Multi annual comparison between satellite-based observations and CTM estimates of surface aerosol concentrations in Northern Italy

Kos, 2-6 Oct 2011

Enrico Minguzzi[1], Giovanni Ballista[2], Giovanni Bonafé[1], Alessandra Cacciari[2], Marco Deserti[1], Walter Di Nicolantonio[2], Michele Stortini[1] and Alessandro Tiesi[2]

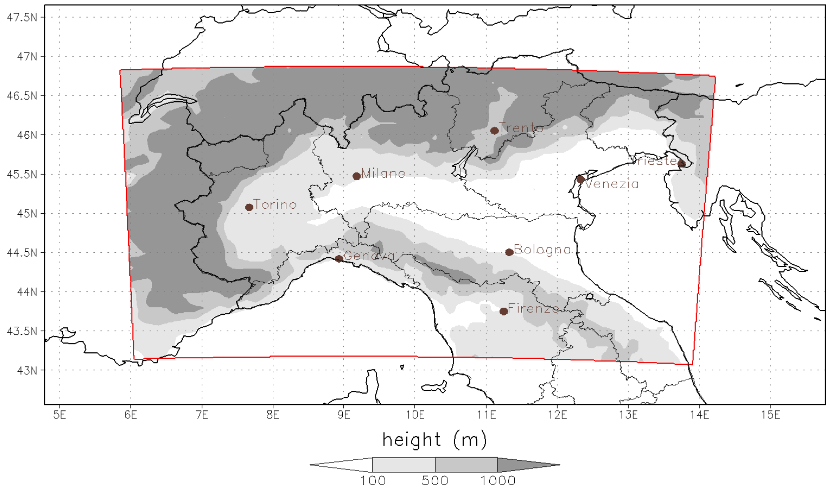
1 CGS SPA – An OHB Technology Company

2 HydroMeteorological Service of ARPA Emilia Romagna (ARPA-SIMC), Bologna, Italy

Background

PM pollution in Po Valley

- It is one of the European regions where air quality standards are less fulfilled, especially when PM is considered
- Eulerian models underestimate PM10 and PM2.5 concentrations by ≈ 40%
- PM concentrations in winter are ≈ double than in summer

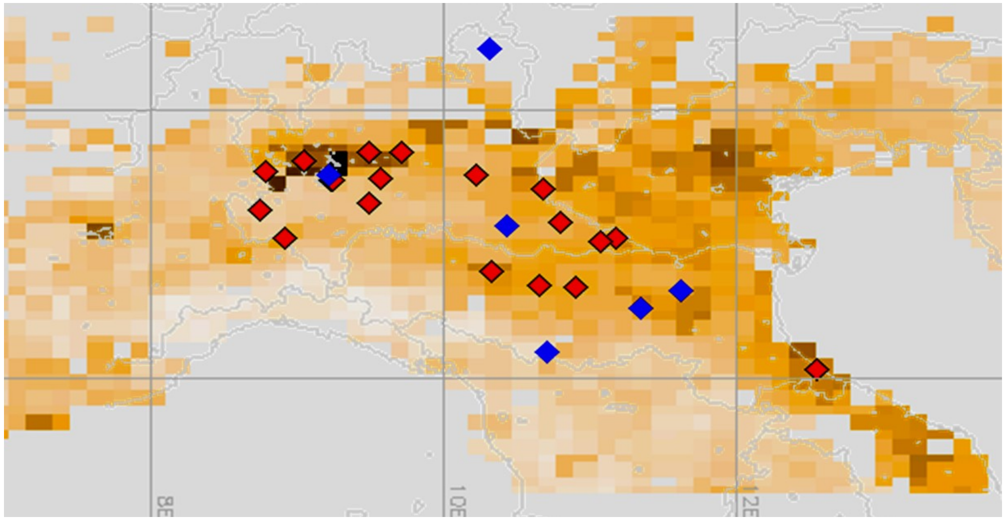


Objectives:

- Can satellite measurements be helpful in the assessment of PM pollution? *(long term concentrations; areas where legislation thresholds are exceeded)*
- Can satellite-based estimates provide an independent validation of CTM outputs? *(spatial distribution, regardless of model bias; inter-annual variability)*
- Extensive PM 2.5 monitoring in Po Valley started only in 2008/2009: can we say something about what happened before? *(are concentration decreasing?)*

Satellite-based PM2.5 (1)

1) The linear regression between PM2.5 (measured at ground level) and AOD/Hmix has been evaluated at 20 calibration sites for year 2007. Independent regressions has been calculated for every month.
2) The coefficients of the regression have been extrapolated, to cover Northern Italy with a 10 km spaced grid (simple $1/R^2$ rule)
3) Gridded data of AOD, η (from MODIS level 2), Hmix and RH (from COSMO met.model) have been used to evaluate gridded PM2.5 concentrations for every satellite overpass, for an 8 years period (2003-2001).
4) *Gridded PM2.5 daily concentrations have also been verified at 6 independent surface stations; correlation are on average 0.8*



Surface stations used for calibration (20, red) and verification (6, blue)

Satellite-based PM2.5 (2)

Assuming that:

- Below the mixing height, the vertical profile of aerosol density has always the same shape (constant or logaritmic)
- Mixing height estimated by the meteorological model (bulk Richardson number) is a good approximation of aerosol scale height
- All the aerosol is confined below mixing height
- Saharan dust episodes ($\eta < 0.4$) are excluded from the analysis

The regression takes the form:

$$PM_{2.5} \cong A_{i,j} \frac{\eta \times \tau_a}{F_{hyg}(RH;\gamma) H_{mix}} + B_{i,j}$$

A_{ij} ($\mu g/m^3$): slope. It is the inverse of aerosol extinction cross section, for the i-th calibration site and the j-th month; it depends on the properties of dry aerosol.

B_{ij} ($\mu g/m^3$): intercept. This coefficient is introduced to take into account non-linear effects; most of the time it turned out to be rather small (<10 $\mu g/m^3$)

τ_a: Aerosol Optical Depth at 550 nm

η: fine fraction of aerosol (in Po valley usually close to 1)

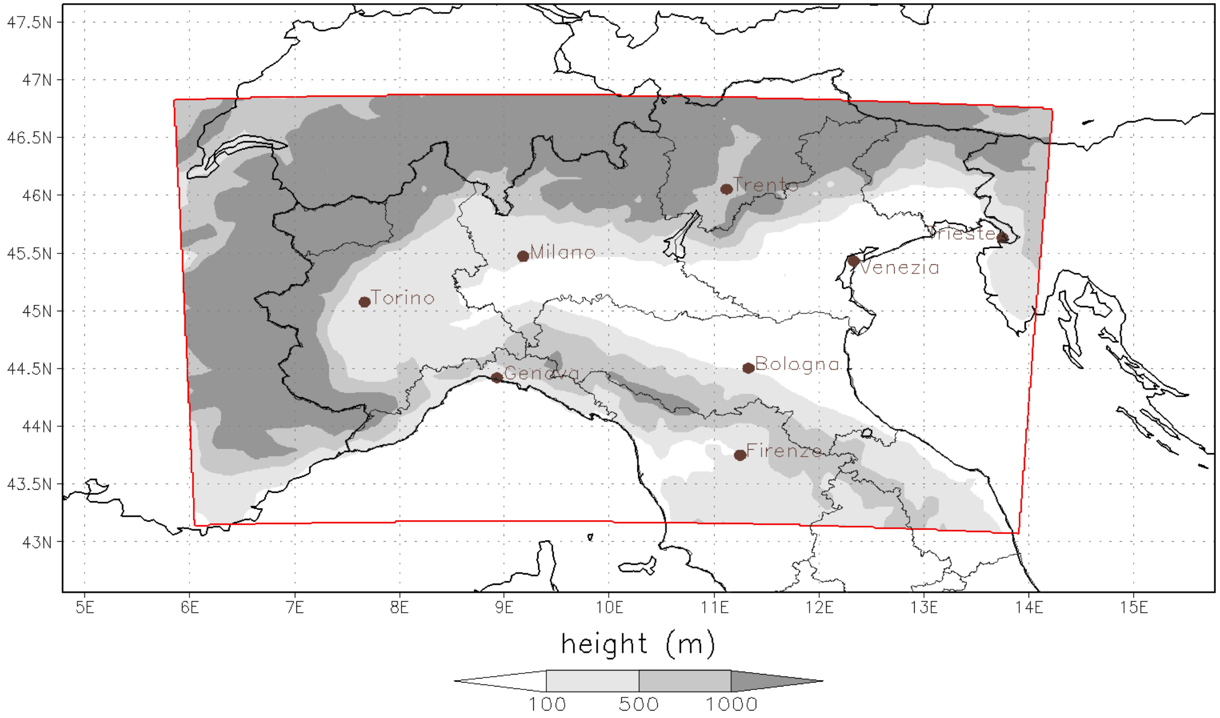
F_{hyg}: factor which takes into account the hygroscopic growth of aerosol

H_{mix}: mixing height

CTM-based PM2.5 (1)

• Chimere CTM has been run continuosly for 8 years: meterological fields and chemical boundary conditions are time-varying; emissions have temporal modulation, but annual totals are fixed (ie. no trend in emisisons).

•The integration domain covers Northern Italy, with 10 km horizontal resolution

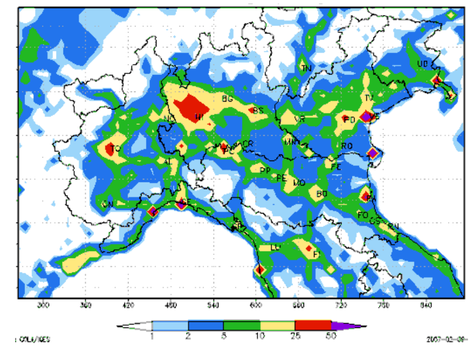


Chimere-SIM integration domain

CTM-based PM2.5: the NINFA modelling system (2)

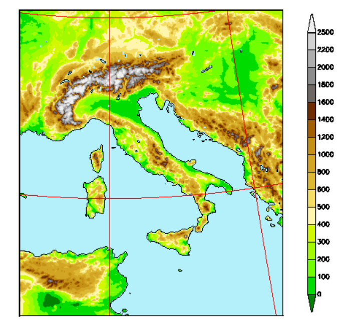
Emission inventory

- Italian National inventory (produced by CTN-ACE group), updated to year 2000
- Top-down approach, explicit description of large point sources



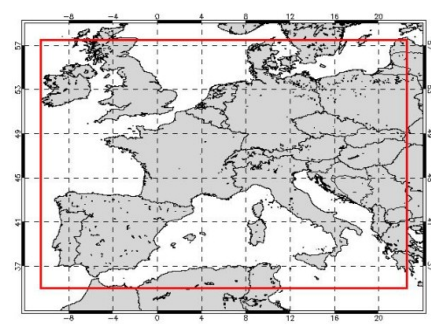
Meteorological input:

- Limited area model "COSMO" run in continuous assimilation mode (surface and upper air GTS data)
- Domain covering Italy and surroundings, with 7 km horizontal resolution
- Boundary conditions by German global model GME



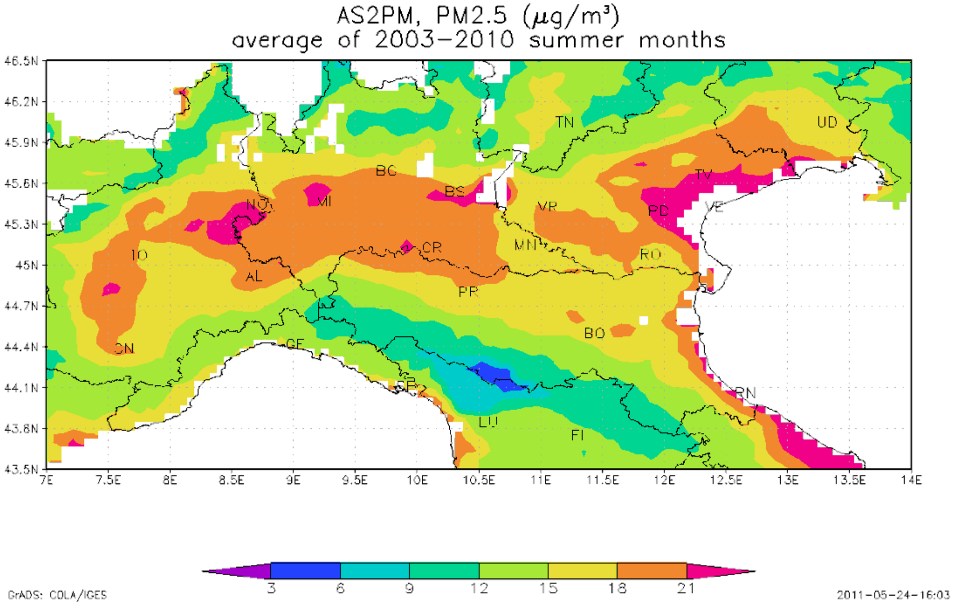
Chemical Boundary conditions

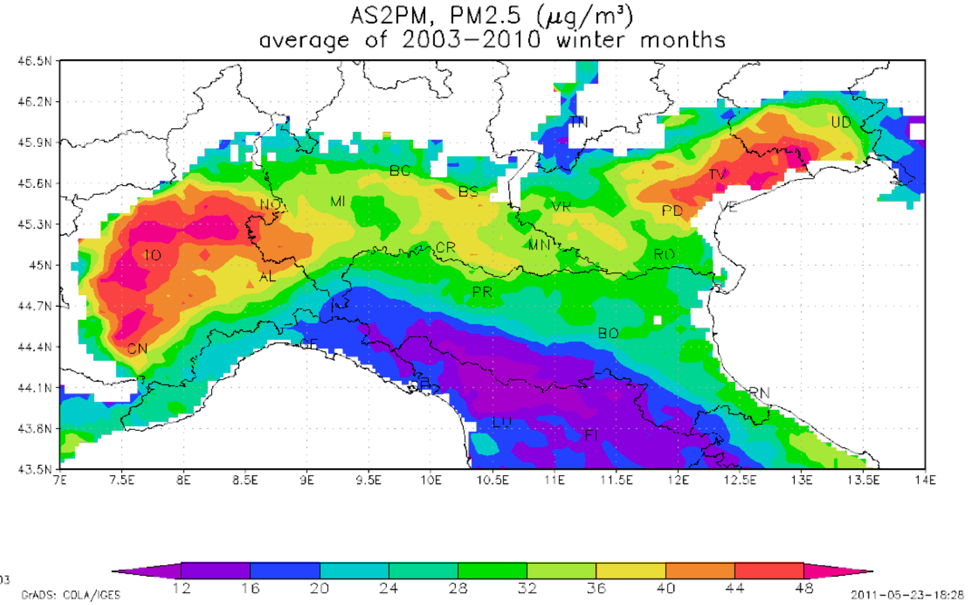
- Chimere operational analysis ("day-1", by INERIS)
- Domain covering most of Europe, with 50 km horizontal resolution



PM 2.5 mapping

- Satellite vaild data are ≈ 60% in summer, ≈ 25% in winter
- Nevertheless, the approach resulted to be sufficiently robust to allow a long-term analysis
- PM 2.5 spatial distribution:
  - higher concentrations north of Po river
  - east-west gradient smoother in summer than in winter





8 years average PM2.5 concentrations in summer (Apr-Sep, left) and winter (Oct-Mar, right) months

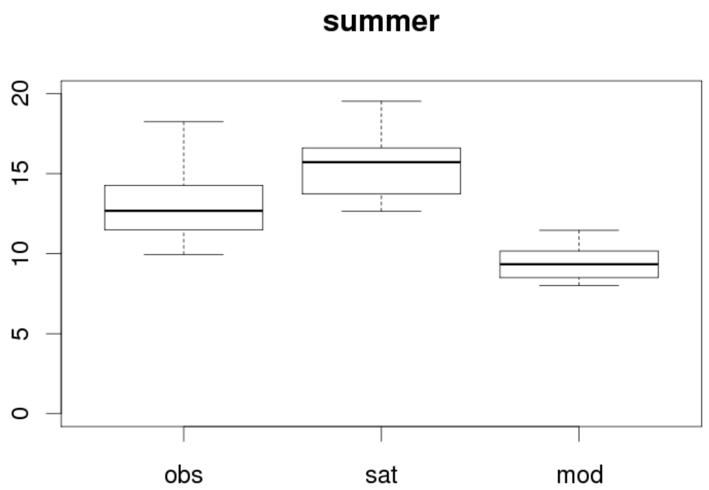
Colour scales are different !!

Preliminary verification

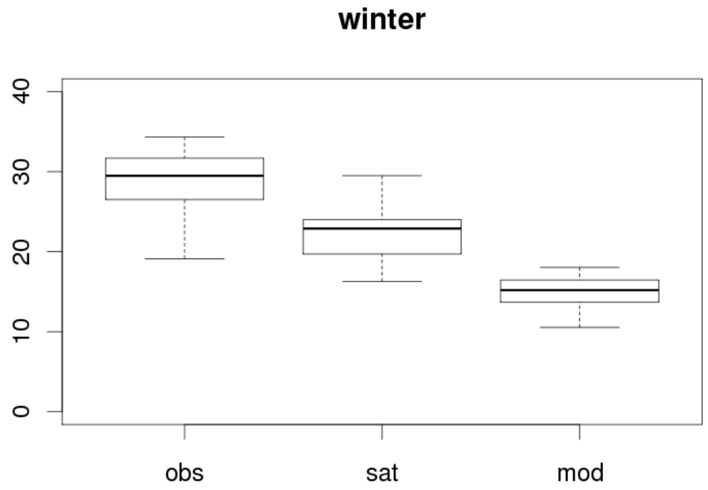
- A preliminary independent verification of Satellite and Chimere was performed:

- 24 stations not used for calibration
- years 2009 and 2010 (calibration used 2007 data).
- stations only cover a small part of the domain

- Satellite is already better than Chimere (smaller bias and RMSE, better spatial variance), although it underestimates seasonal variability



RMSE: sat=3.7, Chimere=4.1

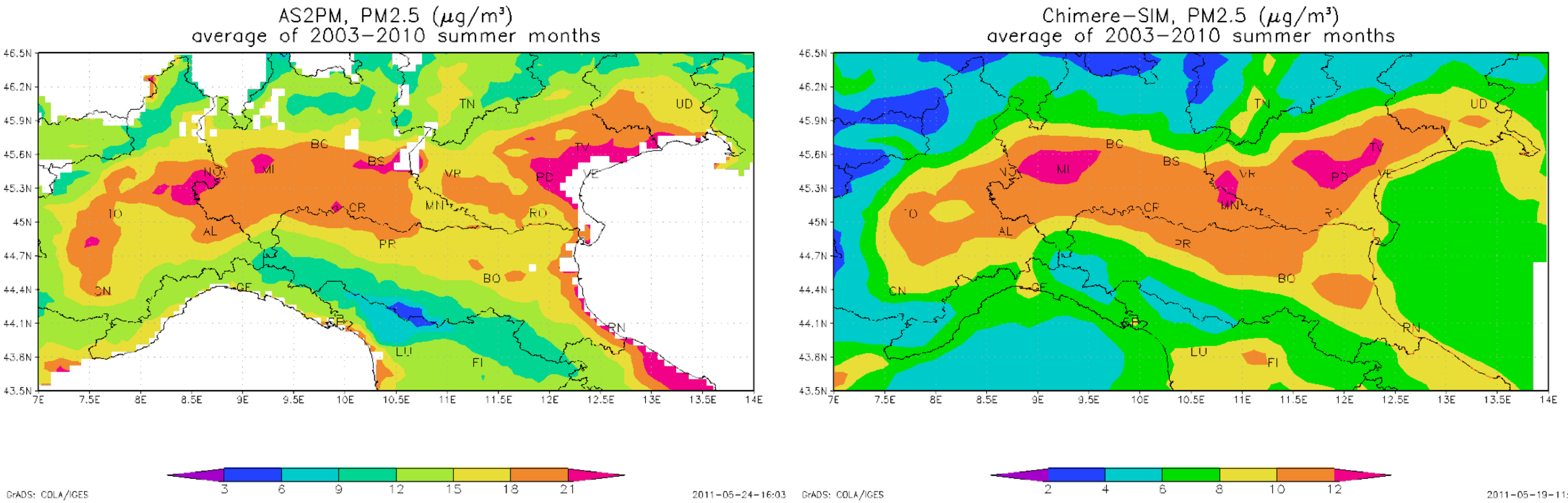


RMSE: sat=8.3, Chimere=13.9

PM2.5 (µg/m³) at 24 stations in Emilia Romagna, years 2009/2010; summer and winter months; observations, satellite estimates, Chimere outputs. **Scales are different!!**

Sat vs CTM comparison: summer

- Chimere underestimates concentrations by ≈ 40%
- The pattern of Sat and Chimere concentrations in Po Valley is similar:
  - higher concentrations north of Po river
  - relatively smooth east-west gradient (*no especially critical area can be identified*)
- Secondary maximum in SE corner of the domain is probably spurious *(outside Po valley: likely a different aerosol composition requires a different calibration)*

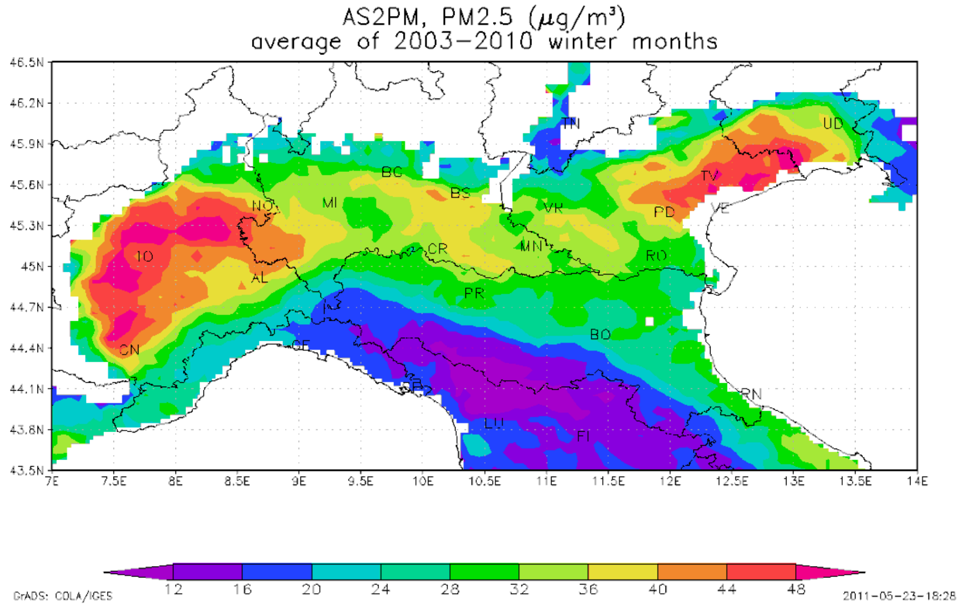


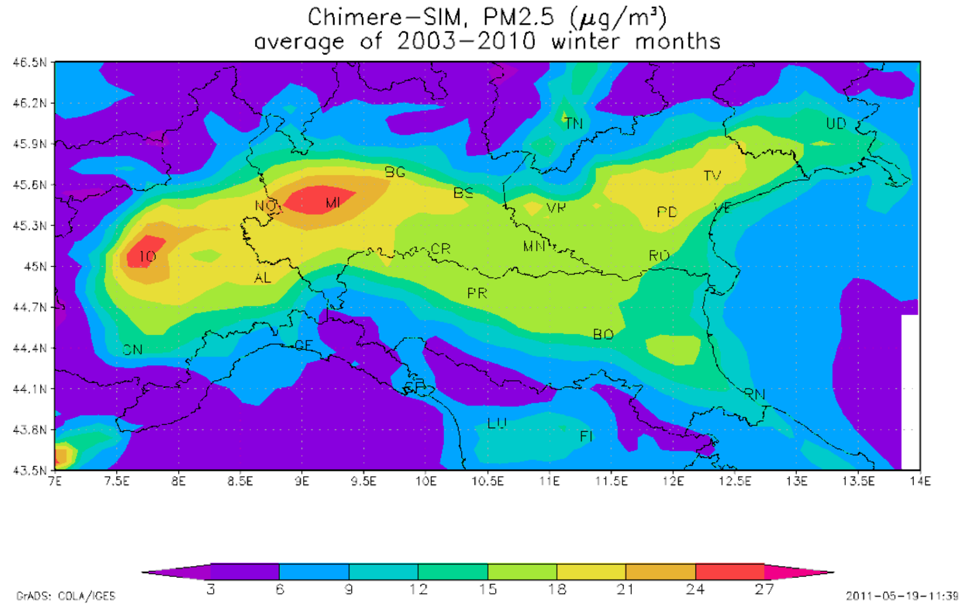
8 years average PM2.5 concentrations in summer months (Apr-Sep): satellite-based (left) and CTM (right).

Colour scales are different !!

Sat vs CTM comparison : winter

- Chimere underestimates concentrations by ≈ 40%
- The pattern of Sat and Chimere concentrations in Po Valley is similar:
  - higher concentrations north of Po river
  - 3 especially critical areas are identified (but big differences in Milan!)
  - spatial gradients are stronger than in summer
- The magnitute of Sat maximum concentrations (in Piemonte and Veneto) may be ovrestimated *(uneven distribution of calibration sites)*



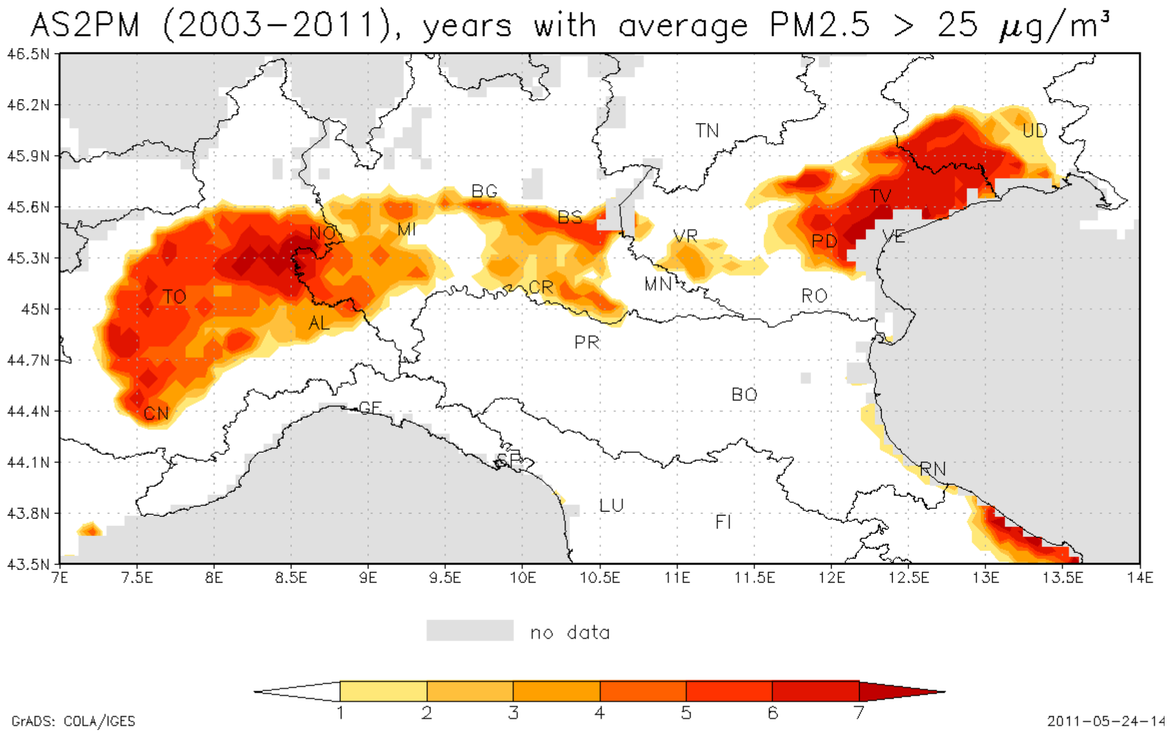


8 years average PM2.5 concentrations in winter months (Oct-Mar): satellite-based (left) and CTM (right).

Colour scales are different !!

Compliance with legislation

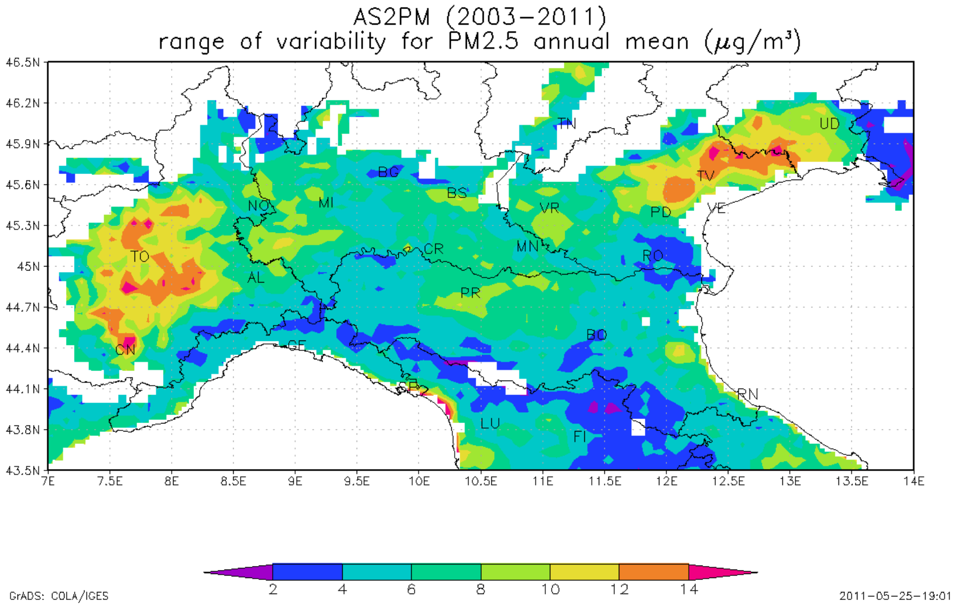
- EU legislation requires (from 2015) annual average PM2.5 concentrations to be < 25 µg/m³: presumably large areas of Northern Po Valley will not fulfill this requirement.
- Interannual variability is not very large, but it can significantly affect the areas in which the legislation threshold is exceeded *(in most locations the threshold is exceeded only in some years)*



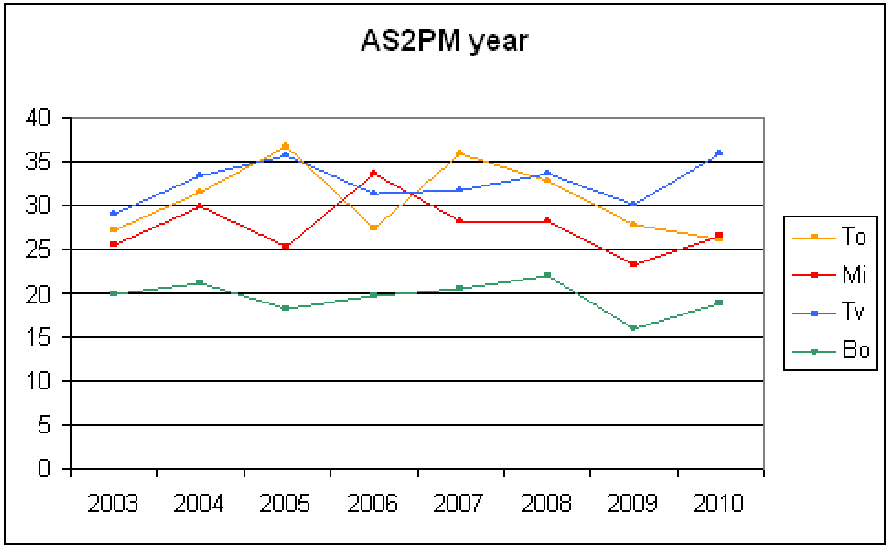
Satellite-based estimates, years 2003-2011:
number of years with PM2.5 annual average concentrations > 25 µg/m³

Interannual variability

- Interannual variability (≈20%) is lower than spatial variability (≈50%)
- Areas with higher concentrations have also a greater variability
- Different locations experience the highest concentrations in different years



Variability of annual averaged PM25 concentrations (max-min value in the 8 years)



Annual averaged PM2.5 concentrations for each year at selected locations

Future developments

- Extension to PM10
- Increase of horizontal resolution to 5 km (possibly 2.5 km)
- Improvement of spatial coverage of calibration sites and of spatial extrapolation of regression coefficients
- Investigation of “sampling error” of satellite data (*is average at valid overpasses representative of true annual average?)*
- Use of more realistic aerosol vertical profiles (eg. taken from CTM)

- *Integration of Satellite, CTM and ground measurements to produce the “best possible” long-term estimate of surface concentrations (at this spatial scale, maybe a post-processing approach is more feasible than data assimilation)*

Conclusions

• Satellite estimates are sufficiently robust to make realistic long-term analysis in an area such as the Po Valley; long term average must be taken into account (at least seasonal or annual average).

• Satellite data can at least provide an independent verification of CTM "final products" (eg. definition of areas in which concentration limits are exceeded) by:

- qualitative comparison of spatial patterns
- quantitative verification (may be possible, especially in summer months).

• Errors of satellite estimates are of the same order as CTM, but the two errors are essentially independent: the integration of the two tools could be beneficial

•Further analysis and improvements are expected within PASODOBLE project, also after MACC ending.

Some Details

Sat-based PM2.5: derivation of linear regression

AOD and aerosol scale height can be defined as:

$$\begin{cases} \tau_a(\lambda) = \int_0^{\infty} \rho(z)\, \tilde{\sigma}_{ext}(\lambda, z)\, dz \\ H_a = \dfrac{\int_0^{\infty} \beta_{ext}(\lambda, z) dz}{\beta_{ext}(\lambda, 0)} \end{cases}$$

$\tau_a(\lambda)$ = aerosol optical depth at wawelenght λ

β_{ext} = extinction coefficient [m^{-1}]

ρ = aerosol mass concentration [$\mu g\ m^{-3}$]

H_a = aerosol scale height [m]

σ_{ext} = extinction cross sect. per unit mass [$m^2\ \mu g^{-1}$]

Assuming that all the aerosol is confined in the mixing layer, and that the vertical profiles of ρ and σ are constant in the mixing layer, these equations become:

$$\rho(0) = \frac{\tau_{a,\lambda}}{\sigma_{\lambda}^{ext}(0)\, H_a}$$

And thus:

$$PM_{2.5} \simeq \frac{\tau_{a,f}}{\sigma_{ext,dry,f}(0)\, F(RH;\gamma)\, H_{mix}}$$

$\rho(0)$ = surface aerosol mass concentration [$\mu g\ m^{-3}$]

$\sigma_{ext}(0)$ = surface extinction cross sect. per unit mass [$m^2\ \mu g^{-1}$]

$\sigma_{ext,dry}(0)$ = surf. extinction cross sect. for dry aerosol [$m^2\ \mu g^{-1}$]

$\tau_{a,f} = \eta . \tau_{a,f}$ = AOD associated with "fine" aerosol

η = fraction of "fine" aerosol (PM2.5)

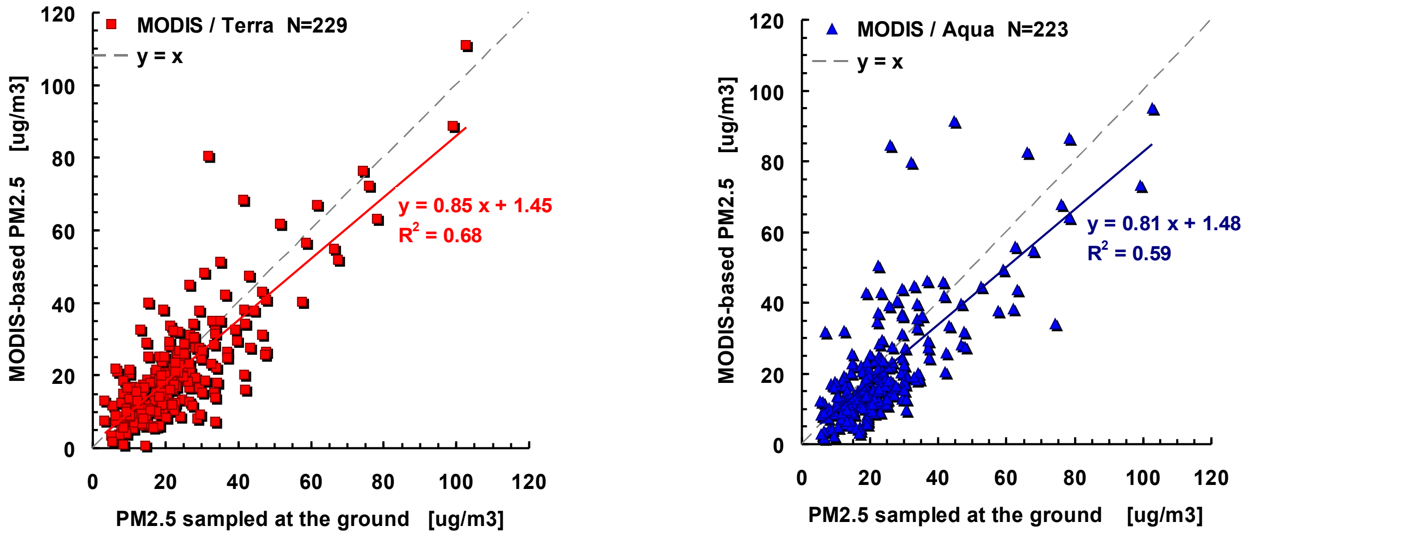
Satellite-based PM2.5: uncertainities

Retireval of AOD: the problem has been extensively studied; the main source of uncertainity is the estimation of surface reflectivity

Estimation of gridded PM2.5 concentrations:

- assumptions on the vertical distribution of aerosol
- assumptions on the effects of humidity on AOD (potentially a factor of 2)
- errors in mixing height and relative humidity estimation by the met. Model
- significance of calibration stations with respect to satellite pixel (10x10 km²)

On the whole, the expected error in satellite estimation of surface aerosol is ≈30% for PM10 and slightly less for PM2.5 (comparbale with CTM uncertainity…)

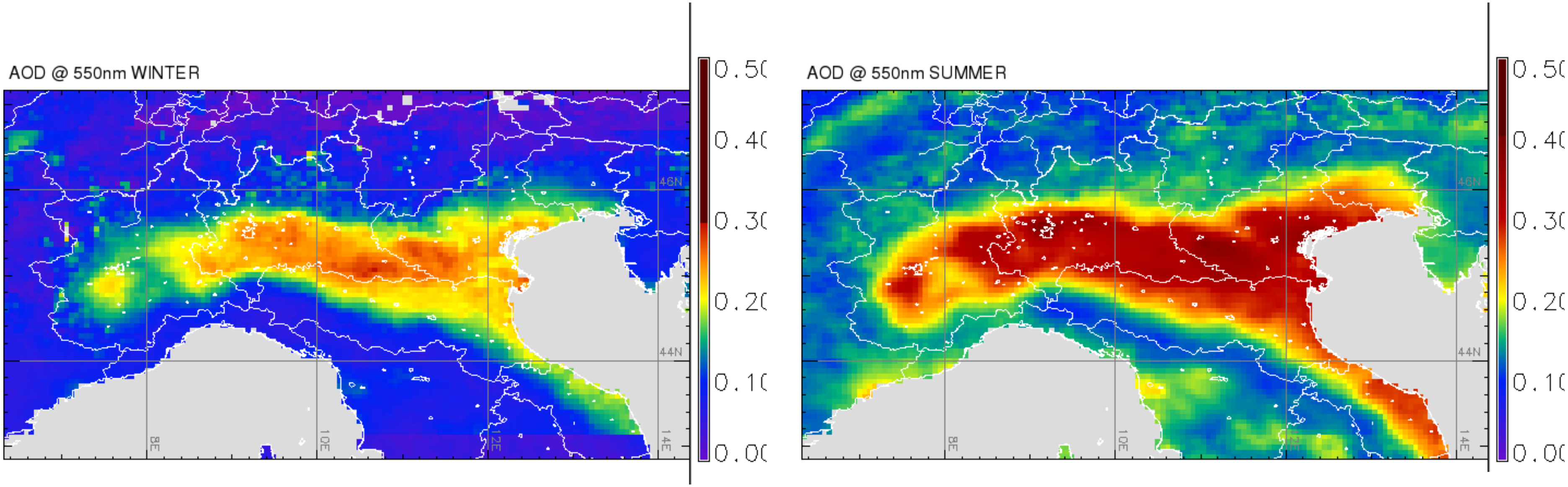


Daily $PM_{2.5}$ concentrations derived from MODIS/Terra (on the left) and MODIS/Aqua (on the right) observations against corresponding in-situ samplings relative to the six validation (blue) sites for summer 2007 and winter 2008. In both plots, the linear regression line (red for Terra and blue for Aqua) and the y = x grey dashed line are also reported

Other remarks

- It is known that Modis estimates of η over land are not correct; nevertheless, in Po Valley η is almost always > 0.9 except during dust transport episodes (in this work, data with $\eta < 0.4$ has been excluded from calculations), so we assume this error to be negligible.
- Multiannual averages are obtained by first averaging for single years, then computing the average over 8 years (missing data are not evenly distributed in years)

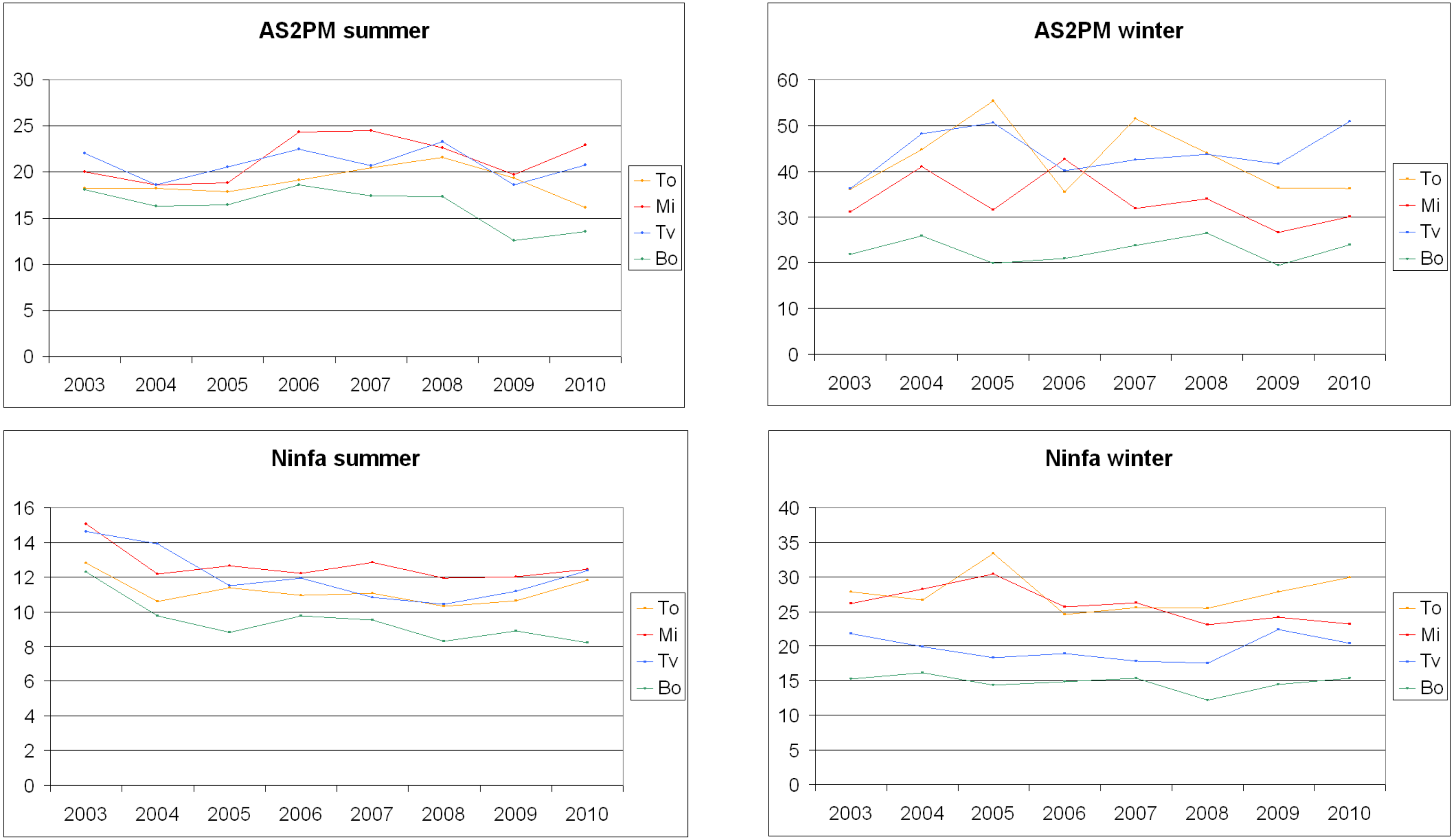
AOD maps



Average AOD observed by Modis: winter (left) and summer (right) months

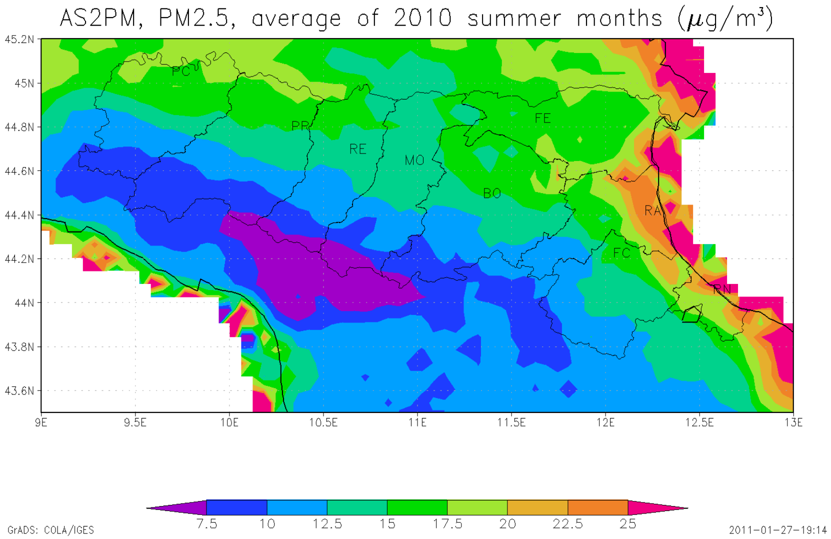
- summer > winter
- spatial patterns
- seasonal averages

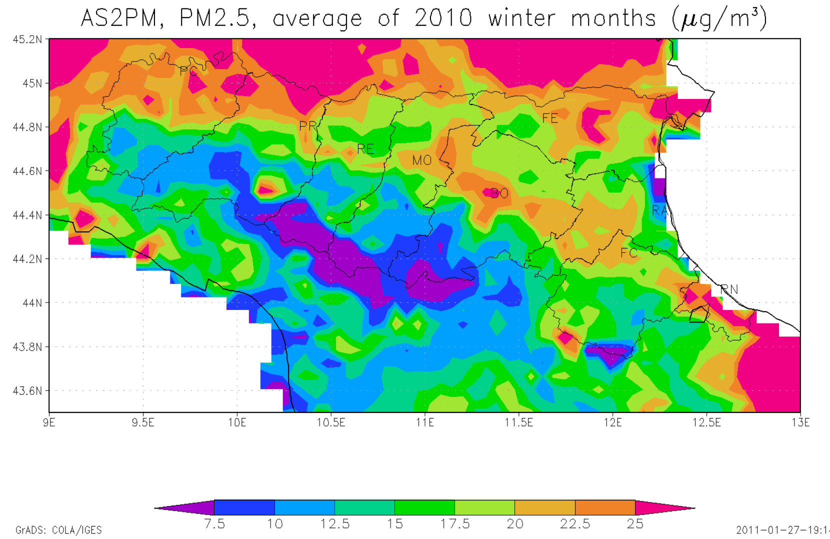
Pm2.5 interannual variability (2)



- No significant trend
- Interannual variability (≈20%) is lower than spatial variability (≈50%)

- Low correlation between AS2PM and Ninfa (sum 0.14, win 0.09)
- Spatial correlation looks better





Stazione	Prov.	Codice	Media estate	Media inverno
BADIA	PR	2000214	10.3	21.3
S. ROCCO	RE	3000022	14.9	32.6
BESENZONE	PC	5000062	14.3	30.3
GAVELLO	MO	4000152	13.9	29.4
S. PIETRO CAPOF.	BO	7000027	13.6	28.5
GHERARDI	FE	8000007	10.6	23.7
OSTELLATO	FE	8000041	12.9	26.1
BALLIRANA	RA	9000068	17.0	31.2
SAN CLEMENTE	RN	10000060	9.7	19.6
Media staz. rurali			**13.0**	**27.0**

Stazione	Prov.	Codice	Media estate	Media inverno
P. MONTECUCCO	PC	5000065	15.1	32.0
S. LAZZARO	RE	3000007	12.8	30.5
MARECCHIA	RN	10000002	11.3	30.1
Media staz. suburb.			**13.1**	**30.8**
CITTADELLA	PR	2000003	11.4	29.5
P. FERRARI	MO	4000022	13.1	30.0
GIAR.MARGH.	BO	7000014	10.5	24.5
P. RESISTENZA	FO	6000010	8.9	27.8
VILLA FULVIA	FE	8000040	12.1	29.2
GIARDINI	RA	9000071	11.1	25.0
Media staz. urbane			**11.2**	**27.7**

Short version

(replacement for slides 3 to 6)

Methodology

PM2.5 concentrations in Northern Italy have been estimated for an 8 years period (2003-2010) in two independent ways:

1) By use of MODIS level 2 data (AOD and η), PM2.5 ground measurments and meterological fields (Hmix and RH)
2) By use of a CTM (Chimere)

Results of the two methods have been qualitatively compared, and their potential usefulness assessed.

Limitations:

The main limitation of this approach is the high number of missing data in satellite measurements: clear sky conditions are required, and in Po Valley days with **valid data** turned out to be ≈ **60% in summer and** ≈ **25% in winter**

This prevents day-to-day use of satellite data: in this work, 6 months averages (Apr-Sep and Oct-Mar) have been taken into account.

Moreover, PM concentrations can not be retrieved over sea, and measurements are unreliable in highly complex terrain.