Influence of inversions upon precipitation deposition of radioactive aerosols

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ABSTRACT

The role of the tropopause as a thermal barrier to aerosol transport and direct stratospheric tapping by precipitation processes has been studied extensively. Several different transport mechanisms across this inversion, including some involving precipitation-scavenging processes, have been postulated. Gradients of radioactive aerosols are also expected across low-level inversions within the troposphere. These are generally more accessible for experimental study.

Several of our studies on the meteorological influences on radioactive aerosol deposition by precipitation have involved the presence of inversions, both at the tropopause and at low levels. The inversion aspects of three prior studies are reviewed. The first involves the penetration of the tropopause by convective storms. Radiochemical and radar-meteorological analyses of two severe storms in Oklahoma in May 1963, both of which penetrated to heights above the tropopause, are compared to data for three contemporary convective storms in central Pennsylvania none of which penetrated the tropopause. The second concerns the changes in radioactivity concentration in precipitation associated with the overturning of the marine layer during a Pacific extratropical cyclone sampled at Santa Barbara, California, on February 7, 1962. The third involves an examination of the vertical distribution and transport by air motion and precipitation across the trade wind inversion at Hawaii during periods in 1963 and 1964.

1. Introduction

The effect of temperature inversions on the transport of aerosols in the atmosphere is of interest in the study of the deposition of radioactive aerosols. Transport mechanisms by air motions across the troposphere have been postulated by DANIELSEN (1959), STALEY (1962), and REITER (1964). Direct stratospheric tapping by convective activity has been suggested by KRUGER & HOSLER (1963) and, more recently, by DINGLE (1965). Temperature inversions also exist in the lower levels of the troposphere, where they are more accessible for experimental study.

During our investigations of meteorological influences upon deposition of radioactive debris by precipitation (KRUGER, HOSLER & MILLER, 1965), temperature inversions were noted to be of importance in three systems, those involving (1) convective activity and severe storms in Pennsylvania and Oklahoma (BOOKER, HAMADA & KRUGER, 1965), (2) a large-scale extratropical cyclone in California (KRUGER & MILLER, 1964) and (3) the trade winds in Hawaii (KRUGER & MILLER, 1965).

The detailed examinations of each of these three precipitation-producing systems have been given in their respective reports. Those features which involve the effect of an inversion are reviewed here.

2. Penetration of the tropopause

Our first indication of the effect of the tropopause on rainout deposition occurred in the study of an intense frontal system in Pennsylvania on March 8, 1961, in which scattered thunderstorms developed (KRUGER & HOSLER, 1963). This storm occurred more than 2 years after the cessation of atmospheric nuclear weapons tests in 1958, and about 6 months before the resumption in September, 1961.

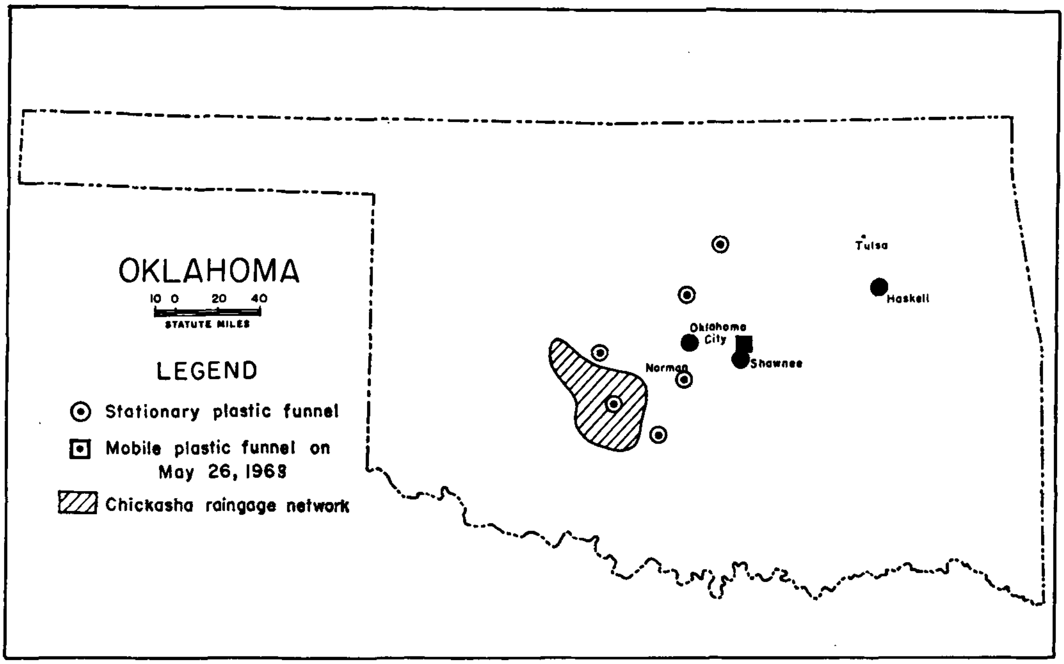


FIG. 1. Collection networks in Oklahoma for 1963. The shaded area is the Chickasha rain-gauge network of the May 4 storm. The solid points are the locations of the time collections of the May 26 storm.

Although the general levels of Sr^{90} in ground-level rain during this period were well below 10 dpm/liter, a rainshower collected from a convective cell during the March 8, 1961 storm yielded a concentration of over 50 dpm/liter. This cell developed, according to radar observations, under one of the "leaves" of the tropopause and in the vicinity of the jet stream.

Additional studies of convective storms in Pennsylvania (KRUGER & HOSLER, 1963) led to a hypothesis of direct tapping of radioactive debris from the stratosphere as condensation nuclei for precipitation occurring in convective storms in accordance with the thunderstorm model of BYERS (1959). High radioactivity concentrations could be expected during the mature stage of the thunderstorm when the cloud reached maximum height and when water might evaporate to sustain the downdraft. When the cloud tops also penetrate the tropopause, the availability of stratospheric radioactive aerosols could enhance the ground-level concentration even further. Such direct tapping of the stratosphere was considered as a possible mechanism acting in concert with the processes involving direct air transfer through the breaks in the tropopause to explain the increased deposition rates during the Spring months. The observations by DANIELSEN (1964), ANDERSON (1965), and others that thin layers of air of recent stratospheric origin could be found in the middle and lower troposphere with conserved aerosol content introduced still another parameter in the study of transport mechanisms across the tropopause.

During the 1963 severe storm season in Oklahoma, a study was made of the effect of tropopause penetration by convective storms. Showers were collected in the 170-raingage network of the Chickasha Agricultural Research Station and at several other sites, including a truck-mounted collector. These sites are shown in Fig. 1. Severe storms were sampled in these networks on May 4 and May 26, 1963. The latter storm included a family of tornadoes and was the subject of extensive studies. Our data for this storm is included in a comprehensive study of the storm being prepared by BROWNING & FUJITA (1965).

These two severe storms (BOOKER, HAMADA & KRUGER, 1965) were sampled during the same general period when three convective

TABLE 1. *Sr^{90} concentration in Oklahoma severe storms and Pennsylvania convective showers,* 1963. (1) is Haskell, (2) is Shawnee plus Midwest City, Oklahoma.

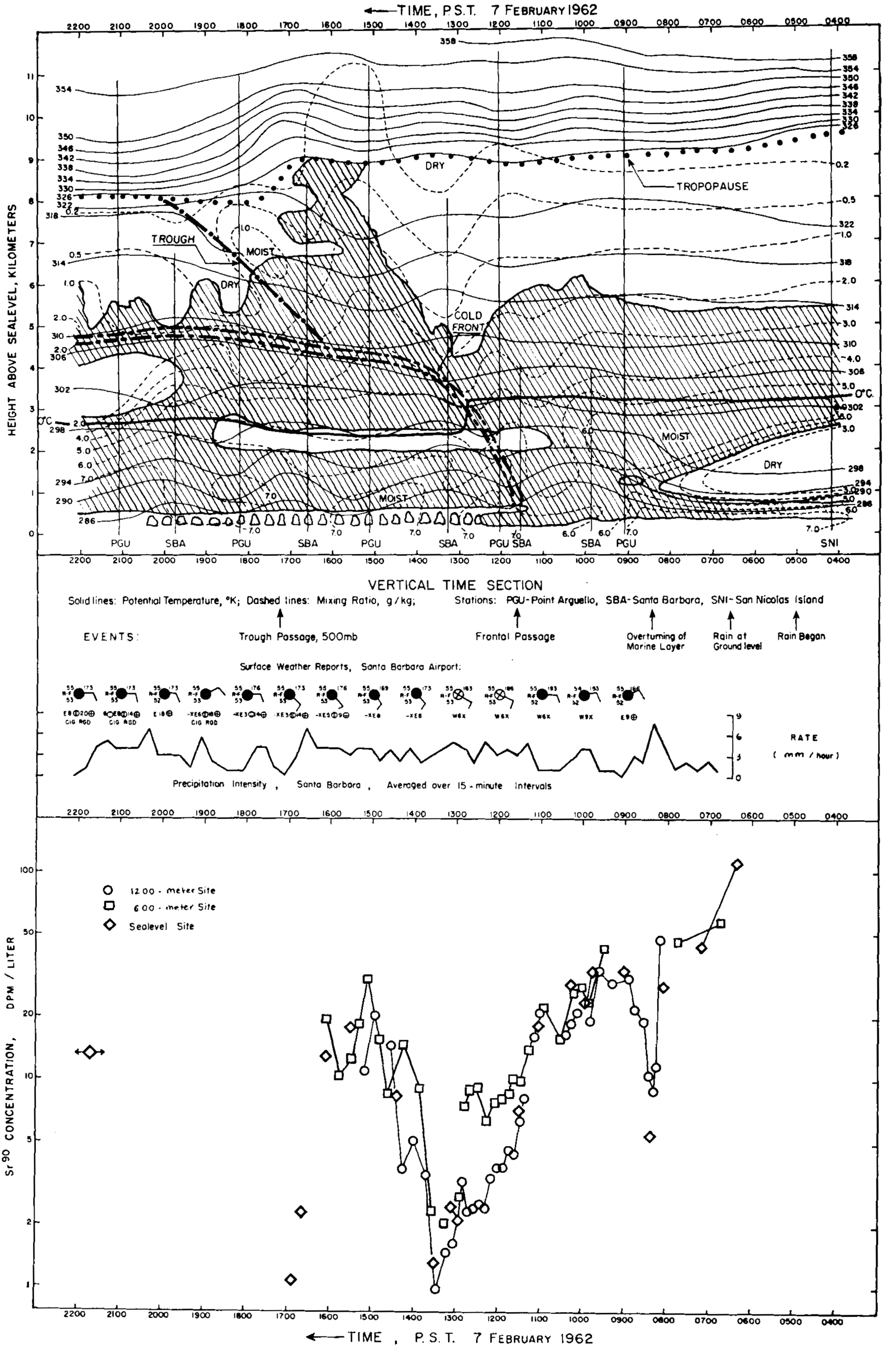
Storm, date	April 22	May 4	May 10	May 21	May 26
Location	Pa.	Okla.	Pa.	Pa.	Okla.
Peak Sr^{90} conc. (dpm/liter)	420	—	250	125	170 (1); 114 (2)
Ave. Sr^{90} conc. (dpm/liter)	205	195	165	85	88; 122 (1) 63 (2)
Max. radar echo tops (meters, MSL)	11,000	17,000	12,000	5,000	18,000; Est. 11,500 (1) 18,000 (2)
Tropopause ht. (meters, MSL)	12,000	11,500	13.500	12,000	12,000

shower storms were being sampled at our Pennsylvania site (KRUGER, DAVIS & HOSLER, 1964). The Sr^{90} data for these five storms, related to the height of the tropopause, are given in Table 1. These data show an apparent lack of high level nuclear debris concentrations in the severe storms. The cloud tops of these severe storms rose to heights of almost 20 km, well above the tropopause, while the cloud tops of the convective showers in Pennsylvania were all below the tropopause. The storms occurred during a period when considerable nuclear weapons debris existed in the stratosphere. The evaluation of these data is underway. However, with reference to temperature inversions, these data show the obvious difficulties associated with observations of the effect of the tropopause on aerosol transport at heights of about 15 km by sampling precipitation at sea level. Subsequent studies of inversion effects were made by examining aerosol transport across low-lying inversions by air motions and precipitation processes.

3. Overturning of a marine layer

Our first observation of the effect of a low-level inversion occurred during the study of a Pacific cyclone (KRUGER & MILLER, 1964) that was sampled near Santa Barbara, California, on February 7, 1962, at elevations of 50, 600, and 1200 m. The time section for this complex Pacific cyclonic storm is given in Fig. 2. The period of interest involving the effect of a marine inversion is shown by the event arrows at 0500 PST when rain began, 0630 when rain reached ground level, and 0830 when the marine layer overturned. During this latter period, the Sr^{90} concentration dropped from about 30 to about 6 dpm/liter, and then recovered to about 30 dpm/liter. The time section shows the existence of a moist marine layer up to about 650 m, topped by a dry middle layer, and an altostratus cloud layer associated with the approaching storm above the dry layer to a height of about 5500 m. The earlier rain from the altostratus clouds resulted in the saturation of the dry layer establishing a moist-adiabatic lapse rate in the layer. Fig. 2 also shows at this time a rise in rainfall intensity from about 1.6 to about 8 mm/hr. Since there was no evidence for strong convective activity in the upper levels, the increase in rainfall intensity was attributed to the water from the marine layer entering the precipitation processes. Since these drops of water formed within and below the marine inversion, it would be expected that the Sr^{90} concentration should be lower. With the completion of the overturning, the separate character of the lowest layer was destroyed and precipitation fell from the total layer between sea level and about 5500 m. It is noted that this description is dependent upon the postulate that a gradient of Sr^{90} aerosol concentration existed across the marine inversion. The postulate is supported by the observations of WOODCOCK (1953) and others on the effect of the trade-wind inversion as a barrier to sea-salt transport. To examine the role of marine inversions more fully, we initiated a study of the transport of radioactive aerosols by air motions and precipitation across the trade-wind inversion at Hawaii.

FIG. 2. Meteorological and radiochemical analysis of a Pacific Coast storm at Santa Barbara, California, on February 7, 1962. The event arrows at 0500, 0630, and 0830 PST, depict the period of interest involved in the overturning of the marine layer.



TIME, P.S.T. 7 FEBRUARY 1962
HEIGHT ABOVE SEALEVEL, KILOMETERS
TROPOPAUSE
TROUGH
MOIST
DRY
COLD FRONT
0°C.
PGU
SBA
SNI
VERTICAL TIME SECTION
Solid lines: Potential Temperature, °K; Dashed lines: Mixing Ratio, g/kg;
Stations: PGU-Point Arguello, SBA-Santa Barbara, SNI-San Nicolas Island
EVENTS:
Trough Passage, 500mb
Frontal Passage
Overturning of Marine Layer
Rain at Ground level
Rain Began
Surface Weather Reports, Santa Barbara Airport:
RATE (mm / hour)
Precipitation Intensity, Santa Barbara, Averaged over 15-minute Intervals
1200 - meter Site
600 - meter Site
Sealevel Site
Sr 90 CONCENTRATION, DPM / LITER
TIME, P.S.T. 7 FEBRUARY 1962

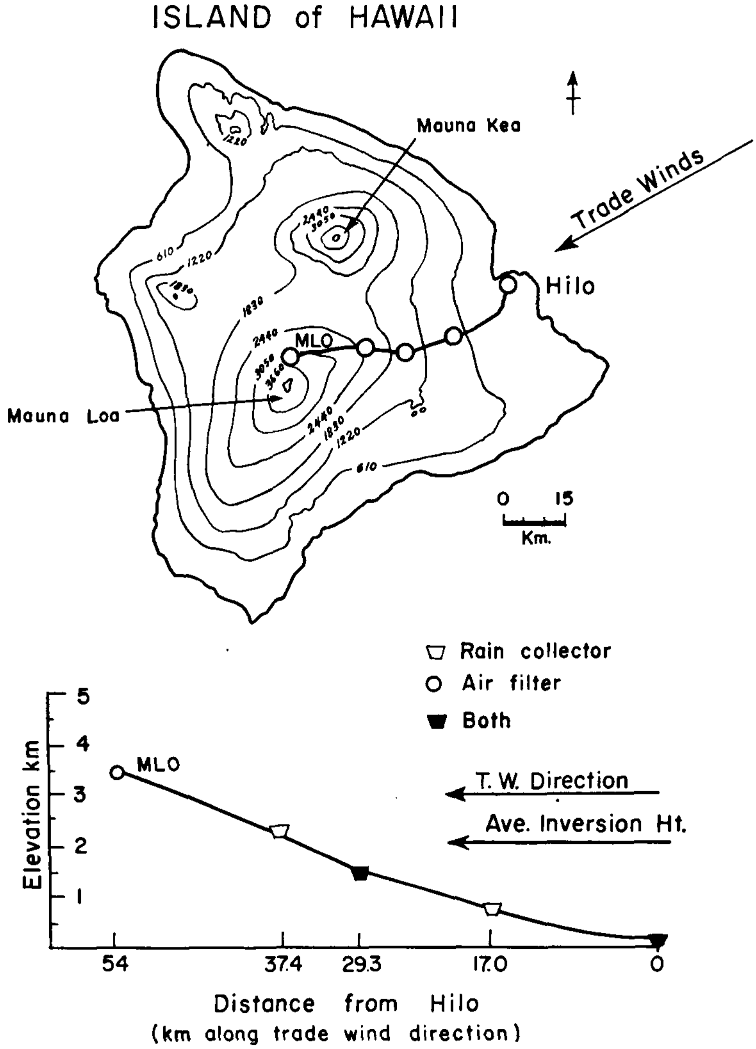


FIG. 3. Mauna Loa Volcano, Hawaii. Topography and collection network.

4. Trade-wind inversion

The collection network on the island of Hawaii is shown in Fig. 3. This location has been shown (PROJECT SHOWER, 1957, and PRICE & PALES, 1963), to be well suited for this study because of the gentle orographic lifting associated with the Mauna Loa Volcano average slope of 7 % to a height of over 4 km, and the trade-wind inversion normally present at a height of about 2 km.

During one-week periods in July, 1963, and August, 1964, air-filtered aerosol samples and trade-wind showers were collected at the locations shown in Fig. 3 (KRUGER & MILLER, 1965). The aerosol samples were collected on microsorban filters in high-volume Staplex air filters for about 4 hours each at a flow rate of about 2 m^3/min. The precipitation samples were taken as time aliquots in 3.34 m^2 stainless steel funnels. Soundings of the atmosphere were taken at frequent intervals by radiosondes released at the U.S. Weather Bureau station at Hilo, Hawaii. Additional soundings were taken by pilot balloon ascents and by an aircraft carrying an aerometeorograph.

During the July, 1963 period very little rainfall occurred. The inversion was strong and persistent at about 3000 m, with little moisture above the inversion. Fig. 4 shows the mean conditions prevailing during this period. The air concentration of radioactive aerosols shows a well-defined gradient across the inversion. The ratio for the altitudes of 10:1500:3400 m is 1:2:5.

The week of collections in August, 1964 was more successful, in that both dry-air filter samples and trade-wind showers were obtained. The atmospheric and radioactive aerosol concentration data were prepared as time sections and are shown in Fig. 5. The atmospheric time section shows the individual radiosondes (R), the pilot balloons (P), the aircraft soundings (A), the temperature and humidity gradients. The inversion heights are given in both time sections as rectangles. The gross beta concentration in the lower time section is given in pc/100 SCM.

The oscillations in the boundary of the surface moist layer are indicated by the mixing ratio gradient (the dashed lines in Fig. 5 are mixing ratios in g/kg). It is noted that these oscillations are accompanied by changes in the vertical distribution of the radioactive aerosols. The lowering of the inversion height and humidity layers during the two dry periods at about 1500 HST on August 6, and about 1500 HST on August 7 corresponds to the two periods of maximum increase in the aerosol radioactivity, especially at the 1500 m level, which would be expected to reflect more strongly small changes in inversion height. With the onset of the

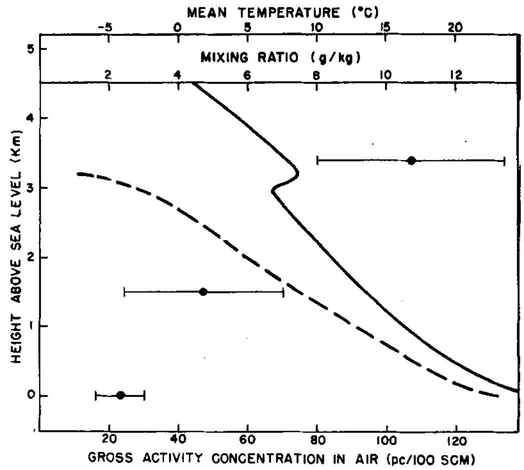


FIG. 4. Relationship of gross activity concentration gradient to the temperature and humidity profiles. The mean temperature (solid line), mixing ratio (dashed line), and gross activity concentrations (with average deviation) are for the period July 10–13, 1963, at Hilo, Hawaii.

TABLE 2. *Sr^{90} concentrations as a function of altitude for showers moving upslope.*

July 12–13, 1963

Collection altitude (meters)	July 12, 1963 Time period (hst)	July 12, 1963 Mean Sr^{90} conc. (pc/l)	July 13, 1963 Time pdriod (hst)	July 13, 1963 Mean Sr^{90} conc. (pc/l)
10	0633–0718	14.8	0940–0952	28
750	0737–0834	7.6	1023–1128	39
1500	0803–0903	1.3	1015–1145	8.5
2250	0842–0951	0.7	1200–1237	4.1

August 8–9, 1964

Collection altitude (meters)	By 4-hour periods				By significant changes			
	Start 2400	0000 0400	0400 0800	0800 end	Start 0310	0310 0500	0500 0710	0710 end
10	7	2.1	1.9	0.4	3.3	0.6	3.0	1.5
750	12	0.8	1.1	2.0	1.4	1.0	1.1	2.0
2500	0.6	0.5	1.0	1.4	0.5	0.5	0.9	1.5
2250	0.3	0.3	0.6	0.6	0.3	0.4	0.6	0.5

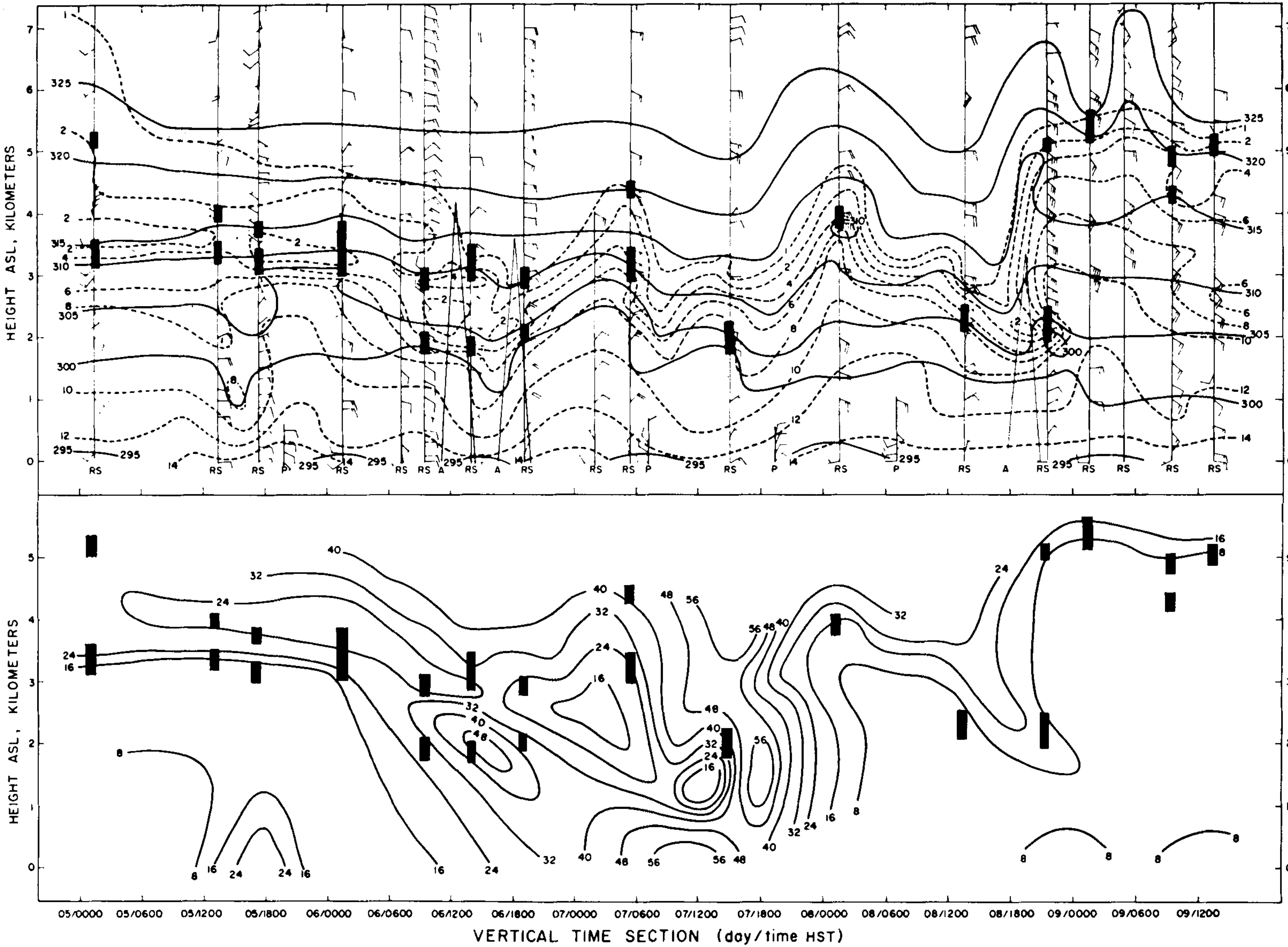


FIG. 5. Cross sections of the atmosphere (top) at Hilo, Hawaii, and radioactive aerosol concentration (bottom) along the slopes of Mauna Loa for the period August 5–9, 1964. The solid lines are potential temperature (°K), the dashed lines are mixing ratio (g/kg). The winds are given with full barb/4 ms^{-1} and the temperature inversion as rectangles. The soundings are shown with RS for radiosondes, P for pilot balloons, and A for aircraft. The gross beta concentration isopleths are in pc/100 SCM.

shower period on August 8, the aerosol concentration decreased at all levels. The temperature inversion and humid layer reached to a height of over 5000 m, as a result of convective activity, destroying the character of the trade wind conditions. A description of the Sr^{90} concentration in these showers is given by KRUGER & MILLER (1965). The Sr^{90} concentrations as a function of altitude for showers moving up the slopes of Mauna Loa are summarized in Table 2. The data show that the concentration gradient below the inversion height is negative, in agreement with terrestrial-origin aerosol studies of WOODCOCK (1953) and DUCE, WINCHESTER & VAN NAHL (1965), even though a positive gradient of radioactive aerosols is expected with height in the air. These results are interpreted (KRUGER & MILLER, 1965) in terms of the cloud physics processes occurring below the trade-wind inversion.

5. Summary

Although the data given here are only the first resulting from our study of inversions, they clearly show the marked effects the presence of temperature inversions may have on transport and deposition of radioactive aerosols. A gradient of concentration has been seen to exist across the trade-wind inversion, and changes in the vertical distribution of moisture with time were coincident with changes in the vertical distributions of the radioactive aerosols. Mixing between the surface moist layer and the upper dry layer appeared to be associated with oscillations of their boundary at the inversion.

Current efforts include the analysis of aerosols and trade-wind showers collected at four altitudes (with one at 2250 m for filtered aerosols in addition to those shown in Fig. 3) over a three-week period in July, 1965, and plans to study the continuity and characteristics of the trade-wind inversion as it moves from the ocean to onshore and up the slopes of Mauna Loa Volcano.

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ВЛИЯНИЕ ИНВЕРСИЙ ТЕМПЕРАТУРЫ НА ВЫМЫВАНИЕ РАДИОАКТИВНЫХ АЭРОЗОЛЕЙ ОСАДКАМИ

Была подробно изучена роль тропопаузы, как теплового барьера для переноса аэрозолей и прямого статосферного вымывания их осадками. Было предположено несколько различных механизмов переноса через зону инверсии, включая некоторые сложные процессы вымывания осадками. В нижнем инверсионном слое тропосферы также ожидается наличие градиента концентрации радиоактивных аэрозолей, но они, как правило, более доступны для экспериментального изучения.

В некоторых исследованиях влияния метеорологических элементов на вымывание радиоактивных аэрозолей нами было рассмотрено наличие обеих инверсий: в тропопаузе и в нижнем слое. С точки зрения наличия инверсии пересмотрено три предшествующих исследования. Первое включает рассмотрение проникновения через тропопаузу посредством конвективных штормов. Сравниваются данные радиохимического и радарного анализов двух сильных штормов в Оклахоме в мае 1963 г. с данными трех умеренных штормов в центральной Пенсильвании. Причем оба шторма в Оклахоме проникали в область над тропопаузой, в то время как в Пенсильвании нет. Второе рассматривает изменения радиоактивности осадков, связанных с сильным перемешиванием приземного слоя во время Тихоокеанского экстратропического циклона в Калифорнии, названного Santa Barbara (7 февраля 1962 г.). Третье исследование рассматривает вертикальное распределение радиоактивных аэрозолей и перенос их посредством движения воздуха и осадков через зоны инверсии в пассате на Гаваях в течение 1963 и 1964 годов.