Treatment of Plume Rise in EMEP MSC-W Model

Status of the implementation in WRF-EMEP

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Overview

- ✓ Sub-grid scale plume modeling
- ✓ Plume-in-grid in operational models
- ✓ Plume rise description
- ✓ Treatment of Plume Rise in the WRF-EMEP model

The problem of fine scales

Correct representation of processes at very fine spatial scales is extremely difficult

- ✓ Near-source transport and dispersion
- ✓ Elevated point sources / plume rise
- ✓ Chemistry near emission / in plume

The problem of fine scales

In Eulerian grid models (EGMs) emissions are averaged within the volume of the grid cell were they are released. This may be appropriate if the source is a rather uniformly distributed area source but is not appropriate for an elevated point source.

EGMs with coarse resolution cannot resolve the sharp concentration gradients between the plume and the background air. For elevated point sources the initial dimensions are often of the order of a few tens of meters.

Artificial dilution of the emission leads to:

1) Lower concentrations of plume material
2) Unrealistic concentrations upwind the stack
3) Incorrect representation of the transport of emitted compounds
4) Incorrect chemical reaction rates

Techniques to address sub-grid scale errors

- ✓ **Nested Grid Modeling**

Smaller domain with fine resolution inside a larger domain with coarse resolution. Limitation: highest resolution practically often limited to 1 km due to computational constraints.

<u>One-way nesting:</u>

information flows from the coarse grids to the inner grids (example: WRF-EMEP development).

<u>Two-way nesting:</u>

built-in nested capability with simultaneous two-way flow of information between the coarse and fine grids (examples: CAMx, TM5, optional in WRF/Chem).

- ✓ **Adaptive Grid Modeling**

Mesh refinement algorithm that allows finer resolution in selected regions by permitting coarser resolution elsewhere. Adaptive grid version of CMAQ was developed but until now no operational application.

Techniques to address sub-grid scale errors

- ✓ Hybrid Modeling

  Superimpose sub-grid variability on top of EGM results, e.g. using Gaussian models.

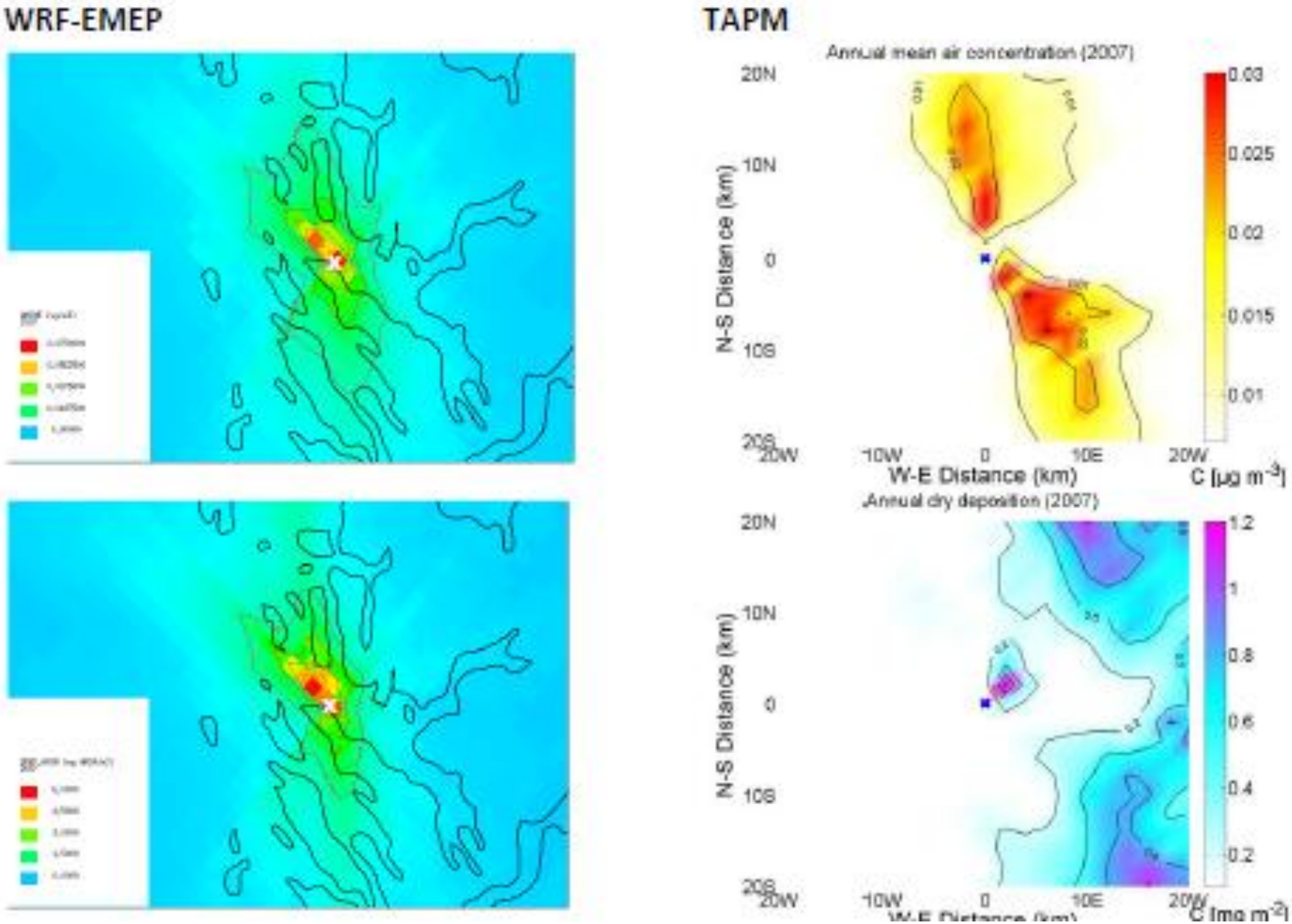
- ✓ Plume-In-Grid (PIG) Modeling

  Embedding a puff or plume model within the grid model. The sub-scale process (e.g. point source emission) is tracked until the fine scale variability becomes unimportant, at which point the grid models takes over the calculation, i.e. the concentration is “dumped” into the grid.

Operational Plume-In-Grid Air Quality Models

TAPM (air quality model developed at CSIRO)

- ✓ Lagrangian particle module LPM
- ✓ Mass presented as puff in horizontal direction and as particle in vertical direction (PARTPUFF)
- ✓ Primary emissions are tracked by the LPM, chemical reactions are accounted using the EGM
- ✓ Deposition processes are neglected in the LPM
- ✓ Once particles have travelled for a certain length of time the particle is no longer tracked and its mass is converted to concentration and added to the EGM grid



Ground-level air concentration

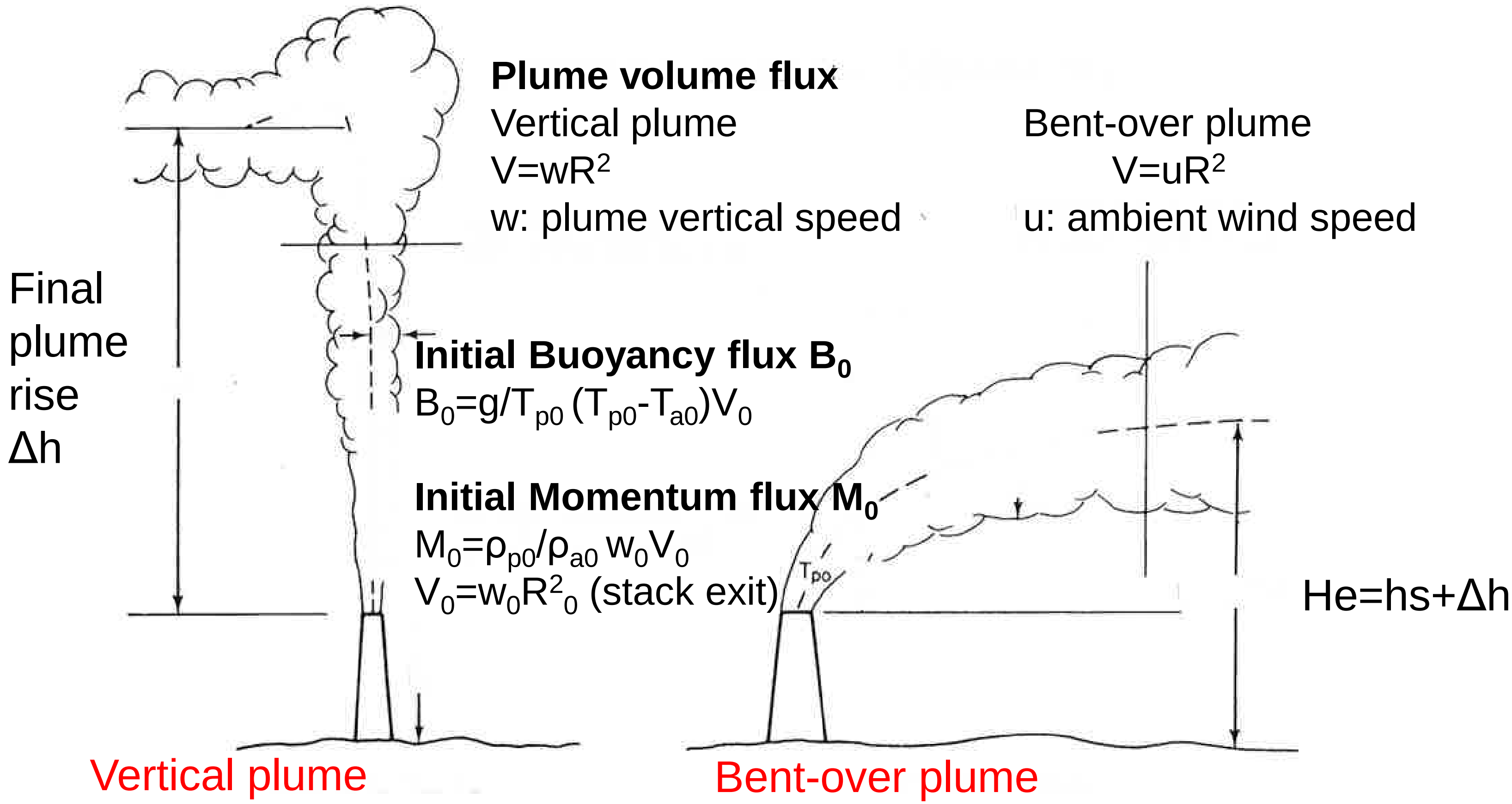
Dry deposition

Figure 17: Annual mean air concentration (ug/m^3), dry deposition (mg/m^2), of an inert tracer emitted at 1 g/s computed by the WRF-EMEP model (left column) and the TAPM model (right column) for year 2007. WRF-EMEP mapa have polar stereographic projection. Location of CCP Mongstad is marked by white X. The extent of the map is about 50km in W-E direction and 40 km in N-S direction. The blue cross in the TAPM maps (40 × 40 km^2) indicate location of Mongstad CCP.

Plume Rise

- ✓ When plume rise is important
  1. Most industrial pollutants are emitted from point sources with high stack exit velocity and high temperature.
  2. Plume rise is very important to determine the maximum ground-level air concentrations. Max. ground-level concentration is roughly proportional to the square of the effective emission height
  3. Plume rise increases the effective emission height from an elevated point source by a factor of 2 to 10 of the actual release height (=stack height).
  4. Plume rise can reduce ground-level concentrations by a factor of as much as 100.

Schematic diagram of plume rise



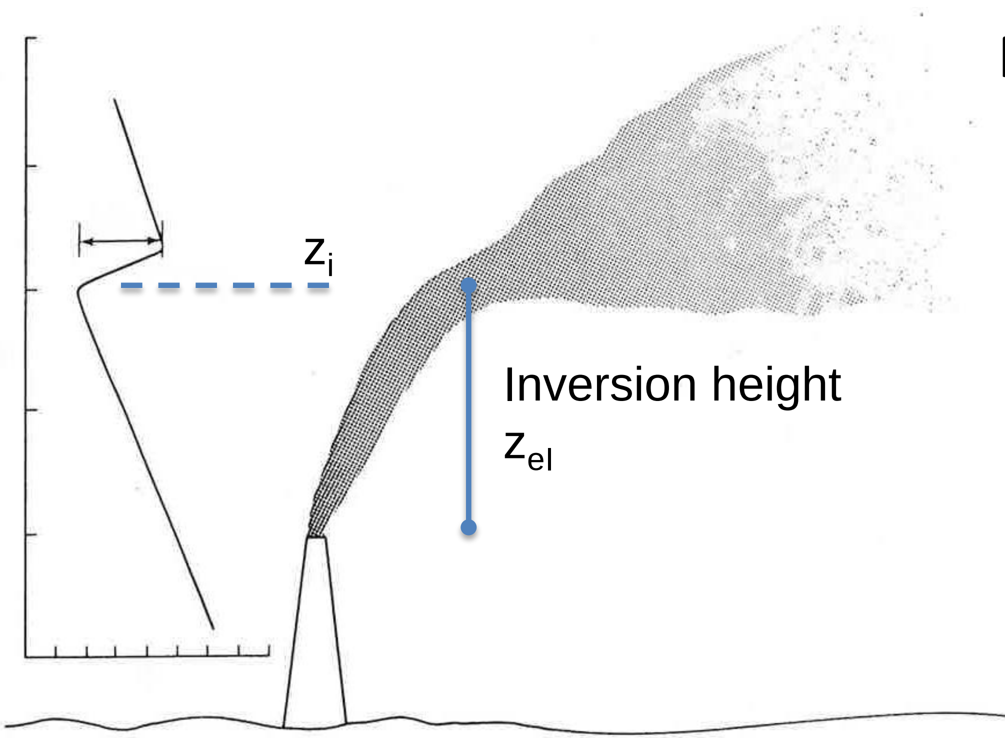
- We are looking at integrated averages of variables in a plume cross section
- The plume description in the following is based on the review by Briggs (1975) and the Briggs plume rise formulations

Plume Rise characteristics

- For most plumes, early rise is dominated by momentum
- Vertical plumes occur in calm conditions
- The transition to buoyancy domination occurs at $t=M/B_0$ typically t is around 5 s, i.e. at travel distance of ~50 m buoyancy starts to dominate
- Environmental stability (s) plays a prime role in slowing the plume's vertical motion: $s = g/T_a\ (dT_a/dz + 0.01°C/m)$
- Final plume rise in stable conditions is well understood.
- However, final rise in neutral conditions, when the plume is affected by turbulence, is uncertain.
- Low pressure in the wake of the stack may cause the plume to be drawn downward behind the stack ("downwash"). Downwash will not occur for $w_0/u > 1.5$

Plume penetration of elevated inversion

- Plumes will nearly always be confronted with stable air layers at some point of their trajectory.
- If the plume can penetrate the elevated inversion, ground-level concentrations will be much smaller. If not, the plume becomes trapped below, leading to high concentrations.

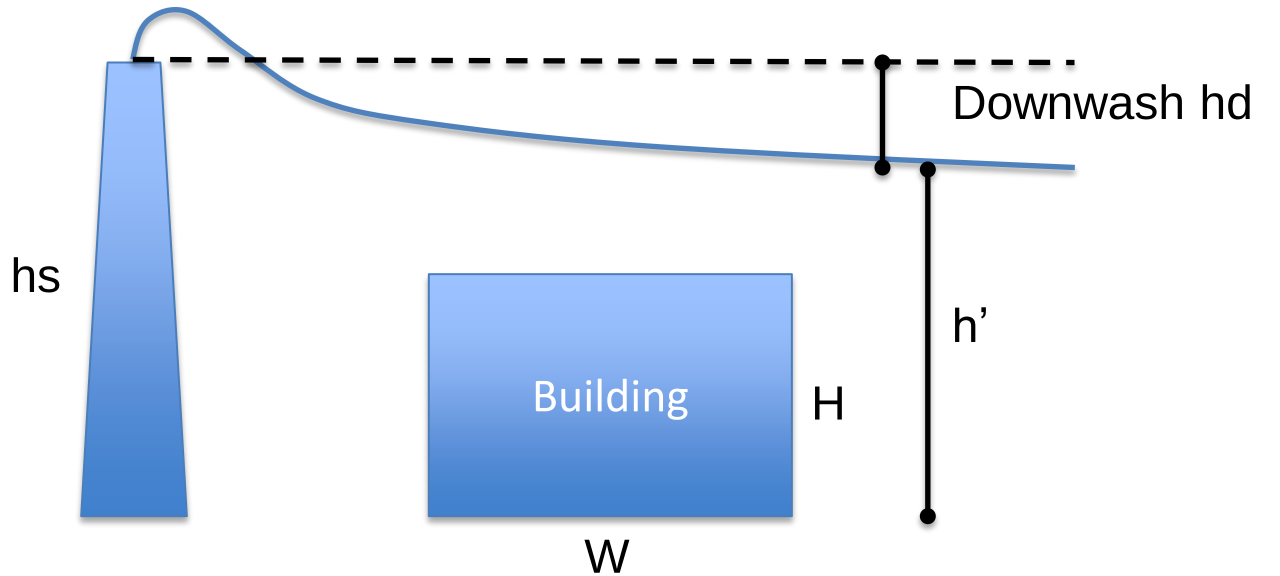


Partial penetration:

Fraction P of the plume that penetrates the stable layer

$P = 1.5 - z_{el}/\Delta h$

Effect of building wake



- If h' is greater than H+1.5ζ the plume is out of the building wake (ζ is the smaller of H and W) → He = h'
- Otherwise the effective plume height He is affected by the building wake
- If He is less than 0.5ζ the plume is trapped in the cavity and the source can be treated as ground-source.

Atmospheric Stability

- The diffusion of air pollutants in the lower atmosphere is strongly influenced by the local atmospheric stability.
- Stability of the atmosphere can be derived from vertical and horizontal turbulence measurement or from measurement of the vertical profile of temperature and wind speed.
- Pasquill (1961) has defined 6 stability classes.
- For practical purposes NILU has merged 3 unstable classes:

Stability class	Ambient Temperature gradient dT (°C/100 m)	Pasquill	Brookhaven
Unstable	$dT < -1$	A + B + C	B1 + B2
Neutral	$-1 \leq dT < 0$	D	C
Slightly stable	$0 \leq dT < 1$	E	--
Stable	$dT > 1$	F	D

Plume Rise recipe (Briggs, 1969, 1971, 1975)

1. **Neutral-unstable momentum rise**
   $\Delta hm = 3\ D\ w_0\ u^{-1}$
2. **Neutral-unstable buoyancy rise**
   Buoyancy flux parameter:
   $Fb = (g\ w_0\ D^2\ \Delta T) / 4Ts$
   if $Fb < 55$: $\Delta hb = 21.425\ F^{0.75}\ u^{-1}$
   if $Fb \geq 55$: $\Delta hb = 38.71\ F^{0.6}\ u^{-1}$
3. If neutral-unstable momentum rise is higher than neutral-unstable buoyancy rise, momentum rise applies
4. **Stable momentum rise** ("cold release" if $Ts < Ta$)
   $\Delta hm = 1.5\ [(w_0^2\ D^2\ Ta) / (4Ts\ u)]^{0.333}\ s^{-0.167}$
   the lower value of the two Δhm is used as final plume rise
5. **Stable buoyancy rise**
   $\Delta hb = 2.6[F/(u\ s)]^{-0.333}$
   $\Delta hb = 4\ F^{0.25}\ s^{-0.375}$ for calm conditions
   the lower value of the two Δhb is used as final plume rise
6. If stable momentum rise is higher than stable buoyancy rise, momentum rise applies
7. Effective emission height $He = hs + \Delta h$

Vertical emission profiles in the EMEP MSC-W Model

Table S3: Vertical distribution of anthropogenic emissions: percentage of each SNAP emission sector allocated to the vertical layers of the EMEP model (given as heights of layers, in m, for a standard atmosphere).

No.	Sources	Height of Emission Layer (m)					
		0-92	92-184	184-324	324-522	522-781	781-1106
1	Combustion in energy and transformation industries			15	40	30	15
2	Non-industrial combustion plants	100[(a)]	0[(a)]				
3	Combustion in manufacturing industry	10	10	15	30	30	5
4	Production processes	90	10				
5	Extraction and distribution of fossil fuels and geothermal energy	90	10				
6	Solvents and other product use	100					
7	Road transport	100					
8	Other mobile sources and machinery	100					
9	Waste treatment and disposal	10	15	40	35		
10	Agriculture	100					

Notes: (a) Up to version rv4β SNAP-2 was split 90% into the lowest layer, then 10% in the next lowest.

EmisHeights.txt

Implementation of plume rise in WRF-EMEP

- Designed for study of maximum ground-level concentration of a certain industrial pollutant from one elevated point source in a certain region (200x200 km^2)
- Input are stack parameters and emitted amounts
- Input format is a ascii table-format file
- Source code is not yet in the CVS
- Online calculation of plume rise based on meteorological input and derived EMEP variables (friction velocity, mixing height, Monin-Obukhov length L_O, T(45m), u(45m))
- Injection of the emissions is based on final plume rise and spread over several vertical layers following Gaussian distribution
- Three different plume methods are available:
  - "NILU plume": based on formulations by Briggs
  - "ASME plume": based on ASME (1973)
  - "PVDI plume": based on Pregger & Friedrich (2009)

PVDI Plume

- Pregger, T. and Friedrich, R. (2009), Effective pollutant emission heights for atmospheric transport modelling based on real-world information, *Environmental Pollution*, 157, 552-560.
- Plume rise calculation based on German VDI Guideline 3782 Part 2 (1985) for 3 different temperature stratifications.
- Main variable: emitted heat flux Mh

  $Mh = cp \times F\,(T - Ta)$

  cp: 1.36×10^{-3} MW s m^{-3} K^{-1}

  F: exhaust gas volume flow rate (m^3/s)
- Case division:

$Mh > 6.0$	$\Delta h = 102 \times Mh^{0.6}\, u^{-1}$
$1.4 < Mh \leq 6.0$	$\Delta h = 78.4 \times Mh^{0.75}\, u^{-1}$
$Mh \leq 1.4$	$\Delta h = (0.35\, Vs \times D + 84 \times Mh^{0.5})\, u^{-1}$
	$\Delta hm = 3.0\, Vs \times D \times u^{-1}$
	$\Delta h = \max(\Delta h, \Delta hm)$

ASME Plume

- American Society of Mechanical Engineers (1973), Recommended Guide for the Prediction of the Dispersion of Airborne Effluents, 2nd ed., ASME, New York
- Coded according to Seinfeld and Pandis (1998) “Atmospheric Chemistry and Physics”, pp. 931-933
- Plume rise function for buoyant plumes
- Main variable: exhaust gas volume flow rate F
- For neutral and stable: $\Delta h = 7.4 \times (F \times hs^2)^{0.333} \times u^{-1}$
- $\Delta h = 2.9 \times (F \times (Ta+273.15)/(g\ dt/dz\ u))^{0.333}$

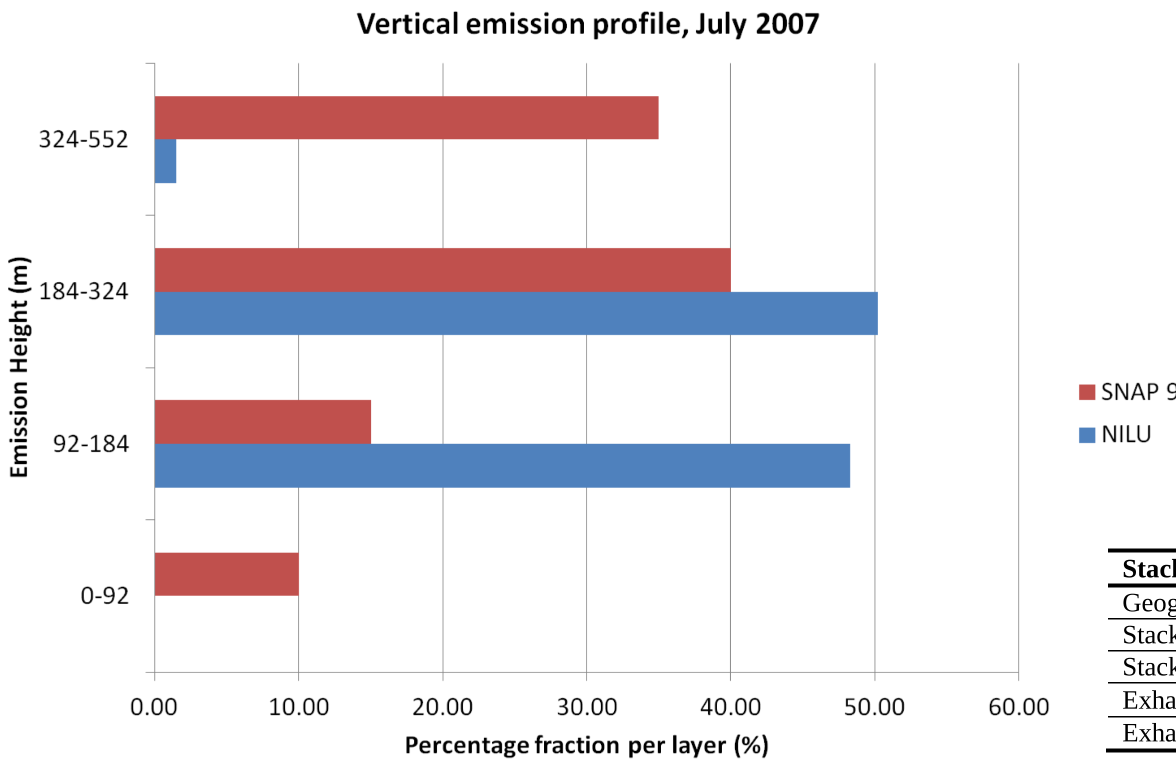
NILU Plume

- Briggs (1969; 1971; 1975)
- Uses temperature and wind speed at 45 m (mid-point of first EMEP layer) to approximate temperature and wind speed at plume height
- Uses similarity theory to calculate wind speed profile
- Considers plume penetration
- Building influence is not considered (too uncertain)
- Surface roughness z_0 = 0.25 (“rough”)
- Both momentum rise and buoyancy rise considered
- Atmospheric stability based on $1/L_O$

User-defined input

- Stack name, country code, snap code
- Geographical location: lat, lon
- Stack exhaust temperature (K)
- Stack height (m)
- Stack diameter (m)
- Stack exhaust exit velocity (m/s)
- Emitted amount (kg/yr)

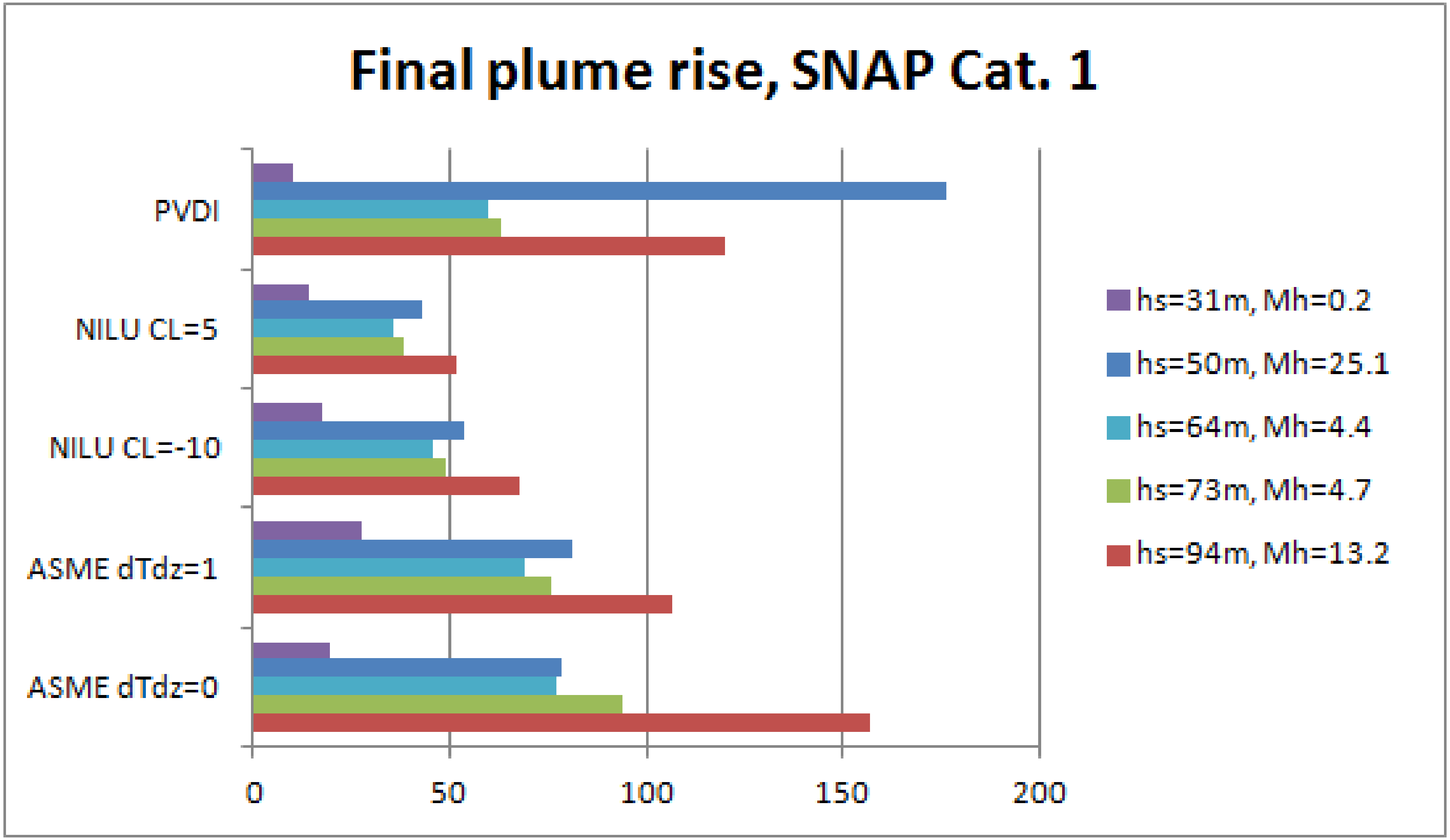
Vertical profile: SNAP profile vs. NILU plume



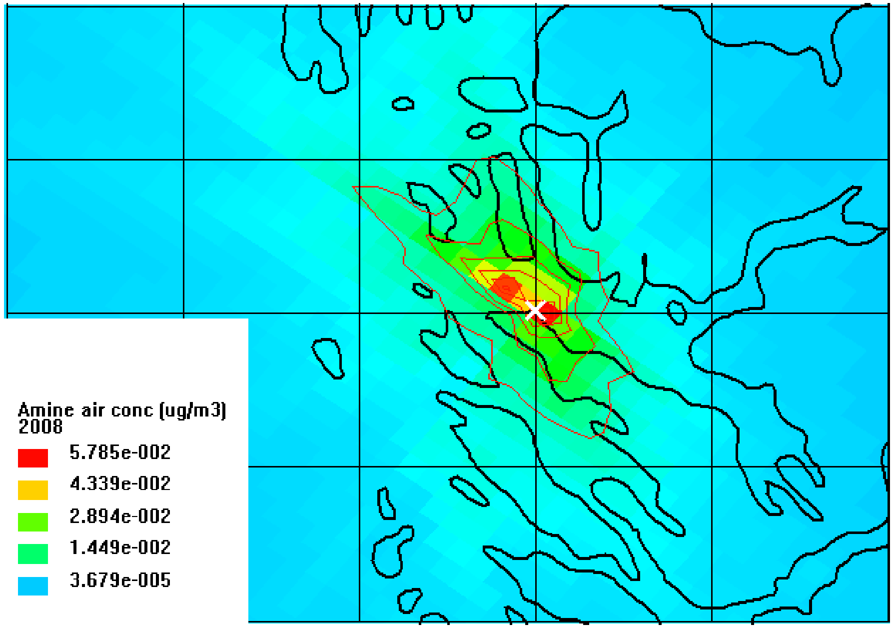
Stack parameter	Value
Geogr. Coordinates (lat | lon)	60.81N | 5.04E
Stack height (m)	60.0
Stack diameter (m)	7.14
Exhaust gas exit temperature (°C)	40.0
Exhaust gas exit velocity (m s^{-1})	10.0

Vertical emission profile of a specific industrial point source for SNAP 9 and for the “NILU Plume” option in WRF-EMEP using stack parameters (in Table) calculated for July 2007. Percentage fraction in the four layers from “NILU Plume” was based on 8928 online calculated profiles.

Comparison of plume methods

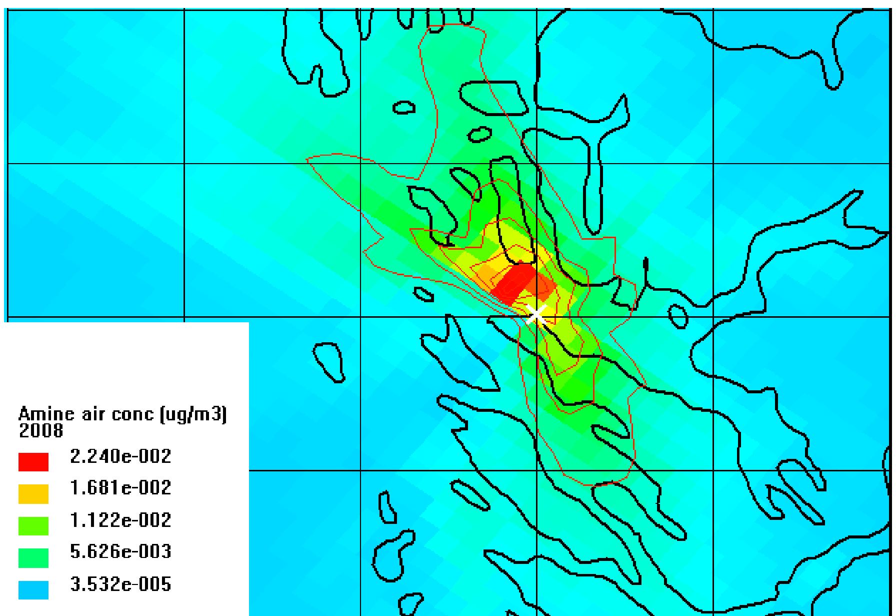


Ground-level air concentration: NILU vs. ASME plume



"NILU Plume"

Max. Conc 5.79 x 10^{-2} ng/m^3



"ASME Plume"

Max. Conc. 2.24 x 10^{-2} ng/m^3

Stack parameter	Value
Geogr. Coordinates (lat | lon)	60.81N | 5.04E
Stack height (m)	60.0
Stack diameter (m)	7.14
Exhaust gas exit temperature (^{o}C)	40.0
Exhaust gas exit velocity (m s^{-1})	10.0

Further development of the plume rise module

- The standard resolution of the EMEP model does per se not require plume rise treatment due to its coarse resolution (uniform area source in $50x50km^2$)
- However plume rise treatment could be important for the vertical distribution of emissions from power plants , since these occasionally will penetrate the inversion layer.
- How to make the plume rise routine a valuable contribution to the standard EMEP model:
  - Typical power plant pollutants (NOx, SOx, CO, PM)
  - Build up European inventory of power plants
  - Possible application: EIA for new large plants
  - Substitute all SNAP Cat. 1 grid sources by point sources

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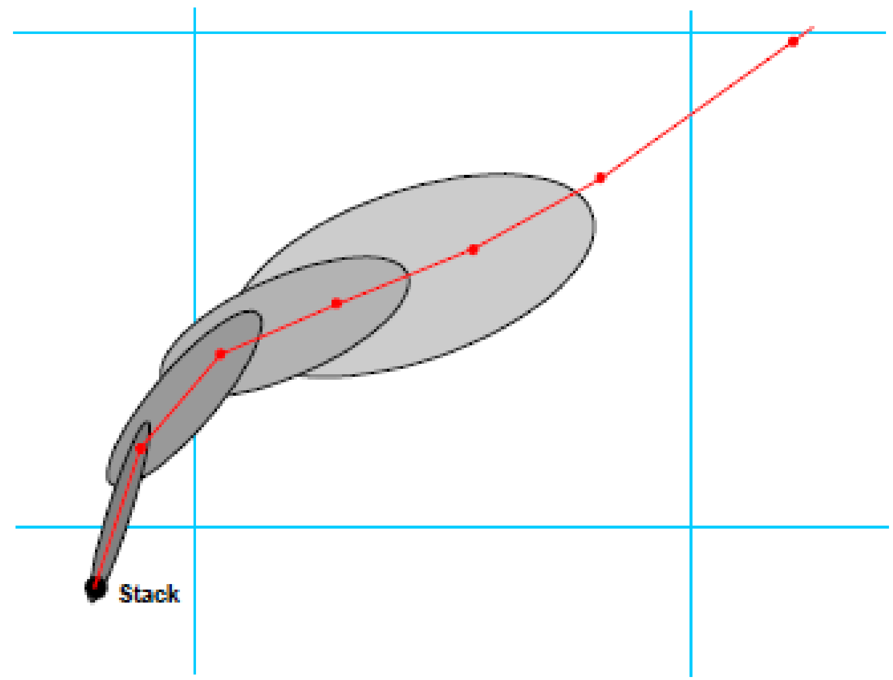
Operational Plume-In-Grid Air Quality Models

CAMx and CMAQ-APT

- ✓ Reactive plume model SCICHEM
- ✓ Plume is represented by thousands of 3-D puffs that are advected and dispersed. Each puff has Gaussian representation of the concentrations of emitted inert compounds. The overall plume is a multitude of these puffs and can have any spatial distribution of the concentrations.
- ✓ Chemical reactions within the puffs are treated as perturbation from the background concentrations (calculated by the EGM).
- ✓ Transfer of puff material to the 3-D grid system when the puff size approaches grid size.
- ✓ SCICHEM has an option to explicitly simulating the effect of turbulence on selected chemical reactions.

Puff transport in CAMx

- ✓ Stream of plume segments (puffs) is released from a point source



- ✓ Points at the leading and trailing edges of the puff centerline are transported individually through the gridded wind fields – accounting for puff stretching due to deforming wind shears.
- ✓ Puff "leaking" instead of "dumping": continuously transferring puff mass to the grid model to avoid sudden dumping