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Carbon-14 Measurements in Atmospheric CO_2 from Northern and Southern Hemisphere Sites, 1962–1993

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Reidar Nydal was [redacted]n the west coast of Norway. Reidar studied physics and mathematics at the University of Oslo and was awarded a master's degree in theoretical physics in 1953. That same year Reidar began work at the newly formed Radiological Dating Laboratory at the Norwegian Institute of Technology (NTH) in Trondheim under the direction of Professor Sverre Westin. In 1960, Reidar became head of the Radiological Dating Laboratory and he continued to direct the laboratory until one year before his retirement in 1995. Reidar received a doctorate from the University of Oslo in 1968, having written a dissertation entitled "An Investigation of Radiocarbon from Nuclear Tests".

Since 1986, Reidar has also served as a professor in the Physics Department at the NTH, where his research has focused on radiological dating. In addition, Reidar's research has focused on the global carbon cycle and the distribution of ^{14}C from nuclear tests in the atmosphere. To facilitate their work, Reidar and other staff (most notably Knut Lövseth) established a worldwide sampling program in the early 1960s to collect measurements in the atmosphere and ocean. Some of these stations have continued collecting measurements for approximately 30 years. Such extended time series are critical for testing global climate models based on CO_2. During his distinguished career, Reidar has published 56 radiocarbon-related manuscripts, with roughly half of them related to the carbon cycle and climate. In November 1995, Reidar received the King Harald V gold medal for his radiocarbon work.

DISCLAIMER

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CARBON-14 MEASUREMENTS IN ATMOSPHERIC CO_2 FROM NORTHERN AND SOUTHERN HEMISPHERE SITES, 1962–1993

Contributed by

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ABSTRACT

Nydal, R., and K. Lövseth. 1996. *Carbon-14 Measurements in Atmospheric CO_2 from Northern and Southern Hemisphere Sites, 1962–1993*. ORNL/CDIAC-93, NDP-057. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee. 67 pp.

In the 1960s, thermonuclear bomb tests released significant pulses of radioactive ^{14}C into the atmosphere. This major perturbation allowed scientists to study the dynamics of the global carbon cycle by measuring and observing rates of isotopic exchange. The Radiological Dating Laboratory at the Norwegian Institute of Technology performed ^{14}C measurements in atmospheric CO_2 from 1962 to 1993 at a network of ground stations in the Northern and Southern hemispheres. These measurements were supplemented during 1965 with high-altitude (9–12.6 km) air samples collected using aircraft from the Norwegian Air Force. The resulting database, coupled with other ^{14}C data sets, provides a greater understanding of the dynamic carbon reservoir and a crude picture of anomalous sources and sinks at different geographical latitudes. This database is outstanding for its inclusion of early ^{14}C measurements, broad spatial coverage of sampling, consistency of sampling method, and $\Delta^{14}C$ calculation results corrected for isotopic fractionation **and** radioactive decay. This database replaces previous versions published by the authors and the Radiological Dating Laboratory.

Fourteen stations spanning latitudes from Spitsbergen (78° N) to Madagascar (21° S) were used for sampling during the lifetime of the Norwegian program. Some of the stations have data for only a brief period, while others have measurements through 1993. Sampling stations subject to local industrial CO_2 contamination were avoided. The sites have sufficient separation to describe the latitudinal distribution of ^{14}C in atmospheric models. The sampling procedure for all the surface (10–2400 m asl) ^{14}C measurements in this database consisted of quantitative absorption of atmospheric CO_2 in carbonate-free 0.5 *N* NaOH solution. The ^{14}C measurements were made in a CO_2 proportional counter and calculated ($\delta^{14}C$) as per mil excess above the normal ^{14}C level defined by the US National Institute of Standards and Technology (NIST). Atmospheric ^{14}C content is finally expressed as $\Delta^{14}C$, which is the relative deviation of the measured ^{14}C activity from the NIST oxalic acid standard activity, after correction for isotopic fractionation and radioactive decay related to age. The data are organized by sampling station, and each record of the database contains the sampling dates; values for ^{14}C excess ($\delta^{14}C$) relative to the NIST standard, fractionation ^{13}C ($\delta^{13}C$) relative to the Pee Dee Belemnite (PDB) standard, and corrected ^{14}C ($\Delta^{14}C$) excess; and the standard deviation for $\Delta^{14}C$. The $\Delta^{14}C$ calculation results presented here are thus corrected for isotopic fractionation and radioactive decay, and constitute the final product of a research effort that has spanned three decades.

The $\Delta^{14}C$ station data show a sharp increase in tropospheric radiocarbon levels in the early 1960s and then a decline after the majority of nuclear tests came to an end on August 5, 1963 (Test Ban Treaty). The sharp peaks in tropospheric radiocarbon in the early 1960s are more pronounced in the Northern Hemisphere, reflecting the location of most atomic weapons tests. The measurements show large seasonal variations in the $\Delta^{14}C$ level during the early 1960s mainly as a result of springtime transport of bomb ^{14}C from the stratosphere. During the 1970s, the seasonal variations are smaller and due partly to seasonal variations in CO_2 from fossil-fuel emissions. The rate of decrease of atmospheric radiocarbon provides a check on the exchange constants of the atmosphere and ocean.

This report and all data it describes are available from the Carbon Dioxide Information Analysis Center (CDIAC) without charge. The Nydal and Lövseth atmospheric ^{14}C database comprises 21 data files totaling 0.2 megabytes in size. The following report describes the sampling methods and analysis. In addition, the report includes a complete discussion of CDIAC's data-processing efforts, the contents and format of the data files, and a reprint of a Nydal and Lövseth journal article.

PART 1

OVERVIEW

1. NAME OF THE NUMERIC DATA PACKAGE

Carbon-14 Measurements in Atmospheric CO_2 from Northern and Southern Hemisphere Sites, 1962–1993

2. PRINCIPAL INVESTIGATORS

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3. KEYWORDS

Radiocarbon, ^{14}C, atmospheric CO_2, quantitative NaOH absorption, carbon isotopes, bomb ^{14}C, $\Delta^{14}C$, $\delta^{14}C$, $\delta^{13}C$, troposphere, stratosphere, aircraft sampling

4. BACKGROUND INFORMATION

Atmospheric carbon dioxide (CO_2) contains, besides ^{12}C (~99%), small amounts of the carbon isotopes ^{13}C and ^{14}C. Only ^{14}C is radioactive with a half-life of 5730 years. In the atmosphere, ^{14}C occurs principally as $^{14}CO_2$ and is usually produced by nuclear reactions between cosmic ray neutrons and the nitrogen atoms of the air (Libby 1952). Solar (heliomagnetic), geomagnetic, and ocean forcing all play a role in atmospheric $^{14}CO_2$ (Stuiver and Braziunas 1993). Before nuclear bomb testing during the 1950s and early 1960s, radiocarbon levels in the atmosphere had been in decline. Suess (1955) demonstrated that forests grown between 1930 and 1950 had $\Delta^{14}C$ values 20–40 per mil below those of pre-1890 woods as a result of anthropogenic ^{14}C-free CO_2 emissions since the Industrial Revolution. Nuclear bomb testing has since swamped the "Suess Effect[1]." After a series of atomic weapons tests were conducted at higher northern latitudes, notably Novaya Zemlya in the former Soviet Union, scientists at the Radiological Dating Laboratory in Norway seized the opportunity to conduct CO_2 sampling to trace the distribution and flux of bomb ^{14}C with funding support from the Norwegian Research Council. In the early 1960s, several ground sampling sites were established in Norway. These Norwegian study sites gradually expanded to a global network of 14 stations spanning latitudes from Spitsbergen (78° N) to Madagascar (21° S) (Fig. 1; Table 1). Sites possibly contaminated by local CO_2 sources were avoided. Additional sites were chosen to improve spatial coverage so that the

[1]The relative change in the ^{14}C or ^{13}C ratio of any carbon pool or reservoir caused by the addition of fossil-fuel CO_2 to the atmosphere. Fossil fuels are devoid of ^{14}C because of the radioactive decay of ^{14}C to ^{14}N during long underground storage and are depleted in ^{13}C because of isotopic fractionation long ago during photosynthesis by the plants that were the precursors of the fossil fuels. Carbon dioxide produced by the combustion of fossil fuels is thus virtually free of ^{14}C and depleted in ^{13}C. The term "Suess Effect" originally referred to the dilution of the $^{14}C/C$ ratio in atmospheric CO_2 but the definition has been extended to both the ^{14}C and ^{13}C ratios in any pool or reservoir of the carbon cycle resulting from human disturbances (Keeling 1979).

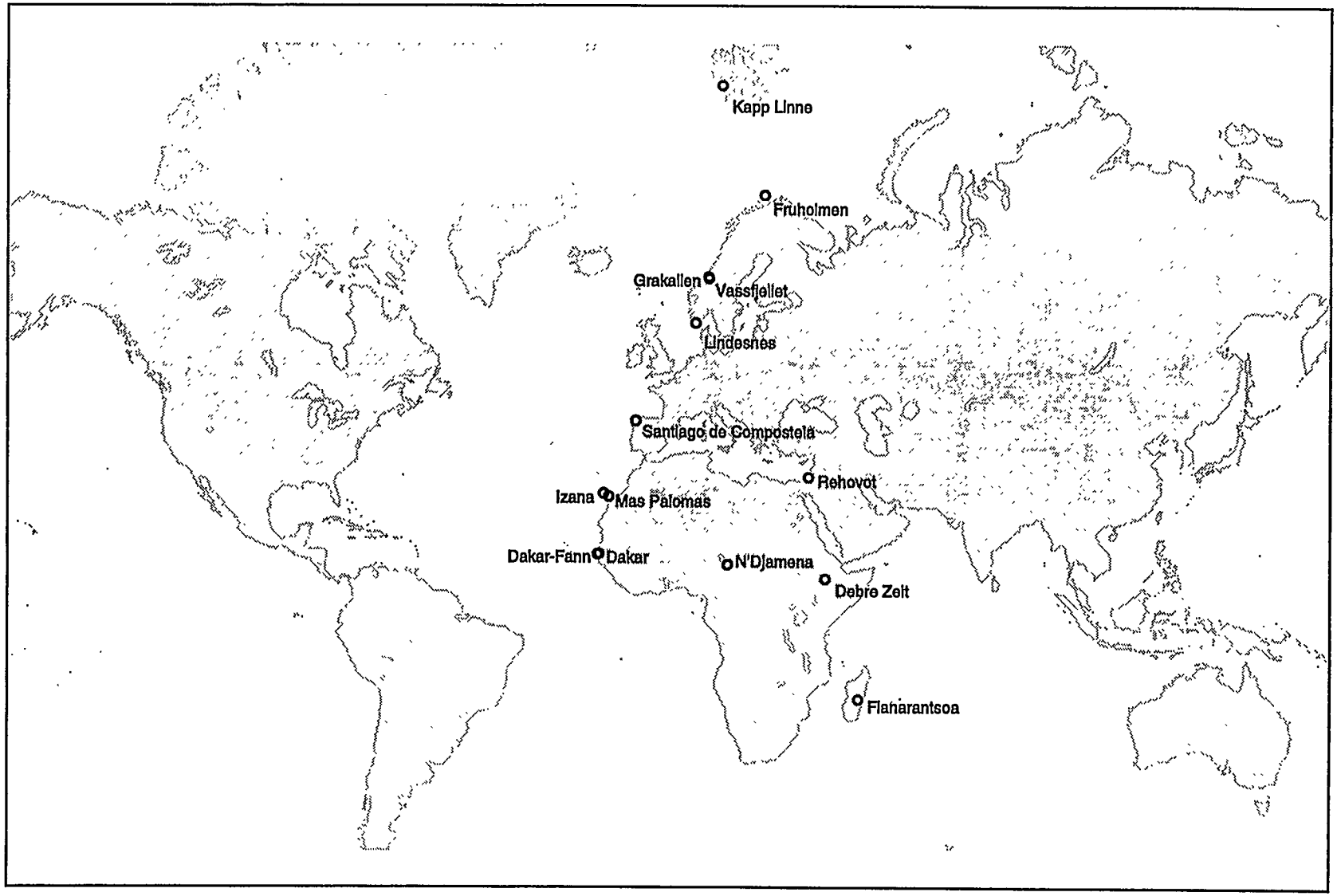

Figure 1. Sampling network for tropospheric ^{14}C measurements in atmospheric CO_2

Table 1. Summary of the tropospheric $^{14}CO_2$ sampling sites

Site code	Site	Country	Agency	Latitude	Longitude	Elevation	Period of record
V	Kapp Linné	Norway	Telegrafstyret	78° 04' N	13°38' E	10 m	1963–64
F	Fruholmen	Norway	Fruholmen lighthouse	71°06' N	23°59' E	70 m	1962–93
K	Gråkallen	Norway	Norwegian Institute of Technology	63°25' N	10°15' E	450 m	1962
Kv	Vassfjellet	Norway	Norwegian Institute of Technology	63°16' N	10°22' E	700 m	1962–63
L	Lindesnes	Norway	Lindesnes lighthouse	57°59 'N	07°04' E	50 m	1963–64
S	Santiago de Compostela	Spain	Local airport	42°53' N	08°26' W	360 m	1963–66
IZ	Izaña	Spain	Observatorio Astronomica, Izaña	28°22' N	16°30' W	2400 m	1963–67, 1976–90
M	Mas Palomas	Spain	NASA	27°45' N	15°40' W	10–100 m	1963–73
R	Rehovot	Israel	Weismann Institue of Science	31°50' N	34°50' E	100 m	1967–68
D	Dakar	Senegal	University of Dakar-Fann	14°33' N	17°07' W	10 m	1963–64
DF	Dakar-Fann	Senegal	University of Dakar-Fann	14°41' N	17°28' W	25 m	1964–68
TC	N'Djamena	Chad	ORSTOM de Fort-Lamy	12°08' N	14°57' E	300 m	1966–76
E	Debre Zeit	Ethiopia	Ethiopian Evangelical College	8°40' N	38°58' E	1900 m	1963–69
G	Fianarantsoa	Madagascar	Missionary station	21°27' S	47°05' E	1100 m	1964–78

distribution of radiocarbon could be characterized with respect to latitude. During 1965 the ground-level measurements were supplemented with measurements made on air samples collected from the lower stratosphere (9000–12600 m) using aircraft from the Norwegian Air Force. This data document provides the surface ^{14}C measurements made by the Radiological Dating Laboratory at this global sampling network and the high-altitude measurements made during 1965. The $\Delta^{14}C$ data presented here are corrected for isotopic fractionation and radioactive decay, and constitute the final product of a research effort that has spanned three decades. The earliest measurements date back to 1962, and a few sites have data through 1993. Earlier versions of this database have been presented by Nydal (1966, 1968, 1993), Nydal and Lövseth (1983), and Nydal et al. (1971).

5. SAMPLING AND CALCULATION

All ground-level air samples represented in this database were collected by dynamic quantitative absorption of atmospheric CO_2 in carbonate-free 0.5 *N* sodium hydroxide (NaOH) solution. During the collection process, a dish of NaOH was exposed to the air for 4 to 7 days. Following exposure, the samples were treated with hydrochloric acid to regenerate the carbon dioxide. After a purification procedure, the CO_2 was analyzed in a proportional counter to assess ^{14}C content. Typically, a counter has gas volumes of 1–2 L and operates at 2 atm pressure. Until 1981 a counting time of 2 days (48 hours) was often used (Nydal and Lövseth 1983), but a counting time of 4 days was used later in order to obtain higher precision.

High-altitude samples were collected in the Trondheim area during 1965 using aircraft from the Norwegian Air Force. Flights originated from Örlandet Airport and covered a region bounded by 62–65° N and 6–10° E, at altitudes of 9000–12600 m. Samples were collected using a filter with a 1.4 kg molecular sieve that absorbs CO_2 from the penetrating air. The filter container was placed under the wing of the plane and opened and closed with electrically-operated shutters at both ends. With the plane traveling at a speed of approximately 900 km/hr the filter shutters were opened 15 minutes to allow sufficient amounts of CO_2 to be absorbed.

After determination of the ^{14}C content in a proportional counter, the $\delta^{14}C$ values were calculated as per mil excess above the normal ^{14}C level defined by the National Institute of Standards and Technology (NIST, formerly the US National Bureau of Standards). Atmospheric ^{14}C content is finally expressed as $\Delta^{14}C$, which is the relative deviation of the measured ^{14}C activity from the NIST oxalic acid standard activity, after correction for isotopic mass fractionation and radioactive decay related to age (Stuiver and Polach 1977). $\Delta^{14}C$ is expressed in per mil (not as a percentage) and calculated using the following two steps:

$$\Delta^{14} = \delta^{14}C - 2(\delta^{13}C + 25)(1 + \delta^{14}C/1000) \qquad (1)$$

$$\Delta^{14}C = \Delta^{14} + 1000(e^{\lambda(1950-t)} - 1) \qquad (2)$$

In step 1, the ^{14}C excess (Δ^{14}) is only corrected for isotopic mass fractionation. $\delta^{14}C$ represents the uncorrected (for decay) ^{14}C relative to the NIST standard and $\delta^{13}C$ represents the deviation in the $^{13}C/^{12}C$ ratio relative to the Pee Dee Belemnite (Pee Dee River, South Carolina) standard. The $^{13}C/^{12}C$ ratio was measured by mass spectrometry. By themselves, the $\delta^{13}C$ values represent data that are highly influenced by fractionation in NaOH in the absorbing dish. In the earlier presentation of the ^{14}C data from the Radiological Dating Laboratory only step 1 was used, and the decay of the NIST ^{14}C reference standard after 1950 was not taken into account (Nydal and Lövseth 1983). Applying the

approximate formula in step 2, where λ is 1/8267 years (T/ln2 where T is the 5730 year half-life of ^{14}C) and t is the year of sampling, this small decay (2–5 per mil) has now been applied to all the $\Delta^{14}C$ data appearing in this database.

For a further discussion of the sampling methods and each sampling site, please see the reprint of Nydal and Lövseth (1983) in Appendix B. For additional information on the high-altitude sampling, see Hagemann et al. (1965), Nydal (1966), and Nydal and Lövseth (1983). For additional information on the sampling sites, radiocarbon standards, and carbon isotope measurements, see Nydal (1966, 1968), Craig (1961), and Levin et al. (1980).

6. APPLICATIONS OF THE DATA

These measurements were originally made to assess potential human health risks from radioactive fallout in the atmosphere. Fortunately it was also recognized that the radioactive isotopes already injected into the atmosphere could be useful tracers in geophysical research. These ^{14}C measurements document the time lag of isotopic sea-air exchange and chronicle a long-term decline in $\Delta^{14}CO_2$ at Northern and Southern hemisphere sites. These measurements complement other radiocarbon data sets (Broecker and Olson 1959; Levin et al. 1985, 1995; Manning et al. 1990; Olsson 1993) and support the pronounced twentieth-century $\Delta^{14}C$ reduction reported by Stuiver and Quay (1981) due to ^{14}C-free carbon dioxide released by fossil-fuel combustion.

This data set is unique for its inclusion of measurements in the early 1960s that trace the bomb ^{14}C released by a series of nuclear tests. All measurements at the global network of sites were taken by dynamic quantitative absorption of CO_2 in NaOH solution. This consistency in sampling technique over a period of three decades is valuable to researchers and modelers.

The $\Delta^{14}C$ tropospheric data show a sharp increase in tropospheric radiocarbon levels in the early 1960s and then a decline after the majority of nuclear tests came to an end on August 5, 1963 through the Test Ban Treaty. The sharp peaks in tropospheric radiocarbon in the early 1960s are more pronounced in the Northern Hemisphere, reflecting the location of most atomic weapons tests. The measurements show large seasonal variations in the $\Delta^{14}C$ level in the early 1960s, mainly as a result of springtime transport of bomb ^{14}C from the stratosphere (Fig. 2). During the 1970s, the seasonal variations are smaller and are partly due to seasonal variations in CO_2 from fossil-fuel emissions. The rate of decrease of atmospheric radiocarbon provides a check on the exchange constants of the atmosphere and ocean.

7. DATA LIMITATIONS AND RESTRICTIONS

Please note that the $\delta^{13}C$ values provided in this database are not representative of atmospheric values. In this database the ^{13}C data serve as guides to the ^{14}C measurements and were used to calculate corrected ^{14}C. It should also be noted that the $^{13}C/C^{12}$ ratio was not measured for every sample. In these instances where the $^{13}C/C^{12}$ ratio was not measured, a mean value is given for $\delta^{13}C$ and identified by a flag code. These mean values were calculated from 20–40 ground-level measurements or 4 high-altitude measurements.

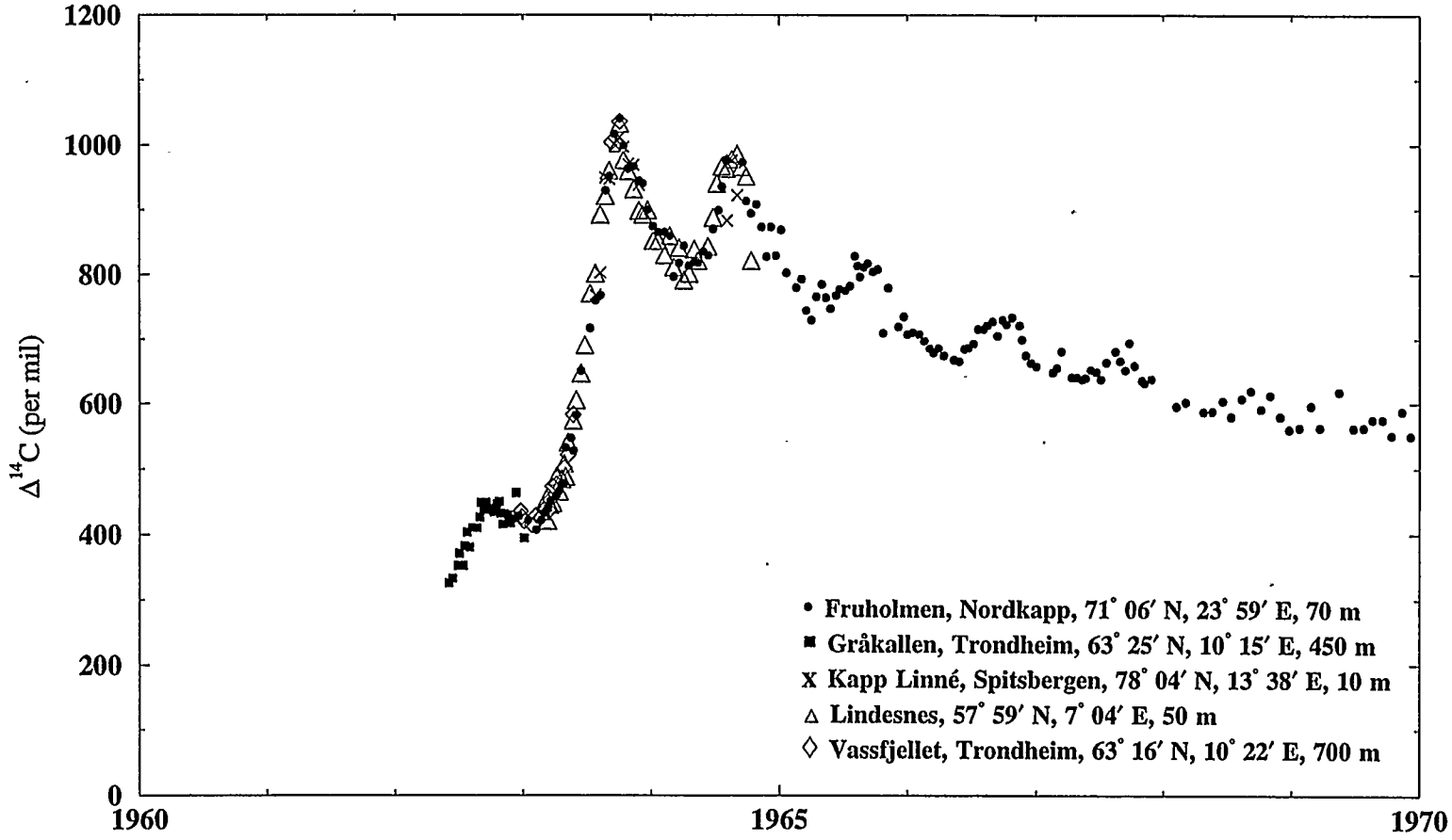

Figure 2. Corrected ^{14}C measurements from air samples collected at five Norwegian sites from 1963 to 1970

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9. DATA-PROCESSING ACTIVITIES AND QUALITY ASSURANCE CHECKS PERFORMED BY CDIAC

CDIAC is committed to the quality assurance (QA) of data before distribution. In order to provide scientists and researchers with high-quality data, CDIAC reviews the data it receives for consistent formatting, completeness, reasonableness, and accuracy. Each review involves programming that is specific to the needs of each data set. These efforts are indicative of CDIAC's mission to provide the international scientific community with high-quality, well-documented data.

DATA-PROCESSING

CDIAC obtained the Nydal and Lövseth database as an electronic-mail message from Reidar Nydal. CDIAC staff edited the message and created the ASCII data files for each site. Working copies of the files were created and processed in the following ways:

1. The original ASCII files were reformatted into a consistent format and combined in a single file with data from all sites.

2. Both SAS® and FORTRAN 77 codes were written and are available to the user for reading any of the ASCII data files.

QA CHECKS

1. Each file was checked to ensure formatting consistency and to confirm the absence of missing data entries.

2. Checks were performed to confirm the uniqueness of each laboratory reference code and to ensure that sampling intervals were formatted consistently.

3. Mean, minimum, and maximum values for $\delta^{14}C$, $\delta^{13}C$, and corrected $\Delta^{14}C$ data at each site were calculated and assessed for reasonableness.

SAS® is the registered trademark of SAS Institute, Inc., Cary, North Carolina, 27511, USA.

4. All $\delta^{14}C$, $\delta^{13}C$, and corrected $\Delta^{14}C$ measurements were plotted and assessed for reasonableness.

5. Any inconsistencies or suspect measurements were reported to and addressed by the investigators before the data set was released.

10. HOW TO OBTAIN THE DATA AND DOCUMENTATION

The Nydal and Lövseth database is available in machine-readable form from CDIAC without charge. The database may also be downloaded from CDIAC's anonymous File Transfer Protocol (FTP) site, by using the address, login instructions, and FTP commands listed below. In addition, the database is available on 9-track magnetic tape, 8-mm tape, or IBM- or Macintosh-formatted floppy diskettes. For tape requests, please include preferred tape specifications (i.e., 1600 or 6250 BPI for 9-track tapes and 8200 or 8500 format for 8-mm tapes, labeled or nonlabeled, ASCII or EBCDIC characters, variable or fixed-record lengths). Requests without tape specifications will be filled on 9-track, 6250 BPI, nonlabeled tapes with file attributes shown in Sect. 11.

This documentation is available only from CDIAC. Electronic versions of the documentation are available via the World Wide Web from CDIAC's home page (http://cdiac.esd.ornl.gov). Requests for printed copies of the documentation should be addressed to

Carbon Dioxide Information Analysis Center
World Data Center–A for Atmospheric Trace Gases
Oak Ridge National Laboratory
Post Office Box 2008
Oak Ridge, TN 37831-6335, USA

The tapes, diskettes, and documentation may also be ordered by telephone, facsimile, or electronic mail:

Telephone: (423) 574-3645 or (423) 574-0390
Fax: (423) 574-2232
Electronic mail: cdiac@ornl.gov

FTP access: **ftp cdiac.esd.ornl.gov** (or 128.219.24.36)
Enter **anonymous** at the userid prompt
Enter your e-mail address as the password
Change the directory to **/pub/ndp057** (i.e., ftp> *cd /pub/ndp057*)
Retrieve all files (i.e., ftp> *mget* *)

NOTE: When using these radiocarbon data in a presentation or publication, **PLEASE** acknowledge the principal investigators, Reidar Nydal and Knut Lövseth, and the Norwegian Institute of Technology!

PART 2

CONTENT AND FORMAT OF DATA FILES

11. LISTING OF FILES PROVIDED

The following is a list of the files that compose the Nydal and Lövseth atmospheric carbon isotope database and that are distributed by CDIAC along with this documentation. These files are available on a variety of media (see Sect. 10, "How To Obtain the Data and Documentation"). This listing has been tailored to reflect a 9-track magnetic tape request. The record formats, block sizes, and record lengths shown are the defaults for those not specifying these parameters when requesting machine-readable data files on 9-track magnetic tape. The default tape density, labeling, and characters are 6250 BPI, nonlabeled, and ASCII, respectively.

File number, description, and name (in parentheses)	Logical records	FTP file size (kB)	Record format[a]	Block size	Record length
1. General descriptive information file (**ndp057.doc**)	255	13.3	FB	8000	100
2. FORTRAN 77 data retrieval code to read and print the files containing the atmospheric carbon isotope records (files 4–18) (**ndp057.for**)	21	0.7	FB	8000	80
3. SAS® data retrieval code to read and print files 4–18 (**ndp057.sas**)	12	0.4	FB	8000	80
Data files containing $\delta^{14}C$, $\delta^{13}C$, and $\Delta^{14}C$ estimates in atmospheric CO_2 from the following Northern and Southern Hemisphere sites					
4. Kapp Linné, Spitsbergen, Norway (**V.asc**)	59	1.6	FB	6100	61
5. Fruholmen, Nordkapp, Norway (**F.asc**)	531	32.5	FB	6100	61
6. Gråkallen, Trondheim, Norway (**K.asc**)	44	2.6	FB	6100	61
7. Vassfjellet, Trondheim, Norway (**KV.asc**)	32	1.8	FB	6100	61
8. Lindesnes, Norway (**L.asc**)	64	3.8	FB	6100	61
9. Santiago de Compostela, Spain (**S.asc**)	104	6.3	FB	6100	61
10. Izaña, Tenerife, Canary Islands (**IZ.asc**)	308	19.3	FB	6100	61
11. Mas Palomas, Grand Canary Island (**M.asc**)	183	11.4	FB	6100	61
12. Rehovot, Israel (**R.asc**)	28	1.6	FB	6100	61

File number, description, and name (in parentheses)	Logical records	FTP file size (kB)	Record format[a]	Block size	Record length
13. Popenguine, Dakar, Senegal (**D.asc**)	48	2.8	FB	6100	61
14. Dakar-Fann, Senegal (**DF.asc**)	84	5.1	FB	6100	61
15. N'Djamena, Chad (**TC.asc**)	119	7.2	FB	6100	61
16. Debre Zeit, Ethiopia (**E.asc**)	84	5.2	FB	6100	61
17. Fianarantsoa, Madagascar (**G.asc**)	185	11.4	FB	6100	61
18. Single data file containing the $\delta^{14}C$, $\delta^{13}C$, and $\Delta^{14}C$ estimates in atmospheric CO_2 from all 14 sites (**nydal.asc**)	1635	101.8	FB	6100	61
19. FORTRAN 77 data retrieval code to read and print the file containing the stratospheric $\delta^{14}C$, $\delta^{13}C$, and $\Delta^{14}C$ estimates in atmospheric CO_2 derived from air samples collected by aircraft during 1965 from the Trondheim area (62–65° N, 6–10° E) (**strat.for**)	26	0.9	FB	8000	80
20. SAS© data retrieval code to read and print file 21 (**strat.sas**)	13	0.5	FB	8000	80
21. Stratospheric $\delta^{14}C$, $\delta^{13}C$, and $\Delta^{14}C$ estimates in atmospheric CO_2 derived from air samples collected by aircraft during 1965 from the Trondheim area (62–65° N, 6–10° E) (**strat.dat**)	27	1.9	FB	7600	76
TOTAL	3862	232.1			

[a]Fixed-block record format.
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12. FILE DESCRIPTIONS

This section describes the content and format of each of the 21 files that compose this numeric data package (NDP) and the Nydal and Lövseth atmospheric carbon isotope database.

DATA FILES

This NDP consists of the following 21 files:

- a descriptive file that contains an overview of the Nydal and Lövseth atmospheric carbon isotope database and detailed descriptions of the data files (**ndp057.doc**);
- one FORTRAN 77 data retrieval routine to read and print any of the 15 data files containing estimates of $\delta^{14}C$, $\delta^{13}C$, and $\Delta^{14}C$ in atmospheric CO_2 from air samples collected at 14 sites (**ndp057.for**);
- one SAS® data retrieval routine to read and print any of the 15 data files (**ndp057.sas**);
- one ASCII data file containing estimates of $\delta^{14}C$, $\delta^{13}C$, and $\Delta^{14}C$ in atmospheric CO_2 from all 14 sites (**nydal.asc**);
- 14 ASCII data files (one for each sampling location) containing estimates of $\delta^{14}C$, $\delta^{13}C$, and $\Delta^{14}C$ in atmospheric CO_2 (****.asc** — *see description of "LABREF" on page 15*),
- one FORTRAN 77 data retrieval routine to read and print the file containing estimates of $\delta^{14}C$, $\delta^{13}C$, and $\Delta^{14}C$ in atmospheric CO_2 collected in the lower stratosphere from aircraft during 1965 (**strat.for**);
- one SAS® data retrieval routine (**strat.sas**) to read and print **strat.dat**; and
- one ASCII data file containing estimates of $\delta^{14}C$, $\delta^{13}C$, and $\Delta^{14}C$ in atmospheric CO_2 collected in the lower stratosphere from aircraft during 1965 (**strat.dat**)

DATA FILE FORMATS (*.ASC)

This NDP contains 15 data files that provide 1619 estimates of $\delta^{14}C$, $\delta^{13}C$, and $\Delta^{14}C$ in atmospheric CO_2 from 14 locations. The period of record differs by station. The earliest measurements were made in 1962, and the latest estimates are from 1993. Most stations have records only for the 1960s. All of the data files have the same format and none contain missing values. Some $\delta^{13}C$ values are flagged as mean values; users are urged to pay attention to these flags before analyzing or interpreting the corresponding values.

Each file is sorted by sample collection date and may be read with the following FORTRAN 77 code:

```
      character labref*9, samdat*13, flag13*1
      real delC14, delC13, corC14
      open(unit=5,file='F.asc')
      open(unit=6)
      read(5,10)
 10   format(////////////////)
 13   continue
      read (5,15, end=99) labref,week,samdat,delC14,delC13,flag13,
     1  corC14,sigma
 15   format(A9,1X,I4,2X,A13,4X,F6.1,2X,F5.1,A1,2X,F6.1,4X,I2)
```

The following SAS® input statement may also be used to read these files:

```
input labref $ 1-9 week 11-15 samdat $ 17-30 @34 delC14 7.1 @42 delC13 5.1
      flag13 $ 47 corC14 50-55 sigma 60-61;
```

Stated in tabular form, the contents include the following:

Variable	Variable type	Variable format	Starting column	Ending column
LABREF	Alphanumeric	9	1	9
WEEK	Numeric	5	11	15
SAMDAT	Alphanumeric	14	17	30
DELC14	Numeric	7.1	34	40
DELC13	Numeric	5.1	42	46
FLAG13	Character	1	47	47
CORC14	Numeric	6.1	50	55
SIGMA	Numeric	2	60	61

where

LABREF is a seven-to-eight character site code and sample reference number (e.g., D_00034). The 5-digit sample reference number follows the site code and is separated from the site code by an underscore (i.e., "_") character. All laboratory reference numbers are unique. The site codes and the sampling stations they represent are as follows:

V	Kapp Linné, Spitsbergen, Norway
F	Fruholmen, Nordkapp, Norway
K	Gråkallen, Trondheim, Norway
KV	Vassfjellet, Trondheim, Norway
L	Lindesnes, Norway
S	Santiago de Compostela, Spain
IZ	Izaña, Tenerife, Canary Islands
M	Mas Palomas, Grand Canary Island
R	Rehovot, Israel
D	Popenguine, Dakar, Senegal
DF	Université Dakar-Fann, Dakar, Senegal
TC	N'Djamena, Chad
E	Debre Zeit, Addis Ababa, Ethiopia
G	Fianarantsoa, Madagascar

WEEK is the week the NaOH tray was exposed relative to the first week of 1963. Values range from -34 to 1591. Zero refers to the week of December 29, 1962 to

January 7, 1963. Negative values denote the number of weeks before 1963 (e.g., -34 refers to the week from April 30, 1962, to May 3, 1962).

SAMDAT — is a thirteen-character field that represents the days, months, and years of the sampling period, typically 4–7 day periods. The beginning date (yy/mm/dd) and ending date (yy/mm/dd) are separated by a hyphen. The earliest sampling date is 620430-620503 (from Gråkallen) and the latest sampling period is 930621-930624 (from Fruholmen).

DELC14 — is the uncorrected (for decay) measurement of excess ^{14}C in atmospheric CO_2 expressed as $\delta^{14}C$ in per mil (‰) relative to the US National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) oxalic acid standard; 95% of the ^{14}C concentration in this standard represents the normal activity in recent wood for the year 1950 A.D. Values for DELC14 range from 108.5 to 1036.0.

DELC13 — represents the deviation in the $^{13}C/^{12}C$ ratio expressed in per mil (‰) relative to the Pee Dee Belemnite or (Pee Dee River, South Carolina) or PDB standard (Craig 1961). The $^{13}C/^{12}C$ ratio was measured by mass spectrometry. The $\delta^{13}C$ values provided are given as a guide for the calculation of the $\Delta^{14}C$ values. When fractionation was not measured, a mean value, normally based on 20–40 samples was used and is denoted by an asterisk (see description of "FLAG13"). Values for DELC13 range from -31.7 to -11.3.

FLAG13 — is a one-character flag code used to denote whether the DEL13C estimate was measured (blank) or represents a mean value (asterisk).

CORC14 — is the atmospheric ^{14}C content expressed as $\Delta^{14}C$ in per mil (not as a percentage). $\Delta^{14}C$ is corrected for isotopic fractionation through $\delta^{13}C$ (DELC13), and for radioactive decay of the ^{14}C reference standard (NIST). Values range from 110.4 to 1040.4.

SIGMA — is the standard deviation for CORC14 expressed as an integer. Values range from 3 to 42.

DATA FILE FORMAT (STRAT.DAT)

This NDP contains one data file that provides eleven estimates of $\delta^{14}C$, $\delta^{13}C$, and $\Delta^{14}C$ in atmospheric CO_2 from the low stratosphere during 1965. High-altitude samples were collected in the Trondheim area using aircraft from the Norwegian Air Force. Flights originated from Örlandet Airport and covered the region bounded by 62–65° N and 6–10° E, at altitudes of 9000-12600 m. Samples were collected using a filter with a 1.4 kg molecular sieve that absorbs CO_2 from the penetrating air. The filter container was placed under the wing of the plane and opened and closed with electrically-operated shutters at both ends. With the plane traveling at a speed of approximately 900 km/hr the filter shutters were opened 15 minutes to allow sufficient amounts of CO_2 to be absorbed.

The file may be read with the following FORTRAN 77 code:

```
      character sample*6, flag13*1
      real delC13, corC14
      open(unit=5,file='strat.dat')
      open(unit=6)
      read(5,10)
 10   format(///////////////)
      write(6,15)
 15   format('Sample',3X,'Altitude',3X,'Date of Collection',6X,
     1 'delta',6X,'delta',2X,'Corrected',4X,'Sigma',/,11X,'(m)',
     2 6X,'(Year, Month, Day)',7X,'C14',8X,'C13',3X,'delta C14',
     3 /)
 20   continue
      read (5,25, end=99) sample,alt,samdat,delC14,delC13,flag13,
     1  corC14,sigma
 25   format(A6,4X,I5,11X,I6,12X,I4,4X,F5.1,A1,4X,I4,8X,I2)
```

The following SAS® input statement may also be used to read this file:

```
input sample $ 1-6 alt 11-15 samdat 27-32 delC14 45-48 @53 delC13 5.1
      flag13 $ 58 corC14 63-66 sigma 75-76;
```

Stated in tabular form, the contents include the following:

Variable	Variable type	Variable format	Starting column	Ending column
SAMPLE	Alphanumeric	6	1	6
ALT	Numeric	5	11	15
SAMDAT	Numeric	6	27	32
DELC14	Numeric	4	45	48
DELC13	Numeric	5.1	53	57
FLAG13	Character	1	58	58
CORC14	Numeric	4	63	66
SIGMA	Numeric	2	75	76

where

SAMPLE is a six character site code and sample reference number (e.g., AS-001). The 3-digit sample reference number follows the site code and is separated from the site code by a hyphen. All laboratory reference numbers are unique. Laboratory reference numbers range from 001 to 013. The site code is always "AS" denoting aircraft sampling.

ALT is the altitude where the air sample was collected expressed in meters. Values range from 9000 to 12600.

SAMDAT is a six-digit field that represents the day, month, and year of the sampling date expressed in a yymmdd format. Values range from 650407 to 651014.

DELC14 is the uncorrected (for decay) measurement of excess ^{14}C in atmospheric CO_2 expressed as $\delta^{14}C$ in per mil (‰) relative to the US National Institute of Standards and Technology (NIST, formerly the National Bureau of Standards) oxalic acid standard; 95% of the ^{14}C concentration in this standard represents the normal activity in recent wood for the year 1950 A.D. Values for DELC14 range from 599 to 1718.

DELC13 represents the deviation in the $^{13}C/^{12}C$ ratio expressed in per mil (‰) relative to the Pee Dee Belemnite (Pee Dee River, South Carolina) or PDB standard (Craig 1961). The $^{13}C/^{12}C$ ratio was measured by mass spectrometry. The $\delta^{13}C$ values provided are given as a guide for the calculation of the $\Delta^{14}C$ values. When fractionation was not measured, a mean value, based on 4 samples was used and is denoted by an asterisk (see description of "FLAG13"). Values for DELC13 range from -11.4 to -3.3.

FLAG13 is a one-character flag code used to denote whether the DEL13C estimate was measured (blank) or represents a mean value (asterisk). Seven of the eleven DELC13 values are flagged with an asterisk.

CORC14 is the atmospheric ^{14}C content expressed as $\Delta^{14}C$ in per mil (not as a percentage). $\Delta^{14}C$ is corrected for isotopic fractionation through $\delta^{13}C$ (DELC13), and for radioactive decay of the ^{14}C reference standard (NIST). Values range from 554 to 1626.

SIGMA is the standard deviation for CORC14 expressed as an integer. Values range from 17 to 47.

REFERENCES

Craig, H. 1961. Mass-spectrometer analysis of radiocarbon standards. *American Journal of Science Radiocarbon Supplement* 3:1–3.

Nydal, R., and K. Lövseth. 1983. Tracing bomb ^{14}C in the atmosphere 1962–1980. *Journal of Geophysical Research* 88:3621–42.

13. LISTING OF THE FORTRAN 77 DATA RETRIEVAL PROGRAMS

The following is a listing of the FORTRAN 77 data retrieval code (**ndp057.for**) written by the preparers to read and print any of the files containing the station ^{14}C data.

```
C This Fortran 77 program was written by VZ to read and write
C Nydal and Lovseth's C14 measurements
      character labref*9, samdat*13, flag13*1
      real delC14, delC13, corC14
      open(unit=5,file='F.asc')
      open(unit=6)
      read(5,10)
 10   format(///////////////)
 13   continue
      read (5,15, end=99) labref,week,samdat,delC14,delC13,flag13,
     1  corC14,sigma
 15   format(A9,1X,I4,2X,A13,4X,F6.1,2X,F5.1,A1,2X,F6.1,4X,I2)
      write(6,20) labref,week,samdat,delC14,delC13,flag13,
     1  corC14,sigma
 20   format(A9,1X,I4,2X,A13,4X,F6.1,2X,F5.1,A1,2X,F6.1,4X,I2)
      goto 13
 99   continue
      close(unit=5)
      close(unit=6)
      stop
      end
```

The following is a listing of the FORTRAN 77 data retrieval code (**strat.for**) written by the preparers to read and print the file containing the stratospheric ^{14}C data.

```
C This Fortran 77 program was written by TAB to read and write
C Nydal and Lovseth's aircraft C14 measurements
      character sample*6, flag13*1
      real delC13, corC14
      open(unit=5,file='strat.dat')
      open(unit=6)
      read(5,10)
 10   format(///////////////)
      write(6,15)
 15   format('Sample',3X,'Altitude',3X,'Date of Collection',6X,
     1 'delta',6X,'delta',2X,'Corrected',4X,'Sigma',/,11X,'(m)',
     2 6X,'(Year, Month, Day)',7X,'C14',8X,'C13',3X,'delta C14',
     3 /)
 20   continue
      read (5,25, end=99) sample,alt,samdat,delC14,delC13,flag13,
     1  corC14,sigma
 25   format(A6,4X,I5,11X,I6,12X,I4,4X,F5.1,A1,4X,I4,8X,I2)
      write(6,30) sample,alt,samdat,delC14,delC13,flag13,
     1  corC14,sigma
 30   format(A6,4X,I5,11X,I6,12X,I4,6X,F5.1,A1,4X,I4,8X,I2)
      goto 20
 99   continue
      close(unit=5)
      close(unit=6)
      stop
      end
```

14. LISTING OF THE SAS® DATA RETRIEVAL PROGRAMS

The following is a listing of the SAS® data retrieval code (**ndp057.sas**) written by the preparers to read and print any of the files containing the station ^{14}C data.

```
*********************************************
* THIS SAS PROGRAM READS AND PRINTS THE NYDAL *
* AND LOVSETH ASCII FILES CONTAINING          *
* GROUND-LEVEL C14 MEASUREMENTS               *
*********************************************
;
data nydal;
infile 'nydal.asc' missover firstobs=17;
input labref $ 1-9 week 11-15 samdat $ 17-30 @34 delC14 7.1 @42 delC13 5.1
      flag13 $ 47 corC14 50-55 sigma 60-61;
proc print;
run;
```

The following is a listing of the SAS® data retrieval code (**strat.sas**) written by the preparers to read and print the file containing the stratospheric ^{14}C data.

```
*********************************************
* THIS SAS PROGRAM READS AND PRINTS THE FILE  *
* (STRAT.DAT) CONTAINING C14 MEASUREMENTS     *
* DERIVED FROM AIR SAMPLES COLLECTED ON       *
* NORWEGIAN AIR FORCE AIRCRAFT DURING 1965    *
*********************************************
;
data strat;
infile 'strat.dat' missover firstobs=17;
input sample $ 1-6 alt 11-15 samdat 27-32 delC14 45-48 @53 delC13 5.1
      flag13 $ 58 corC14 63-66 sigma 75-76;
proc print;
run;
```

15. PARTIAL LISTING OF DATA FILES

The following presents a partial listing of one (**nydal.asc**) of the 15 data files that contain the station ^{14}C data. This file is identical in format to all data files containing the station ^{14}C data.

The first 25 lines of the file **nydal.asc** are as follows:

```
************************************************************
* Carbon-14 Measurements in Atmospheric CO2 from Northern *
* and Southern Hemisphere Sites, 1962-1993                 *
*                                                          *
* Authors: Reidar Nydal and Knut Lovseth                   *
*          Radiological Dating Laboratory                  *
*          The Norwegian Institute of Technology           *
*          N-7034 Trondheim NTH                            *
*          NORWAY                                          *
*                                                          *
* NDP057 (November 1996)                                   *
************************************************************
```

Lab Ref.	Week	Sampling Interval	delta C14	delta C13	corr C14	sigma
D-00001	10	630304-630311	477.0	-26.5	479.4	12
D-00002	11	630311-630318	494.0	-23.1	486.4	7
D-00004	13	630325-630401	562.0	-24.2	557.4	11
D-00006	15	630408-630415	583.0	-24.2	557.4	11
D-00008	17	630422-630429	580.0	-25.0	578.4	11
D-00010	19	630506-630513	653.0	-23.7*	647.4	9
D-00012	21	630520-630527	661.0	-24.6	658.4	10
D-00014	23	630603-630610	704.0	-24.3	700.4	12
D-00016	25	630617-630624	703.0	-25.0	701.4	8

The last 25 lines of the file **nydal.asc** are as follows:

TC-00109	576	740107-740114	435.0	-23.7	428.1	10
TC-00110	580	740204-740211	430.0	-22.0	418.1	9
TC-00111	584	740304-740311	427.0	-22.4	416.1	9
TC-00112	588	740401-740408	425.0	-22.4	414.1	10
TC-00113	595	740524-740601	410.0	-23.2	402.1	10
TC-00114	636	750303-750310	403.0	-21.8	391.0	10
TC-00115	680	760105-760112	396.0	-21.6	382.9	11
TC-00116	684	760202-760209	400.0	-21.0	384.9	6
TC-00117	688	760301-760308	392.0	-18.6	370.9	8
TC-00118	692	760329-760405	369.0	-20.2	352.9	11
TC-00119	696	760426-760503	357.0	-24.2	350.9	9
TC-00120	700	760524-760531	410.0	-22.7	399.9	10
V-00001	25	630619-630626	760.0	-27.8	768.4	13
V-00003	27	630701-630708	801.0	-25.8	802.4	12
V-00005	29	630715-630722	941.0	-27.5	949.4	11
V-00007	31	630729-630805	948.0	-25.2	947.4	10
V-00009	33	630812-630819	998.0	-26.2	1001.4	11
V-00011	35	630827-630903	1006.0	-26.9	1012.4	13
V-00013	37	630909-630916	994.0	-26.4*	997.4	12
V-00015	39	630923-631001	960.0	-28.1	970.4	10
V-00017	41	631007-631015	964.0	-26.4*	969.4	11
V-00019	43	631022-631029	949.0	-22.8	938.4	11
V-00055	79	640629-640706	878.0	-26.8	883.3	11
V-00057	81	640713-640720	973.0	-26.4*	976.3	11
V-00059	83	640727-640803	919.0	-26.4*	922.3	11

The following is a complete listing of the data file (**strat.dat**) containing the stratospheric ^{14}C data.

```
*********************************************************
* Carbon-14 Measurements in Atmospheric CO2 from Northern *
* and Southern Hemisphere Sites, 1962-1993                *
*                                                         *
* Authors: Reidar Nydal and Knut Lovseth                  *
*          Radiological Dating Laboratory                 *
*          The Norwegian Institute of Technology          *
*          N-7034 Trondheim NTH                           *
*          NORWAY                                         *
*                                                         *
* NDP057 (November 1996)                                  *
*********************************************************
```

Sample	Altitude (m)	Date of Collection (Year, Month, Day)	delta C14	delta C13	Corrected delta C14	Sigma
AS-001	12600	650407	1459	-8.5*	1376	28
AS-003	12000	650513	1660	-8.5*	1577	47
AS-004	11900	650601	1140	-8.5*	1067	18
AS-005	12000	650614	1718	-8.5*	1626	47
AS-006	12000	650623	1669	-8.1	1576	32
AS-008	12000	650721	1437	-8.5*	1355	35
AS-009	12000	650804	1116	-11.2	1055	33
AS-010	9000	650821	814	-3.3	734	17
AS-011	12000	650907	854	-8.5*	737	23
AS-012	12000	650924	986	-8.5*	919	26
AS-013	12000	651014	599	-11.4	554	33

16. VERIFICATION OF DATA TRANSPORT

The data files contained in this NDP may be read with the FORTRAN 77 or SAS® data retrieval programs provided. To verify that the data have been correctly transported to their systems, users should generate some or all of the statistics presented in Tables 2 and 3. These tables present simple summary statistics for the file that contains data from all 14 sites (i.e., file **nydal.asc**) and the file that contains the stratospheric ^{14}C measurements (i.e., file **strat.dat**). If the statistics generated by the user differ from those presented here, the data files may have been corrupted in transport.

These statistics are presented only as a tool to ensure proper reading of the data files. They are not to be construed as summaries of the data sets.

Table 2. Characteristics of numeric variables in the file containing carbon isotope data from all 14 sampling locations

Variable	Number of observations	Mean	Standard deviation	Minimum value	Maximum value
WEEK	1619	534.8097591	490.3078555	-34	1591
DELC14	1619	502.1426189	237.0226744	108.5	1036.0
DELC13	1619	-24.2290303	2.3573591	-31.7	-11.3
CORC14	1619	496.9402718	236.6761277	110.4	1040.4
SIGMA	1619	9.1432983	3.1888204	3	42

Table 3. Characteristics of numeric variables in the file containing stratospheric carbon isotope data derived from air samples collected by aircraft during 1965

Variable	Number of observations	Mean	Standard deviation	Minimum value	Maximum value
ALT	11	11772.73	938.1800564	9000	12600
SAMDAT	11	650722.64	188.6336517	650407	651014
DELC14	11	1222.91	387.7791780	599	1718
DELC13	11	-8.50	2.0712315	-11.4	-3.3
CORC14	11	1143.27	380.9330889	554	1626
SIGMA	11	30.82	9.9981817	17	47

APPENDIX A

FIGURES SHOWING TROPOSPHERIC AND STRATOSPHERIC ^{14}C MEASUREMENTS IN ATMOSPHERIC CO_2 FROM 14 NORTHERN AND SOUTHERN HEMISPHERE SITES

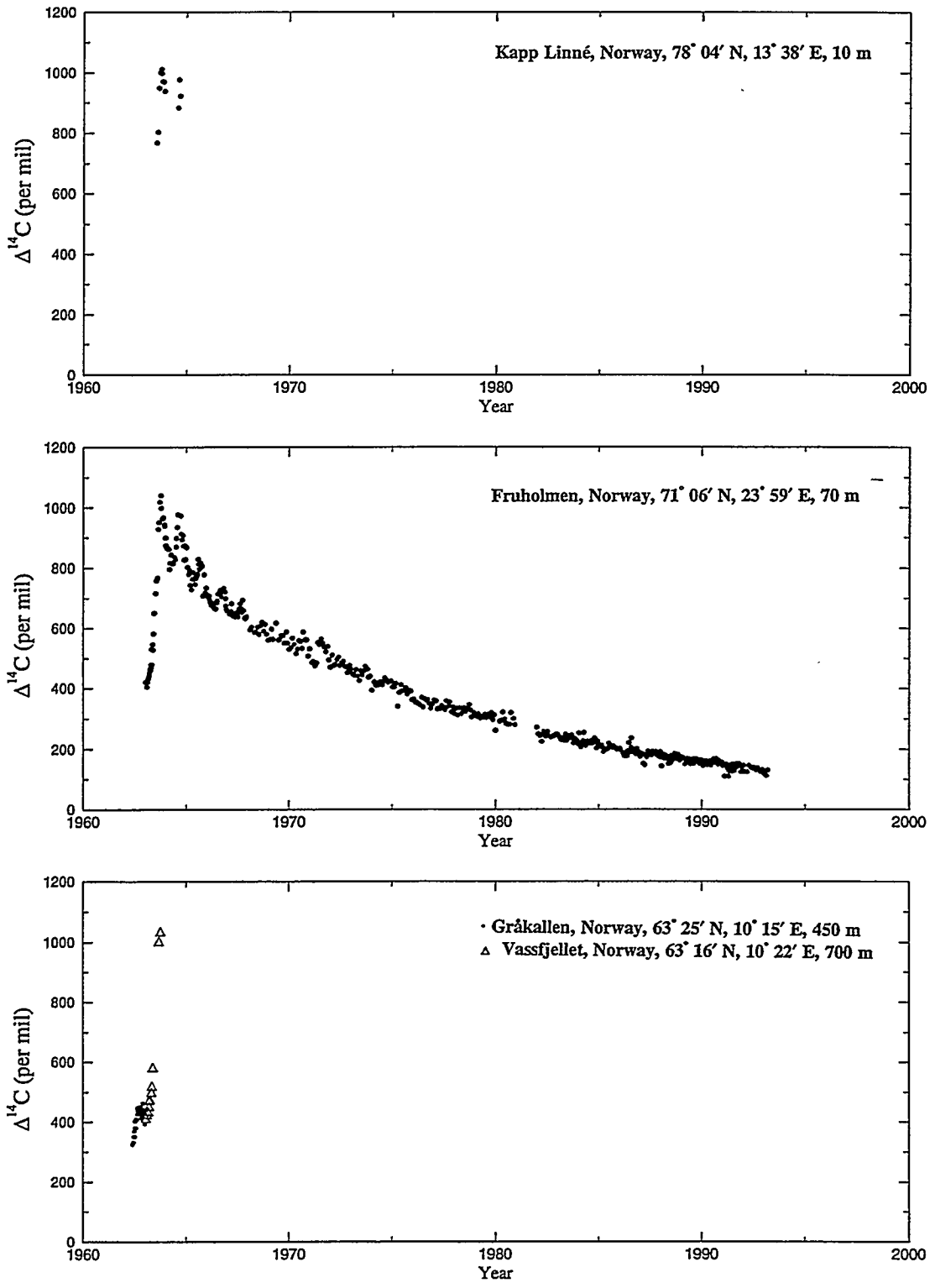

Fig. A-1. Corrected ^{14}C measurements from air samples collected at Kapp Linné, Fruholmen, Gråkallen, and Vassfjellet

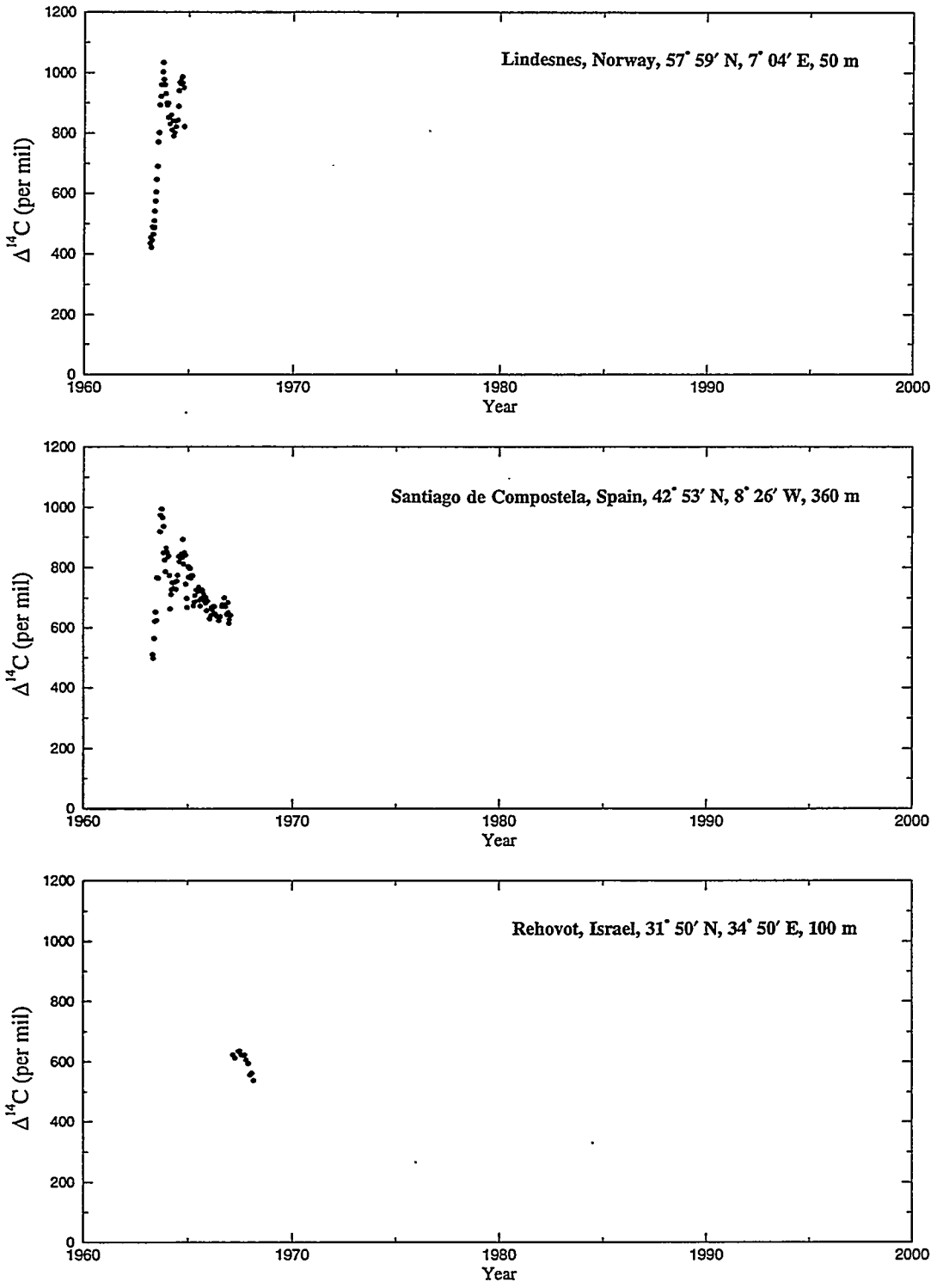

Fig. A-2. Corrected ^{14}C measurements from air samples collected at Lindesnes, Norway; Santiago de Compostela, Spain; and Rehovot, Israel

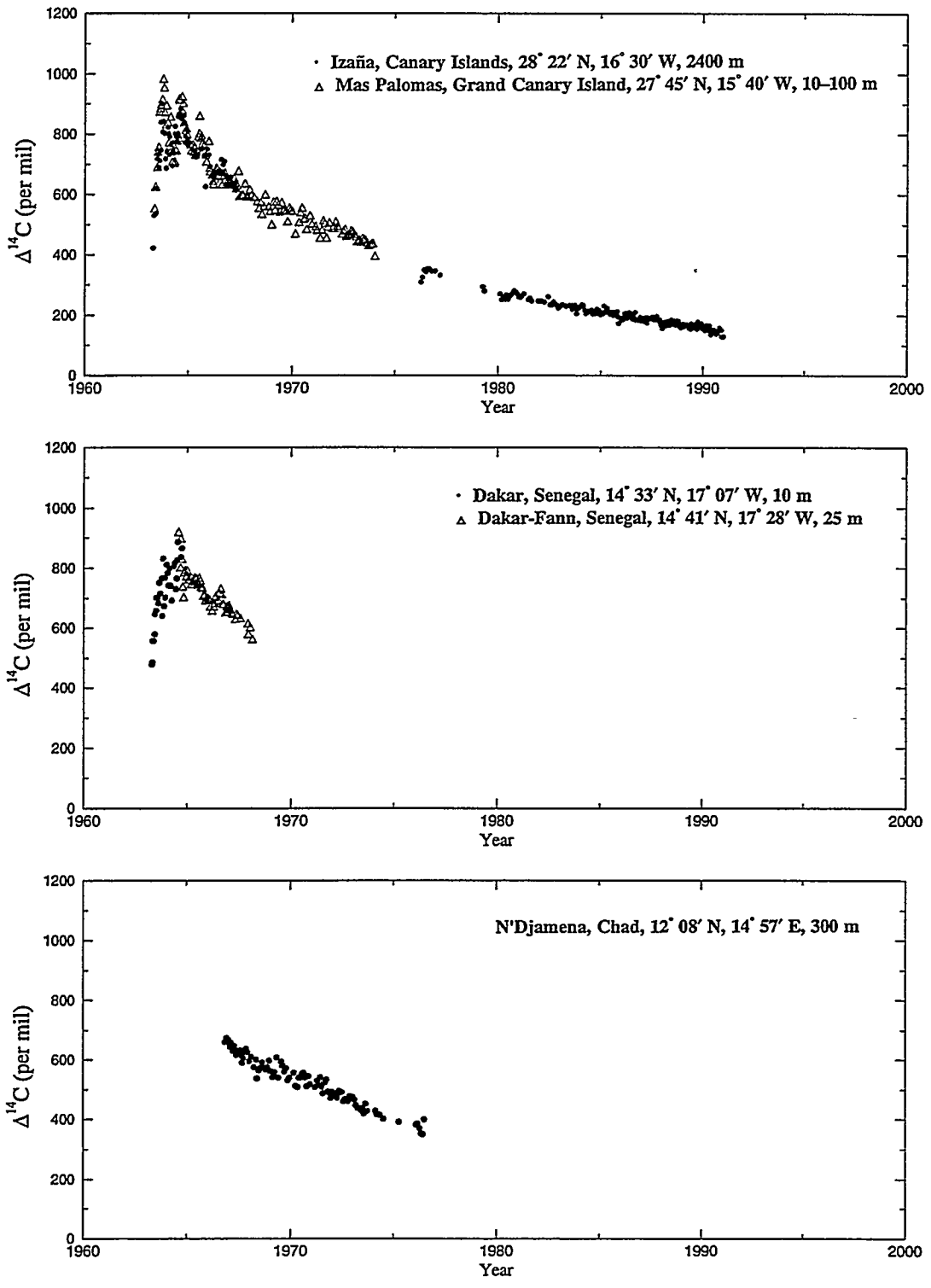

Fig. A-3. Corrected ^{14}C measurements from air samples collected at Izaña, Canary Islands; Mas Palomas, Grand Canary Island; Dakar, Senegal; Dakar-Fann, Senegal; and N'Djamena, Chad

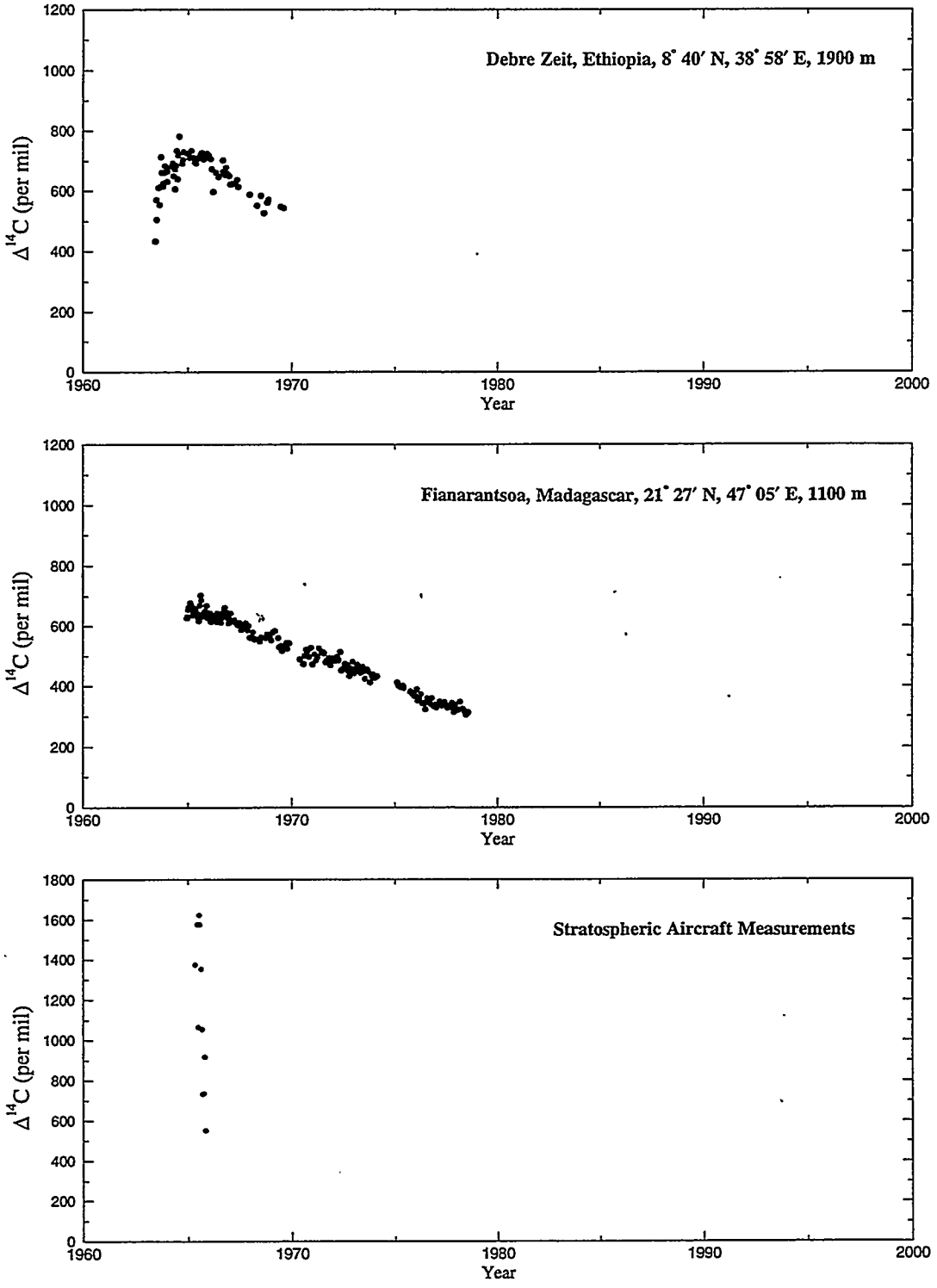

Fig. A-4. Corrected ^{14}C measurements from air samples collected at Debre Zeit, Ethiopia; Fianarantsoa, Madagascar; and by aircraft flying in the low stratosphere above Trondheim, Norway

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