Reconstruction of the Mauna Loa Carbon Dioxide Record using High Frequency APC Data from 1958 through 2004

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1 Introduction

This report accompanies datasets for the atmospheric CO_2 mole fraction at the Mauna Loa observatory from March 1958 through Dec 2004 with 10-minute resolution and with daily resolution (daily "baseline" data). These records complement the standard versions of the Mauna Loa record, for which the data is averaged to produce weekly and monthly baseline values.

The main foreseen purpose of these new high-resolution datasets is to allow studies of CO_2 variability on relatively short time scales, such as on synoptic or diurnal time scales. Users interested only in phenomenon occurring on weekly and longer time scales are advised to continue using the standard weekly and monthly products rather than generating new long-term averages of these reconstructed high resolution data. To generate new long-term products from these short-term data would be engaging in circular data reduction. As described further below, our standard weekly and monthly products are not exactly derivable from the 10-minute record made available here. Rather, the opposite is partly true: the high resolution records have been adjusted to match the standard weekly and monthly products.

This report concerns only the reconstruction of the high resolution record up through December 2004. The mating of this high frequency record with more recent high resolution data, for which the full data reduction path is still active, will be addressed elsewhere.

The CO_2 measurements at Mauna Loa were established in 1958 by C. D. Keeling of the Scripps Institution of Oceanography in collaboration with the Weather Bureau, the predecessor agency to the National Oceanographic and Atmospheric Administration (NOAA). In the early 1970s, a second analyzer was installed for which the data processing was done at NOAA, while the original Scripps instrument also continued to collect data. This report concerns the Scripps record. Air was originally processed by an Applied Physics Corporation (APC) non-dispersive infrared analyzer, which in 2005 was replaced by a Siemens analyzer.

Data have always been collected at high frequency, either as an analog chart trace or digital signal on a 10 second frequency, each of which has been grouped into 10 minute averages before further processing. The 10-minute data were then subjected to a screening criterion to avoid local contamination, which was identifiable based on short-term fluctuations. The procedure involved rejecting all data except when the CO_2 concentration was steady for periods of around 5 hours or more (Pales and Keeling, 1965). These baseline data were then averaged to produce one value per day (daily baseline data), which were then further averaged to produce weekly and monthly averages. The production of monthly averages required a curve fitting algorithm to adjust weekly averages to the middle day of each month.

From program inception, the raw APC output was recorded as pen traces on a strip chart. Processing to produce final results was also done on paper. The transition to additional digital data collection and processing occurred in the late 1970s by group members Bob Bacastow and David Moss. Around this time a process was also begun of transferring the early and ongoing records to digital form. In addition, to facilitate data analyses, Bob Bacastow wrote the main data fitting Fortran program ("stationfit") in the early 1970s working closely with Dave Keeling, relevant here for generating monthly averages.

Shortly after joining the group in 1977, Tim Whorf became the primary analyst of CO_2 data from stations including Mauna Loa. Whorf used Fortran programs to convert the data from raw voltages to CO_2 concentrations, to select baseline data ("blue-lining") and to flag outliers. Periodic re-evaluations of the data by Keeling and Whorf produced systematic corrections, known as “period corrections” that were incorporated into the data set. In general, these adjustments were incorporated into the operational Fortran code used by Whorf. Owing to limitations in disk storage and processing capabilities, data were analyzed incrementally for only weeks at a time, with weekly averages stored online as the primary operational data set. These weekly averages were also routinely processed to yield monthly averages. The weekly and monthly averages were thus the main operational product of the program.

In 2005, both Dave Keeling and Tim Whorf died in close succession. This presented a substantial challenge for data processing since much of the information about the data was stored in file cabinets and stored in both offline and online data files on different types of media. Although the latest versions of the primary weekly and monthly datasets were readily available, the provenance of the underlying raw data at higher time resolution was unclear. With this starting point, the goal of this project was to reconstruct the complete record with 10 minute resolution. Fortunately, Steve Piper, who joined the group in 1984 and had been a regular data user for modeling work as well as the group's computer system manager up through the late 1990s, with some assistance from long-term group members Peter Guenther and Alane Bollenbacher, was able to help recover some of the stored data and relevant processing information.

The methods used to process the data at Mauna Loa were described in early publications (Pales and Keeling, 1965; Keeling et al., 1976). The APC analyzer at Mauna Loa was calibrated using reference gases that were analyzed in La Jolla against manometrically-calibrated gases using a similar APC analyzer. Starting in 1960, air samples were collected at the Mauna Loa Observatory in glass flasks that were analyzed directly on the La Jolla instrument, thus providing a redundant record that eliminated one layer of calibration complexity but with lower time resolution and precision. Both flask and in situ records have been sustained to the present. The flask data helped to establish the “period corrections” applied retrospectively to time intervals when offsets in calibration between the two APC analyzers were suspected. For example, in the early years, offsets in calibration were possible due to variations in the carrier gas effect (Keeling et al., 1976) which was sensitive to variations in composition of the gas (e.g. CO_2 in N_2, or CO_2 in Ar mixtures) filling the APC optical detectors (Keeling, 1984).

Despite the emphasis given to the weekly and monthly products, data at higher resolution than the standard weekly product was presented graphically in several publications: Mar 1958 – Dec 1963 (Pales and Keeling, 1965, Fig. 9), Jan 1963 - Dec 1971 (Keeling et al, 1976, Fig. 4), and Dec 1978 -Nov 1979 (Heimann et al., 1989, Fig. 26). Daily data through 1985 were also tabulated in an internal technical report (Keeling et al, 1986). Rather than working from these daily records, we chose instead to focus on a digital record of 10 minute data that Steve Piper was able to locate in Whorf’s files. The resources included raw voltages, working tank concentrations, and instrument response factors (“recorder scale factors”, RSF), which were sufficient to compute mole fractions. We also had available Tim Whorf’s Fortran code.

Still, the located information was not quite sufficient to exactly reproduce the primary weekly and monthly datasets. First, the 10-minute data did not include baseline flags, thus we lacked information on the exact periods which had been included in the daily baseline record by Whorf or earlier analysts. Our approach to addressing the need for baseline selection was to apply algorithms in current usage (Walker, 2012). These new algorithms had been closely compared with Whorf's methods over an extensive overlap period, from Jan 2003 to Sept 2005. Obviously, this method will identify somewhat different periods as baseline, leading to a slightly different daily record. But the consequences for weekly and monthly averages are quite small, as documented in Walker (2012).

Second, although Whorf's code included many period corrections, subsequent comparisons revealed that these were not comprehensive in the sense that they were missing corrections that had clearly been applied to the standard weekly and monthly products. As Whorf used his Fortran code primarily to append the latest data to the record, the code was not designed to reproduce all corrections that may have been applied to earlier data. An extensive discussion of these corrections was provided in Keeling, C.D. (1984, Unfinalized manuscript) and Keeling, C.D. (1987, Handwritten notes). Rather than relying on these notes, which were possibly somewhat out of date, our approach to addressing incomplete period corrections was to rely on a comparison between a new weekly record, which we generated from our daily product, and the standard version, and thereby establishing corrections required to make the record closely match. These adjustments are generally constant or slowly varying on monthly and longer time scales and therefore have little impact on the variability on shorter time scales.

2 Data Sources

For the first few decades of the record, the voltage output of the Mauna Loa APC analyzer was recorded on paper strip charts that were mailed to Scripps for processing along with a hand-written record of calibration cylinder usage. From these strip charts a 10 minute average instrument response was calculated by a manual process of hand lining. Later, digital data were recorded as discrete points with 10 second spacing that were again averaged over 10 minute time periods before further processing. The 10 minute average data were converted to carbon dioxide concentration through a series of transformations that also took account of calibration data.

At the outset of this project we were aware of three sources of high frequency data that were potentially useful for reconstructing a full 10 minute record.

1) Paper strip charts of analog instrument response.
2) Raw digital instrument response voltage data.
3) 10 minute average instrument response voltage data.

2.1 Strip Chart Data

Strip charts covering parts of the early record are still stored at Scripps, but we opted against working directly with Scripps chart data for several reasons: (1) the work required to manually re-read these charts would be very large, (2) this record would omit corrections to the raw signal that have been made over the years (such corrections may have been made to address known short term instrumental issues that may not have been documented on the charts), and (3) an alternate approach was possible using already digitized records.

2.2 Raw Digital Files

We were able to locate raw digital voltage files, e.g. recording 10 second APC data, going back to 1992 on the project computer *cdrgsun.ucsd.edu* in sub-directories beneath the directories */ud6/cdrg/refgas/mlodata* and */ud6/cdrg/refgas2/mlodata*. These files had names of the form *mloYYxxx_xxx* and header files (that contain working tank information), named *mlo_headers.YY* dating, where *YY*, *MM* and *xxx* indicate the 2-digit year, month and 3-digit day of year respectively. We copied these files to the second project computer *bluemoon* within directories under *mlo/Apc/Data*, while header files were stored in *mlo/Apc/input/whorf_headers.* We were unable to locate raw digital data files from data prior to 1992.

2.3 10 Minute Average Instrument Response Files

We were fortunately able to locate files containing 10 minute average voltage jogs, working tank concentrations on the *I* scale (see below) and recorder scale factors (RSFs) extending March 1958 through December 2004 in Tim Whorf's directories in *cdrgsun*. These files, named *mloYYb.yr* were found in the archive directory */mp0/whorf/mlo/dtaset*. A section of one of these files is shown in Table 1.

Table 1: Section of file mlo04a.yr containing 10 minute average voltage jog value, working tank concentration and RSF

```
1JA 4  1C  38B A  28B C  24B A  21B C18208 35500  5624
1JA 4  2C  24B A  24B C  30B A  32B C18208 35500  5623
1JA 4  3C    B A    B C    B A    B C18208 35500  5622
1JA 4  4C  29B A  27B C  28B A  26B C18208 35500  5621
1JA 4  5C  36B A  34B C  28B A  29B C18208 35500  5620
```

The files contain columns representing the day, month, year and hour of the measurement (Hawaii Standard Time), followed by four columns of a combined integer and 3 character string. Here the integer represents the 10 minute average jog and the string indicates which air line or calibration gas is represented by the data. The strings also give some indication of data quality. Other columns indicate the working tank index concentration and the instrument RSF.

There was some ambiguity as to whether the date and time listed on each line of the files represents the beginning or end of the hour period during which the 10 minute averages were recorded. To resolve this we were able to compare data in these files with that obtained from raw voltage files obtained directly from the APC. Such comparisons are possible for years since 2000 when both data sets are available. Times in the APC raw data files are known unambiguously and so we were able to confirm that the date and time of each row represent the hour following the last 10 minute period recorded in the line.

The files were copied to *bluemoon.ucsd.edu* and are now stored in the directory *mlo/Apc/Data/high_freq*. They were converted to more user-friendly, 10 minute jog files that are compatible with current workup functions by the *matlab* function *cdrgreadwhorfhighfreq.m*, These files are stored in *mlo/Apc/Data/high_freq/mloYYb.yr.csv*.

3 Reconstruction of the Record

Raw data obtained from Mauna Loa are currently processed using a set of *matlab* algorithms that have been developed from *Fortran* code previously used by Tim Whorf at Scripps. The data workup methodology is described in a separate report, Walker (2012). The workup procedure translates raw instrument voltage jogs to *I* and *J* scales that are linearly related to the instrument's voltage response, and then to non-linear, time-varying mole fraction *X* scale concentrations.

Using these 10 minute average instrument jog files, Section 2.3, as input, a *matlab* program *cdrgreconstructhighfreq.m* was written that calculates *I*, *J* and *X* values for each 10 minute data point. The *I* and *J* values are calculated simply as linear extrapolations of the reported working tank *I* based upon the response jog and RSF values that are reported in the voltage file. CO_2 mole fraction *X* values are calculated using a methodology copied from old *Fortran* file *mauna5monx03A_05.f*. This was the standard *Fortran* code last used by Tim Whorf to calculate *X* values from *J* values for the Mauna Loa instrument through September 2005. In our reconstruction, we worked with the last known version of this *Fortran* file.

3.1 Historic Adjustments to the Mauna Loa Record

The file *mauna5monx03A_05.f* applies time-varying calibration gas information to relate the linear *J* to non-linear *X* scales. It also applies a number of corrections to the *X* values over specific time periods that are peculiar to the Mauna Loa instrument.

The *mauna5monx03A_05.f* code also contains hard wired corrections, known as "period corrections" for 9 distinct time periods between Mar 1958 and May 1976, as shown in Table 2. They evidently account for known or suspected calibration offsets that were not fully accounted for by the working tank and RSF based workup.

Table 2: Stepwise Period Corrections applied to Mauna Loa carbon dioxide mole fractions

Period Start	Period End	Correction
14 March 1958	22 May 1964	+0.2
22 May 1964	11 Dec 1965	-0.21
11 Dec 1965	17 Jan 1969	+0.57
17 Jan 1969	04 Apr 1971	-0.16
04 Apr 1971	7 Dec 1973	-0.36
7 Dec 1973	26 Jan 1974	-0.02
26 Jan 1974	31 Jan 1975	-0.46
31 Jan 1975	9 Apr 1976	+0.32
9 Apr 1976	21 May 1976	+0.24

Time-varying spline corrections, apparently based upon observed differences between the flask and continuous record, are made for periods between 30 January 1975 and 20 September 1987. After 30 September 1987 a fixed flask offset of +0.12ppm is applied, extending these flask-based corrections to the present.

At the outset of this effort, the corrections implemented in *mauna5monx03A_05.f* had already been included in the *matlab* function *cdrgj2xmlo.m* that is currently used in the standard workup, e.g. to generate weekly and monthly averages. This function was used with the recovered APC data files described in section 2.3 to create 10 minute average *X* values in an identical fashion to that used for current Mauna Loa data. These 10 minute average reconstructed *X* files are stored in *mlo/Apc/conc/high_freq/YYYY/concYYYY_MMw.csv*, with files being written in the normal format used in the standard Mauna Loa workup for current data. This allows for further analysis of the new high frequency record to be conducted with standard workup code.

The next stages of data workup involve the selection of baseline air that is characteristic of the background atmosphere while excluding the impact of local sources of sinks of CO_2. Since the recovered APC data did not include indication of baseline air, it was necessary to determine baseline averages for the recovered data from scratch. The method used for background air identification is described in more detail in Walker (2012), but it essentially involves finding periods of 5 or more hours during which the CO_2 concentration is stable within the hour and from hour to hour within pre-set amounts. Once these baseline periods are identified daily, weekly, and monthly baseline values could be calculated, again using identical code to that used on a daily basis for the current Mauna Loa record.

In addition to the corrections incorporated automatically through the use of the *mauna5monx03A_05.f* code, we also incorporate additional period corrections as detailed in the next section.

4 Additional period corrections

In this section we describe the basis for additional period corrections that were not present in *mauna5monx03A_05.f*. The need for these corrections became clear on comparing the weekly and monthly baseline records calculated from reconstructed 10 minute data with pre-existing weekly and monthly records previously available through Tim Whorf's workup. The comparison of the weekly baseline records is shown in Figure 1.

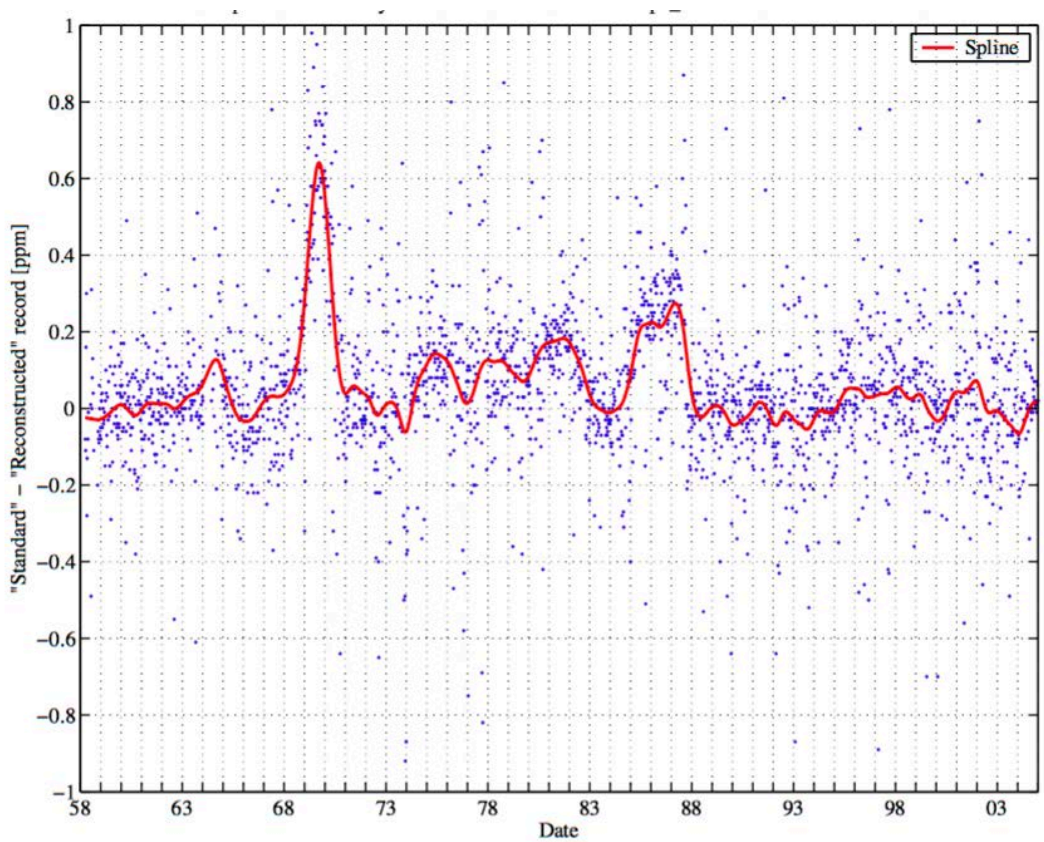

Figure 1: Difference in weekly average Mauna Loa carbon dioxide concentrations between the "Standard" and "Reconstructed" records

The blue dots in this figure represent the difference between individual weekly averages while the red line represents a smooth spline fit through the weekly differences.

Prior to 1967 and since late 1988, the differences between the two records are quite small, with a mean deviation close to zero and a standard deviation of 0.18 ppm. The deviations in these periods are quite likely mainly a result of differences caused by somewhat subjective baseline ("bluelining") selection.

There are however some periods with systematic offsets, most notably between 1968 and 1970, where the reconstructed weekly record is lower with a peak difference of about 0.6 ppm, and between 1984 and 1988, where the reconstructed record is again lower by about 0.25 ppm. Given the nature of these offsets, it is unlikely that the discrepancies were caused by the random differences expected to result from differences in baseline selection. It appears more likely that the cause was manual adjustments made to the Mauna Loa record by Tim Whorf that were not coded into the latest version of *mauna5monx03A_05.f*. As previously stated, this program was generally used by Tim Whorf to append new data to the weekly baseline record, but not to re-work the entire record from the beginning to end, as we are now attempting to do.

To shed further light on the issue of manual adjustments, we consulted successive versions of the weekly record that were saved by Tim Whorf on disk and numbered sequentially (e.g. *cndavNN.mlo,* where *NN* represents the ordered number of the archive). By comparing successive pairs of archived weekly concentration files, we were able to generate a history of the adjustments applied previously to the record. These files were located on *cdrgsun* beneath the directories */ws2/Sep15_vax/dua0/whorf* and */mp9/WhorfVax/dua0000907*.

Figure 2 through Figure 4 present the differences, in ppm, between subsequent pairs of archived Mauna Loa weekly baseline files. In these figures the title on each subpanel lists the names and file dates of the weekly baselines that have been compared. The legend within each subpanel indicates the date of the last data point contained in each of the 2 files.

Acknowledgements

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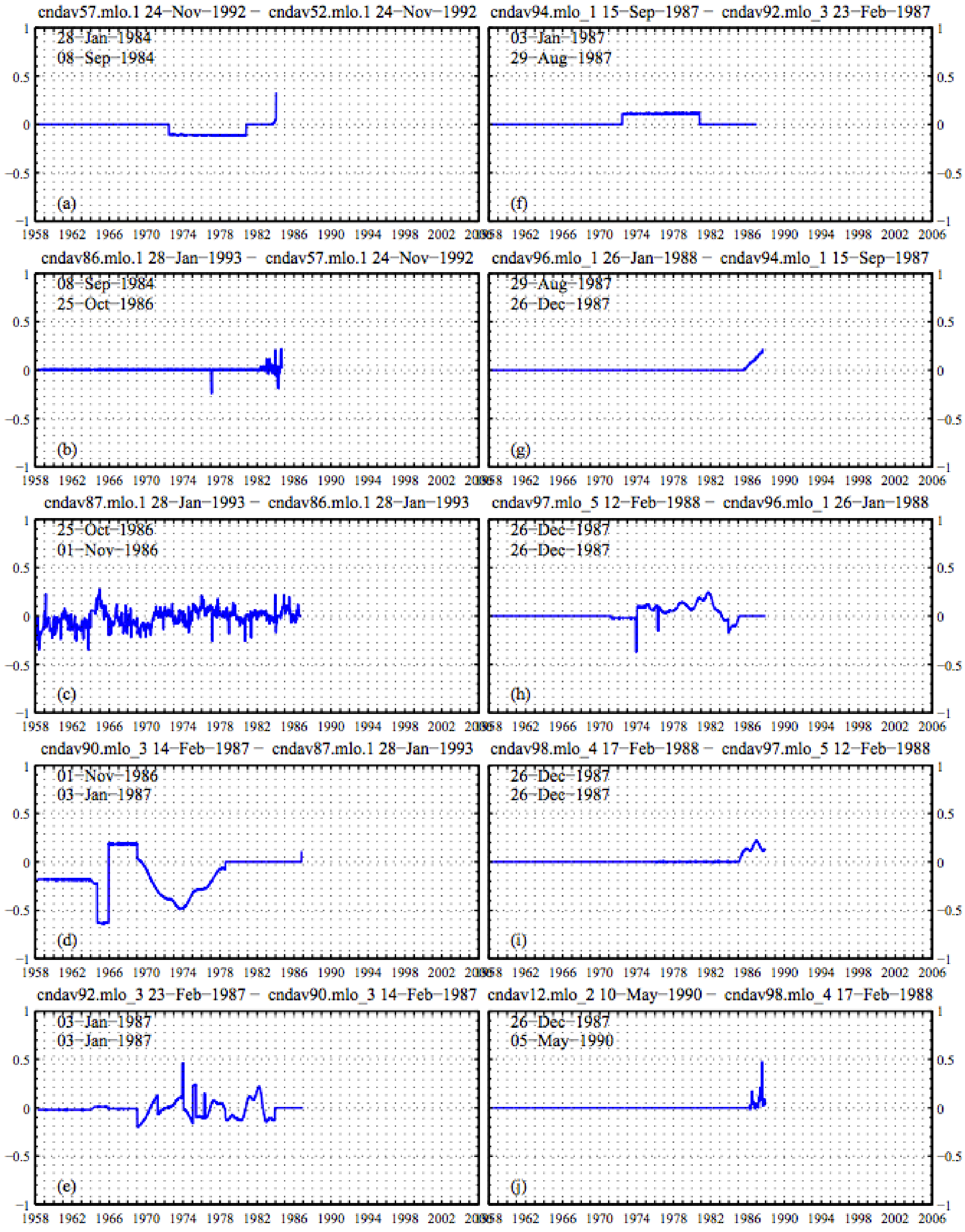

Figure 2: Difference between subsequent archives of the Mauna Loa weekly record indicating periods for which manual adjustments were made between January 1984 and May 1990

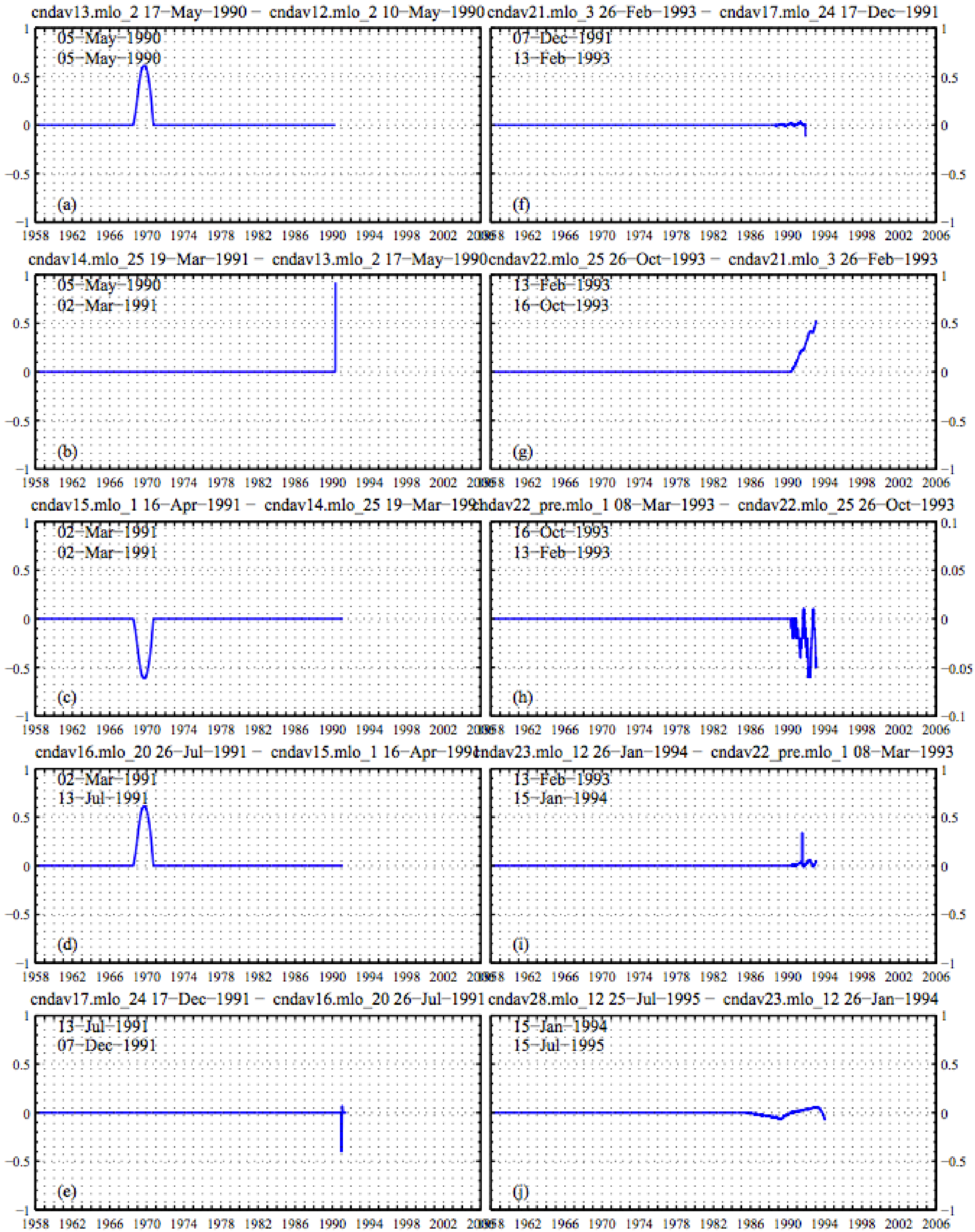

Figure 3: Difference between subsequent archives of the Mauna Loa weekly record indicating periods for which manual adjustments were made between May 1990 and July 1995

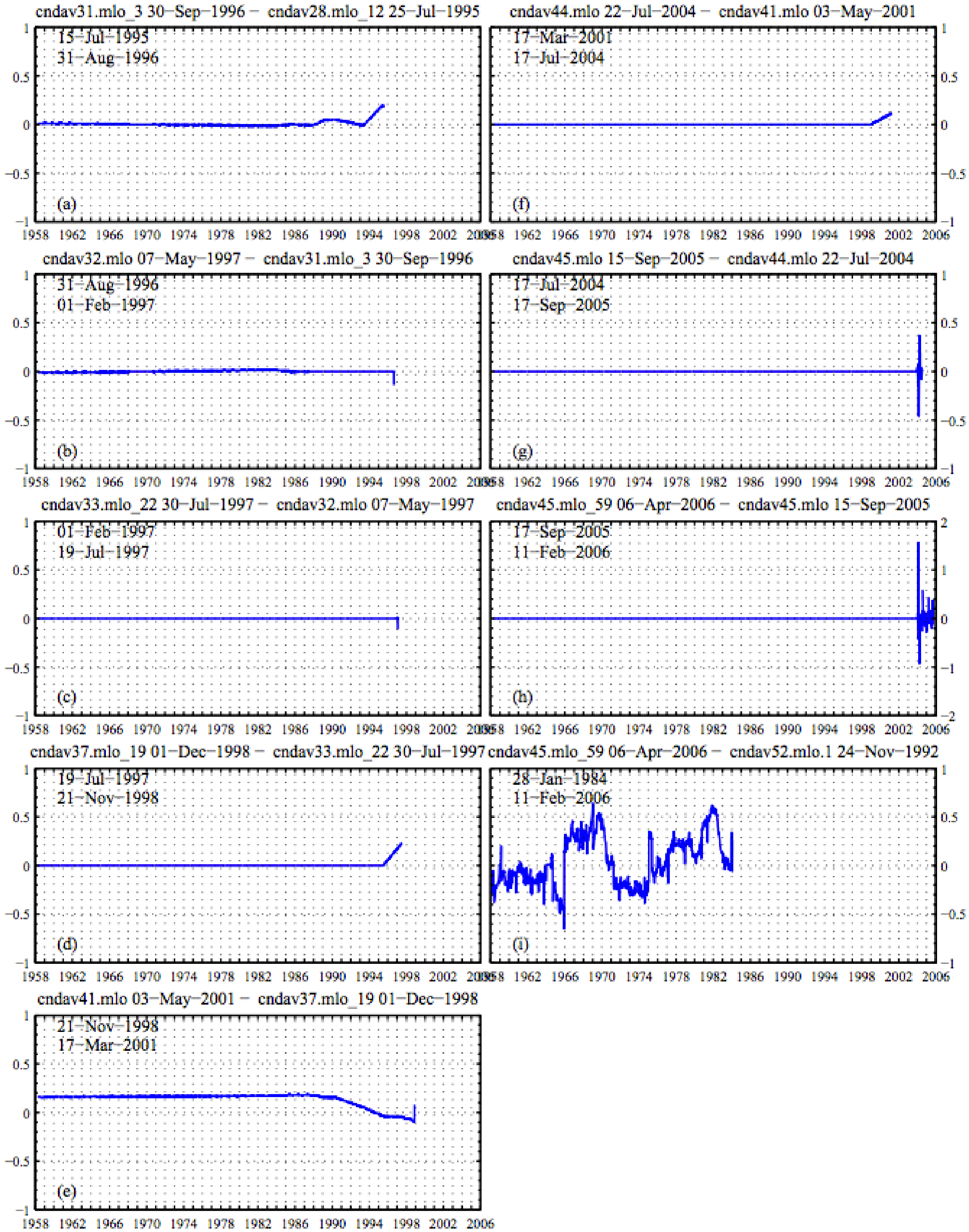

Figure 4: Difference between subsequent archives of the Mauna Loa weekly record indicating periods for which manual adjustments were made between July 1995 and March 2001

In Figure 3a, we observe that at around May 1990, the weekly averages incorporated a shift in carbon dioxide concentration between 1968 and 1970, with the carbon dioxide values adjusted upward by a maximum of about 0.6ppm. This adjustment was removed in March 1991, Figure 3c, and finally reapplied in July 1991, Figure 3d. This correction matches very closely the correction that would be required to bring the “Reconstructed” weekly record in line with the “Standard” in this same time period, Figure 1.

Through a laborious manual search, Steve Piper eventually located some hard copy notes describing adjustments made to the APC analyzer’s data to match flask measurements.

```
“Email from Steve Piper, 16 Aug 2011
Found a manila folder in whorf file cabinet labeled "SPO, MLO 1969 adjustments"

Contained a page from dif113_112.mlo annotated with "MLO correction from (MLO flask
minus analyzer) this file is cndav13.mlo - cndav12.mlohas offsets up to +.60 ppm for
period from 680720 to 700926 highest offsets centered about 690920 also a hand plot
dated 5/18/90 by T Whorf that shows curve for MLO flasks minus MLO analyzer with these
offsets stating to lift by 0.60 ppm”
```

This correction accounts for the largest offset between the “Reconstructed” and “Standard” Mauna Loa records, about 0.6ppm 1968-1970, in Figure 1.

Other significant differences between the two records occur for periods between Jan-1974 and Jun-1982 and between Feb-1985 and Oct-1987. Examination of the weekly archive comparison plots shows that several corrections have been made to the data over these time periods, although none match exactly the changes in concentration shown in Figure 1.

While corrections to the weekly record illustrated in Figure 2 through Figure 4 reveal that many corrections have been applied for time periods between years 1974 and 1988, none of these adjustments exactly matches the observed differences between the “Standard” and “Reconstructed” record as highlighted by the red line in Figure 1. To minimize the differences shown in Figure 1, we opted to add a new group of period corrections between May-1968 and Oct-1987. These new corrections vary in a stepwise fashion over time, with the exception of the Gaussian correction period from May-1968 to Jan-1971 described previously. The new period corrections are listed in Table 3.

Table 3: Adjustment made to the "Reconstructed" record to bring it in line with the "Standard". Values were obtained by sampling the smoothed spline fit between the weekly records, red line in Figure 1, at a 3 month time period.

01-May-1968	+0.00	01-Jul-1968	+0.06
01-Jul-1968	+0.06	01-Sep-1968	+0.13
01-Sep-1968	+0.13	01-Nov-1968	+0.20
01-Nov-1968	+0.20	01-Jan-1969	+0.30
01-Jan-1969	+0.30	01-Mar-1969	+0.40
01-Mar-1969	+0.40	01-May-1969	+0.50
01-May-1969	+0.50	01-Jul-1969	+0.59
01-Jul-1969	+0.59	01-Sep-1969	+0.63
01-Sep-1969	+0.63	01-Nov-1969	+0.63
01-Nov-1969	+0.63	01-Jan-1970	+0.55
01-Jan-1970	+0.55	01-Mar-1970	+0.44
01-Mar-1970	+0.44	01-May-1970	+0.32
01-May-1970	+0.32	01-Jul-1970	+0.20
01-Jul-1970	+0.20	01-Sep-1970	+0.12
01-Sep-1970	+0.12	01-Nov-1970	+0.05
01-Nov-1970	+0.05	01-Jan-1971	+0.00
01-Jan-1971	+0.00	01-Dec-1973	+0.00
01-Dec-1973	-0.40	24-Jan-1974	-0.40
24-Jan-1974	+0.08	01-Apr-1976	+0.08
01-Apr-1976	-0.20	15-May-1976	-0.20
15-May-1976	+0.08	01-Oct-1980	+0.08
01-Oct-1980	+0.17	01-Jun-1982	+0.17
01-Jun-1982	+0.00	01-Feb-1985	+0.00
01-Feb-1985	+0.25	01-Oct-1987	+0.25
01-Oct-1987	+0.00	01-Jan-2012	+0.00

These new period corrections are plotted in Figure 5 as a function of time.

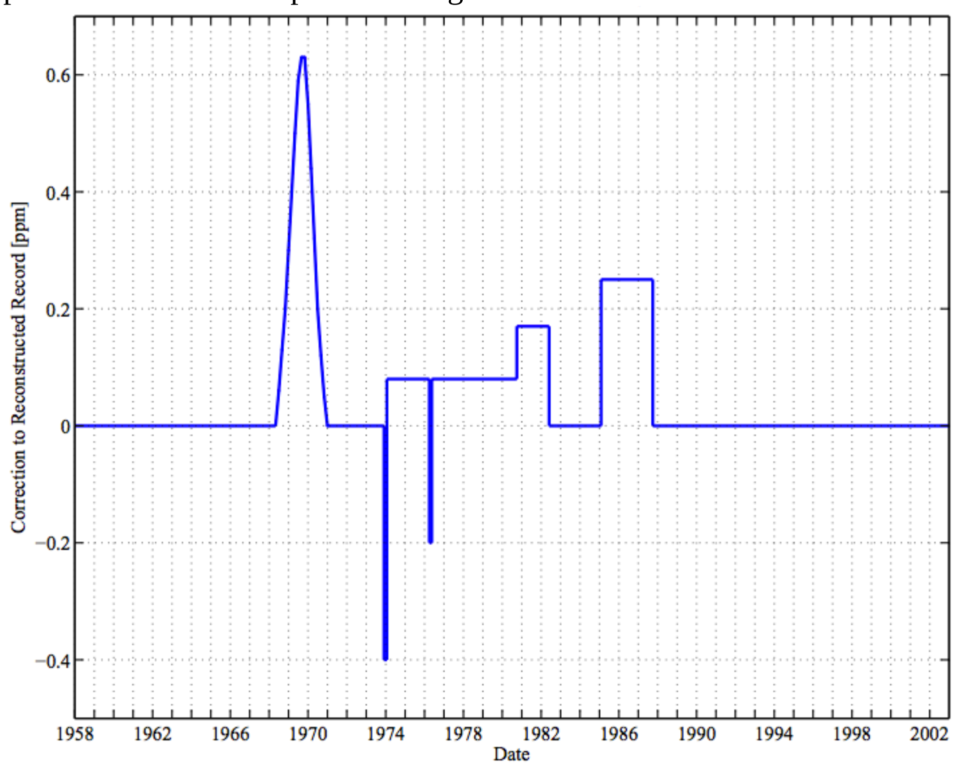

Figure 5: New period corrections applied to the "Reconstructed" record to bring it in line with the "Standard"

Corrections are then made to the “Reconstructed” high frequency and daily records by linearly interpolating in time the corrections list in Table 3. This correction to *X* values is performed in the function *cdrgj2xmlo.m*, as an additional adjustment performed after period and other corrections.

The resulting difference between the adjusted, “Reconstructed” and “Standard” weekly record is shown in Figure 6.

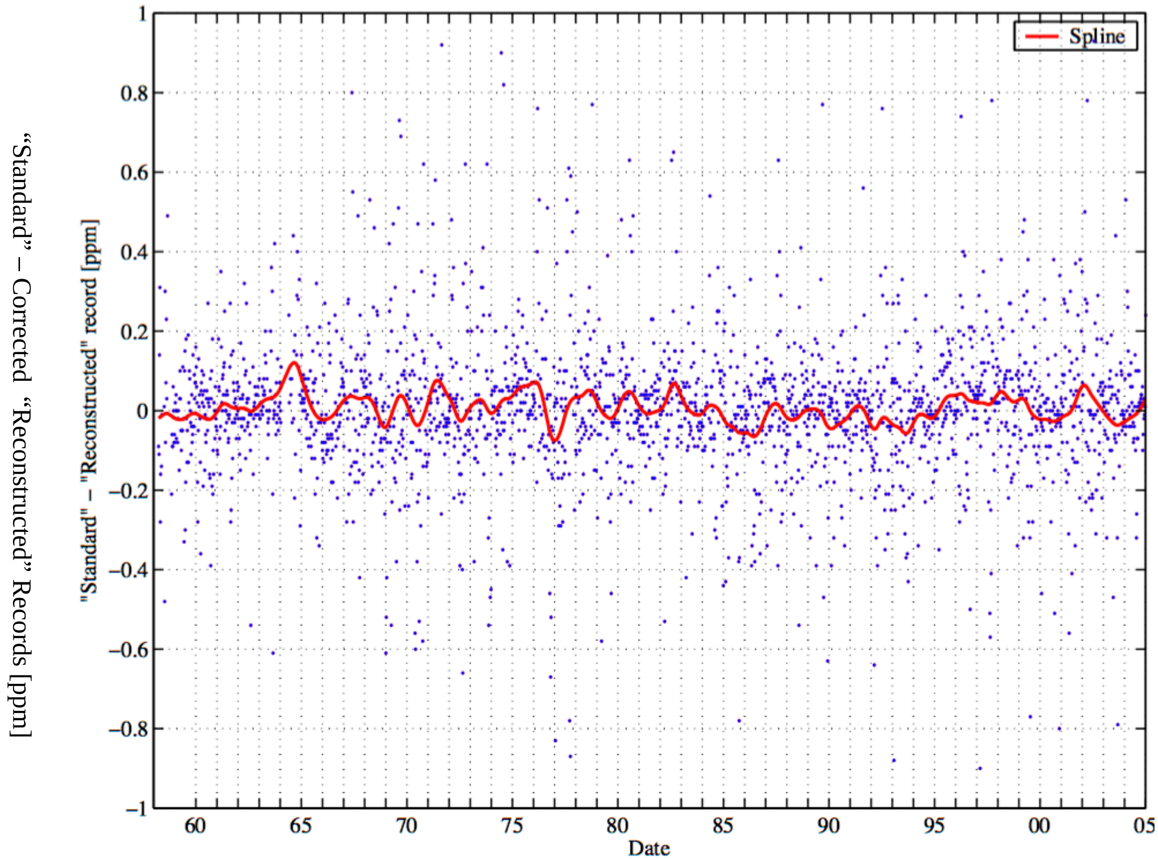

Figure 6: Difference in weekly average carbon dioxide concentrations between the Corrected "Reconstructed" and "Standard" records for Mauna Loa

The standard deviation of the difference between these two weekly records is 0.17 ppm.

The differences between the adjusted “Reconstructed” and “Standard” monthly averages are presented in Figure 7. The standard deviation between these 2 records is 0.11 ppm.

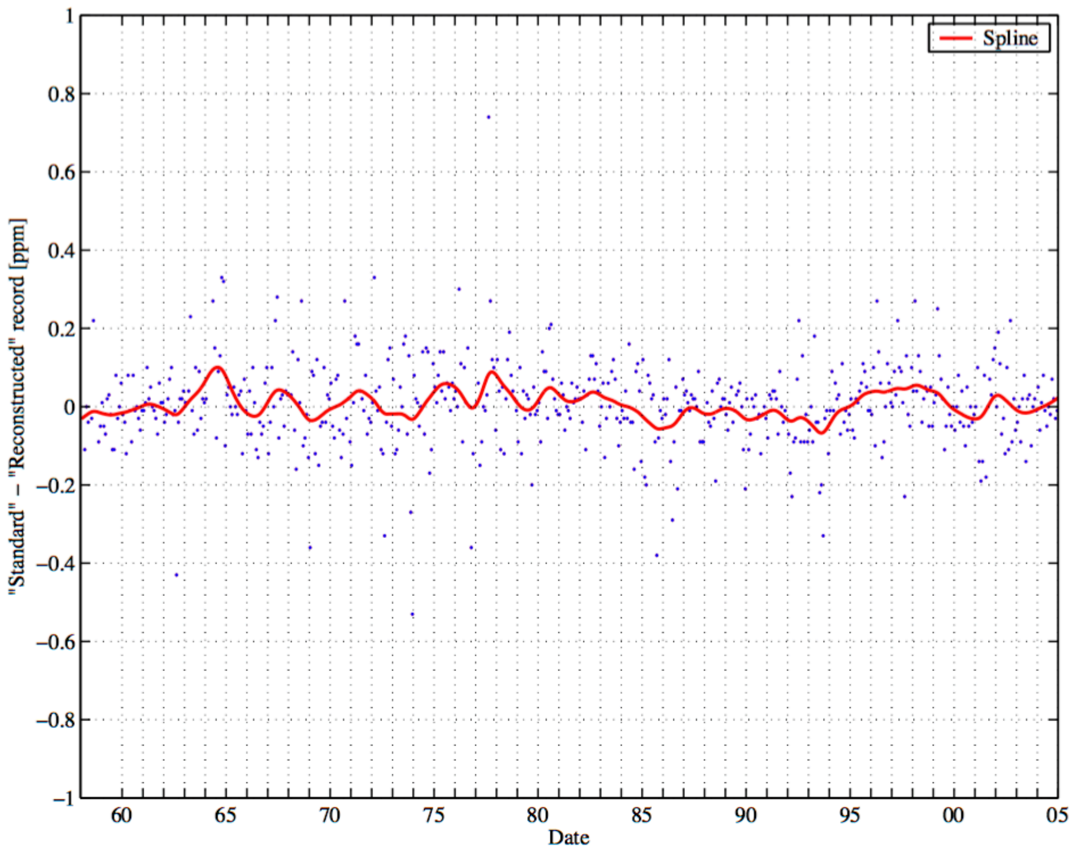

Figure 7: Difference in monthly average carbon dioxide concentrations between the adjusted "Reconstructed" and "Standard" records for Mauna Loa

5 List of Files

The analysis described above has allowed us to re-create both a 10-minute averaged and daily baseline record of CO_2 concentrations at Mauna Loa from March 1958 through December 2004. While these data have been adjusted to better match the standard weekly record over long time scales, they still exhibit some small quasi-random deviations from the standard weekly record. Because of this we recommend that these files be used for analyses of CO_2 on time scales of hours to days.

5.1 10 Minute Average Data File

The high frequency data file, containing CO2 concentrations averaged over 10 minute windows is named mlo_10min.csv. The first 5 columns contain the date in year, month, day, hour, minute format, while the 6th column is the 10 minute averaged CO2 concentration.

5.2 Daily Baseline Data File

The daily baseline concentrations are included in the file mlo_dailybase.csv
The first 3 columns represent the date in year, month and day format.
The 4th column is the daily baseline CO_2 concentration
The 5th column represents the number of hourly averaged points that were included in the daily baseline
The 6th column is a flag indicating the CO_2 calibration scale.

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