Data assimilation of the hydrological cycle

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Abstract

This paper gives an overview of recent activities undertaken in Numerical Weather Prediction (NWP) centres on the assimilation of observation sensitive to water vapour, clouds and precipitation. After highlighting the specific features of data assimilation of "moist" observations, a number of developments are described both at global scale and mesoscale. Finally a number of challenging issues to be addressed in the near future regarding the data assimilation of the hydrological cycle are presented.

1. Introduction

The Earth's hydrological cycle described by the classical picture in Figure 1 shows many storage compartments and fluxes governing the exchanges between them. The content of this paper is limited to the atmospheric reservoir which is the smallest one. Indeed, the value of 12.7×10^3 km^3 is only for atmospheric water vapour. The condensed and precipitating atmospheric water contents are so small that they can be neglected in this global picture. On the other hand, their contribution is essential to the water cycle that is why clouds and rain are displayed in Figure 1. The amount of water stored in the atmosphere is even lower than the frozen soil moisture at high continental latitudes (22×10^3km^3). The assimilation of other components of the hydrological cycle is also important (partly because they deal with larger reservoirs). There is active research in these areas with potential operational applications (oceans, soil moisture, lakes, rivers, deep ground water). Some of them are described in other chapters of these proceedings.

After providing a number of specific features regarding the assimilation of the atmospheric hydrological cycle, the two main chapters concern the assimilation of observations sensitive to water vapour (where developments are the most advanced and where there is a large consensus in terms of methodologies and observations among NWP centres) and the assimilation of observations sensitive to precipitation (where developments are more recent and methodologies vary from one NWP centre to another, and with also differences originating from the scales of interest). In the conclusion, a number of remaining challenges on various aspects of data assimilation of the atmospheric water cycle are summarized.

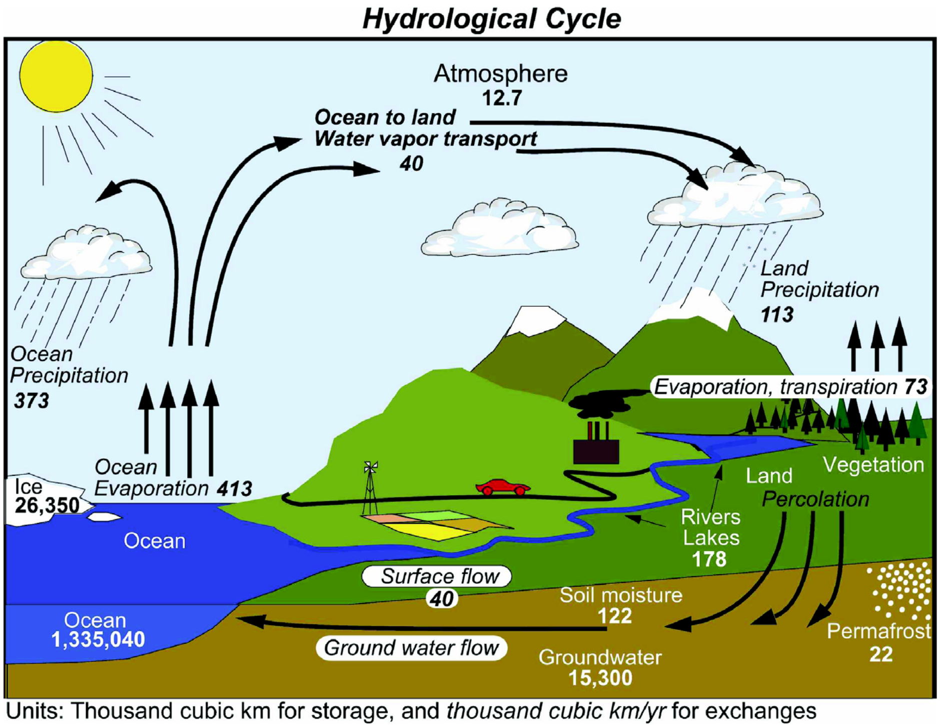

Figure 1: The hydrological cycle. Estimates of the main water reservoirs, given in plain font in 10^3 *km*^{3}*, and the flow of moisture through the system, given in slant font (*10^3 *km*^{3}*/year). Taken from Trenberth et al. (2007)*

2. Specific features of the assimilation of the hydrological cycle

It is important to recall that water vapour and clouds strongly modulate the energy balance of the Earth's system. Water vapour is the first greenhouse gas and clouds have generally a cooling effect in the solar part of the electromagnetic spectrum (higher albedo than the Earth's surface) and a warming effect in the infra-red region (by trapping the thermal emission of the Earth). Their contribution is also essential to the entire water cycle as shown in Figure 1. For deterministic and probabilistic NWP forecasts, surface precipitation, cloudiness, and screen-level temperature are among the most important parameters to be accurately estimated for many applications. Given that some components of the hydrological cycle are difficult to measure over large domains such as precipitation, surface evaporation and runoff, atmospheric analyses (and reanalyses) of water vapour (that is observed by many types of instruments, as detailed hereafter) can provide a consistent picture of these "unobserved" components. An illustration is given by the surface precipitation field in ECMWF reanalyses (Figure 2 taken from Dee et al. (2011)). It shows that this model consistency can lead to the projection of artifacts present in biased analyses of atmospheric moisture on the unobserved components. This picture also reveals that the atmospheric water vapour is better constrained by observations over continents than over oceans (good level of consistency between the ERA-40 and ERA-Interim reanalyses). This statement is also true for analyses of surface precipitation (GPCP product). Another interesting feature is the existence of a "spin-up/spin-down" problem where, during the first hours of model integrations, the fields of atmospheric moisture adjust towards the model equilibrium when too little or too much water vapour is added by the assimilation system (identified by different precipitation rates according to forecast range). Once again, the "spin-up/spin-down" is evident over oceans and almost absent over continents.

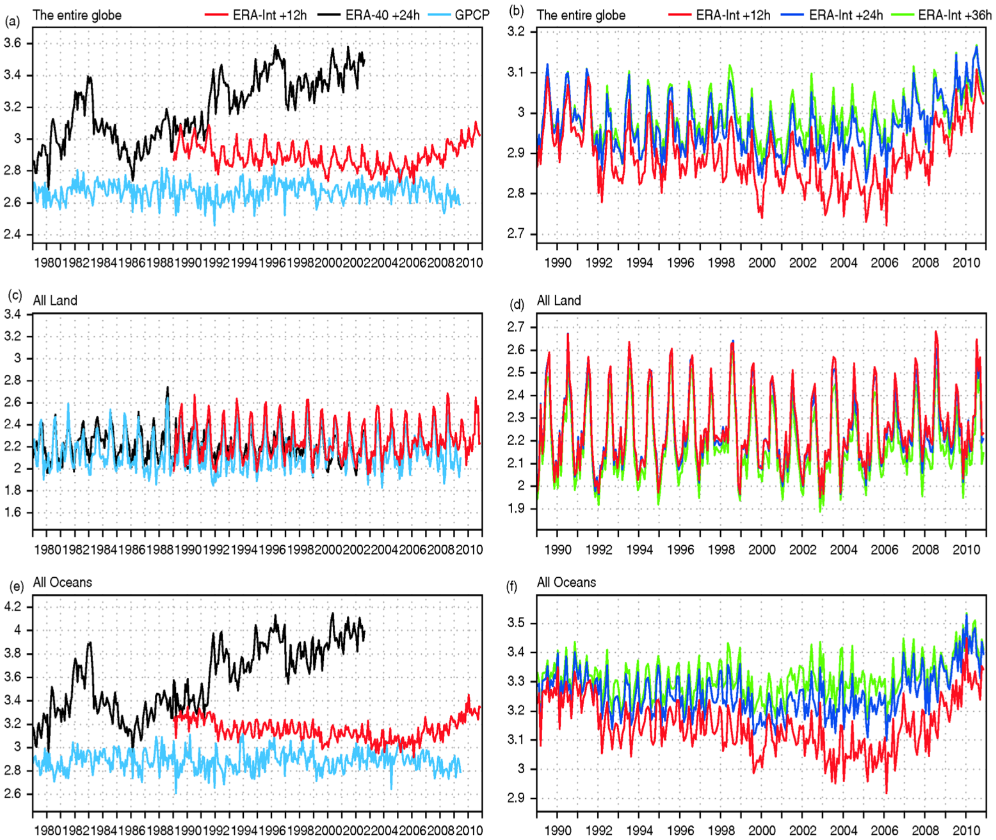

Figure 2: Monthly averaged precipitation and spin-up/spin-down effects: precipitation estimates (mmday^{-1}) for 1979-2010 from ERA-Interim (red), ERA-40 (black), and GPCP (blue), averaged for (a) the entire globe, (b) all land locations, and (c) all ocean locations. Results for ERA-Interim are based on accumulated rainfall in the initial 12-hour forecast segment; for ERA-40 the 12-24 hour segment was used. (d,e,f) show, for 1989-2010 and for ERA-Interim only, corresponding estimates obtained from the initial 12-hour segment (red; identical to (a,b,c)), the 12-24 hour segment (blue), and the 24-36 hour segment (green). Taken from Dee et al. (2011)

If one considers the building blocks of data assimilation (control vector $\mathbf{x}$, vector of observations $\mathbf{y_o}$, observation operator H, background errors $\mathbf{B}$, observation errors $\mathbf{R}$), in most systems the vector $\mathbf{x}$ contains only water vapour as a “moist variable”. I mention in the conclusion recent developments where clouds and precipitating water contents are included in $\mathbf{x}$. A number of references are given on the assimilation of observation types at mesoscale and global scale that are sensitive to atmospheric water (vapour and condensed). The observation operators H (together with their tangent-linear and adjoint versions for variational assimilation) consist principally of a fast radiative transfer model such as RTTOV (Saunders et al., 1999) that simulate satellite radiances over a wide range of electromagnetic frequencies (infra-red and micro-wave regions) in clear-sky, cloudy and rainy atmospheres (Bauer et al., 2006c). When water vapour is the only “moist” control variable, diagnostic cloud and precipitation schemes have to be considered in the observation operator H (e.g. Tompkins and Janiskova, 2004; Lopez and Moreau, 2005). Radar reflectivity simulators need to be used for the assimilation of observed “radar reflectivities” (e.g. Caumont et al., 2006). Background error statistics require special attention when considering the atmospheric hydrological cycle. First cloudy and rainy regions can have rather different errors than clear-sky regions. This implies to split the computation of statistics into samples having similar characteristics and then selecting the appropriate statistics in the assimilation according to the same criteria (Montmerle and Berre, 2010). Another important consideration is to build appropriate background error statistics when extending the control vector to condensed water variables (Michel et al., 2011). Their link with dynamical fields should help reducing model spin-up. Finally, a number of important aspects for the assimilation of any observation type are even more critical for the atmospheric hydrological cycle: specification of observation errors, data selection, bias corrections and quality controls.

Data of interest ("moist" observations) in current observing systems can be split into three categories:

- Conventional data such as surface weather stations and radiosondes measure relative humidity;
- Ground based remote sensing systems: GPS receivers provide information on total column water vapour by measuring the time delay between a surface station and a satellite transmitter; meteorological radars provide information on precipitating hydrometeors (solid and liquid) by measuring the backscatter signal returned to the radar after pulse emissions. These two systems perform at micro-wave frequencies (L, S, C, X bands that range between 1.4 and 10 GHz);
- Satellite instruments can measure the natural emission of the Earth in the infra-red and micro-wave regions. Depending upon the scene observed, information on water vapour, clouds or precipitation is contained in the satellite radiances.

It is useful to summarize specificities of the assimilation of "moist" observations with respect to "dry" ones in order to better understand why methodologies can be different. Moisture fields have high spatial and temporal variabilities. This is true for water vapour but even more acute for condensed and precipitating water. This statement has the following consequences:

- Local measurements can have large representativeness errors (model comparison and spatio-temporal interpolations). In order to reduce such errors, dense observation networks with frequent temporal availability of data are necessary.
- The computation of background errors statistics is more difficult in order to get robust estimates.

Moisture fields are less correlated to other variables. This explains why moisture analyses where univariate in data assimilation systems developed 30 years ago (Tibaldi, 1979; Lorenc and Tibaldi, 1979). Wind and temperature observations are not always informative about moisture (leading to the difficulty of getting reliable background error statistics), whereas a temporal sequence of radiances in the water vapour or ozone absorption bands can provide useful information on wind vectors. They also less predictable, which means that the impact of initial conditions on forecasts can be rapidly lost (Bengston and Hodges, 2005).

Moisture variables are bounded (e.g. non-negative values) and vary by several orders of magnitudes between the equator and the poles and between the surface and the stratosphere. This feature has led to different choices in terms of control variables, to remove the lower bound (log[q] transform) and the spatial variability (pseudo relative humidity transform) that can have advantages either for the computation of increments or for the specification of background error statistics (Dee and da Silva, 2003). This specificity induces non linearities and thresholds that can violate classical hypotheses of error gaussianity and tangent linear approximation made implicitly in most data assimilation systems (Fabry and Sun, 2010).

Finally it must be stated that "reference" measurements of humidity are in general difficult (or very expensive) to obtain which means that most observations on humidity are biased (e.g. Augusti-Panareda et al., 2009). Removing moisture biases prior the assimilation is not always easy.

3. Assimilation of observations sensitive to water vapour

The assimilation of observations sensitive to water vapour began with the infra-red sounder HIRS on board NOAA polar orbiting satellites having channels in the absorption band around 6.7 μm (McNally and Vesperini, 1996). More recently, this H_2O absorption band has been exploited from radiometers on board geostationary satellites in particular for the mesoscale (Montmerle et al., 2007) and from hyperspectral sounders (AIRS/Aqua and IASI/MetOp). Cloud detection being an issue in the infra-red, micro-wave satellite instruments have shown to be more efficient for extracting information on water vapour, first with imagers such as SSM/I (Gérard and Saunders, 1999) and then with sounders such as AMSU-B (available since 1998). Recently, a methodology for improving the specification of surface emissivity over land and sea ice has allowed the assimilation of more channels over these surfaces (Karbou et al., 2010; Gérard et al., 2011). This methodology has also been used in the infra-red region to assimilate more channels sensitive to the surface and to the lower troposphere (Guedj et al., 2010). The assimilation of ground based GPS (providing information on total column water vapour) has proved to be very useful at the mesoscale in particular for the initiation of severe convective storms (Yan et al., 2009). The focus is on the mesoscale due to the lack of global data exchange and it is also particularly suited to this scale because of the high temporal availability (several measurements per hour) and due to the existence of dense regional networks that are increasing. A recent evaluation of the impact on ECMWF forecasts of observations sensitive to water vapour can be found in Andersson et al. (2007).

4. Assimilation of observations sensitive to precipitation

The assimilation of observations sensitive to precipitation started more than 20 years ago with techniques called "physical initialization" and "diabatic initialization", that attempted to used satellite derived rain rates in order to constrain the dynamics of tropical regions (particularly the divergent flow) in global models and also mesoscale convective systems (Krishnamurti et al., 1988; Heckley et al., 1988; Macpherson, 2001) using diabatic normal mode initialization and latent heat nudging.

As for water vapour, microwave instruments are more suited to probe rainy and cloudy systems than infra-red ones (for which most clouds are opaque). With the development of linearized physical parametrization schemes for moist physics (e.g. Lopez and Moreau, 2004) it has been possible to assimilate satellite derived rain rates (Zou and Kuo, 1996; Tsuyuki, 1997; Marécal and Mahfouf, 2002), microwave radiances affected by rain (Bauer et al., 2006ab), and also radar derived rain rates (Lopez, 2011). All sky microwave radiances have required the development of radiative transfer schemes with scattering effects (Bauer et al., 2006c) and suitable cloud overlap assumptions (Geer et al., 2009). Recent activities have concerned data quality controls and error specifications (Geer and Bauer, 2011). For limited area models, 4D-Var with linearized explicit microphysics (Wu et al., 2000) has not been developed for operational applications. Caumont et al. (2006) developed a forward radar operator that allows the simulation of radar reflectivities using explicit microphysics, but the inversion procedure, based on a Bayesian approach, avoids the need of an adjoint observation operator. Moreover, a methodology has been developed in order to use the “no rain” information (despite an ambiguity on the knowledge of water vapour) from radar measurements in order to get more balanced humidity increments (Wattrelot et al., 2012). A two-step approach is often used in order to simplify first the inversion and then the assimilation (Marécal and Mahfouf, 2002; Bauer et al., 2006a, Lopez and Bauer, 2007, Caumont et al., 2010). Evaluations of rain affected radiances on the quality of forecast scores in NWP models are presented in Andersson et al. (2007) and Kelly et al. (2008). In the infra-red region, the assimilation of cloudy radiances has been done either over identified totally cloudy pixels (McNally, 2009) or by retrieving cloud top and effective cloud fraction through a “CO2 slicing method” (Pangaud et al., 2009) or a 1D-Var technique (Pavelin et al., 2008). Radiances informative about water vapour and temperature can then be assimilated over clouds, but no cloud information is actually used in the analyses. For the infra-red spectrum, the next step is to follow an approach similar to the microwave: an explicit simulation of cloudy radiances using model hydrometeor profiles (Martinet et al., 2012). This approach is very challenging due to dominance of the cloud top contribution to the radiances in this spectral region and also to the strong dependency of top of the atmosphere radiances upon cloud geometry (e.g. cloud overlap assumptions).

5. Conclusions

During the last 20 years there has been significant progress in the assimilation of the atmospheric water cycle that can be attributed to three mains factors:

- the development of data assimilation systems that can nowadays handle complex operators (involving the dynamics and the physics of a NWP model and radiative transfer models) that link available observations (remotely-sensed) to the variables to be analyzed (a simple example is surface precipitation that could hardly be assimilated using an optimum interpolation technique);
- the improvements to the observing system with new ground based systems (GPS), and new satellite instruments (micro-wave imagers and sounders). The better usage of existing ones can be illustrated by adaptive bias correction schemes (VarBC) for satellite radiances and by improved specifications of surface emissivities;
- the improvements to the description of physical parameterizations schemes with cloud and precipitation prognostic variables (both at mesoscale and global scale) that allow to simulate realistic cloudy/rainy radiances and radar reflectivities. This has led to the so-called and rather popular “model to observations” validation (i.e. evaluation of model performances in observation space).

As a consequence, many Observation System Experiments (OSE) have shown positive impacts of observations sensitive to water vapour, clouds and precipitation on forecast skill scores on humidity and precipitation, but also on winds and temperature (Andersson et al., 2007; Kelly et al., 2008; Radnoti et al., 2010). This has also been translated into improved analyses of the various components (observed and unobserved) of the atmospheric water cycle available in long term reanalyses such as ERA-40 and ERA-Interim (Dee et al., 2010).

6. Remaining challenges

Regarding the three above aspects, a number of challenges will have to be addressed in the near and more distant futures. Even though hydrometeors are prognostic variables in most cloud schemes developed for NWP models, they are not yet analyzed in operational data assimilation systems. In 4D-Var systems, the analysis being a model trajectory, there is some level of consistency between variables that are not analyzed and available observations over the assimilation window. The extension of the control vector requires the definition of additional background error statistics (in particular variances and cross-correlations with other variables). Studies have started in that direction (e.g. Gong and Holm, 2011; Michel et al., 2011). To which extent condensed variables with fast time scale adjustment (i.e. low predictability) will need a dedicated analysis is yet unknown. However, it is likely that for mesoscale data assimilation with very short time windows (less than one hour) a dedicated analysis of hydrometeors will be needed. A difficulty mentioned in the introduction regarding the assimilation of the atmospheric water reservoir is the important spatio-temporal variability of the associated variables that leads to difficulties in getting robust and representative error statistics. This problem has already led to a number of studies (e.g. Montmerle and Berre, 2010) in order to get more representative statistics of humidity, wind and temperature in specific regions of the atmosphere (clear-sky, cloudy and rainy situations). Studies have also started to handle smoothly the statistics between contrasted regions (Yann Michel, personal communication).

The importance of the time dimension of observations at mesoscale (availability and fast temporal evolution of mesoscale systems; radars, GPS signals, radiances from geostationary satellites) raises the issue of the best analysis technique to handle very frequent observations (3D-Var, 3D-Var FGAT, 4D-Var, EnKF, 4D-EnVar). There is also a need to increase the density of observations at mesoscale (both spectrally for radiances and spatially for all data currently thinned) that implies to diagnose and include error correlations between observations in data assimilation systems (Bormann et al., 2011). The fine grid mesh of mesoscale NWP models (about 1 km) also raises scale issues since it is much smaller than satellite footprints (about 10 km). This requires to up-scale the model equivalent of the observation to its spatial resolution (Duffourg et al., 2010). This issue is more critical for cloudy and rainy atmospheres than for clear-sky situations (Martinet et al., 2012). The current problem raised by the large and non-gaussian errors coming from the mislocation of clouds and rain structures needs specific and ad-hoc treatments (e.g. select situations where rain and/or clouds are both present in the model and in the observations, use “symmetric” errors and bias correction). New approaches based on the assimilation of “coherent structures” have started to be explored (e.g. presentations from T. Landelius and C. Geijo given at the 21st Joint ALADIN workshop and HIRLAM All Staff Meeting: http://www.cnrm.meteo.fr/aladin/spip.php?article163).

The assimilation of other components of the water cycle (oceans, land surfaces, ground water) that evolve more slowly than the atmosphere are usually performed separately (uncoupled mode). Their “physical” coupling with the atmospheric reservoir could lead to more optimal assimilations of the individual components. For example, top of the atmosphere simulated microwave radiances could be adjusted towards observed values by modifying both the atmospheric moisture composition and the soil/vegetation water contents. Similar constraints exist for soil moisture that controls both surface evaporation (interactions with the atmosphere) and surface runoff (interaction with deep ground water and river discharges) (Thirel at al., 2010).

Improved diagnostic tools, such as Forecast Sensitivity to Observations (Cardinali, 2009), should be generalized to evaluate the impact of "moist" observations on analyses and forecasts. A difficulty of validating analyses and forecasts of the various components of the atmospheric water cycle comes from the lack of accurate reference observations or analyses. Field campaign experiments such as AMMA (Redelsperger et al., 2006) in the recent past and HYMEX (water cycle over the Mediterranean basin) that will take place in 2012 help to address these issues, since they provide additional, consistent and accurate data sets that are not available in routine (denser surface networks, flux measurements, airborne in-situ and remote-sensing measurements,…) for the validation of NWP analyses and forecasts. They also provide valuable information on the quality of routine meteorological measurements (particularly on atmospheric moisture).

The assimilation of the hydrological cycle will also progress by an increase usage of already available (satellite) measurements informative about atmospheric water vapour (e.g. use of SSMI/S over land and sea-ice) and clouds (e.g. cloudy IASI radiances) and by considering new instruments (e.g. ATMS/NPP, CrIS/NPP, MADRAS/Megha-tropiques, SAPHIR/Megha-Tropiques) that have been successfully launched by the end of 2011. Regarding ground based networks, there is a number of very useful networks such as GPS and radars that are not exchanged globally for various reasons (e.g. for GPS there is diversity of data producers and for radars the volume of data involved is huge). Observation programmes such as EUMETNET OPERA (radar data over Europe) and EUMETNET E-GVAP (GPS data over Europe) should expand in the future and be supported by all national weather services.

Finally, regarding the development of moist parameterization schemes, some known biased identified by systematic model comparisons with "moist" observations should be reduced by the teams developing these physical schemes. It is likely that when dealing with new data sensitive to hydrometeors such as those provided by dual polarization radars and by high frequency radiometers (above 50 GHz) additional information about microphysics (shape, density, distribution) will be needed. Current bulk microphysical schemes (with one single moment) may not be sufficient to simulate such observations and retrieve useful quantities. Laroche et al. (2005) already shown that radar reflectivity observations can only retrieve accurately lower moments of a particle size distribution (number concentration and liquid water content) when a three-order moment microphysical scheme using a "normalized distribution" concept is considered.

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