Air Mass Modification due to Change in Surface Characteristics[1,2]

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ABSTRACT

A simple empirical model is developed based on physical and dimensional considerations to predict the height of air mass modification due to a change in surface characteristics. Most of the input parameters can be obtained from surface weather maps. The results of the empirical model are found to be in good agreement with observations made in the atmosphere over ocean with cooler downwind temperatures. The model is then used with appropriate parameters to predict flow modification over a heated surface in a wind tunnel for different upwind and downwind surface conditions.

1. Introduction

When the surface boundary conditions of the atmospheric flow change, the effect is propagated upward and a modification of the air mass occurs. This change in the boundary conditions may be a change in roughness or surface temperature, or both. In any case, the new surface causes the flow to change from the upwind equilibrium conditions. The changes in the mean and fluctuating parameters of the flow are initially restricted to a shallow layer near the surface, but gradually diffuse upward as the flow advances downwind. Examples of such modifications in air masses are the atmospheric flows from rural to urban areas, from land to sea, or vice versa.

The variation in the height of the internal boundary layer caused by change in surface roughness has been studied by Elliott (1958), Panofsky and Townsend (1964) and Shir (1972), among others. The change in surface temperature and roughness has also been studied with numerical methods by Taylor (1970, 1971) and Huang and Nickerson (1972).

2. Physical and dimensional considerations

It will be useful to develop a simple formulation for air mass modification due to a change in surface characteristics that would involve a minimum of input parameters. There are several meteorological variables that contribute to the height h of air mass modification, but the ones that are considered to be of importance are as follows:

- Time of travel of the air mass, t (s)
- Upwind surface temperature, T_U (K)
- Downwind surface temperature, T_D (K)
- Downwind friction velocity, u_* (m s^{-1}).

Upwind or downwind roughness lengths have not been included due to the uncertainties involved in their estimation and to keep the formulation as simple as possible. However, the downwind roughness length would be a function of the friction velocity used.

From dimensional considerations using the parameters listed above and defining ΔT as $|T_U - T_D|$, we have

$$h = u_* t \Phi\left(\frac{\Delta T}{T_D}\right), \tag{1}$$

where the function Φ of the nondimensional absolute temperature difference would have to be determined from observational data. Replacing t with the fetch F (m), Eq. (1) can be written

$$h = u_* \frac{F}{\langle u \rangle} \Phi(\Delta T/T_D), \tag{2}$$

where $\langle u \rangle$ is a characteristic mean wind speed of the air mass within the surface layer. A similar formulation was presented earlier (Raynor *et al.*, 1975) that included an upwind temperature lapse rate not obtainable from surface data. A surface drag coefficient C_D could be readily estimated for a given location and is known within reasonable limits for atmospheric flow over sea surface. Hence, substituting $C_D^{\frac{1}{2}}$ for $u_*/\langle u \rangle$ in Eq. (2) yields

$$h = C_D^{\frac{1}{2}} F \Phi(\Delta T/T_D). \tag{3}$$

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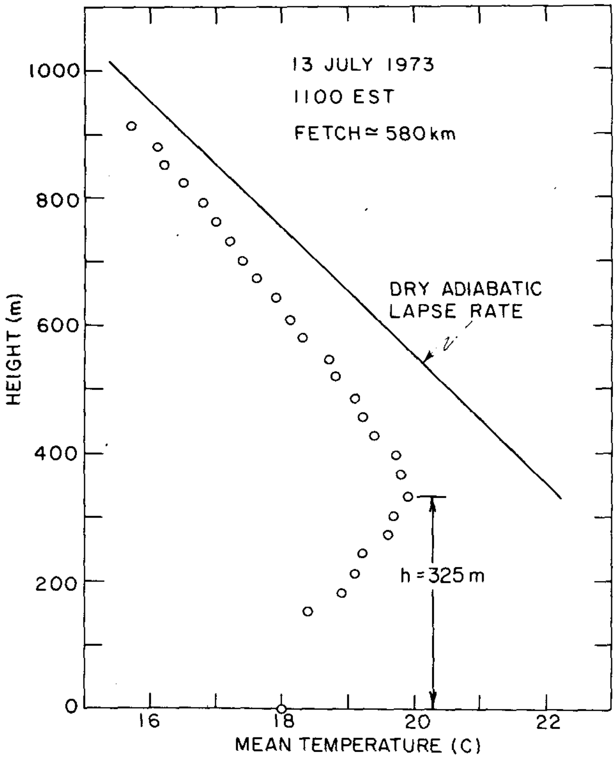

Fig. 1. Mean temperature profile over Atlantic Ocean with an estimated fetch of 580 km.

Since the surface drag coefficient C_D is a function of roughness length, the model indirectly includes the effect of surface roughness. Positive $(T_U - T_D)/T_D$ would indicate a surface-based inversion and negative sign an elevated inversion.

3. Results

Values of this height h at different downwind distances for various surface boundary conditions have been computed using Eq. (3) and are compared with experimental observations. Field values of the height of modification corresponded to warm air mass modified by cooler ocean $(T_U > T_D)$ indicating the following linear functional relationship in Eq. (3) with $\Phi = 1$:

$$h = C_D^{\frac{1}{3}} F(\Delta T/T_D), \tag{4}$$

where C_D is the downwind surface drag coefficient that would include the roughness effects due to both the terrain and heating.

a. Field observations

Field values (Raynor *et al.*, 1975) were obtained from aircraft temperature profiles over the Atlantic Ocean with a fetch varying from 150 to 530 km and represent a change from near-neutral stability to surface-based inversion. Roughness change was from rough to smooth as the air moved from land to sea. Mean temperature profiles measured over the Atlantic Ocean off the south shore of Long Island were used to determine the heights of air mass modification. Fetches varied from 150 to 580 km depending on the wind direction. A typical overwater temperature profile for one of the experiments is shown in Fig. 1. The wind direction for this run was southwesterly with a fetch of about 580 km. Low-level air temperature was estimated to be 24°C over land from surface weather maps. In fact, an adiabatic extrapolation of the mean temperatures above the inversion to the surface in Fig. 1 also yields 24°C. Near the surface C_D overwater was assumed to be 0.00115 (SethuRaman and Raynor, 1975) based on simultaneous observations. Surface temperature of the water was always cooler than that of the land thus causing a surface-based inversion over the water. For cases when the conditions are reversed, C_D could be significantly higher.

A comparison of the predicted values with the observed values for the field experiments is shown in Fig. 2. The values of the parameters are given in Table 1. Linear regression analysis of the observed to predicted values yielded a correlation coefficient of 0.89. Predicted heights are within a factor of 2 of the observations despite the degree of estimation involved in obtaining F and T_U from surface weather maps.

b. Wind tunnel observations

Field data for atmospheric flow from a cold upwind surface to warmer downwind conditions were not available. Hence observations made in a large wind tunnel were used to verify the model for other flow conditions.

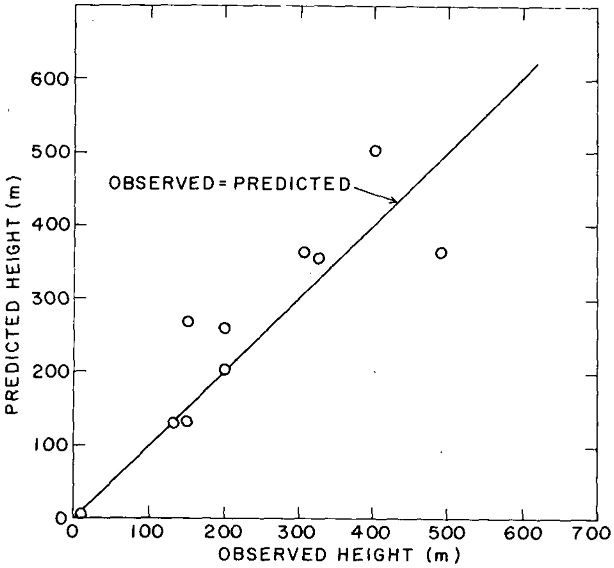

Fig. 2. Comparison of observed heights of air mass modification with predicted values for the atmospheric flow from land to sea (downwind surface temperatures less than the upwind values).

TABLE 1. Field observations.

Fetch (km)	Upwind (land) surface temperature T_U (K)	Downwind (sea) surface temperature T_D (K)	$T_U - T_D$ (K)	Observed height (m)
270	295.0	286.0	9.6	150
580	297.0	291.0	6.0	325
150	292.0	291.5	0.5	10
530	292.0	283.0	9.0	400
240	293.0	278.8	14.2	490
440	280.0	277.2	2.8	130
180	303.0	293.5	9.5	200
160	299.7	285.0	14.7	200
200	299.7	293.5	6.2	150
375	302.0	293.0	9.0	305

Wind tunnel data were obtained from a study pertaining to the simulation of atmospheric flow over a three-dimensional heat island (SethuRaman and Cermak, 1974). Two cases are considered here: 1) a surface-based inversion approach flow changing to a superadiabatic lapse rate, and 2) an elevated inversion approach flow changing to a superadiabatic lapse rate. In both cases, surface temperatures changed from colder to warmer and the roughness from smooth to rough. As air travelled over the heat island, modification was reflected in the mean temperature profiles in terms of the formation of an elevated inversion and increase in the height of the base of this inversion with distance. The mechanism was similar to the case of the elevated inversion approach flow. The height of air modification was taken to be the height up to which the downwind surface features play a predominant role. Mean concentration measurements of krypton 85 released from an upwind two-dimensional source also indicated the height at which the mean temperatures changed from a superadiabatic lapse rate to an inversion (SethuRaman and Cermak, 1976). The near-surface C_D for the heated surface was found to be 0.25 (SethuRaman, 1973).

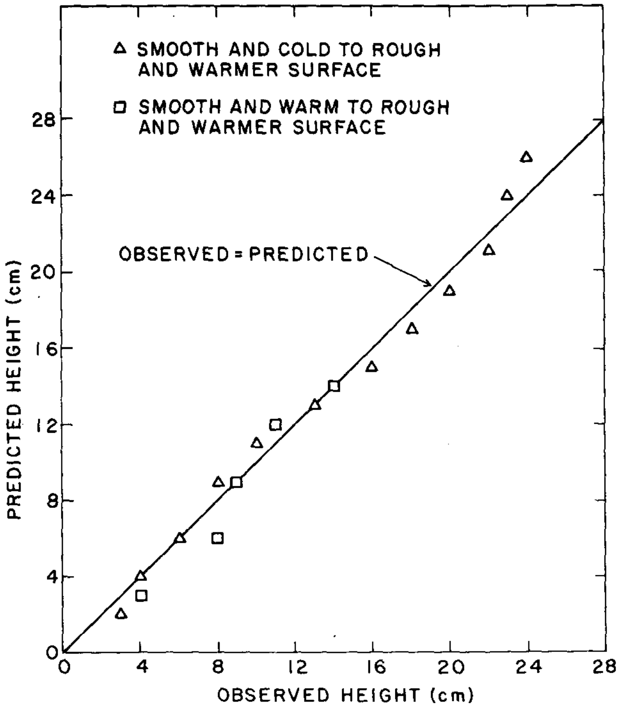

FIG. 3. Comparison of observed heights of air modification with predicted values for wind tunnel flows for different upwind and downwind conditions.

Observations made in the wind tunnel are given in Table 2 and are compared with the predicted values [using Eq. (4)] in Fig. 3. The agreement is obviously better for the wind tunnel data, probably due to controlled conditions and better accuracy that are possible in laboratory experiments. The correlation coefficient was 0.99.

4. Conclusions

A simple empirical formulation based on a downwind surface drag coefficient and an upwind-downwind surface temperature difference predicts the air mass modification with reasonable accuracy (within a factor of 2). The model was formulated with observations pertaining to atmospheric flow from land to sea with warmer upwind temperatures. For a cold air mass advecting over warmer ocean, the functional relationship given by Eq. (4) should still be valid although no data were available to verify the relationship under

TABLE 2. Wind tunnel observations.

Fetch (cm)	Upwind surface temperature (K)	Downwind surface temperature (K)	Observed height (cm)	C_D
	Surface-based inversion upwind			
15	283	394	3	0.25
30	283	394	4	
45	283	394	6	
61	283	394	8	
76	283	394	10	
91	283	394	13	
107	283	394	16	
122	283	394	18	
137	283	394	20	
152	283	394	22	
168	283	394	23	
183	283	394	24	
	Elevated inversion upwind			
30	316	389	4	
61	316	389	8	
92	316	389	9	
122	316	389	12	
152	316	389	14	

these conditions. The downwind C_D in this case would be somewhat larger than the value adopted here.

In the absence of appropriate field data to verify the model for other surface conditions, wind tunnel results pertaining to flow over a heated surface in a simulated atmospheric boundary layer were used. The results indicate that the model would be applicable to other surface features as well provided a representative downwind C_D is used.

For a typical airmass movement from cold sea to warmer land with $C_D \approx 0.15$ and $\Delta T \approx 20°\mathrm{C}$, h/F would be about 1/100 which is close to the value usually observed in the atmosphere.

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