BNWL-1051 V2 Pt1
~~Part 1~~
UC-48 2

11-69

PACIFIC NORTHWEST LABORATORY ANNUAL REPORT FOR 1968 TO THE USAEC DIVISION OF BIOLOGY AND MEDICINE

VOLUME II: PHYSICAL SCIENCES
PART 1. ATMOSPHERIC SCIENCES

November 1969

AEC RESEARCH & DEVELOPMENT REPORT

BNWL-1051
Part 1

BATTELLE NORTHWEST
BATTELLE MEMORIAL INSTITUTE
PACIFIC NORTHWEST LABORATORIES
BATTELLE BOULEVARD, P. O. BOX 999, RICHLAND, WASHINGTON 99352

DISCLAIMER

PACIFIC NORTHWEST LABORATORY
RICHLAND, WASHINGTON
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES ATOMIC ENERGY COMMISSION UNDER CONTRACT AT(45-1)-1830

AEC-RL RICHLAND, WASH.

DIABATIC TRAJECTORIES AND A TRAJECTORY CASE STUDY OF THE EFFLUENT FROM PHOEBUS 1B EP-IV FEBRUARY 23, 1967

W. E. Davis and B. C. Scott

Procedures for estimating diabatic effects and techniques for the inclusion of these effects in a trajectory calculation have been presented.

A trajectory case study of the effluent from Phoebus 1B EP-IV, February 23, 1967, has been utilized to demonstrate the application of some of the procedures for estimating and including the diabatic effects into a trajectory calculation.

INTRODUCTION

The path taken by air parcels in the atmosphere has been of concern to scientist and layman alike. This path has been estimated by assuming isobaric or constant level flow. However, when air motions are quasi-adiabatic, the assumption of constant level or isobaric flow can often result in seriously erroneous trajectory calculations. Danielsen[1] demonstrated that the adiabatic trajectories should be used rather than isobaric trajectories when the air flow characteristics of the atmosphere are quasi-adiabatic. An analogous argument can be used when diabatic conditions exist; when the adiabatic trajectory is no longer valid, diabatic flow should be estimated.

Presently, diabatic effects are being evaluated, and techniques are being developed for including these effects in trajectory determinations.

Research has been directed toward the following objectives:

- Development of techniques to identify diabatic conditions and to estimate diabatic effects and
- Study of the diabatic effects on the trajectory of the effluent from the Phoebus 1B EP-IV reactor test of February 23, 1967.

DIABATIC EFFECTS

Three causes of diabatic effects were studied:

- Convective mixing in the surface layer
- Radiational cooling
- Release of latent heat

The results of these studies were then utilized, when possible, to calculate a trajectory end point through the use of the diabatic energy equation.

Convective Mixing in the Surface Layer

When air parcels moving adiabatically enter turbulent zones such as regions of convective mixing in the surface layer, the adiabatic assumption is invalid. In addition, the assumption that adiabatic trajectories are describing the motion of individual air parcels is no longer valid due to mixing. However, convective mixing in the surface layer and the trajectories in the affected layer can be estimated with the aid of surface potential temperature analysis.

The upper limit of mixing can be estimated from the surface potential temperature (θ). The surface θ is assumed to equal the θ at the top of the mixing layer when air parcels are mixing upward dry-adiabatically. Thus the mixing layer depth will increase as the surface θ increases. When the surface θ falls, air parcels with potential temperatures greater than that at the surface will emerge from the mixing layer as it stabilizes and move down stream on the newly formed potential temperature surfaces. Isentropic trajectory analysis is initiated over the range of potential temperature surfaces re-formed when the surface potential temperature decreases. These trajectories will describe the transport of the material redistributed during the convective mixing process in the surface layer. A detailed surface θ analysis can serve two purposes: first, to identify the region where surface heating will affect the trajectory; and second, to identify when isentropic trajectories enter or leave the mixing layer.

Radiative Cooling

In the lower atmosphere, radiative heating and cooling often produce large temperature changes. Air parcels will cross isentropic surfaces in regions where radiative heating or cooling is a major diabatic effect. Consequently, the accuracy of adiabatic trajectories will deteriorate in these regions. Therefore, to locate regions where the atmosphere is emitting or absorbing significant amounts of radiant energy, radiative flux is calculated and the cooling rate is used in a diabatic trajectory calculation.

The radiative flux through various levels in the atmosphere can be evaluated in several ways. However, a discussion of the application and accuracy of the various techniques for calculating radiative flux is not essential to the discussion developed in the report. A detailed discussion of some of the formulations used to compute radiative flux can be found in Smagorinsky, et al. (2), Manabe, et al. (3), Mintz(4), Rodgers and Wolshaw(5), and Sasamori(6).

Regardless of the procedure used to calculate atmospheric radiation, the technique for including flux divergence in trajectory calculations remains the same. The technique for including flux divergence is as follows.

The first approximation of a diabatic trajectory is obtained by moving an air parcel on an isentropic surface for a 12-hour period. The change in potential temperature ($\Delta\theta$) along the trajectory path is calculated by assuming the averaged value of the radiative flux divergence calculated at the trajectory end points ($t = 0$ hr, $t = 12$ hr) is equivalent to $\Delta\theta$. The air parcel is then returned to the mid-point (in time) of the original adiabatic trajectory and stepped vertically down (up) by the amount $\Delta\theta$. The air parcel is then moved parallel to the streamlines on the new θ surface for the remaining six hours. At the end of the 12 hr movement, the new trajectory end point is adjusted in order to satisfy the diabatic energy equation.

Release of Latent Heat

Areas of precipitation are identified from either available surface maps or from the hourly Weather Bureau station reports. Once the areas of precipitation are delineated, the diabatic effects accompanying precipitation are estimated. The problem of estimating diabatic effects was approached from the aspect of stability of the atmosphere during precipitation processes. Techniques had to be developed for precipitation occurring both during convective instability and in a stable atmosphere. In the first case, mixing will accompany latent heat releases while in the second, no mixing is assumed to take place.

When precipitation occurs, coupled with convective instability, the problem of estimating diabatic effects is treated in a manner analogous to the application of Engelmann and Davis.[7] Specifically, the boundaries of the diabatic zone in regions of convective instability can be estimated by lifting the air mass dry adiabatically on a thermodynamic chart until the lifting condensation level (LCL) is reached. The potential temperature at the LCL is assumed to be the lower boundary of the diabatic zone. The air parcel is then lifted wet-adiabatically until it is in equilibrium with the surrounding atmosphere, and the θ at the equilibrium level is taken to be the upper boundary. The same approach can be used in determining whether cells in a region of convective precipitation can penetrate and "tap" an air parcel moving adiabatically over the region, see Davis, et al.[8], and Reiter and Mahlman[9]. Again, once the boundaries are established, isentropic trajectories are taken throughout the layer delineated by these boundaries. These trajectories then describe the transport of the material redistributed during the convective mixing process.

Stable precipitation is handled by first computing the change in potential temperature resulting from the release of latent heat and then incorporating this effect into the energy equation for the end point calculation. The first estimate of the end point is accomplished by moving the air parcel adiabatically. Then, under the assumption that equivalent potential temperature (θ_e) is conserved, the sounding at the end point is used to find a θ surface where θ_e (initial) = θ_e (final). The change in potential temperature is then found by taking θ (initial) - θ (final) at the trajectory end point. The air parcel is moved along the initial θ surface until reaching the point where precipitation occurs. The air parcel is placed on the final θ surface and moved adiabatically. Using the potential temperature change, the diabatic effect can be incorporated in a diabatic energy equation for end point calculation of the trajectory.

DIABATIC ENERGY EQUATION

In the case of diabatic conditions existing without mixing, it is possible to compute an energy conserving diabatic trajectory. The frictionless-flow energy equation used was computed in Cartesian coordinates (see Haltiner and Martin[10]).

$$\frac{d}{dt}\left(\frac{V^2}{2} + c_pT + gz\right) = \alpha\frac{\partial p}{\partial t} + \frac{dQ}{dt}, \qquad (1)$$

where $\frac{dQ}{dt} = c_p \frac{T}{\theta}\frac{d\theta}{dt}$.

The kinetic energy term is $\frac{V^2}{2}$, c_pT is enthalpy, and gz is potential energy. The $\alpha\frac{\partial p}{\partial t}$ term is the work performed by the atmosphere on the parcel, and $\frac{dQ}{dt}$ is the diabatic term indicating heating of the system.

Previously, Danielsen's[1] energy equation development in θ coordinates has been used. However, significant errors discovered in that approach are discussed in the following.

The corrected integrated energy equation should read

$$\int_{t_1}^{t_2} \alpha\frac{\partial p}{\partial t}\Big|_z dt + \int_{t_1}^{t_2} c_p \frac{T}{\theta}\frac{d\theta}{dt} dt$$

$$= \psi_2(\theta_2, t_2) - \psi_1(\theta_1, t_1)$$

$$+ \frac{V_2^2}{2}(\theta_2, t_2) - \frac{V_1^2}{2}(\theta_1, t_1) \qquad (2)$$

with $\psi = c_pT + gz$ (ψ is Montgomery Stream Function) where the following corrections have been made.

A significant error was found in the original integration of the term involving kinetic energy (KE) where

$\int_{\theta_1}^{\theta_2} \frac{\partial KE}{\partial\theta}\Big|_{t_2} d\theta$ was set equal to

$\overline{\frac{\partial KE}{\partial\theta}}(\theta_2 - \theta_1)$; $\overline{\frac{\partial KE}{\partial\theta}}$ indicates time

averaging along the path of the trajectory, which is an inappropriate estimate of the change in kinetic energy required.

This integral should be:

$$\int_{\theta_1}^{\theta_2} \frac{\partial KE}{\partial\theta}\Big|_{t_2} d\theta =$$

$$KE(t_2, \theta_2) - KE(t_2, \theta_1) \qquad (3)$$

Another problem was found in the original development.[1] It was demonstrated that $\frac{\partial\psi}{\partial\theta}_{x,y,t_o}$

$= c_p \frac{T}{\theta}\frac{(t_o)}{(t_o)}$, but $c_p \frac{T}{\theta}\frac{(t_o)}{(t_o)}$ was

inappropriately set equal to $\frac{c_pT(t)}{\theta(t)}$,

which resulted in two of the terms in the energy equation canceling. Since, in general, this approximation is usually not true, a certain error will be produced. In one case that was experienced, the error was found to be insignificant because the ratio of $\frac{T}{\theta}$ remained essentially constant and the approximation that $c_p \frac{T(t)}{\theta(t)}$

$= c_p \frac{T(t_o)}{\theta(t_o)}$ was within the error of the calculation. Further work will be necessary to delineate the error in the approximation. In the meantime, the energy equation in Cartesian coordinates, where these errors do not occur, is being used.

ILLUSTRATION OF THE TECHNIQUES

The following case study of the effluent from Phoebus 1B EP-IV, February 23, 1967, presented a unique opportunity for testing diabatic trajectory calculations. Confirmation of the trajectory could be checked by the real time aircraft sampling, which provided detailed information about the position of the cloud.

The Phoebus test was conducted at the Nuclear Rocket Development Station (NRDS), 90 miles northwest of Las Vegas, Nevada, on February 23, 1967. At 2154Z, effluent was emitted from the reactor for 41 min [11]. However, for convenience, H-hour has been taken to be 2200Z.

The 2200Z rawinsonde (Figure 1) at NRDS indicated that the effluent would be distributed over a deep mixing layer. Thus, to describe adequately the motions of the effluent downwind, several initial θ values were chosen. Those selected include

θ = 301 at 2405 m MSL
θ = 301.5 at 2375 m MSL
θ = 302 at 2655 m MSL
θ = 303 at 2815 m MSL, and
θ = 305 at 3210 m MSL

For reference, the elevation of NRDS is 1245 m MSL.

Surface θ analyses from H+0 to H+2 (Figure 2) indicated that all but the 305 θ trajectory would be moving in the surface mixing layer. Therefore,

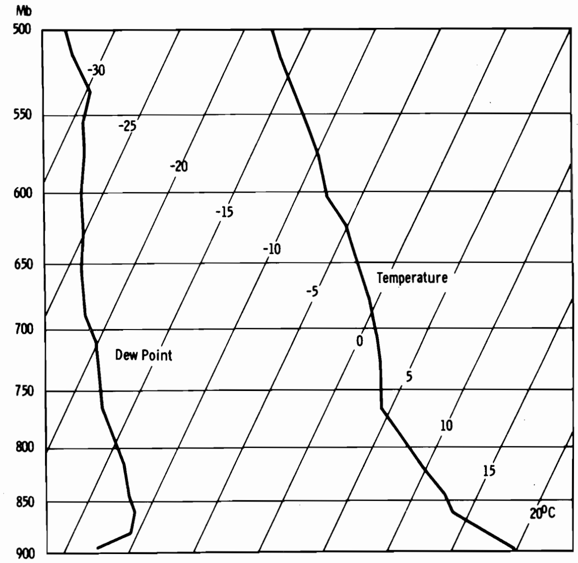

FIGURE 1. Plot of Temperature, Dew Point and Pressure for Radiosonde Report for Jackass Flats, February 23, 1967, 2200Z

the effluent position in the mixing layer was determined by constructing trajectories at constant levels above the surface. By H+3, the ground had cooled sufficiently to allow the reestablishment of all the selected isentropic levels. The constant level trajectory end points were placed on the original isentropic surfaces and the effluent was assumed to move downstream adiabatically using Montgomery Stream functions.

No additional diabatic effects could be identified until H+26. At that time, calculations with the Elsasser radiation diagram indicated a radiative cooling rate of 0.5 °C per 12 hr in the atmospheric layer containing the trajectories (800 to 600 mb). This cooling rate was probably overestimated through the use of the Elsasser diagram [12].

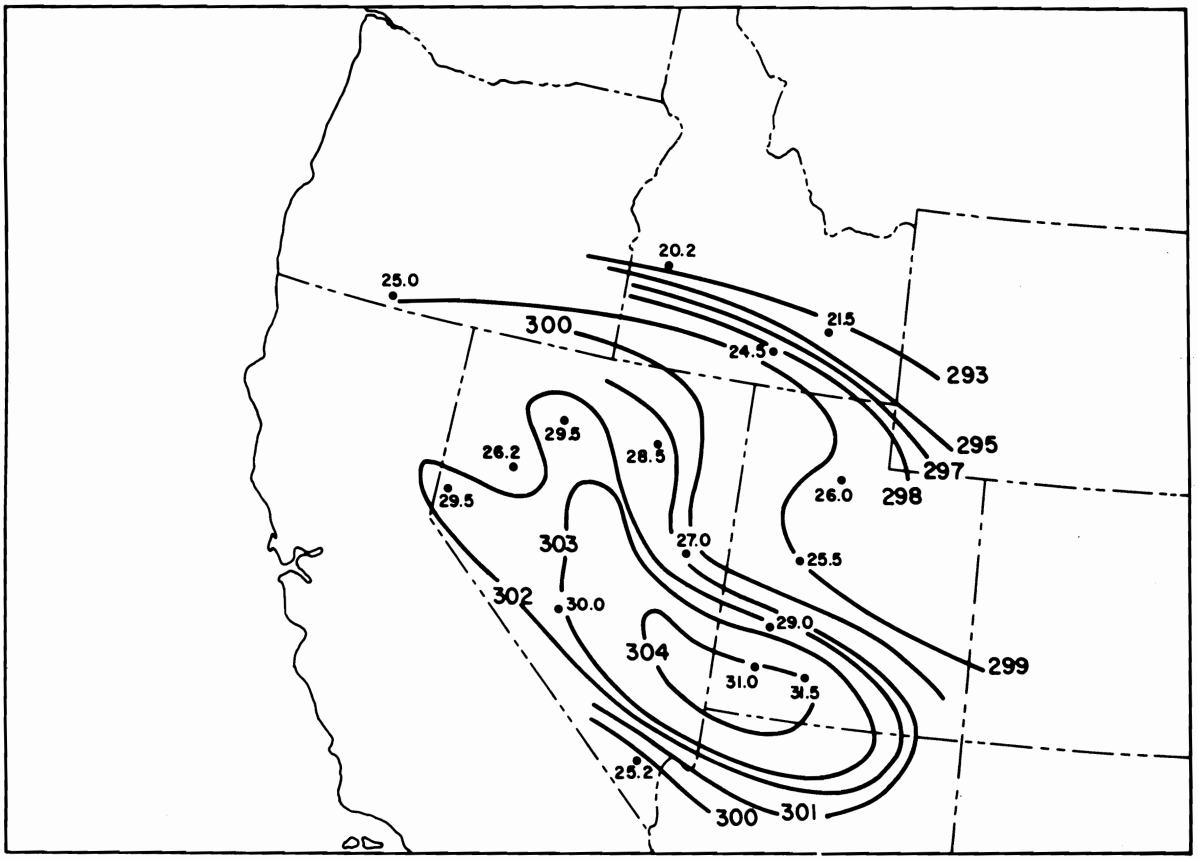

FIGURE 2. Surface θ Analysis - February 24, 1967, 0000Z

However, to illustrate the previously described technique, a diabatic trajectory using the computed cooling rate was initiated from the 302 θ trajectory end point.

The only apparent diabatic effect during the remaining 40 hours of the case study was radiational cooling, which continued to average about 0.5 °C every 12 hr.

Table 1 summarizes the height of each trajectory end point at 12-hour intervals. The effluent clearly is not moving on a constant level or constant pressure surface.

Table 2 summarizes the computed diabatic effects along the trajectory paths. The net cumulative radiational cooling in the atmospheric layer containing the trajectories is 2.0 °C. The maximum surface θ is a measure of the greatest depth of the mixing layer. The surface θ's of 302 to 303° in the maximum surface θ column indicate trajectories, originally at these isentropic levels, have entered the mixing layer.

RESULTS

The indicated effluent position was confirmed at several locations[13] downwind from NRDS (Figures 3 and 4). At H+14, the diabatic trajectory

TABLE 1. Heights of the Trajectory End Points

Time	301.0	301.5	302.0	303.0	35.0	Diabatic
Feb 23/2200 Z	2465[a]	2575[a]	2655[a]	2815[a]	3210	- - -
Feb 24/1200 Z	2500	3188	3400	3400	3500	- - -
Feb 25/0000 Z	2500(b)	2700	2700	2800	3400	2700
Feb 25/1200 Z	3200	3300	3300	3500	4000	3200
Feb 26/0000 Z	3900	3200	2700	2900	- - -	2800
Feb 26/1200 Z	5200	4100	3600	3700	- - -	3500

(a) In mixing layer

(b) Surface potential temperature is 300.3

TABLE 2. Computed Diabatic Effects for 301.5 to 303° θ Trajectories

Time, Z (1967)	Cumulative Net Radiational Cooling at 700 mb,°C	Maximum Surface θ
Feb. 23, 2200 to 24, 1200	-0.3	302-303
24, 1200 to 25, 0000	-0.7	<300 at 25, 0000 Z
25, 0000 to 25, 1200	-1.1	<300 at 25, 0000 Z
25, 1200 to 26, 0000	-1.4	289
26, 0000 to 26, 1200	-2.0	289

analysis indicated that the effluent would be found at 3200 m MSL over Ely, Nevada (altitude 1800 m). The NATS* flying at a pressure-altitude of 3200 m intercepted effluent cloud near Ely at H+14 and followed its movement northward while flying at a pressure-altitude of 3100 m.

The U.S. Public Health Service[15] intercepted the effluent at 3700 m MSL near Wendover (elevation 1520 m), Utah, at H+19, and at 2600 m near Elko, Nevada (elevation 1550 m), at H+20:30. The timing and positioning of the interception near Elko is predicted by the 301.0° Θ trajectory. The trajectory analysis places the material over Wendover at H+19 as

* *NATS is the Nevada Aerial Tracking System, which is a highly instrumented Martin 404 aircraft. The pressure-altitude and corrected temperature[14] data from NATS were used to calculate potential temperatures.*

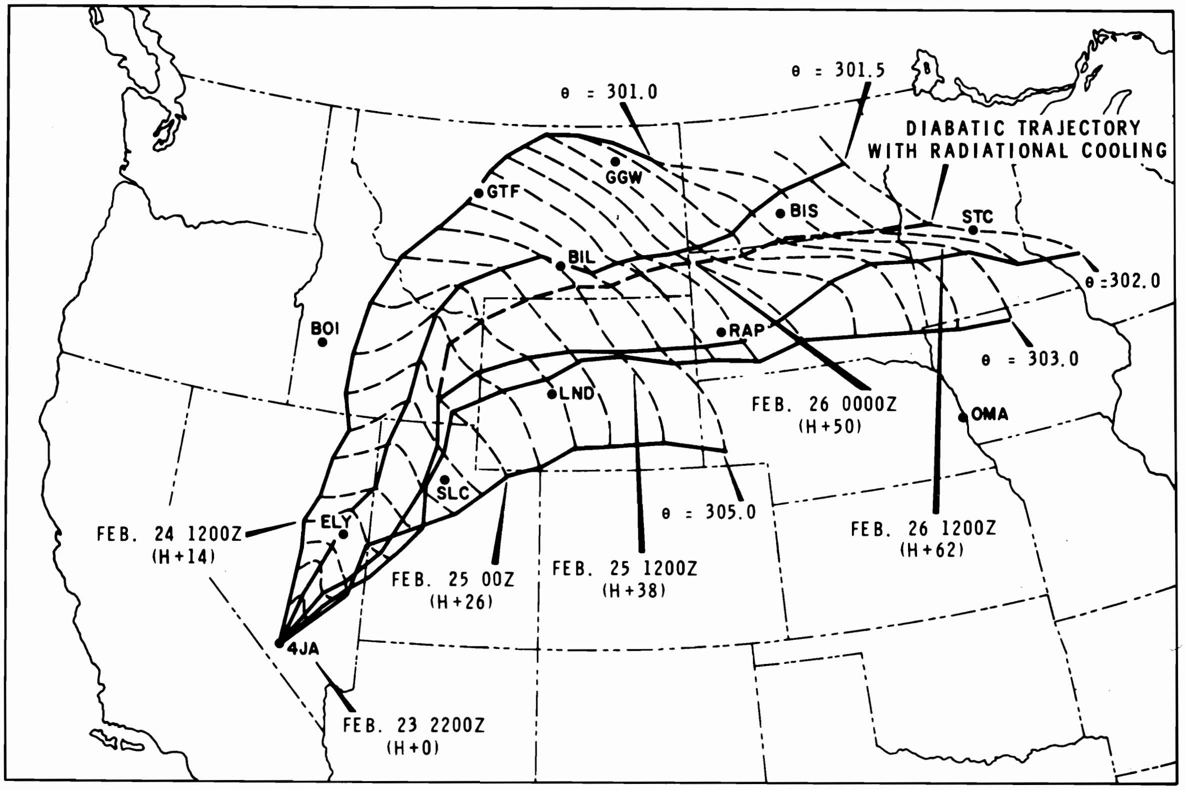

FIGURE 3. Isentropic and Diabatic Trajectories of the Effluent from Phoebus IB-EP-IV Reactor Test February 23, 1967.

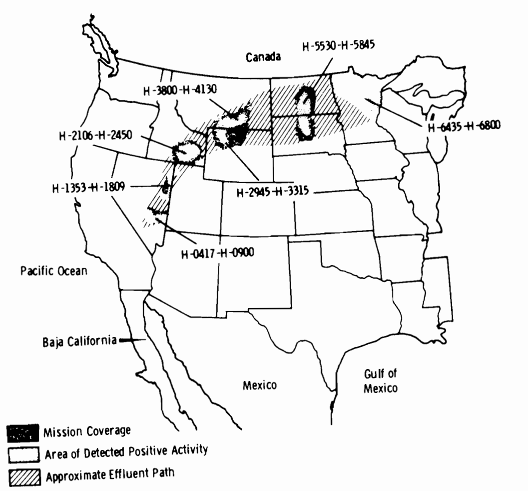

FIGURE 4. Phoebus IB-IV Effluent Trajectory and Diffusion Pattern. Measured from NATS Aircraft Between Altitude Ranges 9500 to 10500 ft MSL, 23-26 February, 1967[13]

observed, but there is no direct explanation for the height discrepancy of 500 m. However, diffusion from lower θ surfaces is a possible explanation for the observation. Further, the U.S. Public Health Service did not report temperatures, so an evaluation of the potential temperature was not available at the points of interception.

All but one of the trajectories indicated that the effluent would enter Southern Idaho between H+23 and H+26 (Figure 3). The heights determined from the analysis of the effluent ranged from 2500 m MSL near Twin Falls to 2800 m MSL near Malad City. NATS flying at the approximate level of θ = 302° contacted the effluent near Malad City at H+21:30 and near Twin Falls at H+22:30. At H+27, the Public Health Service detected the effluent cloud between Malad City and Pocatello. Thus, the indicated effluent positions appeared to have only minimal errors after 26 hr of movement.

The NATS intercepted the effluent at 3000 m near Cody, Wyoming at H+32; at 3300 mm near Billings, Montana at H+40; and at 3300 m near Miles City, Montana at H+41. The altitude of all three contacts was given by the diabatic trajectories, but only the time of arrival at Billings was accurate. The Cody contact indicated an arrival error of at least three hours and the Miles City contact indicated an error of at least 6 hr. Thus, by H+40, the accuracy of the indicated effluent position was beginning to deteriorate for trajectories north of the 302° θ trajectory.

Additional effluent contacts were made by NATS in the Dakotas and Minnesota at a constant pressure altitude of 3000 m. However, the aircraft was sampling the effluent with filters[13] after H+40 so that specific regions of contact were difficult to define. The trajectory analysis did indicate the presence of effluent at 3000 m in the western and central portions of South Dakota.

Theoretically, the diabatic trajectories can be used to describe the altitude of maximum concentration if an initial altitude of maximum concentration is known. An altitude spiral by NATS at H+7 established the level of maximum concentration to be at an altitude corresponding to a potential temperature of 301.5° θ. A 301.5° θ trajectory from the vicinity of the initial spiral indicated that the level of maximum concentration should be at 2700 m MSL near Burley, Idaho. An additional altitude spiral at Burley at H+22:20 shows the actual maximum effluent concentration at 2800 m MSL.

In Figure 3, the diabatic trajectory using radiational cooling is compared with the 302° θ trajectory. In Idaho, a deviation between their paths first appears. By H+50, the diabatic trajectory is approximately 250 km to the NW of the 302° θ trajectory. Thus, the computed diabatic cooling from the Elsasser diagram resulted in a significant change in the path of the trajectories. Applying this diabatic cooling to the rest of the trajectories would have resulted in the shifting of the trajectories further to the north while maintaining the general spread pattern.

DISCUSSION OF RESULTS

The Phoebus 1B EP-IV case study dealt specifically with material released into the surface mixing layer. Trajectory confirmations in Nevada and Idaho demonstrated that the effluent movement could be satisfactorily described out to at least H+40 hr with diabatic conditions of convective mixing and radiation cooling occurring along the path. In addition, the altitude of maximum concentration was correctly indicated up to 700 km from the release point. Altitudes of effluent contact were successfully indicated in Montana and the Dakotas at distances ranging up to 1600 km from the effluent release points.

Surface θ analyses for the first 3 hr of the effluent movement indicate that mixing could have distributed material to the 304° θ isentropic level. An examination of Figure 4 reveals that any upward mixing of the effluent would have produced larger easterly components in the first 26 hr of the trajectory paths. However, aircraft were never at the locations necessary for the verification of this indicated upward mixing for θ > 303°. The diabatic trajectory for radiation cooling indicated a movement of air parcels from the 302 to 300° θ surface. However, no confirmation was available of this movement because of the lack of vertical definition of the measured plume.

Trajectories originating from various altitudes at the source point have described the vertical and lateral spread of the plume (Figures 3 and 4). No known existing diffusion model has this capability of predicting the dispersion of material in an atmosphere where the vertical wind shears are of the magnitude encountered in this case study.

The lack of data, and errors in existing data, eventually produce inaccurate displacements in any trajectory scheme. However, it is difficult to estimate the degree of inaccuracy after H+40 in the Phoebus Study. Aircraft flying in support of radiological monitoring and survey programs covering the Phoebus 1B EP-IV reactor test, continued to search for the effluent at a pressure altitude of 3000 m over regions where the trajectory analyses indicated it would have been located between 3500 and 4100 m. Thus, it is not known if all the trajectories were in error after H+40. The location of effluent at 3000 m may indicate that turbulent diffusion resulted in the downward movement of material.

CONCLUSIONS AND RECOMMENDATIONS

Various assumptions concerning material movement through diabatic zones in the lower atmosphere have been stated and tested. The results indicate that the diabatic techniques incorporated into a trajectory analysis presented in this paper can successfully describe the downwind coordinates of material released into the atmosphere. However, further case studies are needed to evaluate and confirm the movement of air parcels under varying diabatic conditions in the atmosphere.

REFERENCES

1. *E. F. Danielsen. "Trajectories: isobaric, isentropic, and actual," J. Meteorology, vol. 18, pp. 479-486. 1961.*

2. *J. Smagorinsky and Staff Members. "Prediction Experiments with a General Circulation Model," Proc. Intern. Symp. Dynamics of Large-Scale Processes, Moscow, 70-137. 1965.*

3. *S. Manabe, J. Smagorinsky and R. F. Strickler. "Simulated Climatology of a General Circulation Model with a Hydrological Cycle," Monthly Weather Rev. vol. 93, pp. 769-798. 1965.*

4. *Y. Mintz. "Very Long-term Global Integration of the Primitive*

Equations of Atmospheric Motions," *WMO Tech. Note No. 66.* *1964. WMOIUGG Symp. Res. Develop. Aspects of Long Range Forecasting, Boulder, Colorado. 1965.*

5. *C. G. Rodgers and C. D. Walshaw. "The Computation of Infrared Cooling Rate in Planetary Atmospheres," Quart, J. Royal Meteorol.Soc. vol. 92, pp. 67-92. 1966.*

6. *T. Sasamori. "The Radiative Cooling Calculation for Application to General Circulation Experiments," J. Applied Meteorology, vol. 7, no. 5, pp. 721-729. 1968.*

7. *R. J. Engelmann and W. E. Davis. Low-Level Isentropic Trajectories and the MIDAS Computer Program for the Montgomery Stream Function, BNWL-441. Battelle-Northwest, Richland, Washington, April 1968.*

8. *W. E. Davis et al. "Additional Meteorological Analyses of Shot Smoky, Plumbbob Test Series," Pacific Northwest Laboratory Annual Report for 1967 to the USAEC, Division of Biology and Medicine, Volume II: Physical Sciences, Part 3, BNWL-715-3 pp. 74-87. Battelle-Northwest, Richland, Washington. October 1968.*

9. *E. R. Reiter and J. D. Mahlman. "Heavy Iodine-131 Fallout over the Midwestern United States, May, 1962," Technical Paper No. 70. USAEC Progress Report No. 2, Department of Atmospheric Science, Colorado State University. 1965.*

10. *G. J. Haltiner and F. L. Martin. Dynamical and Physical Meteorology. McGraw-Hill Book Company, Inc., New York, N. Y., 1957. pp. 176-177.*

11. *T. V. Crawford. "The Long Range Diffusion of the Effluent Cloud from the Phoebus 1B EP-IV Reactor Test of February 23, 1967, UCRL-50418. Lawrence Radiation Laboratory, University of California, Livermore, California. April 1968.*

12. *W. R. Kuhn. Unpublished Data. University of Michigan, Ann Arbor November 6, 1968. (Personal Conversation at the "Conference on the Composition and Dynamics of the Upper Atmosphere," El Paso, Texas)*

13. *J. E. Hand and V. F. Weissman. Phoebus 1B EP-IV Effluent and Ground Deposition Surveys, No. EGG 1183-1321. 1967.*

14. *J. C. Pales. Unpublished Data, 1968. (Personal Communication)*

15. *Preliminary Report, Monitoring and Sampling Phoebus 1B, February 10 and 23, 1967, U. S. Public Health Service. Las Vegas, Nevada, 1967.*