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THE LIU, KATSAROS, AND BUSINGER (1979) BULK ATMOSPHERIC FLUX COMPUTATIONAL ITERATION PROGRAM IN FORTRAN AND BASIC

ABSTRACT

The computer program described by Liu, Katsaros, and Businger (1979) for calculating the bulk-derived atmospheric fluxes, stability, and roughness is presented in both FORTRAN and BASIC versions. The results of 12 test calculations are presented to ensure that the program has been properly encoded.

INTRODUCTION

Liu, Katsaros, and Businger (1979) present a model developed for the marine atmospheric surface layer which takes into consideration the interfacial sublayers on both sides of the air-sea interface where molecular constraints on transports are important. Flux-profile relations which are based on the postulation of intermittent renewal of the surface fluid are matched to the logarithmic profiles and compared with both field and laboratory measurements. These relations enable numerical determination of air-sea exchanges of momentum, heat, and water vapor (or bulk transfer coefficients) employing the bulk parameters of mean wind speed, temperature, and humidity at a certain height in the atmospheric surface layer and the water temperature.

With increasing wind speed, the flow goes from smooth to rough and the bulk transfer coefficient for momentum also increases. The increase in roughness is associated with increasing wave height, which in the present model results in sheltering at the wave troughs. Due to the decrease in turbulent transport, the transfer coefficients of heat and water vapor decrease slightly with wind speed after the wind speed exceeds a certain value. The bulk transfer coefficients are also found to decrease with increasing stability. By including the effects of stability and interface conditions in bulk parameterization, the model provides a way to account for physical conditions which are known to affect air-sea exchanges.

A computer program utilizing computational iteration is required in order to solve three simultaneous equations of three unknowns, which are formed from five equations containing twelve dependent variables. Although the original program was written in FORTRAN, the recent proliferation of compact desk-top computers usable in the field has warranted its translation into BASIC.

The program requires seven input parameters:

1. Wind speed (u) in m/s;
2. Air temperature (T) in °C;
3. Specific humidity (q) in kg/kg;
4. Water temperature at the surface (T_s) in °C;
5. Altitude of the wind-speed measurement (z_u) in m;
6. Altitude of the air-temperature measurement (z_t) in m; and
7. Altitude of the humidity measurement (z_q) in m.

If the humidity is to be inputted in terms of the wet bulb temperature, dew point temperature, or relative humidity, consult the Appendix at the end of this report.

The results are outputted in the form of eight parameters:

1. The friction velocity (u_*) in m/s;
2. The scaling potential temperature (θ_*) in °C;
3. The scaling specific humidity (q_*) in kg/kg;
4. The roughness length (z_0) in m;
5. The Monin-Obukhov stability (z/L);
6. The wind-speed-roughness Reynold's number (R_r);
7. The temperature-roughness Reynold's number (R_t); and
8. The humidity-roughness Reynold's number (R_q).

From the outputted information it is possible to compute the momentum flux (M) in N/m^2 , the sensible heat flux (H_S) in W/m^2 , and the humidity flux (E) in $kg/(s m^2)$ by

$$M = -\rho u_*^2$$

$$H_S = -\rho C_p \theta_* u_*$$

and

$$E = -\rho q_* u_*$$

where the density of moist air (ρ) in kg/m^3 and the specific heat of moist air at constant pressure (C_p) in $J/(kg/K)$ can be determined by

$$\rho = \frac{(3.4838 \times 10^{-3})P}{T_v + 273.16}$$

and

$$C_p = 1.004[1 + 0.9(q)] \times 10^3,$$

where P is the barometric pressure in pascals (if not recorded, assumed to be 1.01325×10^5 Pascals) and T_v is the virtual potential temperature in °C such that

$$T_v = \{(T + 273.16) \times [1 + (0.608q)]\} - 273.16.$$

By convention, a positive sign is used to indicate an upward flux and a negative sign a downward flux. Because momentum flux is almost always downward (except in a few cases when the water velocity exceeds the wind), the negative momentum flux is traditionally defined as the stress (τ),

$$\tau \equiv -M.$$

Additionally, it is frequently convenient from a thermodynamic perspective to represent the humidity flux in terms of the latent heat flux (H_L) in W/m^2 such that

$$H_L \equiv E L_v$$

where L_v is the latent heat of vaporization in J/kg ,

$$L_v = 4.1868(597.31 - 0.56525 T) \times 10^3.$$

THE FORTRAN PROGRAM

```

00010      PROGRAM LKB79F
00020      COMMON/PIN/U,T,Q,TS,ZU,ZT,ZQ,ID
00030      COMMON/POUT/USR,TSR,QSR,ZO,ZL,RR,RT,RQ
00040      C
00050      C INPUT DATA FROM TTY
00060      C
00070      1000  CONTINUE
00080          USR=0.0
00090          TSR=0.0
00100          QSR=0.0
00110          ZO=0.0
00120          ZL=0.0
00130          RR=0.0
00140          RT=0.0
00150          RQ=0.0
00160          CD=0.0
00170          WRITE (5,1)
00180      1      FORMAT(' INPUT VALUES ARE:')
00190          WRITE (5,2)
00200      2      FORMAT(' U= ', $)
00210          READ(5,900) U
00220          WRITE(5,3)
00230      3      FORMAT(' T= ', $)
00240          READ(5,900)T
00250          WRITE(5,4)
00260      4      FORMAT(' Q= ', $)
00270          READ(5,900)Q
00280          WRITE(5,5)
00290      5      FORMAT(' TS= ', $)
00300          READ(5,900)TS
00310          WRITE(5,6)
00320      6      FORMAT(' ZU= ', $)
00330          READ(5,900)ZU
00340          WRITE(5,7)
00350      7      FORMAT(' ZT= ', $ )
00360          READ(5,900)ZT
00370          WRITE(5,8)
00380      8      FORMAT(' ZQ= ', $)
00390          READ(5,900)ZQ
00400          CALL ASL(IER)
00410          WRITE(5,20)USR,TSR,QSR,ZO,ZL,RR,RT,RQ,IER
00420      20      FORMAT(' OUTPUT VALUES ARE:',/, ' USR= ',G13.6,/,
00430          A          ' TSR=',G13.6,/,
00440          B          ' QSR=',G13.6,/,
00450          C          ' ZO =',G13.6,/,
00460          D          ' ZL =',G13.6,/,
00470          E          ' RR =',G13.6,/,
00480          F          ' RT =',G13.6,/,
00490          G          ' RQ =',G13.6,/, ' IER=',G13.6)
00500      900  FORMAT(G13.6)
00510          WRITE(5,910)
00520      910  FORMAT(' LAST CASE? 0=YES, 1=NO ', $)
00530          READ(5,920)IEND
00540      920  FORMAT(I1)
00550          IF (IEND.EQ.1)GO TO 1000
00560          END
00570          SUBROUTINE ASL(IER)
00580      C
00590      C TO EVALUATE SURFACE FLUXES, SURFACE ROUGHNESS, AND STABILITY OF
00600      C THE ATMOSPHERIC SURFACE LAYER FROM BULK PARAMETERS ACCORDING TO
00610      C LIU EL AL. (79) JAS 36 1722-1735
00620      C WRITTEN BY TIM LIU ON 5/8/79
00630      C
00640      C INPUT:
00650      C U WIND SPEED IN M/S

```

```

00660 C T TEMPERATURE IN DEG C
00670 C Q SPECIFIC HUMIDITY IN KG/KG
00680 C TS SURFACE TEMPERATURE IN DEG C
00690 C ZU HEIGHT OF WIND SENSOR IN METERS
00700 C ZT HEIGHT OF TEMPERATURE SENSOR
00710 C ZQ HEIGHT OF HUMIDITY SENSOR
00720 C ID SEE SUBROUTINE DRAG FOR DETAIL DEFINITION, ID=1 (KONDO),
00730 C ID+2 (SMITH), ID=3 (LARGE)
00740 C OUTPUT:
00750 C USR, TSR, QSR SCALING QUANTITIES FOR U, T, Q
00760 C ZO, ZL ROUGHNESS AND STABILITY PARAMETERS
00770 C RR, RT, RQ ROUGHNESS REYNOLD NUMBERS FOR U, T, Q
00780 C
00790 C IER=1 FAIL TO CONVERGE
00800 C IER=2 LBK ERROR
00810 C
00820 COMMON/PIN/U, T, Q, TS, ZU, ZT, ZQ, ID
00830 COMMON/POUT/USR, TSR, QSR, ZO, ZL, RR, RT, RQ
00840 IER=0
00850 RI=9.81*ZU*(T-TS)/((273.15+T)*U**2)
00860 IF(RI.GT.0.25)IER=-1
00870 VISA=.15E-4
00880 ZL=0.
00890 ZO=.0005
00900 US=0.
00910 CALL HUMLOW(TS, TS, QS)
00920 DU=U-US
00930 DT=T-TS
00940 DQ=Q-QS
00950 USR=.04*DU
00960 N3=0
00970 30 CONTINUE
00980 N1=0
00990 10 CONTINUE
01000 U10=USR*ALOG(10./ZO)/.4
01010 TYPE 8400, ID, U10, CD
01020 8400 FORMAT (' DRAG ', 3G13.6)
01030 CALL DRAG(ID, U10, CD)
01040 TYPE 8400, ID, U10, CD
01050 C=1./SQRT(CD)
01060 ZON=10./EXP(.4*C)
01070 TEST1=ABS((ZON-ZO)/(ZO+1.E-8))
01080 TYPE 8810, TEST1, ZON, ZO, C, CD, N1
01090 8810 FORMAT (' TEST1, ZON, ZO, C, CD, N1', 6G13.6)
01100 IF(TEST1.LT.0.01)GO TO 19
01110 N1=N1+1
01120 IF(N1.GT.50)GO TO 95
01130 ZO=ZON
01140 GO TO 10
01150 19 CONTINUE
01160 PUZ=PSI(1, ZL)
01170 ZTL=ZL*ZT/ZU
01180 ZQL=ZL*ZQ/ZU
01190 PTZ=PSI(2, ZTL)
01200 PQZ=PSI(2, ZQL)
01210 USR=DU*0.4/(ALOG(ZU/ZO)-PUZ)
01220 RR=ZO*USR/VISA
01230 ZTSR=ZT*USR/VISA
01240 ZQSR=ZQ*USR/VISA
01250 CALL LKB(RR, RT, 1)
01260 IF(RT.NE.-999.)GO TO 21
01270 IER=2
01280 WRITE(5, 2)RR
01290 RETURN
01300 21 CALL LKB(RR, RQ, 2)
01310 IF(RT.NE.-999.)GO TO 22

```

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01320      IER=2
01330      WRITE(5,2)RR
01340      RETURN
01350  22    S=2.2*(ALOG(ZTSR/RT)-PTZ)
01360      D=2.2*(ALOG(ZQSR/RQ)-PQZ)
01370      TSR=DT/S
01380      QSR=DQ/D
01390      CALL ZETA(T,Q,USR,TSR,QSR,ZU,ZLN)
01400      TEST3=ABS((ZL-ZLN)/(ZL+1.E-8))
01410      IF(TEST3.LT.0.01)GO TO 39
01420      N3=N3+1
01430      IF(N3.GT.50)GO TO 95
01440      ZL=ZLN
01450      GO TO 30
01460  39    CONTINUE
01470      GO TO 99
01480  95    IER=1
01490      WRITE(5,1)N1,N3
01500  1    FORMAT(1X,21HSL FAILS TO CONVERGE,3I5)
01510  2    FORMAT(1X,21HLKB FAILS BECAUSE RR=,E12.4)
01520  99    RETURN
01530      END
01540      SUBROUTINE DRAG(ID,U,CD)
01550  C
01560  C TO DETERMINE NEUTRAL DRAG COEFFICIENT CD FROM WIND SPEED
01570  C AT 10 M U IN M/S
01580  C ID=1 KONDO(1975) BLM 9 91-112
01590  C ID=2 SMITH(1980) JPO 10 709-726
01600  C ID=3 LARGE & POND (1981) JPO 11 324-336
01610  C RANGE OF U SPECIFIED ARE: KONDO(.3,50),SMITH(6,22),L&P(4,25)
01620  C WRITTEN BY TIM LIU FOR VAX ON 2/10/82
01630  C
01640      DIMENSION RAN(5),A(5),B(5),P(5)
01650      DATA RAN/2.2,5.,8.,25.,50./
01660      DATA A/0.,0.771,0.867,1.2,0./
01670      DATA B/1.08,0.0858,.0667,0.025,0.073/
01680      DATA P/-0.15,1.,1.,1.,1./
01690      K=ID-2
01700      IF(K)100,200,300
01710  100   IF(U.GT.50.)GO TO 131
01720      IF(U.LT..3)GO TO 130
01730      I=1
01740  110   IF(U.LE.RAN(I))GO TO 120
01750      I=I+1
01760      GO TO 110
01770  120   CD=(A(I)+B(I)*U**P(I))/1000.
01780      GO TO 99
01790  130   CD=1.5E-03
01800      GO TO 99
01810  131   CD=3.7E-03
01820      GO TO 99
01830  200   CD=(0.61+0.063*U)/1000.
01840      GO TO 99
01850  300   IF(U.LT.11.)GO TO 301
01860      CD=(0.49+0.065*U)/1000.
01870      GO TO 99
01880  301   CD=1.2E-3
01890  99    RETURN
01900      END
01910      SUBROUTINE HUMLOW(T,TW,Q)
01920  C
01930  C TO EVALUATE SPECIFIC HUMIDITY Q FROM DRY AND WET BULB TEMP
01940  C T AND TW ACCORDING TO LOWE(77) JAM 16 100-103
01950  C WRITTEN BY TIM LIU ON 5/3/79, REVISED FOR VAX ON 2/10/82
01960  C
01970      DIMENSION A(6)

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01980      DATA A/4.436519E-1,1.428946E-2,2.650649E-4,3.031240E-6,
01990      $ 2.034081E-8,6.136821E-11/
02000      P=1013.25
02010      X=0.
02020      DO 100 I=1,6
02030      J=7-I
02040      X=(X+A(J))*TW
02050      100  CONTINUE
02060      ES=6.107800+X
02070      Q=0.622*ES/(P-ES)-4.045E-04*(T-TW)
02080      RETURN
02090      END
02100      SUBROUTINE LKB(RR,RT,IFLAG)
02110      C
02120      C TO DETERMINE THE LOWER BOUNDRY VALUE RT OF THE LOGARITHMIC
02130      C PROFILES OF TEMPERATURE (IFLAG=1) OR HUMIDITY (IFLAG=2)
02140      C IN THE ATMOSPHERE FROM ROUGHNESS REYNOLD NUMBER RR BETWEEN
02150      C 0 AND 1000. OUT OF RANGE RR INDICATED BY RT=-999.
02160      C BASED ON LIU ET AL.. (1979) JAS 36 1722-1723
02170      C WRITTEN BY TIM LIU ON 1/22/78, REVISED FOR VAX ON 2/10/82
02180      C
02190      DIMENSION A(8,2),B(8,2),RAN(8)
02200      DATA A/0.177,1.376,1.026,1.625,4.661,34.904,1667.19,5.88E5,
02210      $ 0.292,1.808,1.393,1.956,4.994,30.709,1448.68,2.98E5/
02220      DATA B/0.,0.929,-0.599,-1.018,-1.475,-2.067,-2.907,-3.935,
02230      $ 0.,0.826,-0.528,-0.870,-1.297,-1.845,-2.682,-3.616/
02240      DATA RAN/0.11,0.825,3.0,10.0,30.0,100.,300.,1000./
02250      I=1
02260      IF (RR.LE.0..OR.RR.GE.1000.) GO TO 90
02270      10  CONTINUE
02280      IF (RR.LE.RAN(I)) GO TO 20
02290      I=I+1
02300      GO TO 10
02310      20  RT=A(I,IFLAG)*RR**B(I,IFLAG)
02320      GO TO 99
02330      90  RT=-999.
02340      99  RETURN
02350      END
02360      FUNCTION PSI(ID,ZL)
02370      C TO EVALUATE THE STABILITY FUNCTION PSI FOR WIND SPEED (IFLAG=1)
02380      C OR FOR TEMPERATURE AND HUMIDITY PROFILES FROM STABILITY PARAMETER ZL
02390      C SEE LIU ET AL. (1979) JAS 36 1722-1723 FOR DETAILS
02400      C WRITTEN BY TIM LIU ON 9/12/71, REVISED FOR VAX ON 2/10/82
02410      C
02420      IF(ZL)10,20,30
02430      10  CHI=(1.-16.*ZL)**0.25
02440      IF(ID.EQ.1)GO TO 11
02450      PSI=2.*ALOG((1.+CHI*CHI)/2.)
02460      GO TO 99
02470      11  PSI=2.*ALOG((1.+CHI)/2.)+ALOG((1.+CHI*CHI)/2.)-2.*ATAN(CHI)
02480      & +2.*ATAN(1.)
02490      GO TO 99
02500      20  PSI=0.
02510      GO TO 99
02520      30  PSI=-6.*ALOG(1.+ZL)
02530      99  RETURN
02540      END
02550      SUBROUTINE ZETA(T,Q,USR,TSR,QSR,Z,ZL)
02560      C
02570      C TO EVALUATE OBUKHOVS STABILITY PARAMETER Z/L FROM AVERAGE
02580      C TEMP T IN DEG C, AVERAGE HUMIDITY Q IN GM/GM, HEIGHT Z IN M,
02590      C AND FRICTIONAL VEL,TEMP., HUM. INMKS UNITS
02600      C SEE LIU ET AL. (1979) JAS 36 1722-1723 FOR DETAILS
02610      C WRITTEN BY TIM LIU ON 10/1/77, REVISED FOR VAX ON 2/10/82
02620      C
02630      VON=0.4

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02640      G=9.81
02650      TA=273.16*T
02660      TV=TA*(1.+0.61*Q)
02670      TVSR=TSR*(1.+0.61*Q)+0.61*TA*QSR
02680      IF(TVSR.EQ.0.)GO TO 10
02690      OB=TV*USR*USR/(G*VON*TVSR)
02700      ZL=Z/OB
02710      GO TO 99
02720      10  ZL=0.
02730      99  RETURN
02740      END
```

THE BASIC PROGRAM

```

10  REM
20  REM   "LKB79B" PROGRAM   12 OCT 83   T.V. BLANC   NRL 4110   DISK #6
30  REM
40  REM   THE BULK FLUX COMPUTATIONAL ITERATION PROGRAM OF LIU, KATSAROS, &
50  REM   BUSINGER (1979) TRANSLATED FROM FORTRAN INTO ELEMENTRY BASIC FOR USE
60  REM   ON A HEWLETT-PACKARD MODEL 9845. THIS PROGRAM WAS ADAPTED FROM AN
70  REM   ORIGINAL TRANSLATION OF A T WILSON NRL 2820 FOR USE ON A DIGITAL
80  REM   EQUIPMENT CORPORATION MODEL DEC-10 COMPUTER.
90  REM
100 REM   INPUTS   U= Wind Speed (m/s), T= Air Temp (C), Q= Spec. Humid. (Kg/Kg),
110 REM            T1=Tw= Water Temp (C), Z1=Zu= U Altitude(m), Z2=Zt= T Alt. (m)
120 REM            Z3=Zq= Q Alt (m)
130 REM
140 REM   NOTES   U SHOULD NOT = 0
150 REM
160 REM   OUTPUTS  U1=Ustr= U* (m/s), T2=Tstr= T* (C), Q1=Qstr= Q* (Kg/Kg),
170 REM            Z4=Zo= Rough Length (m), Z6=Z/L= Monin-Obukhov Stability,
180 REM            R1=Ru= U Rough Reynolds No , R2=Rt= T Rough Reynolds No ,
190 REM            R3=Rq= Q Rough Reynolds No
200 REM
210 DIM R5(5), A2(5), B2(5), P(5)
220 DATA 2 2.5 ,8 ,25 ,50
230 DATA 0 ,0 771.0 867.1 2.0
240 DATA 1 08.0 0858.0 0667.0 025.0 073
250 DATA -0 15.1 ,1 ,1 ,1
260 DIM A1(6)
270 DATA 4 436519E-1,1 428946E-2,2 650649E-4
280 DATA 3 031240E-6,2 034081E-8,6 136821E-11
290 DIM A(8,2), B(8,2), R6(8)
300 DATA 0 177.1 376.1 026.1 625.4 661.34 904.1667 19.5 88E5
310 DATA 0 292.1 808.1 393.1 956.4 994.30 709.1448 68.2 98E5
320 DATA 0 ,0 929,-0 599,-1 018,-1 475,-2 067,-2 907,-3 935
330 DATA 0 ,0 826,-0 528,-0 870,-1 297,1 845,-2 682,-3 616
340 DATA 0 11.0 825,3 0.10 0.30 0.100 0.300 ,1000 0
350 RESTORE 220
360 REM
370 FOR I=1 TO 5
380 READ P5(I)
390 NEXT I
400 FOR I=1 TO 5
410 READ A2(I)
420 NEXT I
430 FOR I=1 TO 5
440 READ B2(I)
450 NEXT I
460 FOR I=1 TO 5
470 READ P(I)
480 NEXT I
490 FOR I=1 TO 6
500 READ A1(I)
510 NEXT I
520 FOR J=1 TO 2
530 FOR I=1 TO 8
540 READ A(I,J)
550 NEXT I
560 NEXT J
570 FOR J=1 TO 2
580 FOR I=1 TO 8
590 READ B(I,J)
600 NEXT I
610 NEXT J
620 FOR I=1 TO 8
630 READ R6(I)
640 NEXT I
650 REM
660 PRINT " "

```

```

670 PRINT "....."
680 PRINT "INPUT DATA: U(m/s), T(C), Q(kg/kg), Tw(C), Zu(m), Zt(m), Zq(m)"
690 LET U1=0
700 LET T2=0
710 LET Q1=0
720 LET Z4=0
730 LET Z6=0
740 LET R1=0
750 LET R2=0
760 LET R3=0
770 INPUT U, T, Q, T1, Z1, Z2, Z3
780 PRINT U, T, Q, T1, Z1, Z2, Z3
790 REM ..... CALL SURROUTINE ASL( IER )
800 LET A9=I9
810 GOSUB 990
820 LET I9=A9
830 REM .....
840 PRINT "OUTPUT VALUES ARE: "
850 PRINT "U* (m/s) =", U1
860 PRINT "T* (C) =", T2
870 PRINT "Q*(kg/kg)=", Q1
880 PRINT "Zo (m) =", Z4
890 PRINT "Z/L =", Z6
900 PRINT "Ru =", R1
910 PRINT "Rt =", R2
920 PRINT "Rq =", R3
930 PRINT " "
940 REM .....
950 PRINT "LAST CASE? 0=YES, 1=NO ";
960 INPUT I8
970 IF I8=1 THEN GOTO 660
980 GOTO 2670
990 REM ..... SUBROUTINE ASL( IER )
1000 LET A9=0
1010 LET R4=9.81*Z1*(T-T1)/((273.15+T)*U^2)
1020 IF R4>.25 THEN GOTO 1040
1030 GOTO 1050
1040 LET A9=-1
1050 LET V1=1.5E-5
1060 LET Z5=0
1070 LET Z4= .0005
1080 LET U2=0
1090 LET H1=T1
1100 LET H2=T1
1110 LET H3=Q1
1120 REM ..... CALL HUMLOW( Tw, Tw, QS )
1130 GOSUB 2290
1140 LET T1=H1
1150 LET T1=H2
1160 LET Q1=H3
1170 LET D0=U-U2
1180 LET W2=T-T1
1190 LET W3=Q-Q1
1200 LET U1=.04*D0
1210 LET N3=0
1220 REM ..... CONTINUE
1230 LET N1=0
1240 LET U0=U1*LOG(10/Z4)/.4
1250 LET D1=D1
1260 LET D2=U0
1270 LET D3=C1
1280 GOSUB 2050
1290 REM ..... CALL DRAG( ID, U10, CD )
1300 LET D1=D1
1310 LET U0=D2
1320 LET C1=D3

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1330 LET C=1/SQR(C1)
1340 LET Z5=10/EXP(.4*C)
1350 LET T3=ABS((Z5-Z4)/(Z4+1E-8))
1360 IF T3<.01 THEN GOTO 1410
1370 LET N1=N1+1
1380 IF N1>50 THEN GOTO 2020
1390 LET Z4=Z5
1400 GOTO 1240
1410 REM ..... CONTINUE
1420 LET P1=FNP(1,Z6)
1430 LET Z7=Z6*Z2/Z1
1440 LET Z8=Z6*Z3/Z1
1450 LET P2=FNP(2,Z7)
1460 LET P3=FNP(2,Z8)
1470 U1=D0*.4/(LOG(Z1/Z4)-P1)
1480 LET R1=Z4*U1/V1
1490 LET Z9=Z2*U1/V1
1500 LET Z0=Z3*U1/V1
1510 LET L1=R1
1520 LET L2=R2
1530 LET L3=1
1540 GOSUB 2410
1550 REM ..... CALL LKB(Ru,Rt,1)
1560 LET R1=L1
1570 LET R2=L2
1580 LET L3=L3
1590 IF R2<-.999 THEN GOTO 1630
1600 LET A9=2
1610 PRINT "LBK FAILS BECAUSE Ru=",R1
1620 RETURN
1630 REM ..... SET VALUE OF 2 TO A VARIABLE
1640 LET L1=R1
1650 LET L2=R3
1660 LET L3=2
1670 GOSUB 2410
1680 LET R1=L1
1690 LET R3=L2
1700 LET L3=L3
1710 IF R2<-.999 THEN GOTO 1740
1720 LET A9=2
1730 GOTO 1610
1740 LET S=2.2*(LOG(Z9/R2)-P2)
1750 LET D=2.2*(LOG(Z0/R3)-P3)
1760 LET T2=W2/S
1770 LET Q1=W3/D
1780 REM ..... CALL ZETA(T,Q,Ustr,Tstr,Qstr,ZU,ZLN)
1790 LET F1=T
1800 LET F2=Q
1810 LET F3=U1
1820 LET F4=T2
1830 LET F5=Q1
1840 LET F6=Z1
1850 LET F7=Y1
1860 GOSUB 2550
1870 LET T=F1
1880 LET Q=F2
1890 LET U1=F3
1900 LET T2=F4
1910 LET Q1=F5
1920 LET Z1=F6
1930 LET Y1=F7
1940 LET T4=ABS((Z6-Y1)/(Z6+1E-8))
1950 IF T4<.01 THEN GOTO 2000
1960 LET N3=N3+1
1970 IF N3>50 THEN GOTO 2020
1980 LET Z6=Y1

```

```

1990 GOTO 1220
2000 REM ..... CONTINUE
2010 GOTO 2040
2020 LET A9=1
2030 PRINT "ASL FAILS TO CONVERGE", N1, N3
2040 RETURN
2050 REM ..... SUBROUTINE DRAG(D1, D2, D3)
2060 REM          R5=RAN, A2=A, B2=B IN DRAG
2070 LET K=D1-2
2080 IF K=0 THEN GOTO 2220
2090 IF K>0 THEN GOTO 2240
2100 IF D2>50 THEN GOTO 2200
2110 IF D2<.3 THEN GOTO 2180
2120 LET I=1
2130 IF D2<=R5(I) THEN GOTO 2160
2140 LET I=I+1
2150 GOTO 2130
2160 LET D3=(A2(I)+B2(I)*D2^P(I))/1000
2170 GOTO 2280
2180 LET D3=1.5E-3
2190 GOTO 2280
2200 LET D3=3.7E-3
2210 GOTO 2280
2220 LET D3=(.61+.063*D2)/1000
2230 GOTO 2280
2240 IF D2<11 THEN GOTO 2270
2250 LET D3=(.49+.065*D2)/1000
2260 GOTO 2280
2270 LET D3=1.2E-3
2280 RETURN
2290 REM ..... SUBROUTINE HUMLOW(T, TW, G)
2300 REM          SUBROUTINE HUMLOW(H1, H2, H3)
2310 REM          A1=A IN HUMLOW
2320 LET P=1013.25
2330 LET X=0
2340 FOR I=1 TO 6
2350 LET J=7-I
2360 LET X=(X+A1(J))*H2
2370 NEXT I
2380 LET E1=6.107800+X
2390 LET H3=.622*E1/(P-E1)-4.045E-4*(H1-H2)
2400 RETURN
2410 REM ..... SUBROUTINE LKB(Ru, Rt, IFLAG)
2420 REM          SUBROUTINE LKB(L1, L2, L3)
2430 REM          R6=RAN IN LKB
2440 LET I=1
2450 IF L1<=0 THEN GOTO 2530
2460 IF L1>=1000 THEN GOTO 2530
2470 REM ..... CONTINUE
2480 IF L1<=R6(I) THEN GOTO 2510
2490 LET I=I+1
2500 GOTO 2470
2510 LET L2=A(I, L3)*R1^B(I, L3)
2520 GOTO 2540
2530 LET L2=-999
2540 RETURN
2550 REM ..... SUBROUTINE ZETA (T, G, Ustr, Tstr, Qstr, Z, Z/L)
2560 LET V=.4
2570 LET G=9.81
2580 LET T5=273.16+F1
2590 LET T6=T5*(1+.61*F2)
2600 LET T7=F4*(1+.61*F2)+.61*T5*F5
2610 IF T7=0 THEN GOTO 2650
2620 LET O1=T6*F3*F3/(G*V*T7)
2630 LET F7=F6/O1
2640 GOTO 2660

```

```
2650 LET F7=0
2660 RETURN
2670 END
2680 REM .....
2690 REM ..... FUNCTION PSI(ID, Z/L)
2700 DEF FNP(I7, X5)
2710 REM ..... TEST Z/L FOR -, 0, +
2720 IF X5=0 THEN GOTO 2800
2730 IF X5>0 THEN GOTO 2820
2740 LET C2=(1-16*X5)^.25
2750 IF I7=1 THEN GOTO 2780
2760 RETURN 2*LOG((1+C2*C2)/2)
2770 GOTO 2830
2780 RETURN 2*LOG((1+C2)/2)+LOG((1+C2*C2)/2)-2*ATN(C2)+2*ATN(1)
2790 GOTO 2830
2800 RETURN 0
2810 GOTO 2830
2820 RETURN -6*LOG(1+X5)
2830 FNEND
```

TEST CALCULATION RESULTS

To ensure that the programs have been properly copied by the user, the results of 12 test calculations are presented. The outputted results should agree with those indicated below to within ± 2 of the fourth significant figure.

<u>Test</u>	<u>Input</u>	<u>Output</u>
1	$u = 9$	$u_* = 0.3490$
	$T = 12$	$\theta_* = -6.922 \times 10^{-2}$
	$q = 0.007$	$q_* = -1.062 \times 10^{-4}$
	$T_s = 14$	$z_0 = 2.501 \times 10^{-4}$
	$z_u = 10$	$z/L = -9.937 \times 10^{-2}$
	$z_t = 10$	$R_r = 5.820$
	$z_q = 10$	$R_t = 0.2705$
		$R_q = 0.4226$

<u>Test</u>	<u>Input</u>	<u>Output</u>
2	$u = 9$	$u_* = 0.3262$
	$T = 14$	$\theta_* = 6.536 \times 10^{-2}$
	$q = 0.007$	$q_* = -5.817 \times 10^{-5}$
	$T_s = 12$	$z_0 = 2.429 \times 10^{-4}$
	$z_u = 10$	$z/L = 7.087 \times 10^{-2}$
	$z_t = 10$	$R_r = 5.282$
	$z_q = 10$	$R_t = 0.2986$
		$R_q = 0.4598$

<u>Test</u>	<u>Input</u>	<u>Output</u>
3	$u = 9$	$u_* = 0.3514$
	$T = 12$	$\theta_* = -6.981 \times 10^{-2}$
	$q = 0.002$	$q_* = -2.879 \times 10^{-4}$
	$T_s = 14$	$z_0 = 2.501 \times 10^{-4}$
	$z_u = 10$	$z/L = -0.1347$
	$z_t = 10$	$R_r = 5.859$
	$z_q = 10$	$R_t = 0.2686$
		$R_q = 0.4201$

<u>Test</u>	<u>Input</u>	<u>Output</u>
4	$u = 9$	$u_* = 0.3334$
	$T = 14$	$\theta_* = 6.614 \times 10^{-2}$
	$q = 0.002$	$q_* = -2.297 \times 10^{-4}$
	$T_s = 12$	$z_0 = 2.466 \times 10^{-4}$
	$z_u = 10$	$z/L = 3.175 \times 10^{-2}$
	$z_t = 10$	$R_r = 5.481$
	$z_q = 10$	$R_t = 0.2875$
		$R_q = 0.4452$

<u>Test</u>	<u>Input</u>	<u>Output</u>
5	$u = 2$	$u_* = 7.230 \times 10^{-2}$
	$T = 12$	$\theta_* = -9.516 \times 10^{-2}$
	$q = 0.007$	$q_* = -1.486 \times 10^{-4}$
	$T_s = 14$	$z_0 = 2.653 \times 10^{-5}$
	$z_u = 10$	$z/L = -3.175$
	$z_t = 10$	$R_r = 0.1279$
	$z_q = 10$	$R_t = 0.2036$
		$R_q = 0.3306$

<u>Test</u>	<u>Input</u>	<u>Output</u>
6	$u = 2$	$u_* = 3.731 \times 10^{-2}$
	$T = 14$	$\theta_* = 4.336 \times 10^{-2}$
	$q = 0.007$	$q_* = -3.831 \times 10^{-5}$
	$T_s = 12$	$z_0 = 4.498 \times 10^{-5}$
	$z_u = 10$	$z/L = 3.578$
	$z_t = 10$	$R_r = 0.1119$
	$z_q = 10$	$R_t = 0.1799$ $R_q = 0.2962$

<u>Test</u>	<u>Input</u>	<u>Output</u>
7	$u = 18$	$u_* = 0.7361$
	$T = 12$	$\theta_* = -5.599 \times 10^{-2}$
	$q = 0.007$	$q_* = -8.643 \times 10^{-5}$
	$T_s = 14$	$z_0 = 5.289 \times 10^{-4}$
	$z_u = 10$	$z/L = -1.802 \times 10^{-2}$
	$z_t = 10$	$R_r = 25.96$
	$z_q = 10$	$R_t = 3.824 \times 10^{-2}$ $R_q = 7.315 \times 10^{-2}$

<u>Test</u>	<u>Input</u>	<u>Output</u>
8	$u = 18$	$u_* = 0.7259$
	$T = 14$	$\theta_* = 5.542 \times 10^{-2}$
	$q = 0.007$	$q_* = -4.975 \times 10^{-5}$
	$T_s = 12$	$z_0 = 5.289 \times 10^{-4}$
	$z_u = 10$	$z/L = 1.203 \times 10^{-2}$
	$z_t = 10$	$R_r = 25.59$
	$z_q = 10$	$R_t = 3.904 \times 10^{-2}$ $R_q = 7.449 \times 10^{-2}$

<u>Test</u>	<u>Input</u>	<u>Output</u>
9	$u = 9$	$u_* = 0.3250$
	$T = 12$	$\theta_* = -7.050 \times 10^{-2}$
	$q = 0.007$	$q_* = -1.081 \times 10^{-4}$
	$T_s = 14$	$z_0 = 2.421 \times 10^{-4}$
	$z_u = 30$	$z/L = -0.3487$
	$z_t = 10$	$R_r = 5.246$
	$z_q = 10$	$R_t = 0.3007$ $R_q = 0.4625$

<u>Test</u>	<u>Input</u>	<u>Output</u>
10	$u = 9$	$u_* = 0.3495$
	$T = 12$	$\theta_* = -6.613 \times 10^{-2}$
	$q = 0.007$	$q_* = -1.059 \times 10^{-4}$
	$T_s = 14$	$z_0 = 2.556 \times 10^{-4}$
	$z_u = 10$	$z/L = -9.575 \times 10^{-2}$
	$z_t = 30$	$R_r = 5.956$
	$z_q = 10$	$R_t = 0.2642$ $R_q = 0.4142$

<u>Test</u>	<u>Input</u>	<u>Output</u>
11	$u = 9$	$u_* = 0.3489$
	$T = 12$	$\theta_* = -6.919 \times 10^{-2}$
	$q = 0.007$	$q_* = -1.016 \times 10^{-4}$
	$T_s = 14$	$z_0 = 2.501 \times 10^{-4}$
	$z_u = 10$	$z/L = -9.777 \times 10^{-2}$
	$z_l = 10$	$R_l = 5.818$
	$z_q = 30$	$R_l = 0.2706$
		$R_q = 0.4227$

<u>Test</u>	<u>Input</u>	<u>Output</u>
12	$u = 6$	$u_* = 0.2359$
	$T = 7$	$\theta_* = -3.787 \times 10^{-2}$
	$q = 0.004$	$q_* = -1.016 \times 10^{-4}$
	$T_s = 8$	$z_0 = 1.536 \times 10^{-4}$
	$z_u = 5$	$z/L = -7.009 \times 10^{-2}$
	$z_l = 15$	$R_l = 2.416$
	$z_q = 25$	$R_l = 0.6049$
		$R_q = 0.8743$

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APPENDIX

The specific humidity (q) in kg/kg is calculated by

$$q = \frac{0.622e}{P - (0.378e)}$$

where P is the barometric pressure and e is the water vapor pressure in pascals. If the humidity is measured by the wet and dry bulb temperatures (T_{wb}, T) in °C then

$$e = e_s - 6.6 \times 10^{-4} \left[1 + (1.15 \times 10^{-3} T_{wb}) \right] P (T - T_{wb})$$

where e_s is the saturated vapor pressure in pascals such that

$$e_s = Pa_1^{b_3} \times 10^{a_2 b_4 + a_4 b_5 + a_5 b_6}$$

where

$$a_1 = \frac{373.16}{T + 273.16},$$

$$a_2 = a_1 - 1,$$

$$a_3 = 1 - \frac{1}{a_1},$$

$$a_4 = (10^{a_2 b_1}) - 1,$$

$$a_5 = (10^{a_3 b_2}) - 1,$$

and the Goff-Gratch humidity formulation constants are

$$b_1 = -3.49149,$$

$$b_4 = -7.90298,$$

$$b_2 = 11.344,$$

$$b_5 = 8.1328 \times 10^{-3},$$

$$b_3 = 5.02808,$$

$$b_6 = -1.3816 \times 10^{-7}.$$

If the humidity is measured by the dew point temperature (T_{dp}) in °C then

$$e = Pa_1^{b_3} \times 10^{a_2 b_4 + a_4 b_5 + a_5 b_6}$$

where

$$a_1 = \frac{373.16}{T_{dp} + 273.16}$$

and a_2 through a_5 are calculated in the same manner as for the saturated vapor pressure. If the relative humidity (RH) in % is measured then

$$e = \frac{e_s RH}{100}$$

where the saturated vapor pressure (e_s) is calculated from the air temperature as shown above.