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RESEARCH ARTICLE

STUDYING AND ANALYSIS OF THE POLLUTANT DISTRIBUTION TRAJECTORY FROM ETHIOPIAN VOLCANO USING HYSPLIT CODE

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Abstract

In this study, the atmospheric transport of airborne contaminants released from an Ethiopian volcanic eruption is investigated using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model.This is done within the framework of environmental radiological dispersion, as defined by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the International Atomic Energy Agency (IAEA). The evolution of plume transport from the initial release phase to long range atmospheric dispersion is charact erized using forward trajectory simulations, which are equivalent to the behavior of radioactive aerosols after an unintentional or unplanned release. The analysis shows that source term characteristics, in particula r buoyancy-driven plume rise and effective release height, have an impact on early plume transmission, which is in line with radiological source-term notions. Advection in the regional and synoptic-scale wind fields, vertical wind shear, and atmospheric stability are the main factors influencing atmospheric transport at later phases. The cumulative consequences of atmospheric variability and stochastic transport processes are shown in the increasing spatial dispersion and divergence of trajectories. the results validate the use of trajectory-based atmospheric transport models for evaluating the long-range dispersion, transboundary movement, and possible environmental effects of radioactive elements in the air.

Introduction:-

On the environment, human health, and air quality at both regional and global levels, atmospheric pollutant dispersal is an important environmental issue that attracts a lot of attention in scientific studies. In situations where pollutants can travel great distances across geographic boundaries, it is especially crucial to comprehend the mechanisms of airborne pollutant transport in order to evaluate environmental hazards and create efficient plans for handling environmental emergencies. Studying the movement of particles, gasses, and aerosols in the atmosphere now requires the use of numerical models of atmospheric pollution dispersal. The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model is one of the most used models for modeling the movement of air pollutants. It is widely utilized in researching how volcanic ash moves, how smoke from forest fires and dust storms spreads, and how radioactive materials spread during radiological emergencies.The behavior of particles suspended in the atmosphere can be studied using volcanic eruptions as a natural model. Large amounts of ash and gasses are ejected into the upper atmosphere during volcanic explosions, where they may travel great distances due to prevailing wind patterns. The physical mechanisms, such as advection, diffusion, and vertical wind shear, that control the dispersion of radioactive aerosols from nuclear accidents also control the movement of volcanic ash clouds[1-5].Thus, understanding long-range atmospheric transport mechanisms—which are essential for evaluating the environmental dangers connected to airborne pollutants—can be gained by examining the transport patterns of volcanic clouds. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and the International Atomic Energy Agency (IAEA) are two international organizations that have stressed the significance of using atmospheric diffusion models when evaluating the environmental effects of radioactive materials and hazardous pollutants.In order to understand the physical mechanisms governing the long-distance transport of volcanic clouds [6-15] , this study will use the HYSPLIT airflow model to analyze the transport pathways of pollutants resulting from a volcanic eruption in Ethiopia. Ethiopia, in Northeast Africa, Ethiopia is 1,104,300 km2 in size and borders Sudan and South Sudan to the west, Djibouti and Somalia to the east, and Eritrea to the north. Kenya to the south. It will also evaluate the implications of these findings in the context of studies of airborne pollutant dispersion and their applications in the fields of environmental safety and radiological emergency response.

Methodology:-

The HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model, a numerical model based on the Lagrangian approach for computing particle motion in the atmosphere, was used to simulate pollutant transport patterns in this work. In order to compute air pathways and the movement of suspended particles in the atmosphere as a result of convection, diffusion, and atmospheric turbulence, the model uses climatic data from NOAA. In this work, the movement of the volcanic cloud released from the Ethiopian eruption site was represented using forward trajectory computations. After the eruption, the movement of air masses from the source site was monitored for a certain amount of time. The wind fields at various air levels, which directly affect the direction and velocity of pollution transport, are the basis for these computations.

Since the emission elevation plays a major role in regulating long-range transport pathways, a number of beginning elevations were chosen to reflect the degree of volcanic cloud injection into the atmosphere. In order to comprehend how several atmospheric elements, including vertical wind shear, large-scale winds, and atmospheric stability, affect the direction of volcanic cloud transport and its dispersion over time, the ensuing trajectories were examined. The HYSPLIT model, a physical model comparable to the dispersion of radioactive particles in the atmosphere during nuclear emergencies, allowed for the analysis of the volcanic cloud's dynamic behavior and the evaluation of its potential for long-distance transmission [16-18].

HYSPLIT MODEL: HYSPLIT is utilized for emergency reaction instances as well as research applications that call for simulating the movement and dispersion of dangerous contaminants in the atmosphere. The ATD (the atmospheric transport and diffusion) modeling of pollutants and hazardous compounds, as well as the deposition of these materials onto the Earth's surface, are all supported by the model. Applications include monitoring and predicting the emission of contaminants (like mercury) from several stationary emission sources, including volcanic ash, radioactive material, and smoke from wildfires [17-18]. Either puff or particle modes can be used in HYSPLIT to calculate a pollutant's dispersion. Additionally, there are hybrid puff/particle modes that can handle dispersion as a combination of puff and particle modes. In puff mode, puffs separate into multiple new puffs, each with its own portion of the pollutant mass, after expanding to a size greater than the meteorological grid cell (either vertically or horizontally). The particle mode uses a random turbulence component to disperse a predetermined number of particles that are advected over the model domain with the mean wind field. Dry deposition in HYSPLIT is either clearly defined as a deposition velocity or calculated using the resistance approach and surface characteristics. In HYSPLIT, deposition is only calculated when the particle center location or the puff's bottom is inside the surface layer. The deposition layer next to the ground is assumed to have a uniform vertical concentration distribution in order to determine the mass deposited. After the mass has been extracted from the puff or particle, it is distributed (deposited) onto the ground. Rainfall through a polluted layer and continuous ingestion of dirty air into a cloud from a polluted boundary layer are the two types of wet deposition processes[19-20]. A scavenging coefficient is employed for pollutant elimination in rain that falls below a cloud layer, while the simplifying assumption of a scavenging ratio is applied to particulate pollutants that are found within a cloud layer. The Henry's Law coefficient of soluble gases can be used to define wet removal. Only the portion of the pollutant below the cloud top is removed by gaseous wet removal. The advection–diffusion equations regulating atmospheric transport are solved using

HYSPLIT using these inputs. The main method used by HYSPLIT is a Lagrangian particle approach, in which pollutant mass constituents are represented by individual particles[21-24].

The trajectory of each particle is calculated using:

$$\frac{d\vec{X}}{dt} = U(x,t) + U^{\backslash}(t)$$

Where:
$\vec{X}(t)$ = vector of particle position
$\vec{U}$ = component of deterministic wind
$\vec{U}$= component of stochastic turbulent velocity
The turbulent component is often parameterized as:

$$U^{\backslash}(t) = \sqrt{2K\Delta t}\ R$$

Where:
K = eddy diffusivity
Δt = time step
R= random number from a Gaussian distribution

Results and Discussion:-

The air trajectory of the volcanic plume released from an Ethiopian volcano is shown in Figure (1), which also shows the routes taken by gases and volcanic ash after an eruption. High eruption temperatures create great thermal buoyancy, which causes the plume to ascend initially. When buoyant forces start to fade, large-scale air circulation takes over plume motion. It shows the early stage of the volcanic cloud's eruption from the Ethiopian volcano, and the curvature of the trajectories shows the influence of vertical wind shear and prevailing wind fields, suggesting that plume transmission is highly height-dependent. At this point, the cloud's direction is determined by the mid troposphere's wind speed. Figure (2) shows the cloud's initial forward motion shortly after eruption, with regional winds controlling the direction of transport while the cloud retains its density. Figure (3) shows the trajectories in the early post-eruption phase, when wind shear effects start to occur. There is a primary northeastward trajectory and a secondary eastward trajectory. The increased influence of vertical wind shear, which causes air parcels at slightly different heights to experience variable wind velocity and directions, is shown in the increasing distance between trajectories. Even when there isn't much turbulence, the plume is stretched both horizontally and vertically by this shear-induced deformation.

The trajectories in Figure (4) exhibit curvature and distinct transport paths, becoming more and more divergent over time. The observed curvature is a clear example of synoptic-scale wind turning with height, which is frequently linked to Coriolis forcing and pressure gradients. Even in the absence of variations in the intensity of eruptions, the plume continuously deforms as various layers are advected by various wind regimes. Plume trajectories that extend farther downwind and span a significantly greater geographic zone are shown in Figure (5). The long transmission distances show that the plume is a part of long-term, extensive circulation patterns. At this point, synoptic winds virtually control plume motion, with little any impact from nearby local meteorological factors. The trajectory envelope clearly widens in Figure (6). This widening is a result of the wind field's small-scale change over time. When combined over extended transport times, even little variations in wind direction and speed result in notable spatial dispersion. Plume paths in Figure (7) show a noticeable curvature.

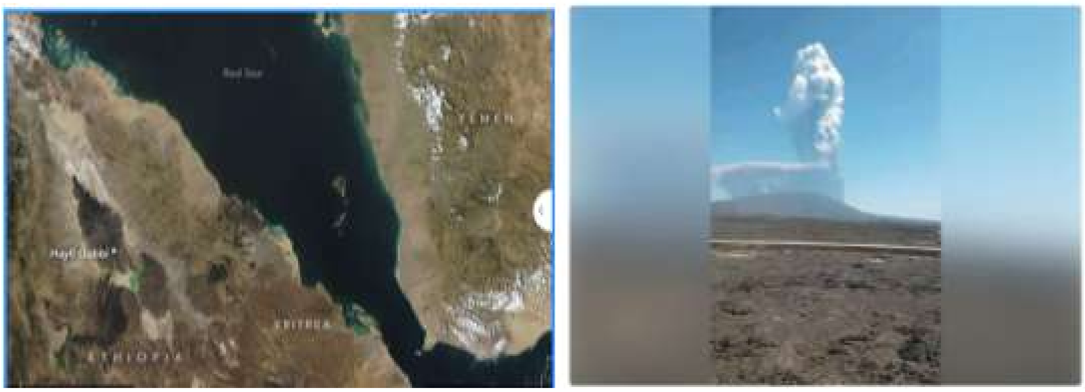
The plume's interaction with changing synoptic systems, including ridges or troughs, which reroute airflow at mid- and upper-tropospheric levels, causes the curvature. This impact has an entirely atmospheric origin and is unaffected by eruption feature. Figure (8) demonstrates that Ethiopian volcanic emissions have the ability to affect areas that are far from the eruption site, with plume trajectories spanning extremely great distances. Figure (9) shows several paths from the same starting point and notable directional diversity brought on by the modeling's differences in stack height. Figure 10: The routes are obviously in line with trade winds or subtropical jet streams and are connected to regional circulation systems. Figure (11): Potential deposition areas shift and the areas of influence gradually shift from a local to a distant regional scale throughout time. Figure (12): Radial propagation and significant spatial dispersion with a diminishing focal focus. Figure (13): The traces extend to regions that are quite remote from the source, such as North Africa and the Eastern Mediterranean. Figure (14): The accumulation of air contacts and lack of cohesiveness are reflected in the emission's final stages, which exhibit comparatively slow movement. Figure (15) shows randomly diverging trails due to severe air turbulence dominance and weak directional cohesiveness. Figure (16): shows the volcanic cloud's final overall track from Ethiopia to Northeast Africa. This all are because the volcanic plume is propelled into a rapid vertical rise within the troposphere by the substantial thermal buoyancy created by the exceptionally high temperatures at the time of eruption. The movement of the cloud is controlled by large-scale circulation systems as the buoyant forces eventually decrease as a result of the reduction of thermal density differences. The measured pathways' curvature, which is a reflection of vertical wind shear—the change in wind direction and speed with altitude—indicates that the vertical injection level has a significant impact on the cloud's movement. At this point, the middle troposphere winds control the main direction of movement, with horizontal advection taking center stage. While regional winds regulate the direction of travel, the air mass maintains its relative density.

The observation of a primary path toward the northeast and a secondary path toward the east indicates the predominance of horizontal advection processes prior to the onset of large-scale dispersion. The variations in wind properties between various atmospheric strata are reflected in this variation. The effect of vertical shear, in which air particles at relatively near altitudes are subjected to varying wind speeds and directions, is indicated by the growing separation between the trajectories. This causes the cloud to expand both horizontally and vertically, even when there aren't any significant atmospheric disturbances. Over time, the pathways clearly diverge and show increasing curvature. This curvature, which is caused by the Coriolis force and atmospheric pressure gradients, is a well-known illustration of wind rotation on the synoptic scale. As each layer moves within a distinct wind system, the cloud continues to experience structural deformation even in the absence of a change in the eruption's intensity. The routes span a larger geographic area and have a greater extension downwind. This suggests that the cloud has made its way into extensive, long-term circulation networks. At this point, local atmospheric influences become less significant, and synoptic winds nearly take over. It is clear that the path envelope is expanding. Little changes in the wind field's timing and location cause this expansion.

The enhanced global distribution can be explained by the substantial spatial dispersion that results from these alterations building up over an extended travel period. Because the cloud interacts with different pressure systems, such as high and low pressure systems, which reroute airflow in the intermediate and higher layers of the troposphere [25-30].Finally, The transport of the volcanic cloud resulting from the Ethiopian eruption is subject to several overlapping physical and atmospheric processes that control its direction of movement and spatial dispersion over time, according to the results of atmospheric trajectory simulations using the HYSPLIT model. The volcanic cloud is quickly lifted into the upper atmosphere during the early stages of the eruption due to the strong thermal buoyancy forces created by the high temperatures within the eruption plume. Large amounts of ash and volcanic gases are injected into the upper troposphere and possibly the lower stratosphere by this first lift. Because particles in these upper layers are subjected to distinct wind patterns than those at the Earth's surface, the cloud's initial injection altitude plays a significant role in determining its future dispersal course. After the first eruption period, the thermal buoyancy gradually decreases and large-scale air circulation takes over as the primary driver of the volcanic cloud's movement.

The vast range of the transport channels depicted in the simulation results can be explained by these winds' ability to carry volcanic particles horizontally over great distances over vast geographic areas. The findings also suggest that regional atmospheric pressure systems have an impact on the volcanic cloud's travel, which could lead to path deviations or direction changes over time. Vertical wind shear, or the change in wind direction and speed with altitude, is another significant factor influencing the volcanic cloud's behavior. The pathways of particles coming from the same source site gradually diverge as a result of this alteration, which causes various movements of air masses in different layers of the atmosphere. Even in the absence of significant atmospheric disturbances, vertical shear allows the volcanic cloud to extend both horizontally and vertically, as demonstrated by the increasing spread and divergence of the pathways over time.

The dispersal process becomes more complicated as the volcanic cloud's air transport lasts longer because of the impact of atmospheric disturbances and wind field fluctuations. This contributes to the widening of the spatial dispersion of the volcanic cloud and increases the uncertainty in estimating the exact paths of particles. According to simulation studies, these processes can carry contaminants far from the eruption site, making it more likely that they will reach far-off places. These results imply that a variety of atmospheric elements, including the height of the initial emission, large-scale wind systems, and vertical wind shear, can combine to cause volcanic cloud transport on regional and continental dimensions. Volcanic cloud research is a crucial natural model for comprehending the mechanisms of long-range atmospheric transport of dangerous pollutants because the study also shows that these same physical processes control the dispersion of radioactive particles in the atmosphere in the event of accidental radioactive emissions. As a result, studying the atmospheric trajectories of volcanic clouds not only helps to comprehend the dynamics of volcanic eruptions but also offers a crucial scientific framework for researching the movement of airborne pollutants and evaluating their possible environmental hazards, particularly in situations where pollution may cross geographical boundaries to areas distant from the emission source [31-36].



(a) (b)

Figure (1):

(a) depicts the air trajectory of the volcanic plume that was ejected from an Ethiopian volcano.

(b) Show that Ash billows from an eruption of the long- dormant HayliGubbi Volcano in Ethiopia

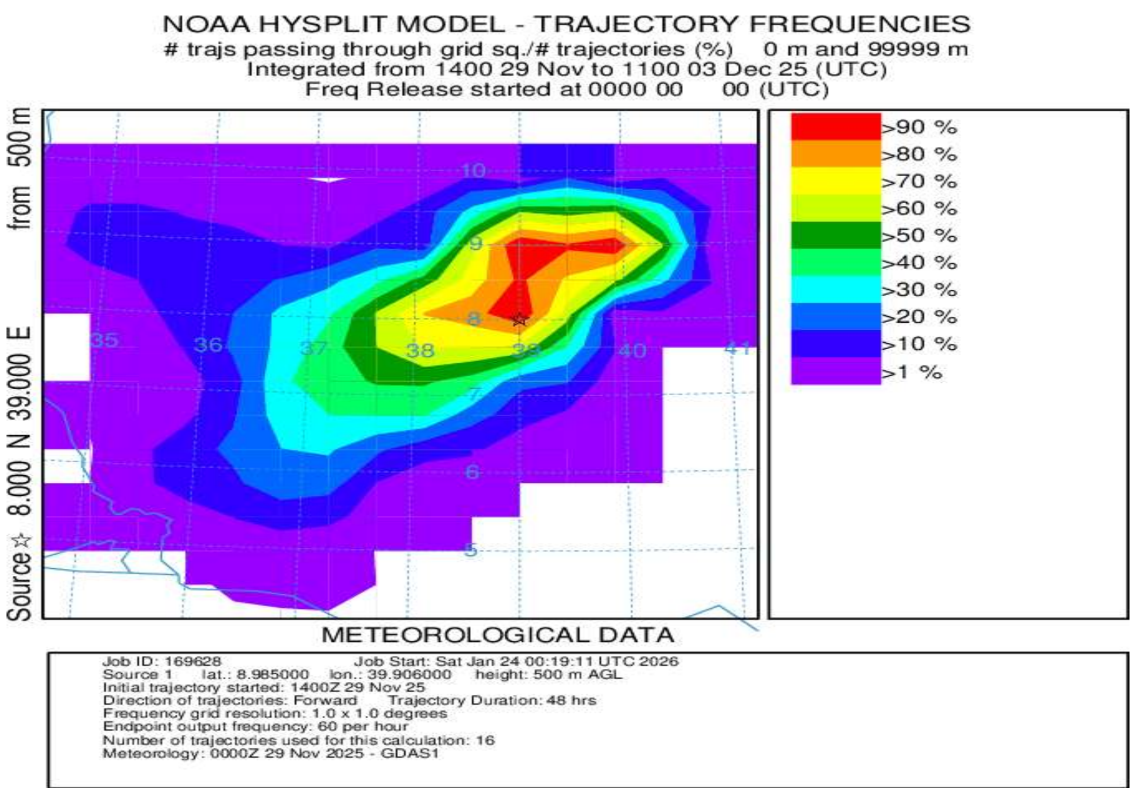


Figure (2) displays the volcanic plume's initial onward motions following the Ethiopian eruption.

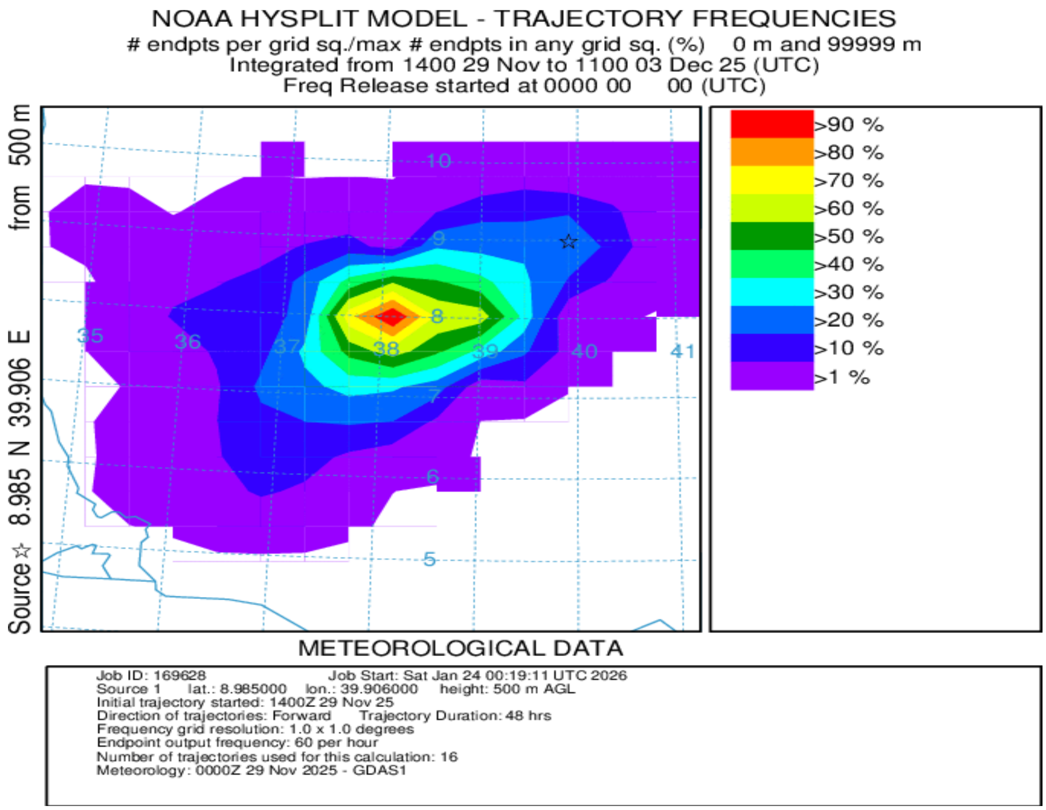


Figure (3) shows the plume trajectories in the immediate aftermath of the eruption.

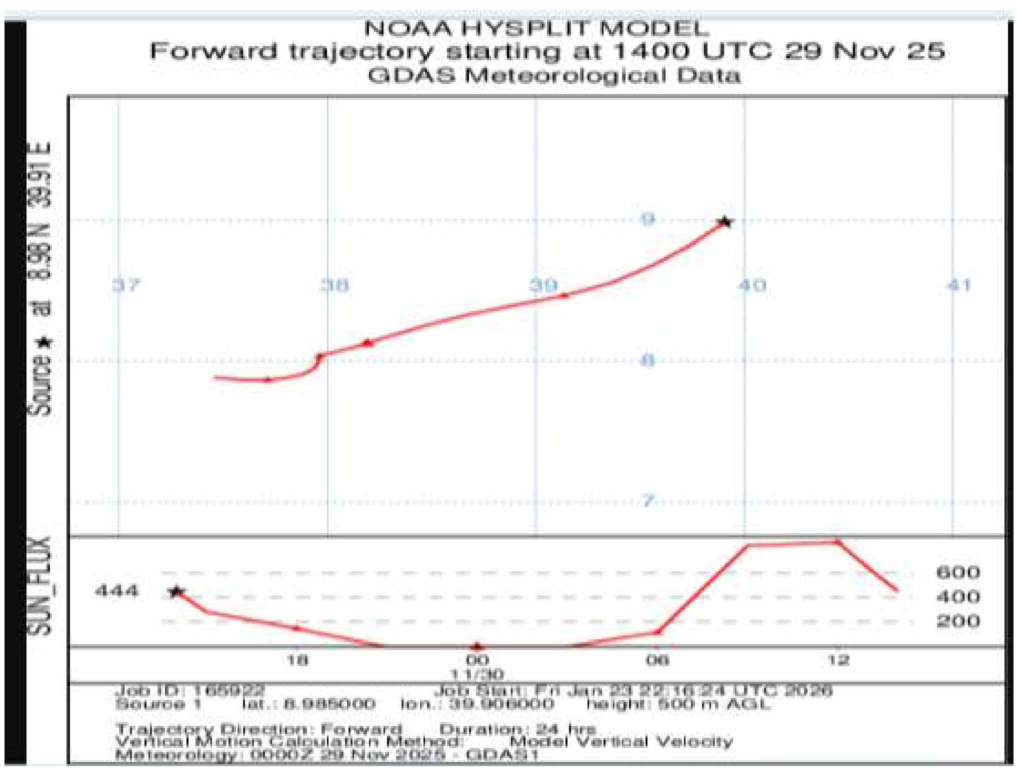


Figure (4) show increasing divergence due to curvature and separate transport pathways.

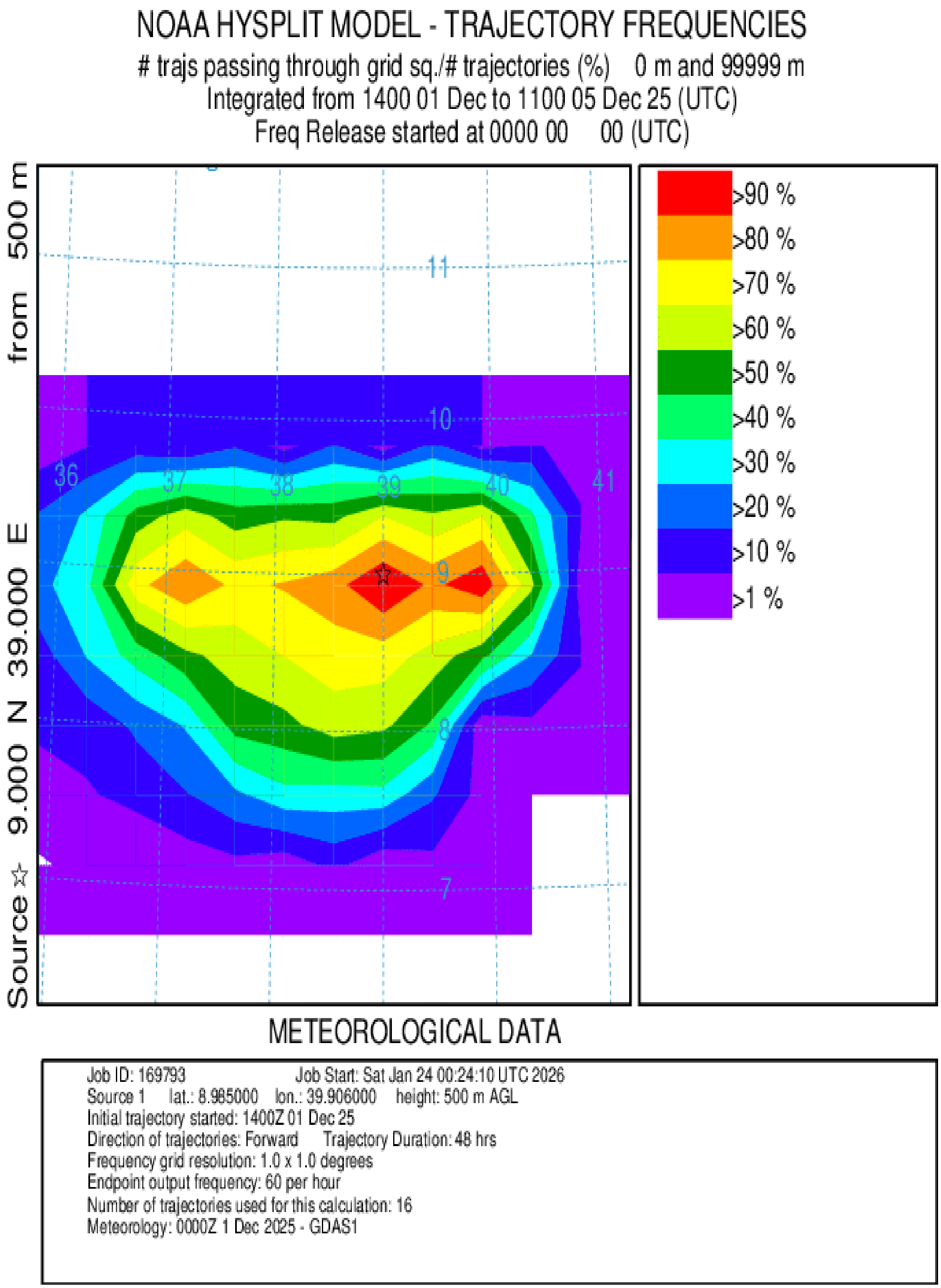


Figure (5) displays plume trajectories that cover a substantially larger geographic zone

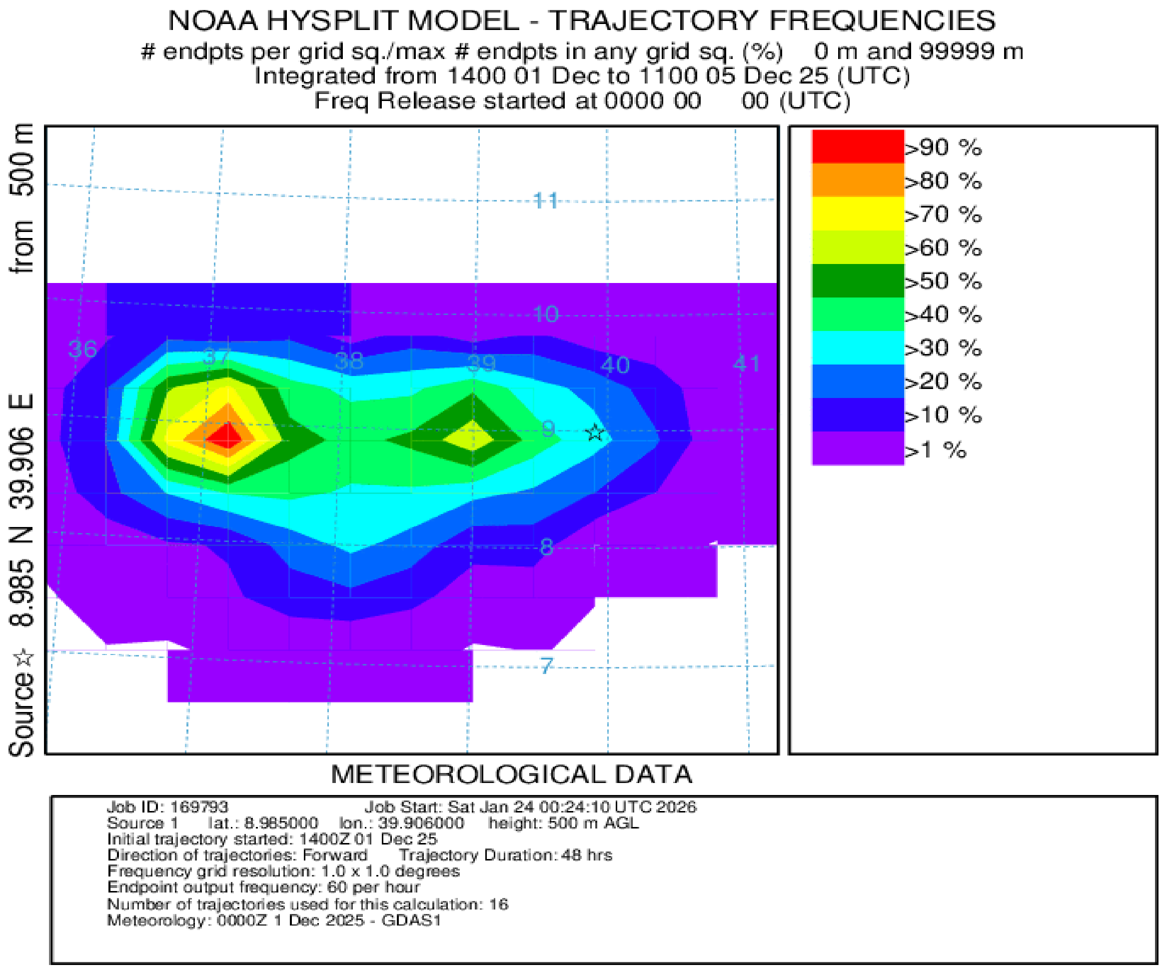


Figure (6) shows a noticeable widening of the trajectory envelope.

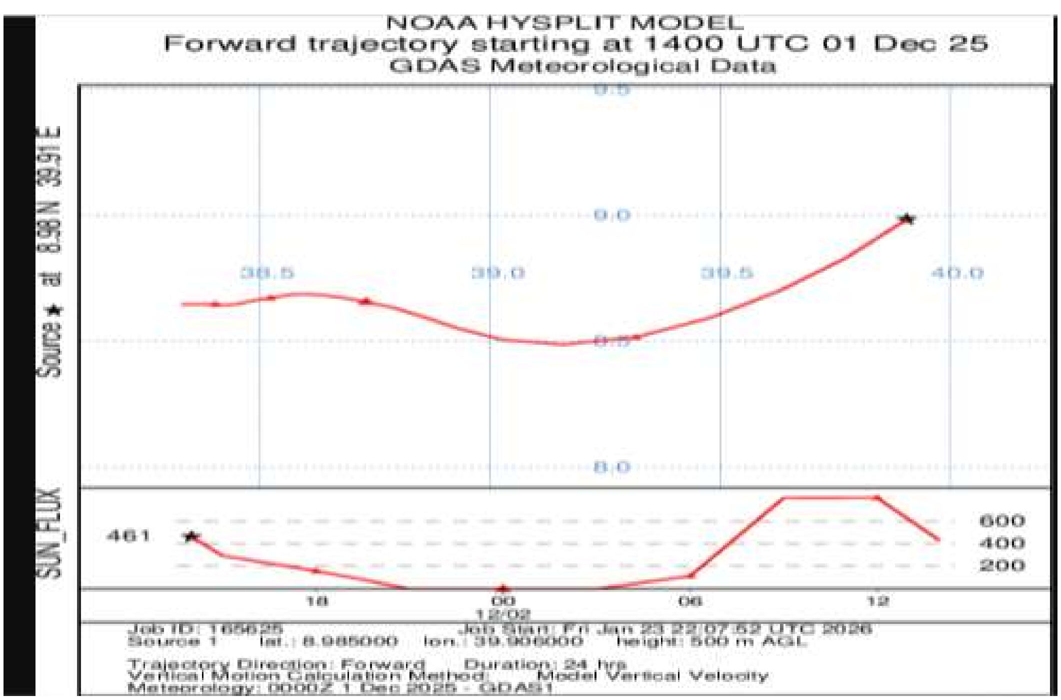


Figure (7) shows plume trajectories have a discernible curvature.

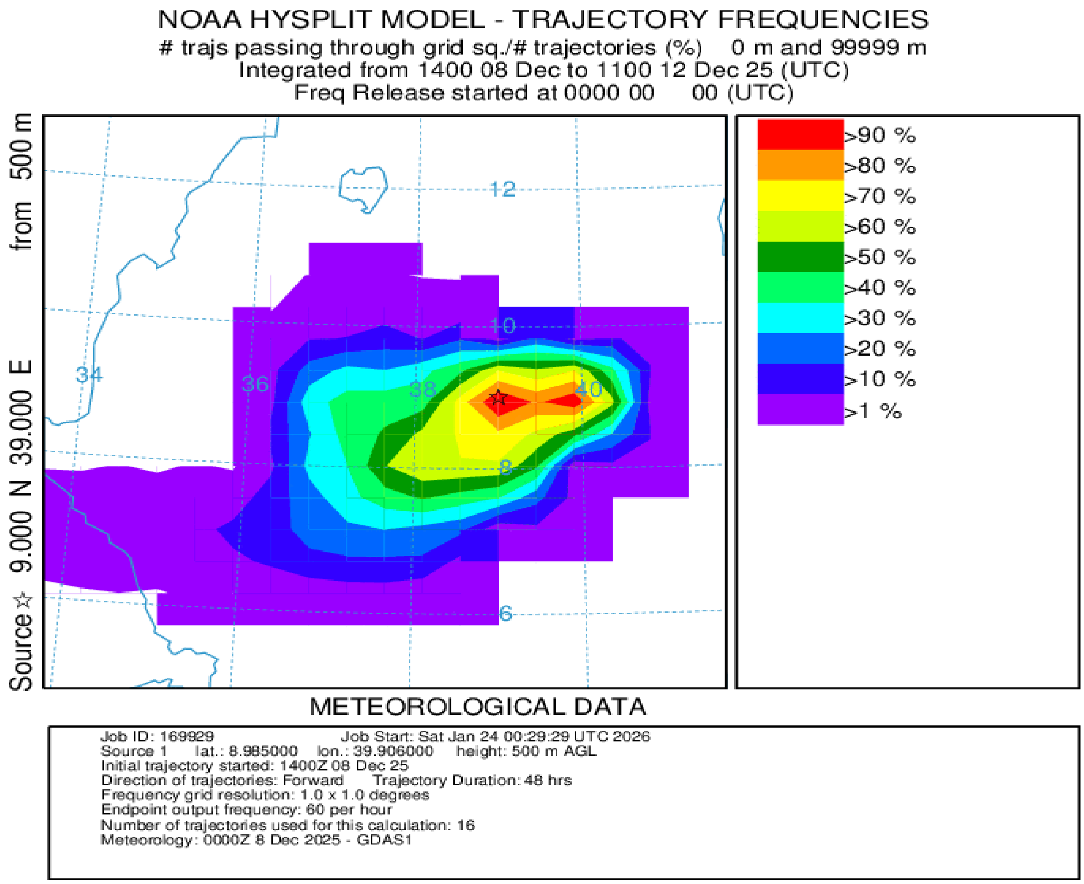


Figure (8) demonstrates that Ethiopian volcanic emissions from the eruption site.

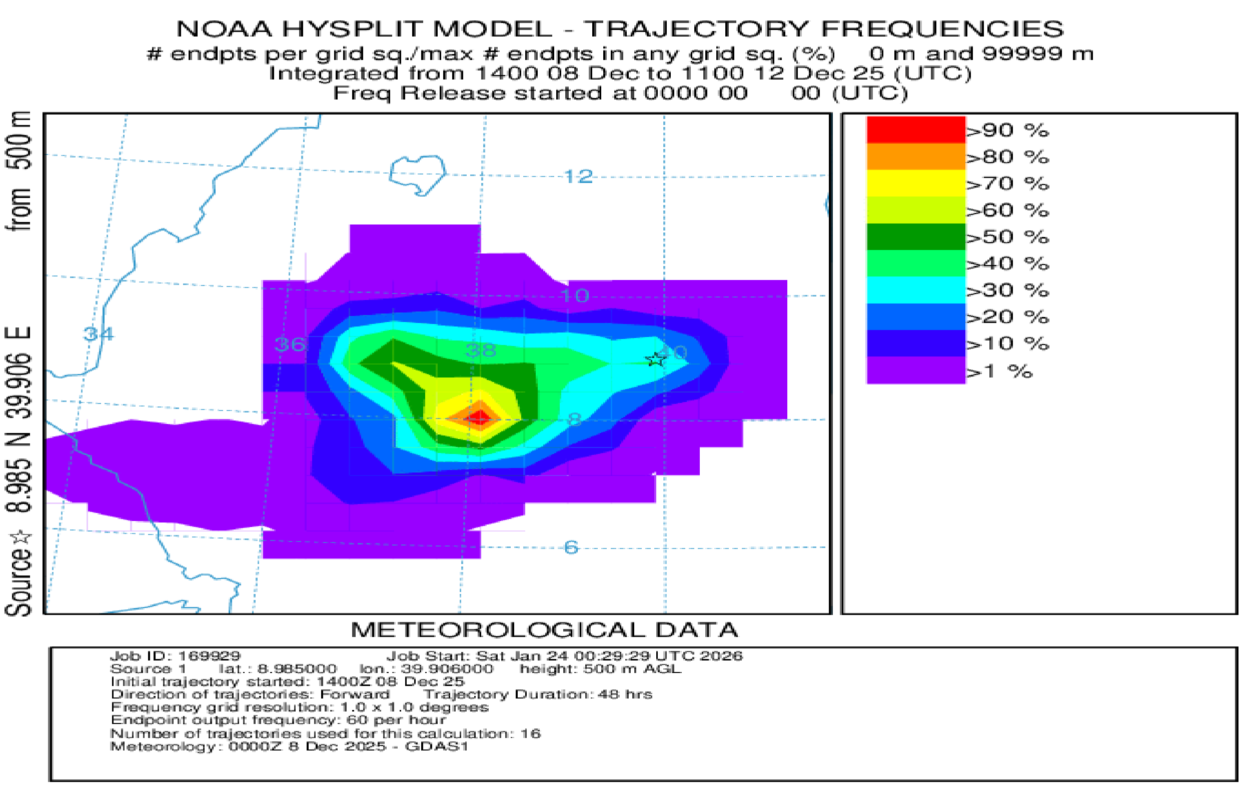


Figure 9 shows a wide range of trajectories with comparable starting conditions.

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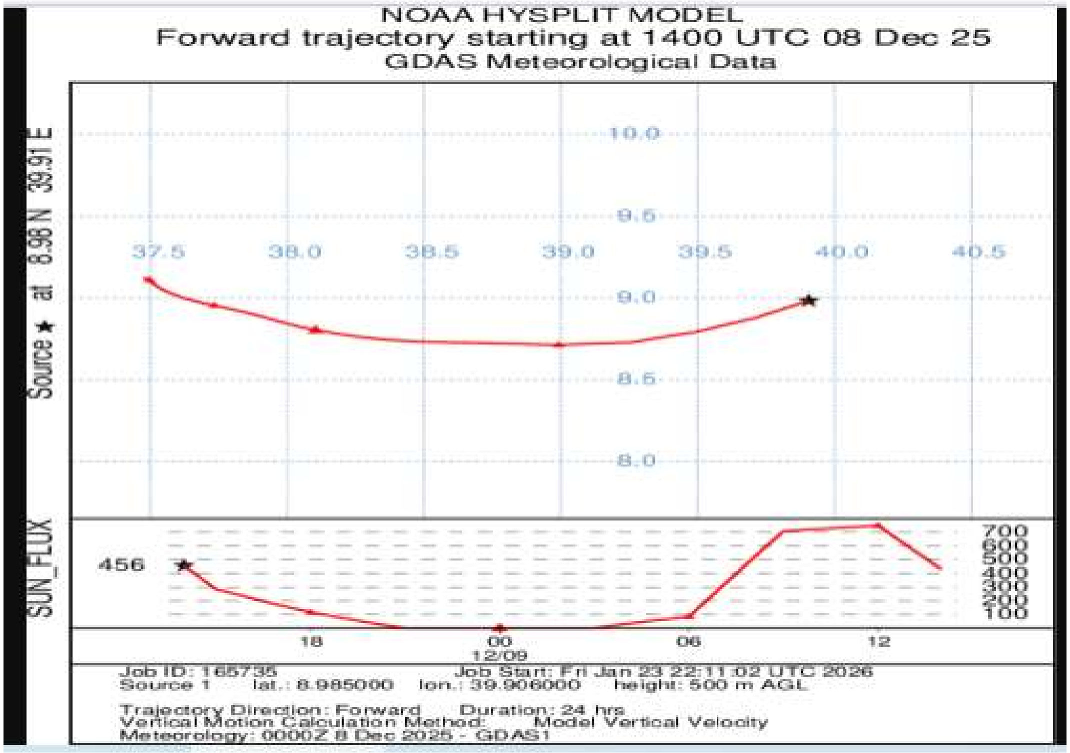

Figure 10 shows plume paths that correspond to the main regional circulation systems.

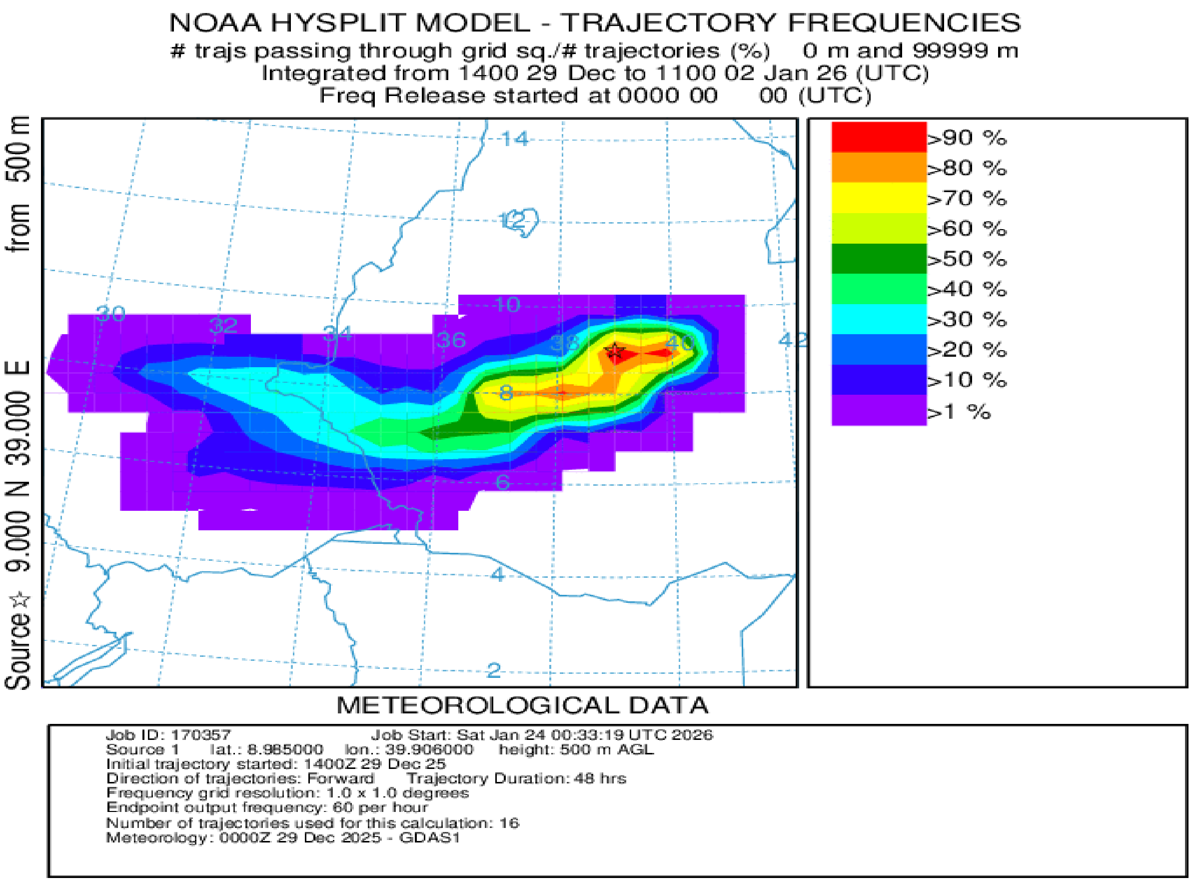

Figure 11 illustrates how plume impact regions can undergo substantial changes over time.

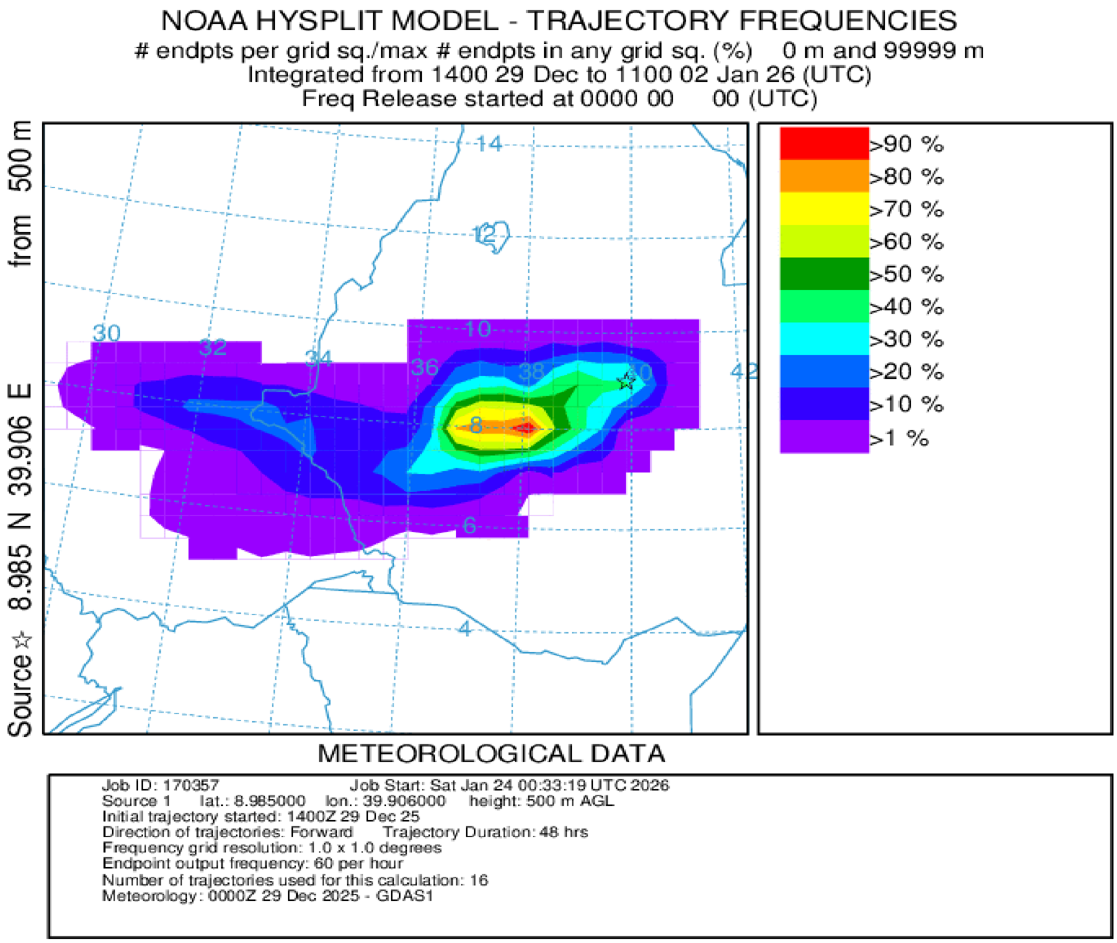

Figure (12) shows several trajectories with significant spatial dispersion.

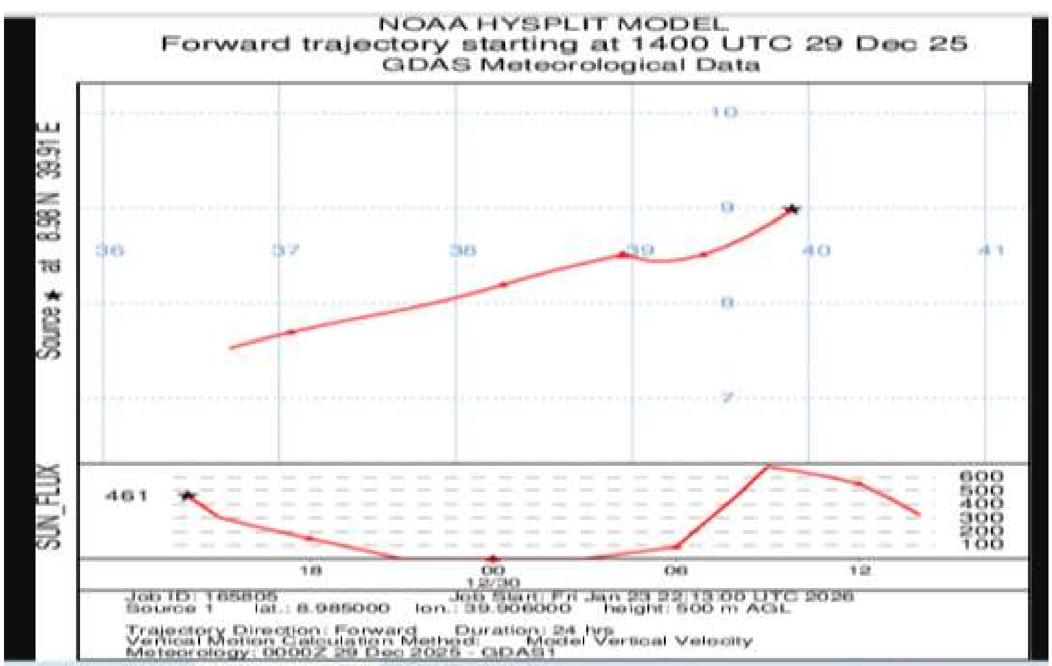

Figure (13) shows trajectories reaching distant regions well beyond the source

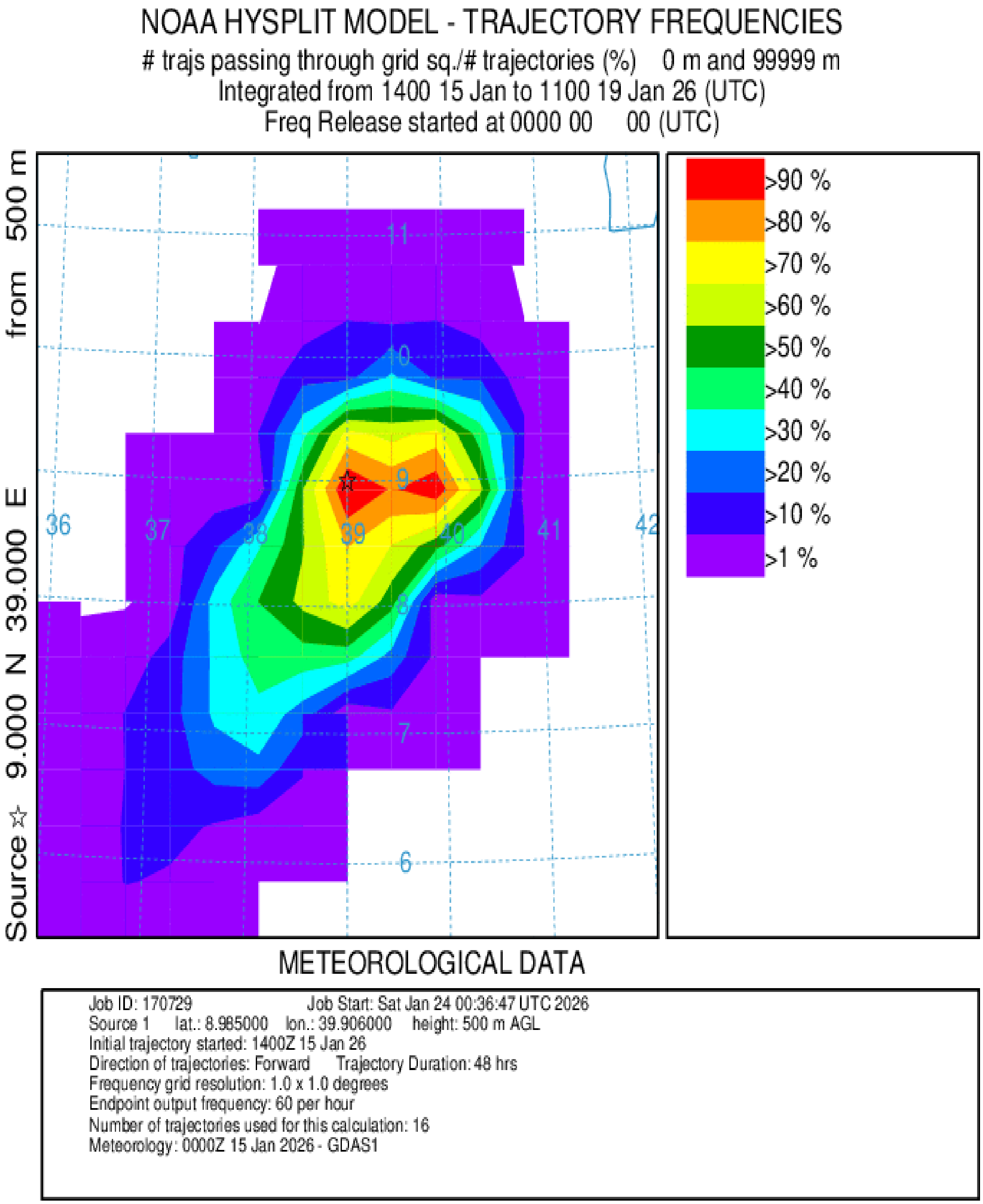

Figure 14 shows the plume paths throughout the late stages of transport.

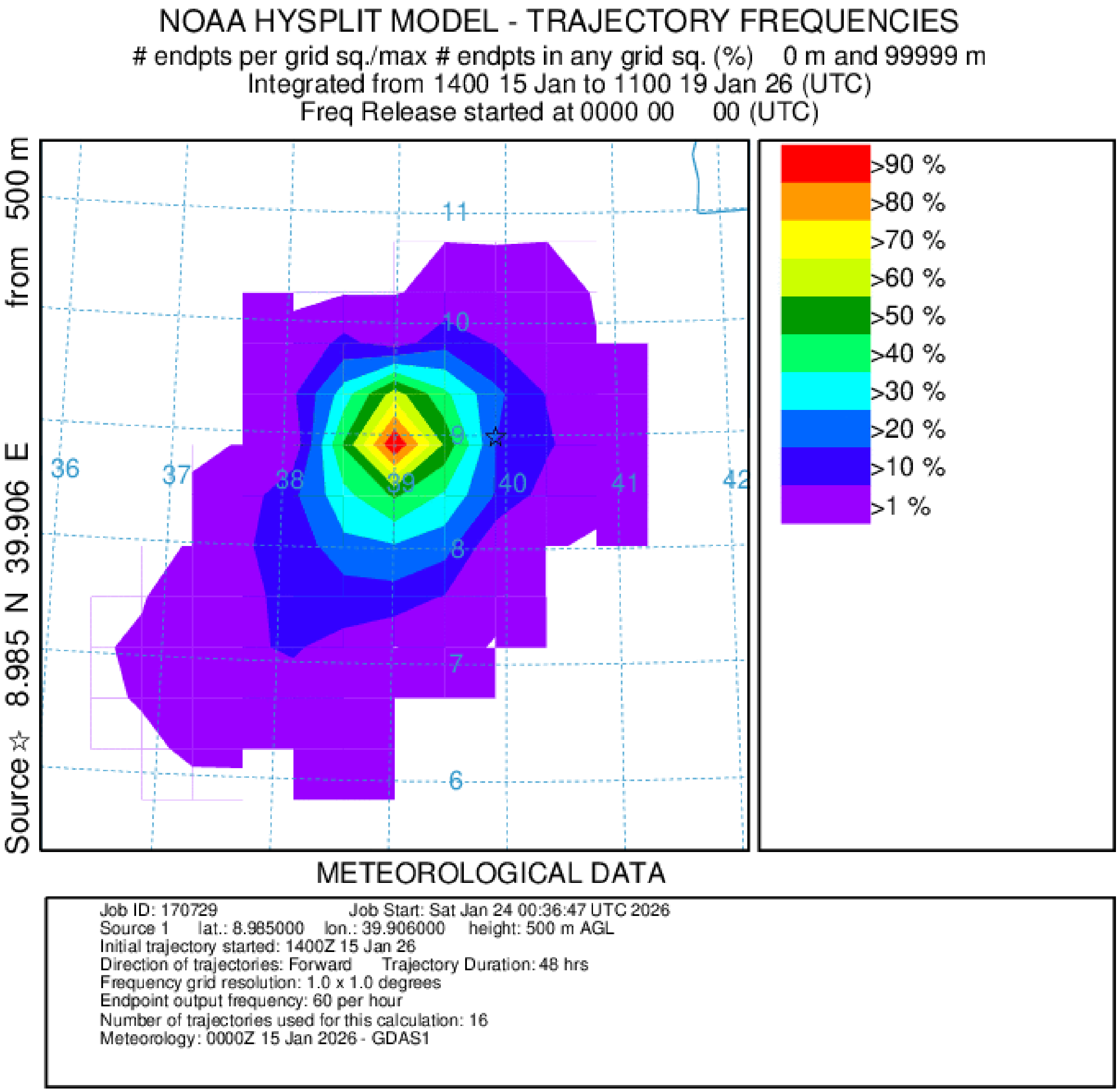

Figure (15). Shows weak directional coherence and widely scattered trajectories

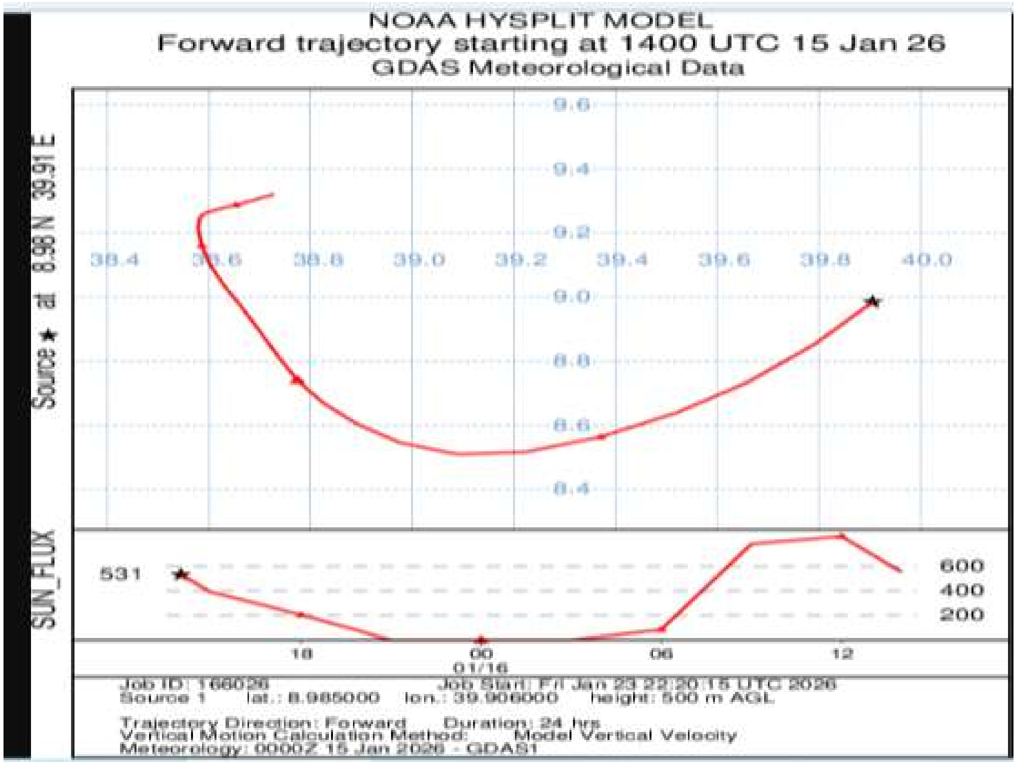

Figure (16) illustrates the volcanic plume trajectory.

Conclusion:-

According to the results of the HYSPLIT model simulation, the main physical elements controlling the temporal and spatial extent of dispersion are injection height, upper-level wind continuity, and vertical wind shear arrangement. The findings also showed that as travel time increases, directional coherence gradually declines, increasing spatial uncertainty. the findings are in full accordance with the International Atomic Energy Agency's (IAEA) recommendations for simulating atmospheric dispersion in radiological emergencies, especially with regard to the significance of figuring out injection height, examining the dispersion envelope's temporal evolution, and evaluating transboundary effects. Moreover, the findings are consistent with the techniques used by the United Nations Scientific Committee on the Effects of Atomic Radiation to describe the long-range movement of radioactive elements and evaluate the geographical and temporal fluctuations in environmental exposure patterns. The study demonstrates that, in spite of its geological origin, the behavior of the volcanic plume serves as a physical model that is comparable to the behavior of radioactive contaminants in the air. Because of this, these results can be utilized as a scientific foundation to improve the accuracy of long term dose estimation, increase the preparedness of environmental monitoring systems, and establish national and regional reaction plans to radioactive release disasters. Therefore, our study helps to close a large knowledge gap about how to combine worldwide radiation protection regulation frameworks with sophisticated numerical modeling of air dispersion.

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