An estimate of the interhemispheric transfer of carbon monoxide from tropical general circulation data

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ABSTRACT

Mean meridional wind data at the equator and carbon monoxide concentration data are used to estimate a mean annual flux of carbon monoxide into the Southern Hemisphere of 5×10^6 g sec^{-1}. Transfer to the stratosphere is found to be very small and not significant in the global CO cycle. Essentially all of the CO observed in the Southern Hemisphere may originate in the Northern Hemisphere. With similar loss rates in both hemispheres the total production in the Northern Hemisphere is estimated to be about 580 million tons per year which compares with about 330 million tons produced from anthropogenic sources. Mean CO residence times are estimated as 0.8 yr and 0.6 yr in the Southern and Northern Hemispheres respectively. It is suggested that more concentration measurements of CO (and other trace substances) be made in the equatorial plane, particularly in the upper troposphere in the Indian monsoon period. The general approach can be applied to other substances once concentration data are available in extenso.

1. Introduction

Radiosonde data from over 330 stations between 40° N and 40° S for the period 1957–64 have been used to construct the mean horizontal wind field for four three-month seasons together with the associated vertical motion field. The detailed data for levels between 1 000 and 100 mb have been published in map form (Newell et al., 1972). From these maps grid point data have been extracted at standard pressure levels and at ten degree longitude intervals. The grid point data may be used, together with trace substance concentration values, to compute horizontal fluxes of trace material. In practice water vapor is the only substance whose concentration is known well enough so that reliable results can be obtained (see e.g. Rasmussen, 1972). The interhemispheric transfer of many other trace substances is an important part of their cycle and it seems valuable to focus on this aspect, if only to provide a logical framework for future observations.

The facts about the global carbon monoxide distribution are as follows: concentrations in surface air are higher in the Northern Hemisphere than in the Southern Hemisphere; there is a fairly sharp drop in concentration when passing southwards across the intertropical convergence zone (ITCZ) which amounts to about 0.09 ppmv (Robinson & Robbins, 1969; Seiler & Junge, 1970; Seiler, 1973; Swinnerton et al., 1973); the volume mixing ratio decreases with altitude in the Northern Hemisphere troposphere then decreases sharply across the tropopause to a lower value of about 0.04 ppmv which is constant for at least a few kilometers above the tropopause (Seiler & Junge, loc. cit.; Seiler & Warnecke, 1972); aircraft flights across the tropics show little evidence of horizontal gradients in the upper troposphere with values in the range 0.10–0.12 (Seiler & Junge, loc. cit.; Seiler, loc. cit.); the spatial variability in the Southern Hemisphere is quite small (Seiler, loc. cit.; Swinnerton et al., loc. cit.); the absolute value of mixing ratio in the surface air of the Southern Hemisphere (0.04 ppmv) is about the same as that in the Northern Hemisphere stratosphere.

From these facts an estimate of the interhemispheric flux of carbon monoxide may be made and related to the overall cycle.

2. Interhemispheric carbon monoxide flux

The observed distribution of carbon monoxide suggests a division of the time-averaged meridional flow into four streams at the equatorial plane: air passing from the Northern Hemisphere to the Southern Hemisphere in the lower troposphere; air passing likewise in the upper troposphere; air passing from the Southern Hemisphere to the Northern Hemisphere in the lower troposphere; and air passing likewise in the upper troposphere. This is clearly a rough approximation; ideally the concentration should be available over the entire equatorial plane as a function of longitude and pressure. With the approximation, concentration values must be selected for each of the four streams for each of the four seasons. Over the Pacific surface air concentrations changed from 0.13 to 0.04 across the ITCZ in November 1972 (Swinnerton et al., loc. cit.) while over the Atlantic the change was from 0.20 to 0.12 in April 1969 (Seiler & Junge, loc. cit.) (recently corrected to 0.17 and 0.08, Seiler, private communication). From the limited sample it is hard to decide whether the differences between the oceans are a function of longitude or season.

Inspection of the distribution of the meridional wind component in the equatorial pressure-longitude plane shows a natural vertical division at about 400 mb (see Newell et al., 1972, pp. 40–41) with, for example, wind above this level mainly from the north and below from the south in June–August. Vertical profiles of CO are necessary to establish the presence or absence of any natural vertical division in the CO distribution.

The interhemispheric mass flux is the sum of the flux in the four streams as follows:

$$\frac{a}{g}\int_0^{2\pi}\left[\int_{100}^{400}\bar{v}\,dp\right]_+ d\lambda+\frac{a}{g}\int_0^{2\pi}\left[\int_{100}^{400}\bar{v}\,dp\right]_- d\lambda$$

$$+\frac{a}{g}\int_0^{2\pi}\left[\int_{400}^{1\,000}\bar{v}\,dp\right]_+ d\lambda+\frac{a}{g}\int_0^{2\pi}\left[\int_{400}^{1\,000}\bar{v}\,dp\right]_- d\lambda$$

where $\bar{v}$ is the mean seasonal value of the meridional wind component, g is gravity, p is pressure, λ is longitude, and a is the earth's radius. Integration with respect to pressure is carried out first and the integrals are grouped for the longitude integration into positive and negative values. The interhemispheric carbon monoxide flux is then found by multiplication of these four integrals by the appropriate mixing ratios.

Table 1. *Flux of mass and CO between the hemispheres.*

Negative sign is flux into the Southern Hemisphere. Average -5.2×10^6 g sec^{-1}. CO mixing ratio values used are in parentheses

	Mass flux (10^{13} g sec^{-1})		CO flux (10^6 g sec^{-1})		
	$v+$	$v-$	$v+$	$v-$	
December–February					
100–400 mb	13.9 (0.12)	−0.7 (0.12)	16.7	−0.8	
400–1 000 mb	2.9 (0.04)	−16.1 (0.13)	1.2	−21.0	
Totals			17.9	−21.8	−3.9
March–May					
100–400 mb	4.4 (0.12)	−2.8 (0.12)	5.3	−3.4	
400–1 000 mb	4.4 (0.08)	−6.0 (0.17)	3.5	−10.2	
Totals			8.8	−13.6	−4.8
June–August					
100–400 mb	0.6 (0.12)	−18.0 (0.08)	0.7	−14.4	
400–1 000 mb	18.0 (0.04)	−0.6 (0.13)	7.2	−0.8	
Totals			7.9	−15.2	−7.3
September–November					
100–400 mb	1.2 (0.12)	−9.5 (0.08)	1.4	−7.5	
400–1 000 mb	9.5 (0.04)	−1.2 (0.13)	3.8	−1.5	
Totals			5.2	−9.0	−4.8

The actual seasonal transfer of mass between the hemispheres is very small, as can be seen from considerations of the global pressure field, but computations from wind data of the interhemispheric mass flux inevitably show systematic transfers of mass. In the present case the residual flux is into the Northern Hemisphere in all four seasons and is equivalent to a mean velocity across the equatorial cross-section from 1000 to 100 mb of 0.18 m sec^{-1} in December–February and 0.16, 0.11, and 0.11 in the three subsequent seasons. These values are small when it is considered that individual grid point values range up to 8.8 m sec^{-1}, that 1000 mb is used instead of the surface and that there is a large area in the eastern equatorial Pacific

with little data. The residual values are subtracted from the entire velocity cross-section so that there is no net mass flux. The resulting mass flux and carbon monoxide flux values are shown in Table 1 for the four streams. The overall average interhemispheric transfer is 5.2×10^6 g sec^{-1} into the Southern Hemisphere. The CO value selected for the upper troposphere stream into the Southern Hemisphere for the latter half of the year (0.08 ppmv) is obviously quite crucial. It has been assumed that one half of the air in this stream originated in the Southern Hemisphere and has risen over the monsoon region before returning to the Southern Hemisphere. This crucial assumption could be checked by aircraft sampling across India during the monsoon period. Ideally of course the entire equatorial plane should be sampled as a function of season.

Another uncertainty concerns the rate of transfer of CO down the mixing ratio gradient by transient eddy processes in the upper troposphere. It has previously been pointed out that transient eddy processes may be comparable to mean motion transfer in the upper troposphere, though not in the lower troposphere, and may add to or subtract from the mean motion flux depending on the direction of the concentration gradient (Newell et al., 1969). These ideas were subsequently demonstrated by the work of Telegadas (1971) with radioactive tracers from the tests by France and China. In order to estimate the transfer by transient eddy processes more detailed information is required about the concentration gradients.

3. Carbon monoxide flux between the troposphere and stratosphere

The mass flux from the troposphere to the stratosphere has been estimated from heat budget considerations at the tropical tropopause (Newell et al., 1969; Newell et al., 1973*b*); heating by radiation is considered to be offset by eddy heat flux divergence and adiabatic rising motion. The deduced rising motion at 100 mb is integrated over area to give the total mass flux into the stratosphere. The mass flux by mean motions passing poleward across 20°N between 10 and 100 mb has been estimated from a stream function constructed from daily vertical motion data for 1964 averaged into months (Newell et al., 1973*a*). The daily vertical motion maps were based on the thermodynamic equation. Both techniques yield a mass flux of about 3×10^{12} g sec^{-1} into the stratosphere at low latitudes (and out at middle latitudes although the second may be an underestimate at it only applies to the Northern Hemisphere).

The CO flux associated with this mass flux will depend on the difference between the CO concentration at the tropical tropopause and that in the lower stratosphere of middle latitudes where the air is extruded into the troposphere (e.g. Danielsen, 1968). The CO concentration in the latter region has been measured as 0.04 ppmv (Seiler & Warnecke, loc. cit.), although the number of measurements is small. The concentration at 10 km in the tropics has been reported as 0.12 ppmv and the main problem is to assign a value for 16 km there. With the assumption of 0.08 ppmv the net flux of CO into the stratosphere is $3 \times 10^{12} \times (0.08 - 0.04) \times 10^{-6}$ g sec^{-1} $= 1.2 \times 10^5$ g sec^{-1}. As with the interhemispheric flux, eddy processes must also be considered although there is a logical limit to these in the sense that the total transfer must be small enough to permit the maintenance of a dry stratosphere, as is observed (cf. Brewer, 1949). The crucial parameter involved in an assessment of the limit is the residence time of a molecule in the stratosphere. Observations of various tracers give a mean residence time for the 100–10 mb region of about two years. The associated mass flux then is the stratospheric mass divided by this time, i.e. $[(100\text{–}10) \times 1/0.98$ g cm$^{-2} \times 5.1 \times 10^{18}$ cm^2 $= 4.7 \times 10^{20}$ g$] \div 2 \times 3.15 \times 10^7$ sec $= 7.4 \times 10^{12}$ g sec^{-1}. This is about double the flux estimated for the mean motion alone and gives a corresponding CO flux into the stratosphere of 3×10^5 g sec^{-1}, which is still very small compared with the amount passing into the Southern Hemisphere. The implication is that the stratosphere is not a major sink for CO.

4. Carbon monoxide cycle

With the present rather meager information on CO distribution the atmosphere may be subdivided into three reservoirs—Northern Hemisphere, Southern Hemisphere and stratosphere with contents of 3.4, 1.3 and 0.4×10^{14} g respectively (from data by Seiler, 1973).

The balance equations for the two hemispheres may be written as follows:

$$\frac{dC_{SH}}{dt} = -kC_{SH} + S_{SH} + F$$

$$\frac{dC_{NH}}{dt} = -kC_{NH} + S_{NH} - F$$

where C represents the total amount of gas, S represents sources, F the interhemispheric flux, and k a decay constant.

If we assume a steady state and negligible local sources in the Southern Hemisphere then the mean residence time for CO there is 0.8 yr ($k = 4 \times 10^{-8}$ sec^{-1}).

If the same loss rate applies to the Northern Hemisphere, the loss there is $4 \times 10^{-8} \times 3.4 \times 10^{14}$ g sec^{-1} = 13.6×10^{6} g sec^{-1}. The total production in the Northern Hemisphere associated with this loss (S_{NH}) is thus $(13.6 + 5.2) \times 10^{6} = 19 \times 10^{6}$ g sec^{-1} = 580 million tons per year.

In order to account for the observed distribution of CO and the estimated fluxes it is necessary to locate a source that is stronger in the Northern Hemisphere than in the Southern Hemisphere. If the oceans were the main source the Southern Hemisphere would be favored; if methane, as suggested by Wofsy et al. (1972), then there is no obvious reason to expect a difference between the hemispheres. An anthropogenic source would be expected to favor the Northern Hemisphere. For example, automobiles each produce about one ton of CO per year (NAPCA, 1970) and there are about 208 million in the Northern Hemisphere yet only 12 million in the Southern Hemisphere. Stationary sources are also more abundant in the Northern Hemisphere; if these are 50% of the automobile source the total production is about 330 million tons per year. Either there is another source of about the same size or our flux estimates are wrong by a factor of two.

Asymmetry of the sinks is another potential contributor to the observed concentration. The finding that soil is an important sink (Inman et al., 1971; Ingersoll & Inman, 1973; Seiler, 1973) is of great interest and the possibility that k may be different in the two hemispheres cannot be ruled out.

The mean residence time for the Northern Hemisphere with a total injection and loss rate of 19×10^{6} g sec^{-1} and a content of 3.4×10^{14} g is 0.6 yr. This is still substantially longer than the value of 0.1 yr reported by Weinstock (1969).

Another item not directly explicable from the present scheme is the origin of the light oxygen in the Northern Hemisphere summer reported in the isotopic analyses of Stevens et al. (1972). If this originates from the Southern Hemisphere its source could perhaps be located by isotopic analysis of samples collected at various points in the equatorial plane. All the estimates herein could be refined by such additional sampling, with the upper and lower troposphere of the eastern hemisphere, particularly during the monsoon, given a high priority.

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ОЦЕНКА ПЕРЕНОСА CO МЕЖДУ ПОЛУШАРИЯМИ

Данные по среднему меридиональному ветру на экваторе и по концентрации CO используются для оценки среднего годового потока CO в южное полушарие, который составил 5×10^6 *гм* сек$^{-1}$. Получено, что перенос в стратосферу весьма мал и не существенен в глобальном цикле CO. Почти весь CO, наблюдаемый в южном полушарии, может возникать в северном полушарии. При одинаковой скорости исчезновения в обоих полушариях общее производство CO в северном полушарии оценивается как 580 млн. тонн в год, что сравнимо 330 млн. тонн, производимыми антропогенными источниками. Среднее время жизни CO составляет по оценкам 0,8 и 0,6 года в южном и северном соответственно. Высказывается предположение о необходимости более частых измерений CO (и других трассеров) в экваториальной плоскости, особенно в верхней тропосфере в период Индийского муссона. Такой общий подход может быть приложим к другим субстанциям, если данные по их концентрации имеются в достаточном количестве.