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Description of the Boundary Layer Scheme in NCMRWF Unified Model

Sandeepan B.S. and E. N. Rajagopal

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National Centre for Medium Range Weather Forecasting
Earth System Science Organisation
Ministry of Earth Sciences
A-50, Sector 62, NOIDA – 201 309, INDIA

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Abstract

A description of the boundary layer scheme in the Unified Model implemented at NCMRWF (Rajagopal et al., 2012) is given in this document. The document presents theoretical details of the boundary layer scheme and it implementation details.

Contents

1. Introduction

Atmospheric Boundary Layer (ABL) is a layer of air close to earth surface whose height varies within a few hundred meters and changes diurnally with sun cycle. PBL schemes are used to parameterize the unresolved turbulent vertical fluxes of heat, momentum, and moisture within the planetary boundary layer. A closure scheme is needed to obtain turbulent fluxes from mean quantities. Mesoscale NWP models use the eddy-diffusivity approach to parameterize turbulent and convective motions in the atmospheric planetary boundary layer.

The model variables with given source terms, say S, from processes other than boundary layer turbulence, Reynolds' averaging gives the following equation for conserved scalar variables, χ, and the two horizontal components of momentum, u on a sphere gives

$$\frac{\partial \chi}{\partial t} = -\frac{1}{r^2\rho}\frac{\partial}{\partial z}(r^2\rho\overline{w'\chi'}) + S$$

$$\frac{\partial u}{\partial t} = -\frac{1}{r^2\rho}\frac{\partial}{\partial z}(r^2\tau) + S$$

where $w'\chi'$ and τ are the vertical turbulent fluxes to be parameterized, r is the height from the centre of the planet and ρ is density. For a 'first-order' closure parameterization the turbulent fluxes with non-local terms as the standard closures are:

$$\overline{w'\chi'} = -K_h\frac{\partial \chi}{\partial z} + K_{\chi}^{surf}\gamma_{\chi}$$

$$\tau = K_m\frac{\partial u}{\partial z} + \tau^{nl}$$

Thus, the parameterization reduces to determiningK_m , $K_h$and γ_χ andτ^{nl}.

The physical parameterizations of global and mesoscale models are essentially one-dimensional (1D) in the vertical direction. 1-D modelling of the PBL for turbulence parameterizations has been developed and validated for a variety of PBL situations and are used for the improvement of weather prediction and climate models.

Due to the turbulent nature of the mixing within the boundary layer it is not possible to derive a closed set of equations for the evolution of a grid box mean of a quantity in a numerical prediction or climate model. This is known as the turbulence closure problem. One way this problem can be overcome is to retain terms up to a certain order and approximate the remaining terms. There are many different parameterisation schemes in use.

In Global and mesoscale models there are different types of parameterisations. For example, there are local schemes where the vertical diffusion for momentum and heat are estimated from the local gradients of wind and temperature at each grid nodes. Diffusion is considered to be proportional to the local gradient in a traditional way. In a highly convective atmosphere however, transport of surface flux takes place to many vertical layers even though the local gradient is small. This effect is included in a couple of nonlocal diffusion schemes.

First-order schemes, also known as gradient transport theory or K-theory schemes, retain prognostic equations for only the mean variables, for example horizontal wind, temperature and humidity and approximate higher order covariances. They use local (nearby) flux-gradient relationships to transfer the problem of unknown covariances to that of specifying an eddy diffusivity which is often specified from vertical shear, static stability and an appropriate length scale.

Second-order closure requires predictive equations for all the covariance terms (e.g., $u'w'$, $w'q'$ and $u'q'$). The equations that need to be solved to obtain these terms are complex and contain triple correlation terms. There are many ways to parameterise these terms but most are based on mixing length theory or Monin-Obukhov similarity theory.

1.1 Local PBL schemes

One traditional approach has been to use a local first order closure (e.g., Louis 1979) to represent the effects of boundary layer turbulence. This method relates the turbulent fluxes to the local mean gradients using eddy diffusivity that itself is related to the local stability. In stable conditions, in which the turbulence is typically in local equilibrium, this approach appears to be well founded. This approach not suitable for unstable condition because it takes no account for transport due to large eddies. These large eddies depend on overall stabilities than local gradient. Also the local schemes underestimate the entrainment at the boundary layer top.

1.2 Nonlocal schemes

To represent mixing in unstable condition nonlocal schemes are developed. One such scheme is that proposed by Holtslag and Boville (1993) extending earlier work by Troen and Mahrt (1986). Rather than relating the diffusivities to local gradients, a profile shape is prescribed, and the magnitude is related to a turbulent velocity scale, which is determined from the surface forcing. Terms representing nonlocal fluxes of heat and moisture are also included. Entrainment effects are simply dealt with by choosing the definition of the boundary layer top such that the prescribed diffusivity profiles do not go to zero until some distance above the mixed layer tops. The disadvantages of these schemes are the results do show considerable sensitivity to the definition of boundary layer top used. Different definitions may change the amount of entrainment, and some can undesirably lead to the boundary layer scheme mixing into cumulus layers (Vogelezang and Holtslag 1996). Furthermore, the scheme can only represent mixing in a single surface-based mixed layer and has no representation of turbulent processes driven from cloud top.

2. PBL scheme in Unified Model

The boundary layer parameterization used in the NCMRWF Unified Model (NCUM) is essentially a two-part scheme split by boundary layer stability (Lock et al. 2000). For unstable boundary layers it uses a K-profile closure. The profile diffusion coefficients are scaled functions of height within the boundary layer with an explicit entrainment parameterization at the boundary layer top. For stable boundary layers a simple down-gradient formulation dependent on local stability using the Richardson number that measures the stability of the atmosphere to turbulent mixing is used. The uniqueness of this particular scheme is the identification of layers of differing mixing regimes and their discrete treatment. This scheme identifies seven different types of boundary layer that are distinguished by the relative positions in the vertical of stable and unstable turbulently mixed layers and cumulus cloud layers.

2.1 Seven mixing regimes in NCUM

- Type I: Stable boundary layer (with or without cloud) — turbulent diffusivities are calculated by the ‘local’ scheme
- Type II: Boundary layer with stratocumulus over a stable near-surface layer — as Type I but with a turbulently mixed cloud layer driven from its top (a DSC layer)
- Type III: Well mixed boundary layer — the classic single mixed layer which may be cloud-topped or clear but is predominantly buoyancy-driven (c.f. a possible type VII below)

- Type IV: Unstable boundary layer with a DSC layer not over cumulus , the surface-based and cloud-top-driven non-local K profiles may or may not overlap and cloud-top entrainment can still include the surface forcing
- Type V: Boundary layer with a DSC layer over cumulus — the cumulus (treated by the model's mass-flux convection scheme) provides coupling with the SML
- Type VI: Cumulus-capped boundary layer — no turbulent diffusivities are allowed at or above the LCL as the mass-flux convection scheme operates here
- Type VII: Shear-dominated unstable layer — potentially wind-shear might allow deeper turbulent mixing in unstable boundary layers than is apparent purely from the thermodynamic profiles (sufficient even to inhibit the formation of cumulus);

In order to treat both dry and cloudy boundary layers in the same way, the scheme is formulated in the moist variables Θ_1, the liquid–frozen water potential temperature, and *qt*, the specific total water content. Because these variables are conserved under adiabatic vertical motion (in the absence of precipitation) eddy-diffusivity profiles can be used that span the whole depth of a well mixed stratocumulus-capped boundary layer, in the same way as the large eddies that perform most of the transports in reality.

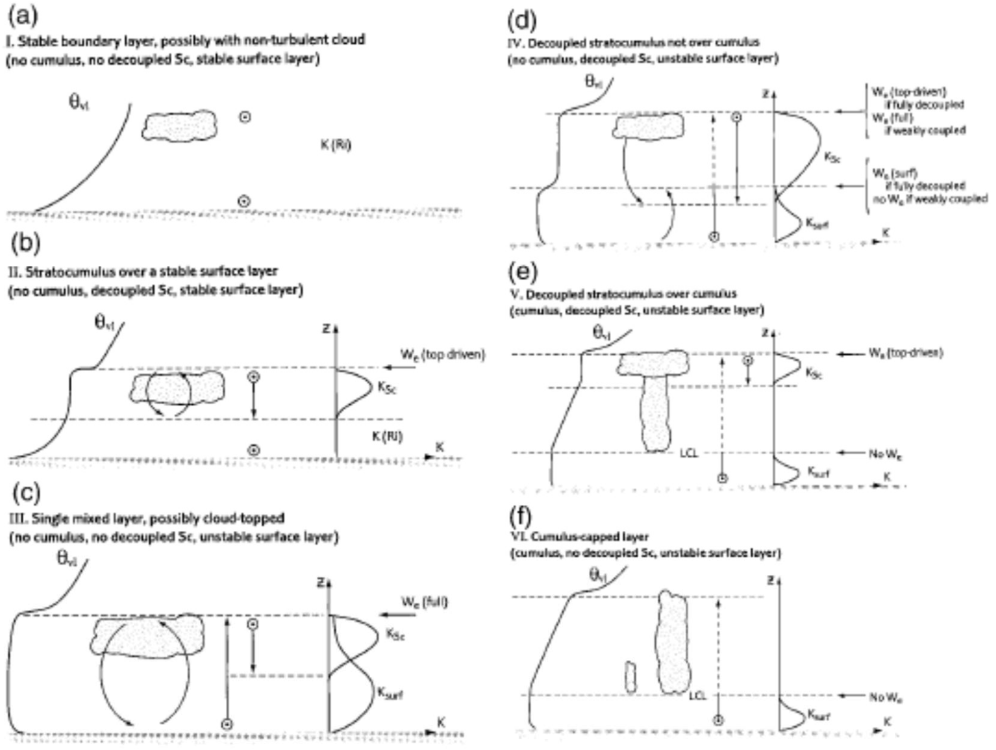

FIG. 1. Schematic representation of the six boundary layer types. The tops of the upward arrows indicate the height of z_{par} while the tops of their respective solid lines indicate z_{ml}.

Fig.1: Representation of the six boundary layer types

2.2 The Local scheme for stable Layer

In the NCUM PBL scheme, stable boundary layer is handled by local first order Richardson number treatment, the diffusivity of momentum and heat are formulated as

$$K_m = \mathrm{L}_\mathrm{m}^2(\mathrm{S} + \mathrm{S}_\mathrm{d})\boldsymbol{f_m}\ (\boldsymbol{Ri})$$

$$K_h = \mathrm{L}_\mathrm{h}\,\mathrm{L}_\mathrm{m}(\mathrm{S} + \mathrm{S}_\mathrm{d})\boldsymbol{f_h}\ (\boldsymbol{Ri})$$

where, L_m and L_h are the neutral mixing lengths and S is the resolved vertical shear of the horizontal wind components, S= $|\partial \mathrm{u}/\partial \mathrm{z}|$. A representation of the wind shear, S_d generated by drainage flows in complex terrain can also be included, as described below.

$$L_m = \frac{k(Z + Z_{0m})}{1 + {k(Z + Z_{0m})}/{\lambda_m}}$$

$$L_m = \frac{k(Z + Z_{0m})}{1 + {k(Z + Z_{0m})}/{\lambda_h}}$$

where Z_{0m} includes the orographic component

The asymptotic mixing lengths are given by

$$\lambda_m = Max[40{,}0.15\ Z_{loc}, 2h_B]$$

$$\lambda_h = Max[40{,}0.15\ Z_{loc}]$$

where, h_B is the orographic blending height and Z_{loc} is boundary layer top measured as the lowest half level at which Ri > 1 .

The Richardson number, $\boldsymbol{Ri}$ that is used as a local measure of stability is given by

$$\boldsymbol{Ri} = \frac{{\boldsymbol{\Delta B}}/{\boldsymbol{\Delta Z}}}{(\boldsymbol{S} + \boldsymbol{S_d})^2}$$

The measure of buoyancy used in $\boldsymbol{Ri}$ is $\Delta B = g(\overline{\beta_T}\ \Delta\Theta_l + \overline{\beta_q}\ \Delta q_t)$

where $\overline{\beta_T}$ and $\overline{\beta_q}$ are the grid-box mean buoyancy coefficients

$\boldsymbol{f_m}$ and $\boldsymbol{f_h}$ are functions of Ri. There are different options for stable boundary layer mixing function available in NCUM some of them are long tail, short tail (Louis) and Sharpest.

The 'long-tailed' functions are

$$\boldsymbol{f_m} = \frac{\mathbf{1}}{\mathbf{1} + \boldsymbol{g_0 Ri}}$$

Alternative functions, which decrease as $\mathbf{1}/\boldsymbol{Ri^2}$ with increasing stability, are from Louis

$$\boldsymbol{f_m} = \frac{\mathbf{1}}{(\mathbf{1} + \mathbf{5}\boldsymbol{Ri})^2}$$

and the 'Sharpest' functions

$$\boldsymbol{f_m} = \begin{cases} (\mathbf{1} - \mathbf{5}\boldsymbol{Ri})^2 \; for\ 0 < \boldsymbol{Ri} < \mathbf{0.1} \\ (\mathbf{20}\boldsymbol{Ri})^{-2} \;\; for\ \boldsymbol{Ri} > \mathbf{0.1} \end{cases}$$

2.3 Convective Boundary layer treatment

The method of calculating diffusivity values for unstable conditions is non-local in the sense that, at a given height within the boundary layer, diffusivity is determined not by any local properties of the mean profiles at that height but solely by the magnitude of the turbulence forcing applied to the layer as measured by the representative velocity scales and the height within the layer. The non-local scheme is therefore particularly robust but care must be taken where the profiles are applied. This is applied exclusively for unstable boundary layers.

In this regime, mixing is assumed to occur in (or lead rapidly to the formation of) well-mixed layers (in which conserved variables are approximately uniform with height) that are capped by an inversion. Mixing is assumed to be driven either from the surface in a 'surface mixed layer' (SML, by a positive surface buoyancy flux and by surface stresses) or by cloud-top buoyancy sources (radiative and evaporative cooling) separate K-profiles are used for these two turbulence sources. If the cloud-top sources generate mixing throughout the SML the layer is said to be 'coupled' but if the K-profile representing surface-driven mixing does not extend up to cloud-top, the layer is referred to as being 'decoupled'. As decoupled layers are restricted to being buoyancy driven and typically below 6 km, they are referred to as decoupled stratocumulus (DSC) layers.

2.3.1 Surface-driven turbulence

The Turbulent sources at the surface experienced due to drag with velocity scale U* and positive surface buoyancy fluxes with velocity scale W* in a layer with boundary layer top at Z = Z_h base at Z=0

$$K_m^{surf} = k\, Z_H\, w_m \frac{Z}{Z_H}\left(1 - \varepsilon_m^{surf}\, \frac{z}{Z_h}\right)^2$$

where, $w_m{}^3 = u_*^3 + w_s^3$; u_* is frictional velocity,

2.3.2 Cloud-top-driven turbulence

The cloud top driven turbulence over a layer of depth Z_{ml} with top at Z_h or Z_h^{Sc} and base at Z_b

$$K_m^{Sc} = 0.63\, k\, Z_{ml}\, V_{Sc}\left(1 - \varepsilon_m^{surf}\, \frac{z'}{Z_{ml}}\right)^{0.8}$$

where, $V_{Sc}{}^3 = V_{rad}^3 + V_{br}^3$; z' is the height above Z_b

The diffusivity for the heat Kh

$K_h = {}^{K_m}\!/_{Pr}$; Where Prandtl number, Pr = 0.75

There are two profiles, one representing turbulence driven from the surface (by both shear and buoyancy production) and the other representing buoyancy production of turbulence from cloud top by both radiative and evaporative processes. The surface profiles and cloud top profile may overlap, or they may not, indicating in the latter case the presence of a turbulent cloud layer that is decoupled from the surface. Mixing coefficients *K*(Ri) based on the the local Richardson number are also calculated. They are used in stable layers. The vertical flux of a quantity χ is given by

$$\overline{w'\chi'} = -\, max\left[\left(K_\chi^{surf} + K_\chi^{Sc}\right), K_\chi(R_i)\right]\frac{\partial\overline{\chi}}{\partial Z} + K_\chi^{surf}\gamma_\chi$$

where K_χ is the appropriate diffusivity (K_m for momentum, K_h for scalars) and the prime denotes deviation from the horizontal mean indicated by an over bar. The last term on the right-hand side represents a nonlocal flux.

2.3.3 Boundary layer height calculation in NCUM

The non-locally specified K-profiles require the height of the base and top of the layer to be diagnosed. The mixing generated by the non-local K profiles is assumed to occur in well-mixed layers capped by an inversion. Thus, the accurate diagnosis of their vertical extent is crucial. If the boundary layer is unstable i.e., there is a positive surface buoyancy flux then the boundary layer height is calculated by the method of diagnostic moist parcel ascent. Typically this is an adiabatic parcel with entraining options being available. In the case of cumulus-capped layers LCL is set to the boundary layer height.

The method assumes that the height to which turbulent mixing driven by surface processes can extend in unstable boundary layers (and therefore the vertical extent of the K profile for surface-driven turbulence) can be determined solely from the properties of the thermodynamic profiles. In more detail, the first step in calculating zh is to lift a parcel, with properties from the first grid-level above the top of the surface layer, upwards allowing for latent heat release. The top of the surface layer is taken to be at the lower of $z = 0.1zh$ (zh is taken from the previous time step) and the grid-level above which $\theta v\ell$ starts to increase with height. The ascent is stopped at the grid-level which the parcel becomes more negatively buoyant than a given threshold, θv. Note that the parcel properties themselves are not perturbed in order to preserve the height of the mixed-layer's lifting condensation level (LCL). However, if cumulus convection is present, the boundary layer scheme is capped at the cumulus cloud base (zh = lifting condensation level (LCL). In stable layers ($FB < 0$), zh is defined where the bulk Richardson number first becomes greater than one.

2.4 Flow of NCUM PBL scheme

The step by step procedure followed in the NCUM PBL scheme is described below:

1) Identification of Unstable layer (clear or cloudy)
   This is done based on the buoyancy (allowing for latent heating effects) of undiluted parcels lifted from the surface and lowered from the top of any layer cloud.

2) Next crucial step is to distinguish between those that are well mixed (i.e., clear and stratocumulus-capped layers), and those in which cumulus convection is present. This allows different mixing schemes to be applied in these two types of unstable layers.

Clear and stratocumulus-capped layer	Cumulus convection present layer
In well-mixed layers, fluxes are calculated using a nonlocal eddy-viscosity-based scheme based on that of HB93, but extended to allow for the effects of turbulence driven from cloud top, by radiative and evaporative cooling, as well as from the surface. Additionally, entrainment at the tops of well mixed layers is parameterized directly using the scheme of Lock (1998).	Cumulus layers are parameterized using a mass-flux convection scheme (Gregory and Rowntree 1990).

3) Finally, a parcel descent is also used to calculate the depth of turbulent mixing driven from cloud top, thereby either allowing decoupling of stratocumulus-capped layers to be diagnosed or allowing the eddy-diffusivity profile representing turbulence driven from cloud top to span the full depth of the boundary layer.

2.5 Flowchart up to boundary layer scheme

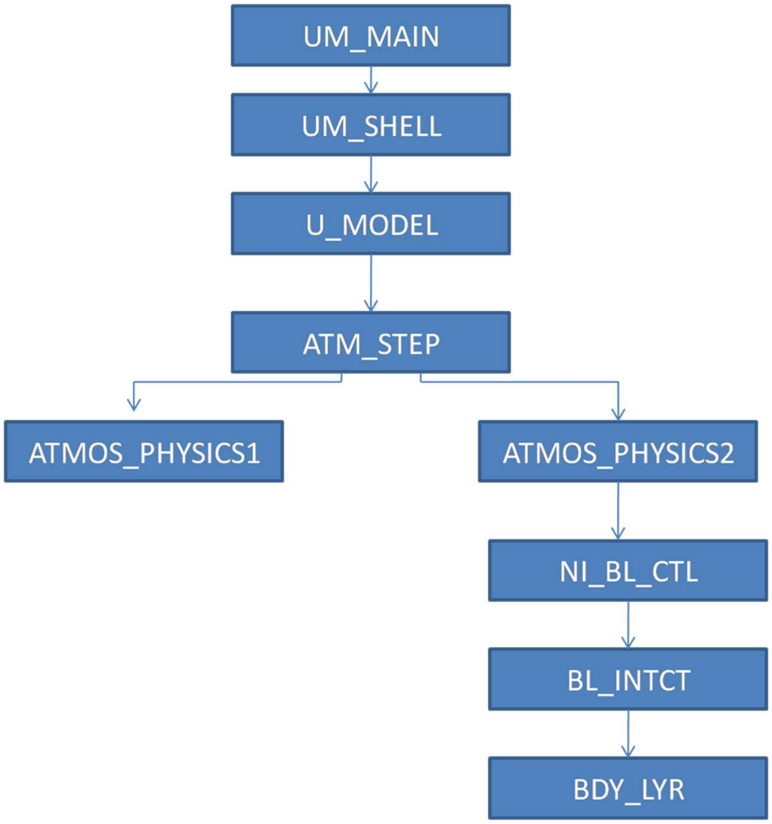

Fig. 2: The flowchart showing the calling sequence up to boundary layer subroutine.

The description of each subroutine shown in the flow chart is given below:

1) UM_MAIN is the main FORTRAN program that drives the NCUM.
2) UM_SHELL is the main control subroutine for the atmosphere model. It acquires size information needed for dynamic allocation of configuration dependent arrays.
3) U_MODEL is the master control subroutine to allocate the arrays and perform the top-level control functions and time stepping
4) ATM_STEP is the subroutine does the forward integration. It calls two group of physics subroutine
5) ATMOS_PHYSICS1 is for microphysics (clouds and large scale precipitation schemes), radiation and gravity wave drag.
6) ATMOS_PHYSICS2 is for convection, boundary layer, hydrology and river routing among this convection and river routing are optional.
7) NI_BL_CTL is the subroutine which works as an interface to boundary layer.
8) BDY_LYR is the boundary layer subroutine which calculates turbulent fluxes of heat moisture and momentum. The outputs available from the BDY_LYR subroutine are listed in Table 1.

Table1: The outputs available from boundary layer subroutine

k_plume :	Model level for parcel start
qw_plume :	Initial parcel water [kg/kg]
sl_plume :	Initial parcel energy [J]
delthvu :	CAPE from conv_diag [J]
z_lcl :	LCL height [m]
cin :	Undilute parcel CIN
cape :	undilute parcel CAPE
DSCbase :	Base of decoupled layer [m]
coupled :	Weakly coupled DSC Indicator
svl_diff_frac :	Decoupling SVL fraction
ScCldBase :	Stratocumulus cloud base [m]
Entr_SML :	SML-top entrainment rate [m/s]
Entr_BL :	BL-top entrainment rate [m/s]
Dsiems_sml :	SML-top D_ctei
Dsiems :	BL top D_ctei
K_ctei_sml :	SML top CTEI parameter
K_ctei :	BL-top CTEI parameter
CHI_S_sml :	SML top CHI_S parameter
CHI_S :	BL-top CHI_S parameter
DB_TOP :	SML inversion strength [m2/s3]
DB_BL :	BL-top inversion strength
QCL_IC_TOP :	BL-top in-cloud water content
df_top :	Radiative flux difference across BL top [Km/s]
zh_loc :	ZH found from Ri [m]
zhpar :	Height of top of parcel ascent [m]

ustar :	Surface friction velocity [m/s]
NTML :	Top level of surface mixed layer [Model level]
NTPAR :	Top level of initial parcel ascent [Model level]
freeze_lev :	Freezing level [Model level]
ind_cumulus :	Indicator for cumulus convection [Indicator]
cfl_limited_deep :	Indicator for CFL limited deep [Indicator]
cfl_limited_mid :	Indicator for CFL limited mid [Indicator]
ind_deep :	Indicator for deep convection [Indicator]
ind_shallow :	Indicator for shallow convection [Indicator]
ind_midconv :	Indicator for mid-level convection [Indicator]
kterm_deep :	Deep convection termination level [Model level]
wthvs :	wthetav flux at surface [K m/s]
cclwp :	Condensed Cloud Water Path [Kg/m2]
cca_2d :	2d Convective Cloud Amount [Fraction]
deep_flag :	History of deep convection
past_precip :	History of convective precip [kg/m2/s]
past_conv_ht :	History of convective depth [m]
qt1p5m :	1.5m total water kg water/kg air [kgH20/kgAIR]
tl1p5m :	1.5m liquid temperature [K]
LWP :	Liquid water path [kg/m2]
IWP :	Ice water path [kg/m2]
lca1p5m :	1.5m layer cloud amount [Fraction]
qcl1p5m :	1.5m cloud water [kg/kg]
pfog1p5m :	Probability of fog at 1.5m [-]
pmist1p5m :	Probability of mist at 1.5m [-]
visnop1p5m :	1.5m visibility outside precip [m]
vislsp1p5m :	1.5m visibility in LS precip [m]
viscp1pm5 :	1.5m visibility in conv precip [m]
vis1p5m :	1.5m visibility [m]
rh1p5m :	Relative humidity at 1.5m [%]
rhw1p5m :	Relative humidity wrt H2O at 1.5m [W/m2]
td1p5m :	1.5m dewpoint temperature [W/m2]
wspd10m :	10m wind speed [m/s]
wdrn10m :	10m wind direction [degs]
gust10m :	10m Gust [m/s]
lat_ht :	Surface latent heat flux [W/m2]
surf_ht_flux :	Net downward heat flux at surface [W/m2]
z0m :	Roughness length for momentum [m]
z0h :	Effective roughness length for heat [m]
z0m_eff :	Effective roughness length for momentum [m]
q1p5m :	1.5m specific humidity [kg/kg]
t1p5m :	1.5m temperature [K]
t1p5m_max :	Max 1.5m temperature [K]
t1p5m_min :	Min 1.5m temperature [K]
u10m :	Zonal 10m wind [m/s]
v10m :	Meridional 10m wind [m/s]
zh :	Boundary layer depth after B.layer [m]
ftl_surf :	Surface sensible heat flux from B.layer [W/m2]

fqt_surf :	Surface sensible moisture flux from B.layer
zht :	Turbulent mixing height after B.layer [m]
bl_type_1 :	Boundary layer type: stable [Indicator]
bl_type_2 :	Boundary layer type: Sc over stable [Indicator]
bl_type_3 :	Boundary layer type: well mixed [Indicator]
bl_type_4 :	Boundary layer type: decoup Sc not over Cu
bl_type_5 :	Boundary layer type: decoup Sc over Cu
bl_type_6 :	Boundary layer type: cumulus capped [Indicator]
bl_type_7 :	Boundary layer type: shear driven [Indicator]
bl_alltypes :	Boundary layer types
can_evap :	Canopy evaporation [kg/m2/day]
lhf_tile :	Tile latent heat flux [W/m2]
soil_evap :	Soil evapotranspiration [kg/m2/day]
t1p5m_tile :	Tile 1.5 m temperature [K]

3. Sensitivity test on Stability Functions

The single column configuration of NCUM has been used for testing the sensitivity of stability function for surface parameters like 1.5 m temperature & humidity and 10 m wind speed. A standard test case data from the Atmospheric radiation Measurement (ARM) site at Southern Great Plane USA is taken for forcing the model. Model has been integrated for three day period by changing the stability functions, the functions used are long tail, Louis and sharpest.

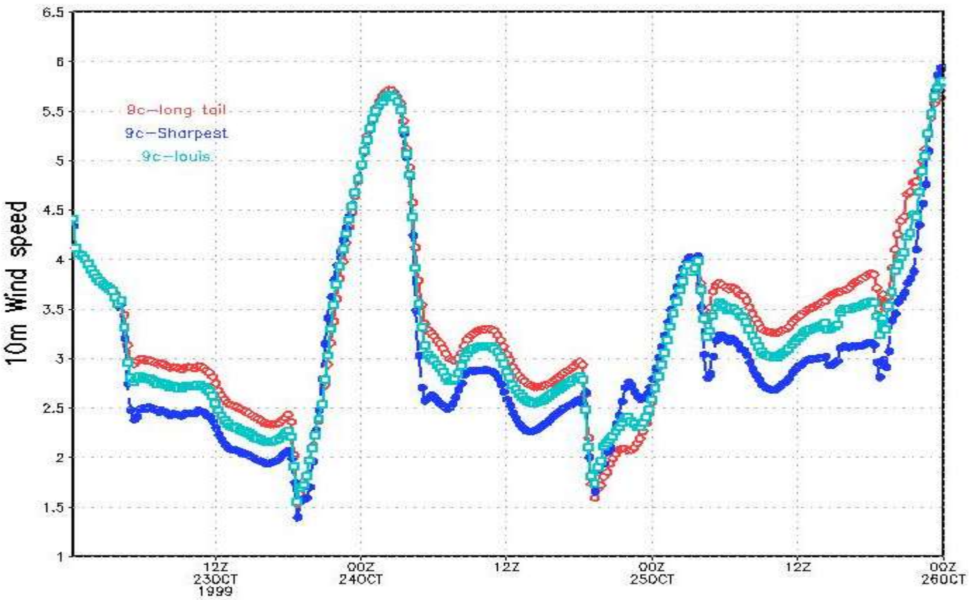

Fig.3: 10 m wind speed simulations for different stability functions

Fig. 3 shows the wind speed at 10 m. During the day time all the three schemes produces same wind speed and during night time sharpest function produces minimum, long tail maximum and Louis in between. In the 1.5m temperature simulations (Fig. 4), during the day time all the three schemes produces similar day time temperatures. During night time sharpest function produces minimum, long tail scheme producess maximum and Louis scheme is in between. These functions influence the diffusivity coefficients directly under nocturnal stable conditions and influences the surface parameters, minimum diffusivity coefficients implies less momentum mixing and thereby low surface wind speed. Similar things happens in the case of temperature .

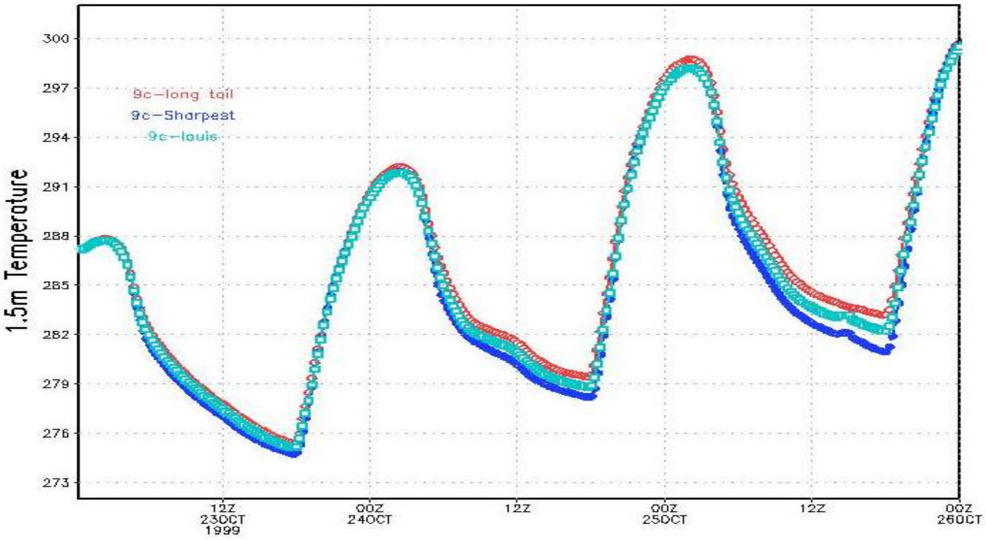

Fig. 4: 1.5 m temperature simulations for different stability functions

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