A NEW 4D VARIATIONAL ASSIMILATION METHOD OF SPACEBORNE DATA FOR MOISTURE BUDGET STUDIES

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1. INTRODUCTION

With the advent of spaceborne remote sensing instruments, global and periodic measurements of the atmosphere became available, allowing a potential incredible advance in our knowledge of many aspects of atmospheric processes. Indeed for the last 10 years, a great number of new space-borne platforms and radiometric instruments have been launched in order to document the dynamic, thermodynamic and microphysics properties of the atmosphere. For instance SSMI on DMSP, TMI on TRMM, MODIS on AQUA brings information on precipitation and water vapour; GOES and MSG allow to access to horizontal winds; AIRS on AQUA, IASI on MetOp-1 to vertical profiles of temperature and humidity. This potential advance results from the higher spatial and temporal coverage of satellite sensors with respect to traditional techniques in particular over ocean or tropical/equatorial regions.

However passive and active infrared/ microwave sensors on spaceborne platforms taken alone provide only a piece of the earth puzzle either on limited spatial domains or with a coarse temporal resolution. This suggest the use of new strategies for observational (synoptic and mesoscale) studies from remote sensing such as the process of merging multiple data sets from different sensors—active and passive, ranging from visible to microwave wavelengths—each of them bringing complementary information of the same scene or identical information with complementary spatial domain or with a better temporal description.

Unfortunately, the application of such a strategy is generally not straightforward due to numerous difficulties to overcome such as the fact that the available complementary spatial view are obtained at different time, or the remote sensing data are obtained with different resolutions. Another concern regarding the use of remote sensing is the topic of calibration accuracy and the need of intercalibration between the used various instruments.

This need of new techniques for estimating meteorological parameters from various spaceborne remote observations for synoptic scale and mesoscale observational studies motivated the present work. It concerns a new method of 4D variational data assimilation (MANDOPAS4D) to retrieve 4D fields such as wind, specific humidity and related quantities (pressure, temperature, potential vorticity, apparent heat source, apparent moisture sink, evaporation rate, condensation rate) by combining information from various spaceborne remote observations with that from in situ or remote sensing platforms or from forecast models.

This method should be able to process analyses product obtained at larger scale or a first guess from a mesoscale simulation. In this last case the first guess is modified by the observations. This approach can be used when the dataset is to poor to retrieve from observations the searched fields or quantities.

This method should take into account non-instantaneous data sets or datasets with a strong time scattering (for example spaceborne observations between radiosoundings at 0, 12, 24UT).

This method should not be constructed on a particular geometry of the data sets in order to take into account new future sets. It should be able to performed space-time filtering or scale selection in order to take into account data with different space-time characteristics. It should use data point where they occur in order to process in a straightforward way the data. It should permit to put in evidence error calibration.

Concerning spatial sensors we chose to assimilate retrieved/inverted products by space agencies or research institutes rather than radiances which allows in a straightforward way to assimilate all type of products. Indeed these products have the advantage of being of the same nature as meteorological variables. This choice results also from the fact the model used in the assimilation method (called constraints in the following) is very simple and limited to equations do not involving any parameterisation (contrarily to classical operational assimilation method using a complete set of equations). This choice allows the method to be independent on the quality of the used parameterisation. This allows also to retrieved fields as close as possible to the used observations.

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Thus the present presentation describes a new method called MANDOPAS4D. It focuses on its mathematical formulation and its relevant advantages. Sensitivity tests on used dataset synthesised from a non-hydrostatic meso-scale numerical simulation (MESONH) are discussed. To conclude, an illustration is given on a real dataset devoted to the documentation of the BRET hurricane observed over the Gulf of Mexico in august 1999.
The present paper is organized as follows: Section 2 is devoted to the mathematical description of the MANDOPAS4D method, while sensitivity tests are presented in section 3. The application on the real case is described in section 4. Then, a discussion and conclusions are presented in section 5.

2. THE MANDOPAS4D ANALYSIS

The proposed MANDOPAS4D is based on an analytical and variational formalism previously used to other specific problems such as the retrieval of 3D wind field using data from a network of Doppler radar (Scialom and Lemaître, 1990), from an airborne Doppler radar (Dou et al, 1996) or from nested wind measurements (Montmerle and Lemaître, 1998). This formalism has been applied on data sets gathered during various experimental campaigns devoted to mesoscale processes involved in the life cycle of tropical systems (Protat et Lemaître, 2001a,b).
The basic principle of this formalism is as follows:

- The searched unknowns are expressed as a product of four functions depending upon each spatial or temporal coordinate.
- Each of these functions is expanded in terms of orthonormal functions series.
- The unknowns are thus under an analytical form and the quantities really observed, which are related to these unknowns, are also expressed under this analytical form;
- The coefficients that define the analytical forms of the unknowns are then retrieved by means of a variational adjustment of the analytical form of the measured quantities to their observed values including physical constraints (such as the anelastic continuity equation for the wind field or boundary conditions) simultaneously verified by the searched unknowns and also expressed under an analytical form. The method thus retrieved the best physical solution which represents as well as possible the whole data sets.
- This variational adjustment is written in a matricial form. Any additional constraint or data set may be introduced in the retrieval process by simply adding the corresponding matrix to the main matrix associated with the adjustment.
- The obtained matricial equation is inverted in order to retrieve the coefficients that define the analytical forms of the unknowns.

The different advantages of this analytical and variational formalism may be summarised as follows:

- The expansion on a basis of orthonormal functions makes it possible to carry out a scale selection.
- The limitation of the functional expansion to a given order makes it possible to filter out the smallest scale motions or to perform a scale selection. It may be shown (see Scialom and Lemaître, 1990 for instance) that the development of the functional expansion up to the order N implies a retrieval with a cutoff wavelength λc of about $2D_i/(N-1)$ with D_i the range of the domain in the x_i direction. The minimal observable scale lc is then $lc=0.26\lambda c$. The order of development N must be chosen as lc is the same in the two horizontal direction and lc is at least equal to $2\Delta x$ (in accordance with the Shannon theorem) where Δx is the mean range between two measurements (radiosoundings of a network, grid points of a first guess, 2 pixel of an image, etc…).
- The least square fitting between the analytical form of the observed quantities and their observed values permits to bypass the filtering and interpolation necessary in classical numerical methods,
- The data are used where and in the order they occur, since simply accumulated in the matricial system.
- The accuracy on the retrieved fields is very good since the retrieval is performed by using all the measurements in the sampled volume. However, it depends, of course, on the density of used measurements.
- As mentioned previously the introduction of constraints allows the retrieval of fields (such as vertical velocity for example) that are generally indirectly retrieved. Since these quantities are obtained at the same time than the others, these indirect parameters are thus also obtained with a very good accuracy. As an example, for a dropsonde data set or a radar network the inclusion of the continuity equation and the boundary condition makes it possible the retrieval of the vertical velocity at the same time as the horizontal components. This avoids errors on the vertical component linked to the integration of the continuity equation generally used in numerical methods.
- The matricial formulation makes it possible to mixed data sets from different instruments, simply by adding the corresponding matrices weighted by the inverse of the covariance error matrix of each instrument.
- The analytical formulation of the searched unknowns makes it possible to obtain under the same form their space derivatives without additional noise. Diagnostic quantities such as deformation fields, vorticity, potential vorticity, forcing commonly used in theoritical study may be deduced from the analytical form. Pressure and temperature may also be derived from the three-dimensional wind field, the

analytical form allowing the necessary derivations and integrations (Protat et al. 1998). Some integrated quantities such as energetic conversions, heat sources and moisture sinks can be also easily derived.

The present MANDOPAS4D analysis considers a four-dimensional analytical representation of the searched fields. The observations are thus also expressed under this form and adjusted to the data through a variational process by using additional constraints derived from the equations of air mass conservation, boundary conditions, water mass conservation, and vorticity production.
The data principally considered in MANDOPAS 4D are, as explained previously, derived from sensors on spaceborne, airborne and ground-based platforms.

The mathematical formulation of the MANDOPAS4D analysis can be express as follow: I is the thermodynamical or dynamical field which is retrieved analytically; O are the observations related to the unknown I by a function or an operator O(I). The quality of the retrieval field will be improved by using all available sources of observation and additional constraints related by fluid equation to *I* noted *P*. In this case a variational formalism is used. The minimized cost function can be written in this case:

$$\sum_{i,i',i''}\left\{\begin{array}{l}\lambda_i * \sum_{observations}(I_{analytical}-I_{measured})^2+\lambda_{i'} * \sum_{observations}(O_{analytical}-O_{measured})^2+\\ \lambda_{i''} * \sum_{constraints}(P(I)_{analytical}-0)^2\end{array}\right\} \quad (1)$$

Where λi, λi', λi'' are weighting factors proportionally inverse to measure error. They allow such to put an equal weight on all terms.

In the following only two quantities are considered, the 4D wind field $\vec{V}$ (U, V, W) and the 4D water vapour field. For these quantities, the constraints, added to force the spatial and temporal derivatives of the retrieved analytical field to be physical are derived from the continuity equation, the boundary conditions, the vorticity equation and the conservation of water mass equation.

3. Evaluation of MANDOPAS4D on simulated data.

a. Test on a simulated case

First, this method is evaluated on a dataset synthesized from a non-hydrostatic mesoscale numerical simulation by using the MESONH model. This simulation concerns a monsoon case observed during HAPEX-SAHEL experiment (Redelsperger, 2002). In order to test the method, the following formalism has been applied: we have considered that the track of the satellite cover the entire domain (we have an observation at each point of the area). The retrieved field (figure 1b) is then compared to the simulated field (MESONH simulation: figure 1a). Moreover profiles error (mean error, absolute mean error, standard deviation and absolute standard deviation) are calculated in order to estimate the capabilities of the method (detection of bias…). Figure 1c and 1d show a horizontal cross-section of the absolute error on the retrieved specific humidity field and the mean vertically profiles error respectively.

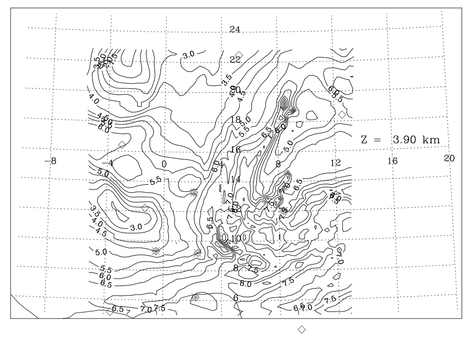

Figure 1a: horizontal cross-section of initial specific humidity field (g/kg) at 3,9km, 12h

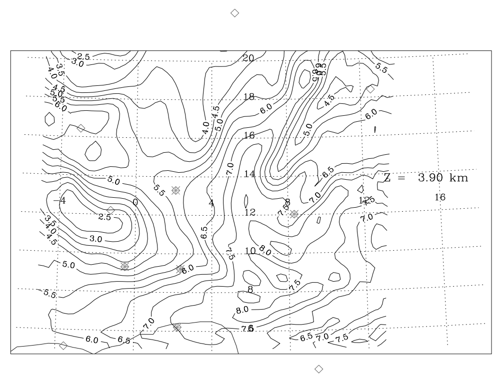

Figure 1b: horizontal cross section of retrieved specific humidity field (g/kg) at 3,9km, 12h

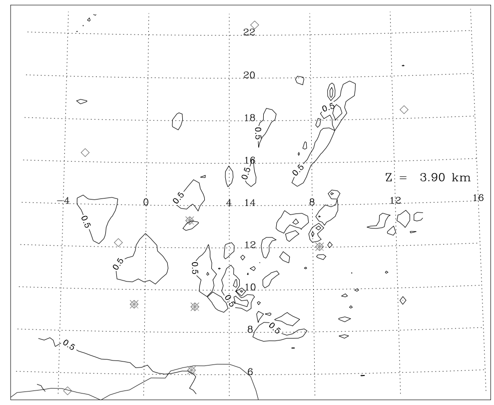

Figure 1c: horizontal cross-section of the absolute errors between the simulated and retrieved field at 3,9km (g/kg), 12h

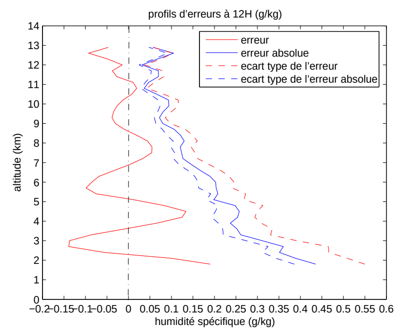

Figure 4: mean vertical profile of error (red line), absolute error (blue line), standard deviation (red dashed line) and absolute standard deviation (blue dashed line)

These figures show that the global tendency of the error is to decrease with altitude from 0.5g/kg to 0.2g/kg (which is around the sensor noise). Therefore, the error profile is centred on 0g/kg, indicating that no bias is introduced in retrieval process.

b. Test on a real case: BRET hurricane

The validation of the method has been also performed through an application to a real dataset. It concerns the BRET hurricane observed over the Gulf of Mexico in August 1999 and in particular the calculation of the moisture budget of the BRET hurricane. The retrieval of four dimensional wind (V) and specific humidity (q) field allow estimating the rate of evaporation (e) and condensation (c), through the resolution of the equation of conservation of the water mass. This equation can be expressed:

$$\frac{\partial q_v}{\partial t} + (\vec{v}.\vec{\nabla})q_v - \vec{\nabla}(\kappa\vec{\nabla}q_v) = e - c \qquad (2)$$

BRET hurricane is a hurricane of category 4 on the Saffir-Simpson hurricane scale which touched land in Texas, the 23rd August. The slow moving of BRET allowed it to intensify fast, but its small size and its trajectory permit to have a few damage.

In order to study this hurricane, all available have been collected. Three types of data are taken into account: airborne and ground based and satellite data. The first and second category of data includes the radiosoundings, dropped on land; the dropwindsondes drop from the plane NOAA Gulfstream IV-SP, the dropsonde and radar data from the plane WP3s Orions. The third category supply complementary information on wind and humidity. Information supply by sensor on satellite is the Integrated Water Vapour. Two imagers give this product: TMI (Tropical Measuring Mission's Microwave Imager) and SSMI (Special Sensor Microwave Imager). The algorithm used to restore this product is the one developed by Wentz. Information on horizontal wind field is brought by the geostationary satellite GOES 8-9 (over America). These wind estimates are produced by tracking features in water vapour and infrared channel (Gray). Surface wind are obtained using the sensor SeaWinds on QuikSCAT satellite.

The vertical wind component is retrieved through the constraint, the continuity equation used in MANDOPAS4D. The instrumental noise and the density of observation points are taken into account in the weighting factor used in the variational minimisation process (equation 1).

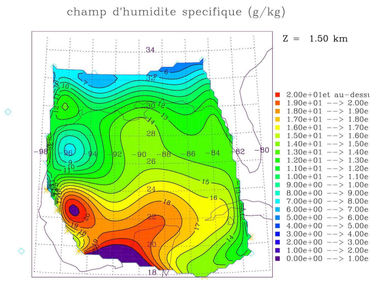

Figure 1: horizontal cross-section of specific humidity at 1,5km, 24h

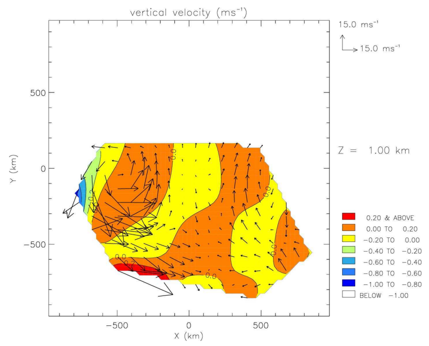

Figure 2: horizontal cross-section of wind field at 23h30. Vertical wind is drawing on background.

Figures 1 and 2 show the horizontal cross-sections of specific humidity and wind field in the Gulf of Mexico. Using these two 4D field, others thermodynamic quantities are retrieved: the potential vorticity, the temperature, the pressure (Protat, 1998). The four dimensional field of these quantities allow us to estimate the moisture, heat and energy budget in the hurricane. Figure 3 show an example of application: the calculation of the moisture apparent sink, Q_2 (equation3). Q_2 measures the apparent sink of moisture due to condensation and eddy turbulent flux. Its expression comes from the equation of temporal evolution of humidity. This vertical variation of Q_2 is quantified in a box encircling the hurricane.

$$\left\{ Q_2 = -\frac{L}{C_p}\left(\frac{\partial \bar{q}}{\partial t} + \overline{(\vec{V}.\vec{\nabla})q}\right) \right. \qquad (3)$$

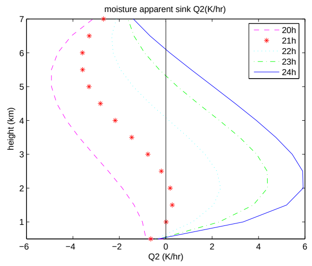

Figure 3: profile of moisture apparent sink (Q2) (K/hr) between 20h and 24h

4. Conclusion

The present paper deals with the need of new techniques for estimating meteorological parameters from various spaceborne remote observations for synoptic scale and mesoscale observational studies. It concerns a new method of 4D variational data assimilation (MANDOPAS4D) to retrieve 4D fields such as wind, specific humidity and related quantities (pressure, temperature, potential vorticity, apparent heat source, apparent moisture sink, evaporation rate, condensation rate) by combining information from various spaceborne remote observations with that from in situ or remote sensing platforms or from forecast models. The proposed MANDOPAS4D method, based on an analytical and variational formalism, is described and applied on a synthesised 4D datasets from conventional (meteorological networks) and spaceborne platforms. This application aims at evaluating this method and its sensitivity on satellite observations in the case of sparsely conventional dataset. These numerical tests show the relevance of this method for regional studies. As expected the quality of the retrieval depends essentially on the density of measurements and their spatial and temporal distribution which define the accessible scales of wind and humidity. In the case of a sufficient density of conventional measurements the retrieval is very good. Such an illustration has been made through the study of BRET hurricane. In the case of a weak density the satellite data is primordial. It totally defines the quality of the retrieval. In this last case, in order to access to smaller scales, a more classical approach must be used assimilating in the MANDOPAS4D procedure a first guess deduced from a numerical simulation. This is simply performed adding a new matrice associated with the cost function corresponding to the new numerical data set. Such an approach will be used on the real datasets gathered during AMMA in order to improve large scale analyses and to derive regional budgets using ground based, airborne and spaceborne not assimilated in the operational assimilation systems.

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