Griggs, JA., & Harries, JE. (2004). Comparison of spectrally resolved outgoing longwave data between 1970 and present. *Proceedings of SPIE*, 5543, 164 - 174. <https://doi.org/10.1117/12.556803>

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Comparison of spectrally resolved outgoing longwave data between 1970 and present

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ABSTRACT

Measurements of spectrally resolved outgoing longwave radiation allows signatures of many aspects of greenhouse warming to be distinguished without the need to amalgamate information from multiple measurements, allowing direct interpretation of the error characteristics. Here, data from three instruments measuring the spectrally resolved outgoing longwave radiation from satellites orbiting in 1970, 1997 and 2003 are compared. The data are calibrated to remove the effects of differing resolutions and fields of view so that a direct comparison can be made. Comparisons are made of the average spectrum of clear sky outgoing longwave radiation over the oceans in the months of April, May and June. Difference spectra are compared to simulations created using the known changes in greenhouse gases such as CH₄, CO₂ and O₃ over the time period. This provides direct evidence for significant changes in the greenhouse gases over the last 34 years, consistent with concerns over the changes in radiative forcing of the climate.

Keywords: outgoing longwave radiation, spectrum, greenhouse gases, simulation, infrared

1. INTRODUCTION

The Earth's climate system has been studied in detail and strong evidence has been found linking surface temperature changes and greenhouse gas concentrations.^{1,2} This system is complicated by feedback processes, the most notable of these being those involving the hydrological cycle. The spectrum of outgoing longwave radiation (OLR) can be used to detect changes in the greenhouse effect, due to the separation of signatures from different gases. The spectrally resolved OLR is a measure of the cooling to space of the planet's surface and atmosphere due to absorption and emission at characteristic wavelengths.

This study builds on the work of Harries et al³ and analyzes the differences seen between spectrally resolved OLR measured in 1970, 1997 and 2003. Changes are detected in the spectrum which, through the use of a band model, are attributed to known long term changes in greenhouse gases. Ideally, a long time period dataset of spectrally resolved OLR would be used. As no such dataset exists, the longest currently available being 2 years of AIRS⁴ data, three shorter datasets are calibrated to the same specifications and compared. In effect, snapshots of the atmosphere at three different times are compared.

2. DATA

Data detailing the spectrally resolved OLR are sparse and comes from only a small number of experiments. The data used in this study were recorded by the IRIS,^{5,6} IMG^{7,8} and AIRS⁴ instruments. Additionally data from HIS,^{9,10} ARIES,¹¹ SI-1^{12,13} and SI-2¹⁴ and 16T¹⁵ are available but are precluded from the study due to the specific characteristics of these datasets. The data characteristics required for detection of long term changes are: sufficient spectral resolution for gas absorption bands to be seen; and adequate temporal and spatial sampling to average out synoptic variability. Aircraft data such as ARIES and HIS fail to meet the temporal and spatial sampling requirements for our purposes. The SI-1 and SI-2 satellite data suffered from similar sampling issues. The spectral resolution of 16T, the first spectrally resolving instrument to be spaceborne, was insufficient for spectral features to be distinguished.

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Table 1. Comparison of the properties of the IRIS, IMG and AIRS instruments.

Characteristic	IRIS	IMG	AIRS
Spectral Range (cm^{-1})	400-1600	600-3030	650-2700
Spatial Field of View	95x95km	8kmx8km	13.5kmx13.5km (nadir) 41kmx22.4km (zenith)
Spectral Resolution (cm^{-1})	2.8	0.10-0.25	0.4-1.0
Noise equivalent spectral radiance ($\text{mW m}^{-2}\text{sr}^{-1}$ per cm^{-1})	± 0.23	$\pm(0.31-0.6)$	$\pm(0.01-0.8)$

Some properties of the IRIS, IMG and AIRS instruments are listed in table 1 with the details presented below. The main time period of overlapping data available is in the months of April, May and June so this is the time period used. The spectral range used is $700\text{-}1400\text{cm}^{-1}$ which is the largest available when considering the high noise at both low IMG wavenumbers and high IRIS wavenumbers.

2.1. IRIS

The oldest instrument used in this study is the IRIS^{5,6} (InfraRed Interferometric Spectrometer) instrument. This was a series of instruments launched by NASA in the late 1960's, 1970's and early 1980's. IRIS-D was the only one of this series which was both Earth orbiting and provided a long time series and so this is the instrument used in this study. IRIS-D (subsequently referred to as IRIS) flew on the NASA Nimbus 4 satellite which was launched in April 1970 into a 1100km altitude sun-synchronous polar orbit. It recorded data until January 1971 when it was switched off having fulfilled its design brief. IRIS was a Fourier Transform Spectrometer and for its time was considered highly adventurous in its aims. It recorded spectra between 400cm^{-1} and 1600cm^{-1} but wavenumbers over 1400cm^{-1} suffer from high noise. Its field of view allowed it to record spectra with a ground footprint of 95km diameter. The IRIS instrument had a path length of 0.36cm giving a spectral resolution of 1.4cm^{-1} which was apodized using a Hamming Window function to a resolution of 2.8cm^{-1} . All aspects of the design of IRIS represented large leap in the design of FTS particularly the high resolution and wide spectral range combined with an instrument small, light and resilient enough to be spaceborne.

2.2. IMG

IMG^{7,8} (Interferometric Monitor for Greenhouse Gases) was a much more advanced Fourier Transform Spectrometer which was launched in August 1996 onboard the ADEOS satellite by the Japanese Space Agency. It recorded data between November 1996 and June 1997 when operations ceased as a result of the break up of the solar paddle. IMG was developed to provide continuous coverage of the spatial distribution of the greenhouse gases and to measure detailed profiles of water vapour and temperature. To do this IMG required spectral resolution of 0.1cm^{-1} and a spectral range of $600\text{-}3030\text{cm}^{-1}$. To achieve an apodized spectral resolution of 0.1cm^{-1} , the mirror in the interferometer must travel a distance of 10cm with optical alignment correct to within angles of 0.0001° .⁷ To ensure that the smooth movement of the mirror and optical alignment were maintained, the mirror movement system was designed with a state of the art magnetic suspension system, the first time such a system was used in a spaceborne instrument. As the instrument was required to have a wide spectral range, one detector could cover not the entire range. Three different detectors were required, each recording a different part of the spectrum. The only detector used in this study recorded between 600 and 2000cm^{-1} . Data are only usable at greater than 700cm^{-1} due to noise in the lower wavenumber section of the spectrum. ADEOS orbited in a 797km altitude polar sun-synchronous orbit giving a square ground footprint of the instrument of 8km by 8km. Except for a 10 day period between 1st and 10th April when the instrument recorded continuously, IMG operated in a 4 day on, 10 day off cycle. At the start of routine operations in November 1996, it was discovered that the moving mirror alignment system was sticking randomly causing unacceptable degradation in the quality of the spectrum being recorded at the time. Tests were ongoing to try and correct the gain system to compensate

for this effect when the satellite failed. The problems caused 85% of the spectra recorded to be discarded as being unacceptably noisy.

2.3. AIRS

The Atmospheric Infrared Sounder (AIRS)⁴ was launched on the EOS-Aqua satellite by NASA in May 2002. Aqua orbits on a 705km polar sun-synchronous orbit giving twice daily global coverage. AIRS is a grating spectrometer rather than the Fourier Transform Spectrometer design of the previous two instruments. It uses this design to achieve similar resolution and spectral range to IMG but records at a much greater speed, enabling far greater coverage than that achieved by either IRIS or IMG. As an example, AIRS recorded 96 spectra including its calibration recordings in 2.667 seconds whereas IMG recorded 8 spectra including its calibration recordings in 110 seconds. The spectral range of AIRS is from 650cm^{-1} to 2700cm^{-1} measured by 2378 channels which are separated into 17 modules of detectors which do not overlap, resulting in discontinuous spectral coverage. The consequences of these spectral gaps are discussed in section 3.1. The detectors all have at least two times redundancy but we still see 238 channels which either have failed or are too noisy to use in the 700cm^{-1} to 1400cm^{-1} region. The spectral resolution of a grating spectrometer is controlled by the aperture of the detectors on the focal plane array of the instrument. The detectors in AIRS are all $10\mu\text{m}$ by $10\mu\text{m}$ squares with $10\mu\text{m}$ gaps between each detector and its nearest neighbour. This gives a resolution of between 0.4cm^{-1} and 1cm^{-1} . The recording geometry of AIRS is very different to that of either of the other two instruments. IRIS and IMG both view nadir through a fixed aperture and image compensation mirror. To enhance the spatial coverage and to take advantage of its speed, AIRS scans to $\pm 49.5^\circ$ cross track as the satellite moves forwards taking 90 spectra each with an instantaneous field of view of 1.1° . This results in a ground footprint of 13.5km diameter at nadir but closer to 41km by 22.4km at the largest zenith angles.

3. COMPARISON METHOD

3.1. Differing Instrument Characteristics

To compare the spectra of the three instruments, it is necessary to degrade IMG and AIRS to the poorer specifications of IRIS. The first difference which must be accounted for is the difference in spectral resolution between the three datasets. The spectral resolution of the IMG data were initially reduced to that of AIRS by multiplying the interferogram by an appropriately sized Hamming window. The AIRS and AIRS resolution IMG data can not be reduced to the resolution of IRIS by multiplying their interferogram by an appropriately sized Hamming window due to the gaps in the AIRS spectrum and so their resolutions are reduced by convolving the spectrum with the fourier transform of the Hamming window. The resolution reduction process uses a variable sized Hamming window to ensure that the resolution of the data is correct across the entire spectrum as the AIRS data resolution varies greatly. This process ensures that all spectral features are the same width in all datasets. The other major difference in the instrument characteristics which must be accounted for is the differences in field of view. In a Fourier Transform Spectrometer, the effect of the finite field of view is to broaden features and shift them to lower wavenumbers. The effect of the broadening is taken into account concurrently with the resolution degradation. Grating spectrometers do not introduce a shift due to the finite field of view but a shift is seen in the AIRS data due to movement in the focal plane array. The shifting to lower wavenumber is taken into account by shifting the IMG and AIRS data along to the IRIS shifted position.

3.2. Identification of Cloud Free Spectra

To reduce the amount of variability seen and thus aid interpretation, only cloud free spectra are used. Brindley and Harries¹⁶ discuss the use of all sky data to make similar studies but concludes that the IRIS and IMG datasets only have adequate sampling to study the clear sky case. A two stage process is used which is specifically designed to identify the properties of a clear sky spectrum. This removes spectra contaminated by cloud from the dataset and also removes spectra contaminated by other effects, such as dust storms or high instrument noise. In the first stage, the equivalent blackbody brightness temperature (subsequently referred to as brightness temperature) in the clearest part of the spectrum (1126.32cm^{-1}) is compared to the known sea surface temperature from the NCEP reanalysis dataset.¹⁷ A threshold to define the difference accepted as clear is determined by looking at the maximum difference in a simulated clear sky spectrum of the atmosphere created using a band model and the

Table 2. Number of spectra for IRIS, IMG and AIRS before and after removing cloud.

	IRIS	IMG	AIRS
Number before removing cloud	3662	420	273977
Number after removing cloud	25	138	37834

NCEP water vapour and temperature fields. Standard deviations are examined to ensure that no signature of cloud, such as high variability in the window, remains. The second stage is designed to remove thin cirrus from the dataset and uses the method of Ackerman et al.¹⁸ The effect of cirrus cloud on the spectrum is to introduce a tilt in the atmospheric window so the brightness temperature difference between 913.57cm^{-1} and 1250.08cm^{-1} is compared to an acceptance threshold. A high difference indicates a high tilt across the atmospheric window indicative of cirrus cloud in the field of view of the instrument when it was recording. The threshold is chosen by the same method as in the first stage.

Differences are examined between spectra in the Central Pacific region (10°N - 10°S , 180°W - 230°W) as this is one of the better sampled regions in all three datasets. The number of spectra before and after removing cloud in each dataset is listed in table 2. A larger proportion of spectra are removed in the case of IRIS than AIRS and IMG respectively, due to the increasing size of their fields of view. The larger the field of view, the more likely it is that it contains cloud. The spatial sampling of the spectra, after cloudy spectra have been removed, is as shown in Fig. 1. The sampling irregularities in IMG are visible in (d) reflecting the 4 day on, 10 day off instrument power sequence and the removal of high numbers of noisy spectra. The sampling of AIRS is seen to be very good. The gap in temporal sampling between 26th May and 12th June is due to the data being corrupted at NASA and not having been reprocessed at the time of writing. Overall, the sampling of all three datasets is reasonable. Additional evidence that the sampling is adequate is derived from the fact that the standard deviation of all datasets are very similar. If either the IRIS or IMG data sampling were insufficient, then the standard deviation would be likely to be a different magnitude as the complete variability of the atmosphere over the three month time period would not be captured.

4. OBSERVATIONAL SPECTRAL OLR DIFFERENCES

Average spectra and the differences between them are shown in Fig. 2. The average spectrum for each instrument for the Central Pacific region is shown in Fig. 2(a). Inspection of individual features in Fig. 2(a) shows consistent width and wavenumber for average spectrum from all instruments indicating that the resolution and field of view corrections have been correctly applied. Figure 2(b) shows the differences between the average spectra shown in Fig. 2(a). The lower line is the 1997 IMG spectrum minus the 1970 IRIS spectrum; the middle line is the 2003 AIRS spectrum minus the 1970 IRIS spectrum; and the upper line is the 2003 AIRS spectrum minus the 1997 IMG spectrum. A negative going brightness temperature difference is observed in the CO_2 band around 700cm^{-1} in the 1997-1970 and the 2003-1970 difference spectra. A signature is observed in the ozone band around 1060cm^{-1} in all difference spectra. A strongly negative going brightness temperature difference in the methane band at 1304cm^{-1} is observed for the 1997-1970 and 2003-1970 difference spectra with a difference in the opposite sense seen in the 2003-1997 difference spectrum, indicating that the methane concentration in 2003 may be less than that observed in 1997, supporting the results of Dlugokencky et al.¹⁹ Studies have been performed for numerous geographic locations and the major features in the difference spectra appear in all cases studied. In Fig. 2(c), the difference spectra observed in the quasi-global region (60°N - 60°S , 0°W - 360°W) are plotted. The similarity between the differences in the Central Pacific and the quasi-global regions highlights the data quality as different number of spectra are averaged in the two cases. To attribute the causes of the shape of the difference spectra seen, simulations of the spectra have been created.

5. SIMULATED SPECTRAL OLR DIFFERENCES

Spectra were simulated using the MODTRAN²⁰ version 3 band model running at a resolution of 1cm^{-1} . The resolution of these spectra are then reduced using a Hamming window as performed on the observed spectra.

Figure 1. (a), (c) and (e) The spatial sampling and (b), (d) and (f) the temporal sampling of the IRIS, IMG and AIRS instruments in the Central Pacific region in April, May and June.

MODTRAN was run with user defined profiles constructed using a number of gas concentration datasets. In Fig. 3 the differences between the simulations of the observed spectrally resolved OLR representative of 1970, 1997 and 2003 are presented from three different gas concentration datasets. In each simulation, profiles are defined for temperature, water vapour, CO_2 , CH_4 , O_3 , N_2O , CFC11 and CFC12. Figures 3(a) and (b) show differences between spectra simulated using averaged reanalysis data. Figure 3(a) used temperature and water vapour (calculated from the specific humidity) profiles from the NCEP reanalysis dataset.¹⁷ The NCEP reanalysis skin temperature is used for the sea surface temperature. Ozone profiles are taken from the STOCHEM chemical transport model forced by realistic emissions scenarios in the troposphere and using measured trends in the stratosphere.²¹ For 2003, these model runs were not available so the 1997 profile is scaled by the TOMS^{22, 23} total column abundance. Concentrations of the other gases are taken from the Climate Monitoring and Diagnostics Laboratory's flask measurement system at the closest available station.^{19, 24, 25} These concentrations are used to scale the standard US atmospheric profiles²⁶ for the correct gases. Figure 3(b) used temperature and water vapour profiles from ECMWF analyses.^{27, 28} (Data from ERA-40 was used for 1970 and 1997 simulations and data from the operational analysis was used for 2003).

The NCEP and ECMWF simulations (Fig. 3(a) and (b)) give a reasonable representation of the observations (Fig. 2(b)). There are however a number of deficiencies. The NCEP simulated differences and the observations

Figure 2. (a) The average spectra for each time period in the Central Pacific. IRIS plotted as solid line, IMG as dotted line and AIRS as dashed line. (b) The differences between the average spectra in the Central Pacific. Lower line, 1997 IMG spectrum minus 1970 IRIS spectrum offset by -10K, middle line, 2003 AIRS spectrum minus 1970 IRIS spectrum offset by -5K and upper line, 2003 AIRS spectrum minus 1997 IMG spectrum. The offsets are applied for clarity. (c) as (b) but for the quasi global (60°N-60°S, 0°W-360°W) region.

both show a brightness temperature difference in the window which is slightly positive whereas the ECMWF simulated difference is negative. The cause of this in both the NCEP and ECMWF simulations is that the window temperature, and by implication the sea surface temperature, is too low. In the case of the 1970 ECMWF simulation, the window temperature is even more erroneously low than the other simulations causing the negative going brightness temperature difference. In both cases, the brightness temperature difference in the 1200-1400 cm^{-1} region of water vapour absorption is sloping toward larger values at higher wavenumbers which is in contrast to the slope towards smaller values seen in the observed differences. The reason for this error, which is most pronounced in the 2003-1970 spectrum, appears to be due to poorly understood temperature structure in the mid to upper troposphere. In the case of the 2003 simulations, the temperature and water vapour concentration structures in the mid and upper troposphere mean that the simulated spectrum has a very similar shape to that observed. In the case of the 1970 simulations, and to a lesser extent the 1997 simulations, the water vapour concentration and temperature profiles ensure that the depth of the absorption lines are very close to the depths seen but the background temperature is too hot, causing the shape of the brightness temperature difference in the 1200-1400 cm^{-1} region not to match that observed.

Figure 3. (a) Simulated differences using NCEP water vapour and temperature. Lower line, 1997 spectrum minus 1970 spectrum offset by -10K, middle line, 2003 spectrum minus 1970 spectrum offset by -5K and upper line, 2003 spectrum minus 1997 spectrum. (b) as (a) but using ECMWF water vapour and temperature. (c) as (a) but using profiles which create a simulated difference with most agreement with the observed differences.

The effects of methane are modelled using the CMDL ground concentration and standard atmosphere profile and hence both simulations will show the same effects. The modelled CH_4 band is not as deep and is wider than the observed. The positive-going brightness temperature difference seen in the 2003-1997 observed spectrum is not seen. The region of absorption by ozone is represented reasonably well, although the errors in the window temperature differences mean that the background temperature from which the signature of ozone is seen is incorrect. The most noticeable difference between the observations and the simulations is the lack of small scale variability in the simulations, especially in the window region. A number of causes of this have been investigated and are discussed in section 6.

To attempt to address some of the deficiencies in the simulations produced using the ECMWF and NCEP datasets, a third simulation (hereafter called simulation 3) has been produced and the results of this are plotted in figure 3(c). Here, we use gas profiles to create a brightness temperature difference spectrum which is as close to the observed differences as possible. The gas profiles used are consistently within the range of profiles available for a variety of sources. Using the profiles from ECMWF, NCEP and CMDL as above as well as ozonesondes,²⁹ HALOE,³⁰ ATSR,³¹ GOME,³² GOES³³ and SAGE³⁴ data, a maximum and minimum measured profile for

each gas at each time are defined. The simulation is then allowed to input any physically reasonable profile between the maximum and minimum measured gas concentration to find the profile which produces a modelled spectrum best reproducing the observed spectrum. The most noticeable improvements in the ability of this simulation to match the observations is in the overall shape of the 1200-1400cm⁻¹ region, the improved shape of the CO₂ band, the fine detail of the shape of the window differences and the distribution of CH₄ brightness temperature difference features. We will discuss the mechanism for each of these improvements in turn.

As was the case for the ECMWF and NCEP simulations, the depth of the water vapour absorption lines in the 1200-1400cm⁻¹ region are correct. In simulation 3 the background temperature of the spectra in this region is the same as the observed whereas it was hotter in the ECMWF and NCEP simulations. The effect on the differences is that the general shape of the region is closer to that seen in the observed differences. The depth of the negative going brightness temperature differences in this region are also closer to those seen in the observations, indicating that the depths of the absorption features modelled is closer to those observed in the average spectrum for each instrument. The major difference still observed in this region is now the seemingly smoother nature of the simulation than the observed differences. The observations produce a more ‘spiky’ difference and we have been unable to reproduce this by changing the input gas profiles in the simulations. Noise as a cause of this difference is discussed in section 6.

The differences in the CO₂ band show much sharper features in this simulation, better representing the observations, than the very smooth differences produced in the NCEP and ECMWF simulations. This improvement was achieved by changing the upper atmosphere temperature profile rather than the CO₂ profile. The fine details of the shape of the window brightness temperature difference in this simulation are made to look more like the observations by fine tuning of the sea surface temperature, and the temperature and water vapour concentration at 1000hPa.

Significant differences in the methane band are seen between this ‘tuned’ simulation, the NCEP and ECMWF simulations and the observational differences. This simulation improves upon the NCEP and ECMWF simulations in that the proportions of brightness temperature difference seen in the case of each difference spectra is correct ie. the 1997-1970 difference is the largest, the 2003-1970 difference is slightly smaller and the 2003-1997 difference is in the opposite sense. The brightness temperature differences in this simulation, whilst being correctly proportioned, are not the same size as those seen in the observational data. No combination of water vapour concentration, temperature and methane concentration using the data available could reproduce the size of the differences observed. Analysing the cause in more depth, we find that the 1970 simulation produces a methane band which is very similar in size and shape to that observed. In the case of the 1997 simulation we are unable to produce a band which is deep enough without increasing the methane concentration to around 45% more methane than the gas concentration measurements would suggest. Similarly in the case of 2003, 32% more methane is required.

Overall the most noticeable difference between the simulation and the observational difference spectra is the smoothness of the simulations when compared to the observations. There could be a number of reasons for this. Firstly, problems in the calibration of the three observational datasets to each other may cause this effect. This was investigated by changing the smoothing on the simulations and failed to produce the fluctuations seen without producing obvious misalignments when the spectra are compared which are not seen in the observations. The most likely cause of this effect now that calibration problems have been discounted is noise in the observational data.

6. EFFECTS OF NOISE EQUIVALENT RADIANCE

Noise is present in all spectra due to multiple noise sources in the instruments such as photon noise, detector noise, source noise and digitizing noise. The amplitude of the noise equivalent spectral radiance for each instrument is given in table 1. As random noise and averaged spectra are being compared, the noise on the average spectra will scale as $1/\sqrt{N}$ where N is the number of spectra in the average. Knowing a profile of the noise equivalent radiance spectrum for each instrument, it can be smoothed to the IRIS resolution and the size of this effect on the difference spectra can be calculated. In figure 4, the same simulation as in figure 3(c) is presented including an estimate of the size of the effect that the noise equivalent radiance would have had on the observed spectrum.

Figure 4. Simulation of the observed difference spectra, as seen in figure 3(c), including the effects of the corresponding instruments’ noise equivalent brightness temperature. The thickness of the line indicates the range of the combined noise equivalent brightness temperatures.

The fluctuations in the observed spectra are within the range of the noise except for features in the methane band where the differences are significantly larger than the modelled noise levels.

7. CONCLUSIONS

Calibration has been performed so that three datasets of spectrally resolved OLR recorded in 1970, 1997 and 2003 can be directly compared. Under clear sky, ocean background conditions for the months of April, May and June, observation of the difference in the spectrally resolved OLR are obtained which show features in the absorption bands of the major greenhouse gases in the atmosphere. Simulation created using the NCEP reanalysis and ECMWF analyses show that these datasets do not capture the same variations seen in the OLR observations. Simulations created using profiles merged from a number of datasets show that we can explain the differences seen in the CO₂ and ozone bands by the known changes in the those gases over the last 34 years. Large changes are seen in the methane band potentially attributable to long term changes in the methane concentration but importantly not consistent with the admittedly sparse independent concentration measurements available.

ACKNOWLEDGMENTS

This work was supported by a NERC studentship. We thank L. Chen and R. Goody for providing access to the IRIS data and H. Kobayashi for providing access to the IMG data. AIRS data was provided by the GES DISC DAAC at <http://daac.gsfc.nasa.gov/atmodyn/airs>. NCEP reanalysis data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA from their ftp at <ftp://ftp.cdc.noaa.gov/>. ECMWF data was provided from ECMWF through the British Atmospheric Data Centre. CMDL gas concentration data provided by the Climate Monitoring and Diagnostics Laboratory, Boulder, Colorado, USA from their website at <http://www.cmdl.noaa.gov/>.

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