# CLOUDS AND CONDENSATION

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**based on notes of**
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## CONTENTS:

A list of wishes

Introduction

- Processes influencing formation of precipitation
- Variables and processes in models of different scales

Main features of the present HIRLAM cloud scheme

- Development of hydrometeors and cloud cover
- Vapour, cloud condensate and precipitation
- Ice or water, convective or stratiform
- Cloud variables and processes in HIRLAM

## Equations and parametrizations

- `Condensation`
- `Precipitation`
- `Evaporation`
- `Cloud cover`

## Developments in cloud parametrizations of HIRLAM

# A LIST OF WISHES: What should the cloud scheme provide us with?

1.
2.
3.
4.
5.
6.
7.
8.

# What should the cloud scheme provide us with? - My opinion

1. Precipitation
    - amount
    - intensity
    - snow/rain/...
    - convective/stratiform?
2. Clouds
    - cloudiness
    - condensate content
    - height (top, base)
    - crystals/droplets
    - size of cloud particles

## 3. Changes of model variables T,q ...

- latent heat
- moisture budget
- cloud-scale circulations

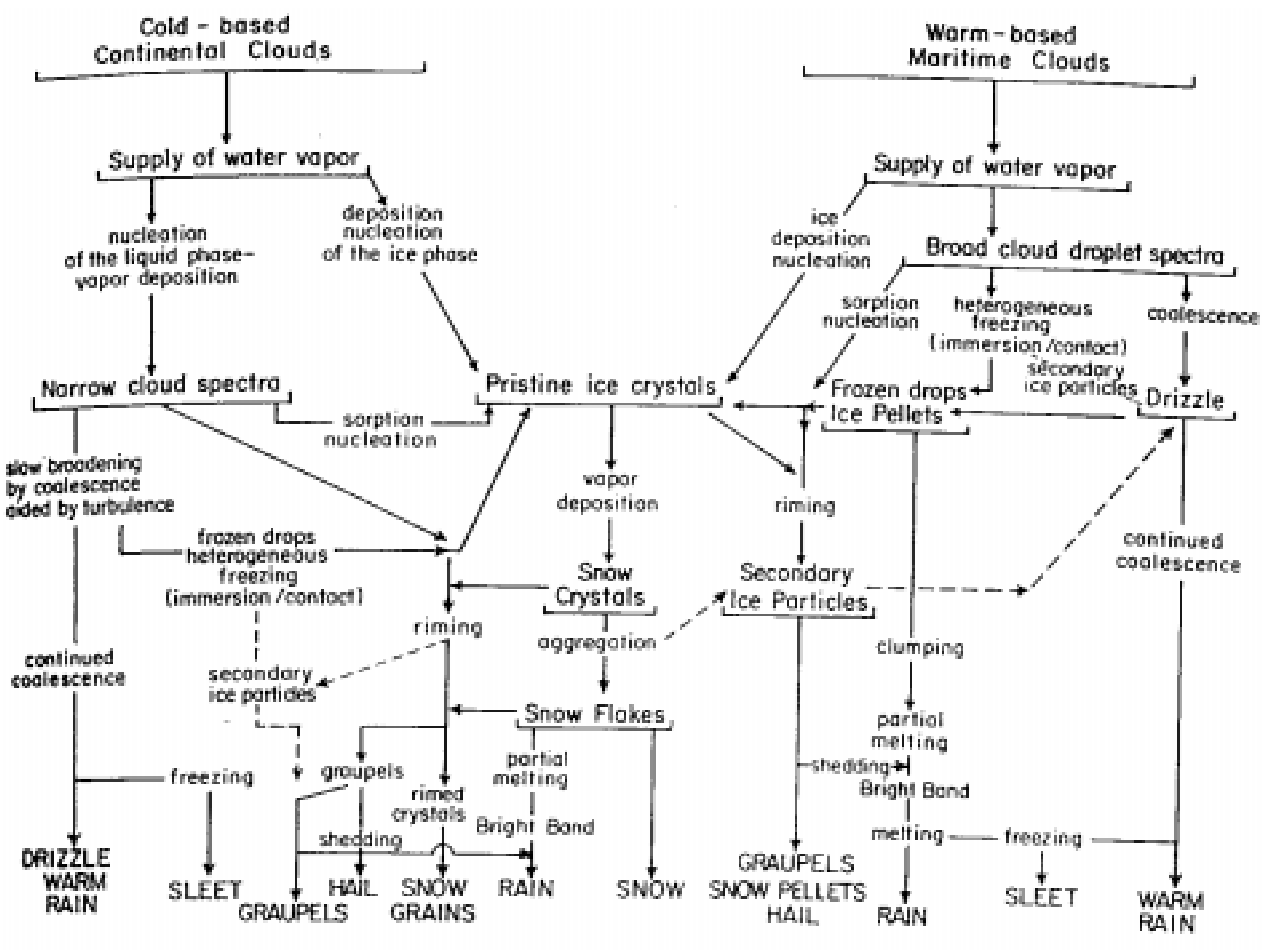


Figure 1: Processes influencing precipitation formation ([Cotton and Anthes (1989)])

## PREDICTED AND DIAGNOSED VARIABLES

### Stratiform/convective condensation

No principal difference in processes, but their relative magnitudes may differ, e.g.

Stratiform ∼ stable, gentle upward motion
⇒ vapour deposition more important

Convective ∼ unstable, strong vertical circulations
⇒ collection of cloud droplets more important

Microphysical processes related to clouds and condensation need to be parametrized in all atmospheric models, but higher resolution models calculate more variables explicitly:

# PREDICTED AND DIAGNOSED VARIABLES

Table 1: Cloud variables in different models

| **Variable** | **GCM**<br>$\approx 300km$ | **HIRLAM**<br>$\approx 30km$ | **Cloud model** [a]<br>$\approx 1km$ |
|---|---|---|---|
| condensate | P | M | |
| droplet | D | D | M |
| crystal | D | D | M |
| precipitation | P | P | |
| rain | D | D | M |
| snow | D | D | M |
| cloud cover | D | D | not needed |
| cloud particle size | | | |
| effective radius | D | D | |
| size distribution | | | M |
| aerosol | none | none | M |

Notation: D - diagnosed variable, P - parametrized variable, M - prognostic variable

# PARAMETRIZED AND EXPLICIT PROCESSES

Table 2: Condensation processes in different models

| Process | GCM<br>$\approx 300km$ | HIRLAM<br>$\approx 30km$ | Cloud model<br>$\approx 1km$ |
|---|---|---|---|
| nucleation | none | none | P |
| growth of cloud particles | none | E | E |
| formation of precipitation | P | P | E |
| melting/evaporation of cloud particles | none | E | E |
| melting/evaporation of precipitation | none | P | E |

Notation: P - parametrized, E - explicitly calculated.

# DEVELOPMENT OF HYDROMETEORS AND CLOUD COVER

**Development of hydrometeors**

governed by

**MICROPHYSICAL PROCESSES**

**Development of cloud cover**

governed by

**HUMIDITY** and **AIR MOTION**

due to

**subgrid-scale release of latent heat**

**large-scale background circulation**

N.B. Scale dependence of definitions!

Two widely separated regimes connected by non-linear relations

# VAPOUR, CLOUD CONDENSATE AND PRECIPITATION

## MICROPHYSICAL PROCESSES

How to partition

Produced condensate

between

CLOUD WATER

and

PRECIPITATING WATER?

## SUBGRID-SCALE CIRCULATIONS

How to partition

Water vapour

between

CONDENSATION

and

MOISTURE CHANGES

in the cloud-free parts of the gridbox?

## MICROPHYSICAL PROCESSES

Different descriptions for

liquid & mixed phase conditions

and

ice phase conditions

because of differences in mechanisms

## SUBGRID-SCALE CIRCULATIONS

different descriptions for

convective condensation

and

stratiform condensation

because of differences in energy conversions

# CLOUD VARIABLES AND PROCESSES IN HIRLAM

**Prognostic variable: Grid volume total cloud condensate content**

**Diagnosed variables:**

- **cloud cover: stratiform and convective**
- **phase of cloud and precipitation particles: ice and water**

**Explicitly calculated:**

- **Condensation**
- **Evaporation of cloud particles**

**Parametrized processes:**

**Formation of precipitation**

- **Vapour deposition**
- **Collection of cloud droplets**
- **Bergeron-Findeisen mechanism**

**Changes of precipitation**

- **Evaporation**
- **Melting**

# CONDENSATION

**Assumption**: abundance of condensation nuclei allows condensation at **100 % relative humidity**: $U = U_s = 1$. In a volume filled with condensation (= in cloud, with $\sim$ - symbol) the equations for the change of temperature $\tilde{T}$, specific humidity $\tilde{q}$ and cloud condensate $\tilde{m}$ are:

$$\frac{\partial \tilde{T}}{\partial t} = A_{\tilde{T}} + \frac{L}{c_p}\tilde{Q} \tag{1}$$

$$\frac{\partial \tilde{q}}{\partial t} = A_{\tilde{q}} - \tilde{Q} \tag{2}$$

$$\frac{\partial \tilde{m}}{\partial t} = A_{\tilde{m}} + \tilde{Q} - \tilde{G}_p \tag{3}$$

where

$A_\alpha$ contains all tendencies expect those from condensation

$\tilde{Q}$ is the rate of release of latent heat (=production of condensate)

$\tilde{G}_p$ is the rate of release of precipitation.

In cloud air is assumed saturated:

$$\tilde{q} = q_s(\tilde{T}) \tag{4}$$

Using definition of vapour pressure and Clausius-Clapeyron equation we can now derive condensation $\tilde{Q}$ from Equations (1-4):

$$\tilde{Q} = \frac{A_{\tilde{q}} - \frac{L}{c_p} S_q A_{\tilde{T}} + \frac{\tilde{q}}{p}\frac{\partial p}{\partial t}}{1 + S_q}, \tag{5}$$

where $S_q = \frac{L}{c_p} q_s \frac{1}{E_s} \frac{\mathrm{dE_s}}{\mathrm{d\tilde{T}}} = \frac{\epsilon L^2 q_s}{R c_p \tilde{T}^2}$

# PRECIPITATION

Rate of precipitation $\equiv$ flux of water

$$\rho_w \tilde{M}_r V_{\tilde{M}} = \tilde{P} \tag{6}$$

where $\rho_w$ is the density of water, $\tilde{M}_r$ is the mass of precipitating water and $V_{\tilde{M}}$ is the terminal velocity of the falling drops

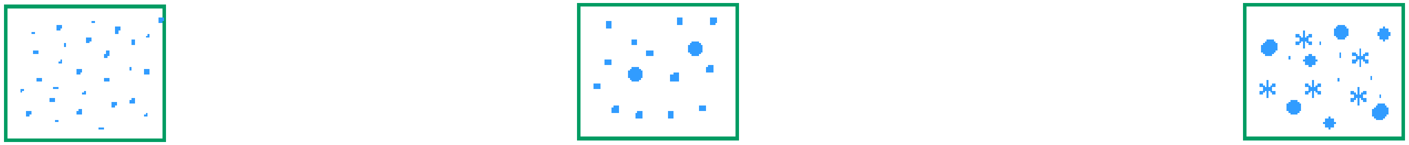
Rate of release of precipitation

$$\tilde{G}_p = C\tilde{m}[1 - e^{-(\frac{\tilde{m}}{m_r})^2}] \tag{7}$$

where $m_r$ is the critical cloud condensate amount needed for precipitation forming processes to start.

and

$$C = \underbrace{C_{00}}_{\text{autoconversion}} \quad \underbrace{+C_c}_{\text{coalescence}} \quad \underbrace{+C_{BF}}_{\text{Bergeron-Findeisen}}$$



## Autoconversion

$$C_{00}$$

## Coalescence

$$C_c \tilde{m} \propto \tilde{m} \tilde{M}_r^{\beta} \tag{8}$$

Integration over size spectrum ([Kessler (1969)]) gives $\beta < 1.$ Neglecting (small) variations of $V_{\tilde{M}}$ we adopt

$$C_c = C_1 \sqrt{\tilde{P}} \tag{9}$$

## Bergeron-Findeisen mechanism

$$\Delta e_{wi} = e_{swv} - e_{siv} > 0 \tag{10}$$

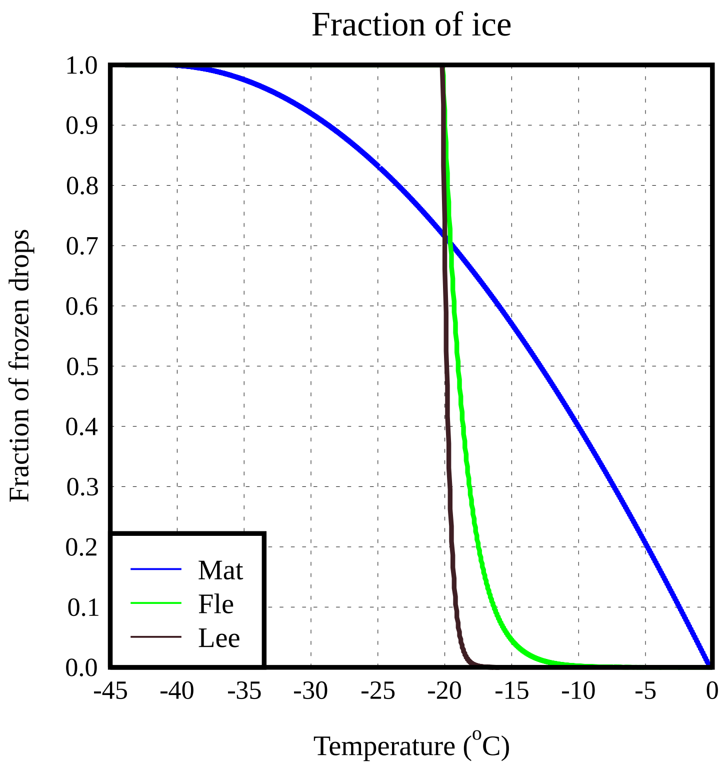
There are ice crystals and supercooled liquid water droplets.

Consider ice crystal probability of **cloud water**

$$0|_{T=273K} \leq f_{ice} \leq 1|_{T=233K} \tag{11}$$

and of **precipitation**

$$f_{ice}^{p} = f_{ice} + (1 - f_{ice})\frac{Snow}{P_{total}} \tag{12}$$



Finally we adopt

$$C_{BF} = C_2 \Delta e_{wi} (1 - f_{ice}) f_{ice}^p \qquad (13)$$

# EVAPORATION

**Cloud water**: small droplets evaporate immediately

**Precipitating hydrometeors**: evaporate slower

$$\tilde{E}_p \propto \tilde{M}_r^{\beta} \tag{14}$$

where $\beta = \frac{13}{20}$ ([Kessler (1969)]).

Adopt for the **rate of evaporation of precipitation**

$$\tilde{E}_p = k_E(U_s - U)\sqrt{\tilde{P}} \tag{15}$$

where $\mathrm{U}$ and $\mathrm{U}_s$ are relative humidity and saturated relative humidity, $\mathrm{k}_E$ is a coefficient of evaporation.

# MELTING

Similarly, for the **rate of melting of precipitation**

$$\tilde{S}_{melt} = k_{melt}(T - T_0)\sqrt{\tilde{P}} \tag{16}$$

where T and $T_0$ are temperature and melting temperature, $k_{melt}$ is a coefficient of melting.

In the model calculations the melting effect can be integrated over the thickness of the layer containing precipitation.

# FRACTIONAL CLOUD COVER

Problem: subgrid-scale condensation $\Leftrightarrow U < U_s$

Basic questions:

1. When may the condensation occur? $U_0 \leq U \leq U_s$
2. How to partition available vapour in gridbox between condensation in clouds and moisture changes in clear parts?

Interplay between resolved-scale circulation and subgrid-scale circulation due to release of latent heat

$\Rightarrow$ Fractional cloudiness

$\Rightarrow$ Gridbox values = weighted means of the subgrid features

# GRIDBOX AVERAGES

$$X = b\tilde{X} + (1-b)X_0 \tag{17}$$

where b is cloud cover, and $\tilde{X}$ is in-cloud value and $X_0$ is the mean value in the clear part.

In particular,

$$U = bU_s + (1-b)U_0 \tag{18}$$

$$m = b\tilde{m} \tag{19}$$

$$G_p = b\tilde{G}_p = Cm[1 - e^{-(\frac{m}{bm_r})^2}] \tag{20}$$

Note that the coalescence term $C_c$ becomes

$$C_c = C_1\sqrt{\frac{P}{b}} \tag{21}$$

# AVERAGED EQUATIONS

Applying averaging to the thermodynamic, moisture and cloud condensate equations (1-3) we obtain

$$\frac{\partial T}{\partial t} = A_T + \frac{L}{c_p} Q \tag{22}$$

$$\frac{\partial q}{\partial t} = A_q - Q \tag{23}$$

$$\frac{\partial m}{\partial t} = A_m + Q - G_p \tag{24}$$

## Net heating

$$Q = b\tilde{Q} + (1 - b)E_v \tag{25}$$

where$E_v$ denotes evaporation in the clear parts of the gridbox.

Important difference!
generally $q < q_s(T)$ since $U < U_s$

$$\Rightarrow$$

$$\frac{\partial q}{\partial t} = \frac{\partial U q_s}{\partial t} = q_s \frac{\partial U}{\partial t} + U \frac{\partial q_s}{\partial t} \tag{26}$$

The net heating in the gridbox can now be derived in the same way as Equation (5)

$$Q = \frac{M_q - q_s \frac{\partial U}{\partial t}}{1 + U S_q}, \tag{27}$$

where

$$M_q = A_q - \frac{c_p}{L} U S_q A_{\tilde{T}} + U q_s \frac{1}{p} \frac{\partial p}{\partial t} \tag{28}$$

For **CLOSURE** of the system we need relations for $\frac{\partial U}{\partial t}$ and $b$

Equation (17) provides an expression for $b$:

$$b = \frac{U - U_0}{U_s - U_0} \tag{29}$$

**if** the subgrid-scale feature $U_0$ **is known.**

Assume, that a fraction $\mathrm{H}_0$ of $\mathrm{M}_q$ is used to change cloud cover and moisture in the clear part of the gridbox:

$$(Q_s - q_0 + \frac{m}{b})\frac{\partial b}{\partial t} + (1-b)\frac{\partial q_0}{\partial t} = H_0 M_q + E_v \tag{30}$$

Relation for $U_0$ → Equation (29) → $\frac{\partial b}{\partial t} \propto \frac{\partial U}{\partial t}$

Relation for $H_0$ → Equation (30) gives $\frac{\partial U}{\partial t}$

**Valid for both stratiform and convective condensation**

# HIRLAM stratiform cloud cover

$$H_0 = 1 - b \tag{31}$$

and

$$U_s - U_0 = (1 - b)(U_s - U_{00}) \tag{32}$$

lead to

$$b = 1 - \sqrt{\frac{U_s - U}{U_s - U_{00}}} \tag{33}$$

where $U_{00}$ is a treshold value for stratiform condensation in the clear parts of the gridbox.

# Cloud cover problems

Fractional cloud cover: a category with strong scale dependence

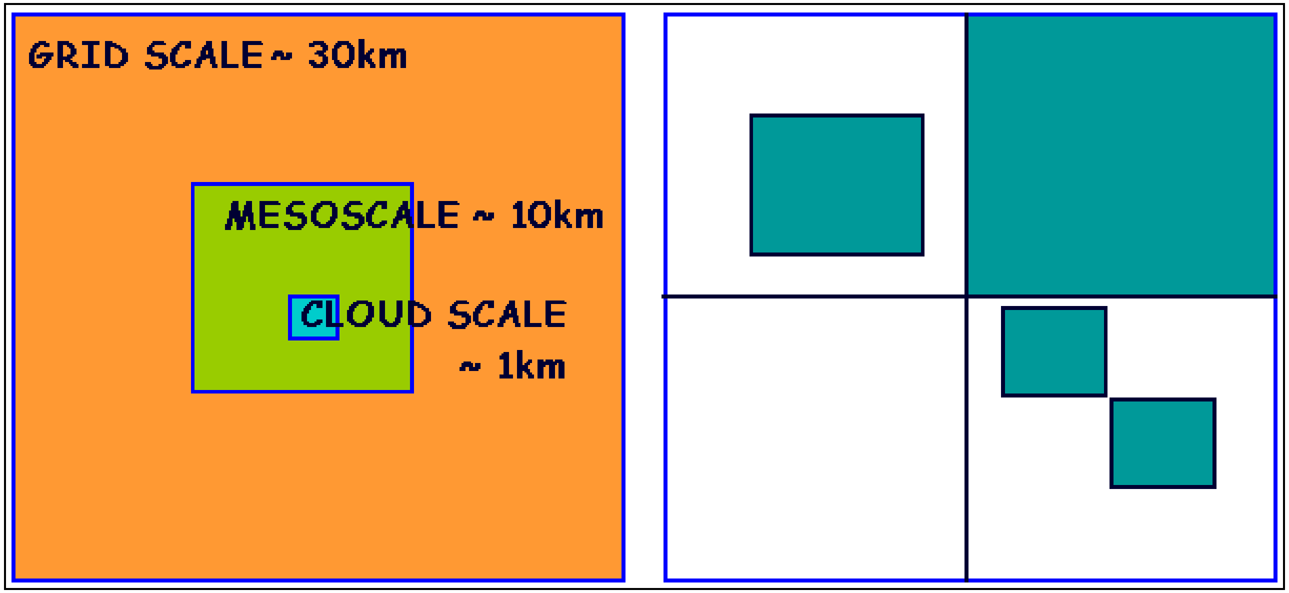


Figure 2: Cloud cover and grid size

- Tuning of $U_{00}$
- Dependence of cloud cover on
  - relative humidity
  - vertical velocity
  - stability
  - convective mass flux

  ([Slingo (1987)])
- Convective cloud cover $\propto$ process of convection $\propto$ convection scheme
- Problems of boundary layer clouds
- Cloud overlapping: random/maximum

# Tuning and validation problems

**Excercise:** Collect all violet variables of the notes and tune them with the help of observations and theory?

| | |
|---|---|
| $m_r$ | treshold m for cloud particles → precipitation particles |
| $C_{00}$ | autoconversion coefficient |
| $C_1$ | coalescence coefficient |
| $C_2$ | Bergeron-Findeisen effect coefficient |
| $k_E$ | evaporation coefficient |
| $k_{melt}$ | melting coefficient |
| $V_{\tilde{M}}$ | terminal velocity of precipitation particles |
| $U_{00}$ | treshold value for stratiform cloud cover to form |
| $\ldots$ | |

| | |
|---|---|
| `he273 -` | saturation vapor pressure for $t = 273K$ |
| tvirtc - | constant needded to compute virtual temperature |
| hkevap - | coefficient for evaporation from stratiform precipitation |
| u00max - | maximum allowable value of modified hu00 |
| hu00 - | threshold relative humidity for stratiform condensation over |
| tcir - | temperature below which cirrus (pure ice crystal) clouds are considered |
| conae - | constant for the development in series of the equivalent potential temperature |
| aecon - | exp(conae) |
| coales - | parameter of the coalescence factor |
| hccu - | parameter c00 for cumulus, that is the conversion rate of cloud to precipitation drops in convective clouds |
| hcunrm - | that is cloud cover depens on cloud depth compared to hcunrm |
| hmrcu - | mr for convective clouds, that is cloud water mixing ratio at which conversion becomes efficient in convective clouds |

**hmrst -** mr for stratiform clouds, that is cloud water mixing ratio at which conversion becomes efficient in stratiform clouds

htaucu - characteristic time used in convective cloud cover scheme

hp0 - reference pressure $(= 100kpa)$

cbfeff - parameter for the Bergeron-Findeisen effect

hvterm - terminal velocity of precipitation

hvsnow - terminal velocity of snow

asnow - a parameter together with bsnow and snoref to govern the rate of ice precip before the Bergeron-Findeisen mechanism becomes effective, even if the precip from above is pure ice; the factor cbfsno = asnow*(snowrate/snoref)**bsnow and cbfsno = cbfsno/$(1 + cbfsno)$ which multiplies the modified ice probability

bsnow - see asnow

snoref - see asnow

# DEVELOPMENTS IN HIRLAM CLOUD PARAMETRIZATIONS

## Original formulation with no cloud condensate

stratiform: **COND**
convection: **KUO**

Grid volume total cloud water content as prognostic variable

**HIRLAM 2.0 ⇒**
stratiform+microphysics: Sundqvist
convection: Kuo scheme

e-mail: hildings@misu.su.se

## HIRLAM 4.1 ⇒

## STRACO

stratiform+microphysics: recoded Sundqvist

convection: recoded and modified Kuo scheme

e-mail: bhs@dmi.min.dk

or

## MFX

stratiform+microphysics: Sundqvist

convection: Tiedtke mass flux scheme

e-mail: png@inm.es

# HIRLAM 4.2.x ⇒

## Modular code structure

## RK

microphysics: Sundqvist scheme developed by Rasch and Kristjansson ([Rasch and Kristjánsson (1998)])

convection: mass flux

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## Not too distant future?

stratiform: explicit large scale precipitation

convection: a scheme with moist downdrafts + CAPE-closure

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