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CONDENSATION TRAILS -

WHERE THEY OCCUR AND WHAT CAN BE DONE ABOUT THEM

By Richard V. Rhode and H. A. Pearson

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

NACA

WASHINGTON

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CONFIDENTIAL BULLETIN

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FOREWORD

A brief, nontechnical discussion of condensation trails is presented for flying personnel. World maps showing trail-forming zones at different altitudes and seasons are presented. Means for suppressing trails are given.

NATURE OF CONDENSATION TRAILS

Condensation trails are of three types:

1. Exhaust trails - Formed by condensation of moisture from the engine exhaust.

2. Convection trails - Formed under certain atmospheric conditions as a result of rising of air warmed by passage of the airplane.

3. Aerodynamic trails - Formed by precipitation of atmospheric moisture as a result of adiabatic temperature drop associated with air flow past the airplane.

The enumeration of three distinct types of condensation trails should not, of course, be construed to mean that combinations of these types are not possible.

<u>Exhaust trails</u>.- The exhaust trail is the most important from military considerations, as it may be rather consistently encountered at some altitudes and latitudes. It is peculiar to high-altitude operations and is explained as follows:

The hydrogen of the fuel used combines with oxygen from the air and forms water. When normal aviation gasoline is burned in an engine, about 1.25 pounds of water is formed as vapor and is discharged with the exhaust for each pound of fuel burned.

Behind the engine-carrying body (fuselage or nacelle) a turbulent region or wake is formed as the airplane flies. The exhaust moisture and some of the engine heat are discharged into this wake and become diffused throughout the wake as a result of the mixing action of the turbulence. The moisture and heat do not, however, mix with the air outside the wake because there the air is "smooth."

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The vortices in the wake grow and rotate more slowly as they pass downstream from the airplane. Thus the wake expands and decays. During this process the energy of the turbulence is dissipated as heat as a result of viscosity or friction, and finally so much energy has been dissipated that the wake can no longer continue to grow. This point is reached at a mile or more behind the airplane, the exact distance being somewhat indefinite and dependent upon the speed and power of the airplane. By this time, because of the action of wing-tip vortices, the wake has changed in form from its original compact cross section to a more or less flat ribbonlike form with curled-up edges, but this change in form does not involve any further mixing of the water vapor with the air.

It is easy to see that, if the air is so cold that it cannot hold much water as vapor, the water in the exhaust may be sufficient, when added to the moisture already in the atmosphere, to raise the humidity in the turbulent wake to or beyond the saturation value. If this condition exists, some of the water vapor will condense and a visible trail will form.

Since the turbulent wake is narrow near the airplane, the density of moisture will be greatest at this location. Farther away, where the wake is larger and the exhaust moisture is more widely diffused, there will be less moisture density. Thus, under some conditions, a short trail may form that evaporates where the wake cross section becomes too large to maintain 100-percent humidity. If the amount of moisutre is great enough to more than saturate the wake at its final and greatest cross section, however, the trail will be persistent and will not disappear until it is finally blown away by the wind or dissipated by atmospheric turbulence.

From the foregoing explanation it is clear that exhaust trails are favored by

(a) Low temperatures.

(b) High atmospheric humidity (but at very low temperatures, persistent trails may form with very low humidity).

(c) High fuel consumption (high power and high specific fuel consumption)

(d) Low drag (less turbulence and narrow wake)

(e) Low speed (smaller final diameter of wake because of lower turbulent energy)

Convection trails.- All the heat from combustion of the fuel is discharged into the air behind the airplane except the heat lost by radiation. The air behind the airplane is thus warmed and expanded slightly, and it will therefore rise slowly, pushing up the unwarmed air above it. If the atmospheric lapse rate at flight level is not more than slightly less than the moist adiabatic lapse rate and, if the humidity is rather high, a continuous "natural" cloud will form behind and somewhat above the airplane. This type of trail is very wide and, in general, does not connect with the airplane.

Convection trails are favored by

(a) High power and fuel consumption

(b) Lapse rates on the verge of "conditional instability"

(c) High humidity

Aerodynamic trails.- When the air flows past the wings, the propeller, and other parts of the airplane, there are reductions of pressure that cause "adiabatic cooling" of the air. This cooling may be great enough to raise the humidity relative in the affected regions to 100 percent or more and, in such cases, condensation will take place. For the most part, after passing the airplane, the air comes back to atmospheric pressure and to substantially atmospheric temperature, and the condensate will evaporate immediately and leave no trail. There are, however, regions within which the pressure and the temperature remain less than atmospheric for a considerable distance downstream, such as, for example, the cores of the wing-tip and propeller-tip vortices. Condensate may persist in such regions until the vortices decay.

When the humidity is very high, evaporation can be so slow that a persistent or semipersistent trail will form even in the regions where the pressure and the temperature have returned to atmospheric values. If conditions are favorable for such trails to form at subfreezing temperatures, furthermore, the condensate may freeze and may remain more persistent than at high temperatures.

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In general, under conditions of very high humidity (both specific and relative) "wing" trails or "wing-tip" trails will form. As a rule, but not without exception, wing-tip trails will persist where ordinary wing trails will immediately evaporate.

Wing trails are favored by

(a) High speed and wing loading

(b) Very high humidity

(c) High temperatures (the trails may persist longer if the temperature is not above freezing)

Wing-tip trails are not appreciably affected by speed changes. They are favored by

(a) High wing loading

(b) High humidity

(c) High temperature (the trails may persist longer if the temperature is not above freezing)

In general, both the aerodynamic trail and the convection trail are sporadic and rather rare in occurrence because they require relatively unusual combinations of conditions. At present they cannot be predicted with certainty or with ease. The exhaust trail, on the other hand, will nearly always occur at certain high altitudes and latitudes and is most important from the military standpoint.

ZONES OF OCCURRENCE OF EXHAUST TRAILS

World maps are included herein to show the zones of occurrence of exhaust trails at the different seasons of the year. These maps are based on available data on monthly

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mean values of temperature and humidity and apply specifically to the B17-E airplane in normal heavy cruising condition. The maps will apply reasonably well, however, to any modern airplane, provided the power output per engine at the upper altitudes is about the same as that of the B17-E.

At the time of preparation of these maps, sufficient data were available to permit reasonably exact determination of the trail zones only over the North American continent, the western half of the Atlantic Ocean, and the eastern third of the Pacific Ocean in the Northern Hemisphere. The zone boundaries shown elsewhere are pure estimates, and they are presented as such, pending compilation of the data required to construct more exact maps.

No boundary lines are shown in the Southern Hemisphere because of lack of data. Trail zones in this hemisphere may be roughly estimated from the following rules:

1. The mean south latitudes of the zone boundaries in the Southern Hemisphere for the month of July will be about the same as the mean north latitudes of the zone boundaries in the Northern Hemisphere for the month of January. The same rule applies for the other complimentary months.

2. Zone boundaries will have a tendency to bulge toward the poles over the Southeast Pacific and the Southwest Atlantic and to bulge toward the equator of the western coasts of the continents of South America and Africa.

It should be borne in mind that such maps are merely representative of average conditions, because the maps are based on mean atmospheric temperatures and humidities. It should also be borne in mind that the maps apply to specified operating conditions of a single airplane. In general, the boundary lines on any given map will come toward the equator for climbing conditions, recede toward the poles for diving or gliding conditions, approach the equator for airplanes having greater single-engine power than the B17-E, and recede toward the poles for airplanes having less power than the B17-E.

SUPPRESSION OF TRAILS

If a trail is formed, there are certain measures available to the pilot for suppressing or eliminating them. An enumeration of these measures follows:

Exhaust trails.— In principle, the only completely effective method of preventing exhaust trails is to remove the water from the exhaust by means of water-recovery apparatus. Because such equipment is not available and apparently is not practicable at the moment, other means of suppression that can be only partly effective must be resorted to. These other means will, of course, be more effective in regions or at altitudes where the trails are not of great density and vice versa.

1. If reduction of altitude is permissible, throttle engines and glide at high speed to a lower level.

2. If net loss of altitude is not permissible, go into a shallow power dive at substantial increase in speed. Regain altitude by zooming. (Short lengths of persistent trail may be formed during latter part of zoom.) Alternative: Fly at reduced power.

3. If some reduction in speed is permissible with same power output and fuel consumption, as during climb, open engine cowl flaps as wide as possible. (Airplanes without cowl flaps could be equipped with similar drag-producing devices.)

The effect of these various expedients will, if conditions are not too difficult, be to transform a long, persistent trail into a short dissipating one or to shorten still further a dissipating trail. The trails will probably not disappear entirely in all cases except when rule 1 is applied.

Convection trails.—

1. Climb or descent to new level. (A change of altitude of 1000 to 2000 feet should be ample in most cases to eliminate trail completely.)

2. Stay away from level of stratus and strato-cumulous cloud formations.

Aerodynamic trails.– Owing to the fact that wing-tip trails are little affected by speed changes, there is no way in which the pilot can manipulate the airplane to cause immediate and complete cessation of all aerodynamic trails. In general, however, the following procedures should help if they can be applied:

1. Throttle engine and reduce speed.

2. Reduce altitude below freezing level.

3. Climb or descend to new altitude to get out of humid layers.

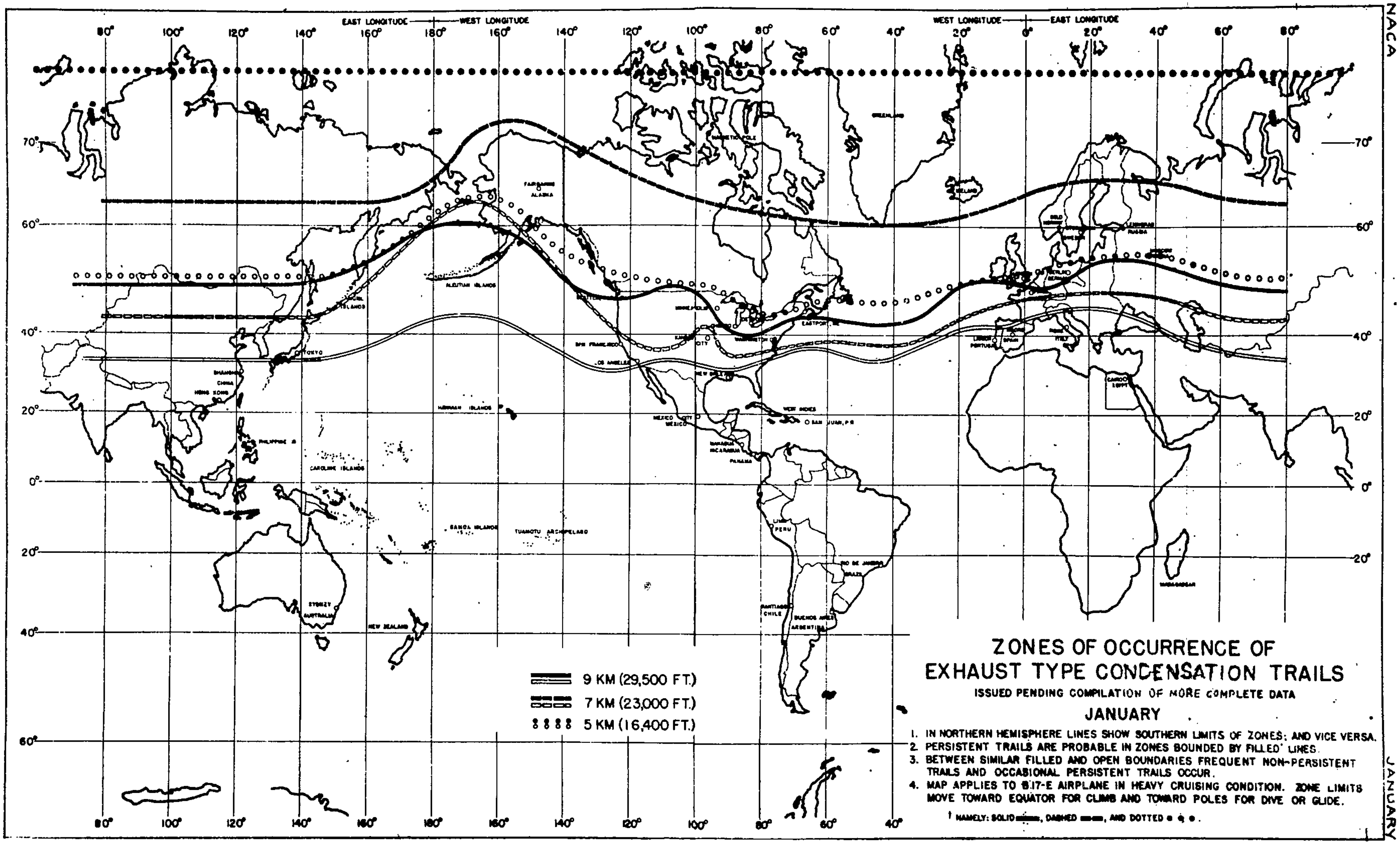
4. Avoid flying near the elevation of stratus-type cloud formations.

FLIGHT IN THE STRATOSPHERE

The British in preliminary investigations have concluded that persistent exhaust trails will cease a short distance above the tropopause. They lay great stress, therefore, on the desirability of flying in the stratosphere on bombing missions. It should be pointed out here that the NACA investigation does not bear out this conclusion. The true explanation of the British findings is believed to be that in their tests the tropopause was close to the ceilings of the airplanes used and considerably above the critical altitudes. The engine powers, therefore, were at low levels and the trails ceased because of reduced power and amount of moisture discharged per unit volume of trail. Their trails probably could have been made to cease at any elevation below the tropopause by throttling the engines in accordance with rule 1 or 2 governing suppression of exhaust trails. An exhaust trail from any airplane should be greatly suppressed, if not entirely eliminated, when the airplane is flying well above its critical altitude and near its ceiling, wherever these altitudes may be and regardless of the elevation of the tropopause.

It should be clearly understood that flying into the stratosphere will not, of itself, cause cessation of trails as far as is shown from the fundamental nature of trail phenomena.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va.



ZONES OF OCCURRENCE OF EXHAUST TYPE CONDENSATION TRAILS

ISSUED PENDING COMPILATION OF MORE COMPLETE DATA

JANUARY

1. IN NORTHERN HEMISPHERE LINES SHOW SOUTHERN LIMITS OF ZONES; AND VICE VERSA.
2. PERSISTENT TRAILS ARE PROBABLE IN ZONES BOUNDED BY FILLED† LINES.
3. BETWEEN SIMILAR FILLED AND OPEN BOUNDARIES FREQUENT NON-PERSISTENT TRAILS AND OCCASIONAL PERSISTENT TRAILS OCCUR.
4. MAP APPLIES TO B-17-E AIRPLANE IN HEAVY CRUISING CONDITION. ZONE LIMITS MOVE TOWARD EQUATOR FOR CLIMB AND TOWARD POLES FOR DIVE OR GLIDE.

† NAMELY: SOLID, DASHED, AND DOTTED.

JANUARY

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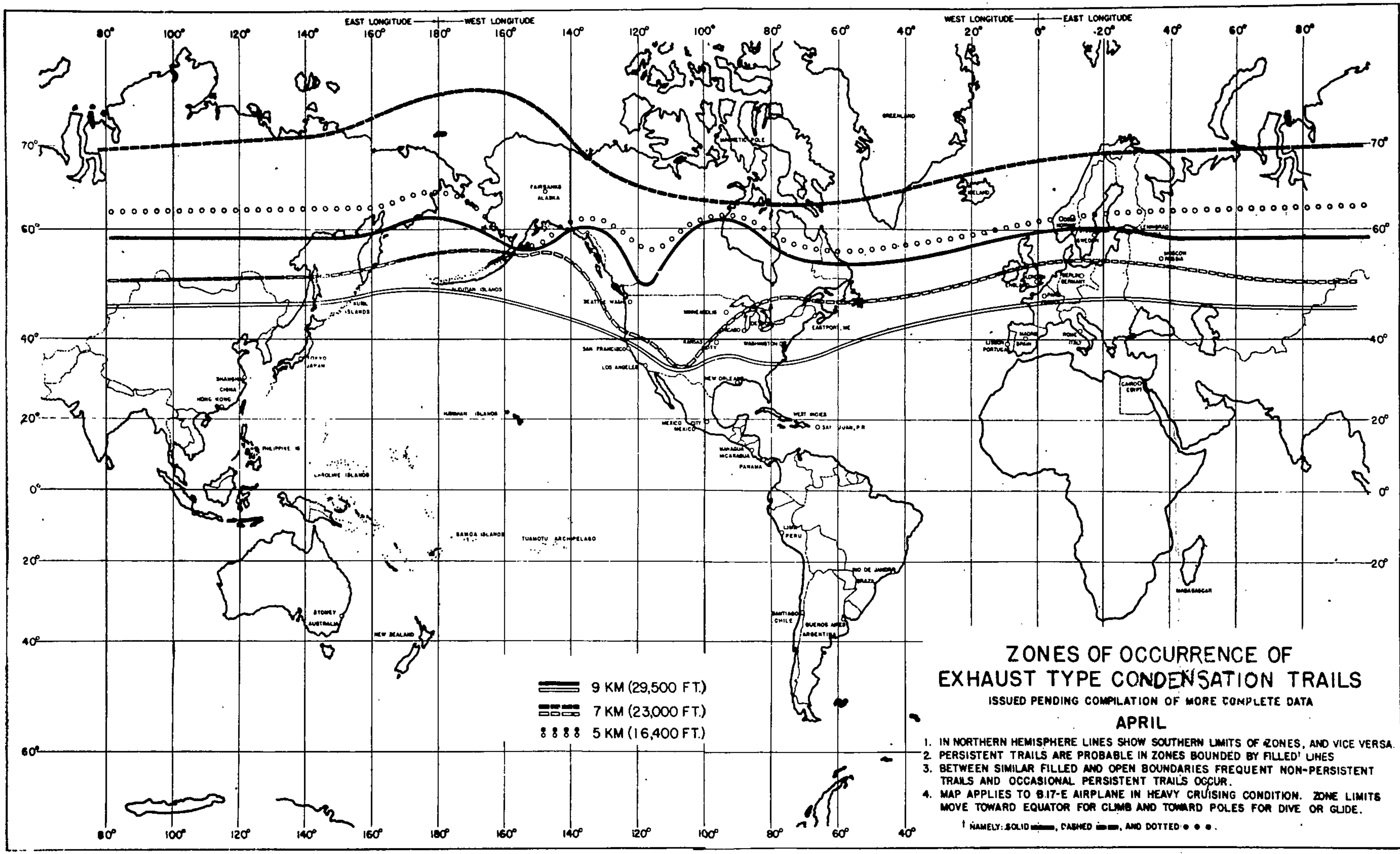

ZONES OF OCCURRENCE OF EXHAUST TYPE CONDENSATION TRAILS

ISSUED PENDING COMPILATION OF MORE COMPLETE DATA

APRIL

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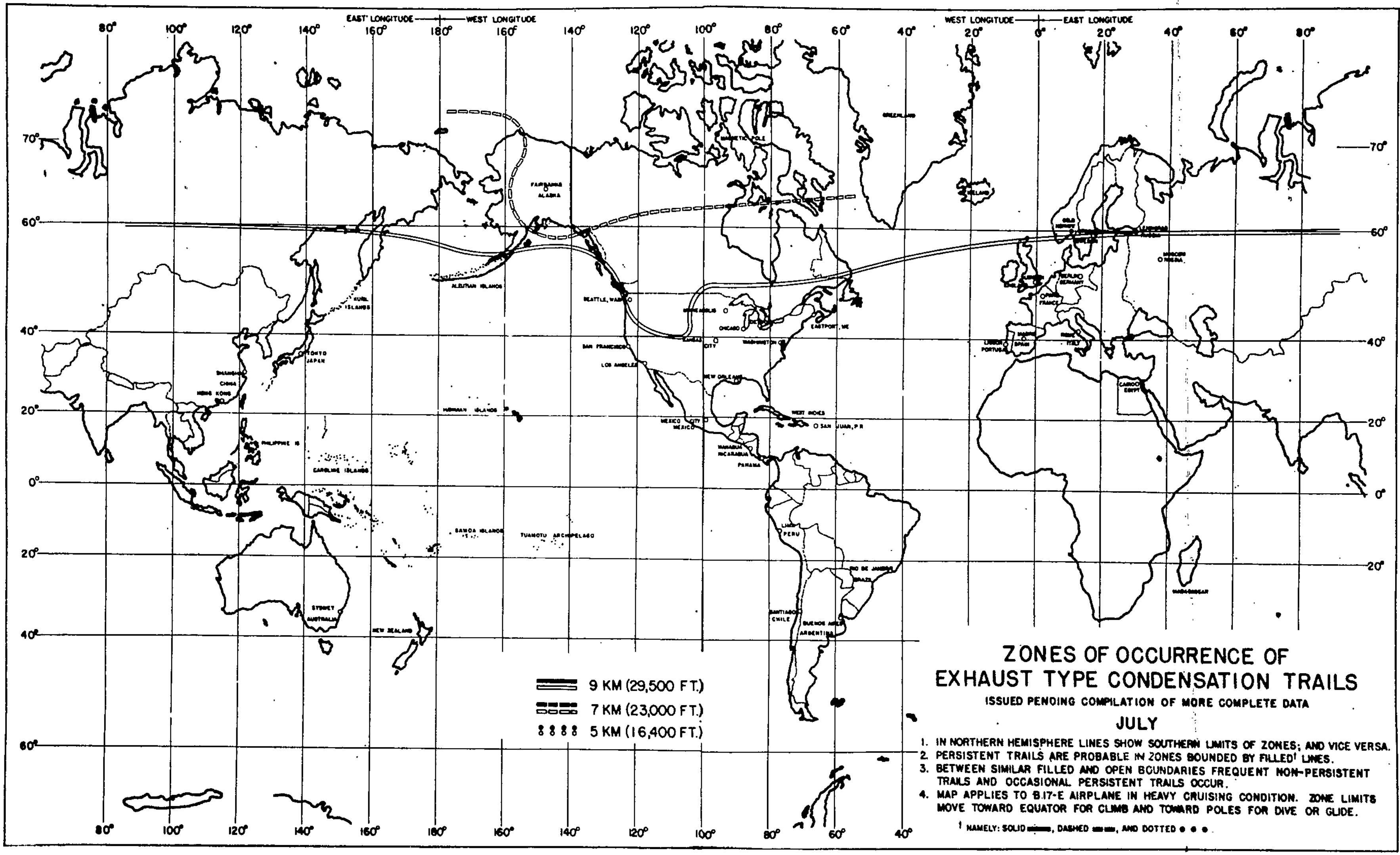

ZONES OF OCCURRENCE OF EXHAUST TYPE CONDENSATION TRAILS

ISSUED PENDING COMPILATION OF MORE COMPLETE DATA

JULY

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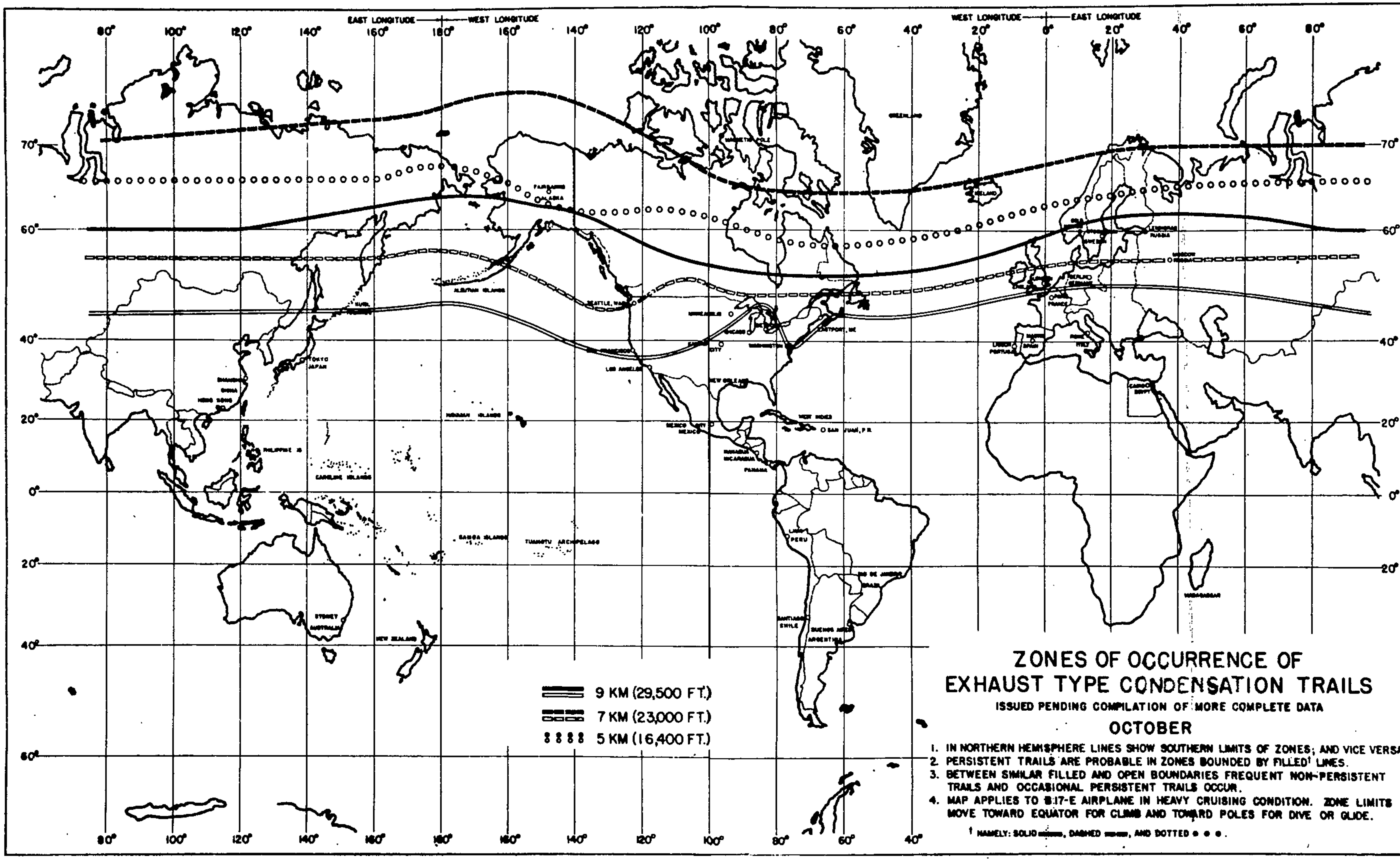
JULY



ZONES OF OCCURRENCE OF EXHAUST TYPE CONDENSATION TRAILS

ISSUED PENDING COMPILATION OF MORE COMPLETE DATA

OCTOBER

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