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# MEASUREMENTS OF THE VERTICAL WATER VAPOR TRANSPORT AND DISTRIBUTION WITHIN UNSTABLE ATMOSPHERIC GROUND LAYERS AND THE TURBULENT MASS EXCHANGE COEFFICIENT

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# I. INTRODUCTION

1. *Evaporation and turbulent diffusion in an unstable air mass.*

The series of observations described in this report were planned with the double purpose of measuring the evaporation and transport of water vapor from the ocean into an unstable atmosphere, and of studying the diffusion processes operating in air of this stability class. Measured values of the evaporation from ocean surfaces were conspicuously absent from the meteorological literature until Craig and Montgomery (1949) published values for hydrostatically stable air. The present set of measurements extends our knowledge to include evaporation into a hydrostatically unstable air mass. In addition to evaporation values at the surface, net transports of water vapor at many levels up to 2000 meters have been measured.

Coefficients of the turbulent mass exchange have been computed at several heights from transport values and measured mixing ratio gradients. These computations show that the exchange coefficient can attain values over the wide range of 780 to 15,000 gm $cm^{-1}$ $sec^{-1}$. Previously, the coefficient was measured under more stable conditions and values between 1 and 1000 gm $cm^{-1}$ $sec^{-1}$ were thought representative of most conditions encountered in the atmosphere. It is found that the coefficient may be three orders of magnitude larger in an unstable than in a very stable air mass, while a factor of five to one exists between the unstable class and a slightly stable class. The variation of the coefficient of turbulent mass exchange throughout the entire ground layer has been investigated. The coefficient is shown to increase rapidly in the first 100 m to a maximum value of about 2000 gm $cm^{-1}$ $sec^{-1}$. From this level the turbulence dies slowly to a value of 100 gm $cm^{-1}$ $sec^{-1}$ at about 1500 m near the base of the temperature inversion at the top of the ground layer. In the inversion region turbulence is slight and the coefficient drops to between 1 and 10 gm $cm^{-1}$ $sec^{-1}$.

The analysis on the basis of the coefficient of turbulent mass exchange is not a complete one, since it does not consider the effects of free-convection, which is always present or incipient in an unstable air mass. An approximate evaluation of the magnitude and transport by convection has been made on the basis of available information concerning the frequency of convection parcels, their velocities, and water vapor content. The final description of the processes operating in an unstable layer of air is not reached in this paper but must be worked out in terms of buoyant parcels or jets rising through highly turbulent regions of the atmosphere. The buoyancy forces of the parcels may be dissipated rapidly by the effects of entrainment and diffusion of the outside air, so that only under very critical conditions can convection become fully developed.

The observing techniques were modelled after the meteorological work of the Radiation Laboratory of Massachusetts Institute of Technology. Their technique of flying psychrograph equipped airplanes in helical soundings was successfully adapted to the needs of the present study. In addition to the thermistor aero-psychrograph, the airplane usually carried a water-column accelerometer which recorded the vertical accelerations imparted to the sounding aircraft by the turbulent gusts.

The temperature and roughness observations were continued upward through the inversion existing at the top of the ground layer of air and extended a hundred meters or so into the smooth air above the inversion. Particular attention has been concentrated in this paper on the 30 m to 2000 m region, which is not easily observable by ground-, boat-, or tower-based instruments, and has been neglected in the past. The observing procedure was organized so that the two quantities, mixing ratio gradient and vertical flow of water vapor, could be determined with sufficient accuracy to yield significant values of the coefficient of turbulent mass exchange. Accuracy in the vertical gradient determination was achieved by executing slow ascents with the airplane, thereby eliminating errors due to the lag of the psychrograph thermistors. Accuracy in the determination of the vertical flow of water vapor was attained by measuring the mixing ratios in areas sufficiently separated downwind to assure that the observed mixing ratio increases were much greater than the probable errors of the mixing ratio determination.

Air masses moving from land out over the water were followed by the sounding airplane. From two or more soundings, accumulations of water vapor in the downwind air were obtained and rates of transport determined. Dry- and wet-bulb temperature, or dry-bulb and dew-point temperatures were recorded alternately every five seconds, while the plane made helical ascents. The slow ascent of the plane, 60 m per minute, allowed the accurate measurement of the mixing ratio gradient throughout the layer.

The computed values of the vertical flow of water vapor and mixing ratio gradients have been placed in the eddy diffusion equation,

$$E_z = -A_z \frac{\partial q}{\partial z} \qquad (1)$$

to obtain values of $A_z$, the coefficient of turbulent mass exchange. The value of $A_z$ as determined from the original observations, includes any influence of convection that may be present in the atmosphere. Since both large convection currents and "convective turbulence", as defined by Priestley and Swinbank (1947) will modify the value of $A_z$ descriptive of eddy diffusion alone, it is logical to re-define $A_z$ by equation (1), rather than by a definition based on the statistical treatment of small scale eddies. By this change, $A_z$ is made to describe the state of mixing of the atmosphere as it actually exists, regardless of the process creating the turbulence or mass exchange. The analysis in Section IV, 1, is made with this definition of the coefficient. In Section IV, 3, a separation of the transport by diffusion and convection is accomplished.

Indirect methods of determining the rates of evaporation or transport of water vapor from land and water surfaces have been devised and used by numerous workers since Dalton (1802) established the relation between evaporation and the difference between aqueous vapor pressure in the air in contact with the water and in the air at a higher level. Sverdrup (1936, 1937), Montgomery (1940), Thornthwaite and Holzman (1942), and others, have used moisture and wind gradients in conjunction with theoretical turbulence relations, such as are summarized and developed more completely by Dryden (1943), to obtain expressions for the evaporation or transport in the atmosphere.

The evaporation and transport have been studied directly by several workers by observing modification of air masses. Lettau (1937) obtained observations from free balloon flights. Radiosonde data were studied by Petterssen (1940). Burke (1945) studied air mass modifications from weather maps, radiosonde, and ship reports, developing charts for use as forecasting aids. Craig (1949) studied airplane soundings taken over water surfaces to determine the eddy diffusion of water vapor in stable air.

2. *The ground layer and its inversion.*

*a.* Nomenclature.

The lower layers of the atmosphere studied in this work have received a confusing number of names from previous workers in the field. Some names are based on processes operating in the air: e.g., *turbulent layer*, *convective layer*, and *layer of frictional influence*. Others are based on properties of the layer: e.g., *homogeneous layer*, *mixed layer*, and *unstable layer*.

The notation *ground layer*, as defined by Flohn and Penndorf (1950) seems best suited for the general case, and is adopted in the present report. The layer has been subdivided into three regions: a *bottom frictional region* defined by an increase in the value of the coefficient of turbulent mass exchange, an *upper frictional region* defined by a decrease in the coefficient, and a third region, called *peplopause* by Schneider-Carius (1947), but here designated as the *inversion region*. The ground layer, continuing with the Flohn and Penndorf nomenclature, is bounded below by the two meter stratum, called the *bottom layer*, and above by the *advection layer*.

The normal type ground layer (Schneider-Carius, 1947a) has been studied exclusively in the present work. Figure 1 has been drawn to show the main features of the normal type ground layer and to identify and compare the regions studied by authors using different nomenclature. Schematic temperature, mixing ratio, and exchange coefficient curves are shown with frequently occurring height ranges of a few significant boundaries. The well-developed, normal type ground layer is identified more easily by the approximately dry-adiabatic temperature lapse rate and small mixing ratio lapse rate ($10^{-9}$ cm$^{-1}$) than by the defining height variation of the wind. This is particularly true at the upper boundary where the upper frictional region is topped by the turbulence inversion.

*b.* The inversion region.

The low values of the turbulent mass exchange coefficient in the inversion cause the great decrease

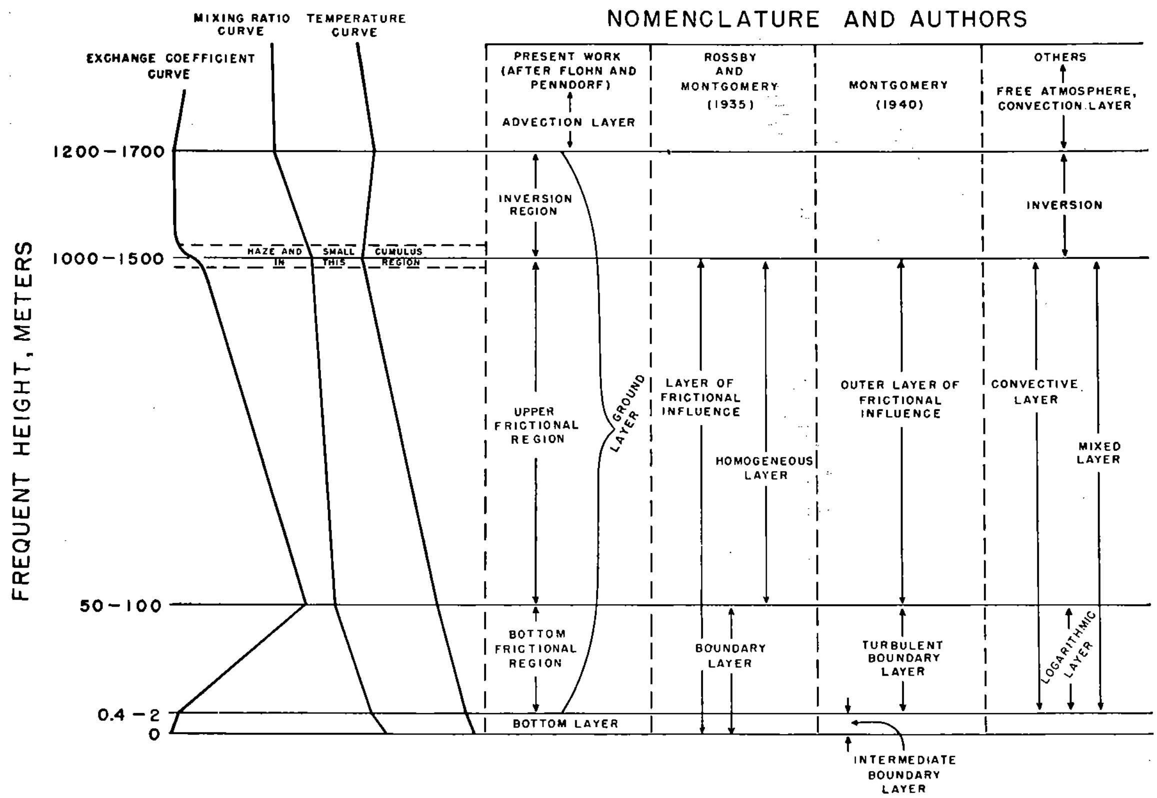


FIG. 1. Schematic vertical distribution of properties throughout the ground layer, and nomenclature of the subdivisions of the ground layer.

in the mixing ratio value that frequently is encountered in passing from the upper frictional region into the inversion. The sharpness of the boundary is shown by the potentiometer records of a test airplane flight with a humidity strip on January 5, 1951. Figure 2, a photograph of part of the record, shows a relative humidity decrease from 60% to 25% in a height interval of but 120 m.

The base of the temperature inversion may be observed visually from an airplane on many occasions through the development of a haze-layer. This phenomenon occurs whenever the inversion is strong, and relative humidities above 60–70% are created in the top of the upper region of the ground layer. Condensation of water vapor on the hygroscopic nuclei present in the air cause considerable absorption and scattering of light in a relatively thin layer of air. Figure 3, a photograph taken from an airplane flying at the level of the haze-layer, shows the dark band created by the absorption and scattering of light by distant water drops. Scattering of sunlight by drops nearer the plane produces a whitish light extending several degrees above and below the dark band. The effect is much more pronounced to the eye or on color film than on a black and white photograph, and is a great aid to an observer wishing to locate the top of the upper region of frictional influence.

The property of small transport between the ground layer and the advection layer, whenever separated by a strong inversion, has been used in the present work in the determination of the flow of water vapor into the atmosphere.

The magnitude of the flow of water vapor through the inversion during a polar outbreak has been investigated by the author (1950)[1] in an unpublished report, following the techniques of Hewson (1936, 1938). Radiosonde observations of the Weather Bureau were used as the source of humidity values. Two outflows of cPk air masses were followed from the Dakota-Montana region to the east coast. The increase in moisture above

[1] A. F. Bunker. Woods Hole Oceanographic Institution, Reference No. 50–21. Manuscript report to the Office of Naval Research.

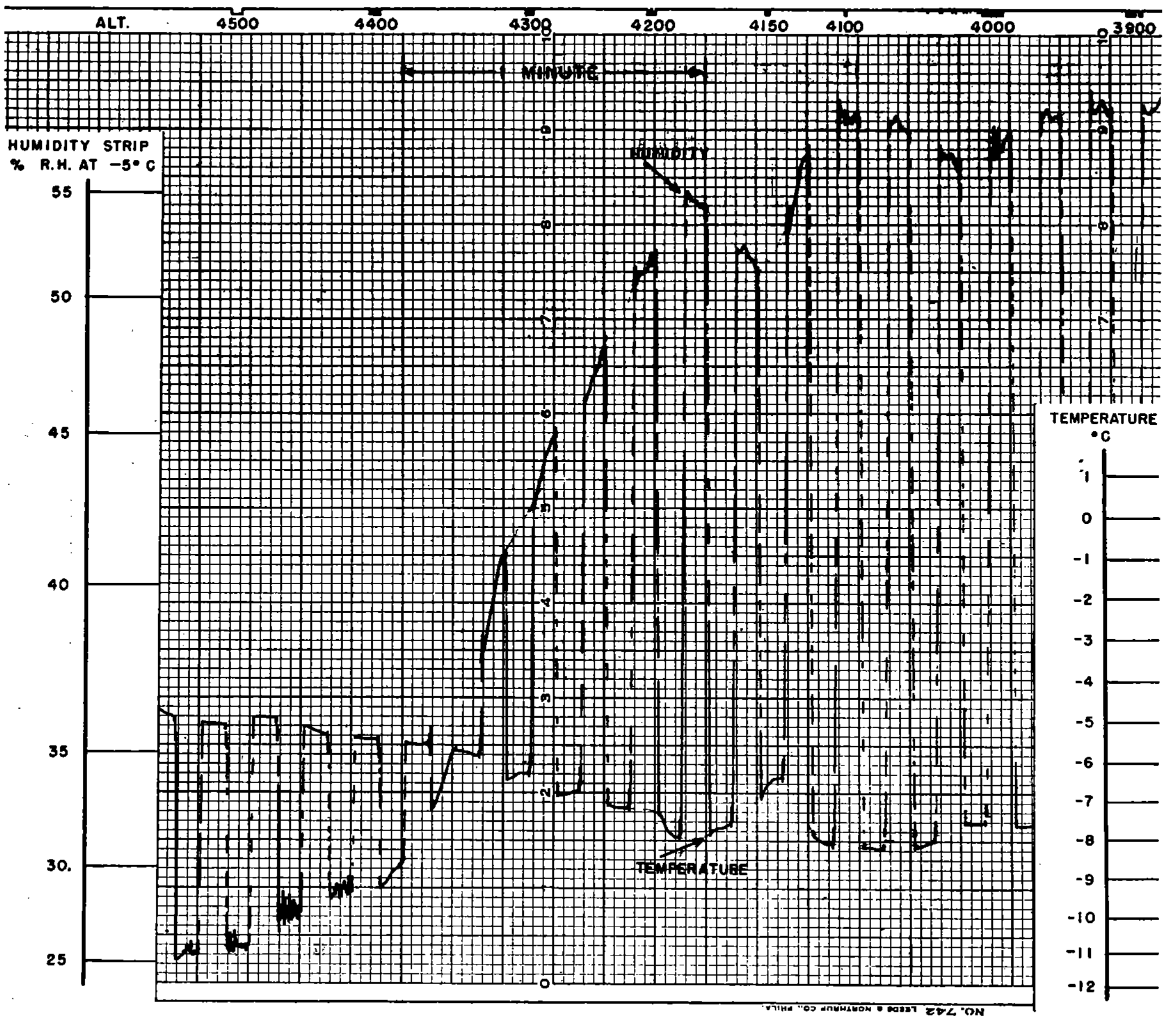


FIG. 2. Rapid humidity decrease through inversion base recorded during test flight January 5, 1951, with a radiosonde humidity strip adapted for airplane soundings.

the inversion during the passage of the air was noted. Flows through the base of the inversion were determined to lie between $1 \times 10^{-7}$ to $10 \times 10^{-7}$ gm cm$^{-2}$ sec$^{-1}$ $\pm$ $2 \times 10^{-7}$ gm cm$^{-2}$ sec$^{-1}$. The coefficient of turbulent mass exchange varied between 80 and 140 gm$^{-1}$ cm$^{-1}$ sec$^{-1}$ $\pm$ 75 gm cm$^{-1}$ sec$^{-1}$. The values of the flow and the coefficient at the top of the inversion vary from $1 \times 10^{-8}$ to $10 \times 10^{-8}$ gm cm$^{-2}$ sec$^{-1}$ $\pm$ $11 \times 10^{-8}$, and from 14 to 26 gm cm$^{-1}$ sec$^{-1}$ $\pm$ 100 gm cm$^{-1}$ sec$^{-1}$. As these probable errors are large, it is planned to recheck these values with airplane observations in place of the radiosonde observations. Taking into account the large probable errors, it is proven that a probable maximum of only $21 \times 10^{-8}$ gm cm$^{-2}$ sec$^{-1}$, or roughly 1.5% of the surface flow, diffuses through the top of the inversion. The average flow will be much less than this possible maximum flow.

The decision to use the ground layer inversion as a meteorological tool in the study of evaporation and water vapor flow by eddy diffusion was made after a brief study for this purpose of airplane soundings taken during the war years by the M.I.T. Radiation Laboratory. No reliable values were found since the soundings extended to only 1000 feet, while water vapor was transported to higher levels in cases of an unstable layer. This limitation prevented the determination of the total amount of water vapor transported and stored in the atmosphere. An approximate value could be found by using the lowest inversion shown by

FIG. 3. Layer of haze photographed from an airplane flying overland at the inversion base level on February 3. 1950. Air to ground visibility below haze was better than 50 km.

radiosonde observations taken in the region. The values determined from the study of the M.I.T. data have never been published, but agree quite well with values found in the present investigation. The study of these data was invaluable in that it pointed out the need of continuing the airplane soundings up through the inversion region.

It should be pointed out, however, that this negligibly small transport through the inversion is not a general property of the upper boundary of the ground layer, but rather is an infrequent occurrence. An inversion capable of severely limiting transport develops in a cP air mass only when the air aloft is quite stable and subsidence occurs in the air mass as it travels out of the polar regions. At other times, and in other geographical regions, considerable amounts of water vapor are transported through the ordinarily weak inversion or stable region. In fact, the entire hydrological cycle of water vapor through the atmosphere depends on easy passage through this boundary layer.

Cumulus clouds occasionally developed in the ground layer studied in this report, but rarely broke through the inversion into the air aloft. Instead, the clouds came to rest after penetrating only 100 or 200 meters of the inversion air, then fell back into the turbulent air.

Figure 4 is a photograph of the clouds over the Gulf of Maine, February 3, 1950. Their small vertical development and uniform tops are the result of the rapid damping by the strong inversion and demonstrate that, at least on this particular day, no moisture escaped by convection into the upper air.

### 3. *Geographic areas and synoptic situation studied.*

The coastal water of New England served as the warm water surface for the study of diffusion