Vertical diffusion
(in HIRLAM)

Sander Tijm

•••• Forgot to mention yesterday…..

- HIRLAM scientific documentation (2002):

- Go to www.hirlam.org
- Documentation
- Scientific documentation (large pdf-file)

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- HIRLAM scientific documentation (2002):

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- And then for those of you who can stay awake:

Contents of lecture

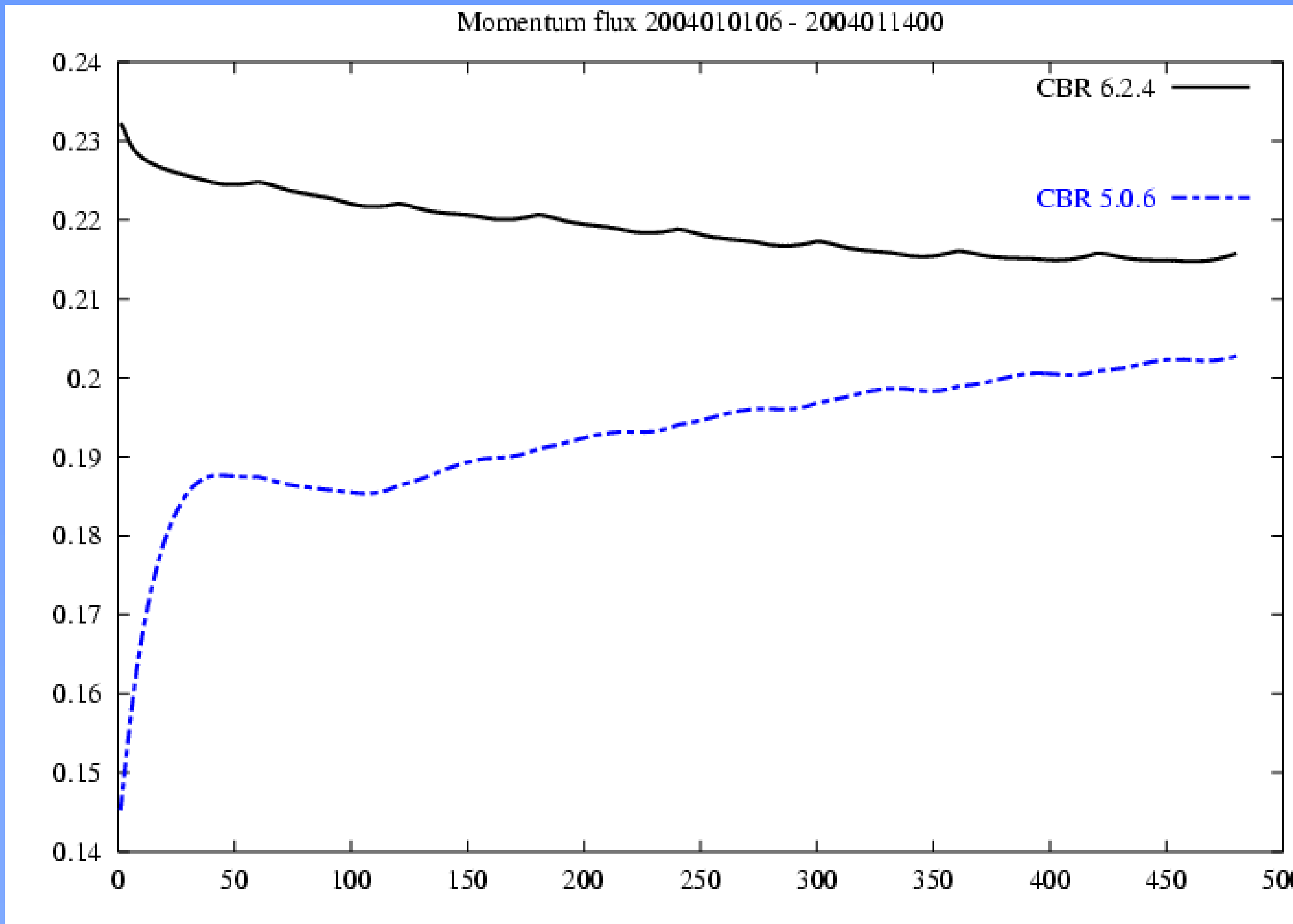
- Importance of vertical diffusion scheme
- Vertical diffusion, flux calculations
- 1st, 2nd and 3rd order schemes
- Local and non-local schemes
- HIRLAM CBR
- Dry and wet conservative parameters
- Characteristics of HIRLAM vertical diffusion

Importance of vertical diffusion

- Vertical diffusion scheme determines the characteristics of the boundary layer in NWP-models
- Also impact on synoptic scale behaviour of model
- Too weak mixing: too little Ekman pumping and low pressure systems becoming too intense, increasing activity in model during forecast, chance of decoupling of surface and atmosphere
- Too much mixing: too deep boundary layer, especially for stable (very sensitive) conditions, can have large impact on ACT modelling
- Most NWP-models have too much mixing in stable conditions

Impact of vertical diffusion

- From too active to too damped



Turbulence

- Vertical transport due to turbulence, example potential temperature:
- First law of thermodynamics:

$$\frac{\partial \theta}{\partial t} + U_j \frac{\partial \theta}{\partial x_j} = \frac{1}{\rho C_p}\left[L_v E + \frac{\partial Q_j^*}{\partial x_j} \right]$$

- Continuity equation:

$$\frac{\partial \rho}{\partial t} + U_j \frac{\partial \rho}{\partial x_j} = -\rho \frac{\partial U_j}{\partial x_j}$$

Turbulence

KNMI

- Reynolds decomposition

$$\theta = \overline{\theta} + \theta', \quad \overline{\theta'} = 0$$

- First law of thermodynamics

$$\frac{\partial \overline{\theta}}{\partial t} + \overline{U}_j \frac{\partial \overline{\theta}}{\partial x_j} + U'_j \frac{\partial \theta'}{\partial x_j} = \frac{1}{\rho C_p}\left[L_v E + \frac{\partial Q_j^*}{\partial x_j} \right]$$

- Incompressible continuity equation:

$$\frac{\partial(\overline{u} + u')}{\partial x} + \frac{\partial(\overline{v} + v')}{\partial y} + \frac{\partial(\overline{w} + w')}{\partial z} = 0$$

Turbulence

- Splitting into average and turbulent part (Reynolds decomposition)

$$\frac{\partial \bar{u}}{\partial x}+\frac{\partial \bar{v}}{\partial y}+\frac{\partial \bar{w}}{\partial z}=0 \quad \textit{and} \quad \frac{\partial u'}{\partial x}+\frac{\partial v'}{\partial y}+\frac{\partial w'}{\partial z}=0$$

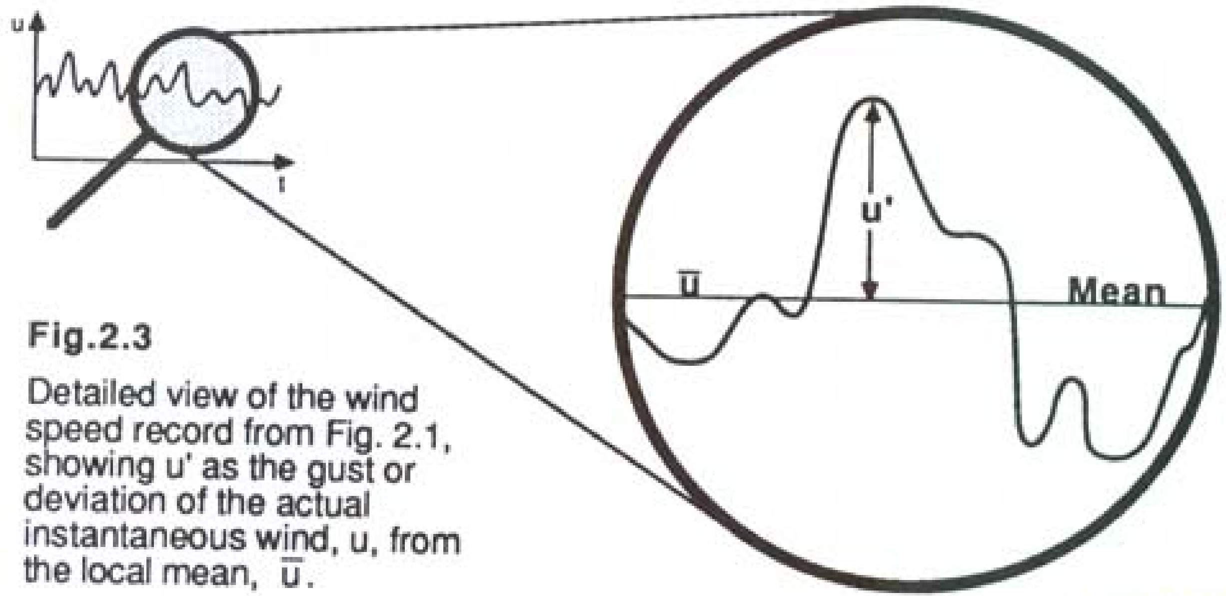
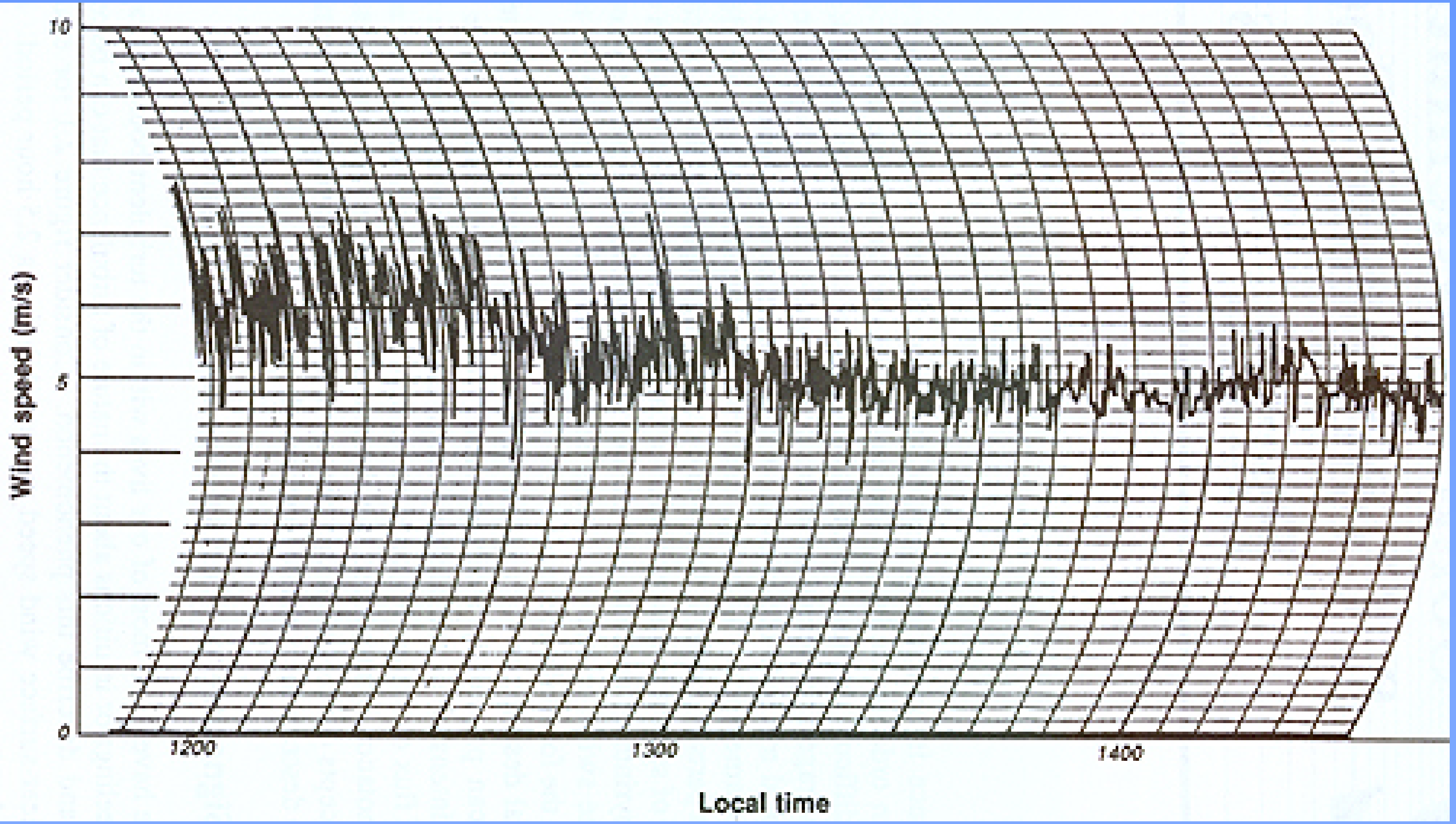


Fig.2.3

Detailed view of the wind speed record from Fig. 2.1, showing u' as the gust or deviation of the actual instantaneous wind, u, from the local mean, ū.

from Stull 1988

Turbulence in observations



Time series of wind speed

Turbulence

- First law of thermodynamics

$$\frac{\partial \bar{\theta}}{\partial t} + \bar{U}_j \frac{\partial \bar{\theta}}{\partial x_j} + \frac{\partial \overline{U'_j \theta'}}{\partial x_j} = \frac{1}{\rho C_p}\left[L_v E + \frac{\partial Q_j^*}{\partial x_j} \right]$$

- Turbulent flux term in vertical direction:

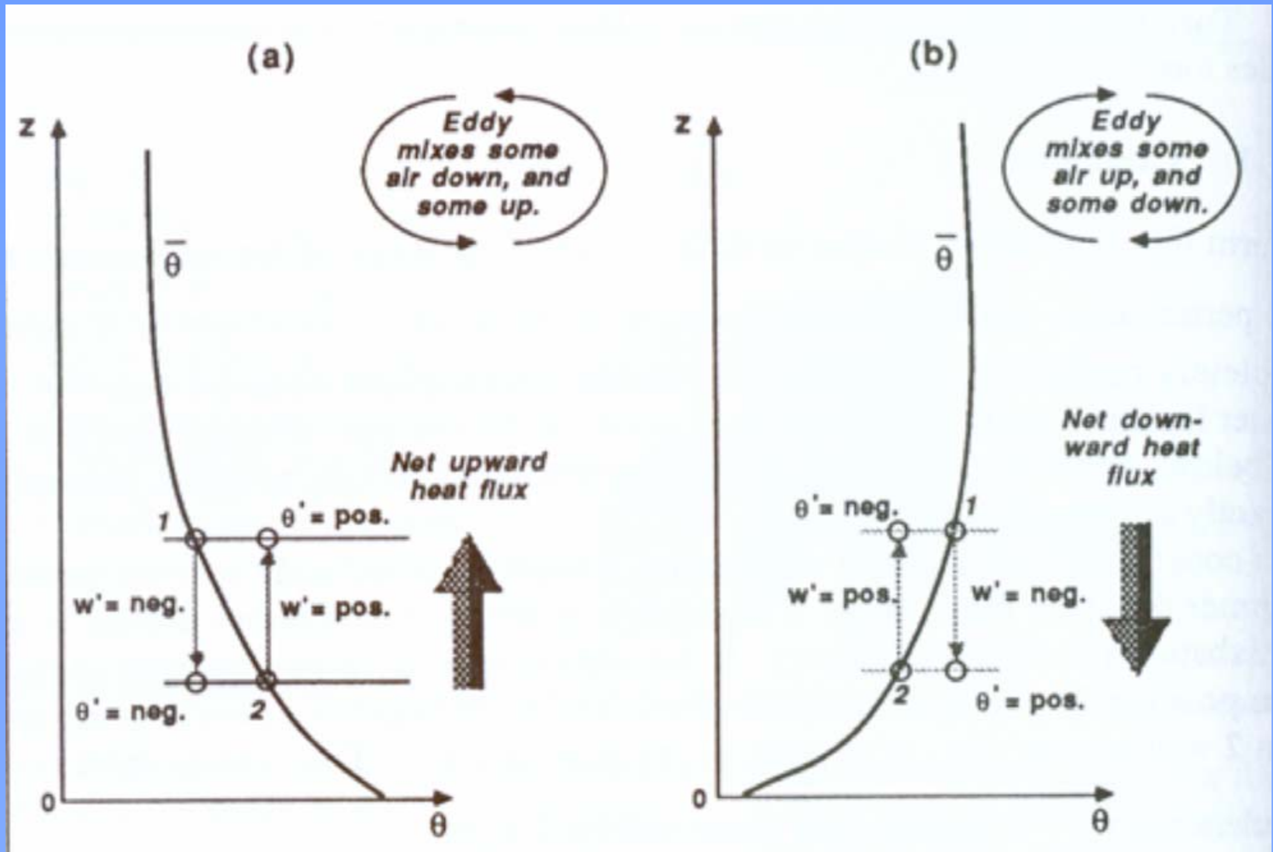
$$\frac{\partial \theta}{dt} = -\frac{\partial \overline{w'\theta'}}{\partial z}$$

- In synoptic scale NWP-models horizontal turbulent terms are usually ignored

Turbulence

- Flux:

$\overline{w'\theta'}$ Unstable Stable



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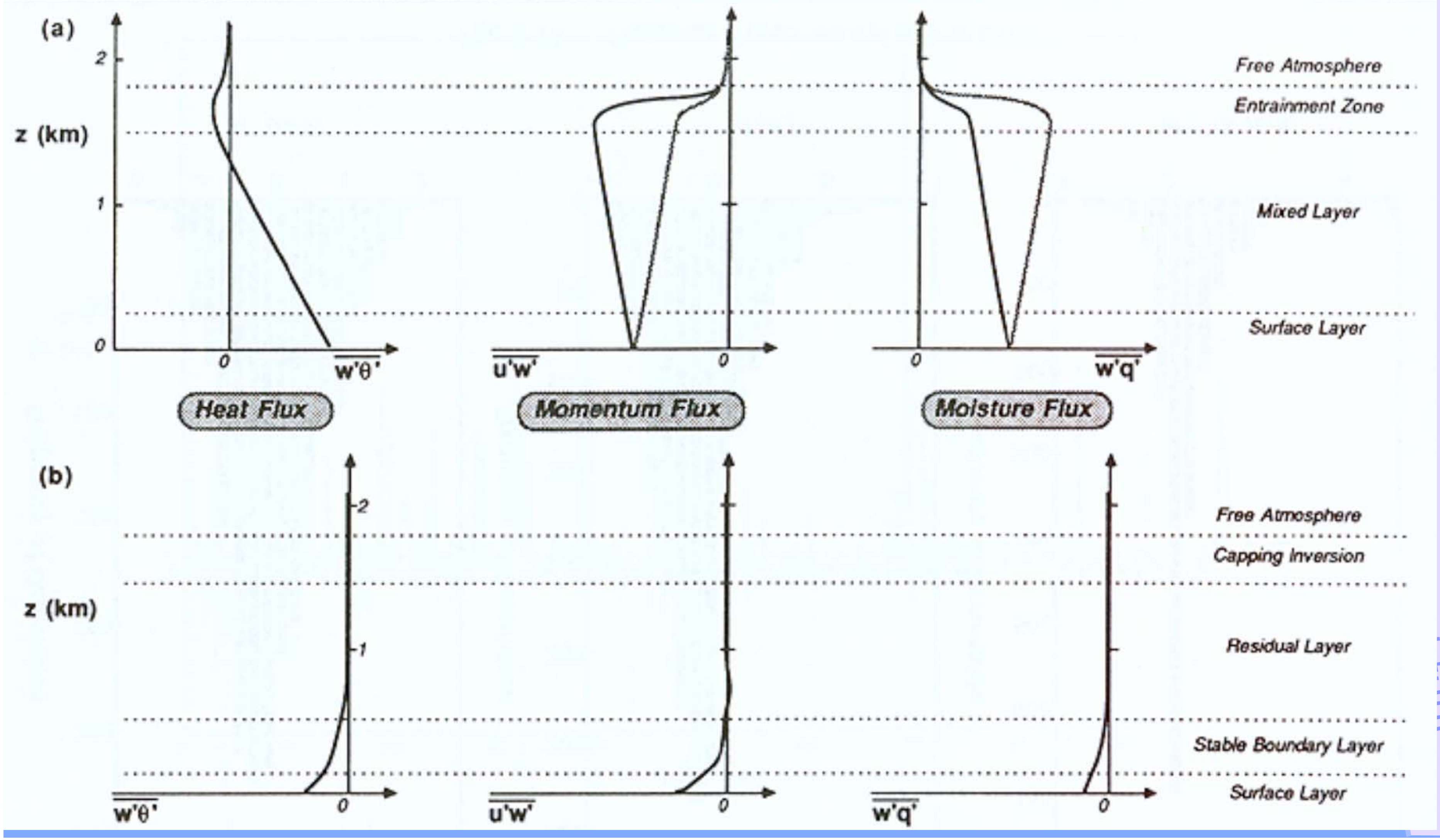
Turbulence

- Flux profiles:



Vertical diffusion schemes

- How to calculate the flux from the model profile, that represents average conditions -> vertical diffusion scheme.
- Options: 1st order, 2nd order or 3rd order. Order dependent on where closure for new parameter (flux) is put.
- First order: flux calculated directly from profiles of wind and temperature
- Second order: flux dependent on another extra parameter: Turbulent Kinetic Energy (TKE). Closure in description of parameters determining TKE

Vertical diffusion schemes

- Higher (third) order: TKE dependent on production and destruction terms. Production and destruction are calculated explicitly. Closure in parameters determining production and destruction. Other correlation terms are taken into account

Vertical diffusion schemes

- First order scheme (local):

$$\overline{w'\theta'} = -K_h \frac{\partial \overline{\theta}}{\partial z}$$

- Combination of eddy diffusion coefficient and gradient in average potential temperature

$$K_h = l_h^2 S F_h(Ri)$$ Louis et al, 1982

- l_h: length scale; S: shear; F_h function dependent on Richardson number
- First scheme in HIRLAM

Vertical diffusion schemes

- First order scheme (non-local, K-profile):

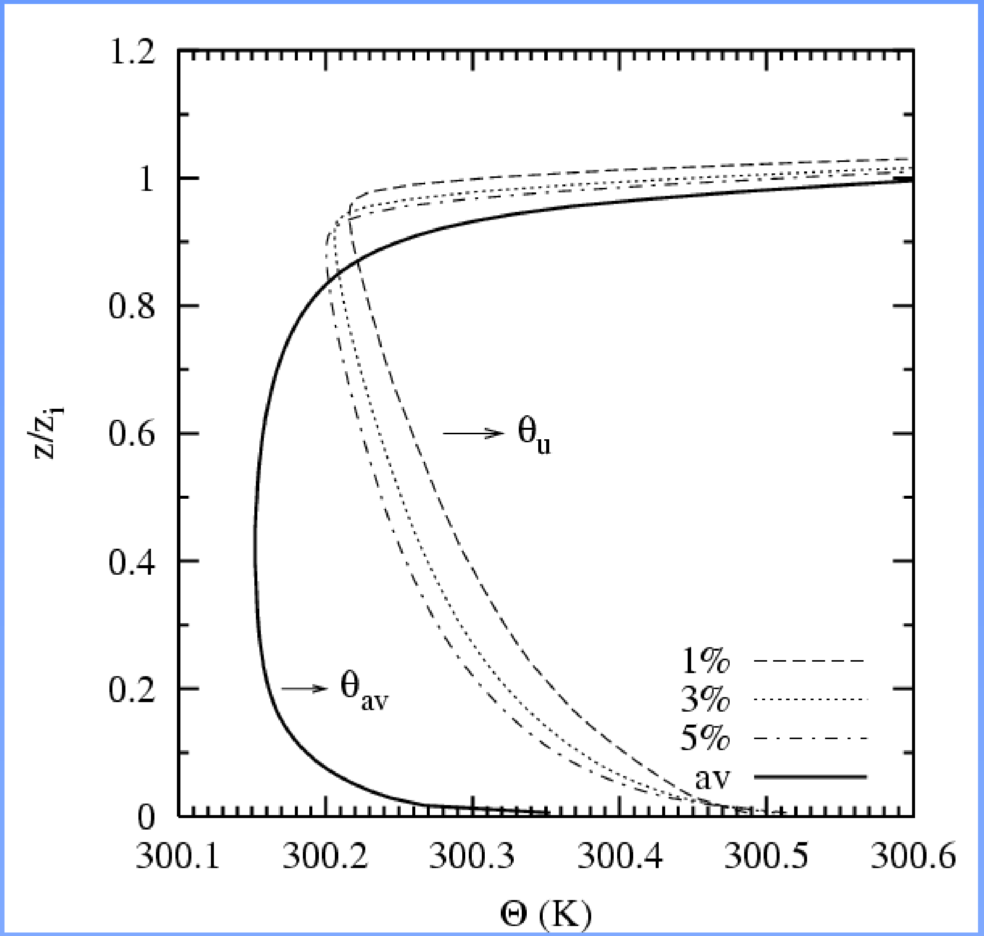
$$\overline{w'\theta'} = -K_h \frac{\partial \bar{\theta}}{\partial z} + \overline{w'\theta'}_{NL}$$

- Similar to local scheme, with addition of non-local flux term to take counter gradient flux into account

$$K_h = k w_t z \left(1 - \frac{z}{h}\right)^2$$ Troen and Mahrt, 1986

- z: height, h: boundary layer height, w_t: turbulent velocity velocity scale

Non-local flux



Potential temperature profiles in boundary layer eddies, average and in strongest ..% of updrafts (from LES)

Vertical diffusion schemes

- Non-local flux part:

$$\overline{w'\theta'}_{NL} = K_h a \frac{w_* \left(\overline{w'\theta'}\right)_0}{w_m^2 h}$$ Holtslag and Boville, 1993

- Non-local part gives fluxes that are caused by the strongest eddies in boundary layer.
- Non-local scheme works due to smart choice of profile of $K_{h,}$ strongly dependent on boundary layer height!
- Second scheme in HIRLAM

TKE-schemes

- TKE: Turbulent kinetic energy, measure for amount of turbulence (and mixing) in atmosphere
  - Strong correlation with transport in atmosphere
  - TKE-tendency important. TKE decreasing-> boundary layer becoming less turbulent. TKE increasing-> boundary layer bcoming more turbulent.
  - Different processes that produce and destroy TKE
- Definition TKE:

$$\frac{TKE}{m} = \bar{e} = 0.5\left(u'^2 + v'^2 + w'^2\right)$$

TKE (2)

- TKE tendency equation:

$$\frac{\partial \bar{e}}{\partial t} = -\bar{u}\frac{\partial \bar{e}}{\partial x} + \frac{g}{\theta_v}\left(\overline{w'\theta'}\right) - \overline{u'w'}\frac{\partial \bar{u}}{\partial z} - \frac{\partial \overline{w'e'}}{\partial z} - \frac{1}{\bar{\rho}}\frac{\partial \left(\overline{w'p'}\right)}{\partial z} - \varepsilon$$

1 2 3 4 5 6 7

- 1: local change of TKE
- 2: advection of TKE
- 3: buoyancy production/destruction
- 4: shear production
- 5: vertical diffusion of TKE

TKE (3)

- TKE tendency equation:

$$\frac{\partial \bar{e}}{\partial t} = -\bar{u}\frac{\partial \bar{e}}{\partial x} + \frac{g}{\theta_v}\left(\overline{w'\theta'}\right) - \overline{u'w'}\frac{\partial \bar{u}}{\partial z} - \frac{\partial \overline{w'e'}}{\partial z} - \frac{1}{\bar{\rho}}\frac{\partial \left(\overline{w'p'}\right)}{\partial z} - \varepsilon$$

1 2 3 4 5 6 7

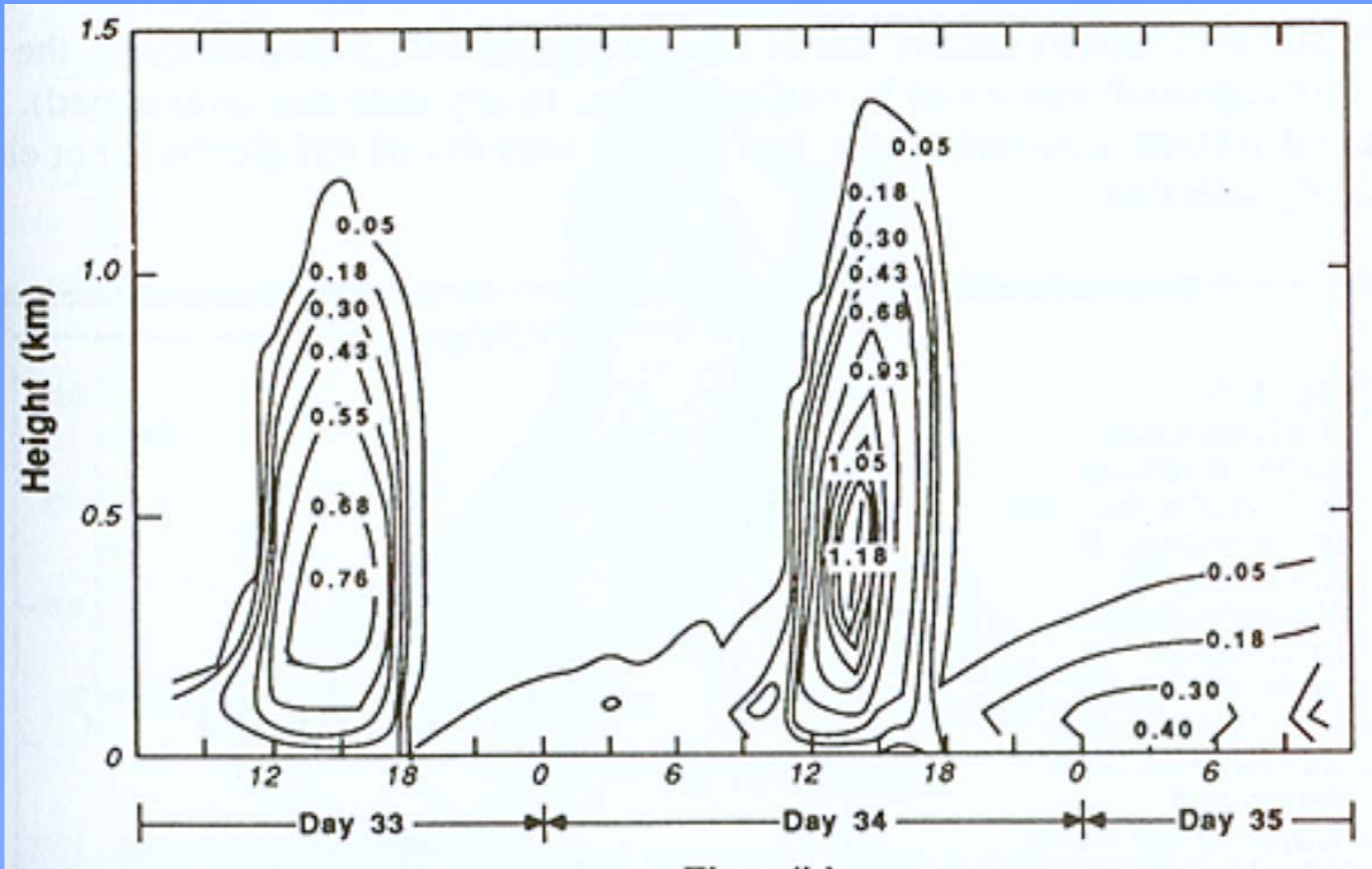
6: pressure-correlation

7: dissipation

- Equation describes all sources and sinks of TKE:

TKE (4)

- 1: TKE during the day: $\frac{\partial \bar{e}}{\partial t}$



HIRLAM vertical diffusion scheme

- CBR: Cuxart, Bougeault and Redelsperger (2000)
- In TKE scheme flux is calculated through:

$$w'\theta' = -K \frac{\partial \theta}{\partial z}$$

- The eddy diffusion coefficient is given by:

$$K = l\sqrt{e}$$

- The diffusion therefore is a function of the TKE, a length scale and the gradient of the parameter that is diffused
- Mixing very sensitive to TKE and l in stable conditions

HIRLAM vertical diffusion scheme

KNMI

- Length scale in eddy diffusion coefficient:

$$\frac{1}{l_{m,h}} = \frac{1}{\max(l_{\text{int}}, l_{\min})} + \frac{1}{l_s}$$

- Minimum length scale:

$$\frac{1}{l_{\min}} = \frac{1}{l_{\lim}} + \frac{1}{c_n \kappa z}$$

- Stable length scale:

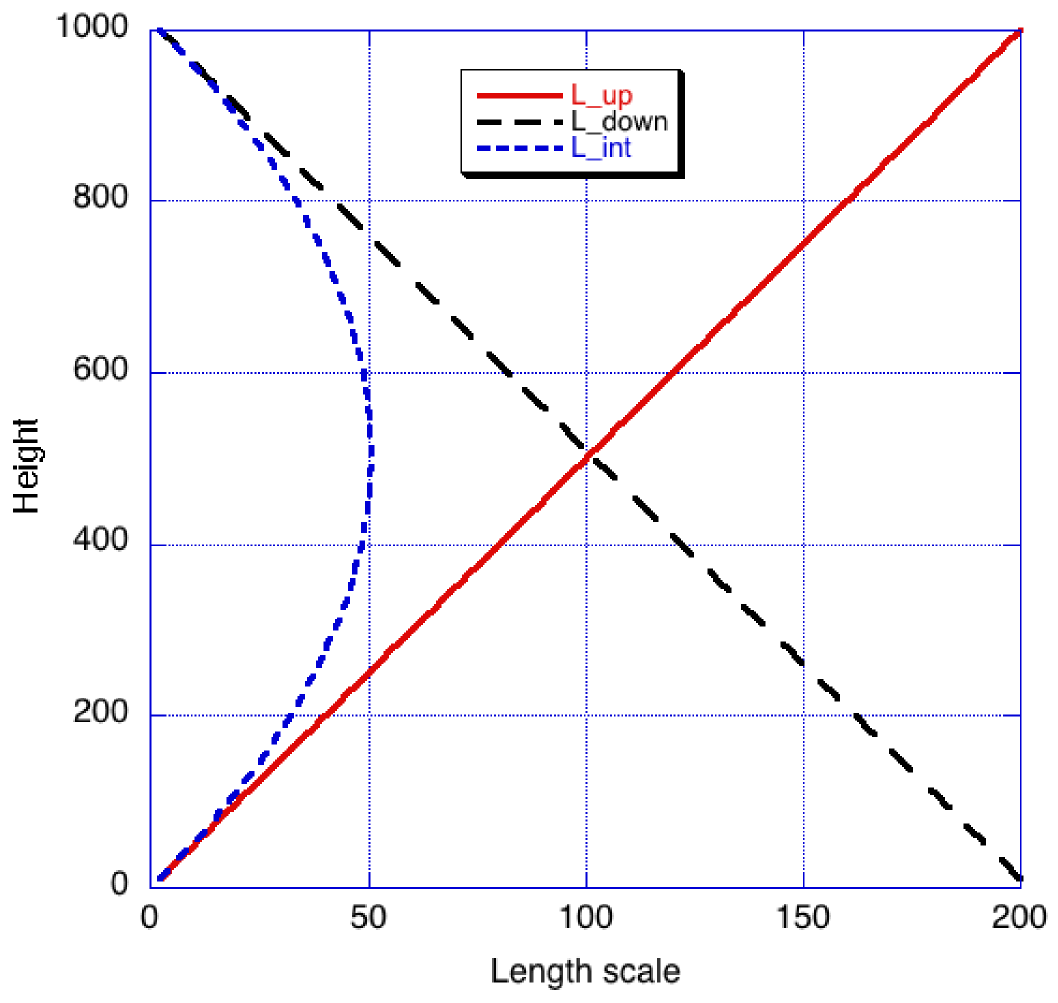
$$\frac{1}{l_s} = c_{m,h} \frac{\sqrt{e}}{N}$$

HIRLAM vertical diffusion scheme

- Integral length scale

$$\frac{1}{l_{\text{int}}} = \frac{1}{l_{up}} + \frac{1}{l_{down}}$$

with $l_{up}(z)$ integral from surface to z of stability F(N), similar for l_{down}

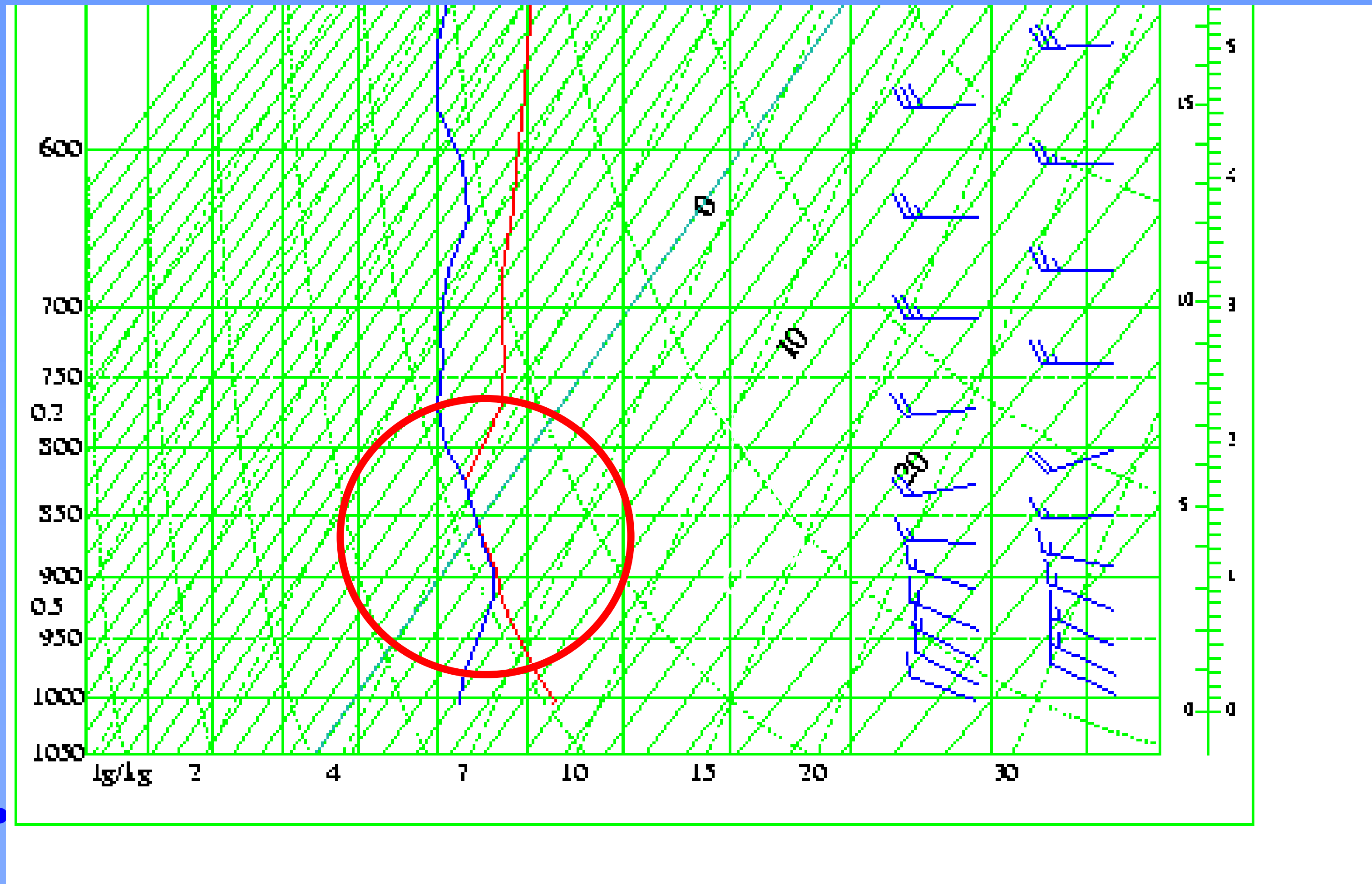


Moist conservative parameter

- Until HIRLAM 7.2 stability in vertical diffusion scheme dependent on dry potential temperature
- Can lead to dry adiabatic profile in saturated environment (stratiform clouds) with cooling at cloud top
- Convection parameterization taking over where there should only be large scale clouds
- Use of liquid potential temperature leads to more mixing in moist conditions such as stratus, stratocumulus and fog

Moist conservative parameter

- Dry unstable profile in moist conditions



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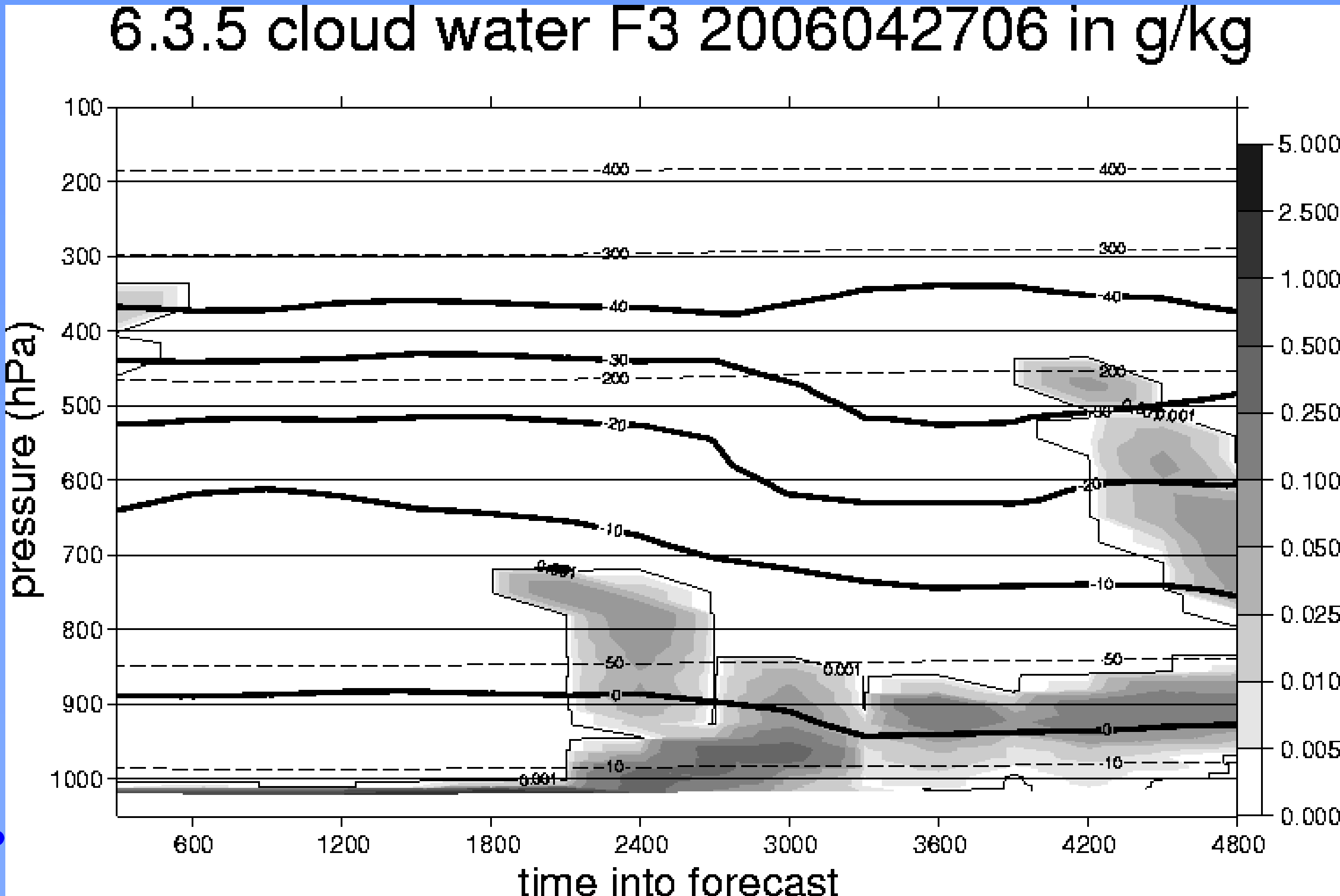
Moist conservative parameter

KNMI

- Mixing to the surface of cloud water



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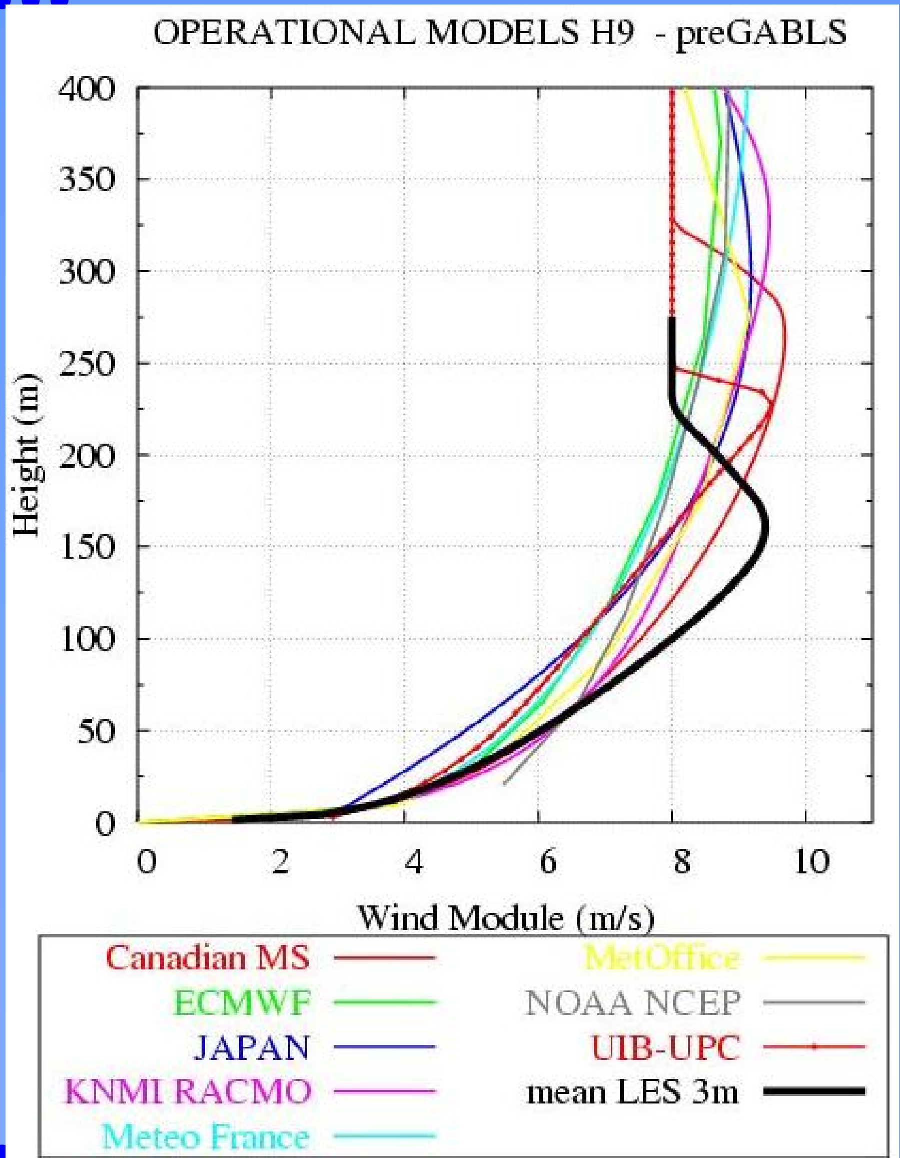


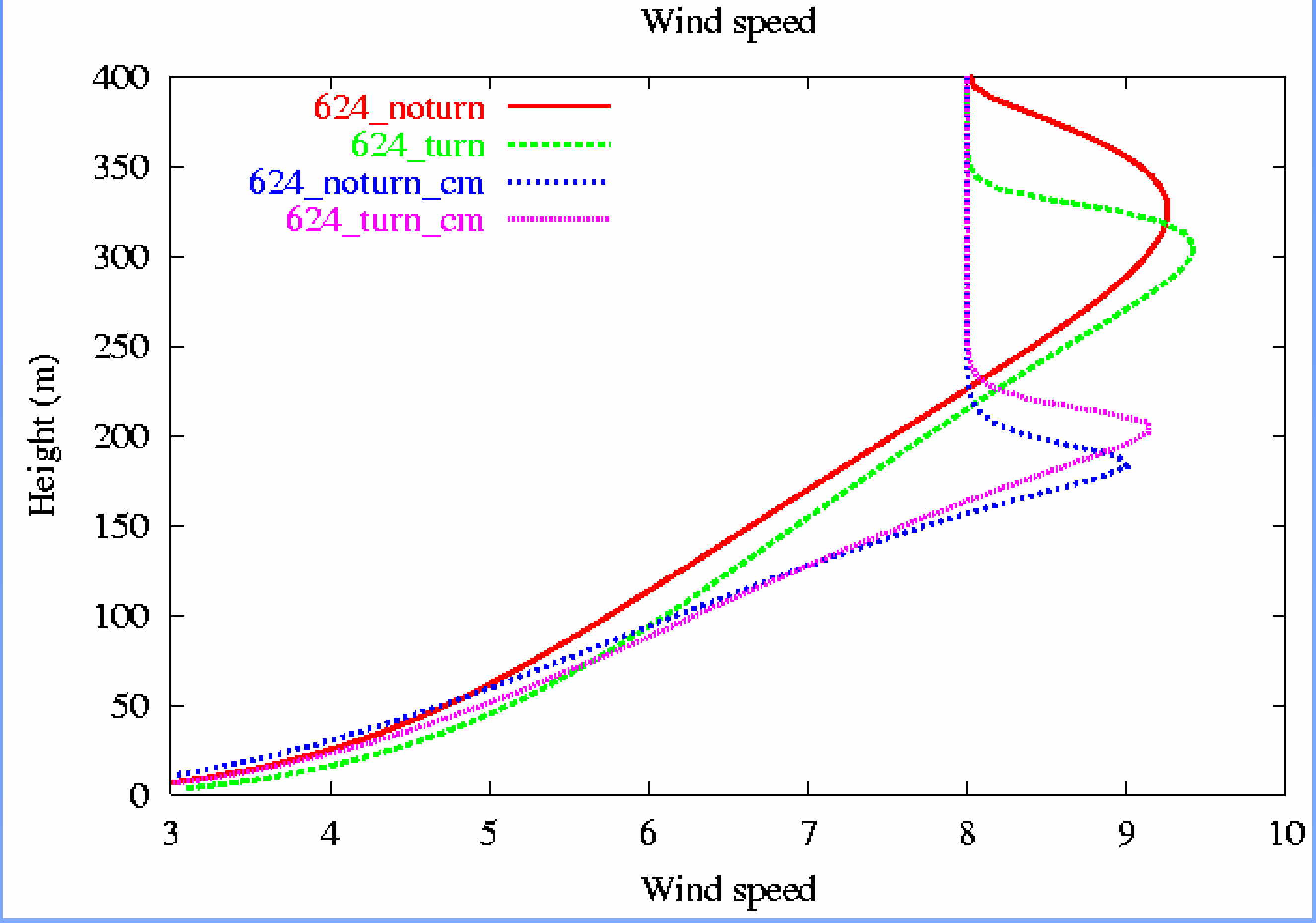
Intercomparison (GABLS 1) shows weaknesses of models: too much mixing in stable conditions

Conclusions GABLSI

- None of the operational models was able to describe wind profile properly
- Stable boundary layer too thick
- Cooling over too thick layer, too much energy taken out from the atmosphere
- Windmaximum at too high level in atmosphere (steady state experiment, impact on max wind speed small)
- Increase in wind and temperature close to the surface too small, wind near surface too strong

HIRLAM before and after GABLSI

extra tuning necessary for good synoptic behaviour



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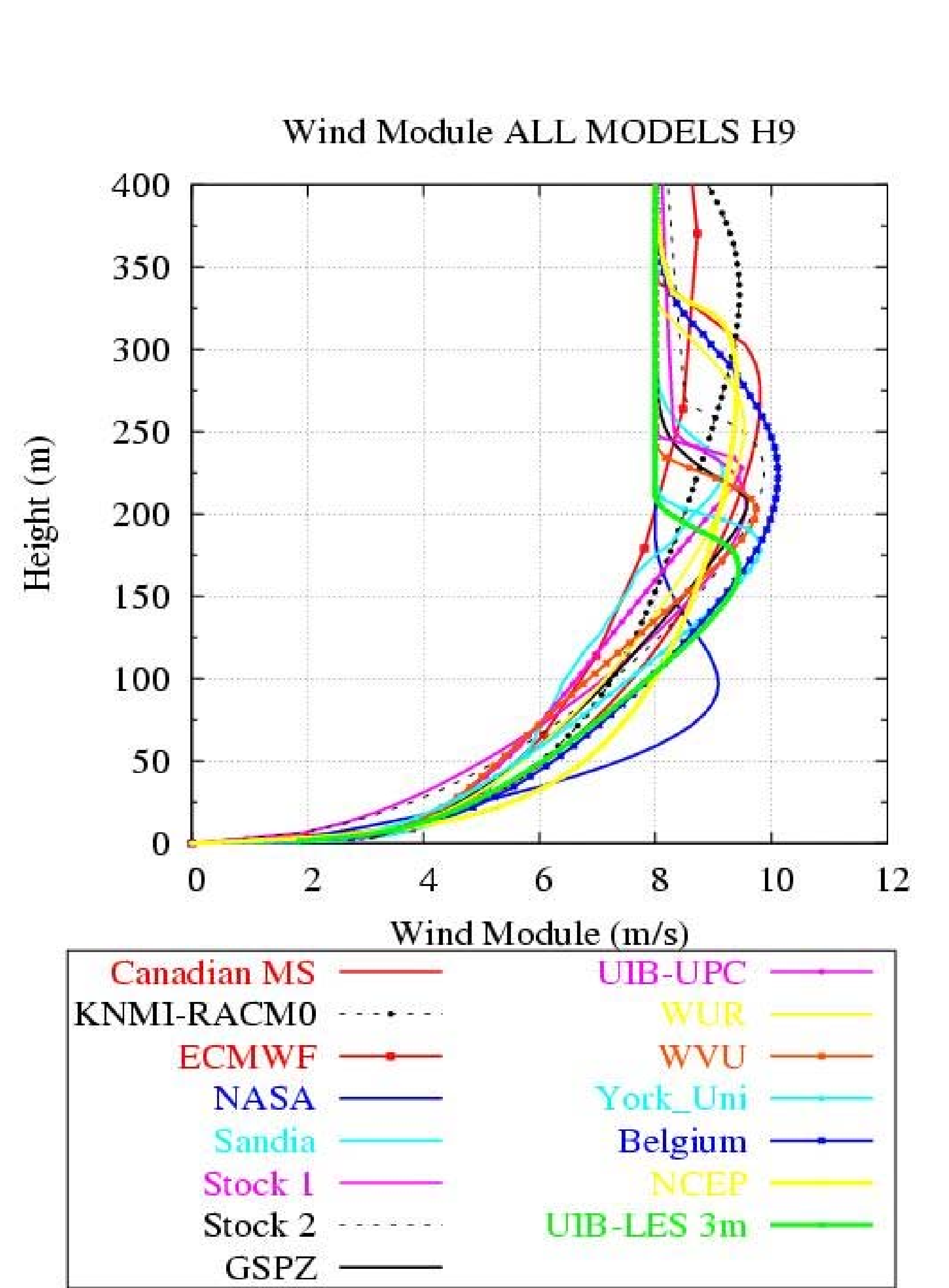
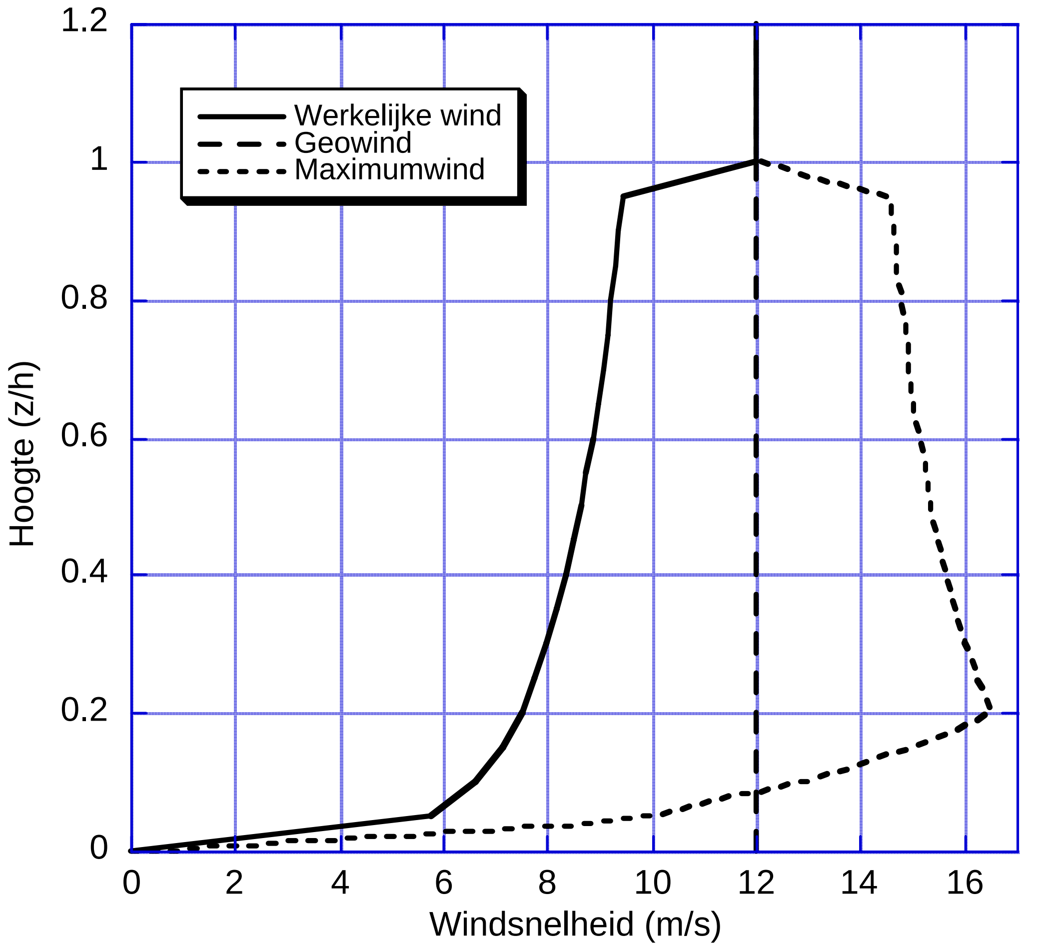


Same case, but after intercom-parison of GABLSI

Low level jet



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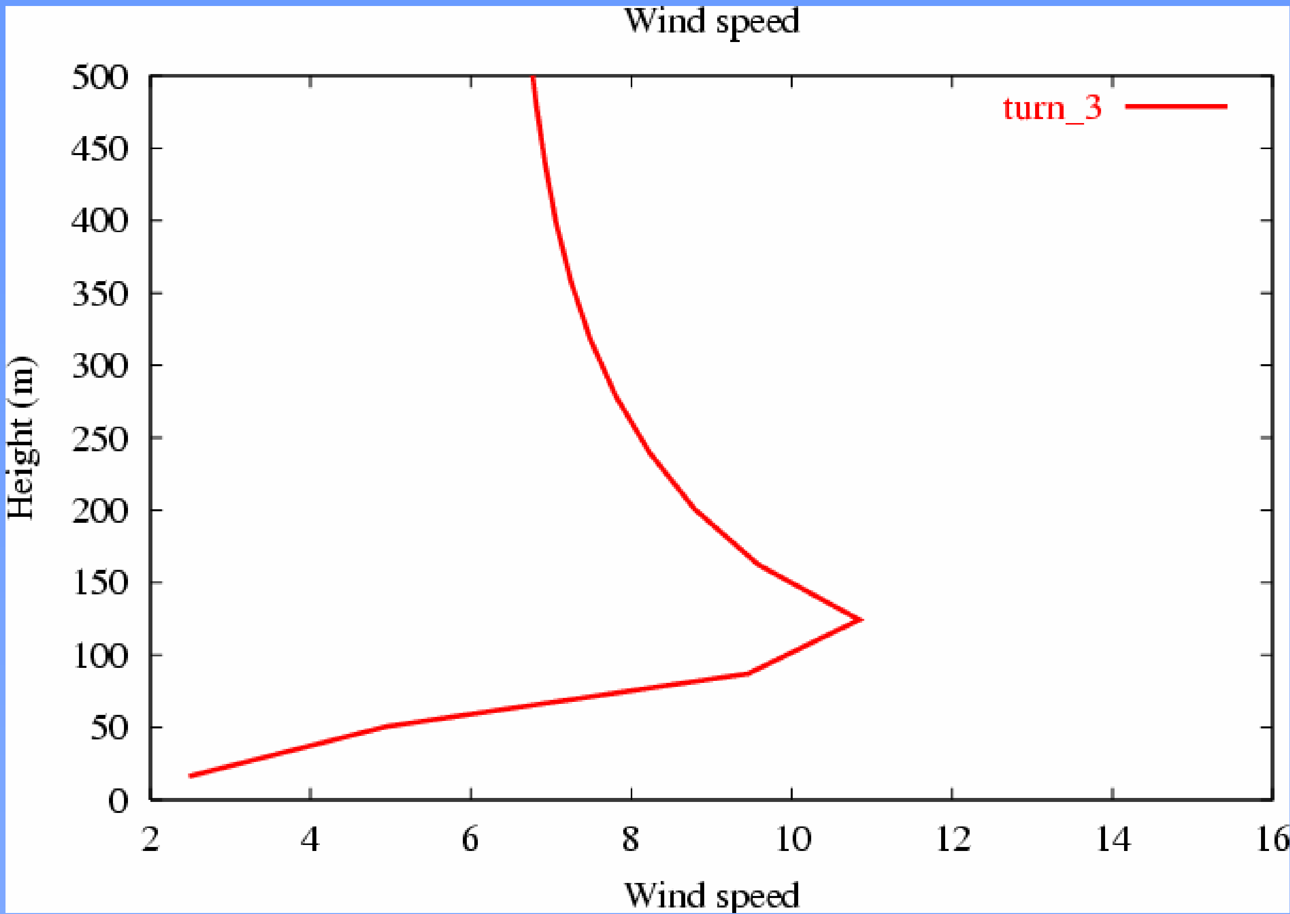
Low level jet



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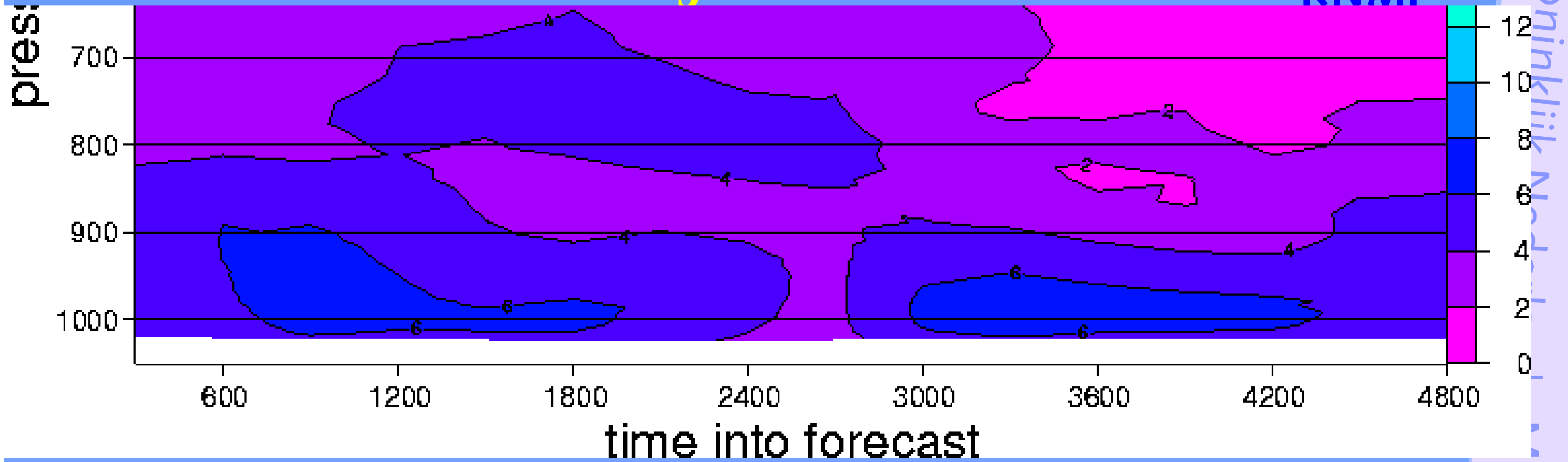
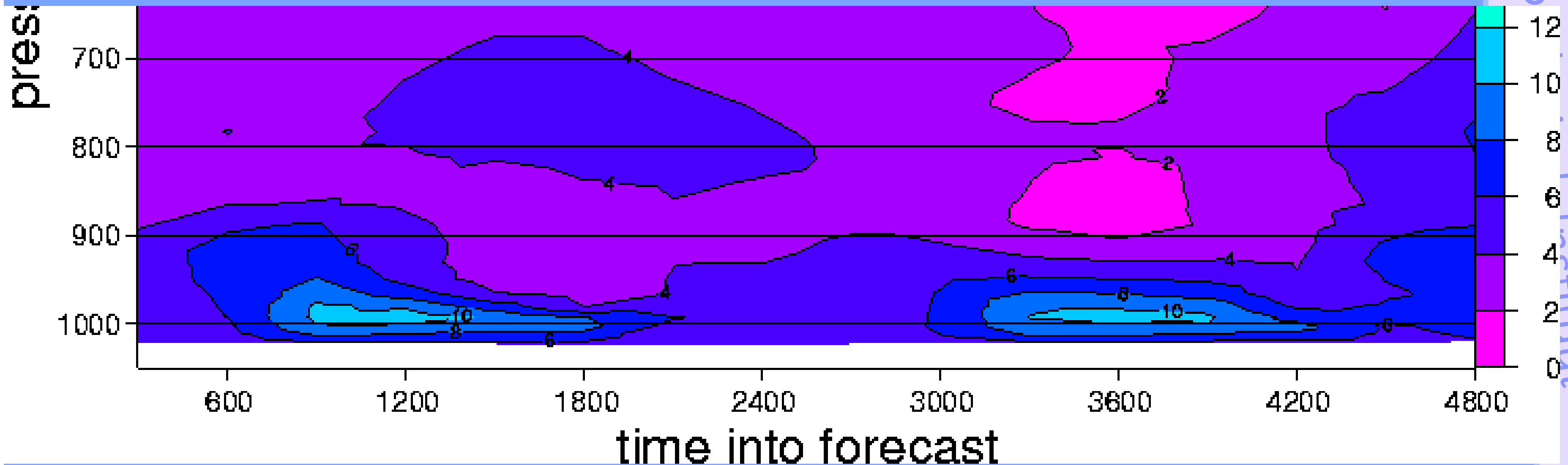
•••• Low level jet in HIRLAM



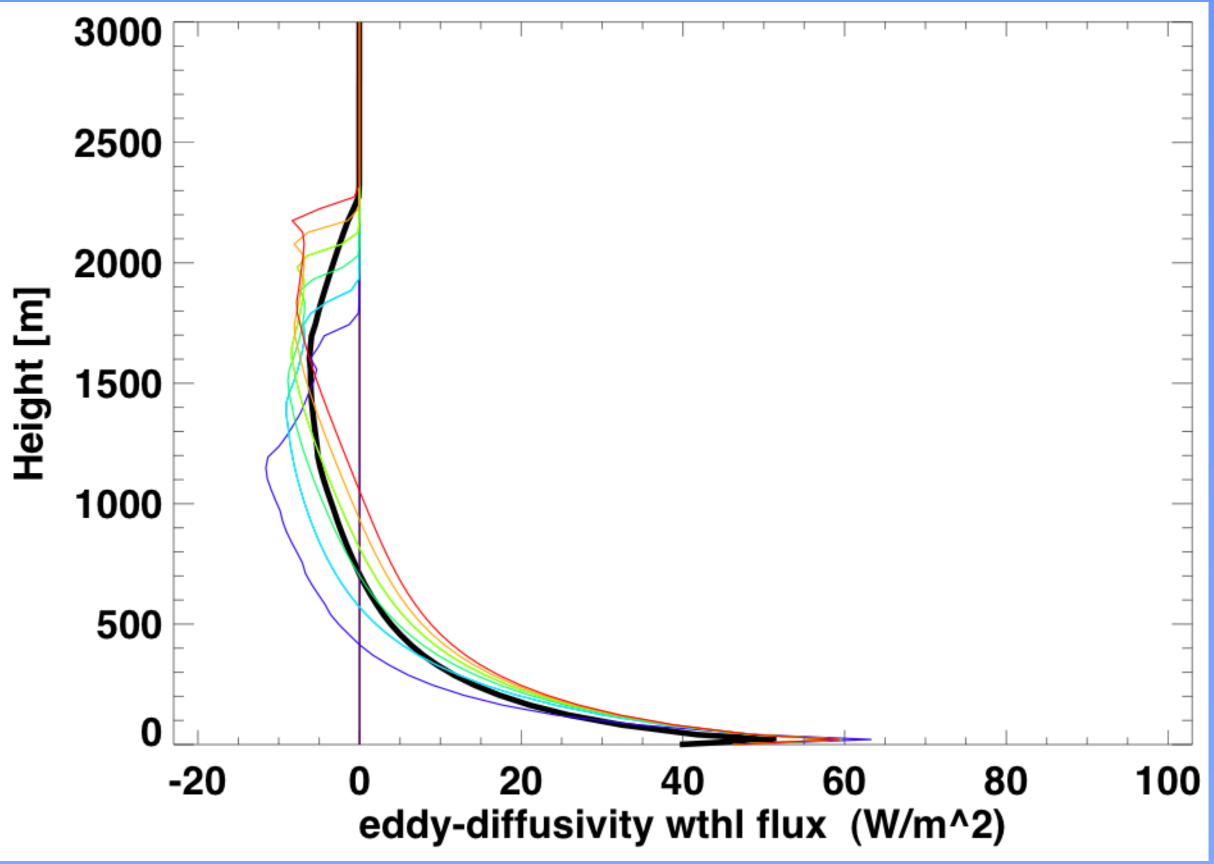
6.2.4 (before 2005) 6.3.5 (2005-now)



New development: EDMF

- Eddy diffusion mass flux scheme
- Mass flux describes transport due to strongest eddies
- Eddy diffusion scheme describes local transport caused by smaller eddies
- Mass flux scheme can also handle shallow moist convection, cumulus clouds etc. No additional scheme necessary for shallow convection, natural connection between boundary layer and shallow convection
- Mass flux scheme describes non-local transport, relatively large transport with slightly stable profile.
- PBL-scheme for HARMONIE, maybe also for HIRLAM.

Dry CBL: ED



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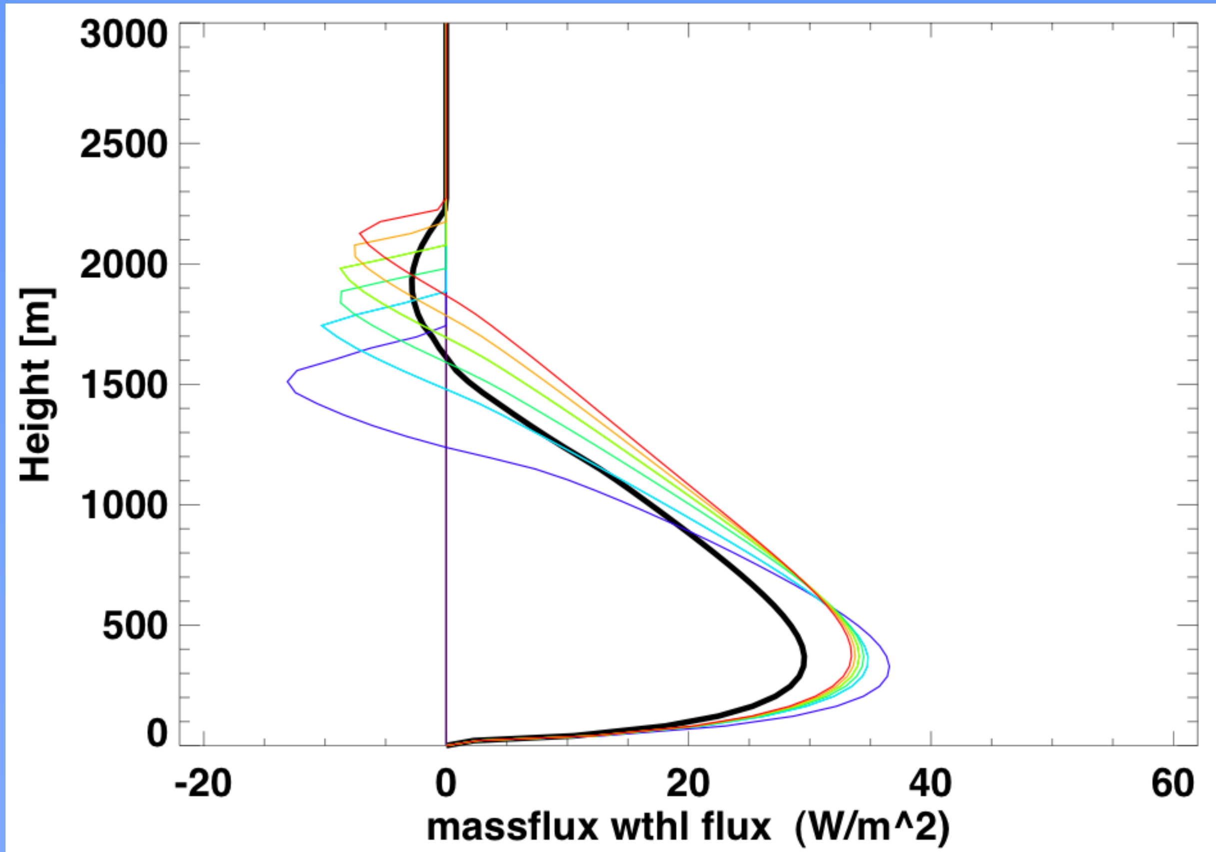
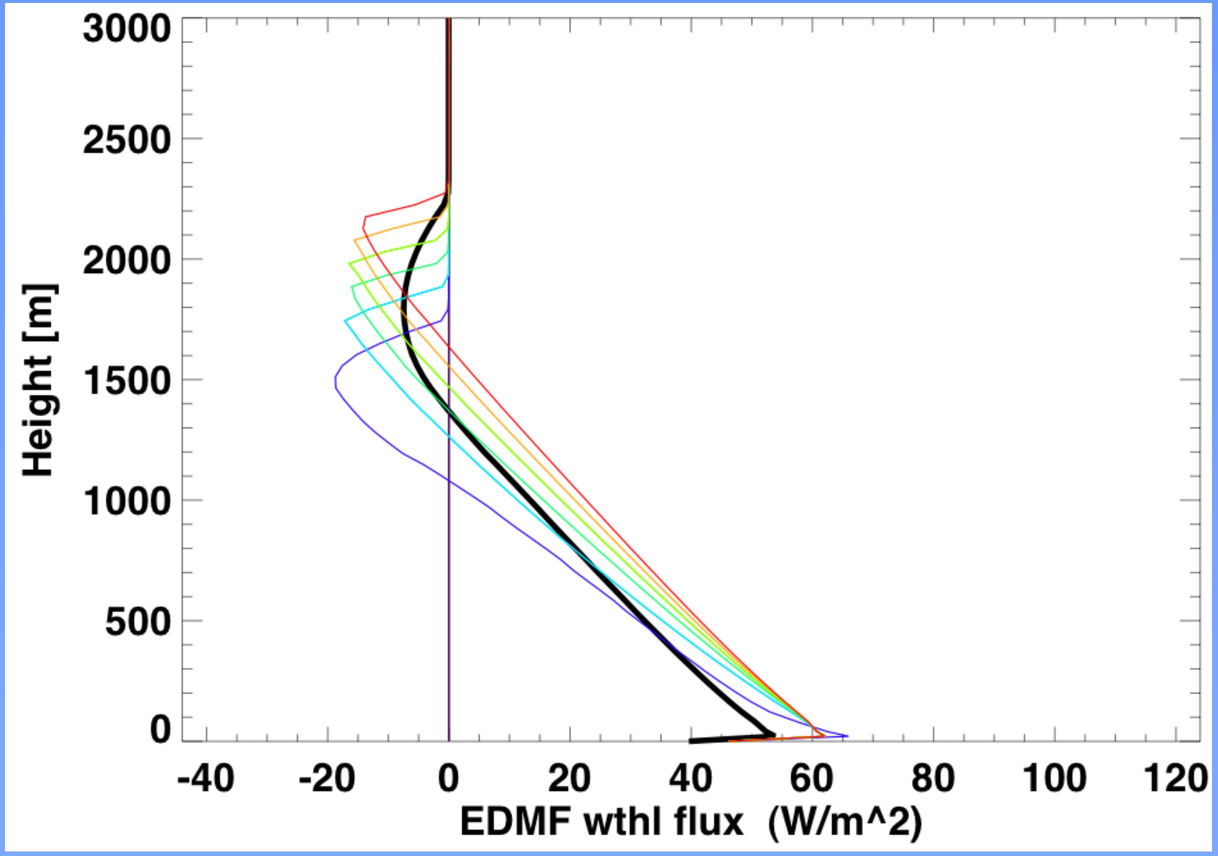
Dry CBL: MF



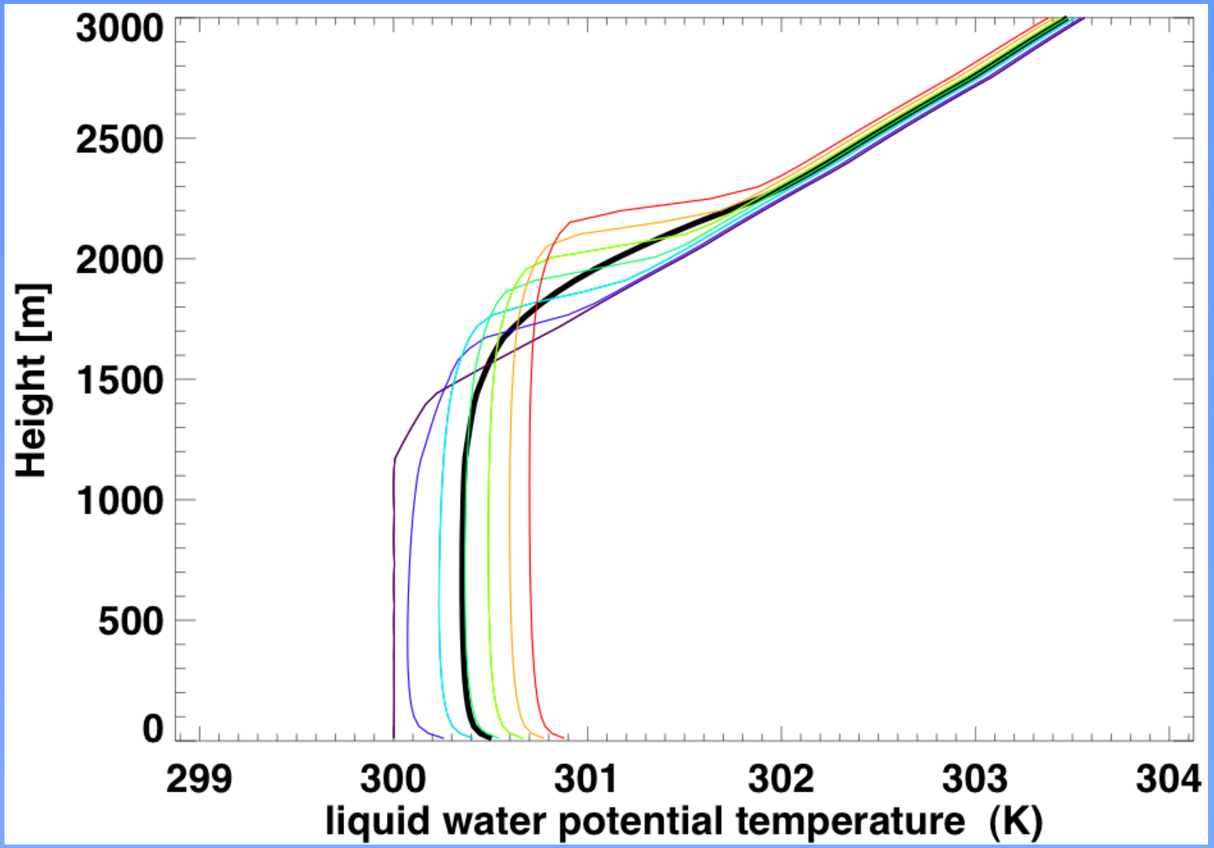
3000
2500
2000
1500
1000
500
0
Height [m]
-20
0
20
40
60
massflux wthl flux (W/m^2)

Dry CBL



3000
2500
2000
1500
1000
500
0
Height [m]
-40
-20
0
20
40
60
80
100
120
EDMF wthl flux (W/m^2)

•••• Dry CBL: T-prof



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HIRLAM vertical diffusion scheme

- CBR: Cuxart, Bougeault and Redelsperger (2000)

$$-\left[u'w'\frac{\partial u}{\partial z}+v'w'\frac{\partial v}{\partial z}\right]=K_m\left[\frac{\partial^2 u}{\partial z^2}+\frac{\partial^2 v}{\partial z^2}\right]$$

$$\frac{g}{\theta_v}\overline{w'\theta_v'}=-K_h\frac{g}{\theta_v}\frac{\partial\theta_v}{\partial z}$$

$$-\frac{\partial\overline{w'e'}}{\partial z}-\frac{1}{\overline{\rho}}\frac{\partial\left(\overline{w'p'}\right)}{\partial z}=2K_m\frac{\partial\bar{e}}{\partial z}$$

$$\varepsilon=c_d\frac{\left(\bar{e}\right)^{3/2}}{l_m}$$