THE THEORY OF LOCAL ADVECTION: I

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ABSTRACT

This paper is the first of a series in which the theory of local advection (the exchange due to horizontal heterogeneity) of energy and moisture will be developed and applied to a number of problems of practical and theoretical interest. The paper provides an introduction to the practical implications and physical basis of local advection, but it is mainly devoted to developing methods of analysis to be applied in later papers. The treatment aims to provide simple and rapid numerical procedures for the solution of advection problems.

Methods are given for solving the two-dimensional atmospheric-diffusion equation subject to "concentration," "flux," and "radiation" types of boundary conditions. Appendices give discussions of the properties of the functions entering the solutions and provide simple means for their computation. Extensive tables of the relevant functions are given for the case \( m = 1 / 7, n = 6 / 7 \) (\( m, n \) being the exponents in the power-law approximations to the vertical profiles of mean wind speed and eddy diffusivity, respectively).

The rudiments of a quantitative theory of advective inversion are developed, expressions being obtained for the equation of the inversion surface, and for the maximum height and downwind extent of the inversion.

1. Introduction

In this real world, irrigated fields adjoin deserts, reservoirs are of finite extent, dry lands exist beside seas, and cornfields beside close-grazed pasture. It is not surprising, then, that many important problems of micrometeorology require that we take cognizance of advection. This we define as the exchange of energy, moisture, or momentum due to horizontal heterogeneity. One symptom of the presence of advection is that vertical mean profiles of (potential) temperature, specific humidity, and wind speed are non-equilibrium profiles, even under conditions steady in time.

However, most attempts at quantitative studies in micrometeorology have been based on the assumption of horizontal homogeneity and equilibrium profiles. The possibility of advection has been recognized mainly in a negative way. Experimenters attempt to avoid it by working on sites downwind of extensive "homogeneous" areas. Sometimes advection is invoked to explain otherwise inexplicable observations, but this tends to be a last resort.

The situation has been worse in fields of applied micrometeorology (such as agronomy, ecology, reservoir engineering, irrigation engineering), where neglect or ignorance of the importance of advection has often led to experiments, interpretations, and methods of prediction and design which have not achieved the intended goals.

In particular, the neglect of advection has tended to vitiate many attempts to treat the problem of natural evaporation. There is a logical flaw in treating the humidity and temperature of the air solely as the cause of evaporation at the underlying surface. They are equally the consequences of the upwind evaporation and energy conditions. [Compare Priestley, 1951; Deacon et al., 1958].

The present study deals with the advection of heat and moisture. It bears on such problems of practical importance and theoretical interest as (i) the influence of the size of an irrigated area and of position within the area on evapotranspiration, (ii) the influence of reservoir size on evaporation losses, (iii) the effect of the presence of an irrigation area and/or a body of water on the microclimate above and downwind of such regions, (iv) the physical basis of advective dewfall, (v) the theory of advective inversion, (vi) quantitative analysis of the errors introduced into micrometeorological (equilibrium) studies by advective effects.

Our problem is, essentially, to solve simultaneously for the temperature and humidity diffusion fields in the lower atmosphere, subject to boundary conditions upwind and at the surface of the region considered. These conditions must be such that the energy balance at the surface is satisfied.

In this first paper of the present study, we discuss the basic physical theory and provide the mathe-
metrical apparatus which enables us, in later papers, to investigate the various practical and theoretical aspects of advection noted above.

2. Symbolism

\( a \): constant introduced in (36), and evaluated in (47).

\( A \) (cal cm\(^{-2}\) sec\(^{-1}\)): sensible heat exchange between surface and air, positive upward.

\( b \): constant introduced in (39), and evaluated in (48).

\( c \): quantity defined by (45).

\( C_w(\eta) \): function of \( \eta \) defined by (17).

\( E \) (cm sec\(^{-1}\)): evaporation rate.

\( f_1(\alpha) \): function of \( \alpha \) defined by (51).

\( f_2(x) \): function of \( x \) defined by (52).

\( F(\eta, \beta) \): function of \( \eta \) defined by (34).

\( F_w(\eta) \): \( F(\eta, 2 + \frac{1}{m}) \).

\( I(\eta, \rho) \): \( \int_{0}^{\eta} e^{-t\rho dt} \int_{0}^{\infty} e^{-t\rho dt} \).

\( K \) (cm\(^2\) sec\(^{-1}\)): eddy diffusivity.

\( K_\lambda \): constant in equation (4).

\( L \) (cal g\(^{-1}\)): latent heat of evaporation of water (= 585).

\( m \): exponent in equation (3).

\( n \): exponent in equation (4).

\( Q \) (cal cm\(^{-2}\) sec\(^{-1}\)): soil heat-flux density at the surface, positive upwards. At water surfaces, the net energy exchange (by conduction, radiation, and convection) between the surface and the underlying body of water, again positive upwards.

\( r \): reflection coefficient of surface for shortwave radiation.

\( R_a \) (cal cm\(^{-2}\) sec\(^{-1}\)): flux density of atmospheric (long-wave) radiation received at the surface.

\( R_s \) (cal cm\(^{-2}\) sec\(^{-1}\)): flux density of short-wave radiation received at the surface.

\( T_\theta(K) \): surface temperature.

\( u \) (cm sec\(^{-1}\)): mean wind speed.

\( u_1 \): constant in equation (3).

\( x \) (cm): horizontal coordinate, positive in downwind direction.

\( \bar{x} \) (cm): geometrical mean value of \( x \) in \( x \)-range of interest.

\( x_1 \) (cm): value of \( x \) at which integrated error in matching boundary condition is zero.

\( x_{\text{max}} \) (cm): maximum downwind extent of advective inversion.

\( X \): quantity defined by (38).

\( \bar{X} \): value of \( X \) for \( x = \bar{x} \).

\( z \) (cm): vertical co-ordinate, positive upwards, zero at surface.

\( z_{\text{max}} \) (cm): maximum height of advective inversion.

\( \beta \): constant defined by (69).

\( \gamma \): constant defined by (46).

\( \Gamma(\rho + 1) \): \( \int_{0}^{\infty} e^{-t\rho dt} \).

\( \Delta \beta \): difference in \( \theta \) (over upwind regions) between \( z = 0 \) and \( z = 10^4 \), positive when \( \theta \) at \( z = 0 \) is the greater.

\( \Delta \theta_\theta \): difference in \( \theta_\theta \) between upwind and downwind regions, positive when the upwind value is the greater.

\( \epsilon \): emissivity of surface (long-wave radiation).

\( \zeta \): dimensionless quantity defined in (62).

\( \eta \): dimensionless quantity defined in (10).

\( \theta \): concentration of diffusing entity.\(^2\)

\( \theta_0 \): value of \( \theta \) at \( z = 0 \).

\( \rho_w \) (g cm\(^{-3}\)): density of liquid water (= 1.0).

\( \sigma \) (cal sec\(^{-1}\) cm\(^{-2}\) K\(^{-4}\)): Stefan-Boltzmann constant (= 1.36 X 10\(^{-12}\)).

\( \phi \): flux density of diffusing entity.\(^2\)

\( \phi_0 \): value of \( \phi \) at \( z = 0 \).

\( \phi_{00} \): value of \( \phi \) over upwind region.

\( \chi \): dimensionless quantity defined in (63).

3. The energy balance: the physical background to advection

At any point at the lower boundary of the atmosphere, the instantaneous energy balance may be written

\[
(1 - r) R_a + R_s - c_\theta T_\theta^4 + Q = A + L \rho_\theta E. \tag{1}
\]

Usually, we shall be applying (1) to land surfaces, but the equation holds also at water surfaces as long as we redefine \( Q \) to denote the net energy exchange (by conduction, radiation, and convection) between the water surface and the underlying body of water.

Evidently, if any one of the quantities entering (1) differs between any two surface points in the same vicinity, at least one (and often more than one) other component of the energy balance will also differ between the points. See Philip (1957) for an elementary treatment of the partition of energy at freely and imperfectly evaporating surfaces.

These horizontal differences in the energy balance occur both in nature and as a result of man's artifice. They may originate from a change in the energy fluxes to the surface due to causes external to the surface, or they may arise from differences in the thermal or radiative properties of the surface, or they may result from differences in the availability of water.

It is of interest to consider ways in which such differences can originate through the various quantities entering (1).

\(^2\) Units of \( \theta \) and \( \phi \) depend on nature of diffusing entity, and are therefore omitted here.
$r, \epsilon$: The albedo and the emissivity at the two points may differ either naturally (differences in vegetation, soil color, snow cover) or artificially.

$R_r, R_\epsilon$: Horizontal changes in received radiation may arise due to shading by clouds, trees, mountains, and artificial constructions. Such effects may be of short time duration or may be attended by other complications which put them beyond the scope of the present study. An equally important cause of horizontal differences in received radiation, and one which is more amenable to analysis by the present approach, is that due to change of slope of the ground surface (usually natural, but possibly artificial). It will be understood that we shall not be concerned here with points so far apart that their $R_r$-values differ significantly for astronomical reasons.

$Q$: In principle, the heat flux of the soil may differ due to horizontal variation in thermal properties of the soil. This seems unlikely to be a major cause of advective effects. A more interesting case arises where a water surface adjoins land. Here the $Q$-differences may be a dominant factor.

$A, E$: Horizontal differences in both $A$ and $E$ may be caused by horizontal differences in the intensities of turbulent exchange. Such differences may arise from (natural or artificial) changes in surface roughness. Where wind structure changes markedly, this aspect will be outside the scope of the present treatment.

$E$: It will be apparent from the later developments that the most common effect of importance arises from differences, either natural or artificial, in the availability of water for evaporation at the surface. It is to this effect that we shall give most attention.

For the sake of completeness, we note that artificial releases of heat should be recognized as a further source of horizontal heterogeneity. Heat production by industries and cities can be regarded as accidental instances while, under some circumstances, the use of oil burners in frost-threatened orchards represents a more intentional production of advective effects. The present approach has only limited application to these problems because there are often other complicating factors.

4. Advection and two-dimensional atmospheric diffusion

In this study, we shall deal only with two-dimensional problems; that is, we assume that cross-wind diffusion may be neglected. Practical application of the theory is therefore limited to regions where the cross-wind dimension is not too small.

The theory to be developed here uses the mathematics of atmospheric diffusion. Certain of the results we use are well known, but others are new. It has seemed to the present author that application of the mathematical theory and, indeed, a feeling for the general character and significance of the results requires that solutions be readily available in numerical form. With Lord Kelvin, we feel that "When you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind." Accordingly, the present treatment aims to provide numerical values of the functions entering the solutions and to supply simple and rapid numerical procedures for finding solutions to the problems discussed. In later papers, we shall illustrate various aspects of the theory which seem of interest and significance by means of numerical examples.

The equation which concerns us is

$$
\frac{\partial \theta}{\partial x} = \frac{1}{K \frac{\partial \theta}{\partial z}} \left( K \frac{\partial \theta}{\partial z} \right)
$$

with

$$
u = \nu z^n
$$

and

$$K = K z^n.
$$

We shall be dealing with three basic types of boundary conditions. The first, which we designate the concentration type, is of the general form conveniently represented by (5):

$$
x = 0, \quad z > 0, \quad \theta = 0
$$

$$
x \geq 0, \quad z = 0, \quad \theta = \theta_0(x).
$$

Because linear superposition holds, it will be sufficient for us to consider here the solution only for

$$
x = 0, \quad z > 0, \quad \theta = 0
$$

$$
x \geq 0, \quad z = 0, \quad \theta = 1.
$$

We designate the second type of boundary condition the flux type. This may be expressed in the following general form:

$$
x = 0, \quad z > 0, \quad \theta = 0
$$

$$
x \geq 0, \quad z = 0, \quad \phi = \phi_0(x).
$$

Here, $\phi$, the flux density, is equal to $-K \theta / \partial z$, so that $\phi_0 = \lim_{z \to 0} (-K \theta / \partial z)$. Because linear superposition holds here also, it is sufficient for us to consider the solution only for

$$
x = 0, \quad z > 0, \quad \theta = 0
$$

$$
x \geq 0, \quad z = 0, \quad \phi = 1.
$$

The third type of boundary condition is a special case of mixed boundary condition, known as the radiation type (Carslaw and Jaeger, 1947, p. 13).
which involves a linear combination of concentration and flux conditions at \( x \geq 0, \ z = 0 \). We shall deal primarily with the form

\[
x = 0, \ z > 0, \ \theta = 0 \\
x \geq 0, \ z = 0, \ \phi = 1 \\
\phi = 1.
\]

We develop the required solutions in the following sections 5 through 7. Note that the analysis is valid for \( m, n \) quite general, apart from certain mild restrictions on \( m \) and \( n \), which we indicate. However, it is convenient in micrometeorological work to give particular attention to the case \( n = 1 - m \), which is consistent with the assumption that the diffusivities for momentum and for the diffusing entity vary in a similar manner with \( z \) in that zone of the lower atmosphere in which the shearing stress is virtually constant ("Schmidt's conjugate power law"). Accordingly, we shall give the most important results not only in the form with \( m \) and \( n \) general, but also for the case \( n = 1 - m \). Furthermore, it is of interest to assign a numerical value to \( m \) (in the case \( n = 1 - m \)) so that we gain some insight into the forms our solutions take. Therefore, we shall also present these results in the particular form for \( m = 1/7 \), a value appropriate to conditions of near-neutral stability (cf. Calder 1949, Sutton 1953, p. 238), and of relevance to the problems we later investigate.

We distinguish results for \( n = 1 - m \) by the letter A and results for \( m = 1/7 \) by the letter B. Thus, equation (10) is a general result; (10A) is the particular form of (10) for \( n = 1 - m \); (10B) is the particular form of (10A) for \( m = 1/7 \).

5. Two dimensional diffusion: concentration boundary condition

The solution of (2), (3), and (4) subject to (6) is well known. It is most simply found by introducing the substitutions:

\[
\eta = \frac{u_1}{(2 + m - n)^2K_1 x} \tag{10}
\]
\[
= \frac{u_1}{(1 + 2m)^2K_1 x} \tag{10A}
\]
\[
= \frac{49u_1}{81K_1 x} \tag{10B}
\]

This enables reduction of (2), (3), and (4) to

\[
\frac{d^2 \theta}{d \eta^2} + \frac{1}{\eta} \frac{d \theta}{d \eta} \left[ 1 + \frac{1 + m}{2 + m - n} \eta^{-1} \right] = 0, \tag{11}
\]

provided that

\[
2 + m - n > 0, \tag{12}
\]

so that conditions (6) reduce to

\[
\eta = 0, \ \theta = 1; \ \eta \to \infty, \ \theta \to 0. \tag{13}
\]

The micrometeorologically possible values of \( m \) and \( n \) are such that (12) will always be satisfied.

A first integration of (11) with respect to \( \eta \) yields

\[
\frac{d \theta}{d \eta} = B \eta^{-(1+m)/(2+m-n)} e^{-\eta}, \tag{14}
\]

with \( B \) a constant of integration. A second integration and use of conditions (13) give

\[
\theta = 1 - \int_0^\infty \eta^{-(1+m)/(2+m-n)} e^{-\eta} d\eta \tag{15}
\]

\[
\int_0^\infty \eta^{-(1+m)/(2+m-n)} e^{-\eta} d\eta = \int_0^\infty \eta^{-(1+m)/(2+m-n)} e^{-\eta} d\eta
\]

i.e.,

\[
\theta = 1 - I \left( \eta, -\frac{1 + m}{2 + m - n} \right) \tag{16}
\]

\[
\theta = 1 - I \left( \eta, -\frac{1 + m}{1 + 2m} \right) \tag{16A}
\]

\[
\theta = 1 - I \left( \eta, -\frac{1 + m}{1 + 2m} \right) \tag{16B}
\]

Here, \( I(\eta, \rho) \) is the form of the incomplete gamma function given by Pearson (1951).

\[
I[\eta, -(1 + m)/(2 + m - n)]
\]

does not exist for \( (1 + m)/(2 + m - n) \geq 1 \), i.e., for \( n \geq 1 \). In practice, this is a somewhat more restrictive condition than (12) is, but we are still able to represent the \( K(z) \) profiles observed in nature to reasonable accuracy.

Unfortunately, the tabulations presented by Pearson are not suitable for micrometeorological purposes. The author has found it simpler to compute the necessary functions \( ab \) using \( \Gamma(1 - \rho) = \pi/\sin \pi \rho \) by use of the following identity (Whittaker and Watson, 1927, p. 239):

\[
\Gamma(\rho) \cdot \Gamma(1 - \rho) = \pi/\sin \pi \rho.
\]

\[\]
Table 1. The functions $C_{117}$ and $F_{117}$.

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<th>$C_{117}$</th>
<th>$F_{117}$</th>
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Table 1. The functions $C_{117}$ and $F_{117}$—Continued.

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</tr>
<tr>
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</tr>
</tbody>
</table>

The equation:

$$C_m(\eta) = 1 - I \left( \eta, \frac{1 + m}{1 + 2m} \right).$$  \hspace{1cm} (17)

Thus, equation (16A) may be written as

$$\theta = C_m(\eta).$$  \hspace{1cm} (18)

We now investigate the distribution of the vertical flux of the diffusing entity, $\phi$:

$$\phi = -K \frac{\partial \theta}{\partial z} = -K \frac{\partial \eta}{\partial z} \frac{\partial \eta}{\partial z},$$ \hspace{1cm} (19)

so that it follows from equations (4), (10), and (16) that

$$\phi(\eta, x) = \phi(0, x) e^{-x}. \hspace{1cm} (20)$$

Here, $\phi(0, x)$ is the flux at the surface $z = 0$ ($\eta = 0$) and has the following value:

$$\phi(0, x) = \frac{(2 + m - n)K_1}{\Gamma(1 - n)} \left( \frac{1 - n}{2 + m - n} \right)^{-(1-n)/(2+m-n)} n_1.$$ \hspace{1cm} (21)

$$\phi(0, x) = \frac{(1 + 2m)K_1}{\Gamma(1 + 2m)} \left( \frac{1 + 2m}{n_1} \right)^{-(1+2m)/(1+2m)} n_1.$$ \hspace{1cm} (21A)

$$\phi(0, x) = \frac{9K_1}{7\Gamma(1/9)} \left( \frac{81K_4}{49n_1} \right)^{-1/9}. \hspace{1cm} (21B)$$

6. Two-dimensional diffusion: flux boundary condition

We now proceed to the solution of (2), (3), and (4) subject to (8). We may rewrite (2) in terms of $\phi$ (i.e., as a continuity equation) in the form

$$\frac{\partial \theta}{\partial z} = -\frac{1}{n} \frac{\partial \phi}{\partial z}. \hspace{1cm} (22)$$

* Accuracy of values for $\eta = 4.0$ is dubious. See text.
Differentiating with respect to \( z \),
\[
\frac{\partial \phi}{\partial x \partial z} = -\frac{\partial}{\partial z} \left( \frac{1}{u} \frac{\partial \phi}{\partial z} \right),
\]  
(23)

which we may rewrite, using (19) and the fact that \( K \) is a function of \( x \) only, as
\[
\frac{1}{K} \frac{\partial \phi}{\partial x} = -\frac{\partial}{\partial z} \left( \frac{1}{u} \frac{\partial \phi}{\partial z} \right).
\]  
(24)

Equation (24) evidently describes the “diffusion” of \( \phi \).

The conditions governing (24) are found from (8) to be:
\[
x = 0, \quad z > 0, \quad \phi = 0
\]
\[
x > 0, \quad z = 0, \quad \phi = 1.
\]  
(25)

It will be seen that we have reduced the present problem to a form identical to that solved in section 5, except that we must now replace \( m \) by \(-n\), \( n \) by \(-m\), \( u \) by \( K^{-1} \), and \( K \) by \( u^{-1} \). Substitution (10) is again appropriate, and the solution is
\[
\phi = 1 - I \left( \eta, \frac{1 - n}{2 + m - n} \right).
\]  
(26)

This solution is valid for
\[
2 + m - n > 0; \quad m > -1.
\]  
(27)

Neither of these restrictions is of importance in meteorological applications.

Equations (4), (10), (19), and (26) now yield
\[
\frac{d\theta}{d\eta} = -\frac{1}{(2 + m - n)K_1} \left( \frac{(2 + m - n)^2 K_1 x}{u_1} \right)^{(1-n)/(2+m-n)}
\]
\[
\times \left[ 1 - \frac{1 - n}{2 + m - n} \right].
\]  
(28)

Integration by parts gives
\[
\theta(\eta, x) = \frac{1}{(1-n)\Gamma \left( \frac{1}{m'} \right) K_1}
\]
\[
\times \left( \frac{(2 + m - n)^2 K_1 x}{u_1} \right)^{(1-n)/(2+m-n)}
\]
\[
\times \left[ e^{-x} - \Gamma \left( \frac{1}{m'} \right) \right]
\]
\[
\times \left[ 1 - \frac{1 - n}{2 + m - n} \right].
\]  
(29)

The limits of this integration depend on the result that conditions (8) imply the further condition
\[
x > 0, \quad z \to \infty, \quad \theta \to 0.
\]  
(30)

Equation (29) also makes use of the result that
\[
\lim_{\eta \to \infty} \left[ e^{-x} - \Gamma \left( \frac{1}{m'} \right) \right] = 0,
\]  
(31)

which follows very simply from the asymptotic expansion of \( 1 - I \) for large \( \eta \). Compare Appendix 1.

Equation (29) is obviously of the form
\[
\theta(\eta, x) = \theta(0, x) \cdot F \left( \frac{2 + m - n}{1 - n} \right),
\]  
(32)

where
\[
\theta(0, x) = \frac{1}{(1-n)\Gamma \left( \frac{1}{m'} \right) K_1}
\]
\[
\times \left( \frac{(2 + m - n)^2 K_1 x}{u_1} \right)^{(1-n)/(2+m-n)}
\]  
(33)

\[
\theta(0, x) = \frac{1}{m\Gamma \left( \frac{1}{m'} \right) K_1}
\]
\[
\times \left( \frac{(2 + m - n)^2 K_1 x}{u_1} \right)^{(1-n)/(2+m-n)}
\]  
(33A)

\[
\theta(0, x) = \frac{7}{\Gamma(8/9)K_1}\left( \frac{81K_1 x}{49u_1} \right)^{(1-n)/(2+m-n)}
\]  
(33B)

and
\[
F(\eta, \beta) = e^{-\gamma} - \Gamma \left( \frac{1}{\beta} \right) \eta^{1/\beta} \left[ 1 - I \left( \frac{1}{\beta} \right) \right].
\]  
(34)

For the case \( n = 1 - m \), it is convenient to introduce the notation \( F_n(\eta) \) to denote \( F[\eta, 2 + 1/m] \).

In this case, we may therefore write
\[
\theta(\eta, x) = \theta(0, x) \cdot F_n(\eta).
\]  
(35)

The properties of \( F_n \), and its calculation, are treated in Appendix 2. \( F_{1/2} \) is tabulated in table 1 and graphed in figs. 4 and 5.

7. Two-dimensional diffusion: radiation boundary condition

Our method of solution of (2), (3), and (4) subject to (9) is to find a suitable linear combination of the solutions of sections 5 and 6 which satisfies (9) to a reasonable accuracy. A more elaborate method of superposition would, doubtless, enable (9) to be satisfied to any desired accuracy. However, the present method has the merit of simplicity and yields results to an accuracy which is almost certainly adequate in the practical applications. Essentially, our method relies on the fact that the quantity \( x^\gamma + x^{-\gamma} \), where \( \gamma \) is a small positive number, varies only slowly as \( x \) varies through several orders of magnitude centered on \( x = 1 \).

From section 5, as part of the solution of (2), (3),...
and (4) subject to
\[ x = 0, \quad z > 0, \quad \theta = 0 \]
\[ x \geq 0, \quad z = 0, \quad \theta = a \]  \hspace{1cm} (36)
we have
\[ \phi_0 = a \cdot \frac{2 + m - n}{\Gamma \left( \frac{1}{1 + m - n} \right)} \cdot X^{-1}, \]  \hspace{1cm} (37)
where
\[ X = \frac{1}{K_i} \left( \frac{(2 + m - n)^2 K_i x}{n_1} \right)^{(1-n)/(2+m-n)} \]  \hspace{1cm} (38)

Also, from section 6, as part of the solution of (2), (3), and (4) subject to
\[ x = 0, \quad z > 0, \quad \theta = 0 \]
\[ x \geq 0, \quad z = 0, \quad \phi = b \]  \hspace{1cm} (39)
we have
\[ \theta_0 = \frac{b X}{(1 - n) \Gamma \left( \frac{1 + m}{2 + m - n} \right)} \]  \hspace{1cm} (40)

Superposing the two solutions, we obtain
\[ \theta_0 = a + \frac{b X}{(1 - n) \Gamma \left( \frac{1 + m}{2 + m - n} \right)} \]
\[ \phi_0 = a \frac{2 + m - n}{\Gamma \left( \frac{1}{2 + m - n} \right)} \cdot X^{-1} + b. \]  \hspace{1cm} (41)

We note, now, that in order to satisfy (9) by this superposed solution, we should require that
\[ aa + \frac{ab X}{(1 - n) \Gamma \left( \frac{1 + m}{2 + m - n} \right)} + (1 - \alpha) a \frac{2 + m - n}{\Gamma \left( \frac{1}{2 + m - n} \right)} \cdot X^{-1} + (1 - \alpha) b = 1. \]  \hspace{1cm} (42)

Evidently, (42) cannot in general be satisfied exactly, since \( X \) is not a constant. However, we are free to choose the constants \( a \) and \( b \) in such a way that the deviations from (42) are minimal in the range of \( X \) of interest. For this to be so, the terms in \( X \) and \( X^{-1} \) must be equal when \( X \) assumes the value \( \bar{X} \), which is the geometrical mean of the range \( X \)-values of interest. Thus, if we wish to study the \( x \)-range \( 10 \) to \( 10^4 \) cm, the appropriate value of \( \bar{X} \) is the value obtained for \( X \) in (38) with \( x = \bar{x} = 10^4 \).

We then have
\[ a = \alpha \Gamma \left( \frac{1 - n}{2 + m - n} \right) \frac{\bar{x}}{\bar{x}^2} \]
\[ b = \frac{1 - \alpha}{\Gamma \left( \frac{1 + m}{2 + m - n} \right)} \]
\[ \frac{(1 - n)}{(2 + m - n)} \bar{x}^2. \]  \hspace{1cm} (43)

We could then proceed by satisfying (42) exactly at \( x = \bar{x} \), and using (42) and (43) to evaluate \( a \) and \( b \). In the cases where \( 0 < \alpha < 1 \), which are of greatest interest to us here, this would produce a systematic error in the satisfaction of the boundary condition, the deviations both as \( x \) increases, and as \( x \) decreases, from the value \( \bar{x} \) being in the same sense. A preferable procedure is to match the boundary condition in such a way that the integrated error in fitting the boundary condition is zero over some appropriate region, say from \( x = 0 \) to \( x = x_1 \). Thus, for our numerical example, it would be suitable to take \( x_1 = 10^6 \). The equation to be used in conjunction with (43) for evaluating \( a \) and \( b \) is then
\[ aa + \frac{2cba \bar{X}}{(1 - n) \Gamma \left( \frac{1 + m}{2 + m - n} \right)} + (1 - \alpha) b = 1, \]  \hspace{1cm} (44)
where \( c \) is a factor of order-of-magnitude unity and is given by
\[ c = \frac{\bar{x}}{2x_1} \int_0^{x_1/\bar{x}} (y^{\gamma} + y^{-\gamma} - 1) dy = \frac{1}{2} \left[ \frac{(x_1/\bar{x})^\gamma + (x_1/\bar{x})^{-\gamma}}{1 + \gamma} \right] \]  \hspace{1cm} (45)
with
\[ \gamma = (1 - n)/(2 + m - n). \]  \hspace{1cm} (46)
For \( \bar{x} = 10^4 \) cm, \( x_1 = 10^6 \) cm, \( m = 1 - n = 1/7, \ c = 1.0879. \)

The expressions finally obtained for \( a \) and \( b \) are
\[ a = \frac{a \Gamma \left( \frac{1 - n}{2 + m - n} \right) \bar{x}^2}{a^2 \Gamma \left( \frac{1 - n}{2 + m - n} \right) \bar{x}^2 + 2c(1 - \alpha)(2 + m - n)\bar{x} + (1 - \alpha)^2 \Gamma \left( \frac{1 + m}{2 + m - n} \right)(1 - n)(2 + m - n)} \]  \hspace{1cm} (47)
\[
    b = \frac{(1 - \alpha) \Gamma \left( \frac{1 + m}{2 + m - n} \right) (1 - n) (2 + m - n)}{\alpha^2 \Gamma \left( \frac{1 - n}{2 + m - n} \right) \bar{X}^2 + 2\alpha (1 - \alpha) (2 + m - n) \bar{X} + (1 - \alpha)^2 \Gamma \left( \frac{1 + m}{2 + m - n} \right) (1 - n) (2 + m - n)}.
\]

(48)

With \( a \) and \( b \) evaluated, the solution is effectively complete. The required result is now the appropriate linear combination of the solutions developed in sections 5 and 6.

**Accuracy of the approximation.** The error in the satisfaction of the boundary condition

\[
    a\theta_0 + (1 - \alpha) \phi_0 = 1
\]

(49)

is found to be of the form

\[
    f_1(\alpha) \cdot f_2(\alpha) = \frac{f_1(\alpha)}{f_2(\alpha)} = \frac{2\alpha (1 - \alpha) (2 + m - n) \bar{X}}{\alpha^2 \Gamma \left( \frac{1 - n}{2 + m - n} \right) \bar{X}^2 + 2\alpha (1 - \alpha) (2 + m - n) \bar{X} + (1 - \alpha)^2 \Gamma \left( \frac{1 + m}{2 + m - n} \right) (1 - n) (2 + m - n)}
\]

(50)

and

\[
    f_3(x) = 1 - \frac{1}{2.1758} \frac{\Gamma \left( \frac{x}{10^4} \right)^{1/3}}{\Gamma \left( \frac{x}{10^4} \right)^{1/3}}.
\]

(54)

Note that \( f_2 \) is independent of the adopted values of \( u_1 \) and \( K_1 \). This \( f_2 \) function is shown in fig. 2.

The magnitude of the errors of the method are then readily illustrated with the aid of figs. 1 and 2. Thus, for the worst case with \(-0.3 < \alpha < 1.1\), \( \alpha \approx 0.56 \), \( f_1(\alpha) \approx 0.48 \), the errors at \( x = 10^4 \); \( 10^5 \) and \( 10^6 \); \( 10^7 \) and \( 10^8 \) are respectively: \(-3.9\) per cent; \(-2.4\) per cent; \(+2.0\) per cent; \(+9.7\) per cent. The typical values \( \alpha = 0.1 \), \( f_1(\alpha) = 0.136 \) yield the following corresponding errors: \(-1.1\) per cent; \(-0.7\) per cent; \(+0.6\) per cent; \(+2.8\) per cent.

---

**Fig. 1.** The function \( f_1(\alpha) \) for the numerical values given in the text. The error in fitting the radiation boundary condition is equal to \( f_1(\alpha) \cdot f_3(x) \).

**Fig. 2.** The function \( f_2(x) \) for the numerical values given in the text. The error in fitting the radiation boundary condition is equal to \( f_1(\alpha) \cdot f_3(x) \).
It is evident that, as long as \( \alpha \) lies in the range specified above, the present method yields results of sufficient accuracy over an \( x \)-range large enough for micrometeorological purposes.

8. The theory of advective inversion

We may develop the quantitative theory of advective inversion by superposing on the preceding results a steady vertical flux of the diffusing entity, \( \phi_0 \), which is supposed to occur uniformly, both upwind and downwind of \( x = 0 \). We have

\[
\phi_0 = \frac{K_1(1 - n)}{10^4(1 - n)} \cdot \Delta \theta_0,
\]

where \( \Delta \theta \) denotes the difference in \( \theta \) (over the regions upwind of \( x = 0 \)) between the surface and \( 10^4 \) cm. We shall here assume that \( K(\alpha) \) is the same for both the upwind and downwind regions. The validity of this assumption will be discussed later in this series.

**Advecitive inversion with concentration boundary condition.** We shall show in a later paper that, although the boundary conditions for most advection problems of interest are of the radiation type, they tend to approach closely either the concentration type or the flux type. Concentration-like advective effects lead to the type of advective inversion which is of greatest practical and theoretical importance. We may study this case adequately by investigating the case where the downwind boundary condition is purely of the concentration type.

We here define an inversion surface as one at which

\[
\frac{\partial \theta}{\partial z} = 0; \quad \frac{\partial \theta}{\partial x} < 0.
\]

We denote by \( \Delta \theta_0 \) the difference between values of \( \theta \) at \( z = 0 \) upwind and downwind of \( x = 0 \). The condition that an inversion (not present upwind) exists is that both \( \Delta \theta \) and \( \Delta \theta_0 \) be positive. From section 5, we then have, on the inversion surface,

\[
c^\eta = \frac{10^4(1 - n)}{\Gamma \left( \frac{3 + m - 2n}{2 + m - n} \right) \left( 1 - n \right) / \left( 2 + m - n \right) \cdot \frac{\Delta \theta_0}{\Delta \theta}}.
\]

The maximum downwind extent of the inversion, \( x = x_{\text{max}} \), occurs at the intersection of the inversion surface and \( z = 0 \). That is, we put \( \eta = 0 \) in (57),

\[
x_{\text{max}} = \frac{u_1}{K_1(2 + m - n)^2} \left[ \frac{10^4}{\Gamma \left( \frac{3 + m - 2n}{2 + m - n} \right) \left( 1 - n \right) / \left( 2 + m - n \right) \cdot \frac{\Delta \theta_0}{\Delta \theta}} \right]^{2 + m - n - 1}
\]

obtaining

\[
x_{\text{max}} = \frac{u_1}{K_1(2 + m - n)^2} \left[ \frac{\Delta \theta_0}{\Gamma \left( \frac{3 + m - 2n}{2 + m - n} \right) \left( 1 - n \right) / \left( 2 + m - n \right) \cdot \Delta \theta} \right]^{2 + m - n - 1}
\]

(58)

**Note:** The theory could be developed similarly for any other reference height, the value of \( 10^4 \) cm being quite arbitrary.
\[ \zeta = \left( \frac{2 + \frac{1}{m}}{m} \right)^{1/(2 + m n)} \frac{\Gamma \left( \frac{1 + 3 m}{1 + 2 m} \right)}{10^4} (\Delta \theta_0 / \Delta \theta)^{-1/m} \zeta (2) \text{ (62A)} \]

\[ \zeta = \left( \frac{15}{7} \right)^{7/2} \frac{10}{9} \frac{1}{10^4} \left( \Delta \theta_0 / \Delta \theta \right)^{-7} \zeta \]

\[ = 1.71 \times 10^{-4} \left( \Delta \theta_0 / \Delta \theta \right)^{-7} \zeta \text{ (62B)} \]

and

\[ x = x / x_{\text{max}}. \text{ (63)} \]

Note that \( \zeta \) is dimensionless since the \( 10^4 \) in the denominator of (62) represents the reference height \( 10^4 \text{ cm} \) and has the dimension of length.

The \( \zeta(x) \) function of (61B) is shown in fig. 3. It illustrates the general form of advective inversions of this nature.

It is simply shown by differentiation that the maximum height of the inversion, \( x_{\text{max}} \), occurs at

\[ x = x_{\text{max}} / e, \text{ (64)} \]

and that

\[ z_{\text{max}} = \left( \frac{1 - n}{2 + m - n} \right)^{1/(2 + m - n)} \]

\[ \times \frac{10^4}{\Gamma \left( \frac{3 + m - 2 n}{2 + m - n} \right)} \left( \Delta \theta_0 / \Delta \theta \right) \] \text{ (65)}

\[ z_{\text{max}} = \left( \frac{m}{1 + 2 m} \right)^{1/(2 + m n)} \]

\[ \times \frac{10^4}{\Gamma \left( \frac{1 + 3 m}{1 + 2 m} \right)} \left( \Delta \theta_0 / \Delta \theta \right)^{1/m} \] \text{ (65A)}

\[ z_{\text{max}} = (9/4)^{-7/9} \frac{10^4}{\Gamma \left( \frac{10}{9} \right)} \left( \Delta \theta_0 / \Delta \theta \right)^{-7} \]

\[ = 0.09 \times 10^4 \left( \Delta \theta_0 / \Delta \theta \right)^{-7}. \text{ (65B)} \]

The expressions for \( \zeta \) and \( z_{\text{max}} \) are independent of \( K_1 \) and \( u_1 \). That is, for constant values of \( m, n \) and \( \Delta \theta_0 / \Delta \theta \), the vertical scale of the inversion, and its maximum height, are independent of wind strength and surface roughness.

We note here again the extreme sensitivity of the properties of the inversion to the ratio \( \Delta \theta_0 / \Delta \theta \).

**Advecive inversion with flux boundary condition.** This case is discussed only for the sake of completeness. It will be shown later in this series that this form of inversion is most unlikely to occur in practice. We consider the situation where the upwind flux is again \( \phi_0 \) at all levels and the downwind boundary condition is that the flux at \( z = 0 \) has the constant value \( \phi_{00} - \Delta \phi_0 \). Obviously, an inversion (not present upwind) develops only when \( \Delta \phi_0 > \phi_{00} > 0 \). In this case, the equation of the inversion surface is, from section 6,

\[ I \left( \eta, -\frac{1 - n}{2 + m - n} \right) = 1 - \phi_{00} / \Delta \phi_0. \text{ (66)} \]

The inversion surface is a surface of constant \( \eta \), the \( \eta \)-value, and thus the relative height of the inversion, being determined by \( \phi_{00} / \Delta \phi_0 \). The equation of the inversion surface clearly reduces to the form

\[ z \propto x^{1/(2 + m - n)} \text{ (67)} \]

\[ z \propto x^{1/(1 + 2 m)} \text{ (67A)} \]

\[ z \propto x^{7/9}. \text{ (67B)} \]

This type of advective inversion is quite dissimilar to the concentration type. It extends downwind indefinitely and exhibits no maximum height.

9. **Conclusion**

The aim of the present paper has been to present the basic methods of analysis to be used in this study of the theory of local advection. We defer application of the methods to specific problems, the presentation of illustrative numerical examples, and critical discussion of the assumptions on which the analysis is based to later papers in this series.

**REFERENCES**

Calder, K. L., 1949: Eddy diffusion and evaporation in flow over aerodynamically smooth and rough surfaces: a treatment based on laboratory laws of turbulent flow with special


APPENDIX 1

The function C_m, its properties and its computation.

Using the Taylor expansion of e^x in (15), we obtain

$$
\theta = 1 - \frac{\eta^{1/\beta}}{\Gamma \left( \frac{\beta + 1}{\beta} \right)} \left\{ 1 - \frac{\eta}{\beta + 1} + \frac{\eta^2}{2!(2\beta + 1)} \left[ \frac{\eta^3}{3!(3\beta + 1)} + \frac{\eta^4}{4!(4\beta + 1)} - \cdots \right] \right\}.
$$

where

$$
\beta = \frac{2 + m - n}{1 - n};
$$

$$
\beta = 2 + \frac{1}{m} \quad \text{(69A)}
$$

$$
\beta = 9. \quad \text{(69B)}
$$

For m and n values of interest, the series in the curly bracket of (68) converges rapidly for a large part of the η-range, so that (68) is very suitable for numerical computation. In particular, the use of (69A) in (68) yields a simple method of computing C_m. We have used this method to compute C_{17} in the range 0 ≤ η ≤ 3, the results being given in table 1. We give only illustrative values for η < 10^{-6}; fuller tabulation is unnecessary, since for small values of η we may use the very good approximation, derived from (68), that

$$
C_m \approx 1 - \frac{\eta^{m/(1+2m)}}{\Gamma \left( \frac{1 + 3m}{1 + 2m} \right)}.
$$

For large η, we may use the asymptotic expansion of (15),

$$
\theta = \frac{e^{-\eta}}{\Gamma \left( \frac{1}{\beta} \right)} \left( \frac{\beta - 1 + (\beta - 1)(2\beta - 1)}{(\beta \eta)^{\beta}} \right) \left[ \frac{1}{\beta \eta} + \frac{(\beta - 1)(3\beta - 1)}{(\beta \eta)^{3}} + \cdots \right]. \quad \text{(71)}
$$

where β is again specified by (69). We have used (71) to compute the values of C_{17} for η > 4 shown in table 1.

The error in the table of C_{17} should not exceed one in the last figure given, additional decimals having been retained in the computation. However, we note an exception at η = 4, which arises because (71) cannot yield sufficient accuracy for η-values as small as this. Comparison of the present results with the short four-decimal table of C_{17} given by Frost (1946) reveals a number of instances where Frost's result is apparently incorrect by one unit in the fourth decimal and two instances where the discrepancy in the fourth decimal is two.

The following asymptotic properties of C_m follow from (68) and (71):

$$
\lim_{\eta \to 0} C_m = 1 - \frac{\eta^{m/(1+2m)}}{\Gamma \left( \frac{1 + 3m}{1 + 2m} \right)};
$$

$$
\lim_{\eta \to \infty} C_m = e^{-\eta} \frac{\eta^{m}}{\Gamma \left( \frac{m}{1 + 2m} \right) \eta^{(1+m)/(1+2m)}}. \quad \text{(72)}
$$

These properties of C_m are reflected in the plots of C_{17} shown in figs. 4 and 5. Fig. 4 shows C_{17} (η) plotted with the scales of η and (1 - C_{17}) logarithmic, while in fig. 5 the scale of η is linear and that of C_{17} logarithmic.

We have here dealt specifically with the function C_m; however, it will be evident that the results apply also with little or no modification to the Pearson 1-function.

APPENDIX 2

The function F_m, its properties and its computation.

Use of the Taylor expansion of e^x leads to the following series form of equation (34):

$$
F(\eta, \beta) = 1 - \Gamma \left( \frac{1}{\beta} \right) \left[ \frac{1}{\beta - 1} + \frac{\eta}{\beta - 1} \frac{\eta^2}{2!(2\beta - 1)} + \frac{\eta^3}{3!(3\beta - 1)} + \frac{\eta^4}{4!(4\beta - 1)} + \cdots \right]. \quad \text{(73)}
$$

For m- and n-values of interest, this series converges rapidly over most of the relevant η-range, so
that (73), like (68), is very suitable for numerical computation.

We have used (73) to compute \( F_{1/7} \) in the range \( 0 \leq \eta \leq 3 \), the results being given in table 1. We give only illustrative values for \( \eta < 10^{-6} \), fuller tabulation being unnecessary, since, for small values of \( \eta \), we have to have a very good approximation

\[
F_m \approx 1 - \Gamma \left( \frac{1 + m}{1 + 2m} \right) \eta^{m/(1+2m)}.
\]

(74)

Also, for large \( \eta \), we may use the asymptotic expansion of equation (34), which is

\[
F(\eta, \beta) = \frac{e^{-\eta}}{\beta \eta} \left\{ 1 - \beta + \frac{1}{\beta \eta} + \frac{(\beta + 1)(2\beta + 1)}{(\beta \eta)^2} \right. \\
- \frac{(\beta + 1)(2\beta + 1)(3\beta + 1)}{(\beta \eta)^3} + \cdots \right\}.
\]

(75)

We have used (75) to compute the values of \( F_{1/7} \) for \( \eta \geq 4 \) shown in table 1. The accuracy of the table of \( F_{1/7} \) follows closely that of the \( C_{1/7} \) table. Once again, the value at \( \eta = 4 \) is of uncertain accuracy, due to the use of asymptotic expansion (75) for this relatively small value of \( \eta \).

The following asymptotic properties of \( F_m \) follow from (73) and (75) and are reflected in the plots of \( F_{1/7} \) shown in figs. 4 and 5:

\[
\lim_{\eta \to 0} F_m = 1 - \Gamma \left( \frac{1 + m}{1 + 2m} \right) \eta^{m/(1+2m)}.
\]

\[
\lim_{\eta \to \infty} F_m = e^{-\eta} \left( \frac{1 + 2m}{m} \right) \eta.
\]

(76)

The general similarity of the power series and asymptotic expansions of \( C_m \) and \( F_m \) will be noted, as well as the very similar behavior and nearness of values of \( C_{1/7} \) and \( F_{1/7} \). We have the following results from (72) and (76):

\[
\lim_{\eta \to 0} \left( \frac{F_m}{C_m} \right) = \frac{1 - \Gamma \left( \frac{1 + m}{1 + 2m} \right) \eta^{m/(1+2m)}}{1 - \eta^{m/(1+2m)}} \Gamma \left( \frac{1 + 3m}{1 + 2m} \right) \\
\approx 1 - \frac{\pi^2}{6} \left( \frac{m}{1 + 2m} \right)^2 \Gamma \left( \frac{1 + m}{1 + 2m} \right) \eta^{m/(1+2m)}.
\]

\[
\lim_{\eta \to \infty} \left( \frac{F_m}{C_m} \right) = \Gamma \left( \frac{1 + 3m}{1 + 2m} \right) \eta^{-m/(1+2m)}.
\]

(77)

Neither of these limits will vary much from unity in the \( m \)- and \( \eta \)-ranges of interest. We have the further result that

\[
\lim_{m \to 0} \left( \frac{F_m}{C_m} \right) = 1.
\]

(78)
That is, when \( m \) is small, as it will usually be, \( F_m \) and \( C_m \) will not differ greatly from each other throughout the whole \( \eta \)-range. This leads to the conclusion that, in any practical applications of advection theory, it may be sufficiently accurate to put \( F_m \approx C_m \), thus simplifying the formulation and enabling the required solutions to be obtained solely from tabulations of \( C_m \).

We have dealt here specifically with the function \( F_m \); however, it will be evident that similar results hold for the function \( F(\eta, \beta) \). The treatment of the ratio \( F_m/C_m \) has, as its more general counterpart, treatment of the ratio \( F(\eta, \beta)/[1 - I(\eta, (1 - \beta)/\beta)] \).