A preview on the determination of mass return flow of air and water vapour into the stratosphere using tritium as a tracer

By R. MICHAEL SMITH, *International Meteorological Institute, Stockholm*[1]

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ABSTRACT

A preview is presented of recent work on the uses of tritium in tracing general atmospheric motions. Using monthly moisture flux data it was possible to determine the regions of major outflow of air and water vapour through the tropopause into the stratosphere over North America for July 1962. It was found that these areas were closely related to the mean position of the jet stream. Computations were made of the total masses of air and water vapour leaving the troposphere. It is postulated that the energy involved in the outflow of air from the troposphere in the vicinity of the mid latitude jet stream and originating entirely from the large scale transient eddies is transferred directly into the lower stratosphere. This transfer of kinetic energy through the tropopause is considered to be the principal mechanism for the maintenance of the dynamic circulation of the lower stratosphere. It is tentatively suggested that such outflow of tropospheric air at least in mid latitudes initiates extrusions of stratospheric air as a compensatory mechanism in an effort to restore equilibrium in an otherwise dynamically inactive stratosphere.

Since the atomic explosions were set off in 1954 which injected the first vast quantities of manmade tritium into the atmosphere a considerable amount of data, mostly as tritium concentrations in rain, river and sea-water, has been collected. However, applications of this data to meteorology on a continental or synoptic scale have been up to now very few. Eriksson (1965) was one of the first to demonstrate the possibilities of using tritium on such a scale using a limited amount of available meteorological data. Previous workers (Craig & Lal, 1961; Begemann & Libby, 1957) completely neglected the effects of eddy diffusion. In order to make a detailed investigation into using tritium as a tracer for atmospheric motions it is absolutely necessary to have moisture flux data. In this case monthly averages of zonal and meridional transport of water vapour for July 1962 were obtained for North America from computations made at Travelers Research Center. The complete data was for the time 0000Z but incomplete 1200Z data was also obtained and used for comparing the diurnal variations in the precipitable water and moisture flux. Rasmussen (1966) has demonstrated the significance of these diurnal variations. For July 1962 it was found that the interior had the highest values of the precipitable water at 0000Z, while the coasts had highest values at 1200Z. The divergence field of moisture, and thus evapotranspiration, particularly exhibited these time variations. Another feature which came to light during the work was the striking correspondence of the field of evapotranspiration at 0000Z with that of the map of thunderstorm occurrences. It has previously been observed (Long, 1966) that in the interior of the continent the frequency of storms is greatest during the evening and early morning hours.

Benton & Estoque (1954) attempted to calculate the moisture flux field, and also the field of eddy flux of moisture from a limited amount of data. In the present work the zonal and meridional fields of eddy flux for July 1962 present distinct anomalies, particularly the latter whose largest anomaly extends, northwestwards as a ridge in the lee of the Rockies from a maximum over the Dakotas and Nebraska, into the Canadian Arctic. The second largest field of meridional eddy flux is situated over northern Quebec and Labrador (>300 g

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cm^{-1} sec^{-1}). Previous workers in tritium and other tracers have assumed that the horizontal eddy diffusion coefficient k_H could be reasonably assumed to have a value of 10^{10} cm^2 sec^{-1}. It was clearly evident from the fields of eddy flux that such an approximation could not be applied to the July 1962 data. From the moisture transport equation:

$$\bar{\mathbf{Q}} = \overline{w}\,\overline{\mathbf{v}} + \overline{w'\mathbf{v}'} = \overline{w}\,\overline{\mathbf{v}} - k_H \nabla \overline{w}$$

the coefficient k_H was determined for the continent. It is obvious from the very large range in these values of 10^9 to 10^{12} cm^2 sec^{-1} that it would be a great mistake to make computations involving the flux of tritium using constant values of k_H, being equally as catastrophic as in neglecting the eddy flux term altogether. As it will be seen later, the introduction of k_H as a variable in the equations has opened a whole new field for the uses of tritium for tracing air motions. Earlier attempts (Smith, (1966) involving the flux of tritium must necessarily assume constant k_H values owing to the lack of eddy flux data which resulted in erroneous results and therefore an unsatisfactory interpretation.

The equations set out by Eriksson (1965) were used as a basis for the tritium computations, and are summarised elsewhere (Smith, 1966). The flux of tritium for July 1962 reveals especially two distinct regions of maximum flux, one extending from Montana northwards to the North-West Territories, with values generally of over 800. 10^{10} TU g cm^{-1} and the other covering a wide area from the vicinity of the Great Lakes to Kansas, with general values of over $400 \cdot 10^{10}$ TU g cm^{-1}. The directions of the fluxes are similar to those of water vapour except in the area of highest tritium flux values centred over Northern Alberta, the direction here being predominantly north to north-easterly.

Before discussing the most important results of the work it should first be mentioned that the month of July 1962 was unseasonably cool over much of the continent, caused generally by a strong blocking wave moving across Canada from the Atlantic, thus displacing the storm track and jet stream axis southwards.

Precipitation was well above average over most of the Great Plains and northwards into Canada. Computations were made of the vertical flux of tritium at the tropopause. The most important aspect of the results demonstrated the principal regions of outflow from the troposphere into the stratosphere. These coincided almost precisely with the mean position of the jet axis, thus confirming the results obtained from a completely different manner of investigation by Reiter *et al.* (1967). The association of the jet stream region and its baroclinic zones with return flow into the stratosphere was proposed by Newell (1961 and 1963). It is only in recent years that attention has been concentrated on the problem of return flow into the stratosphere and not until 1966 has a theoretical approach been attempted. Observational evidence that such flow does exist is small, there being a few reports of, for instance, water vapour rich—ozone poor layers above the tropopause (Helliwell, 1960; Brewer, 1960; Roach, 1961). There is, however, considerable evidence in the literature of strong ascending motions associated with cloud and moisture, occurring usually at and on the anticyclonic side of the jet axis (Endlich, 1953; Endlich & McLean, 1957; Briggs & Roach, 1963). A closer examination of the field of tritium flux at the tropopause reveals distinct maxima within the region of general outflow from the troposphere, near the jet axis, which correspond to the positions of large eddy flux of moisture or more exactly, to the positions of high values of the diffusion coefficient. Computations of the approximate mean vertical velocities for July 1962 for the layer 300–400 mb reveal that in general the regions of ascending motions also agree closely with those of large values of the diffusion coefficient k_H. Vertical velocities of $+5$ to $+10$ cm sec^{-1} are common in the regions near the jet axis.

It should be noted that the relatively broad band of outflow in relation to the narrow region normally occupied by a jet stream is explained by the fact that during a period of a month the position of the jet axis with its associated region of outflow will naturally fluctuate considerably.

From this work, and from that of Reiter *et al.* (1967), the jet stream region has been shown to be one of the major areas of return-flow into the stratosphere. The mechanism of this flow has been explained by Reiter *et al.* (1967) as being mainly due to direct flow and "seepage" near the jet core through the tropopause gap. The magnitude of the outflow of tritium in the

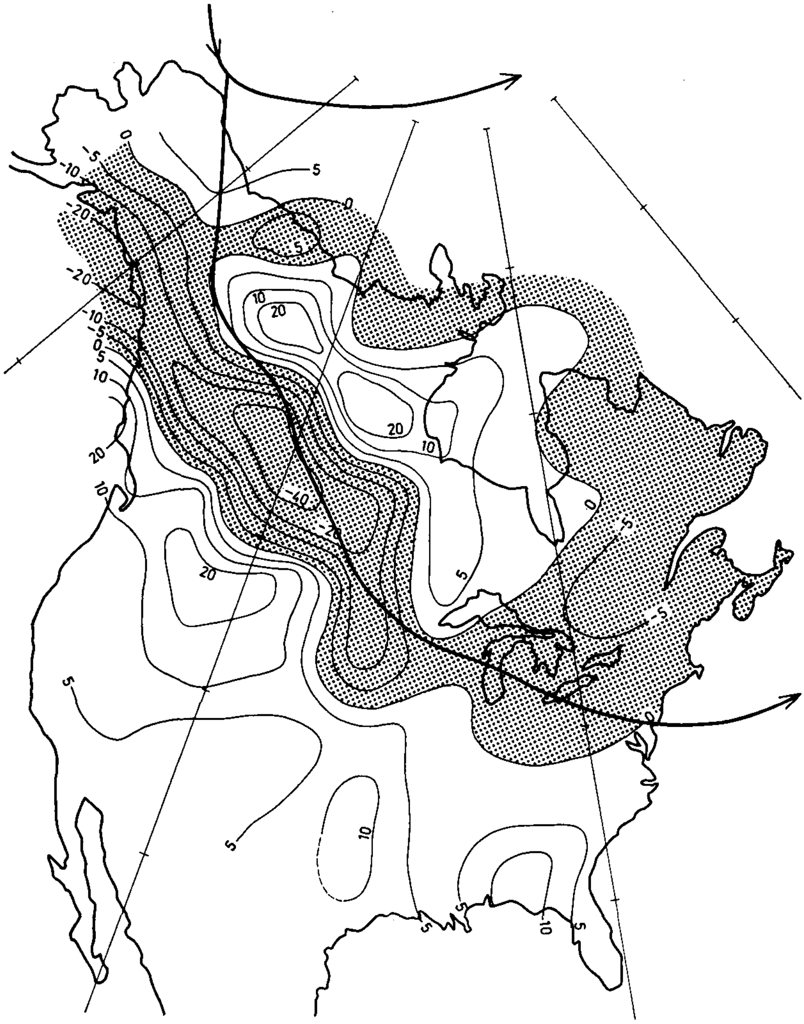

Fig. 1. Mean transport of tritium through the tropopause in July 1962 at 0000 Z. Units in TU cms. × 10^3. Dotted regions indicate ascending (negative) motions. Long thick arrows denote mean positions of jet axes.

jet stream region, corresponding to the zones of maximum eddy diffusion on a meso and synoptic scale, suggests that here the outflow consists of powerful currents of perhaps partly a turbulent nature associated with the large scale eddies and drawn quasi-horizontally from a considerable depth of the upper troposphere, probably much deeper when averaged over longer periods than the 70 mb found by Reiter *et al.* (1967). In Fig. 1 the cyclonic side of the jet stream is the normal region of maximum concentration of radioactive material, as indicated by many workers (Danielsen, 1964; Reiter, 1963). The mechanism of stratospheric extrusion of this material is widely accepted to be associated with folding of the tropopause in connection with the jet stream front. Up to the time of writing no measurements of tritium at such heights have been published but evidence from air sampling at lower altitudes over Sweden has indicated that extremely rich layers of tritium may be found which are clearly associated with the jet stream front. In Fig. 1 to the south-west of the outflow region associated with the baroclinic zones of the jet stream front the direction of flux is again downwards, attaining a maximum value of 33,000 TU cm over the Montana–Idaho area.

Examination of the stability in this region between the isentropic surfaces 341° and 361°K shows that these surfaces are in the stratosphere. Two prominent ridges of lower stability situated over Alberta and Quebec, coinciding with the position of the upward flux, suggest that although still within the stratosphere (seen from the gradients of the thickness) they represent regions of ascending motions within the lower stratosphere. Such an analysis may be continued to see whether these effects may be detected at greater heights. The evidence presented by the distribution of tritium flux at the tropopause clearly suggests that tropospheric air may be found at considerable heights within the lower stratosphere over the regions of maximum upward flux, as for instance, over Alberta and Quebec. It is also tentatively suggested that during the winter months the tropospheric air, forced by the vigorous circulations of the large scale transient eddies into the lower stratosphere, is brought at times under the direct influence of the Arctic stratospheric jet. The significance of this will be discussed in a following paper. From what has been said above it is obvious that tropospheric flow into the lower stratosphere implies a significant intrusion of water vapour and aerosols, and a widespread contamination of the concentrations of radioactive material, particularly of tritium.

Computations were made of the inflow and outflow of water vapour across the coastal boundaries of North America for July 1962. The results obtained were remarkable in that there was an exact balance between inflow and outflow, i.e., an outflow of $1 \cdot 32 \cdot 10^{16}$ g and an inflow of $1 \cdot 31 \cdot 10^{16}$ g. When comparing these figures with those of Benton & Estoque (1954), who actually computed the average flow for three months periods, it is apparent that the total flow in July 1962 was well below the average. This is understandable when it is remembered that July 1962 was unseasonably cool with a predominantly northerly flow. Previous attempts to compute the water balance (Benton & Estoque, 1954; Rasmussen, 1966) have disregarded the activities of moisture flux near the top of the troposphere. By summing the area of upward tritium flux through the tropopause it is possible to calculate the total mass of water vapour leaving the troposphere.

Assuming a tritium concentration of this air of 5000 TU and a water vapour mixing ratio of $0 \cdot 25$ g kg^{-1} would result in the amount 11.10^{16} g of moisture being lost to the stratosphere in one month through the influence of the jet stream region, the baroclinic zones and tropopause gaps. This amount corresponds to a total mass of 44.10^{19} g of air. Reiter *et al.* (1967) computed that 3.10^{16} g of air per hour flowed into the stratosphere which corresponds, when averaging over a month, to 22.10^{18} g/month. Their depth of air, however, was only 70 mb, and the area covered was considerably smaller than that in the present investigation. There is good reason to believe that over monthly periods the average depth of the outflowing tropospheric air may be at least 200 mb. Taking into account these factors would readily produce a figure corresponding to 44.10^{19} g obtained in this work. The present figures are only very approximate owing to the unknown tritium concentrations and moisture mixing ratios at these heights. They do, however, show the orders of magnitude involved in the transport of air and water vapour into the stratosphere. In addition the transport of kinetic energy through the tropopause would at least partly account for the large-scale motions observed in the lower stratosphere. This would apparently satisfy the conditions required by Oort (1964) and originally suggested by Starr (1960) that the lower stratosphere derives its energy by pressure forces and/or eddy stresses at its bottom boundary. From the close correlation in the present case between the regions of large mean eddy fluxes and those of outflow into the stratosphere it follows that the mean kinetic energy in the lower stratosphere of middle latitudes is mostly acquired from transient eddy kinetic energy introduced from the troposphere. In connection with the computed amount of moisture flowing out of the troposphere it is obvious that a saturation of the lower stratosphere would soon ensue if there was no compensatory mechanism to avoid such an occurrence. It is suggested that outflow of moist tropospheric air is the cause of extrusions of stratospheric air. In other words stratospheric extrusions, in association with the jet stream front and a folding of the tropopause, are a direct consequence of the outflowing moist tropospheric air in an effort to restore equilibrium in an otherwise dynamically stable lower stratosphere; saturation is therefore never reached. Thus, just as jet streams are a fundamental part of planetary long waves so is the two way exchange of energy between stratosphere and troposphere an integral part of the general circulation. This theme will be discussed at greater length in a following paper.

On the basis of the water vapour estimates it would seem necessary to completely revise the methods of computing the water balance of a region in order to include this vital factor. Computations of the quantities of tritium flowing out of the troposphere, assuming a concentration of 5000 TU, gives a total amount of 0.18 kg for one mean planetary wave. Thus the yearly hemispheric stratospheric inventary of tritium will decrease at a considerably slower rate than was previously supposed, assuming that similar outflow from the troposphere occurs in the vicinities of other mid latitude jet stream regions in the northern hemisphere.

Returning finally to the map of the flux of tritium at the tropopause (Fig. 1), as already stated, there is excellent agreement between the average position of the jet axis and the field of upward flux. Exact correspondence is obviously not possible owing to the fact that the moisture flux suffers diurnal variations which would lead to displacements of the maxima and minima. In the tritium equations (Smith, 1966) the term $-k_H \nabla^2 \overline{c'w'}$ has been neglected as yet of necessity (where c' and w' are deviations from the time averages of tritium concentration and precipitable water respectively) but a knowledge of this term is not expected to change the general field of the tritium flux at the tropopause. Owing to the good results already obtained it may be possible in future work to constantly neglect this term.

In conclusion it may be stated that tritium as a tracer for atmospheric motions has proved to be an invaluable tool in meteorology. It is the author's intention that similar investigations will also be made for other months for North America, and later for various regions of the world when enough satisfactory moisture flux data is available. To support this work detailed isentropic analyses are necessary, and new sampling projects for tritium and other tracers in the troposphere and lower stratosphere would considerably help to verify the theoretical results. In a following paper many of the aspects mentioned briefly in this preview will be presented in detail.

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К ОПРЕДЕЛЕНИЮ ВОЗВРАЩЕНИЯ МАССЫ ВОЗДУХА И ВОДЯНОГО ПАРА В СТРАТОСФЕРУ С ИСПОЛЬЗОВАНИЕМ ТРИТИЯ В КАЧЕСТВЕ ТРАССЕРА

Представлен предварительный обзор работ по использованию трития при прослеживании общих атмосферных движений. Используя месячные данные потока влажности, можно определить области крупных потоков воздуха и водяного пара через тропопаузу в стратосферу над Северной Америкой в июле 1962 г. Было найдено, что эти области тесно связаны со средним положением струйного течения. Проделаны вычисления общих масс воздуха и водяного пара, покидающих тропосферу. Постулировано, что энергия, заключенная в потоке воздуха из тропосферы в окрестности струйного течения средних широт и возникающая целиком из крупномасштабных вихрей, переносится целиком в нижнюю стратосферу. Этот перенос кинетической энергии через тропопаузу рассматривается как главный механизм поддержания динамической циркуляции в нижней стратосфере. Предполагается, что этот поток тропосферного воздуха, по крайней мере в средних широтах, вызывает вытеснение стратосферного воздуха, что является компенсирующим механизмом в попытке восстановить равновесие в стратосфере, которая в остальном является динамически неактивной.