Note on the exchange rate between the northern and southern atmosphere

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ABSTRACT

Differences in CO_2 and CH_3T data for the northern and southern hemispheres are used to estimate the net exchange rate between the hemispheres. The most likely exchange rate is found to be 0.3–0.5 year^{-1}.

Introduction

Measurements of atmospheric constituents have recently become available which enable the estimation of the rate of exchange between the atmospheres of the two hemispheres. Although we deal here primarily with the exchange between the tropospheres, any exchange via the stratosphere is included. Constituents which can be used for these considerations must meet the following requirements:

1. Their sources, sinks, or variations must be restricted to one hemisphere.

2. The atmospheric residence time of these constituents must be long compared with the exchange time between hemispheres.

3. Representative measurements must be available.

Aerosols have tropospheric life times of about a month and are thus excluded from these considerations. Only rather stable gases can be used but up to now we have found only two gases which meet these requirements, namely carbon dioxide and tritiated methane, CH_3T.

Carbon dioxide

KEELING (1960) has published data on the global distribution of CO_2 in both hemispheres, which show the following characteristics: If local influences of pollution and of vegetation near the ground are excluded, that is, if data from aircraft, mountains, arctic and ocean stations are used, the northern hemisphere shows a pronounced seasonal variation in CO_2 concentration with a maximum in May and June, and a minimum between August and October. This, most likely, reflects the uptake and release of CO_2 by and from the biosphere. During the growing season, CO_2 is taken from the atmosphere and the minimum is reached when the winter starts. During winter, organic matter decays and an excess of CO_2 is released to the atmosphere. The observed variation of the ratio C^{13}/C^{12} seems to support this explanation. The amplitude of the CO_2 concentration is about 5 ppm, with an average level of 313 ppm. There are differences in the annual variation by 1 to 2 months in phase and also in amplitude. Such differences become even more pronounced if a network of ground sampling stations of CO_2 in populated and wooded areas are considered as in Scandinavia (BISCHOF, 1960). On the other hand, the horizontal air exchange, at least within the belt of west-wind circulation, is rather fast and it can be shown from an analysis of surface ozone data, e.g., that the average time required for active mixing within the northern hemisphere is about 4 weeks (JUNGE, 1961).

The consistent differences in the annual variation of CO_2 in the northern hemisphere, despite the intensity of horizontal mixing, point to the presence of fixed sink and source areas which superimpose their system of low and high partial pressure upon the general pattern. However, these variations do not modify the general picture very much and will not be considered here further.

In contrast to the northern hemisphere, the southern hemisphere shows practically no annual variations. The concentrations from the

Pacific and from Antarctica are accurate and consistent enough to indicate a small but steady increase within the limits of 0.3 to 1.4 ppm per year. This increase is due to the burning of fossil fuel and the average value of this increase over the last 20 years from all data in the northern hemisphere is close to 0.7 ppm per year. The lack of a seasonal variation in the southern hemisphere is consistent with the explanation given above. The areas with plant growth in the southern hemisphere are located primarily in the tropical zones which have no seasonal variation. In middle and higher southern latitudes the areas of grown land become very small.

If, however, the air exchange between the hemispheres is sufficiently fast, one would expect that the variations of the northern hemisphere penetrate into the southern hemisphere, though with a lesser amplitude. The rate of uptake of CO_2 by the oceans is of the order of 5 years and in addition the buffering mechanism of the ocean water is such that only a small portion of any variation of atmospheric CO_2 can be absorbed by the ocean water (BOLIN and ERIKSSON, 1959). It is therefore unlikely that there is a considerable influence of the oceans upon the annual variation of CO_2. Under the assumption that the source of the annual variation of CO_2 is restricted to the northern hemisphere and that there is no influence of the ocean we can use the large scale natural tracer experiment which the terrestrial biosphere performs in the atmosphere for an estimate of the global exchange rate between the hemispheres.

If c_1 and c_2 are the total CO_2 content of the northern and southern hemispheres in any unit, $k_{12} = k_{21} = k$ the exchange rate between the hemispheres, and t the time in years, c_2 is determined by:

$$dc_2/dt = k(c_1 - c_2). \tag{1}$$

The seasonal variation of c_1 can be approximated by a sine function and we can write:

$$c_1 = a_1 + b_1 \sin(2\pi t); \quad t \text{ in years.} \tag{2}$$

Equations (1) and (2) result in the solution for c_2.

$$c_2 = a_2 + b_2 \sin(2\pi t + t_2), \tag{3}$$

in which $a_2 = a_1$,

$$b_2 = b_1 \Big/ \sqrt{\left(\frac{2\pi}{k}\right)^2 + 1},$$

and $\tan(t_2) = -2\pi/k.$

The observations indicate that the amplitude of a seasonal variation in the southern hemisphere caused by the northern hemisphere is not larger than

$$b_2 = 0.15 \times b_1,$$

so that $k \leqslant 0.94$ years^{-1} and $\tau \geqslant 1.1$ years, where τ is the exchange time $\tau = 1/k$. For $k < 0.94$ we obtain $\tan(t_2) \leqslant -6$ or $-2.7 > t_2 > -3.0$ months. The delay in phase of the southern hemisphere is thus close to 3 months. Keeling's data of the southern hemisphere suggest a slight maximum in August 1958 as should be expected if mixing with the northern hemisphere occurs to some extent. On the other hand, a delay of 3 months makes it unlikely that a small exchange with the northern hemisphere is just counterbalanced by a small seasonal variation from the southern hemisphere with exactly the opposite phase.

An immediate consequence of a hemispherical exchange time of this magnitude would be a consistently higher level of CO_2 in the northern hemisphere due to the burning of fossil fuel. Almost all the artificial CO_2 is produced in the northern hemisphere and the recent rate of increase is $d_1 = 0.7$ ppm/year. A linear increase in the northern hemisphere of the form

$$c_1 = a_1 + d_1 t, \tag{4}$$

applied to (1) results in a solution for c_2 of

$$c_2 = a_2 + d_2 t, \tag{5}$$

with $d_1 = d_2$,

and $a_1 - a_2 = d_1/k.$

This gives the numerical values:

k =	1.0	0.5	0.3	0.2 year^{-1}
τ =	1.0	2.0	3.3	5.0 years
$a_1 - a_2$ =	0.7	1.4	2.3	3.5 ppm

From the seasonal variations, one should conclude that $a_1 - a_2 \geqslant 0.6$ ppm. Keeling states that the relative accuracy of the CO_2 recordings on the individual stations is ± 0.3 ppm, but that the uncertainty in the absolute values is considerably larger and had not been established. The given CO_2 concentration for the two hemispheres do not seem to show a difference

larger than about 1 ppm, but the uncertainty about the absolute accuracy does not allow any conclusion.

Tritium in methane

BISHOP *et al.* (1961) published a very interesting study on the tritium (T) content of methane, i.e., on CH_3T. They show that in the southern hemisphere, CH_3T increases approximately exponentially between 1953 and 1958 (the year of the latest data), whereas the measurements from the northern hemisphere comprise only the time interval from October 1958 to February 1959, which is too small to conclude any large scale trends. The meridional cross-section of their data show clearly that the highest concentrations are in the *northern troposphere* (22×10^3 Tritium Units. T.U.). The concentra- in the southern troposphere is 8×10^3 T.U., which is also about the level in the lower stratosphere in both hemispheres. The source of the tritiated methane is still rather mysterious, but can hardly be natural nor from bomb tests. The data seem to show that CH_3T is produced in the *northern troposphere*, either primarily or exclusively, and the difference in level between the two hemispheres must be due to the rate of exchange. These data offer another possibility to estimate k.

We will calculate k on the basis of the two assumptions, that the increase of c_2 for methane is (*a*) exponential with a doubling time of 1.5 years, as Bishop *et al.*, stated, and (*b*) linear. In the first case we have:

$$c_2 = f_2 \cdot e^{g_2 t}, \quad \text{with} \quad g_2 = 0.46 \text{ year}^{-1}.$$

The solution is:

$$c_1 = f_1 \cdot e^{g_1 t}, \quad \text{with } t = 0 \text{ for September 1957,}$$

$g_1 = g_2$, $f_1 = 22 \times 10^3$ T.U. and $f_2 = 8 \times 10^3$ T.U.

This gives

$$k_{exp} = g_2 f_2/(f_1 - f_2) = 0.26 \text{ year}^{-1},$$

and

$$\tau_{exp} = 3.8 \text{ years.}$$

For the linear case we have:

$$c_2 = f_2 + i_2 \cdot t, \quad \text{with } i_2 = 3.5 \times 10^3 \text{ T.U./year and } t = 0 \text{ for September 1957,} \quad (7)$$

and the solution

$$c_1 = f_1 + i_1 \cdot t, \quad \text{with} \quad i_1 = i_2.$$

This gives $k_{lin} = i_2/(f_1 - f_2) = 0.25 \text{ year}^{-1}$,

and $\tau_{lin} = 4.0$ years.

Apparently the type of increase has little effect on the calculated values of k and τ. Four years is a long time and it would result in a difference in CO_2 content between northern and southern hemisphere of 2.8 ppm, which certainly should be detectable. We feel that the data on CH_3T, especially the actual rate of increase and the regularity[1] of this increase are not well enough known to give reliable values of k, but they definitely point to rather small exchange rates. The life time of methane in the atmosphere is about 50–100 years, if HUTCHINSON'S (1954) estimates of the production rate are used. This life time is long compared with the exchange time between the hemispheres and can hardly influence the hemispheric distribution of CH_3T.

The exchange time of 3 to 4 years is comparatively long. It is longer even than the exchange time between troposphere and lower stratosphere, which is of the order of one year. It should be mentioned that tropospheric ozone data and considerations about large scale horizontal exchange processes point to mixing times *within* the (northern) hemisphere, including the tropical zone, of the order of four weeks (to be published elsewhere). These results imply that the northern and southern troposphere represent two atmospheric reservoirs which are relatively well mixed within themselves, but which are fairly well separated along the meteorological equator. A major possible exchange mechanism between the hemispheres is the monsoon circulation over the Indian Ocean and India, where air masses cross the equator on a large scale. It remains, of course, a question to what degree this air actually undergoes mixing within the other hemisphere before it returns.

It would be interesting to have corresponding figures of the hemispheric exchange rate based on wind and other meteorological data, but to

[1] New data by Dr. Begemann (personal communication) indicate that the increase of the CH_3T concentration in the northern hemisphere starts to level off during 1958.

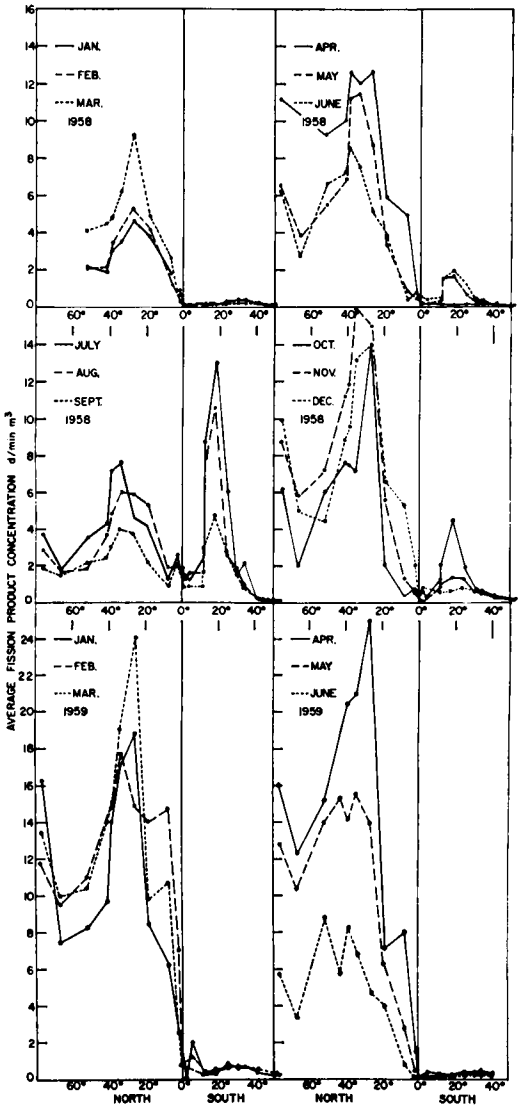

FIG. 1. Monthly average profiles of gross fission products in the air along the 80th meridian from January 1958 to June 1959. Values are given in disintegration per minute and cubic meter. From LOCKHART *et al.*, (1959; 1960).

the knowledge of the author such figures are not yet available.

If the hemispheric exchange time is about 3 to 4 years it is clear that tropospheric constituents like aerosols and fission products, which have an atmospheric residence time of about one month cannot penetrate the equator to any extent. This is well demonstrated by Fig. 1, which is based on data from the 80th meridian network (Lockhart *et al.*, 1959; 1960). The U.S.A. test series in summer 1958 injected debris into both hemispheres, but no debris from the U.S.S.R. test series in October 1958 entered the southern stratosphere and could thus not mix down into the southern troposphere. The source for the debris of the troposphere after November 1958 was restricted to the northern hemisphere and the difference in the concentration level between the two hemispheres and the sharp separation at the equator are remarkable. It must be concluded from Fig. 1 that the transition zone between the two hemispheres is rather narrow, at least along the 80th meridian. It was suggested earlier that the rainbelt along the equator removes the fission products so efficiently that any exchange between the tropospheres across the equator is practically prevented. Our discussion on the exchange rate between the two hemispheres shows that this is no longer a necessary assumption, although washout will undoubtedly support the hemispheric separation so far as aerosols are concerned.

There are other gases which could be used to check the exchange rate between the hemispheres. For instance, N_2O has an atmospheric residence time of about 4 years and is supposedly produced by the soil, i.e., primarily in the northern hemisphere. It should have higher concentrations in the northern hemisphere. The CO observed in the atmosphere is supposedly produced by industry so that the hemispheres should again show pronounced differences, depending on the life time of CO. On the other hand, measurements of CO_2 and other gases along the equator, for instance over India, could be used to elucidate the monsoon or other large scale circulations. It is our hope that this note will stimulate future atmospheric research on these problems.

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