, are given in Table 9.

TABLE 9 : ^{90}Sr from nuclear weapons tests and radiation doses to bone tissue of Australian adults

Atmospheric nuclear test program	^{90}Sr integrated deposit in Australian dairying areas mCi/km^2	Period of deposition	^{90}Sr in adult bone tissue in Australia				
			Dose commitment(1)		Dose rate(1) in 1979		
			red bone marrow, mrad	bone lining cells, mrad	^{90}Sr pCi/gCa 1979	red bone marrow, mrad/yr.	bone lining cells, mrad/yr.
USSR, USA & Britain	17.9	1953–73	25	34	.4	.6	.8
France	3.6	1966–79	5	7	.2	.2	.3
China	.8	1967–82	1	1.5	<.1	<.1	.1
TOTAL	22.3	1953–82	31	42	.6	.9	1.2

(1) P_{23} 7.5 pCi.y/gCa per mCi/km^2; P_{34} .15
P_{45} 1.4 mrad per pCi.y/gCa for red bone marrow (UNSCEAR (1977))
1.9 " for bone lining cells "

The analysis reveals that the programs of atmospheric nuclear testing by France and China, to date, will contribute some 16% and 4%, respectively, of the dose commitments to adult bone tissue in Australia to arise from ^{90}Sr in fallout. The remainder will come mainly from the earlier nuclear test programs mounted in the atmosphere by USSR and USA. The fractional contributions to the current dose rates to adult bone tissue are 25%, 7% and 68% respectively. The analysis confirms that about 80% of the integrated deposit of ^{90}Sr in Australia will come from nuclear tests in the atmosphere of the northern hemisphere.

These conclusions cannot be applied to other countries in the southern hemisphere without qualification; for example, both the magnitude of the integrated deposit of ^{90}Sr and transfer of the radionuclide to diet vary from region-to-region in the southern hemisphere and so, too, will the dose commitment from ^{90}Sr. However, the fractional contributions by the national programs of nuclear testing can be expected to be less variable throughout the hemisphere.

CONCLUSIONS

From the vantage point of some 25 years of fallout monitoring in the southern hemisphere, three main shortcomings can be identified in the data now available

- all of the substantial bodies of information are for countries in the temperate zone, supporting western cultures and western-type diets; few data were obtained for the tropical and sub-tropical regions of high population,

..../18

- insufficient attention was given to the determination of external γ-radiation dose from tropospheric fallout and
- few data were obtained on tropospheric fallout in the period up to 1958 - no data at all for ^{131}I in milk supplies (UNSCEAR (1958)) - when, at that stage of nuclear weapons development programs, heavy fallout probably entered the southern hemisphere from explosions in the Central Pacific Ocean.

From the data that are available, however, it is evident that

- populations of mid-latitudes, from 20^{o} to $50^{o}S$, have the highest dose commitments in the southern hemisphere, both from short-lived and from long-lived radionuclides in fallout,
- while there is about a fourfold difference in dose commitments to populations in the southern hemisphere and northern hemisphere (UNSCEAR (1977)), the difference does not relate simply to the magnitudes of atmospheric releases of debris in the two hemispheres; about 80% of long-lived fission products in the southern hemisphere derived from nuclear explosions in the northern hemisphere and
- for some countries in the southern hemisphere, with high environmental transfer factors for particular radionuclides, dose commitments approach those for the northern hemisphere.

The programs of nuclear weapons testing conducted in the atmosphere by France, by China and by USSR, USA & Britain are estimated to be responsible for 16%, 4% and 80%, respectively, of the dose commitments to the population of the southern hemisphere from long-lived fission products in stratospheric fallout. Deficiencies in data collection, discussed above, make it uncertain to estimate dose commitments from short-lived fission products in tropospheric fallout in the southern hemisphere. However, the available information suggests contributions of about 60%, nil and 40% from the national programs of nuclear testing, respectively, at least for the Australian population.

REFERENCES

Angell J.K. (1959) A climatological analysis of two years of transonde flights from Japan, Monthly Weath. Rev. 87, 427, 1959.

Beninson D. (1973 etc.) Monitoring of strontium-90 and caesium-137 arising from fallout in Argentina, Comisión Nacional de Energía Atómica, Report RS48/119, 1973 and earlier reports from this survey.

Bennett B.G. (1972) Strontium-90 in human bone, p.I-51 - I-70 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-257, July 1972.

_____(1974a) Fallout ^{239}Pu dose to man, p.I-42 - I-63 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-278, 1974.

_____(1974b) Environmental pathways of transuranic elements, p.131-154 in Plutonium and other transuranium elements, USAEC Report WASH-1359, 1974.

_____(1976) Fallout ^{239,240}Pu in diet, p.I-115 - I-126 in Health and Safety Laboratory environmental quarterly report, USERDA Report HASL-306, July 1976.

_____(1978) Environmental aspects of americium, USDOE Report EML-348, 1978.

Bolin B. (1965) The general circulation of the atmosphere as deduced with the aid of tracers, p.27-56 in Technical Note No.68, Meteorological aspects of atmospheric radioactivity, WMO Publication No.169, 1965.

Bryant F.J., Dwyer L.J., Martin J.H. & Titterton E.W. (1959) Strontium-90 in the Australian environment, 1957-58,Nature 184, 755, 1959.

Bullock G.E., Duggleby J.C., Kotler L.H. & Wise K.N. (1975a etc.) Strontium-90 and caesium-137 in the Australian environment during 1971, 1972 and 1973, p.12-14 in Fallout over Australia from nuclear tests, Australian Ionising Radiation Advisory Council Report AIRAC No.2, October 1975 and earlier publications from this environmental survey.

Bullock G.E., Duggleby J.C., Nunn R.O. & Wise K.N. (1975b etc.) Fallout over Australia from nuclear weapons tested by France in Polynesia from June to September 1974, p.15-17 in Fallout over Australia from nuclear tests, Australian Ionising Radiation Advisory Council Report AIRAC No.2, October 1975 and earlier publications from this monitoring program.

Butement W.A.S., Dwyer L.J., Eddy C.E., Martin L.H. & Titterton E.W. (1957) Radioactive fallout in Australia from Operation Mosaic, Australian J. Sci. 20, 125, 1957.

Butement W.A.S., Dwyer L.J., Martin L.H., Stevens D.J. & Titterton E.W. (1958) Radioactive fallout in Australia from Operation Buffalo, Australian J. Sci. 21, 63, 1958.

Cambray R.S., Fisher E.M.R., Playford K., Eakins J.D. & Peirson D.H. (1979 etc.) Radioactive fallout in air and rain: results to the end of 1978, UKAEA Report AERE-R9441, May 1979 and earlier reports from this monitoring program.

Carter M.W. (1979) Nuclear testing 1975-1978, Health Physics 36, 432, 1979.

Carter M.W. & Moghissi A.A. (1977) Three decades of nuclear testing, Health Physics 33, 55, 1977.

Crocker G.R., Connors M.A. & Wong D.T.K. (1966) Some factors for the calculation of infinite-plane exposure rates from gamma radiation, Health Physics 12, 1327, 1966.

Davidson B., Friend J.P. & Seitz H. (1966)
Numerical models of diffusion and rain-out of stratospheric radioactive materials, Tellus 18, 301, 1966.

de Geer L-E., Arntsing R., Vintersved I., Sisefsky J., Jakobbson S. & Engström J-A. (1978) Particulate radioactivity, mainly from nuclear explosions, in air and precipitation in Sweden, mid-year 1975 to mid-year 1977, Försvarets Forskningsanstalt, FOA Report C40089-T2(A1), November 1978.

Devlin B.A., Moroney J.R., Nunn R.O. & Stewart F.M. (1971) Measurements of total beta activity in the fallout, p.6-15 in Fallout over Australia from nuclear weapons tested by France in Polynesia from May to August 1970, Defence Standards Laboratories, Report AWTSC No.1, February 1971.

Dwyer L.J., Martin J.H., Stevens D.J. & Titterton E.W. (1959) Radioactive fallout in Australia from Operation Antler, Australian J. Sci. 22, 97, 1959.

Fabian P., Libby W.F. & Palmer C.E. (1968) Stratospheric residence time and interhemispheric mixing of strontium-90 from fallout in rain, J. Geophys. Res. 73, 3611, 1968.

Feely H.W. & Toonkel L.E. (1979 etc.) Worldwide deposition of ^{90}Sr through 1978, p.I-87 - I-108 in Environmental Measurements Laboratory environmental quarterly report, USDOE Report EML-363, October 1979, and earlier reports from this study.

Feely H.W., Toonkel L.E. & Larsen R.J. (1979) Radionuclides and trace metals in surface air, p.C-1 - C-191 in Environmental Measurements Laboratory environmental quarterly report, USDOE Report EML-363, October 1979.

France (1967) Radioactive fallout following the nuclear tests in Polynesia, June-December 1966.

_____ (1969) Radioactive fallout following the nuclear tests in Polynesia, 1967 and 1968.

_____ (1977) Monitoring of radioactivity in 1976, Département de Protection, Commissariat à l'Energie Atomique.

Hardy E. (1968) ^{89}Sr to ^{90}Sr ratios in monthly fallout: some qualitative observations, p.I-28 - I-31 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-200, October 1968.

_____ (1970) ^{89}Sr fallout from atmospheric nuclear testing, p.I-81 - I-93 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-227, July 1970.

Harley J.H. (1971) UNSCEAR-WHO bone program, p.II-4 - II-7 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-245, 1971.

_____ (1974) UNSCEAR-WHO bone program, p.II-7 - II-9 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-281, April 1974.

_____ (1975) UNSCEAR-WHO bone program, p.II-7 - II-9 in Health and Safety Laboratory environmental quarterly report, USERDA Report HASL-297, October 1975.

Harley N., Fisenne I., Ong L.D.Y. & Harley J.H. (1965) Fission yield and fission product decay, p.251-260 in Health and Safety Laboratory fallout program summary report, USAEC Report HASL-164, 1965.

Health and Safety Laboratory (1977) Final tabulation of monthly ^{90}Sr fallout data : 1954-1976, USERDA Report HASL-329, October 1977.

Hunt B.G. & Manabe S. (1968) Experiments with a stratospheric general-circulation model: large scale diffusion of tracers in the stratosphere, Mon. Weath. Rev. 96, 503, 1968.

International Commission on Radiological Protection (1977) ICRP 26: Recommendations of the International Commission on Radiological Protection, Annals of the ICRP 1, 1, 1977.

Karol I.L. (1970) Numerical model of the global transport of radioactive tracers from the instantaneous sources in the lower stratosphere, J. Geophys. Res. 75, 3589, 1970.

Kocher D.C. (1977) Nuclear decay data for radionuclides occurring in routine releases from nuclear fuel cycle facilities, ORNL Report NUREG/TM-102, 1977.

Krey P.W., Kleinman M.T. & Krajewski B. (1969) ^{90}Sr stratospheric inventories : 1967-1968, p.I-45 - I-75 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-210, July 1969.

_____(1970) ^{90}Sr, ^{95}Zr and ^{238}Pu stratospheric inventories 1967-1969, p.I-39 - I-69 in Health and Safety fallout program quarterly summary report, USAEC Report HASL-227, July 1970.

Krey P.W. & Krajewski B. (1969) HASL model of atmospheric transport, USAEC Report HASL-215, September 1969.

_____(1970) Comparison of atmospheric transport model calculations with observations of radioactive debris, J. Geophys. Res. 75, 2901, 1970.

_____(1971a) Seasonal and latitudinal modification of the HASL model of atmospheric transport, p.I-63 - I-79 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-239, January 1971.

_____(1971b) Updating stratospheric inventories to January 1970, p.I-80 - I-91 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-239, January 1971.

_____(1971c) Updating stratospheric inventories to February 1971, p.I-103 - I-124 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-245, October 1971.

_____(1972) Updating stratospheric inventories to July 1971, p.I-33 - I-51 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-257, July 1972.

Krey P.W., Schonberg M. & Toonkel L. (1973) Updating stratospheric inventories to March 1972, p.I-37 - I-63 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-273, April 1973.

_____(1974) Updating stratospheric inventories to January 1973, p.I-130 - I-142 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-281, April 1974.

_____(1975) Updating stratospheric inventories to April 1974, p.I-124 - I-142 in Health and Safety Laboratory environmental quarterly, USERDA Report HASL-294, July 1975.

Kulp J.L., Schulert A.R. & Hodges E.J. (1959) Strontium-90 in man, Science 129, 1249, 1959.

Leifer R., Larsen R. & Toonkel L. (1979) Updating stratospheric inventories to July 1978, p.I-109 - I-124 in Environmental Measurements Laboratory environmental quarterly, USDOE Report EML-363, October 1979.

Leifer R., Schonberg M. & Toonkel L. (1976) Updating stratospheric inventories to July 1975, p.I-127 - I-142 in Health and Safety Laboratory environmental quarterly, USERDA Report HASL-306, July 1976.

Leifer R. & Toonkel L. (1978) Updating stratospheric inventories to April 1977, p.I-3 - I-14 in Environmental Measurements Laboratory environmental quarterly, USDOE Report EML-334, January 1978.

List R.J., Salter L.P. & Telegadas K. (1966) Radioactive debris as a tracer for investigating stratospheric motions, Tellus 18, 345, 1966.

List R.J. & Telegadas K. (1969) Using radioactive tracers to develop a model of the circulation of the stratosphere, J. Atmos. Sci. 26, 1128, 1969.

Lockhart L.B., Patterson R.L. & Saunders A.W. (1963) Airborne fission products along the 80th meridian (West) during 1961, Radiol. Health Data 4, 71, 1963.

Machta L., List R.J. & Smith M.E. (1970) Use of natural radioactivity to estimate large-scale precipitation scavenging, p.465-474 in Precipitation Scavenging, USAEC Symposium Series 22, 1970.

Machta L., List R.J. & Telegadas K. (1964) Inventories of selected long-lived radioisotopes produced during nuclear testing, p.243-271 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-142, January 1964.

McNaughton G.S. & Woodward R.N. (1961) Barium-140 in New Zealand rainwater, Nature 131, 1344, 1961.

Meek M.E. & Rider B.F. (1972) Compilation of fission product yields, General Electric Co., Vallecitos Nuclear Centre, Report 71-NED-41, January 1972.

Menossi C., Escribano T.L. & Bruno H.A. (1975 etc.) Radioactive contamination in Argentina following the nuclear explosions in the South Pacific during 1974, Comisión Nacional de Energía Atómica, Report RS56/163, 1975 and earlier reports from this monitoring program.

Moroney J.R. & Stevens D.J. (1975) Radiation doses to the Australian population from fallout, p.8-11 in Fallout over Australia from nuclear tests, Australian Ionising Radiation Advisory Council, Report AIRAC No.2, October 1975.

Newell R., Vincents D.G. & Kidson J.W. (1969) Interhemispheric mass exchange from meteorological and trace substances observations, Tellus 21, 641, 1969.

N.Z. National Radiation Laboratory (1974) Fallout from nuclear weapons tests conducted by France in the South Pacific from June to September 1974, New Zealand Department of Health, Report NRL-F/53, 1974.

_____(1978) Environmental Radioactivity Annual Report for 1977, New Zealand Department of Health, Report NRL-F/57, April 1978.

O'Brien B.J. (1977) Internal radiation dose commitments in the northern temperate zone from ^{89}Sr, ^{140}Ba, ^{131}I and ^{136}Cs produced in nuclear tests, p.I-3 - I-28 in Health and Safety Laboratory environmental quarterly, USERDA Report HASL-318, April 1977.

Peirson D.H. & Cambray R.S. (1967) Interhemispheric transfer of debris from nuclear explosions using a simple atmospheric model, Nature 216, 755, 1967.

Peterson K.R. (1970) An empirical model for estimating world-wide deposition from atmospheric nuclear detonations, Health Physics 18, 357, 1970.

Rangarajan C., Gopalakrishnan S. & Vohra K.G. (1970) Interhemispheric mixing of fallout debris in monsoon regions, J. Geophys. Res. 75, 1753, 1970.

Reiter E.R. (1974) The role of the general circulation of the atmosphere in radioactive debris transport, USAEC Report COO-1340-38 (1974).

Scott Russell R., Newbould P., Comar C.L. & Burton J.D. (1966) Food chains on dry land : strontium, p.173-294 in Radioactivity and Human Diet, ed. R. Scott Russell, Pergamon Press, 1966.

Seitz H., Davidson B., Friend J.P. & Feely H.W. (1968) Final report on Project Streak - numerical models of transport, diffusion and fallout of stratospheric radioactive material, Isotopes Inc., Report NYO-3653-4, May 1968.

Sotobayashi T., Suzuki T. & Furusawa A. (1969) Interhemispheric transfer of debris from French nuclear tests in 1968, Nature 224, 1096, 1969.

Stebbins A.K. (1961) Second special report on high altitude sampling program, US Defence Atomic Support Agency, Report DASA-539B, 1961.

Telegadas K. (1969) The seasonal stratospheric distribution of plutonium-238 and strontium-90, March through November 1967, p.I-2 - I-16 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-204, January 1969.

_____(1974) Radioactivity distribution in the stratosphere from Chinese and French high yield nuclear tests (1967-1970), p.I-3 - I-112 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-281, April 1974.

_____(1976) Radioactivity distribution in the stratosphere from the Chinese high yield nuclear test of June 27 1973, p.I-7 - I-30 in Health and Safety Laboratory environmental quarterly, USERDA Report HASL-298, January 1976.

_____(1979) Radioactivity distribution in the stratosphere from the Chinese high yield nuclear test of November 17 1976, p.I-3 - I-24 in Environmental Measurements Laboratory environmental quarterly, USDOE Report EML-356, July 1979.

Telegadas K. & List R.J. (1964) Global history of the 1958 nuclear debris and its meteorological implications, J. Geophys. Res. 69, 4741, 1964.

Toonkel L.E. (1979) ^{90}Sr deposition at world land sites, p.A-1 - A-41 in Environmental Measurements Laboratory environmental quarterly, USDOE Report EML-363, October 1979.

Trefry G.R. (1975) Atmospheric dispersion of radioactive material from nuclear explosions, p.57-71 in Fallout over Australia from nuclear tests, Australian Ionising Radiation Advisory Council, Report AIRAC No.2, October 1975.

Trefry G.R. & Callus F. (1968) A report on the meteorological aspects of radioactive fallout over Australia from the 1966 nuclear tests at Mururoa Atoll - including a note on fallout following the 1967 nuclear tests, Australian Bureau of Meteorology, Meteorological Study No.17, September 1968.

UNSCEAR (1958) Report of the United Nations Scientific Committee on the Effects of Atomic Radiation,Official Records of the General Assembly : Thirteenth Session, Supplement No.17 (A/3838), 1958.

_____ (1962) Seventeenth Session, Supplement No.16 (A/5216), 1962.

_____ (1964) Nineteenth Session, Supplement No.14 (A/5814), 1964.

_____ (1966) Twenty-first Session, Supplement No.14 (A/6314), 1966.

_____ (19[illegible]) Twenty-fourth Session, Supplement No.13 (A/7613), 1969.

_____ (1972) Ionizing Radiation : Levels and Effects, A report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, with annexes, Volume 1: Levels, 1972.

_____ (1977) Sources and Effects, United Nations Scientific Committee on the Effects of Atomic Radiation 1977 report to the General Assembly, with annexes.

U.S. Federal Radiation Council (1963) Estimates and evaluations of fallout in the United States from nuclear weapons testing conducted through 1962, FRC Report No.4, May 1963.

Volchok H.L. & Kleinman M.T. (1971) Global ^{90}Sr fallout and precipitation : summary of the data by 10 degree bands of latitude, p.I-2 - I-83 in Health and Safety Laboratory fallout program quarterly summary report, USAEC Report HASL-245, October 1971.

Wise K.N. (1979) Personal communication

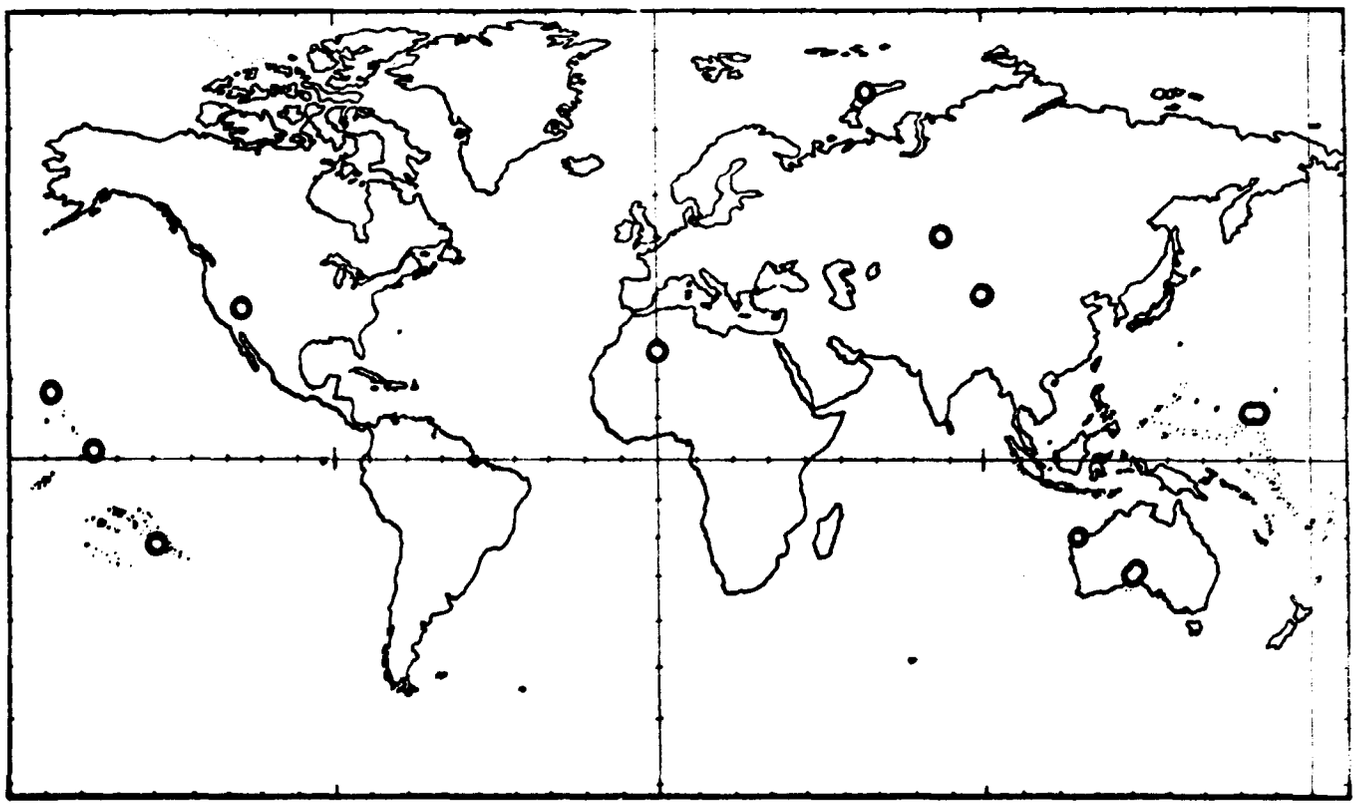

FIGURE 1: Locations of the main sites at which nuclear weapons tests were carried out in the atmosphere.

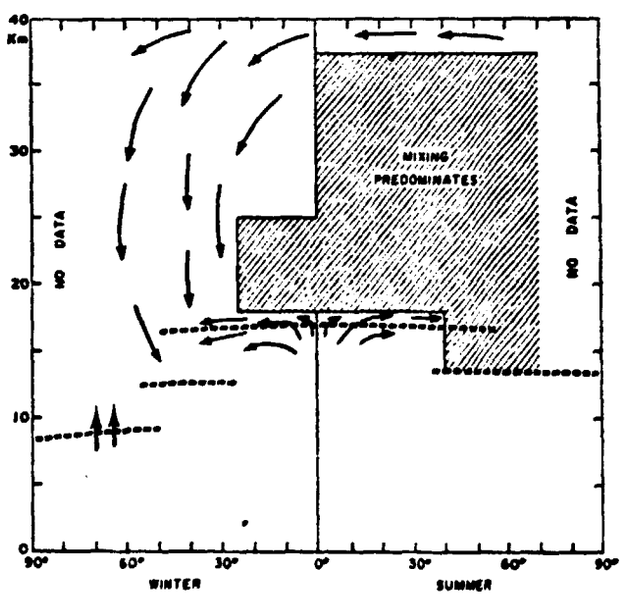

FIGURE 2: Schematic representation of the stratospheric circulation as deduced from radioactive tracer studies (List & Telegadas (1969)).

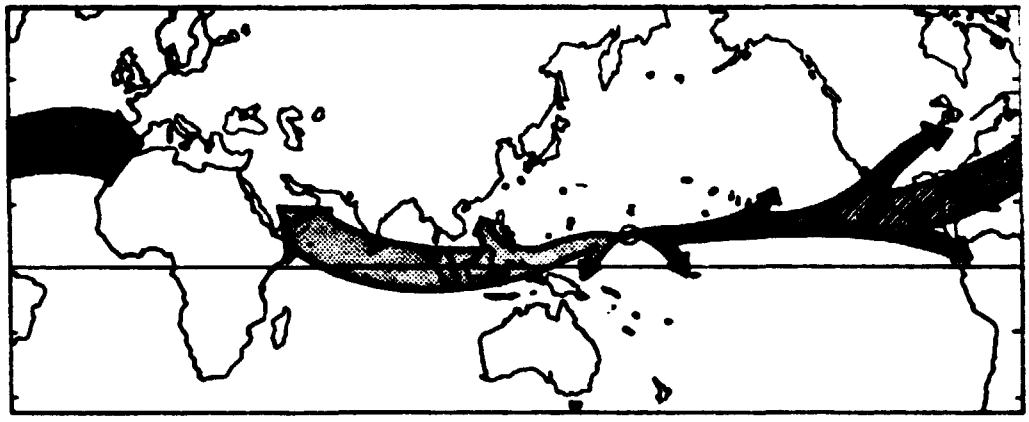

FIGURE 3(a): Debris trajectories from a nuclear explosion in the Central Pacific Ocean during the northern hemisphere winter (Trefry (1975)).

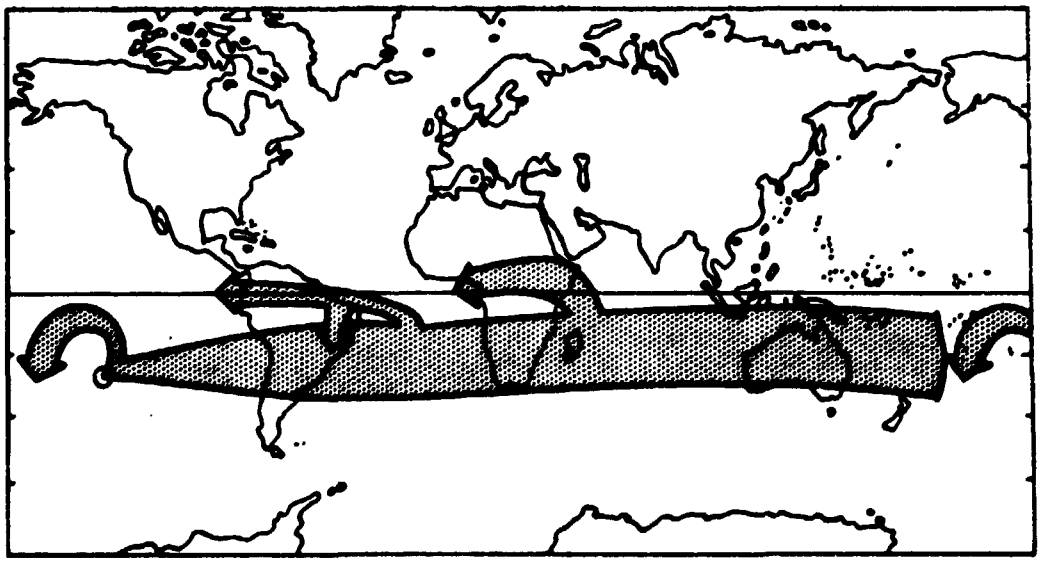

FIGURE 3(b): Debris trajectories from a nuclear explosion in the South Pacific Ocean during the southern hemisphere winter (Trefry (1975)).

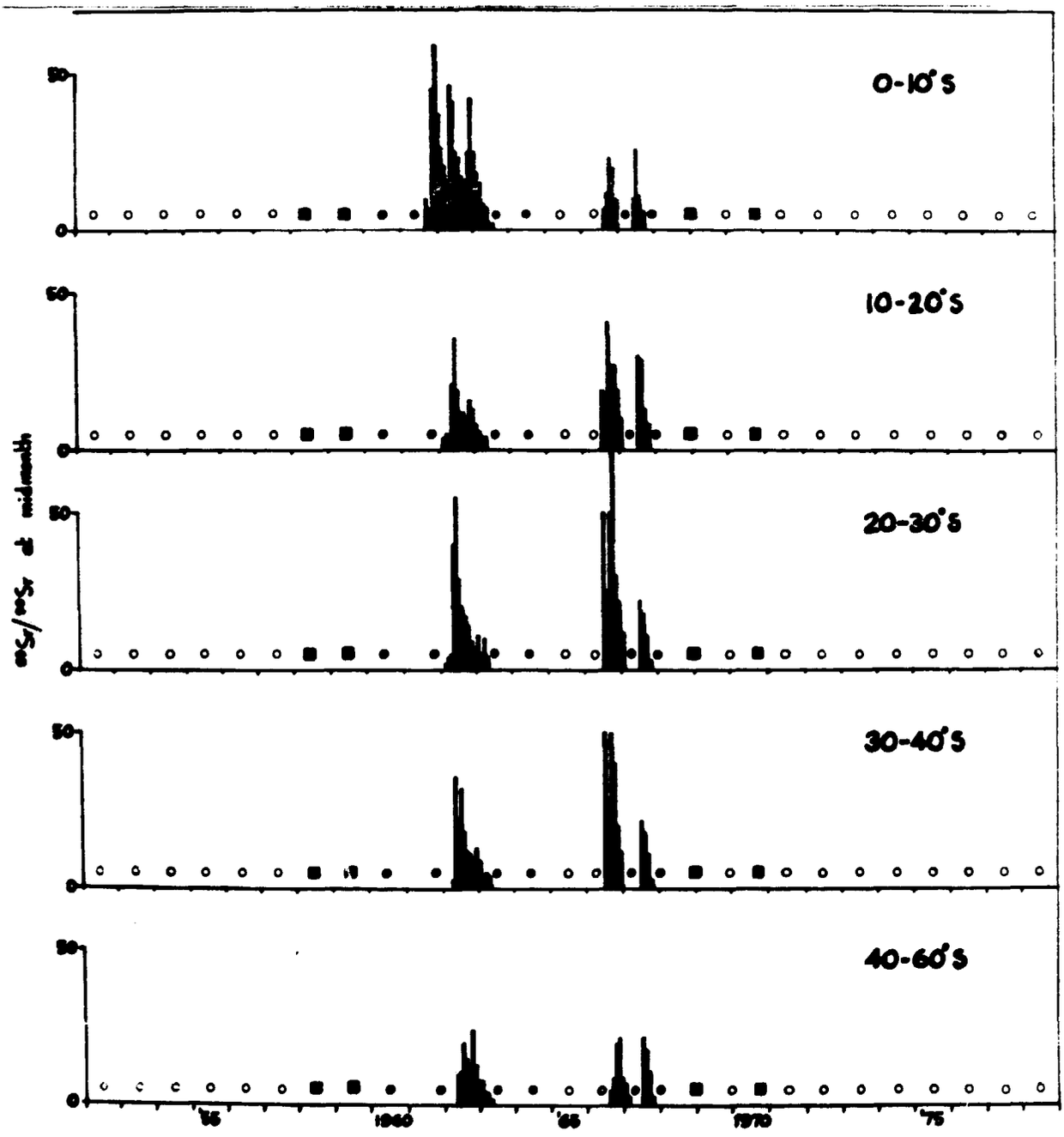

FIGURE 4: Average ratio of ^{89}Sr to ^{90}Sr in monthly fallout deposit for stations in the latitude band. ^{89}Sr was not detectable during the periods ● . Further data are available for the periods ■ , but no measurement for ^{89}Sr was made for the years ○ .

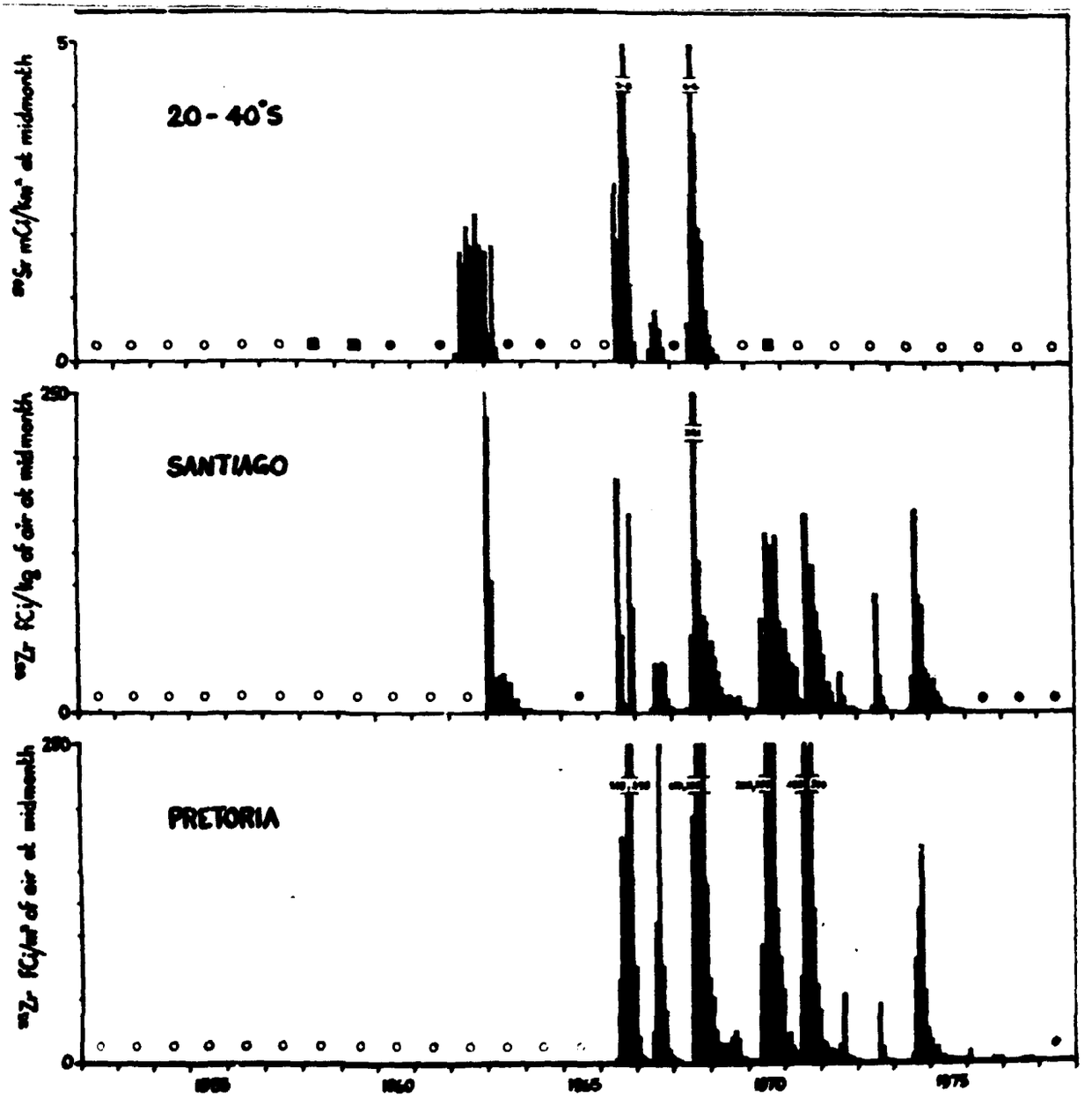

FIGURE 5: Monthly fallout deposition of ^{89}Sr, averaged over the stations in the latitude band 20° to 40°S, and ^{95}Zr in ground level air at Santiago (Chile) and Pretoria (South Africa). The radionuclides were not detectable during the periods ● . Further data are available for the periods ■ , but no measurement made for the years ○ .

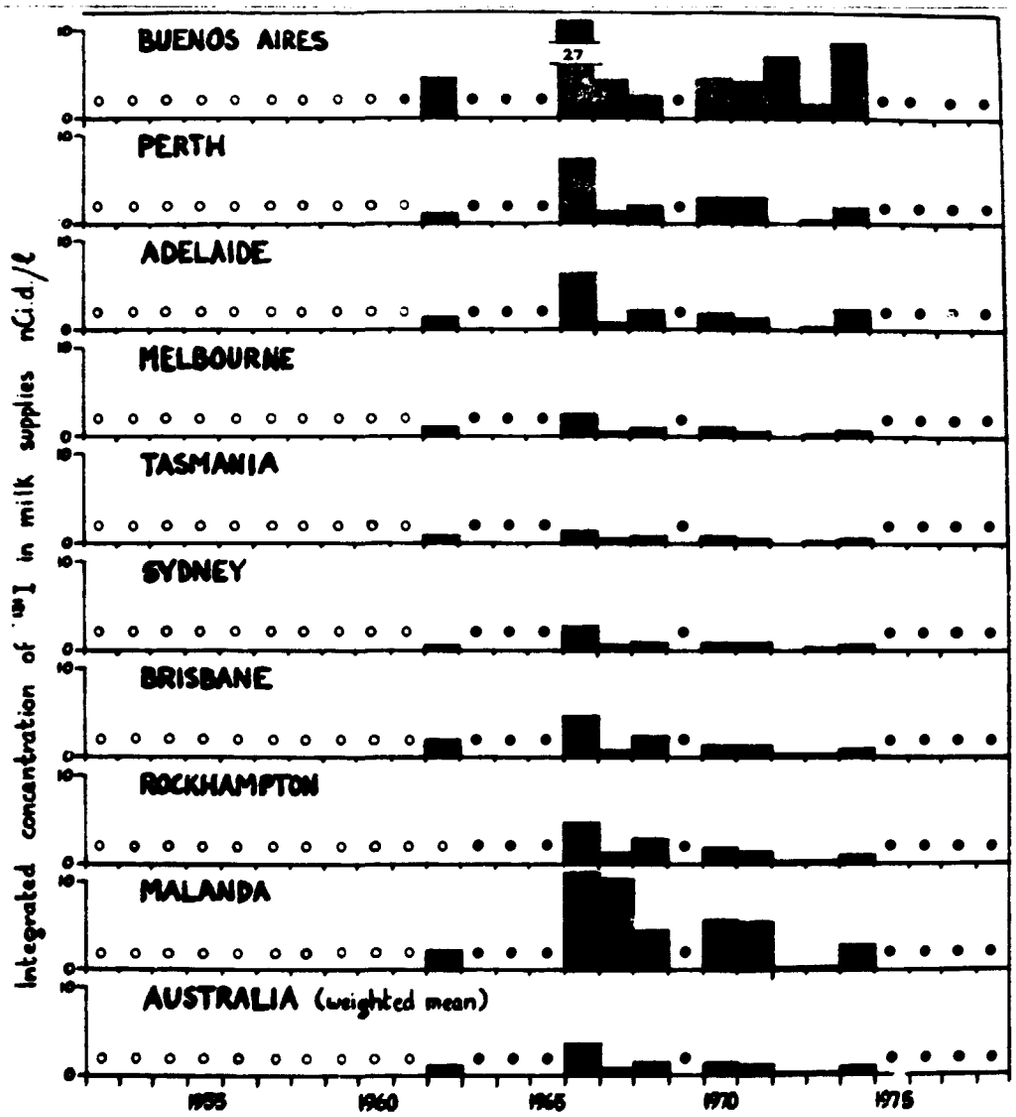

FIGURE 6: Integrated concentrations of ^{131}I in the milk supply of Buenos Aires, and in the major milk supplies of Australia, plotted against the year in which the contemination occurred. ^{131}I was not detectable in the milk supplies during the periods ● ; no measurement was made for ^{131}I in milk during the years ○ .

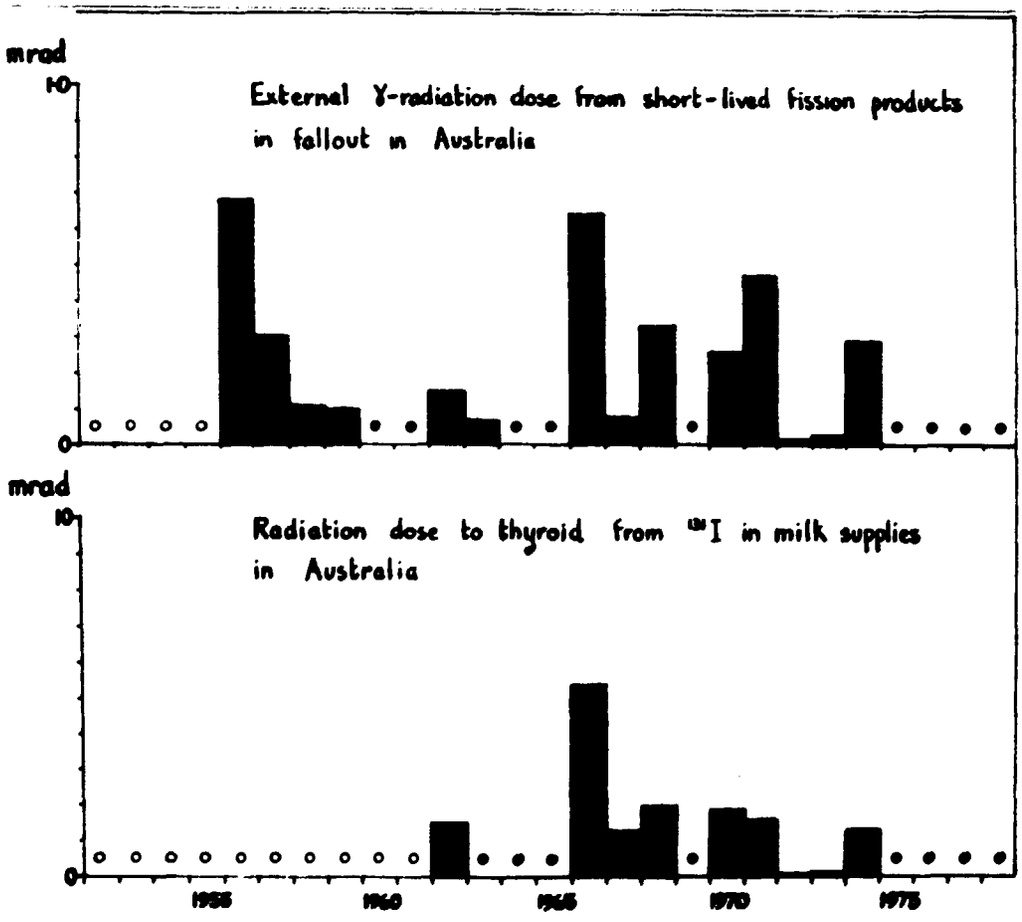

FIGURE 7: Population-weighted average radiation doses from short-lived fission products in tropospheric fallout in Australia. The external γ-radiation doses are summed to one year from deposition of the fallout and include provision for shielding effects. Both the whole-body doses and the thyroid doses are plotted against the year in which the dose commitment was incurred. Short-lived fission products were not detectable in fallout in Australia in the periods ● . Measurements were not made in the years ○ .

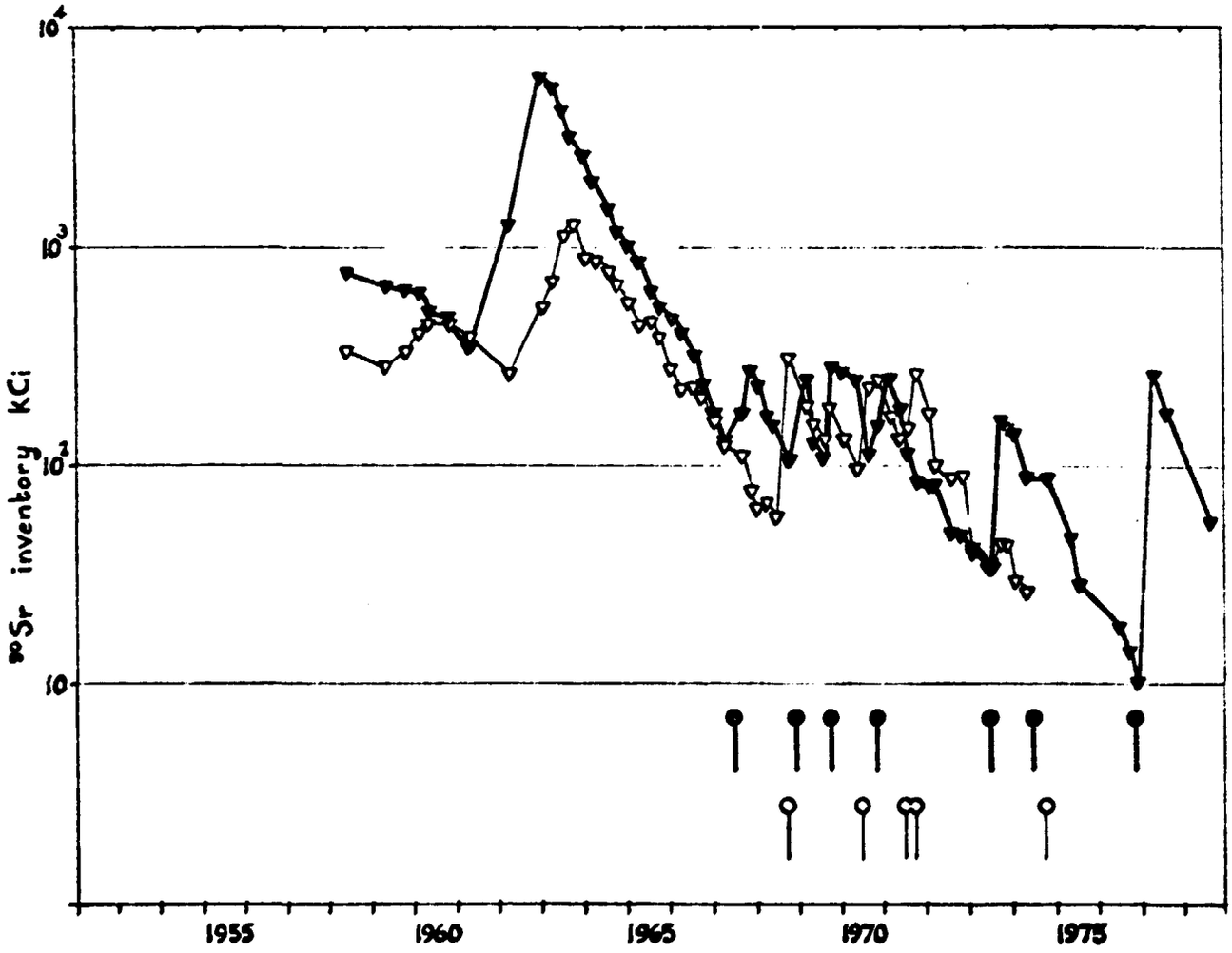

FIGURE 8: ^{90}Sr inventories of the stratosphere in the northern hemisphere ▼ and the southern hemisphere ▽. The data on stratospheric injections of ^{90}Sr are taken from Tables 1 & 6.

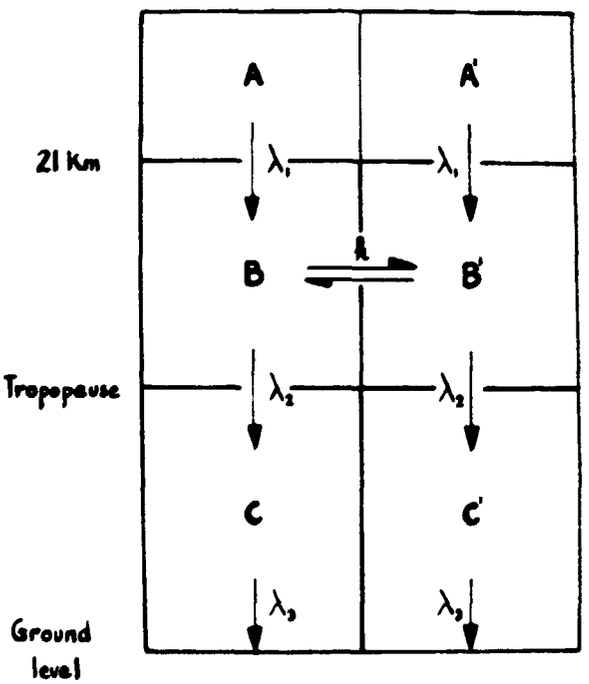

FIGURE 9: The HASL Box Model of atmospheric transport. The transport between compartments follows first order kinetics : λ_1 = .116 month^{-1}, λ_2 = .0693 month^{-1}, λ_3 = .693 month^{-1} and k = .0116 month^{-1}. For injections of debris into the upper atmosphere - well above 21 km - the model assumes rapid mixing and immediate interhemispheric exchange, with equal partitioning of debris between compartments A & A'.

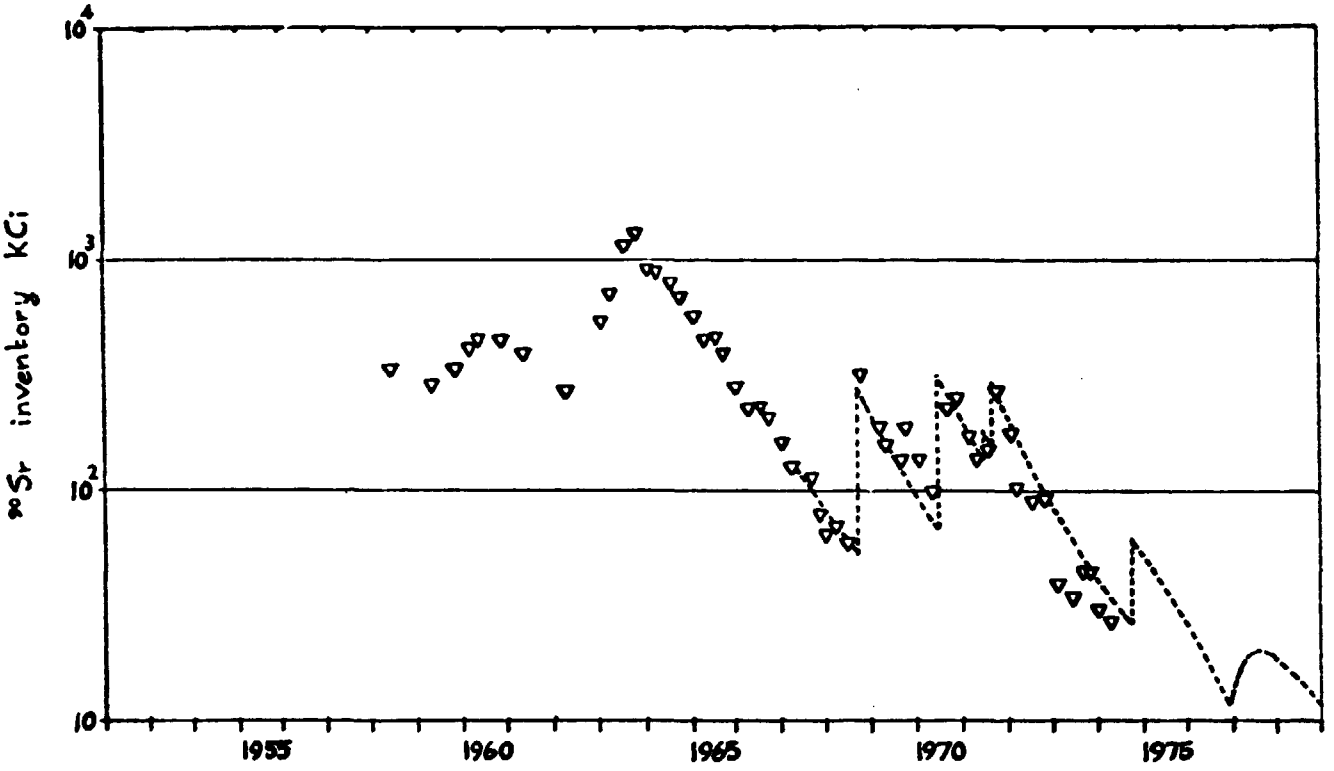

FIGURE 10(a): ^{90}Sr inventories of the stratosphere of the southern hemisphere, measured ▽ and predicted by the HASL Box Model---.

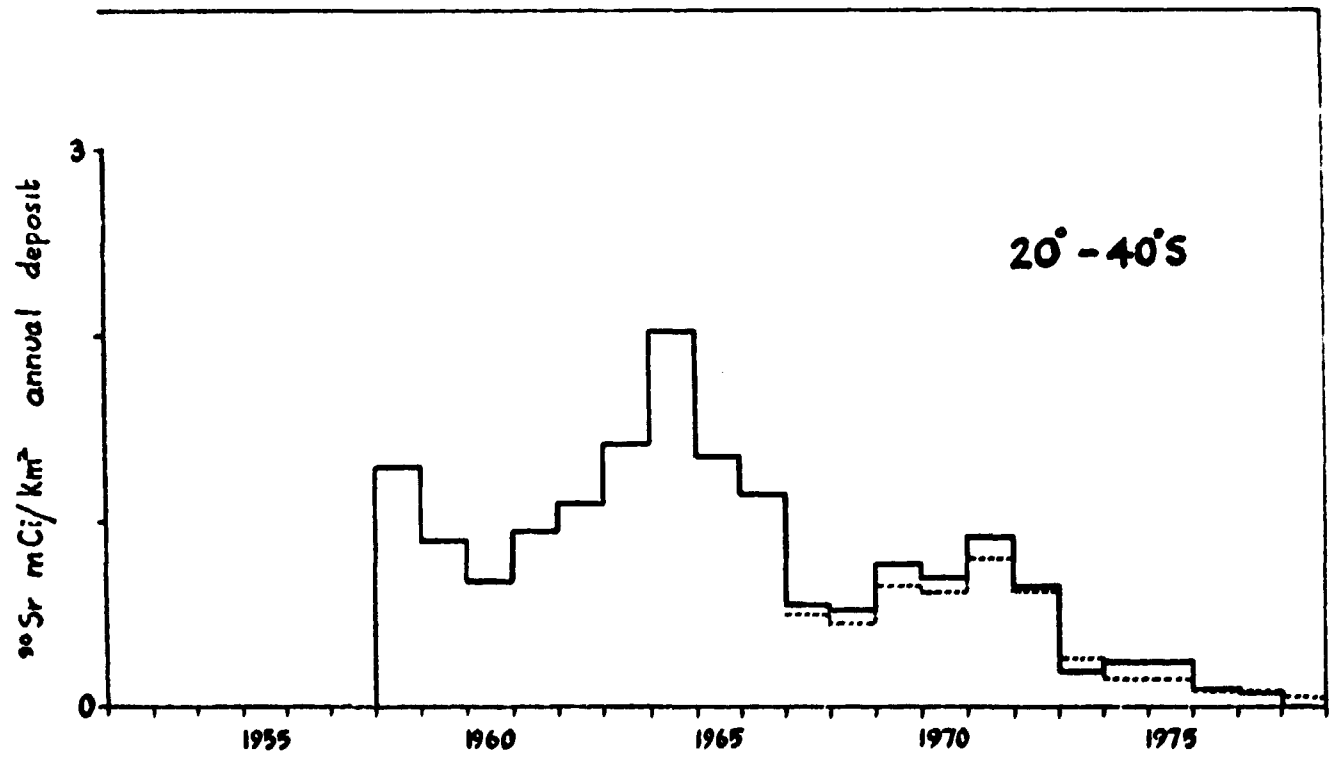

FIGURE 10(b): Annual deposition of ^{90}Sr averaged over the latitude band 20° to 40°S, measured —— and predicted by the HASL Box Model---.

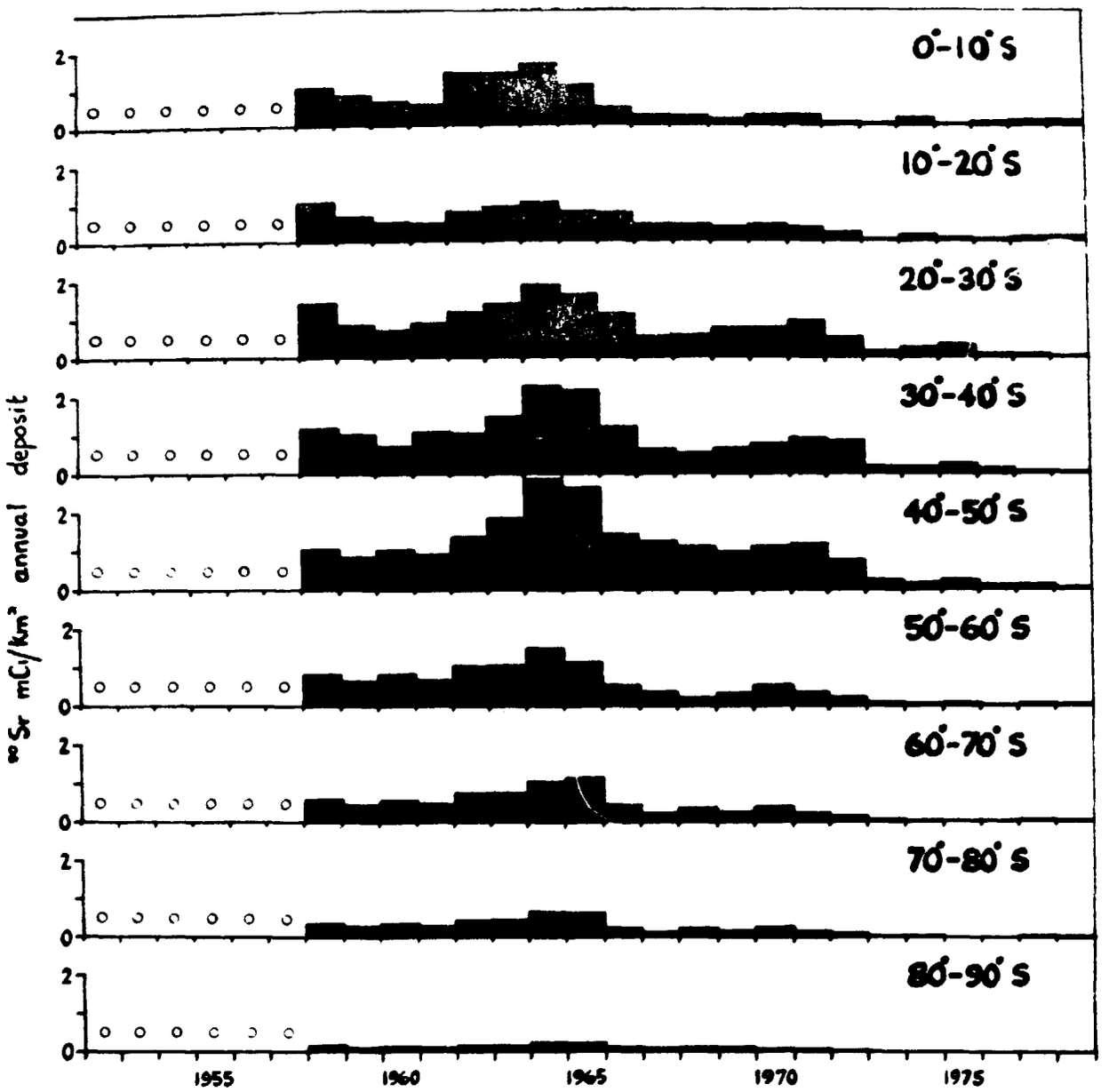

FIGURE 11: Annual deposition of ^{90}Sr averaged over the stations in the latitude band. Measurements were not made for the years o .

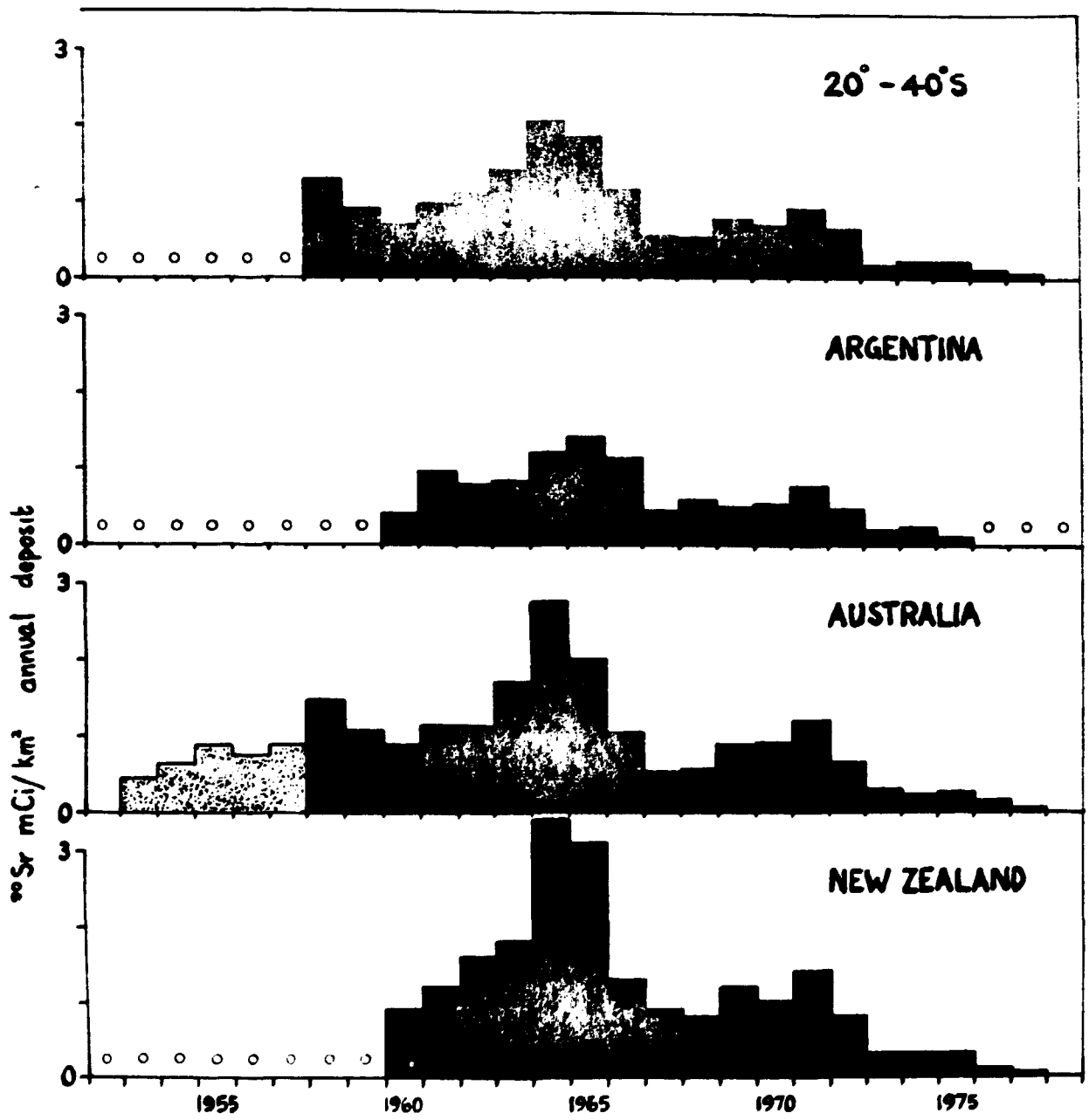

FIGURE 12: Annual deposition of ^{90}Sr averaged over stations in the latitude band 20° to 40°S (21 stations), Argentina (3), Australia (the six major dairying areas) and New Zealand (9). Measurements were not made for the years o and estimated values are included for Australia to extend coverage to the commencement of ^{90}Sr fallout in the southern hemisphere.

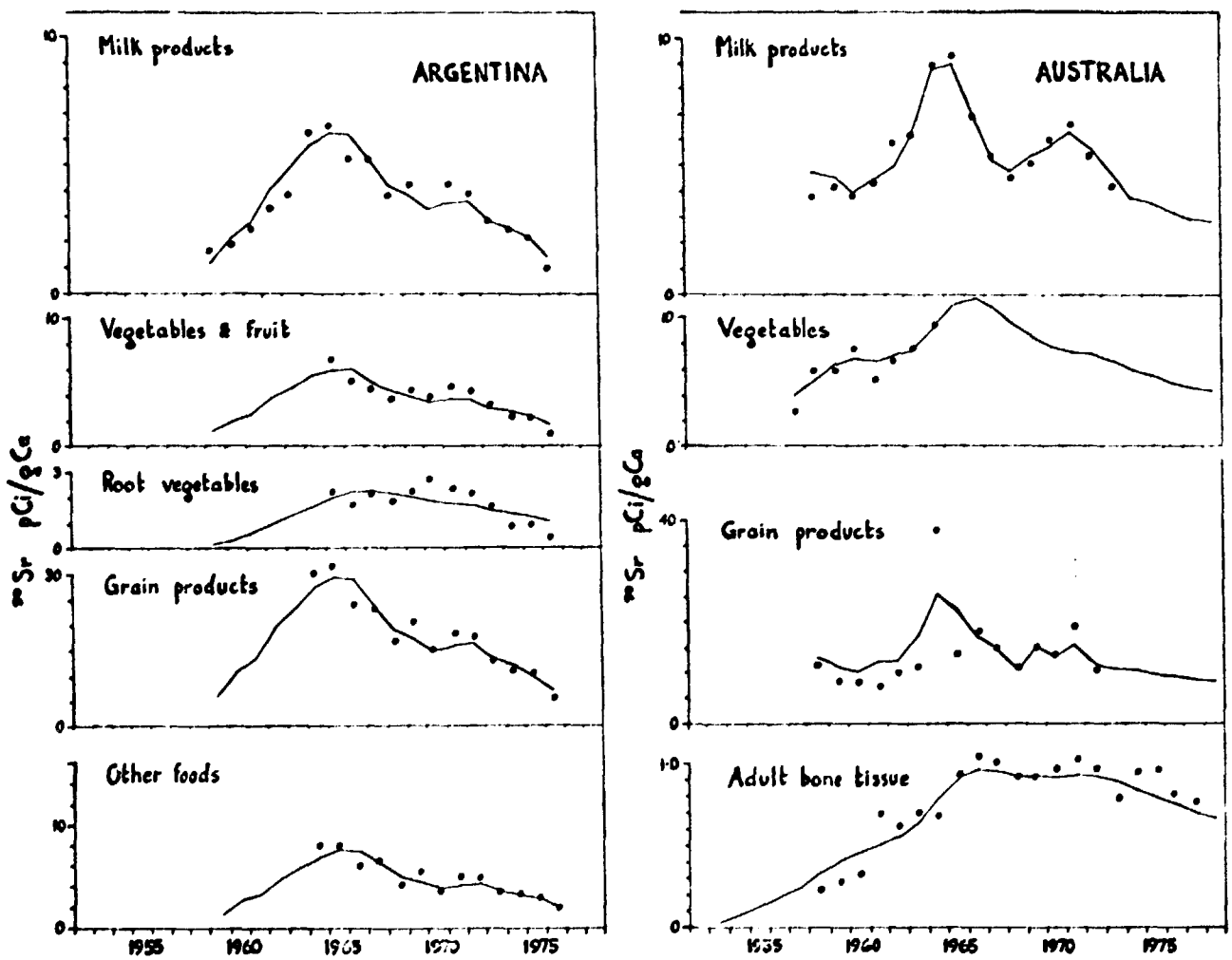

FIGURE 13: ^{90}Sr in components of the Argentine and Australian diets and in bone tissue of adults of the Australian population. The transfer functions are shown as fitted to the measurement results ● .

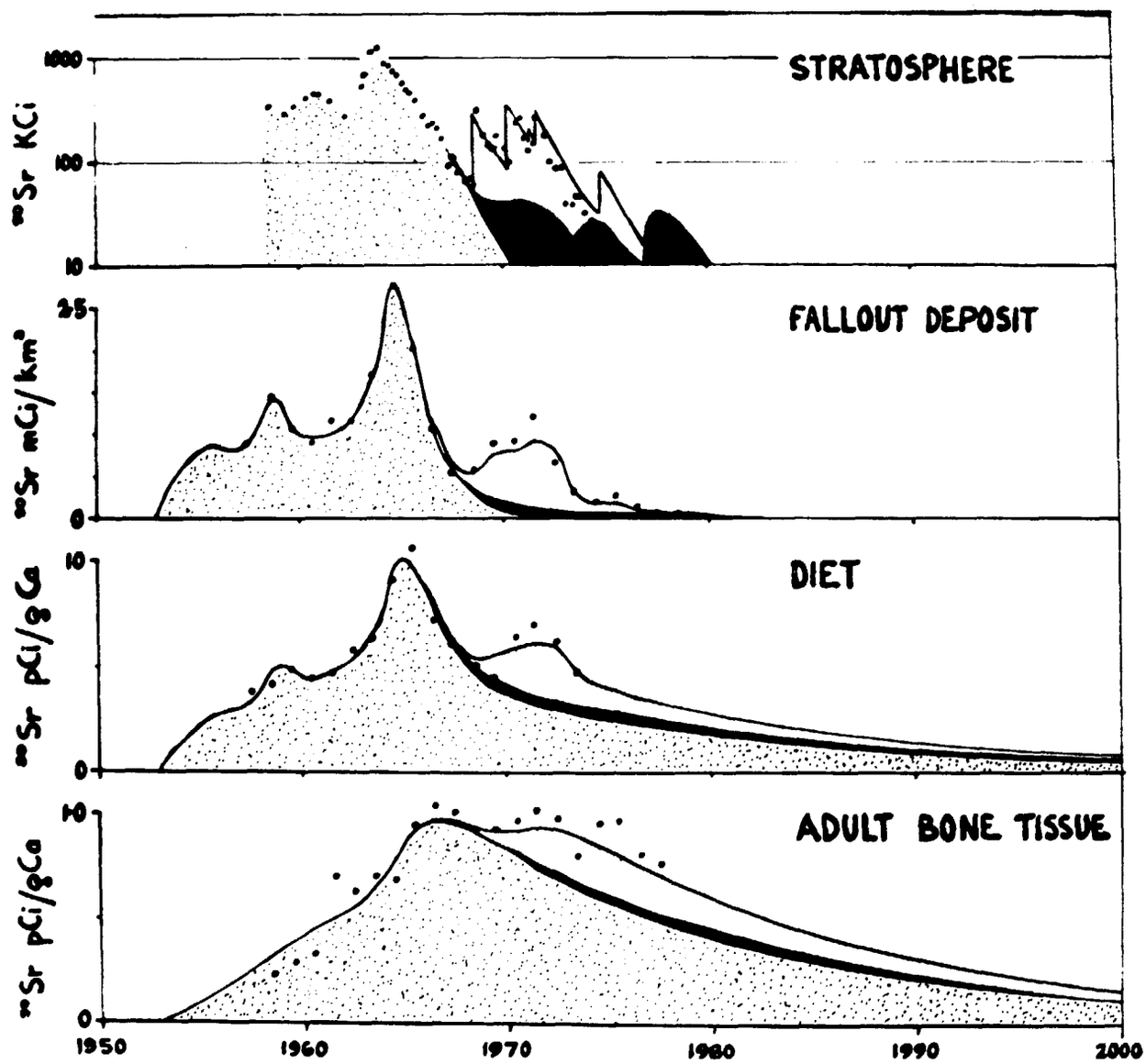

FIGURE 14: ^{90}Sr in the Australian environment from nuclear weapons tests in the atmosphere by France □ , by China ■ and by USSR, USA & Britain ▨ .