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An Investigation of the
Marine Boundary Layer During Cold Air Outbreak

Principal Investigator:

Steven A. Stage
Department of Meteorology
Florida State University
Tallahassee, Florida 32306-3034

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ATMOSPHERIC BOUNDARY LAYER
MARINE ENVIRONMENT
REMOTE SENSING
HEAT FLUX
AIR WATER INTERACTION

LATENT HEAT
OCEAN SURFACE
WATER VAPOR
HEAT TRASFER
MATH MODELS
SATELLITE OBSERVATI

OUTLINE

1. INTRODUCTION

The principal goals of this research have been to develop and evaluate methods for use in the remote estimation of ocean surface sensible and latent heat fluxes. were developed and evaluated. Three different techniques ~~have~~ were been developed for determining these fluxes. ~~The first is~~ discussed in section 2 and the other two are discussed ~~together in section 3. Then section 4~~ summarizes the work and ~~gives general~~ comments and suggestions. to sect. 4.

The details of the work performed under this grant have been given in the thesis, publications, and papers listed below in section 5 and will not be reproduced here. The purpose of this report is to provide a summary of the most significant work and results and to draw these together into a consolidated statement of what has been learned about methods for remote estimation of ocean surface heat and vapor fluxes.

2. A METHOD OF OBTAINING SURFACE SENSIBLE AND LATENT HEAT FLUXES FROM SATELLITE MEASUREMENTS.

2.1. Synopsis of the Method:

Satellite estimates can be obtained for the total integrated water vapor in the atmosphere, q_{vI}; the total integrated liquid water, q_{lI}; the cloud top temperature, T_{B-}; the sea surface temperature, T_o; and either the surface wind speed, U, or the surface friction velocity, u_*. Under the assumption that equivalent potential temperature and total water vapor mixing ratio are uniformly mixed throughout the MABL and making some assumption about the profile of water vapor above the mixed layer it becomes possible to calculate values for the layer depth, z_B; the mean mixed layer equivalent potential temperature, θ_e; and the mean mixed layer total water vapor mixing ratio, q_T and then to calculate the surface sensible and latent heat fluxes.

2.2. Discussion of the Method:

This method is discussed in detail by Allison (1984) and Allison and Stage (1986). Let z_B, θ_e, and q_T denote the mixed layer depth, mixed layer mean equivalent potential temperature, and mixed layer mean total water mixing ratio respectively. Under the assumption that the equivalent potential temperature and total water vapor mixing ratio are uniformly mixed throughout the MABL and making an assumption for the profile of water vapor above the top of the mixed layer, the thermodynamical equations dictate that there is an explicit set of equations which gives T_{B-}, q_{vi}, and q_{li} as functions of z_B, θ_e, and q_T. This set of equations can be not be explicitly inverted but can be implicitly inverted using standard mathematical techniques. One simple technique for doing so is given by Allison (1984) and Allison and Stage (1986). The satellite measurements can, therefore, be used to determine z_B, θ_e, and q_T. The satellite values of T_O and either U or u_* can them be used along with any standard bulk transfer relationship to obtain estimates for the surface sensible and latent heat fluxes. Allison uses a bulk transfer method which combines the method proposed by Stage and Businger (1981a) and the widely accepted method of Liu, *et al.* (1979).

The beauty of this method lies in the fact that the only physical assumptions used are that the MABL is well-mixed, that one can find a suitable profile to use for water vapor above the mixed layer, and that the bulk transfer relationship used is appropriate. Another advantage of this method is that instantaneous fluxes can be computed rather than the weekly or monthly average fluxes which are computed by previously existing methods (e.g. Prabhakara et al., 1982). It must be emphasized that this method in no way relies on any assumption about the rate of entrainment into the MABL. The accuracy of this method is determined by how well the actual MABL structure matches the assumed structure and by the accuracy of the data used in the computation.

2.2.1. Applicability of the Method: Data from cold air outbreak episodes such that obtained during as the International Field Year for the Great Lakes (IFYGL, Stage and Businger, 1981a) and from the MASEX experiment show that the MABL is such cases has well mixed equivalent potential temperature and total water mixing ratio. This is because large amounts of vertical mixing are generated by the large surface buoyancy fluxes associated with cold air outbreak.

Data taken in stratus-topped mixed layers along the California coast (Neiburger et al., 1961) indicate that the MABL is often well-mixed there. In that case the ocean and air temperatures are close to each other and surface buoyancy fluxes are small; mixing is mostly generated by infrared radiative cooling of the cloud top. Davidson et al. (1983) noted that the water vapor mixing ratio values in coastal MABL profiles often decreased slightly with height and found that it was necessary to include that decrease in the MABL model of Stage and Businger

(1981a) in order to simulate the coastal MABL evolution. The vertical changes in mixing ratio which they observed were, however, small enough that they are not a serious source of error in flux computation by the method described here.

Nichols and Leighton (1986) show MABL profiles of cloud-topped boundary layers taken around the United Kingdom. In several of their cases there was not uniform mixing of potential temperature or mixing ratio between the surface and the cloud top. A marked example is shown in their figure 1. In that case this method would not work well. It should, however, be noted that the cases studied by Nichols and Leighton had near-surface air temperatures which were close to the sea surface temperatures and therefore had small surface sensible heat flux. In fact, the reason these layers were not well mixed from surface to cloud top is that the infrared cooling of the cloud top generated mixing in the cloud layer, but the associated buoyancy flux was mostly offset by absorption of solar radiation in the cloud layer thus giving only very small buoyancy flux in the lower boundary layer.

We therefore conclude that the method described here can be applied to cold air outbreak episodes and to cases which have air which is sufficiently colder than the water surface to give mixing by the surface buoyancy flux. Since these cases provide a large fraction of the air-sea energy exchange, the technique is useful for obtaining fluxes during the most significant episodes. The technique can also be used when air-sea temperature differences are more moderate including cases of coastal stratus-topped layers.

2.2.2. Accuracy of the Method: Allison (1984) and Allison and Stage (1986) study the sensitivity of this method to errors in the data and determine the size of errors which would be expected when measurements are made using currently available technology. The cloud top temperature may be found with an accuracy of +/-2°C and the accuracies of the sea surface temperature, the 10 m neutral wind speed, and the friction velocity are +/-1.5°C, +/-2 m/s or 20%, and +/-20%, respectively (Allan, 1983, using SEASAT and NIMBUS 7 data). According to Chang and Wilheit, 1979) the expected retrieval errors of the integrated liquid water and water vapor contents for the SMMR package on NIMBUS 5 are +/-0.65 m and +/-1.50 m. Table 1 summarizes the uncertainties in surface heat and vapor fluxes which are caused by each of these measurement errors and the expected overall R. M. S. errors in the fluxes. If the needed satellite parameters are measured simultaneously each set of measurements produces a flux estimate. The R. M. S. errors shown in the table are for each such flux estimate. When several such estimates are averaged together errors become smaller. For instance if twice daily values are averaged for one week and the errors assumed to be random, the expected R. M. S. errors of the weekly average will be 6% and 22% respectively for heat and vapor. Non-random errors could be removed through calibration.

The largest source of error is from the uncertainty in the total integrated water vapor (the vapor flux error would be reduced from 84% to 32% if the error in q_{ii} could be eliminated). In most situations nearly all of the water vapor is in the mixed

Table 1 : Individual Expected Errors due to Each Satellite Parameter and Total Expected Model Error

PARAMETER	SATELLITE RMS ERRORS	HEAT	MOISTURE
u_{10n}	20%	20%	20%
θ_b	2.0 °C	8%	9%
θ_0	1.5 °C	4.5%	6.75%
q_{li}	650 m g/kg	1.6%	22.75%
q_{vi}	1500 m g/kg	9%	75%
Total Expected R.M.S. Errors:		24%	82%

layer and very little above. If one assumes that the water vapor above the mixed layer can be approximated from the water vapor profile above the mixed layer in some nearby radiosonde sounding, or uses a water vapor profile appropriate for that particular meteorological situation, or even uses a profile suitable for that location and month; then the uncertainties associated with the amount of integrated water vapor which is above the MABL will be negligible compared to the errors in measuring q_{1i} using current techniques.

There are also errors in the heat and vapor fluxes which are associated with use of bulk transfer relationships. These errors would be present even in computations of these fluxes using _in situ_ measurements of air sea temperature and humidity differences and wind speed in bulk transfer formulae.

3. A METHOD OF OBTAINING SURFACE SENSIBLE AND LATENT HEAT FLUXES FROM AN MABL MODEL AND A METHOD USING HORIZONTAL TRANSFER COEFFICIENTS.

3.1. _Synopsis of the Methods:_

There are two related methods which can be used to calculate heat and vapor fluxes during cold air outbreak situations, which we have evaluated, and which need to be discussed together. Assuming that the near-surface air temperature and humidity are known at the shore and that the sea surface temperature and the wind speed are also known; one either knows or makes educated guesses for the lapse rates of temperature and humidity at the shore, for the divergence of the MABL, and for the radiative sky temperature. In the first method a computer model is then run which calculates the rates of change of z_B, Θ_m, and q_T as the air moves off the coast and which gives values for the surface heat and vapor fluxes, for the total radiative cooling, and for the rate of entrainment of inversion layer air into the mixed layer. The fluxes which are computed by the model are not very sensitive to the accuracy of the measured or guessed quantities and the model is computationaly simple enough to be economically run on a small computer.

In the second method the need to make a run of a computer model is replaced by use of horizontal transfer coefficients. Based on the mathematics of the MABL equations and the inspection of model results, it has been found that the heat flux per unit travel between the shore and any given fetch is nearly proportional to the difference between the near-surface air temperature and the water temperature with a constant of proportionality known as the horizontal transfer coefficient. The latent heat flux per unit travel can also be expressed as the product of a horizontal transfer coefficient and the air-sea humidity difference. The sensible and latent heat horizontal transfer coefficients are functions of nondimensional fetch which can be specified graphically or in tables. The computations required to find the fluxes then become simple enough to be made with a hand-held calculator or even by hand.

3.2. Discussion of the Methods:

The two methods are closely intertwined and will be discussed together. More complete explanations and discussions of these techniques are given by Chang (1986) and Chang and Stage (1986).

3.2.1. <u>The Model Used for the MABL:</u> This work uses a model for the evolution of an MABL during cold air outbreak which was developed by Stage and Businger (1981a). It predicts the rates of change of mean mixed layer equivalent potential temperature, total water mixing ratio and mixed layer depth following a column of air as it moves across the water. The effects of surface fluxes, infrared radiation, divergence, and entrainment at the layer top are included. Stage and Businger studied a cold air outbreak episode over Lake Ontario and found that the model was able to accurately match changes in temperature and dewpoint experienced by mixed layer air as it crossed the lake. Good agreement was also obtained between profiles observed at the south shore of the lake and those predicted by the model. As discussed by Stage and Businger (1981b) this model uses a relationship for the rate of entrainment of air into the mixed layer which appears to be more logically based on the energetics of the layer than previous models for stratocumulus cloud-topped marine mixed layers and is thus expected to be more accurate.

3.2.2. <u>The Method of Horizontal Transfer Coefficients:</u> Atlas <u>et al.</u> (1981) and Chou and Atlas (1982) considered the Stage and Businger model and found that it held promise for the determination of sea-surface heat and vapor fluxes from satellite measurements. By empirically studying the behavior of the model for several profiles based on a cold-air outbreak episode off New

York on February 17, 1979, Chou and Atlas (1982) found that in the area between the shore and the edge of the cloud (the cloud-free region) the sensible and latent heat flux per unit travel at a particular distance from shore are not very sensitive to divergence or to the lapse rates of the temperature and dewpoint soundings at the shoreline. They therefore suggested that the sensible heat flux could be approximately modeled by the product of a transfer coefficient and the potential temperature difference between the air at the shore and the sea surface temperature. Similarly, the latent heat flux could be modeled by the product of a transfer coefficient and the difference between the mixing ratio of the air at the shore and the saturation mixing ratio corresponding to the SST. They called these coefficients horizontal transfer coefficients because they connect the fluxes to horizontal differences between shore air properties and water properties rather than the vertical differences usually used in bulk transfer formulae.

3.2.3. <u>The Analytic Solution for a Dry Case:</u> Stage (1983) studied the model equations as they apply to the cloud-free region. By assuming that potential temperature and humidity profiles at the shore may be treated as linear, he was able to obtain analytic solutions which give the mixed layer potential temperature, mixing ratio, dewpoint, and layer depth as functions of fetch; which can be solved numerically to find the location of the edge of the cloud; and which allow calculation of heat and vapor fluxes. Stage (1983) examined the form of these solutions and found that to completely specify a particular cold-air outbreak episode requires the measurement of more parameters than can be obtained using data which is currently available from space. He then investigated the use of the horizontal transfer coefficients as proposed by Chou and Atlas (1982). He found that it is possible to nondimensionalize the MABL equations and to determine the horizontal transfer coefficients, g_1 and g_2, for virtual temperature and latent heat respectively as universal functions of the nondimensional fetch. He found that the functions g_1 and g_2 depend only very weakly on divergence and was able to show that even very crude estimates of the lapse rates of potential temperature and mixing ratio at the shore allow accurate estimates to be made for the heat fluxes in the cloud-free region. He was thereby able to demonstrate that the findings of Chou and Atlas (1982) can be generalized to any cold-air outbreak episode and provide a method for the simple computation of heat fluxes in the cloud-free region.

3.2.4. <u>Generalization to a Cloudy Case:</u> Stage (1983) showed that the dry case can be nondimensionalized so that plots of the transfer coefficients, g_1 and g_2, as functions of the nondimensional fetch, X, give universal curves. Once a cloud forms in the boundary layer, latent heat release and radiation become important; the equations increase in complexity; and it is no longer possible to find an analytic solution. Nonetheless, Chang (1986) and Chang and Stage (1986) have run the computer model in cloudy cases and inspected the results using the dry-case nondimensionalization. The reader is referred to Chang and Chang and Stage for mathematical details of their analysis. In the cloudy case the curves obtained for g_1 and g_2 depend to wind speed, shoreline near-surface temperature and humidity, shoreline lapse rates of temperature and humidity, boundary layer divergence, radiative sky temperature, and SST. The papers cited examine the curves obtained for g_1 and g_2 when each of these parameters are varied over the range which would be encountered during cold air outbreak. Figure 1 shows the plot which they obtained by varying T_{sky}, the radiative sky temperature, between -80 and 0°C. As expected, the curves reproduce the dry case analytic curves for fetches in the cloud-free region. After cloud formation the curves depend on T_{sky}, but the separation is not great. Table 2 shows the ranges of g_1 and g_2 associated with this range of T_{sky} for selected fetches. Even with the large range chosen the percentage change in g_1 and therefore in the heat flux remains less than +/-25%. The range for g_2 and latent heat flux remains less than +/-5.2%. It will nearly always be possible to obtain a value of T_{sky} with a much smaller range than that even if seasonal averages are used. The variation of g_1 and g_2 with each of the other parameters which is important in the cloudy case has been determined. Table 3 is a summary of the variations in the horizontal transfer coefficients when each of the parameters of the problem varies over a wide range of values. None of the flux variations is large. Errors in each of these parameters will be smaller than these ranges thus heat and vapor flux errors will be quite small.

A few words on the significance of the Chang (1986) and Chang and Stage (1986) work are in order. First of all, the main significance of this work is that it shows that if one begins

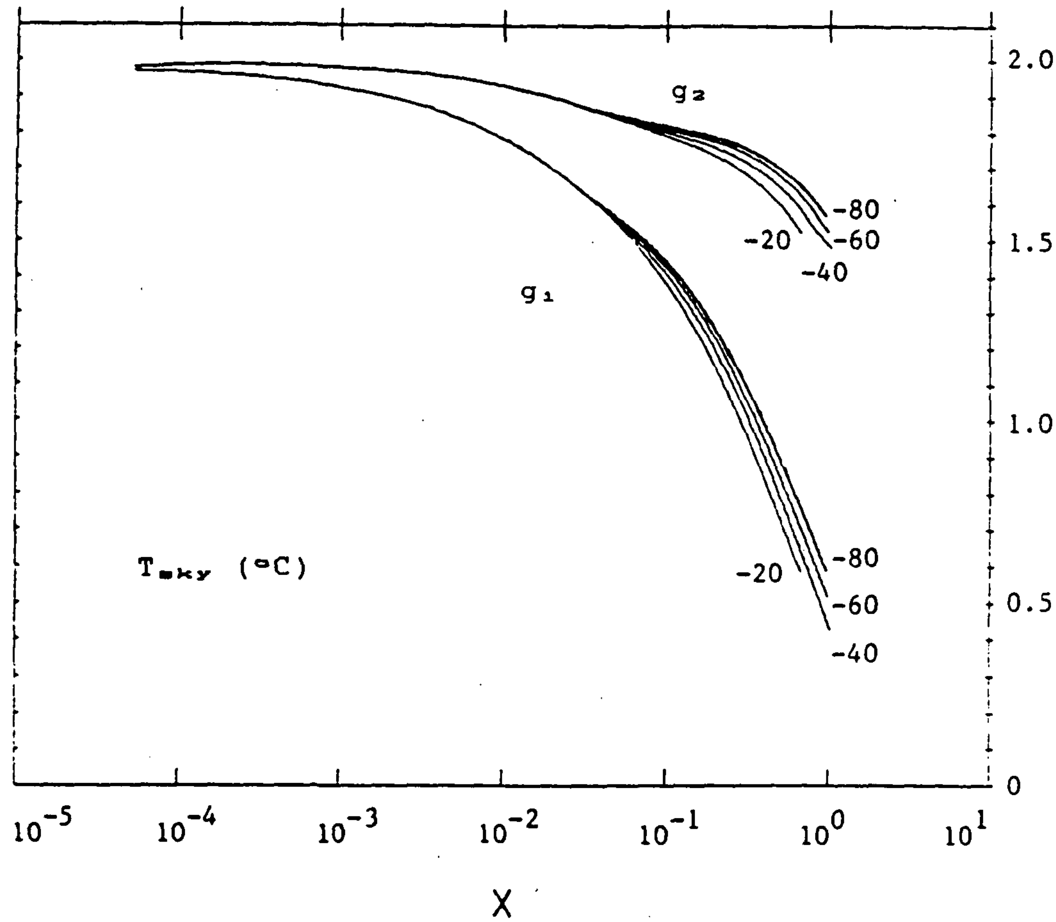

Figure 1: g_1 and g_2 as functions of X for various radiative sky temperatures, T_{sky} from -80 to 0 in increments of 20 °C.

Table 2

The changes of g_1 and g_2 caused by T_{SKY}. T_{SKY}: 0 to -80 C, in increments of -20 C.

Log X	x (km)	Range of T_{SKY} (°C)	Range of g_1 ($\bar{g}_1 \pm \Delta g_1$)	Range of g_2 ($\bar{g}_2 \pm \Delta g_2$)	Percent Change in g_1 ($2\Delta g_1/\bar{g}_1$)	Percent Change in g_2 ($2\Delta g_2/\bar{g}_2$)
-1.0	193	-20 to -80	1.43 ± 0.03	1.80 ± 0.02	4.4%	1.8%
-0.5	611	-20 to -80	1.03 ± 0.07	1.72 ± 0.04	13.8%	4.6%
0.0	1932	-20 to -80	0.51 ± 0.06	1.53 ± 0.04	25.0%	5.2%

Table 3

The uncertainties of g_1 and g_2 caused by the errors of the external parameters at fetch equal to 600 km (The measurement errors are allowed to be up to 50%).

external data (w/ standard sounding values)	tolerance of data	range of parameters	resulting errors (fetch ≅ 600km) $(\overline{g}_1 \pm \Delta g_1)$ $(2\Delta g_1/\overline{g}_1)$	$(\overline{g}_2 \pm \Delta g_2)$ $(2\Delta g_2/\overline{g}_2)$
Initial sounding:		(changes of) sounding data		
θ_{E1} (°C)	11.5,	11.5 to 13.5		
q_{T1} (g/kg)	3.4,	3.4 to 4.4	1.07±0.01 (1.9%)	1.59±0.05 (6.3%)
$\Gamma_{\theta E}$ (C/km)	3.8,	3.0 to 3.8		
Γ_{qT} $(\frac{g/kg}{km})$	-0.75,	-0.75 to 0.0		

Table 3 (continued)

external data (w/ standard sounding values)		tolerance of data	range of parameters	resulting errors (fetch ≅ 600km) $(\overline{g}_1 \pm \Delta g_1)$ $(2\Delta g_1/\overline{g}_1)$	$(\overline{g}_2 \pm \Delta g_2)$ $(2\Delta g_2/\overline{g}_2)$
U (m/sec)	16,	50%	8 to 24	1.01±0.02 (3.9%)	1.73±0.02 (2.3%)
D_1 (10^{-6}/sec)	4,	50%	2 to 6	0.96±0.06 (12.5%)	1.58±0.06 (7.6%)
D_2 (10^{-6}/sec)	4,	50%	2 to 6	0.84±0.03 (7.1%)	1.41±0.10 (13.5%)
T_o (C)	12,		8 to 16	1.03±0.11 (21.4%)	1.72±0.03 (3.5%)
T_{SKY}(C)	-40,		-20 to -60	1.00±0.04 (8.0%)	1.72±0.02 (2.9%)
R_B (mK/sec)	0.1,	50%	.05 to .15	1.01±0.05 (9.9%)	1.72±0.03 (3.5%)
RH_1(%)	40,	50%	20 to 60	1.03±0.03 (6.1%)	1.55±0.08 (10.7%)

with available measurements or best estimates of the needed parameters and uses the MABL model to compute heat and vapor fluxes per unit travel, the computed answers will not be very sensitive to errors or uncertainties in the input parameters. Therefore the model is a promising tool for flux computation. Secondly, it is possible to make plots of the horizontal transfer coefficients, g_1 and g_2, as functions of nondimensional fetch, X, using typical values of the parameters; e.g. typical conditions for cold air outbreak off New York during December. These plots may then be used to make estimates of the heat and vapor fluxes for a particular case. Use of the MABL model will have the smallest errors and is therefore preferred whenever sufficient computational power is available (The model can be run on a PC class microcomputer.) Because of the large number of parameters affecting g_1 and g_2 it is not practical to plot or tabulate values for all possible combinations of parameters. However, since the curves do not change very much as these parameters change, it is possible to use g_1 and g_2 values from a few typical cases. Because of this simplification, use of horizontal transfer coefficient plots has larger errors than a model run based on parameter values which fit a particular case, but has the advantage of enabling computations to be made with a hand-held calculator or even by hand.

3.3. Discussion of the Reliability of this MABL Model:

There has been much discussion in the literature which compares the MABL model of Stage and Businger (1981a) with those used by other authors. Most discussion has relied on heuristic grounds rather than measurements because data sets with sufficient detail to evaluate the models are rare, however Davidson et al. (1983) have used this model (with minor changes) to obtain good simulations of the structure and diurnal cycle of the stratocumulus-topped MABL. Nichols (1984), Nichols and Leighton (1986), and Nichols and Turton (1986) studied flux profiles from near the UK and found that the mixed layer model from Stage and Businger underestimated the rate of entrainment. Those profiles had air temperatures which were close the sea-surface temperatures so that surface heat fluxes were small and were primarily mixed by infrared cooling of the cloud top. Furthermore, the IR cooling was nearly balanced by solar warming in the cloud layer, thus turbulent fluxes were small below the cloud base and there was often a layer near the surface which was not well-mixed with the cloud layer. Since this does not satisfy the MABL structure assumed by Stage and Businger, it is not surprising that the observed flux profiles do not agree with those computed by the model.

The good simulation of IFYGL data obtained by Stage and Businger (1981a), has verified their model for use in cold air outbreak situations. Nonetheless, a test was done by Chang and Stage (1986) to determine the importance of the entrainment rate on the above-listed conclusions about flux calculations. Figure 2 shows the curves obtained for g_1 and g_2 when the entrainment coefficient, A, changes from its usual value of 0.2 to 0.0, 0.4, 0.6, and 0.8. The changes in g_1 are extremely small, just barely visible. g_2 has somewhat larger changes, however the range of

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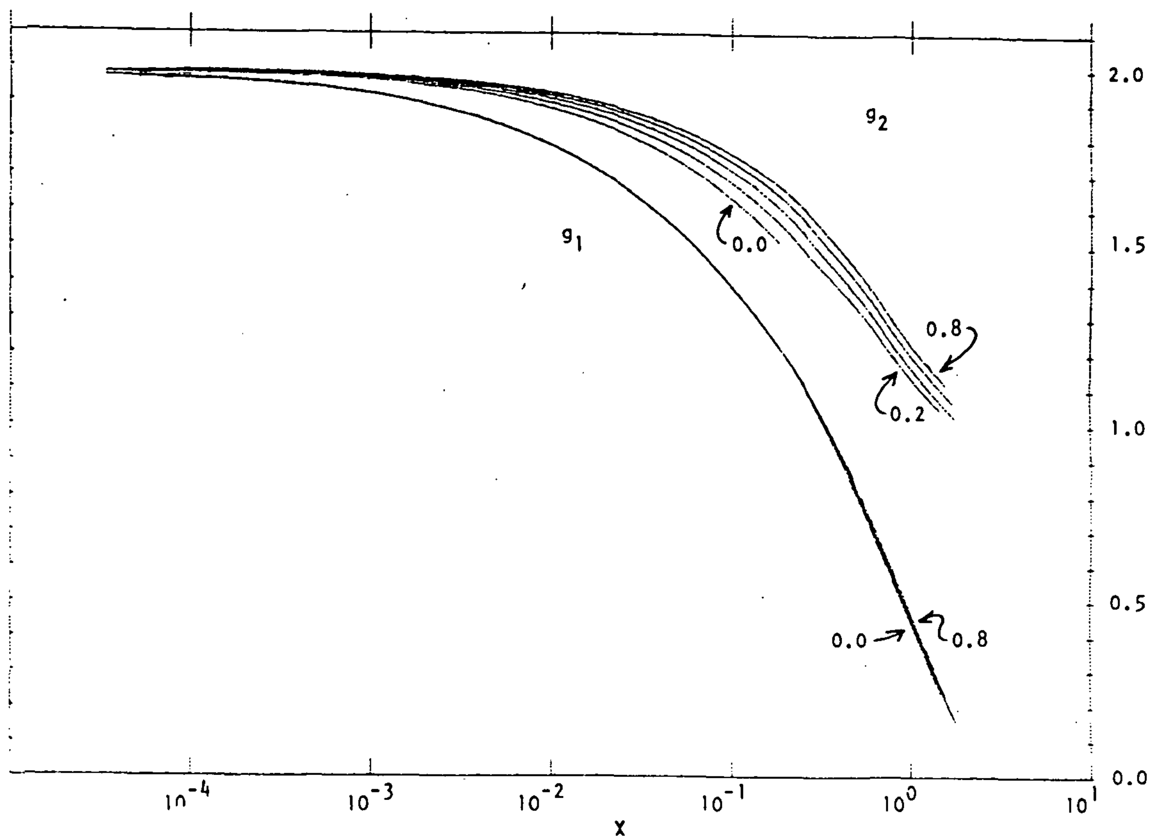

Figure 2: g_1 and g_2 as functions of X for various values of the entrainment coefficient, A from 0.0 to 0.8 in increments of 0.2.

values remains less than 10% for all fetches. Furthermore, if the plots of g_1 and g_2 for variations of the cold air outbreak parameters were redone using one of these different values of A, then the curves would be shifted slightly, but the conclusions about the usefulness of the model would not be changed. Similarly, if an entirely different closure where used for the entrainment rate (e.g. the closure used by Deardorff, 1972 or Kraus and Schaller, 1978) were used, the curves would be slightly shifted, but the conclusions of the usefulness of the horizontal transfer coefficients would not be changed. In short, the values computed for heat flux per unit travel are not very dependent on the entrainment closure used in the model.

4. SUMMARY, GENERAL COMMENTS AND SUGGESTIONS

The work done under this grant has developed and tested techniques for the remote estimation of ocean surface heat and vapor fluxes. These techniques are not very sensitive to errors in the data and therefore appear to hold promise of producing useful answers. However, questions still remain about how closely the structure of the real atmosphere agrees with the assumptions made for each of these techniques, and, therefore about how well these techniques can perform in actual use. It is, unfortunately, a difficult problem to satisfactorily verify any of the three techniques. Full verification of the techniques requires analysis of a large number of cases in which the needed input data exists along with surface truth measurements of the fluxes. The value of these techniques is that they promise to provide methods for the determiniation of fluxes over regions where very few traditional measurements exist. The irony is that the absence of such traditional methods makes verification of these methods difficult. These techniques have now been shown to be theoretically sound. Further work is needed to demonstrate that they are practically usable.

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