D. Guide to running the model

D-1. Flow charts of the program

D-1-1. Job step

Job is divided into 3 job steps currently.

Job Step 1

Preparation of eigen-vectors and values which are used in pressure equation slover is made in disk by sub. CVEVSI. The grid structure and lateral boundary conditions must be specified in the same way as those specified in the running model.

Job Step 2

Running the model (time integration of the equations).

See the main program SIMAIN in men. SFXMAIN2.

Job Step 3

Plotting the results of the model. See the main program PLCONV in mem. PLPMN.

D-1-2. Flow chart of the main program "SIMAIN" for the job step 2

initial set-up procedures

VRGDIS --- generates variable grids in arrays VRDX, VRDX2......

INIFLD --- set environmental initial fields

ORGIN0 --- generate system constants such as mountain shape Z_s, metric tensors $G^{1/2}$, G^{12}, G^{13} and reference atomosphere.

SETEXT --- set external environmental fields which are currently the same as the initial environmental fields in arrays EXTU, EXTV ,,,EXTQV.

if (itst=0) then initial start-up; store system constants in disk sub. STMTC1.

else if (itst>0) then restart the model; load the results of the previous model run by sub. LADMTS.

load eigen-vector and eigen-values in array EIGVCX, EIGVLX,,, from magnetic tape

start the time integration from it=itst to itend.

CADVC3 --- compute advection term of u, v and w.

CRSTUV --- compute Reynolds stress of u, v and w in the free atomsphere and at the lower boundary. Sensible and latent heat fluxes at the lower boundary are also computed. (see B-10)

CETUR5 --- time integration of the subgrid scale turbulent kinetic energy. (See Eq.B-(10-1))

CPTQUVS--- time integration of Θ, Qv, Qc, Qr, Qi, Qs, Qg, including all cloud microphysical processes.

CBUOYC --- buoyancy term is set in array BUOY. $\partial \mathrm{BUOY}/\partial t$ is set in array DBUYDT.

SUVPBD --- set the time tendency of u and v at the open lateral boundaries in array DUDTBC and calculate some data necessary for the specification of the lateral boundary condition of the pressure equation. (see B-7-2 c) and B-7-3).

```
time integration of $u$, $v$, $w$, and puressure
    if (swcmp=0) then anelastic scheme, iteration for pressure equation
            do 10 i=1, itrmx (i: iteration counter)
            MODADV        --- modify advection term to provide forcing terms
                              for pressure eq.
         10 SCPI          --- Poisson equation solver
            SVELC         --- time integration of $u$, $v$ and $w$.
    else if (swcmp=1) then E-HI-VI scheme
            MODADV        --- compute Eqs. B-(3-31), (3-33), (3-35).
            SCPI          --- Helmholtz eq. solver
            SVELC
    else if (swcmp=2) then E-HE-VI scheme
            MODADV        ---
            FTVELC        --- repeat small time step integration of $u$, $v$, $w$, $p$
    end if
```

CNVED3 --- the eddy diffusion coefficients K_m are dianostically determined from the turbulent kinetic energy computed by sub. CETUR5.

if (mod(it, istrmt)=0) store the numerical results into disk by sub. STRMTS.

```
        it ←—— it+1

if (it<itend) then repeat time integration
else stop
```

D-1-3. Flow chart of the subroutine CADVC3

```
    CADVC3  ---  compute advection term in flux form
    compute ADVW:
        compute flux $Uw$, and ADVW ←—— $\partial x U w$
        compute flux $Vw$, and ADVW ←—— ADVW + $\partial x V w$
        compute flux $W^*w$, and ADVW ←—— ADVW + $\partial z W^* w$
        artifical diffusion DMP2DN (see B-12-2) DUMPNL (see B-12-1)
        LTRLB2  ---  adjust the values at the lateral boundary taking into account the
                     cyclic or open lateral conditions
    end of computation of ADVW
    compute ADVV in a similar way as ADVW
    compute ADVU in a similar way as ADVW
    return
```

D-1-4. Flow chart of the subroutine SVELC

```
    SVELC   ---  time integration of $U$, $V$, $W$ for AE (plus $P$ for E-HI-VI)
        UADVB (V,,)     set array FUBD1 for $V$. At the inflow boundary of $u$, FUBD1 is
                        set to be zero. At the outflow boundary of $u$, FUBD1 is set to be
                        non-zero.
        UADVB1 (W,,)    set array FUBD1 for $W$.
        VADVB1 (U,,)    set array FVBD1 for $U$.
        VADVB1 (W,,0    set array FVBD1 for $W$.

        time integration of $U$ inside the domain
        if (swcmp=0) then (AE)
          $U^{it+1}$ ←—— $P^{it}$, ADVU
        else if (swcmp=1) then (E-HI-VI-PI)
          $U^{it+1}$ ←—— $\Delta^2 P$, ADVU
```

```
    end if

    time smoothing of $U$ by applying Assellin's time filter.

    ORUCPH    --- estimate the phase speed of $U$ at the open boundary following
                  Orlanski (see B-7-2 b))
                  input :$U^{it-1}$, $U^{it}$, $U^{it+1}$
                  output: array CPHU
    EXTNRU    --- time integratonof $U$ outside the boundary plane normal to
                  $U$-componet (see B-7-2 b)).
                  input: DUDTBC, $U^{it}$, $U^{it-1}$, EXTU
                  output: $U^{it+1}(1,j,k)$, $U^{it+1}(2,j,k)$, $U^{it+1}(nx,i,j)$
    EXTRX1A   --- time integration of $U$ outside the boundary plane parallel to
                  $U$-component (see B-7-2 a)).
                  input: FVBD1($u$), $U^{it}$, $U^{it-1}$, EXTU
                  output: $U^{it+1}(i,1,k)$, $U^{it+1}(i,ny,k)$,
    set $U^{it+1}$ outside the upper and lower boundary
              output: $U^{it+1}(i,j,1)$, $U^{it+1}(i,j,nz)$,
    ADJ2DM    --- adjust the values of $U$ outside the lateral boundary taking
                  account of the cyclic or open lateral boundary conditions

time integration of $V$ in the similar way to $U$ except that EXTNRV is called instead of
EXTNRU.

time integration of $W$ in the similar way to $U$, except that EXTNRU is not called, and
upper and lower boundary conditions are kinematical conditions, i.e., always $W^{it+1} = -G^{1/2}G^{13}U^{it+1}$

if (swcmp=1) then (E-HI-VI)
  time integration of $P$; obtain $P^{it+1}$ from $\Delta^2 P$;    time smoothing
  ADJ2DM
end if

return
```

D-1-5. Flow chart of sub.SCPI

Sub.SPAI in mem.SFXHEL is the pressure equation solver.

```
SCPI
    SPFORI  ---  prepare forcing term $F$ in Eq. B-(6-1)
    SFPBD   ---  prepare boundary forcing $Bx$, $By$ and $Bz$ in Eqs. B-(6-3)—(6-5).
    SPAI    ---  forward transformation in the $x$-direction (operate $I \otimes P^{-1}$ from left)
            ---  VHELMX
                 ---  forward transformation in the $y$-direction (operate $Q^{-1} \otimes I$ from left)
                 ---  TRIDIG: solve vertical structure Eq. B-(6-24),
                          $C\,S_{i,j},; = R_{i,j},;$
                          $C$ is tridiagonal matrix.
                 ---  backward transformation in the $y$-direction.
                      (operate $Q \otimes I$ from left)
                      return
            ---  backward transformation in the $x$-direction (operate $I \otimes P$ from left)
            return
return
```

D-1-6. Flow chart of the subroutine FTVELC

FTVELC: time integration of U, V, W and PRS by E-HE-VI scheme

set arrays PRSF,UF,,WF used for small time step integration

```
    PRSF    ←——  PRS(,,,it–1)
    UF      ←——  U(,,,it–1)
    VF      ←——  V(,,,it–1)
    WF      ←——  W(,,,it–1)
    FPFORI  ---  forcing terms on the pressure equation invariant during small time
                 step integration (FP.HE.INV and FPB.HE.INV; see Eqs.B-(4-8)
                 and B-(4-11)) are stored in array PFORCI
    small time integration start
```

```
    do its=1, MSW(9)
        small time step integration of $UF^{\tau+1}$ and $VF^{\tau+1}$
        at the open lateral boundary.
                $\frac{\partial UF}{\partial x} = \frac{\partial VF}{\partial x} = 0$ is imposed, currently.
        FPFORV  --- forcing terms on the pressure equation variant during small
                    time step integration (FP.HE.VAR and FPB.HE.VAR; see
                    Eqs. B-(4-9) and B-(4-12)) are stored in array PFORCV
        VRPOIS  --- solve 1-dimensional pressure equation for $\overline{P}^{\tau\beta}$.
        small time integration of $WF^{\tau+1}$ and $PRSF^{\tau+1}$ from $\overline{P}^{\tau\beta}$.
        WF outside the upper and lower boundaries are set.
    end doloop
small time integration end
set arrays PRS, $U$, $V$, $W$ at $it+1$ large time step using PRSF,UF,,WF obtained from
small time step integration
    PRSF  ——→ PRS(,,,it+1)
    UF    ——→ U(,,,it+1)
    VF    ——→ V(,,,it+1)
    WF    ——→ W(,,,it+1)
time smoothing of $U$, $V$, $W$, PRS

set values of $U$, $V$ and $W$ outside the lateral boundary in the same way as AE or E-HI-VI
schemes
    UADVB1(V,,)   set array FUBD1 for $V$. At the inflow boundary of $u$, FUBD1 is
                  set to be zero.
                  At the outflow boundary of $u$, FUBD1 is set to be non-zero. (see
                  B-7-2 a))
    UADVB1(W,,)   set array FUBD1 for $W$.
    VADVB1(U,,)   set array FVBD1 for $U$.
    VADVB1(W,,)   set array FVBD1 for $W$.
    ORUCPH ---    estimate the phase speed of $U$ at the open boundary following
                  Orlanski.
                  input: $U^{it-1}$, $U^{it}$, $U^{it+1}$
```

```
                 output: array CPHU (see B-7-2 b))
    EXTNRU ---   time integration of $U$ outside the boundary plane normal to $U$-component.
                 input: DUDTBC, $U^{it}$, $U^{it-1}$, EXTU
                 output: $U^{it+1}(1,j,k)$, $U^{it+1}(2,j,k)$, $U^{it+1}(nx,i,j)$ (see B-7-2 b))
    EXTRX1 ---   time integration of $U$ outside the boundary plane parallel to $U$-component.
                 input: FVBD1($u$), $U^{it}$, $U^{it-1}$, EXTU
                 output: $U^{it+1}(i,1,k)$, $U^{it+1}(i,ny,k)$, (see B-7-2 a))

ADJ2DM  adjust the values of $U$, $V$, $W$ outside the lateral boundary taking account
        of the cyclic or open lateral boundary conditions
return
```

D-1-7. Flow chart of sub.CPTQVS

```
CPTQVS
    if (msw(18)=3) then (dry case)
        time integration of $\Theta$ by sub.CPT5
    if (msw(18)< 2) then (warm rain and cold rain)
        CLDPHY:  compute all source terms for $\Theta$, $Q_v$, $\cdots Q_g$ due to cloud micro-
                 physical processes and store them in array PPT, PQV, ,,,PQG.
                 (see B-11)
        time integration of $Qv$ by sub.CQS3
        time integration of $Qc$ by sub.CQS3
        time integration of $Qr$ by sub.CQS3
    if (msw(18)< 1) then (cold rain)
        time integration of $Qi$ by sub.CQS3
        time integration of $Qs$ by sub.CQS3
        time integration of $Qg$ by sub.CQS3
        time integration of $Ni$ by sub.CQS3
    if (msw(18) $\leqq -1$) then
        time integration of $Ns$ by sub.CQS3
    if (msw(18) $\leqq -2$) then
```

```
        time integration of $Ng$ by sub.CQS3
    end if
    if (msw(18)$<$ 2) then
        ADJQV4  ---  instantaneous adjustment on $Qv^{it+1}$, $Qc^{it+1}$, $\Theta^{it+1}$, condensation of water vapour into cloud water and warming (see B-11-5 a))
        time smoothing to $Qv^{it}$, $Qv^{it}$, $Qcw^{it}$
        ADJQV4  ---  instantaneous adjustment on $Qv^{it}$, $Qc^{it}$, $\Theta^{it}$; condensation of water vapour into cloud water and warming
        set lower and upper boundary values for $\Theta$ and $Qv$.
            (MSW(13)=0) no flux of $\Theta$ and $Qv$ from the lower boundary
            (MSW(13)=1) flux for $\Theta$ and $Qv$ from the lower boundary
    end if
    if (msw(18) $\leqq$ 0) then
        ADJNUM  ---  adjustment on $Ni$ for the fixed $Qi$ (see B-11-7)
    if (msw(18) $\leqq -$ 2) then
        ADJNUM  ---  adjustment on $Ns$ for the fixed $Qs$
    if (msw(18) $\leqq -$ 2) then
        ADJNUM  ---  adjustment on $Ng$ for the fixed $Qg$
    end if
    return
```

D-1-8. Flow chart of sub.CQS3

```
CQS3  ---  time integration of $QQ$ with the given production term $PQQ$ ($QQ = QV,\ Qcw \ldots Qg > 0$)

    CADVET  compute advection term of the flux form
    CDIFE3  compute diffusional term (subgrid eddy) (see B-10)
    DMPNL   compute non-linear damping and 4-th order linear damping (see B-12-1 and B-12-2)
    RLDUMP  compute Rayleigh friction near the lateral boundary and the upper boundary is not active (see B-12-3 and B-12-4)
    time integration of $QQ$ ($QQ^{it+1} \longleftarrow QQ^{it}$, $QQ^{it-1}$, $PQQ$)
```

UADVB1(QQ,,)	set array FUBD1 for QQ. At the inflow booundary of u, FUBD1 is set to be zero. At the outflow boundary of u, FUBD1 is set to be non-zero. (see B-7-2 a))
VADVB1(QQ,,)	set array FVBD1 for QQ. At the inflow boundary of u, FVBD1 is set to be zero. At the outflow boundary of u, FVBD1 is set to be non-zero, (see B-7-2 a))
EXTRX1	time integration of QQ at the lateral boundary plane normal to the u-component using array FUBD1 which is set by sub.UADVB1
EXTRY1	time integration of QQ at the lateral boundary plane normal to the v-component, using array FVBD1 which is set by sub.VADVB1.
CHKMN2	check whether QQ is negative or not, and if positive, QQ is adjusted to become zero, transferring positive QQ from adjacent grid points, under the constraint of conservation of QQ.
TSMOTH	apply Asselin's time filter
ADJ2DM	adjust the values of QQ outside the lateral boundary taking account of the cyclic or open lateral boundary conditions

return

D-2. Specification of system parameters

They are divided into 4 classes, namely, P1, P2, P3 and P4 as below. An example of the parameter list P3 and P4 is shown in Table D-1.

D-2-1. P1

Specification is made in the usual program. Load module must be renewed for changing these parameters.

ex. NX, NY, NZ (The dimension of arrays in the program)

D-2-2. P2

Specification is made in MAIN.MAIN program which calls the main program SIMAIN.

SWCMP 0 for AE: PRCMP . . . dummy
1 for E-HI-VI; PRCMP1=1 (no other choice)
2 for E-HE-VI PRCMP=β

MSW(1) 0 – – – no flux (free-slip) condition of u and v at the lower boundary
1 – – – flux (non-slip) condition of u and v at the lower boundary

MSW(2) 1 – – – no other choice

MSW(3) 0 – – – no other choice

MSW(4) 2 – – – no other choice (related to open outflow condition for non-normal u, v, w)

MSW(5) 2 – – – no other choice (related to open outflow condition for Θ, QV..)

MSW(6) 0 – – – dummy

MSW(7) 1 – – – no other choice

MSW(8) 0 – – – dummy

MSW(9) N – – – N is the number of iteration in solving pressure equation for AE and E-HI-VI schemes. 3 is sufficient for most cases. For E-HE-VI, the number of small time integration during one large time integration, $\Delta\tau = (2\Delta t)/N$

MSW(10) 0 – – – 3-dimensional mode ($NY > 1$ is additionally needed)

1 --- 2-dimensional mode ($NY = 1$ is additionally needed)

MSW(11) 0 --- no other choice

MSW(12) 0 --- in the presence of a mountain, mountain growing method is activated to educe the initial shock (see B-13-4 a))

1 --- in the presence of a mountain, wind growing method is activated to reduce the initial shock (see B-13-4 b))

MSW(13) 0 --- no flux condition of Θ and Qv at the lower boundary

1 --- flux condition of Θ and Qv at the lower boundary together with MSW(1)=1 (see B-8 and B-10-2)

MSW(14) −1 --- open in x-direction and wall in y-direction; only effective for the 3-dim mode (MSW(10)=0, $NY > 1$)

0 --- open in both x and y-directions; only effective for the 3-dim mode (MSW(10)=0, $NY > 1$)

1 --- non-cyclic in x-direction, but cyclic in y-direction

2 --- cyclic in both x and y-directions

MSW(15) 0 --- no other choice

MSW(16) 0 --- no other choice

MSW(17) 0 --- dummy

MSW(18) 2 --- no cloud microphysics . . . dry model

1 --- cloud microphysics . . . no ice phase is included; warm rain parameterization

0 --- cloud microphysics . . . ice phase is included.

--- (Qc, Qr; Qi, Qs, Qg; Ni) are predicted.

−1 --- cloud microphysics . . . ice phase is included.

--- (Qc, Qr; Qi, Qs, Qg; Ni, Ns) are predicted.

−2 --- cloud microphysics . . . ice phase is included (see B-11).

--- (Qc, Qr; Qi, Qs, Qg; Ni, Ns, Ng) are predicted.

MSW(19) 0 --- no other choice

D-2-3. P3

Specificatin is made in the input parameter list, VALINO:

ITST	start tiem step "it"; for initial start ITST=0
ITEND	end time step. time integration from it=ITST to ITEND

Table D-1 An example of input parameter list for job step 2 (running the model).

```
\ SET NAME  E01MI04.JCL.CNTL
}ER NAME  SNGPLG
                //GO.SYABEND DD SYSOUT=A
                //GO.SYSIN    DD *
                S33,4:PG.CNS(*4.0) BIGG=E+5:IACW->G(A=0.2):RS=75
                :NCW=**8,NO SEED(*100,-8):IDSN*10**0(0.6):H-M(-8C):CTR:MOD
                 2-DIM,CYCLIC NEW ( 1.0*E-11)
                      IIST     ITEND    ITMATU    ISTRMT     ITOUT     ITCHK
                      2600      3200     80021       100      1200      1200
    valin0.DT        DT        DX        DY         DZ  **ECTURB..CHKMNS.THRESH 0.0
              ---->4.0     400.0     400.0     200.0
                PTRF      UGRF      PTDIS     PRESRF(MB)**   0.1  10 PERCENT MOIST
                  283.15      0.0       1.5   1000.0
                EKMHRF    EKMZRF    EKTHRF    EKEZRF    EKBACK   200
                   50.0      50.0      50.0      50.0      10.00
                 U   TOBISIMA 1989.2.04 15JST
                         1         2         4        16 LATERAL BD.DIFFUSION  11
    valin(1,1)->  -13.0       0.0      -0.0       0.0      0.000    1.0
                        20        30        39        60 UVWEXT(1)  MEAN(O)
                    3.0      10.0      10.0      10.0      0.0      1.0
                        21        50        60        12 PTQEXT(1)  INFLOW
                   15.0      20.0      20.0                0.0
                        13        14        15        16 NRM.U.V  EXTV+(1-RATIO)*VOLD
                                                           0.0      0.0
                        17        18        19        20           RATIOW  MSWBW
                                                                    5.0   valin(36,1)
                        21        22        23        24  SWCMP    PRCMP
                 V                                       VARIABLE DIFFUSION CONST.
                         1         2         4         9 NON-L.DIF 20 ASTFC
    valin(1,2) ->  -2.0       0.0       0.0       0.0     100.0     0.3
                        14        18        24        36  PTZO      DPTDZM
                    0.0       0.0       0.0       0.0
                        36        60        11        12  EOVER(HI-VI)
                    0.0       0.0                          0.5
                        13        14        15        16  EKMHU  EKMZU UPPER B.C.
                                                          100.0     100.0
                        17        18        19        60  EKMHW  EKMZW LARGE DIFF.
                                                          100.0     100.0
                        21        22        23        24  EKMHT  EKMZT PREVENT REFLECTIO
                                                          100.0     100.0
                PT                                         VARIABLE GRID
     valin(1,3)          1         2         4         5   INITIAL THERMAL BUBBLE
               ->-10.15    -10.15     -9.85     -9.84      0.00     -0.3
                         9        10        16        17   DXL      DXL  VARIABLE GRID
                   -8.80     -8.25     -4.50     -3.60    400.0     400.0
                        20        30        39        60   IX1      IX2
                   -1.35      9.35     15.85      90.0     20.0     180.0
                        13        14        15        16   DYL      DYR
                                                          400.0     400.0
                        17        18        19        60   IY1      IY2
                                                           3.0      133.0
                        21        22        23        60   COOLING FOR INITIATING CONV
                  000.0     -0.0008    40.0       4.0
                QV                                          OROGRAPHY
     valin(1,4)          1         2         4         5             CIN   valin(36,3)
               ->  1.0000    0.7700    0.6800    0.7100              -1.0
                         9        10        16        17     IXTST     IXTEN
                    0.8900    0.9100    0.8750    0.830     1.0     200.0
                        20        30        39        60     JYTST     JYTEN
                    0.22      0.20      0.20      0.00      1.0       4.0
                         9        10        11        12     XCENT     YCENT
                                                          120.0       4.0
                        13        14        15        60       PWX       PWY
                                                           10.00     10.00
                        17        18        19        20      ZTOP      PWDT
                                                            0.0       1.0
                QC                                                   valin(36,4)
     valin(1,5) ->       1         2         3         4
                                                            0.1      -0.3
                         5         6         7         8   VARIABLE GRID Z
                                                           20.0     200.0
                         9        10        11        12   IZL       IZU
                                                            5.0      15.0
                        13        14        15        16RLDUMP.IZL  RLDUMP.IZU
```

```
                                                      15.0      35.0
                   17        18        19        80RLDUMP X    RLDUMP Z
                                                       0.0      80.0
                   21        34        36        45
                                         50000.0000
           QR                                      PTGRD        EXP(  *R2)
                    1         2         3         4
  valin(1,6) →                                        10.0      -0.00
                    5         6         7         8PTGRD.RAND  PT.RANDOM
                                                      0.000      0.0000
                    9        10        11        12   WMAX      Z1 INITIAL CONVERGE
                                                       0.0       6.0
                   13        14        15        16    X1        X2
                                                      75.0000   85.0000
                   17        18        19        80 PTDIF.LAND  IXB.LS
                                                               250.0
                   21        34        36        45 U.BIAS     V.BIAS
                                                      13.0     -0.0
          /*                                                    valin(36,6)
          //
```

ISRTMT	results are stored in magnetic tape at the time step 'it' which fulfills mod(it, ISTRMT)=0
ITOUT	results are printed out by line printer at the time step 'it' which fulfills mod(it, ITOUT)=0; for quick look.
DT	time step Δt(sec)
DX	grid distance at the central part of the domain in the x-direction, the unit of which is meter (see D-4).
DY	grid distance at the central part of the domain in the y-direction, the unit of which is meter.
DZ	grid distance at the central part of the domain in the z-direction, the unit of which is meter.
PTBIAS	PTBIAS=Θ_{bias}; $\Theta = \theta + \Theta_{\text{bias}}$; θ is the potential temperature deviation stored in array PT which is acturally predicted in the model.
PTDIS	a parameter which specifies the amplitude of the potential temperature for thermal bubble initiation (see D-7-1).
EKBACK	the parameter associated with the coefficient for the 4-th order artificial diffusion for damping small scale noises (2 grid noises) (see D-9-2).

D-2-4. P4

Specification is made in the input parameter list, VALIN and KZIN. Initial environmental fields and system parameters, such as coefficients of Rayleigh friction are given in the input parameter list as shown in Table D-1.

D-3. Scheme selection among AE, E-HI-VI and E-HE-VI

The parameter SWCMP=0 --- AE
The parameter SWCMP=1 --- E-HI-VI
The parameter SWCMP=2 --- E-HE-VI

Parameter SWCMP is set in MAIN.MAIN program which calls main program SIMAIN.

D-4. Size of the domain, grid indexing and variable grid generation

The array size (NX, NY, NZ) must be set in the parameter statement of the main program SIMAIN. For the 2-dimensional simulation, $NY = 1$ must be specified in addition to MSW(10)-1. For the 3-dimensional simulation, $NY > 1$ must be specified in addition to MSW(10)=0.

In the program, the array index (IX, JY, KZ) is used instead of the logical index, such as $(i,\ j+1/2,\ k)$. The model adopts the staggered grid system shown in Figs. B-5-1, B-5-2 and B-5-3. Table D-2 shows the correspondence between the logical index and the array index in the program code for various kinds of field variables. The dimension of the array in program is $(NX,\ NY,\ NZ) = (nx,\ ny,\ nz)$. Table D-3 shows the inner grid points and their indexing for various kinds of field variables.

Variable Grid is generated as follows. Let us take the case of $\Delta x_{i+1/2}$. As shown in Fig. D-1, the grid distance $\Delta x_{i+1/2}$, which is the distance between the grid points $(i,\ j,\ k)$ and $(i+1,\ j,\ k)$, is the constant value of DX at the central part of the domain, *i.e.*, Δx for $i_\ell < i < i_r$. Δx for the two leftmost grid distances, *i.e.*, for $i = 1/2$ and $i = 1 + 1/2$ is

Table D-2 Correspondence between the logical index $(i,\ j,\ k)$ and the array index (IX, JY, KZ) in the program code.

logical index	array index in the program code
$\Theta_{i,j,k}; (P; Qv...)$	PT(IX,JY,KZ);
$U_{i+1/2,j,k}$;	U(IX+1,JY,KZ);
$V_{i,j+1/2,k}$;	V(IX,JY+1,KZ)
$W_{i,j,k+1/2}$;	W(IX,JY,KZ)
$W^*_{i,j,k+1/2}$;	OMW(IX,JY,KZ)
$\bar{\rho}_{i,j,k}$	DNSRFT(IX,JY,KZ)
$G^{1/2}_{i,j}$	G2(IX,JY)
$1/G^{1/2}_{i,j}$	G2INV(IX,JY)
$\bar{\rho}G^{1/2}_{i,j,k}$	DNSG2(IX,JY,KZ)
$G^{12}_{i+1/2,j,k+1/2}$	G12(IX+1,JY,KZ)
$G^{13}_{i,j+1/2,k+1/2}$	G13(IX,JY+1,KZ)
$\mathrm{BUOY}_{i,j,k+1/2}$	BUOY(IX,JY,KZ)
$g/Cs^2_{k+1/2}$	RGRTMN(KZ)

Table D-3 Inner grid points (outer grid points are dummy grids) and their indexing. Array size is indicated by (NX, NY, NZ) in the program code. (see Figs. B-5-2 and B-5-3)

for P, Qv	IXST=2 ≦ IX ≦ IXEN=NX-1; 2 ≦ i ≦ nx-1 ; KZST=2 ≦ KZ ≦ KZEN=NZ-1 2 ≦ k ≦ nz-1	JYST=2 ≦ JY ≦ JYEN=NY-1 2 ≦ j ≦ ny-1
for U	IXST=2 ≦ IX ≦ NX; 1+1/2 ≦ i ≦ nx − 1/2 KZST=2 ≦ KZ ≦ KZEN=NZ − 1 2 ≦ k ≦ nz − 1	JYST=2 ≦ JY ≦ JYEN=NY-1 2 ≦ j ≦ ny − 1
for V	IXST=2 ≦ IX ≦ IXEN=NX − 1; 2 ≦ i ≦ nx − 1 ; KZST=2 ≦ KZ ≦ KXEN=NZ − 1 2 ≦ k ≦ nz − 1	JYST=2 ≦ JY ≦ NY 1+1/2 ≦ j ≦ ny − 1/2
for W	IXST=2 ≦ IX ≦ IXEN=NX − 1; 2 ≦ i ≦ nx − 1; 1 ≦ KZ ≦ KZEN=NZ − 1 1+1/2 ≦ k ≦ nz − 1/2	JYST=2 ≦ JY ≦ JYEN=NY − 1 2 ≦ j ≦ ny − 1

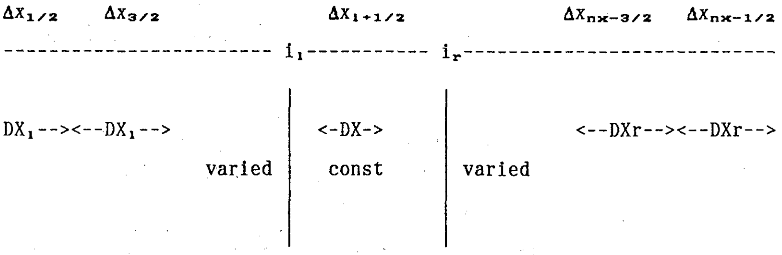

Fig. D-1 Generation of variable grid.

DX_ℓ; Δx for rightmost grid distances, *i.e.*, for $i = nx - 1/2$ and $nx - 2/1/2$ is DXr. Grid distances Δx for $3/2 < i + 1/2 < i_\ell$ are linearly dependent on $i + 1/2$ and between DX and DX_ℓ. Grid distances Δx for $i_r < i + 1/2 < nx - 3/2$ are linearly dependent on $i + 1/2$ and between DX and DX_r.

$$\Delta x_{i+1/2} = \frac{DX_\ell - DX}{3/2 - i_\ell}(i + 1/2 - i_\ell) + DX \quad for\ 3/2 < i + 1/2 < i_\ell \tag{4-1}$$

$$\Delta x_{i+1/2} = DX \quad for\ i_\ell < i + 1/2 < i_r, \tag{4-2}$$

$$\Delta x_{i+1/2} \frac{DX_r - DX}{nx - 3/2 - i_r}(i + 1/2 - i_r) + DX \quad for\ i_r < i + 1/2 < nx - 3/2. \tag{4-3}$$

The grid distance Δx_i, which is the distance between the grid points $(i-1/2, j, k)$ and $(i+1/2, j, k)$, is given as

$$\Delta x_1 = 0.5(\Delta x_{1+1/2} + \Delta x_{i-1/2}) \tag{4-4}$$

Δy and Δz are determined in a similar way.

Variable grids are generated by sub.VRGDIS. Calling sequence is as follows:

sub.VRGDIS ⟵ sub.INIVG1 ⟵ sub.CVEVSI
⟵ sub.SFXMAIN2.

DX_ℓ, DX_r, i_ℓ, j_r are given in array VALIN (11,3)(12,3)(17,3), (18,3)
DY_ℓ, DY_r, i_ℓ, j_r are given in array VALIN (23,3)(24,3)(29,3), (30,3)
DZ_ℓ, DZ_r, k_ℓ, k_r are given in array VALIN (11,5)(12,5)(17,5), (185)
DX, DY, DZ are given in the input parameter list VALINO.

D-5. Specification of the boundary conditions

D-5-1. Lateral boudary conditions

First, open or cyclic or wall conditions must be selected.

MSW(14)	-1 ---	open in the x-direcition and wall in the y-direction
	0 ---	open in both the x- and y-directions
	1 ---	open in the x-direction, but cyclic in the y-direction
	2 ---	cyclic in both x- and y-directions

For the case of open boundary conditions, several parameters must be specified. Near the lateral boundary, a sponge layer can be imposed.

a) Open boundary conditions

a-1) For Θ, Qv, Qc .... and velocity components non-normal to the boundary plane (see Fig. B-7-1)

i) At the inflow boundary

Boundary values are specified as below.

$$Fb^{it+1} = \mu F.\text{ext} + (1+\mu)Fb^{it-1} \qquad \text{B-(7-1)}$$

Fb: the value just outside the boundary

F.ext: external value specified from outside

μ for U, V or W is set in array VALIN(11,1).

μ for Θ, Qv is set in array VALIN(17,1).

The array FUBD is set to be zero by sub.UADVB1 at the inflow boundary.

F.ext is set in arrays EXTU, EXTV, EXTΘ, EXTQV.

ii) At the outflow boundary

If the left boundary ($i = 3/2$) is th eoutflow boundary, boundary values are extrapolated from the values of the inner domain as below:

$$F_b^{it+1} = 2F_{b+1}^{it} - F_{b+2}^{it-1} \qquad \text{B-(7-2)}$$

For the right boundary case, boundary values are extrapolated in a similar way.

The array FUBD is set to be non-zero by sub.UADVBI at the outflow boundary. F_b is computed subs. EXTRX1, EXTRY1 with input array FUBD.

a-2) *Velocity components normal to the boundary plane*

For simplicity, one dimensional case shown in Fig. B-7-2 is considered. First, the phase speed, $Cp*$ of waves at the boundary is estimated. Next, it is determined whether the waves are outgoing or incoming from the sign of the phase speed.

In the case of an incoming case, *i.e.*,

$$\text{at the left boundary (at } i = JS\text{)}, \ Cp* \geq 0 \quad \text{or}$$

$$\text{at the right boundary (at } i = JM\text{)}, \ Cp* \leq 0,$$

the time tendency of U at the boundary, DUDTBC, is computed in order to restore the boundary value to the external value, U.ext, to a certain degree as follows:

$$\text{DUDTB} \equiv \left(\frac{\partial U}{\partial t}\right) = [\mu U.\text{ext} + (1-\mu)U^{it-1} - U^{it-1}]/2\Delta t. \qquad \text{B-(7-11c)}$$

Note that $\mu = 1$ makes U^{it+1} at the boundary equal to U.ext. μ is specified in the input parameter list VALIN(23,1).

b) Sponge layer

Rayleigh damping near the lateral boundary is imposed to prevent the false reflection of internal gravity waves from the lateral boundary, enforce the environmental external conditions (designated by f.exp below) and suppress the noises.

$$\left.\begin{array}{l} D_{r\ell}(f) = -\dfrac{1}{2m_{r\ell}\Delta t}\left(1+\cos\left(\dfrac{\pi(LX-x)}{x_d}\right)\right)(f - f.\text{ext}) \\ \text{for } x > LX - x_d. \end{array}\right\} \qquad \text{B-(7-23)}$$

$$\left.\begin{array}{l} D_{r\ell}(f) = -\dfrac{1}{2m_{r\ell}\Delta t}\left(1+\cos\left(\dfrac{\pi x}{x_d}\right)\right)(f - f.\text{ext}) \\ \text{for } x < x_d. \end{array}\right\} \qquad \text{B-(7-24)}$$

See sub.RLDMP1 in mem.CVTDIF1 for more detail. x_d is set in array VALIN(6,1). Relaxation time constant $m_{r\ell}$ is set in array VALIN(29,5).

D-5-2. Lower boundary conditions

No-flux or lux conditions must be selected.

```
1  2 -------------------->↑<-------------------->↑<-------------- nx
     sea              VALIN(30,6)   land    VALIN(34,6)    sea
   PTDIFs=VALIN(5,6)        PTDIFℓ=VALIN(29,6)

1  2 -------------------->↑<-------------------->↑<-------------- nx
     land               VALIN(34,6)    sea     VALIN(30,6)     land
   PTDIFℓ=VALIN(29,6)        PTDIFs=VALIN(5,6)
```

Fig. D-2 Specification of the sea or land surface.

MSW(13) 0 − − − no flux condition of Θ and Qv at the lower boundary

MSW(13) 1 − − − flux condition of Θ and Qv at the lower boundary together with MSW(1)=1

For the surface condition, land surface or sea surface can be specified as shown in Fig.D-2. If VALIN(34, 6)>VALIN(30, 6), the region VALIN(30, 6)<IX<VALIN(34, 6) is assumed to be the land surface, and the remaining region is assumed to be the sea surface. If VALIN(34,6)<VALIN(30,6), the region VALIN(34,6)<IX<VALIN(30, 6) is assumed to be the sea surface, and the remaining region is assumed to be the land surface.

$$\text{Land surface potential temperature} = \Theta\text{bias} + \Theta\text{init}(\text{KZ} = 1) + \text{VALIN}(5,\ 6)$$

$$\text{Sea surface potential temperature} = \Theta\text{bias} + \Theta\text{init}(\text{KZ} = 1) + \text{VALIN}(29,\ 6)$$

The surface mixing ratio of water vapour is given by the saturation mixing ratio corresponding to the surface temperature.

$$\text{QVGRD(IX, JY)} = \text{QVSATU (IX, JY)}\text{....saturation mixing ratio}$$

In case of the land surface, surface friction z^* must be specified in the program, sub.CRSTUV in mem.CVTURBXZ. The relative translation speed of the numberical model frame to the earth surface (Galilean transformation) is specified as

$$U^* = \text{UGRND} = \overline{\rho} \times \text{VALIN}(35,\ 6),$$

$$V^* = \text{VGRND} = \overline{\rho} \times \text{VALIN}(36,\ 6),$$

In the program, the velocity component of air relavive to the model frame in the x direction, $U = U - U^*$, is stored in the array U, and this is predicted. The velocity component of air relative to the model frame in the y direction, $V' = V - V^*$, is stored in the array V, and this is predicted.

See sub.GENPTD in mem.CVTINIT for more detail.

D-5-3. Upper boundary conditions

The parameters for the upper absorption layer must be specified. Rayleigh damping near the upper boundary is imposed in order to prevent the false reflection of internal gravity waves from the upper rigid wall.

$$D_{ru}(f) = -\frac{1}{m_{ru}\Delta t}\left(1-\cos\left(\frac{\pi(LZ-z)}{LZ-z_d}\right)\right)(f - f.\mathrm{ext}) \qquad \text{B-(9-6)}$$

for $z > z_d$,

where LZ is the height of the domain.

See sub.RLDMP1 in mem.CVTDIF1 for more detail. z_d is set in array VALIN(23, 5). Relaxation constant m_{ru} is set in array VALIN(30, 5).

D-6. Specification of initial environmental fields

They are specified by the pari of arrays, KZIN and VALIN for U, V, Θ, and Qv.

KZIN(m+4(n−1), kind) (m≤ 4)	. . . integer indicates k, the vertical location, for the variable denoted by "kind".
VALIN(m+6(n−1), kind) (m≤ 4)	. . . real number indicates the initial value at the vertical grid point denoted by KZIN (m+4(n-1), kind), for the variable denoted by kind

kind=1 .... u (m/s) not $\overline{\rho}G^{1/2}u$

kind=2 .... v (m/s) not $\overline{\rho}G^{1/2}v$

kind=3 .... $\Theta - \Theta_{\mathrm{bias}}$

kind=4 .... relative humidity $Qv/Qvsw$

The values between the two vertical grid points in KZIN are obtained by linear interpolation as

$$\mathrm{F}(,,\mathrm{k}) = \frac{\mathrm{VALIN}(m+1,) - \mathrm{VALIN}(m,)}{\mathrm{KZIN}(m+1,) - \mathrm{KZIN}(m,)}(\mathrm{k} - \mathrm{KZIN}(m,)) + \mathrm{VALIN}(m,). \qquad (6\text{-}1)$$

Horizontal wind velocity components u and v specified in the input list are the speed of air relative to the numerical model frame, and not relative to the ground surface. The translation speed of th model frame to the ground surface can be specified by VALIN(35, 6) in the x-direction and by VALIN(36, 6) in the y direction. Horizontal velocity components u and v are converted to $\overline{\rho}G^{1/2}u$ and $\overline{\rho}G^{1/2}v$ by sub.UCVDNU and stored in arrays U and V, respectively.

The mixing ratio of water vapor is computed from relative himidity and stored in the array QV.

See sub.INIFLD, INIVAL in mem.CVTINIT.

D-7. Initiation method of convection

Currently, two kins of initiation methods are implemented. One, thermal bubble initiation, and the other, cold dome initiation.

D-7-1. Thermal bubble initiation

Warm perturbation in the Θ field is given at the initial time such as:

$$\Theta = \text{PTDIS} \sin(f(k)) \exp(\text{VALIN}(6,3) \times R^2) \tag{7-1}$$

$$R^2 = (i - i_c)^2 + (j + j_c)^2,$$

where i_c and j_c (integer index) are the center position of the horizontal domain. PTDIS is given in the input parameter list VALIN0. Functional form of $f(k)$ is given in sub.GENPTD in mem.CVTINIT.

D-7-2. Cold dome initiation

Artificial cooling, SRC.Θ, is added to from a cold dome in the lower part of the atmosphere in sub.CPTQV.

$$\text{SRC.}\Theta(\text{cooling}) = \exp(-(k-3))\text{VALIN}(32,\ 3) \exp\left(-\left(\frac{i - \text{VALIN}(33,3)}{\text{VALIN}(34,3)}\right)^2\right) \tag{7-2}$$

for$k < 7$ and $0 \le it \le$ VALIN (31, 3).

D-8. Generation of mountain shape and metric tensors

Mountain shape is specified by input parameters. After mountain shape is determined, metric tensors such as $G^{1/2}$, G^{12}, G^{13} are computed. As an initial start-up procedure in the presence of mountains, two methods, *i.e.*, mountain growing method (with specification of MSW(12)=0) and wind growing method (with specification of MSW(12)=1) are implemented to reduce the initial noises (see B-13-4).

Mountain shape function is stored in array ZS which is generated by sub.SETZS which is called from sub.ORGIN0. Input parameters for the specification of the bell shaped mountain is as follows:

$$Z_s(i,\, j) = \frac{a^2 b^2 h}{(a^2 + (i - i_m)^2)(b^2 + (j - j_m)^2)} \tag{8-1}$$

h . . .	mountain height (meter).........	VALIN(35, 4)
i_m . .	integer indexing grid point in the x-direction	VALIN(23, 4)
j_m . .	integer indexing grid point in the y-direction	VALIN(24, 4)
a . . .	half width in the x-direction; integer	VALIN(29, 4)
b . . .	half width in the x-direction; integer	VALIN(30, 4)

Metric tensors such as $G^{1/2}$, G^{12}, G^{13} are generated after Z_s is generated in sub.ORGIN0.

D-9. Specification of computational diffusion

Artificial computational diffusion is added to suppress computational noises and to overcome some porblems near the upper and lateral boundaries.

D-9-1. Nonlinear damping Dn

$$Dn(f) = \frac{DX^3}{8m_n \Delta t|\Delta f|}\frac{\partial}{\partial x}\left(\left|\frac{\partial}{\partial x}\right|\frac{\partial}{\partial x}\right) + \frac{DZ^3}{8m_n \Delta t|\Delta f|}\frac{\partial}{\partial z}\left(\left|\frac{\partial(f - f.\mathrm{ext})}{\partial z}\right|\frac{\partial(f - f.\mathrm{ext})}{\partial z}\right), \qquad \text{B-(12-1)}$$

where f.ext denotes the horizontally averaged value of initial f.

See. sub.DMPCN in mem.CVTDIFH for more detail. Relation time constant, m_n, is set in VALIn(5, 2). Δf must be set in the program (e.g., 2m/s for U, V and W; 1K for Θ, 0.001kg/kg for Qv, Qc, Qs...)

D-9-2. Fourth-order linear damping

For suppressing mainly 2 grid noises, the damping is given as

$$D_{4\ell}(f) = \frac{DX^4 \mathrm{EKH}(k)\mathrm{EKMXF}(i)}{16 m_{4\ell} \Delta t}\frac{\partial^4 f}{\partial x^4} \qquad \text{B-(12-2)}$$

See DMPCN in mem.CVTDIFH for more detail. The relaxation coefficient, $m_{4\ell}$, is given in VALINO.EKBACK in the input parameter list.

a) EKH(KZ) is determined from VALIN0.EKMZ and VALIN(17, 2) in the input parameter list as follows:

$$\left.\begin{array}{l} \text{for KZ} < 0.7\text{NZ} \\ \qquad \mathrm{EKH(KZ)} = \mathrm{EKMZ} \\ \text{for KZ} > 0.7\text{NZ} \\ \qquad \mathrm{EKH(KZ)} = \dfrac{(\mathrm{kz} - 0.72\mathrm{NZ})(\mathrm{EKMHU} - \mathrm{EKMZ})}{0.3\mathrm{NZ}} + \mathrm{EKMZ} \end{array}\right\} \qquad (9\text{-}1)$$

b) EKMXF(IX) is specified from the input parameter list VALIN as follows:

$$\left.\begin{array}{l}
\text{for IX} < \text{VALIN(6, 1)} \\
\text{EKMXF(IX)} = (1 + \text{VALIN(5, 1)} * \text{VALIN(6, 1)})\dfrac{\text{VALIN(6, 1)} - \text{IX}}{\text{VALIN(6, 1)}} + 1 \\
\text{for IX} > \text{NX} + 1 - \text{VALIN(6, 1)} \\
\text{EKMXF(IX)} = (1 + \text{VALIN(5, 1)} * \text{VALIN(6, 1)})\dfrac{\text{VALIN(6, 1)} - \text{NX} + \text{IX} - 1}{\text{VALIN(6, 1)} - 1} + 1
\end{array}\right\} \quad (9\text{-}2)$$

D-9-3. Rayleigh damping near the upper boundary

This dampint is imposed in order to prevent the false reflection of internal gravity waves from the upper rigid wall.

$$D_{ru}(f) = -\frac{1}{2m_{ru}\Delta t}\left(1 + \cos\left(\frac{\pi(LZ - z)}{Lx - z_d}\right)\right)(f - f.\text{ext}) \qquad \text{B-(12-3)}$$

for $z > z_d$.

Here, LZ is the height of the model domain.

See sub.RLDMP1 in mem.CVTDIF1. z_d is set in the input parameter list VALIn(23,5). Relaxation constant m_{ru} is set in the input parameter list VALIN(30, 5).

D-9-4. Rayleigh damping near the laterral boundary

This damping is imposed in order to prevent the false reflection of internal gravity waves from the lateral boundry, enforece the environmental external conditions and suppress the noises.

$$D_{r1}(f) = -\frac{1}{2m_{r1}\Delta t}\left(+\cos\left(\frac{\pi(LX - x)}{x_d}\right)\right)(f - f.\text{ext}) \qquad \text{B-(12-4)}$$

for $x > LX - x_d$.

$$D_{r1}(f) = -\frac{1}{2m_{r1}\Delta t}\left(1 + \cos\left(\frac{\pi x}{x_d}\right)\right)(f - f.\text{ext})$$

for $x < x_d$.

Here, LX is the width of the model domain.

See sub.RLDMPI in mem.CVTDIFH for more detail. x_d is set in the input parameter list VALIN(6, 1). Relaxation constant $m_{r\ell}$ is set in the input parameter list VALIN(29, 5).

D-9-5. Damping in the time integration schemes

i) Asselin's time filter

$$f(it) = f^*(it) + 0.5\nu(f^*(it+1) - 2f^*(it) + f(it-1)) \qquad \text{B-(12-5)}$$

ν is given in the input parameter list VALIN(6, 2).

ii) α parameter used in E-HI-VI scheme (Eq. B-(3-4))

α is set in the input parameter list VALIN(17, 2).

iii) β and γ parameters usedin E-HE-VI scheme (Eqs. B-(4-4) and B-(4-5))

β and γ are set by β=PRCMP in MAIN.MAIN and γ=VALIN(18, 2).

D-10. Store of the reults and restart

ITST	start time step ‘it’; for initial start ITST=0
ITEND	end time step (time integration from it=ITST to it=ITEND)
ISTRMT	results are stored in magnetic tape at ‘it’ which fulfills mod(it, ISTRMT)=0.