INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Team clime

Couplage de la donnée environnementale et des modèles de simulation numérique pour une intégration logicielle

Paris - Rocquencourt

THEME NUM

Activity Report

2007

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2. Overall Objectives

2.1. Overall Objectives

The international political and scientific context is indicating the serious potential risks related to environmental problems, and is also pointing out the role that can be played by models and observation systems for the evaluation and forecasting of these risks. At the political level, agreements such as the Kyoto protocol, European directives on air quality or on major accident hazards involving dangerous substances (Seveso directive) and the French Grenelle de l'Environnement establish objectives for the mitigation of environmental risks. These objectives are supported at a scientific level by international initiatives like the European GMES program (Global Monitoring of Environment and Security), or national programs such as the Air Chemistry program which give a long term structure to environmental research. These initiatives emphasize the importance of observational data and also the potential of satellite acquisitions.

The complexity of the environmental phenomena as well as the operational objectives necessitate a growing interweaving between physical models, data processing, simulation and database tools.

This situation is met for instance in atmospheric pollution, an environmental domain whose modeling is gaining an ever-increasing significance, either at local (air quality), regional (transboundary pollution) or global scale (greenhouse effect). In this domain, modeling systems are used for operational forecasts (short or long term), detailed case studies, impact studies for industrial sites, as well as coupled modeling (e.g. pollution and health, pollution and economy). These scientific subjects strongly require linking the models with all available data; these data being either of physical origin (e.g. models outputs), or coming from raw observations (satellite acquisitions and/or information measured *in situ* by an observation network), or obtained by processing and analysis of these observations (e.g. chemical concentrations retrieved by inversion of a radiative transfer model).

Clime has been created for studying these questions by joining in one single team researchers in data assimilation, modeling, and image processing. Clime carries out research activities in three domains:

- Environmental data processing: image processing accounting for the available physical information; Image Assimilation, aiming to the assimilation of data characterized by a strong spatio-temporal coherency.
- Data and model coupling, by means of data assimilation techniques and related issues (optimization problems, targetting observation, uncertainties propagation, ...).
- Development of integrated chains for data/models/outputs (system architecture, workflows, databases, visualization, ...).

3. Scientific Foundations

3.1. Environmental images and data processing

Keywords: *fluid flow*, *image assimilation*, *image processing*.

Data with image nature, and especially satellite data, represent a huge amount of observations which is up to now largely unexploited by the environmental numerical forecast models. The state-of-the-art is the assimilation of satellite data on a pixel basis: each pixel constitutes an independent information, expressed as a more or less simple function of the model's state variable. The objective is to exploit the structure of the image observations by defining Image Assimilation methodologies: how to assimilate data with spatial and temporal coherency, such as observations of evolving fronts or eddies? Three alternative approaches are considered:

- Extension of image processing techniques by accounting for all available physical information, either on the observed phenomena (evolution laws) or on the process of image formation (radiative transfer), to derive estimates of the forecasting model's state variables, that can be directly assimilated. A typical example is the assessment of apparent motion from image observations of turbulent fluids, the approach taking advantage of the fluid mass conservation principle as well as numerical regularization techniques (div-curl) preserving the vorticity of turbulent motion.
- Definition of Image Models to solve ill-posed image processing problems, usually addressed using numerical regularization techniques. The Image Model describes the dynamic of the image and makes it possible to formulate a data assimilation problem, where image observations are assimilated within the Image Model. This approach constitutes a relevant way to solve image processing problems based on dynamics, in which difficult issues such as occlusions or missing data are easily formulated.
- Definition of Image Models coupling variables from the image domain and from the forecasting model (as the Conceptual Models developed by meteorologists to describe specific meteorological phenomena and their signature on image data). The assimilation is then performed in two steps: first, in the Image Model to yield "bogus" observations of the forecasting model's state variables, then directly in the forecasting model.

3.2. Data assimilation and inverse modeling

Keywords: *data assimilation*, *ensemble forecast*, *inverse modeling*, *network design*.

This activity is currently one of the major concerns of environmental sciences. It matches up the setting and the use of data assimilation methods, notably variational methods (4D-var). An emerging point lies in the propagation of uncertainties in models, notably through ensemble forecasting methods.

Although modeling is not part of the scientific objectives of Clime, we have complete access to models developed by CEREA (joint ENPC/EDF R&D laboratory): Polair3D (photochemical pollution forecasting at continental and regional scales) and CASTOR (urban scale) for air quality problems. In regard to other modeling domains, Clime accesses models through co-operation initiatives either directly (for instance the shallow water model developed at MHI, Ukrain, has been provided to the team), or indirectly (for instance, image assimilation methodologies for meteorology are tested by our partners on their models).

The research activities tackle scientific issues such as:

- Which observational network should be set up to perform a better forecast, while taking into account additional criteria such as observation cost? What are the optimal location, type and mode of deployment of sensors? How should the trajectories of mobile sensors be operated, while the studied phenomenon is evolving in time? This issue is usually referred as “network design”.
- How to assess the quality of the prediction? How do data quality, missing data, data obtained from sub-optimal locations, affect the forecast? How to better include information on uncertainties (of data, of models) within the data assimilation system?
- Within a family of models (differing by their physical approximations or their discretization parameters) which is the optimal model for a given set of observations?
- How to make a forecast (and a better forecast!) by using several models corresponding to different physical formulations? It also raises the question: how should data be assimilated in this context?

3.3. Software chains for environmental applications

Keywords: *database*, *system architecture*, *visualization*, *workflow*.

An objective of Clime is to participate in the design and creation of software chains for impact assessment and environmental crisis management. Such software chains bring together static or dynamic databases, data assimilation systems, forecast models, processing methods for environmental data and images, complex visualization tools, scientific workflows, *etc*.

Clime is currently building, in partnership with CEREA and EDF R&D, such a system for air pollution modeling: Polyphemus (see Internet page http://cerea.enpc.fr/polyphemus/), whose architecture is specified to satisfy the data requirements (e.g. various raw data natures and sources, data preprocessing) and to support different uses of an air quality model (e.g. forecasting, data assimilation, ensemble runs).

4. Application Domains

4.1. Panorama

The central application is atmospheric chemistry, on which the majority of resources are affected. We develop and maintain the air quality modeling system Polyphemus which includes several numerical models (Gaussian, local scale, the 3D Eulerian model Polair3D) and their adjoints, and different high level methods: simple forecast, ensemble forecast, sequential and variational data assimilation algorithms. Advanced data assimilation, network design, inverse modeling, ensemble forecast problematics are studied in the context of air chemistry, since addressing these high level issues requires controlling the full software chain (models and data assimilation algorithms): this is the current situation due to the priority put on air chemistry. An activity on assimilation of satellite data is also starting in this context, but due to the lack of expertise on available image structures, Clime decided to tackle Image Assimilation on other applications.

Meteorology and oceanography, are addressed in cooperation with external partners who provide the numerical models. These two applications are privileged for addressing Image Assimilation studies, e.g. assimilation of structures observed on satellite images. Concerning meteorology, the focus is on the forecast of high impact weather events (cyclones, convective storms, *etc*.). Concerning oceanography, the aim is to improve the forecast of ocean circulation, in relation with global warming issues.

Finally, Clime carries out applied remote sensing activities in close cooperation with environmental experts. These studies concern the potential use of satellite data for monitoring agriculture and natural risks: assessment of hail damage, soil degradation (desertification). For these studies, an image model of the observed phenomenon is first established, then tracking and change detection techniques are applied in the state space of this model.

4.2. Air quality

Air quality modeling implies studying the interactions between meteorology and atmospheric chemistry in the various phases of matter which leads to the development of highly complex models. The different usages of these models comprise of operational forecasting, case studies, impact studies, *etc*, with both societal (e.g. public information on pollution forecast) and economical impacts (e.g. impact studies for dangerous industrial sites). Models lack some appropriate data, notably emissions, to perform an accurate forecast and data assimilation techniques are recognized as a key point for the improvement of forecast's quality. These techniques, and notably the variational ones, are progressively surfacing in atmospheric chemistry.

In this context, Clime is interested in various problems, the following being the crucial ones:

- The definition of second order data assimilation methods for the design of optimal observation networks. Management of combinations of sensor types and deployment modes. Dynamic management of mobile sensors' trajectories.
- The development of ensemble forecast methods for estimating the quality of the prediction, in relation with the quality of the model and the observations. Sensitivity analysis with respect to the model's parameters so as to identify physical and chemical processes, whose modeling must be improved.
- The development of methodologies for super-ensemble forecasts (different models, or different configurations of the same model). Investigation on how super-ensembles must be generated, with how many members and with which constraints?
- How to estimate the source of an accidental release of a pollutant, using observations and a dispersion model (from the near-field to the continental scale)? How to optimally predict the evolution of a plume? Hence, how to help people in charge of risk evaluation for the population?
- The assimilation of satellite measurements of troposphere chemistry.

The activities of Clime in air quality are supported by the development of the Polyphemus air quality modeling system. This system has a modular design which makes it easier to manage high level applications such as inverse modeling, data assimilation and ensemble forecast.

4.3. Meteorology

Meteorological forecasting constitutes a major application domain for Image Assimilation. Although satellite data are operationally assimilated within models, this is done on an independent pixel basis: the observed radiance is linked to the state variables via a radiative transfer model that plays the role of an observation operator. Indeed, because of their limited spatial and temporal resolutions, numerical weather forecast models fail to exploit image structures, such as precursors of high impact weather:

- cyclogenesis related to the intrusion of dry stratospheric air in the troposphere (a precursor of cyclones);
- convective systems (supercells) leading to heavy winter time storms;
- low-level temperature inversion leading to fog and ice formation, *etc*.

To date, there is no available methods for assimilating data which are characterized by a strong coherence in space and time. Meteorologists have developed Conceptual Models (CMs) for describing the high impact weathers and their signature on images, and have developed tools to detect CMs on image data. The result of this detection is used for a manual correction of numerical models, for instance by modifying the initialisation. The challenge is therefore to develop a methodological framework allowing the assimilation of the detected CMs within numerical forecast models, a very important issue considering the considerable impact of these meteorological events.

4.4. Oceanography

The capacity of performing an high quality forecast of the state of the ocean, from the regional to the global scales, is a major requirement of global warming studies. Such a forecast can only be obtained by systematically coupling numerical models and observations (*in situ* and satellite data). In this context, as in meteorology, being able to assimilate image structures becomes fundamental. Examples of such structures are:

- apparent motion linked to surface velocity;
- trajectories, obtained either from tracking of features, or from integration of the velocity field;
- spatial structures, such as fronts, eddies or filaments.

Image Models for these structures are developed taking into account the underlying physical processes. Image data are assimilated within the Image Models to derive pseudo-observations of the state variables which are further assimilated within the numerical ocean forecast model.

4.5. Remote sensing for natural risks and agricultural monitoring

Clime is involved in several research actions related to environmental monitoring which are interrelated from a methodological point of view. These studies are based on the analysis of satellite images time-series at low (AVHRR, MODIS) or high (SPOT) spatial resolution for monitoring changes in the environment. Among the ongoing projects are land degradation monitoring, desertification monitoring, and hail damage assessment.

These studies have their origin in previous activities and cooperation initiatives of the team. However, as these applications lack the availability and expertise of numerical forecasting models, it is difficult to address these applications in the framework of data and models coupling, hence these activities are of lower priority and will progressively cease.

5. Software

5.1. Polyphemus

Participants: Vivien Mallet, Meryem Ahmed de Biasi, Lin Wu, Irène Korsakissok, Marilyne Tombette, Yelva Roustan, Bruno Sportisse.

Polyphemus (see Internet page http://cerea.enpc.fr/polyphemus/) is a modeling system for air quality. As such, it is designed to yield up-to-date simulations in a reliable framework: aerosols, data assimilation, ensemble forecast and daily forecasts. Its completeness makes it suitable for use in many fields: photochemistry, aerosols, radionuclides, *etc*. It is able to handle simulations from local to continental scales, with several physical models. It is divided into three main parts:

- libraries that gather data processing tools (SeldonData), physical parameterizations (AtmoData) and postprocessing abilities (AtmoPy);
- programs for physical preprocessing and chemistry-transport models (Polair3D, Castor and Gaussian models);
- drivers on top of the models in order to implement advanced simulation methods such as data assimilation algorithms.

Figure 1 depicts a typical result produced by Polyphemus. Clime is involved in the overall design of the system and in the development of advanced methods in data assimilation and ensemble forecast (through drivers and post-processing). The main achievements in 2007 are (1) the development of local-scale models and their coupling with the higher-scale models, (2) the improvement in model physics and in data assimilation algorithms, (3) the release of two stable versions (1.1 and 1.2), and (4) a better transfer and support activity that includes two training days (one in Paris, the other in Santiago de Chile).

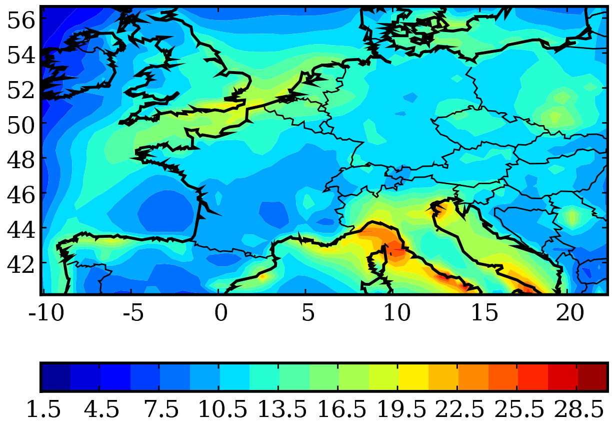

Figure 1. Map of the standard deviation (or spread) of an ensemble built with Polyphemus (ozone simulations, $\mu g\ m^{-3}$). The standard deviations are averaged over the summer of 2001. They provide an estimation of the simulation uncertainties.

6. New Results

6.1. Ill-posed problems in computer vision and variational data assimilation

Keywords: *data assimilation*, *ill-posed problem*, *image processing*, *spatial regularization*.

Participants: Dominique Béréziat, Isabelle Herlin.

We began last year a study for using data assimilation as a generic tool to solve computer vision problems. The common feature of these problems is to be ill-posed (in the Hadamard sense) and an usual way to solve them is to perform a spatial regularization using the Tikhonov formulation. This approach gives a solution which is simultaneously close to the observation and regular in the spatial domain. If a temporal process is considered, such as motion estimation, spatio-temporal segmentation or object tracking, the regularization usually remains static. Even if it is possible to perform this regularization in space-time, this would not provide a realistic description of the temporal dynamic.

Variational data assimilation can solve efficiently a system of three components: 1) the evolution model describes the evolution in time of the state variables, 2) the observation equation describes the link between the state variables and the observations, 3) the initial condition. This data assimilation framework makes it possible to handle the lack of data and the model inaccuracy by weighting each component with an error covariance matrix.

We proved that ill-posed problems in computer vision may be solved in space-time using variational data assimilation methods: the evolution model acts as the Tikhonov regularization term and the observation equation constrains the solution being close to the observations. The difficult task is the choice of an evolution model adapted to the experimental context:

- a first possibility is to consider the transport of state variables. For example, the transport of velocities provides an admissible evolution model;
- a second possibility is a diffusion equation. Diffusion schemes, widely used in computer vision for filtering images, have interesting smoothing properties and strong links with the Tikhonov regularization.

The definition of covariance matrices is obviously important. The use of an exponential covariance matrix for the evolution model achieves the spatial regularization of the solution in L^2 sense. The covariance matrix of the observation equation handles a possible lack of data by quantifying the quality of observation.

6.2. Optical flow computation using variational data assimilation

Keywords: *data assimilation*, *optical flow*.

Participants: Dominique Béréziat, Isabelle Herlin.

We hereby present the first application of the theorical framework described in section 6.1 for the computation of motion vectors.

- The evolution model describes the transport of velocities. This model constrains the temporal regularity of the motion field. Spatial regularity is achieved by assigning to this evolution model an isotropic exponential covariance matrix.
- The observation equation is derived from the optical flow constraint equation (EOFC) that describes the transport of the image brightness. EOFC is used in its non-linearized form in order to handle large displacements.

The transport of velocity has the drawback of being highly non-linear and the discretization leads to an unstable numerical scheme. It is however possible to obtain a convergent scheme using an additive diffusive term (known as the Lax method). This fact motivates an ongoing study on the use of a diffusion equation as evolution model instead of a velocity transport equation.

6.3. Surface velocity estimation from oceanographic images

Keywords: *data assimilation*, *motion estimation*, *oceanography*, *remote sensing*.

Participants: Etienne Huot, Gennady Korotaev [Marine Hydrophysical Institute, Ukrain], Isabelle Herlin, François-Xavier Le Dimet [MOISE], Lin Wu.

The objective of this study is to compute the surface velocity from a sequence of oceanographic satellite images. The problem of motion estimation from a sequence of images has been long addressed by the image processing scientific community. It can be tackled by solving a PDEs system based on a conservation equation and a regularity equation.

Last year we proposed a new method using the data assimilation framework: the available satellite images constitute observations of Sea Surface Temperature (SST), to be assimilated within a dedicated *Image Model* (IM), used to describe motion. The major drawback of this approach was the lack of physical meaning of the evolution equations used in IM.

In this study, we define a new IM taking into account the physical evolution of the observed quantity. The state space of this IM is defined by the SST, the 2D components of the apparent motion and the elevation of the sea surface. IM equations implement an advection-diffusion of SST expressed in the 2D image space coupled to a *Shallow Water* model. Shallow Water equations are commonly used to express the evolution of elevation and velocity.

SST images are further assimilated into the IM using a 4D-variational approach. Figure 2 displays a velocity estimation result performed with the assimilation of 5 SST images into the IM. It shows the capability of the model to handle missing data (here, a cloud occlusion visible as a dark area in the second image).

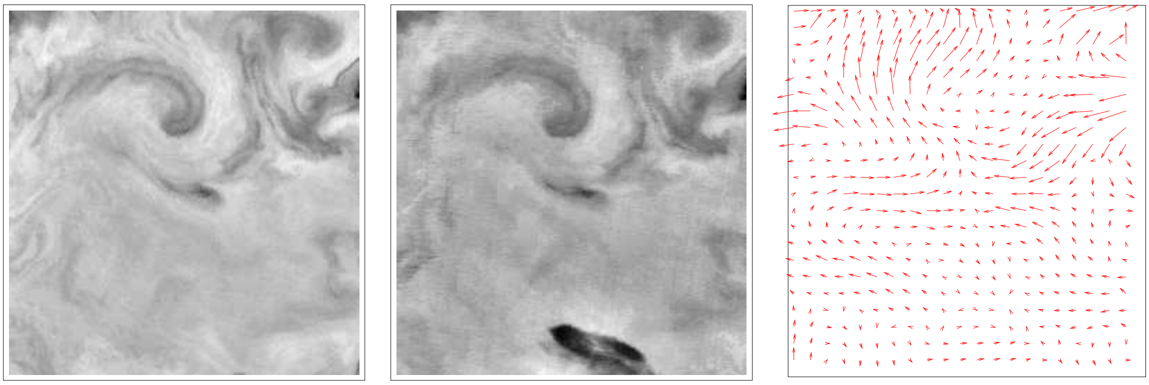

Figure 2. Example of velocity estimation using the Image Model on a Black Sea surface image sequence. Left: two of the five SST images used. Right: estimated velocity field.

6.4. Satellite data assimilation for air quality forecast

Keywords: *air quality*, *data assimilation*, *ozone*, *satellite*.

Participants: Jean-Paul Berroir, Marc Bocquet, Isabelle Herlin, Vivien Mallet, Bruno Sportisse.

This study concerns the feasibility of assimilating satellite soundings of the troposphere's chemical composition for improving air quality forecast. The study is led on simulated data for assessing the feasibility and on real data for the first experiments.

The ozone column, as measured by space-borne sensors, mainly carries information on the ozone concentrations in the free troposphere. The question is whether an improved knowledge of free troposphere ozone will lead to an improved ozone forecast at ground level. To answer this question, a sensitivity study is carried out: are ground level ozone concentrations sensitive to free troposphere ozone concentrations? This study is performed in the framework of twin numerical experiments using simulated data. A perturbed ozone simulation is created by artificially changing the initial concentrations in the free troposphere, and compared to the reference simulation. The maximal impact on the forecasted ground-level ozone is observed 27 hours after the perturbation and its intensity is 15% of the initial perturbation. This figure is rather small but justifies carrying out the assimilation of satellite ozone columns.

The assimilation of real data is currently starting, first with tropospheric NO_2 (provided by IUP Bremen from SCIAMACHY soundings), followed by tropospheric ozone to be soon provided by EUMETSAT from IASI soundings. The application to air quality forecast is performed by assimilating on day 1, then letting the model run for a forecast on day 2. The improvement of forecast, if any, will be achieved by comparing forecast results obtained with and without data assimilation.

This study is part of an ESA-EUMETSAT project (EPS METOP Research Announcement of Opportunity), Clime being Principal Investigator on assimilation of IASI data for air quality forecast. The studies led under this theme also constitute the backbone of Clime's contribution to the TRAQ proposal, coordinated by KNMI (The Netherlands) and CNES (France) for the definition of future ESA Earth Observation missions.

6.5. Comparison of data assimilation algorithms for ozone forecast

Keywords: *air quality model*, *comparison study*, *data assimilation*.

Participants: Lin Wu, Vivien Mallet, Marc Bocquet, Bruno Sportisse.

This work assesses the performance of different data assimilation schemes for short-range (24h) ozone forecast. The underlying air quality models are stiff but stable systems with high uncertainties. The main difficulty of the ozone data assimilation problem is therefore how to account for the strong uncertainties of model. Four assimilation methods have been implemented, namely optimal interpolation (OI), reduced-rank square root Kalman filter (RRSQRT), ensemble Kalman filter (EnKF), and four dimensional variational assimilation (4DVar). The model uncertainties are either parameterized based on the assumption of homogeneous correlations or approximated by perturbing the sources of the uncertainties. All of the four assimilation algorithms are compared under the same experimental settings.

It is found that the assimilations decrease the errors of ozone forecast considerably. The comparison of results reveals the limitations and potentials of each assimilation algorithm. OI provides overall better performance during the assimilation period and the beginning of the prediction period. It benefits from the Balgovind's parameterization of the model error. EnKF shows great potential to produce better forecasts during the end of prediction period. The model error is approximated by the statistics of the ensemble generated using perturbation methods. We pay less attention to RRSQRT, since in our implementation of RRSQRT is quite similar to EnKF. Strongly constrained 4DVar does a mediocre job, because the model uncertainties are taken into account only at the initial date of the assimilation. Nevertheless there are no final conclusion because of the unsettled formulation of the model error.

The sensitivities of assimilation performances with respect to the algorithm parameters are also investigated. The sensitivity analysis suggests that further studies are needed in the design of advanced assimilation methods for better ozone forecasts. Promising subjects are the approximation of model error by enlarged ensemble, and the adaptive assimilation, in which in addition to model state, uncertain model parameters, e.g. vertical diffusion coefficients, are adjusted too.

6.6. Ensemble forecasting with machine learning algorithms

Keywords: *air quality*, *chemistry-transport model*, *data assimilation*, *ensemble forecast*, *impact study*, *multi-pollutants*, *multi-scales*.

Participants: Vivien Mallet, Gilles Stoltz [CNRS & HEC Paris], Boris Mauricette.

In order to account for the uncertainties in air quality forecasts, ensemble simulations are carried out in the Polyphemus system. An ensemble of 48 forecasts is built with different model formulations (physical formulation and numerical discretization), with different input datasets and with perturbed input data.

Based on this ensemble, improved forecasts are generated by means of linear combinations of the individual-model forecasts. A weight is associated to each model, depending on past observations and simulations (see figure 3). Machine learning algorithms (sequential aggregation) were developed and used for this purpose. These methods provide theoretical bounds on the performances (relatively to the optimal constant model combination), and deliver significantly improved forecasts in all configurations.

6.7. Design of a monitoring network over France in case of a radiological accidental release

Keywords: *accidental release modeling*, *geostatistic*, *network design*, *radionuclides dispersion*, *simulated annealing*.

Participants: Rachid Abida, Marc Bocquet.

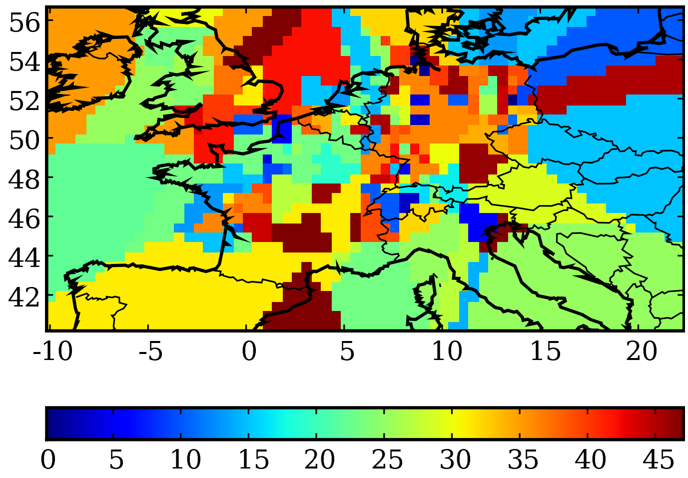

Figure 3. Map of best model indices. This result is built from an ensemble of 48 models (ozone simulations). In each cell of the domain, the color shows which model (marked with its index, in $[\![0, 47]\!]$) gives the best ozone peak forecast on 7 May 2001 at the closest station to the cell center. It shows that many models can deliver the best forecast at some point. Combining the models is therefore a promising approach.

The Institute of Radiation Protection and Nuclear Safety (France) is planning the set-up of an automatic nuclear aerosol monitoring network over the French territory (Descartes network) which complements the Teleray network. Each of the stations will be able to automatically sample the air aerosol content and to provide with activity concentration measurements on several radionuclides. This should help monitor the French and neighbouring countries nuclear power plant park, and evaluate the impact of a radiological incident on this park.

This year work builds on the preliminary study conducted last year devoted to the spatial design of such a network. The potential network is judged on its ability to extrapolate activity concentrations measured on the network stations over the whole domain. The performance of a network is quantitatively assessed through a cost function that measures the discrepancy between the extrapolation and the true concentration fields. These true fields are obtained through the computation of a database of dispersion accidents over one year of meteorology and originating from twenty French nuclear sites, using the dispersion model Polair3D forced by ECMWF meteorological fields. A close to optimal network is then looked for using a simulated annealing optimization. The results emphasize the importance of the cost function in the design of a network aimed at monitoring an accidental dispersion. Several choices of norm used in the cost function are studied and give way to different designs. The influence of the number of stations is studied. A comparison with a purely geometric approach which does not involve simulations with a chemistry-transport model is performed.

6.8. Inverse modeling of atmospheric tracers: non-Gaussian methods and second-order sensitivity analysis

Keywords: *dispersion*, *inverse modeling*, *non-Gaussian model*, *second-order sensitivity*.

Participant: Marc Bocquet.

This work builds on the recent techniques devoted to the reconstruction of sources of an atmospheric tracer at continental scale. The method based on the principle of maximum entropy on the mean is reviewed here. Moreover, a second approach which has not been applied in this field yet is introduced. It is based on an exact Bayesian approach, through a maximum *a posteriori* estimator. The two methods share common grounds, and both perform equally well in practice. When specific prior hypotheses on the sources are taken into account such as positivity, or boundedness, both methods lead to purposefully devised cost-functions. These cost-functions are not necessarily quadratic because the underlying assumptions are not Gaussian. As a consequence, several mathematical tools developed in data assimilation on the basis of quadratic cost-functions in order to establish *a posteriori* analysis, need to be extended to this non-Gaussian framework. Concomitantly, the second-order sensitivity analysis needs to be adapted, as well as the computations of the averaging kernels of the source and the errors obtained in the reconstruction. All of these developments are then applied to a real case of tracer dispersion: ETEX. Comparisons are made between a least squares cost function (4D-Var) approach and a cost-function which is not based on Gaussian hypotheses. Besides, the information content of the observations which is used in the reconstruction is computed and studied on the application case. A connection with the degrees of freedom for signal is also established. As a by-product of these methodological developments, conclusions are drawn on the information content of the ETEX dataset as seen from the inverse modeling point of view.

6.9. Probing ETEX-II data set with inverse modeling

Keywords: *dispersion*, *inverse modeling*, *model error*.

Participants: Monika Krysta [MOISE], Marc Bocquet, Jorgen Brandt [National Environmental Research Institute, Dannemark].

During this task, an account on the results of source inversion of the ETEX-II experiment is given and new results on ETEX-II are obtained. Inversion has been performed with the maximum entropy method on the basis of non-zero measurements and in conjunction with the transport model Polair3D. The discrepancy scaling factor between the true and the reconstructed mass has been estimated to be equal to 7. This strong mismatch agrees with earlier assumptions by J. Brandt.

The results contrast with the method's performance on the ETEX-I source. In the latter case its mass has been reconstructed with an accuracy exceeding 80%. The large value of the discrepancy factor for ETEX-II could be ascribed to modeling difficulties, possibly linked not to the model itself but rather to the quality of the measurements.

6.10. Geophysical fluid motion estimation

Keywords: *fluid motion*, *multiscale*, *optical flow*, *quasi-interpolation*, *radial basis function*, *turbulence*, *vector spline*.

Participants: Till Isambert, Jean-Paul Berroir, Isabelle Herlin, Christine Graffigne [Université Paris V].

This study is part of a PhD on apparent motion estimation from sequences of oceanographic and meteorological images where fluid flows (ocean surface or air masses) are observed. The vector spline framework is applied to the motion estimation problem, owing to two characteristics:

1. the conservation equation, either luminance or mass conservation, is only taken into account at selected control points where image data provide sufficient information on motion;
2. the second order div-curl regularity constraint is easily minimized using vector splines. As this constraint makes it possible to control the spatial variations of divergence and curl of the motion field, it is advocated for turbulent flows.

However, the rigorous vector spline solution is based on thin-plate splines, preventing a multiscale motion representation, although the latter is highly required for turbulent motion.

An adaptation of vector splines is proposed for allowing multiscales motion representation.

- At each spatial scale, the vector spline problem is formulated as a minimization problem: an energy function is defined as the sum of residuals of the conservation equation at the control points plus the regularity constraint. The solution is searched among a predefined class of splines, linear combinations of bell-shaped compactly supported radial basis functions, thus suitable to multiscale representation.
- The motion at different scales is computed from a pyramidal representation of two successive images. The motion field is the sum of the coarse resolution motion and of motion increments computed at different scales.

The algorithm is on average ten times faster than the rigorous vector spline method and less prone to numerical instabilities. The retrieval of the vector spline remains numerically stable with respect to the number and location of the control points, whereas the retrieval of the rigorous spline is practically impossible for a large number of control points (above $5,000$). The increments of motion at different scales capture motion patterns such as limited-size eddies. For example, we can see in figure 4 a vortex in the bottom part which is not localized at coarse scale and appears at finer scale.

Figure 4. Left to right: Image of SST; Reference streamline of the motion field (OPA circulation model, thanks to Marina Lévy, LOCEAN, IPSL); Streamline of the motion estimated at coarse and fine scale.

6.11. Estimation of hail damages on vineyards from SPOT images

Keywords: *GIS*, *change detection*, *hail damage*, *vegetation*.

Participants: Christian Rossi, Jean-Paul Berroir, Isabelle Herlin.

This study on using SPOT satellite images for assessing hail damages to wineyards is led in co-operation with the LYNX company. Previous results were the definition of image indices, well correlated to human damage expertises.

This year, the objective was to refine this statistical approach by: (1) leading a spatial analysis using a GIS, in view of determining spatial features to refine the correlation between human damage expertises, satellite image indices, and effective harvest records; (2) adapting a grape growth phenological model in an attempt to forecast the production of wine parcels from satellite images.

The correlation between satellite indices and human expertises happens to disappear if the hail intensity decreases. As we could not exhibit spatial features explaining this lack of correlation, we interpret it as a consequence of the low density of wineyards vegetation cover – hence a low satellite signal.

The adaptation of the phenological model to satellite data was difficult because of the lack of data (unsufficient temporal sampling, absence of meteorological data, lack of ground truth). A coupling of high spatial and high temporal resolution data, together with ancillary data such as meteorological records, seems necessary to reach the objective.

6.12. Automating the learning process of a large scale classification chain

Keywords: *environmental monitoring*, *fuzzy logic*, *learning*.

Participants: Carlos de la Torre, Isabelle Herlin, Jean-Paul Berroir, Eleni Tomai [FORTH-IACM], Nicolas Mercier.

This study concerns the automation of the learning process required for operating a large scale classification from time-series of low resolution satellite images. In such an application, the satellite provides profiles (e.g. time-series of vegetation indices) which are fit by polynomials in order to reduce noise and to define a feature space where to classify them. Each specific application requires adaptation to site, sensor, nature of classes, and hence a learning must be performed. The objective of the present study is to automate as much as possible this learning.

The issues addressed are:

- Determination of low resolution classes by clustering of temporal profiles.
- Characterization of profiles by high-level features, taking advantage of the algebraic expression of profiles provided by the fit;
- Selection of relevant features (allowing class discrimination) among an initial large set of features describing the profiles;
- Statistical analysis of the feature distribution per class, in view of selecting the most adapted classifier: correlated as well as saturated feature distributions, that cannot be considered as Gaussian, are modelled using fuzzy membership functions. Each feature is then considered as an information source. The classification results from the fusion of these sources by techniques such as Dempster-Shafer combination rule or weighted average of membership functions.

6.13. Desertification monitoring from AVHRR data

Keywords: *desertification*, *learning*, *vegetation index*.

Participants: Jean-Paul Berroir, Isabelle Herlin, Sonia Bouzidi [INSAT, Tunisia], Flavio Parmiggiani [CNR ISAC, Italy], Gianpaolo Marra [CNR ISAC, Italy], Gianvito Quarta [CNR ISAC, Italy].

The INRIA P3+3 project DESMED aims to analyze long term time-series of vegetation indices acquired by the NOAA-AVHRR sensor, in order to characterize desertification processes occurring in Northern Africa and Southern Italy. DESMED involves Clime, CNR in Italy, INSAT in Tunisia, and the Ibn Tofail University in Morocco.

A large scale classification chain has been defined according to the automatic learning described in section 6.12. The first experiments allowed to determine the land use classes that can be discriminated at NOAA spatial resolution (1km); these experiments also highlighted the limits of the NOAA sensors in the context of a highly fragmented landscape (case of the Salento test site) and hence the need of upgrading to a higher resolution sensor such as MODIS.

7. Contracts and Grants with Industry

7.1. IRSN

A convention has been established between CEREA (Clime is simultaneously a team of CEREA and a project-team of INRIA) and IRSN. This convention notably includes the installation of the Polyphemus software at the technical crisis centre of IRSN. A research contract is furthermore underway concerning network design: its objective is the optimal definition of an aerosol monitoring network for detection and diagnosis in the event of an accident/event in a French or neighbouring nuclear power plant.

7.2. INERIS

Clime is partner with INERIS (National Institute for Environmental and Industrial Risks) in a joint cooperation devoted to air quality forecast. This includes research topics in data assimilation and ensemble modeling.

8. Other Grants and Activities

8.1. National initiatives

- The project “Application of advanced inverse modelling and data assimilation methods to accidental dispersion of pollutants in an emergency situation” has been accepted under the framework of the LEFE-ASSIM program of INSU. It will finance a cooperation with the Finnish Meteorological Institute. A postdoctoral grant of IRSN has been labelled by this program.
- Clime is member of the ADDISA contract (Ministry Grant, started at the beginning of 2007), with the MOISE project-team (INRIA Grenoble Rhône-Alpes), the LEGI, the CNRM/GAME laboratory of Météo-France and the MIP laboratory of Université Paul Sabatier in Toulouse. This contract deals with image assimilation and application to forecast of extreme meteorological events and marine circulation.
- Clime is leading ADDISAAF (*Assimilation de Données Distribuées et Images SAtellite pour l’AFrique*) funded by IRD in the Corus program framework, in collaboration with ENIT (Tunisia), the Yaoundé University, and MOISE project-team.
- Clime is participating to the TRAQ proposal (TRophospheric composition and Air Quality) for the definition of the future ESA troposphere chemistry mission (before 2015), currently pre-selected in a short list. Clime is therefore involved in the “GST TRAQ” (TRAQ scientific group), involving the French community of atmospheric remote sensing and coordinated by CNES.
- Clime provides support to INERIS in order to operate the Polyphemus system, primarily for local-scale applications (dispersion of water plumes).
- A project aiming to optimal design of an air quality monitoring network at regional and national scale has been accepted by the Ile-de-France region in the framework of the R2DS program, granting two years of postdoctoral fellowship.
- Clime takes part to the ANR project ATLAS ("From Applications to Theory in Learning and Adaptive Statistics"). Clime collaborates with Gilles Stoltz, co-leader of ATLAS, on the application of machine learning to ozone forecasting.

8.2. European initiatives

- Clime is a Principal Investigator of the ESA-Eumetsat “EPS-Metop” Research Announcement of Opportunity on assimilation of space-borne chemical measurements of the troposphere with application to air quality forecast. The EPS-Metop satellite is officially operational since May 2007 and the “level 2” chemical products will be soon available. Clime has so far performed preliminary studies and has started researches on the assimilation of EPS data.
- A cooperation with the Max-Planck Institute (Hamburg, Germany) has been initiated on the modeling of the long range transport of biomass burning aerosol plumes observed on satellite images.
- Clime is member of the ERCIM working group “Environmental Modeling”. Within this working group, Clime cooperates with FORTH-IACM on remote sensing methodologies, GIS and definition of ontologies for complex applications.

8.3. International initiatives

- Clime has strong cooperations with CMM (Chile) and University of Cordoba (Argentina) on establishing air quality forecast systems and data assimilation capacities in Chile and Argentina. This cooperation is currently supported by the research project STIC-AmSud. The objective is the forecast of air quality using data assimilation techniques in South America. This project involves CMM (Chile), the Chilean weather office (DMC, Chile), the University of Cordoba (Argentina), and the environmental monitoring group of CNEA (Argentina).
- A new collaboration with the Nansen-Zhu International Research Center (Institute of Atmospheric Physics, Chinese Academy of Sciences) started with two objectives: attempting to perform operational forecast with Polyphemus for the Beijing Olympic Games (2008), and a long-term collaboration for air quality forecast, data assimilation and ensemble forecast.
- An ECO-NET project, ADIMO, started in 2006. This contract is led in cooperation with the MOISE project-team, the Institute for Numerical Analysis in Moscow (Russia), and the Institute of Oceanography in Sevastopol (Ukraine). The objectives of ADIMO concern the assimilation of images within ocean circulation models.
- A Stic-Asia project (MSND, Models and Simulations for Natural Disasters) started in 2006 with ESIEE (France), the Chinese Academy of Surveying and Mapping, the Faculty of Engineering Multimedia (University of Malaysia), the Faculty of Social Sciences and Humanities (University of Kebangsaan, Malaysia), and the Malaysian Centre for Remote Sensing. Clime is involved in the detection of precursors of extreme meteorological events.
- A Safeti project (cooperation with South Africa in Information Technologies) has been initiated in 2007 with F'SATIE, MERAKA Institute (RSA), IRD and ESIEE (France) on the detection, recognition, tracking and characterization of satellite image features for environmental forecast and monitoring, with applications to ocean circulation and fire detection.
- An INRIA P3+3 Méditerranée project, DESMED, started in 2006 on the study of desertification in Northern Africa and Southern Italy using long term time series of vegetation indices. This project involves CNR-ISAC in Italy, INSAT in Tunisia, and University Ibn Tofail in Morocco.
- A research project, ENVIAIR, was accepted under the framework of the INRIA-CNPQ programme, with the State University of Rio de Janeiro, Federal University of Rio de Janeiro and Embrapa Solos. This contract aims at monitoring deforestation and sustainable agricultural practices in the Taquari basin (Brasil).

9. Dissemination

9.1. Leadership within scientific community

- Dominique Béréziat is member of the commission of specialists for University Paris 6.
- Isabelle Herlin is member of the commission of specialists for University Paris 12.
- Bruno Sportisse is member of Editorial Board of Journal of Computational Geosciences.
- Bruno Sportisse is member of the Scientific Committee of the Research Cluster "Sustainable Urban Development" (Villes et Mobilité Durable, VMD).
- Clime is strongly involved in the national and European scientific community of satellite data for atmosphere chemistry: Clime is member of the ADOMOCA project (PNCA, atmospheric chemistry national programme) on assimilation of satellite atmospheric chemistry missions, is Principal Investigator of a ESA-EumetSat project for the exploitation of EPS-MetOp data for air quality forecast, and member of the TRAQ proposal for the definition of the future ESA tropospheric missions.

9.2. Teaching

- Computer Vision, 36 hours, Master EDITE de Paris / UPMC (Dominique Béréziat).
- Programming (C, Java), 30 hours at ESIEE Management (Jean-Paul Berroir).
- Data Assimilation for Geophysics (ENSTA/ENPC): 30 hours (Marc Bocquet, Vivien Mallet, Bruno Sportisse).
- Algorithmics, 50 hours, ESIEE Management and PULV (Isabelle Herlin).
- Multimedia, 21 hours, ESIEE Management (Isabelle Herlin).
- Computational Physics for Environmental Applications (ENSTA/ENPC): 20 hours (Vivien Mallet, Bruno Sportisse).
- Air Pollution (ENPC & TPE, TRADD/Renault Master): about 80 hours (Bruno Sportisse).
- Applied Mathematics (ENPC): 30 hours (Bruno Sportisse).

9.3. Conference and workshop committees, invited conferences

- Marc Bocquet organized the "Environment" symposium at SMAI 2007 and gave a presentation (June 2007).
- Isabelle Herlin made a presentation on "Inverse Modeling Issues" at Total Solaize Research Center (September 2007).
- Isabelle Herlin made a presentation on "Data Assimilation, Images and Monitoring" at EDF R&D (October 2007).
- Bruno Sportisse gave a lecture on "Air Quality Modeling and Simulation" at Workshop SMAI/IHP, "Mathematics and Environment" (recorded by Canal-U), Institute Henri Poincaré (March 2007).
- Bruno Sportisse gave a talk on "Air Quality Modeling and Transport" at IDEA League, Brussels, European Commission: (June 2007).
- Bruno Sportisse was invited lecturer at Teratech, Versailles: "Air Quality Modeling and Simulation: a Few Issues for HPCN" (June 2007).
- Bruno Sportisse organized a session devoted to "Model Reduction" during the PNLA School CEA/INRIA/EDF and gave one course: "Reduction for Air Quality Modeling" (October 2007).

9.4. Visiting scientists

- Umair Ahsan Cheema [FAST-Geoinformatics, Pakistan, from 11/20 to 12/11]
- Laura Dawidowski [CNEA, Argentine, from 06/30 to 07/15]
- Ines Karouia [ISET, Tunisie, from 07/14 to 07/29]
- Gennady Korotaev [MHI, Ukrain, from 08/27 to 08/31]
- Karla Longo [CPTEC, Brazil, from 04/02 to 04/06]
- Flavio Parmiggiani [ISAC-CNR, Italy, from 05/13 to 05/16]
- Poulicos Prastacos[IACM-Forth, Greece, from 03/19 to 03/23]
- Gianvito Quarta [ISAC-CNR, Italy, from 05/09 to 05/16]
- Eleni Tomai [IACM-Forth, Greece, from 05/06 to 05/20]
- Gustave Udahemuka [F'SATIE, Pretoria, from 11/24 to 12/08]
- Michael Van Wyk [University of Technology Pretoria, South Africa, from 09/29 to 10/10]

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