# Application of Variational Methods of Inverse Modelling for Environmental Risk/ Vulnerability Assessment

*Vladimir Penenko* [1,*], *Alexander Baklanov* [2], *Elena Tsvetova* [1], *Alexander Mahura* [2]

*(1) Institute of Computational Mathematics and Mathematical Geophysics (ICMMG), Siberian Branch, Russian Academy of Sciences (RAS), Novosibirsk, Russia;*
*(2)Danish Meteorological Institute (DMI), Copenhagen, Denmark*
** Corresponding author: penenko@sscc.ru*

## Concept of Environmental Modelling

A methodology has been developed to build the combined methods of forward and inverse modelling for the problems of the air quality, environmental risk assessment and control (*Baklanov, 2007; Penenko et al., 2002; Penenko & Tsvetova, 2007; 2009*). It is based on variational principles and methods of adjoint sensitivity theory (*Penenko, 1981*). This allows one to obtain the optimal numerical schemes and a universal algorithm of the forward - inverse modelling. Following the concept, the functionals describing the generalised characteristics of the processes, data, and models are considered together with the basic model components. To combine all these elements in the frames of forward and back relations, we suppose that each of them may contain uncertainty. In this case, it is naturally to formulate a weak-constraint variational principle for the augmented functional which contains the model description in the form of integral identity and the cost functional including the total measure of all uncertainties. The stationary conditions for the augmented functional with respect to the variations its functional arguments define the mutually agreed structure of numerical schemes for forward and adjoint problems, and sensitivity relations.

For quantitative risk assessment the following characteristics are used: the values of goal functionals and their variations in the form of sensitivity relations; risk functions and sensitivity functions to the variations of the sources. It is convenient to take the risk function multiplied by the source function as a distributed risk measure.

The variational technique provides the backward propagation of information, contained in the target functionals, to parameters and sources of the models through the sensitivity and uncertainty functions. This gives a base for realisation of the feedback algorithms and methods of control theory which are necessary for formulation of multi-criteria optimisation accounting different constraints of ecological, economical, and social essence while solving environmental problems such as air pollution control, design of new industrial unit's placement, etc. The scheme of the variational methods and control theory approach for the environmental risk assessments and mitigation strategy optimization is shown in Fig. 1.

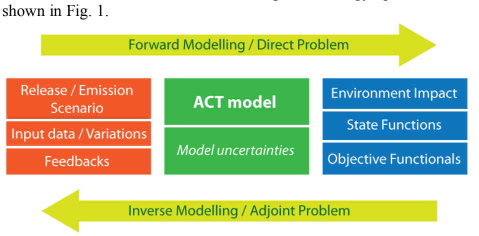


***Figure 1.*** *Simplified scheme of the variational methods and control theory approach for the environmental risk assessments and mitigation strategy optimization.*

The problems of the long-term environmental forecasting demand revealing the dynamical active zones and the areas of increased sensitivity to the variations of forcings (model parameters). The proposed methodology of accounting the climatic data into environmental studies is suitable for studying such kind of problems. Analysis of the long-term behaviour of the global climatic system and orthogonal decomposition of the multivariate series of meteorological data with respect to the scales of processes allows one to identify activity centers and to use this information for construction of scenarios for assessment of risk/vulnerability for sources/receptors.

## Siberian Region: Applications

### *Scenario Approach*

This approach is widely used in numerical modelling for the assessment of current and future states of environmental and ecological systems. *Penenko & Tsvetova (2008)* proposed a methodology for a quantitative description of behaviour of a dynamic system for a long time interval in a compressed generalised form.

Main goal is to include climate information into environmental studies. A necessary information for deterministic/stochastic scenarios is extracted from a database containing measured and/or calculated data on hydrodynamic state functions. The methodology is a development of ideas of principal component and factor analyses. Calculations are made with the help of a method of orthogonal decomposition of phase spaces formed by multivariate, multidimensional state and sensitivity functions from the database.

The method is cost-effective and unlimited by the sizes of the phase spaces. Some results of analysis of the global climatic system behaviour for 56 years (1950-2005) based on reanalysis data of 500-hPa geopotential height are shown in Fig. 2.

For orthogonal decomposition the NCEP/NCAR reanalysis database (*Kalnay et al., 1996*) was used. Two types of bases are calculated: principle components (PC) and orthogonal base subspaces (OBV). The first characterize variability of the initial sampling with respect to the constructed OBV-system, the latter consists of 4D (space-time) orthogonal base vectors.

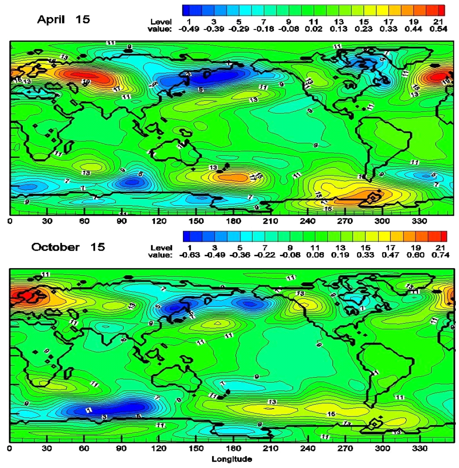


***Figure 2.*** *Fragments of the leading orthogonal base subspaces corresponding to maximum eigenvalues of the Gram matrix /Each fragment corresponds to 00 UTC; areas of local extremes show regions of increased energy activity of the climatic system/.*

### *Long-Term Environmental Impact*

A methodology for multidisciplinary probabilistic environmental risk and vulnerability assessments was suggested (*Baklanov et al., 2006; Mahura et al., 2006*). The DERMA model was employed to simulate air concentration, time integrated air concentration, dry and wet deposition patterns resulted from continuous emissions of chemical risk sites (chemical and metallurgical enterprises). To perform such simulations the European Center for Medium-Range Weather Forecasts 3D meteorological fields were used. For each daily release the followed transport through the atmosphere and deposition due to dry and wet removal processes were estimated on an interval of 2 weeks. Analysis of simulated concentration and deposition fields for each site allow evaluating spatial and temporal variability of these resulted patterns on regional and hemispheric scales (Fig. 3). These results are applicable for GIS integration and essential input for evaluation of doses, impacts, risks, short- and long-term consequences for population and environment from potential sources of continuous emissions.

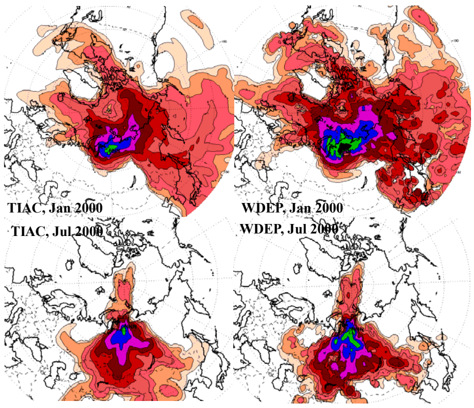


***Figure 3****. Results of the long-term dispersion modelling: time integrated air concentration (TIAC) and wet deposition (WD) for sulphates from the Norilsk nickel plant during Jan and Jul .*

### *Principle Factors*

The Siberian region is of special interest from a viewpoint of decomposition of circulation mechanisms and their manifestation in formation of environmental dynamics. Analysis showed that Siberia is situated in places which separate circulation systems of high energy activity. The areas of increased activity are seen in the leading OBV near the Baikal Lake region (110°E, Fig. 4-left), and 2nd leading OBV, the areas of local extremes indicate the West Siberian wetlands (75°E) and Verkhoyansk region of Yakutiya (130°E) (Fig. 4-right).

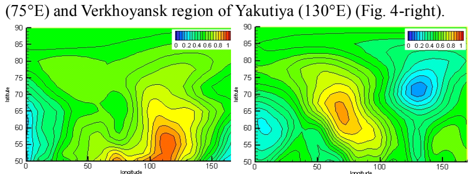


***Figure 4.*** *Fragments of the July leading (left) and second (right) orthogonal base subspaces for the Euro-Asian region /see as above/.*

Analysis of orthogonal subspaces allows to reveal areas of energy active climatic zones in global and regional scales, and it should be considered in studying of environmental processes. Calculated by means of inverse modelling, the risk/vulnerability areas for the objects located in these active zones are characterised by enlarged time-space scales as compared with the outside objects.

### *Risk assessment*

As a consequence of the specific industrial activity, the level of man-made load on environment in Siberia is traditionally high. Besides, recently aerosol emissions increased due to dust storms in the Central and South-East Asia, forest fires, and even military conflicts in Afghanistan and Irak. Due to climate change in Western Siberia the methane emission from wet soils and wetlands became stronger. As a result of photochemical reactions, the increased concentrations of formaldehydes and other active species are produced. The methods of inverse modelling and organising prognostic scenarios allow to obtain necessary estimates acceptable for practical applications without specifying information on emissions. The sensitivity-risk-observability functions with respect to sources of emissions for some industrial regions of Siberia (Khanti-Mansiisk and Jakutsk) are shown in Fig. 5. All cities are located in the corresponding energy active zones. For each scenario the functional describing results of observations by means of ground-based sun/sky photometers from AeroSibNet observational system was used as the response functional.

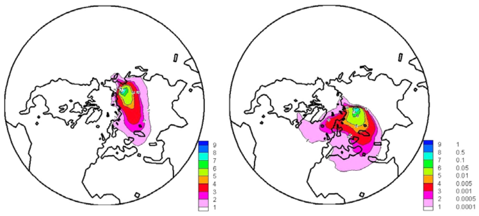


***Figure 5****. Risk/vulnerability/sensitivity functions (reference values) for the Ural and Siberian industrial regions: Ekaterinburg (left) and Tomsk (right).*

Estimates of the relative contribution of the pollutants emissions from acting and potentially possible sources located in the region to the functional of the atmosphere quality in the receptor area are shown in Fig. 6. This fragment is 2D cross-section of 3D function obtained by integration, with respect to time, of 4D SF of the prognostic functional to variations of the source function of the model. The higher the SF values, the greater the risk of pollution of the receptor area from sources. To estimate the risk of pollution of the receptor area owing to transboundary transport, it is necessary to take into account information contained in sensitivity functions on the domain boundaries.

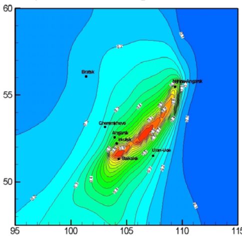


***Figure 6****. October estimates of the relative contribution of pollutant emission from acting and potentially possible sources /corresponds to the lower level of the model/. The values on the isolines are obtained by normalization of the integrated SF to its maximum in the entire 3D domain of the atmosphere in the region.*

## Conclusion

In this study, the concept of environmental modelling based on variational technique is considered. The advantage of this technique is the fact that results of estimating the objective functional, which is a generalised characteristic of the atmosphere quality, are independent of variations of the state functions under conditions of minimising the total measure of uncertainty explicitly included into formulations of mathematical models. From viewpoint of system analysis, the methods of orthogonal decomposition along with the methods of sensitivity theory and risk assessment offer a tool which allows to move results of global atmospheric and climatic studies onto the regional level with concrete questions on environmental quality and its changes.

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