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METEOROLOGY

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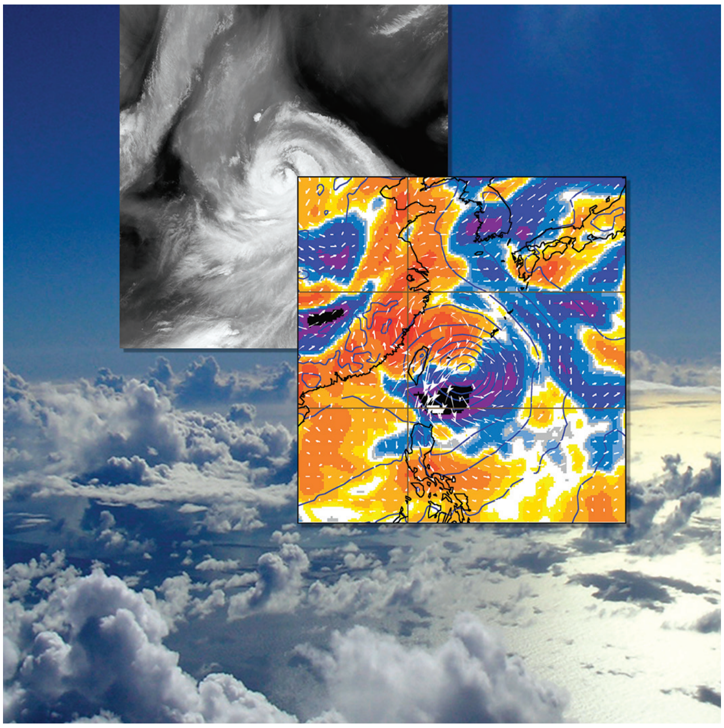

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The assimilation of cloud and rain observations from space

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Over the last 10–15 years satellite data has taken over the role as the major source for observations that constrain the analysis. Today, about 4 million satellite observations are assimilated per 12-hour assimilation window. This is more than 90% of the total number of observations. The bulk of these observations relate to atmospheric temperature and moisture but the near future will add satellite data that contains information on the three-dimensional atmospheric wind field, on land surfaces and, already in operations since June 2005, on clouds and precipitation.

The use of satellite radiance observations in data assimilation requires running a radiative transfer model that simulates observable radiances given model input fields. These models have to be fast and accurate because information on the atmospheric state is extracted that corresponds to variations of, for example, less than 0.5–1 K in temperature or less than 1–5% in relative humidity. Until recently, fast and accurate models have only been available for clear-sky observations and could not simulate the interaction of radiation with cloud droplets, ice particles, rain and snow. This required the screening of observations that are affected by clouds and precipitation.

Keeping in mind that the global average of cloud cover is about 50% and regional averages of the frequency of rain occurrence amount up to 25% at ECMWF model resolution, a significant part of the atmosphere remains unobserved from space. This means that while the analysis in clear-sky areas is strongly constrained by observations, the analysis in areas affected by clouds and precipitation depends upon conventional observations if they are available, but otherwise it is mainly constrained by the model.

History

It has been clear for many years that we should make better use of cloud and rain affected satellite observations. However fast progress has been prevented by a lack of knowledge on how to do this, and the potential for uncontrollable side-effects from running complex physical schemes in the assimilation. At ECMWF, the first activities in this direction were initiated by the EuroTRMM-project that was co-funded by the European Community (EC) and the European Space Agency (ESA) between 1997 and 2001. The ECMWF contribution to EuroTRMM was led by Jean-François Mahfouf and Virginie Marécal. This project explored the potential use of data from the Tropical Rainfall Measuring Mission (TRMM) in the ECMWF data assimilation system. The TRMM satellite had been launched in November 1997 as the first dedicated rainfall observatory in space with a passive microwave radiometer and the first spaceborne precipitation radar. As an example Figure 1 shows the TRMM rainfall observations for tropical cyclone Emily on July 19, 2005 in the Caribbean Sea.

The initial studies dealt with the main issue in cloud and precipitation assimilation, that is the understanding of the sensitivity of moist physics parametrizations to observed rainfall information. These parametrizations are likely to exhibit non-linear and non-regular behaviour, in particular in the presence of convection. Jean-François Mahfouf and Virginie Marécal implemented a system that performed a one-dimensional variational (1D-Var) retrieval of atmospheric temperature and specific humidity in the presence of clouds and precipitation from TRMM observations of surface rainfall. Following sensitivity studies, 1D-Var experiments and single-observation 4D-Var experiments, they implemented the first system to assimilate TRMM observations. It was based on the 1D-Var retrievals using the simple linearized moist physics parametrizations available at that time, followed by the assimilation of only total column water vapour (TCWV) as a pseudo-observation in 4D-Var. This was performed outside the Integrated Forecasting System (IFS) once per 6-hour assimilation window.

Since then, the ECMWF modelling system has greatly evolved employing refined physical parametrizations, better spatial resolution (from 40 to 25 km) and finer vertical resolution in the planetary boundary layer and the stratosphere (from 60 to 91 model layers), an extended model top (from 0.1 to 0.01 hPa), an improved moisture analysis, and a large number of additional satellite observations. The rain assimilation system has been entirely redesigned but the philosophy of the 1D+4D-Var approach remained. Leading up to the first operational implementation, the most important modifications to the original approach have been as follows.

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- ***New observational data processing path.*** An entirely new observational data processing path has been created inside the IFS that paves the way for the use of future observations requiring complex physics operators. 1D-Var retrievals are performed along the first model trajectory at full model resolution and for each time step (currently 25 km and 12 minutes).
- ***Assimilation of microwave radiances.*** We now assimilate microwave radiances rather than derived rain rates, introducing a much improved sensitivity to atmospheric temperature, moisture, cloud water and precipitation at once regardless of the model state. This only became computationally feasible and sufficiently accurate with the inclusion of a fast multiple-scattering radiative transfer code in the radiative transfer model RTTOV (Radiative Transfer for TOVS). For the future, this greatly facilitates the assimilation of radiance observations from a large variety of microwave observations with different sensors such as the Special Sensor Microwave/Imager (SSM/I), its successor the Special Sensor Microwave Imager Sounder (SSMIS), the TRMM Microwave Imager (TMI) and the Advanced Microwave Scanning Radiometer (AMSR-E).
- ***Improved moist physics parametrizations.*** We now have much improved moist physics parametrizations. These represent the best compromise between being the best approximation to the non-linear physics run in the forecast model, whilst giving a more linear and more regular behaviour as required in incremental data assimilation systems. The moist physics parametrization schemes comprise large-scale condensation and convection and were developed by Marta Janisková, Adrian Tompkins and Philippe Lopez. The schemes will become part of the operational linearized physics package with IFS model cycle 32r1 (hereafter referred to as Cy32r1).

Today, the system uses SSM/I radiance observations over oceans at frequencies of 19.35 and 22.235 GHz that are mainly sensitive to the integrated paths of precipitating (and some degree cloud) liquid water, to TCWV and to surface roughness, which depends on near-surface wind-speed. We are still limited to assimilation over ocean surfaces, where there is a better knowledge of the surface emissivity, which is crucial for radiative transfer modelling at these wavelengths.

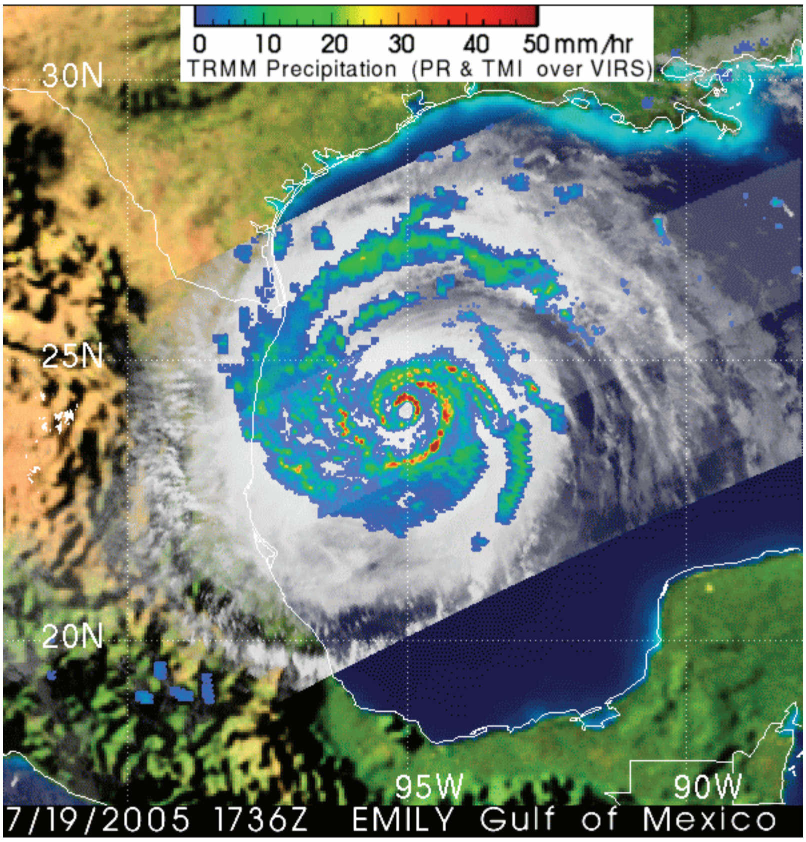

Figure 1 Tropical cyclone Emily on July 19, 2005, as seen by TRMM. Derived surface rainfall from TRMM Microwave Imager (TMI) and Precipitation Radar (PR) (in colour) and Visible Infrared Scanner (VIRS; greyscale). Courtesy NASA.

Impact

Analysis

Before new observations are assimilated it is usual to compare large sets of model simulations with the new observations. This helps to establish bias corrections and indicates the accuracy of the observation operator. In our case, the observation operator consists of the above-mentioned moist physics parametrizations and multiple-scattering radiative transfer model. Since clear-sky SSM/I radiances were already assimilated in a separate stream, it was possible to compare observation versus model statistics in rain and cloud affected areas with those from the existing assimilation, which employs only clear-sky radiative transfer calculations in the observation operator.

Figure 2 shows biases and standard deviations for all seven SSM/I channels from clear-sky and rain-affected observations. Initially, it was expected that the rain-affected simulations would be substantially worse than clear-sky. Instead, it is very encouraging to note that both show biases of similar magnitude and that the standard deviations differ by only a factor of 2–4. The reduction in departures (observations minus their modelled equivalents) between the first guess and the analysis suggests that the 1D-Var retrieval algorithm performs rather well. The departures are consistently reduced by 50–75% in the active channels (channels 1–3; 19.35 GHz v, h, and 22.235 GHz v) and by 20–50% in the passive channels (channels 4–7; 37.0 GHz v, h and 85.5 GHz v, h) – see the caption to Figure 2 for an explanation of the 'v' and 'h' symbols Apart from the accuracy of the observation operator, such performance was the result of a careful estimation of modelling errors, biases and data screening. As a consequence, about 30,000 rain-affected observations are actively assimilated in the operational configuration which roughly matches the number of clear-sky SSM/I observations.

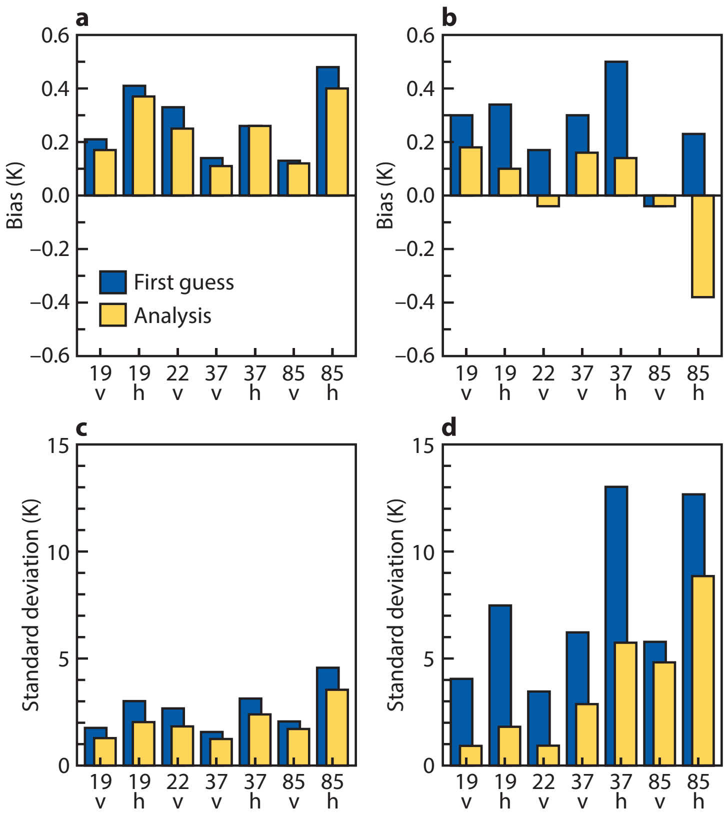

Figure 2 Bias-corrected first-guess and analysis departure statistics (in degrees Kelvin) from clear-sky and rain affected SSM/I radiance assimilation. Mean observation-minus-model differences for (a) clear-sky and (b) rain affected radiances for all SSM/I channels. Standard deviations for (c) clear-sky and (d) rain affected radiances. First-guess departures are in blue and analysis departures are in yellow. The symbols 'v' and 'h' refer to SSM/I channels that measure radiation with a constant polarization that is aligned vertically (v) or horizontally (h) to the plane defined by the paths of the incoming and surface-reflected radiation. The difference between polarizations helps distinguishing between surface and atmospheric signal contributions.

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Because each 1D-Var retrieval runs a moist physics operator prior to the radiative transfer, there is also a ‘retrieval’ of the vertical profile of cloud and precipitation. Though only the retrieved TCWV is assimilated in 4D-Var, it is informative to look at the changes in moisture and rainfall in 1D-Var, which may already give some indications of the potential effect of these new observations in the global analysis. This is illustrated in Figure 3 from a one-month experiment with Cy29r2. TCWV increments are shown in relative terms to avoid the emphasis of increments in areas with large moisture abundance. The increments in surface rainfall are separated into stratiform and convective rain-types and use a logarithmic scale. This scale accounts for the quasi log-normal probability distribution of global rainfall. A change of 1 dBR corresponds to 1⁄10 of an order of magnitude increase or decrease in rainfall.

It is interesting to look at the response of stratiform rainfall to TCWV increments because the large-scale condensation scheme usually shows greater sensitivity to moisture changes. The moisture increments highlight certain areas with systematic drying, in particular in southern mid-latitudes, and smaller-sized regions of systematic moistening in the tropics. The stratiform precipitation increment patterns follow the moisture signal rather closely. Even in areas with small and more localized drying, large areas of stratiform precipitation reduction are produced. This occurs mainly in the northern and southern Pacific and the northern Atlantic where the model’s rainfall frequency of occurrence is too high. But also the relative contribution of stratiform and convective to total rainfall is modified in some areas, namely in the southern sub-tropics where rainfall intensity is rather weak. Here, the 1D-Var retrieval tends to suppress convection.

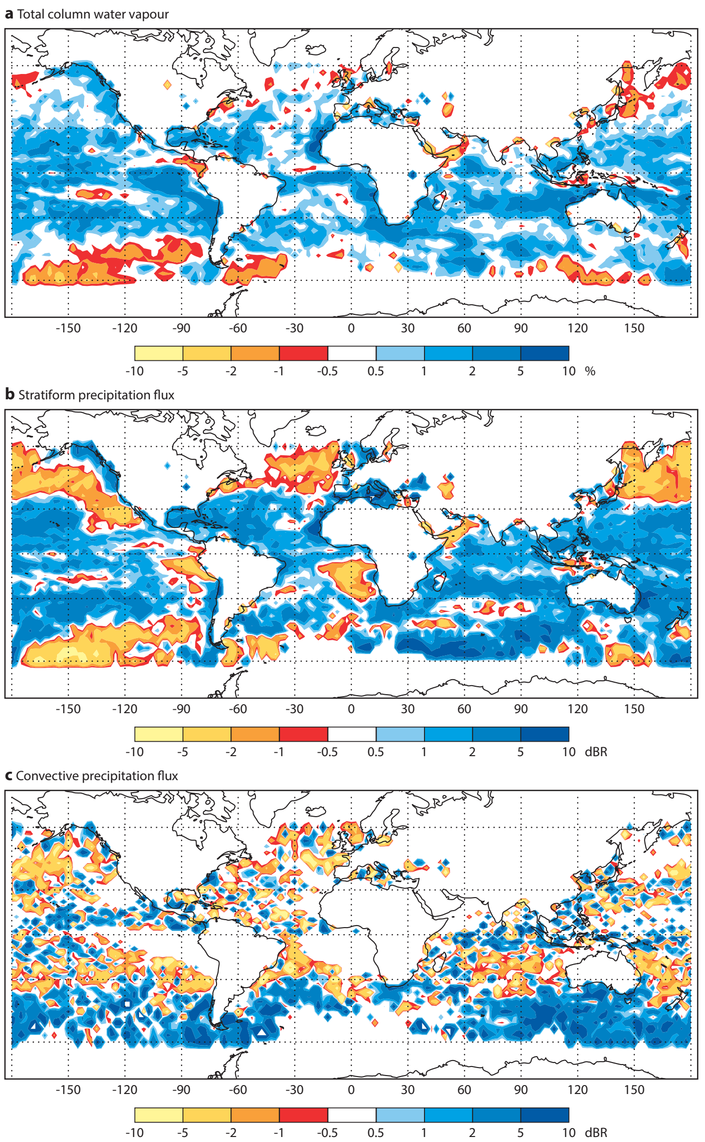

Figure 3 Global increment distribution of (a) total column water vapour (%), (b) stratiform precipitation flux (dBR), and (c) convective precipitation flux (dBR) from 1D-Var retrievals in September 2004 binned to 2.5° resolution.

Figure 4(a) shows an example of mean 4D-Var TCWV-increment differences from a pair of three-month experiments in 2004. One experiment employed the operational rainfall assimilation scheme in Cy29r2 (RAIN) while these observations were withdrawn from the other (NORAIN). The increment patterns that were produced by the 1D-Var retrieval can also be identified in the moisture analysis of the 4D-Var system. However, those areas in which the effect of the rainfall observations was a drying of the analysis were amplified in the course of 4D-Var analysis. These are now much more wide-spread and cover the part of the East Pacific along the American continent, the North Pacific and the South-Eastern Atlantic. During the forecast, the areas with reduced moisture survive longer while the more localized moistening remains only for 24 hrs because of the removal of additional moisture through precipitation, often known as “rain out”. Figures 4(b) and 4(c) show the corresponding mean analysis differences of mean sea-level pressure and 850 hPa divergence differences. Together, these results nicely illustrate the response of the model dynamics to these moisture observations, namely by increasing low-level convergence and by reducing surface pressure in areas of moistening and vice versa. The hatched areas indicate that these mean signals are statistically significant and by comparing RAIN with NORAIN, we can safely assume that these increments originate from the rain-affected observations.

While it is possible that there may be model biases with respect to moisture, it is most likely that the overall drying effect of the rain and cloud assimilation comes from the set-up of the 4D-Var moisture analysis. In clouds and precipitation, the variational analysis performs near saturation. This means that in already saturated areas further moistening is penalized by upper thresholds and by the formulation of humidity background errors. From case studies, we noticed that in these areas many of the positive humidity increments that are produced by the 1D-Var disappear in the 4D-Var analysis. This effect may be unwanted and clearly requires more research focused on the definition of analysis control variables and moisture background error formulation.

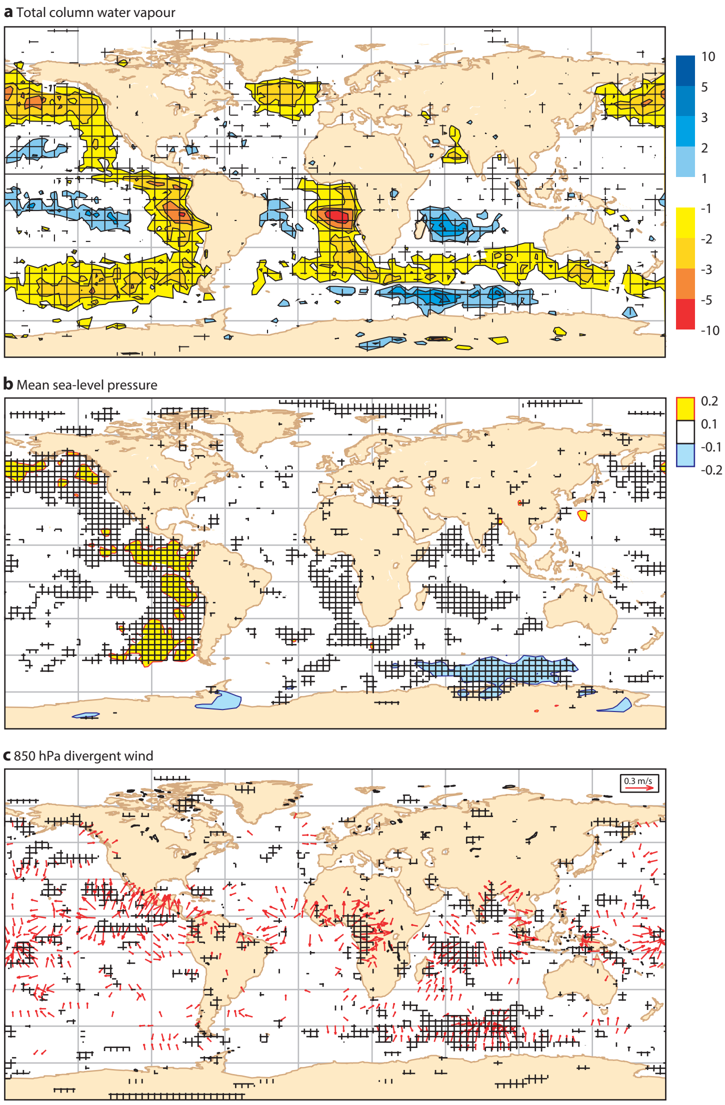

Figure 4 Mean normalized analysis difference of (a) total column water vapour (%), (b) mean sea-level pressure (hPa), and (c) 850 hPa divergent wind fields (ms^{-1}) between RAIN and NORAIN experiments for period August–October 2004 (hatching denotes 95% significance interval with t-test on analysis differences against zero-difference).

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Forecast

Between the operational implementation in 2005 and today, numerous impact experiments have been run to assess the contribution of the new cloud and rain-affected observations to forecast skill. The change of skill between Cy29r2 and Cy31r1 reflects the improvements that have been introduced to the 1D-Var algorithm and to the 4D-Var assimilation of TCWV as well as the evolution of model physics, data assimilation system, and the introduction of new observations.

As an illustration, Figure 5 shows zonal cross-sections of normalized root-mean-square (RMS) 48-hour forecast error differences for relative humidity and temperature. The reference is the own analysis in each case, and the scores were calculated from forecasts between August and October 2004 based on the original implementation of cloudy and rainy SSM/I assimilation in Cy29r2. As above, the difference refers to RAIN minus NORAIN. Negative numbers indicate forecast improvements by RAIN and positive numbers indicate deterioration.

The biggest statistically significant improvements are seen in the tropics (here ±30° latitude) over most altitude levels. But also smaller areas of negative impact can be identified which seem to have little statistical significance but still dominate an area, for example, near the surface, poleward of 60°S. What was causing these degradations in the southern winter? Our first investigation focused on near-surface wind-speed because it affects sea-surface emissivity at microwave frequencies. The Southern Ocean is prone to high wind-speeds for which a potential model bias could alias into the TCWV-retrievals. Another candidate was that most of the precipitation column in these areas is composed of frozen particles, to which the active microwave channels exhibit little sensitivity.

Consequently, the rain assimilation was upgraded with a more conservative data screening in the presence of frozen precipitation, the inclusion of 10-metre wind-speed in the 1D-Var control vector, an improved bias-correction for the rain-affected radiances and a more detailed definition of TCWV-observation errors in 4D-Var. All these improvements originated from the post-operational experience with the system and most proved to produce forecast skill improvements in the critical areas when tested independently.

Along with Cy31r1, other significant model upgrades were introduced. Among these are the variational bias-correction (VarBC, see *ECMWF Newsletter, No. 107*) and the increase of super-saturation in the presence of ice – both affect the moisture analysis. The first RAIN-NORAIN experiments with Cy31r1 exhibited problems in areas where previously none had been found. Tropical scores of temperature and geopotential near 200–300 hPa as well as relative humidity near the surface and at 200 hPa were worse in the RAIN experiments.

The subsequent evaluation revealed that Cy31r1 was affected by an increased temperature spin-down at these levels, which only developed during the forecast and therefore indicated a physical feedback initiated by the moisture analysis. The improvements made between Cy29r2 and Cy31r1 resulted in a reduction in the first guess departures biases in the TCWV pseudo-observations, and this would usually be considered an improvement. However, we found that in the original implementation at Cy29r2, a small moist bias in the tropical TCWV departures had been offsetting the tendency of the 4D-Var analysis to cause a net drying when presented with observations in areas near saturation. The offsetting moist bias in the rainy TCWV observations was largely removed at Cy31r1, with the result that the RAIN analyses are now slightly drier than the NORAIN analyses in the tropics. A drier tropics leads to less convection and less latent heating of the upper troposphere over the forecast period.

However, the introduction of VarBC at Cy31r1 requires a much more careful experiment set-up than before. In a similar framework, a large number of impact experiments have been conducted in collaboration with EUMETSAT by Graeme Kelly and Jean-Noël Thépaut in 2006. For the bulk of the operationally assimilated satellite observations Observing System Experiments (OSEs) were performed to address the individual impact of sensors when denied from the full operational system or when added to a poor baseline observing system. These experiments were set up with an initial two-week period allowing for model and VarBC to spin up, followed by 8 weeks with fixed bias-correction. Initial conditions came from operational analyses from 2006 that already use VarBC. With such a set-up, it is hoped that any effects coming from the spin-up of VarBC can be reduced.

The results of the observing system experiments are shown in Figure 6. This shows that RAIN assimilation leads to bigger improvements in the relative humidity forecast than before (Figure 5). The temperature forecasts, while showing a better picture than our early experiments, still show an ambiguous picture; there is a stronger positive impact near 200 hPa and everywhere in the southern hemisphere but also a stronger negative impact localized at 300 hPa. In general, the cloud and rain-affected observations improve the forecast skill but there are small areas in the tropics where the slight tropical drying in the RAIN experiments appears to reduce skill through feedbacks into temperature. It is good to note, however, that in the southern winter where RAIN was previously causing a slight forecast degradation (Figure 5), our modifications now allow RAIN to make a small positive impact on the forecasts here (Figure 6).

In the course of experiment evaluation, the fit of the analysis to conventional observations that are also assimilated was shown to improve. For example, the model's fit to drop-sonde temperature and wind observations in the Caribbean became better while it remained neutral with respect to other satellite observations (e.g. Advanced Microwave Sounding Unit, AMSU-B) that are sensitive to moisture. Independent comparisons to TCWV obtained from radiometer measurements onboard the Jason-1 oceanographic satellite mission showed that RAIN led to improved mean TCWV analyses in Cy29r2.

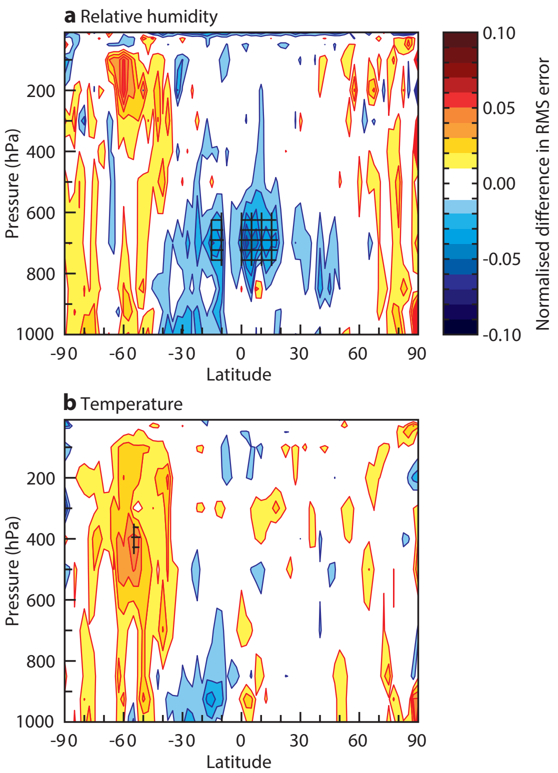

Figure 5 Zonal cross-section of normalized root-mean-square (RMS) 48-hour forecast error RAIN-NORAIN differences for (a) relative humidity and (b) temperature for August–October 2004 based on Cy29r2 where 0.1 corresponds to 10% RMS (hatching denotes 90% significance interval with t-test on analysis differences against zero-difference).

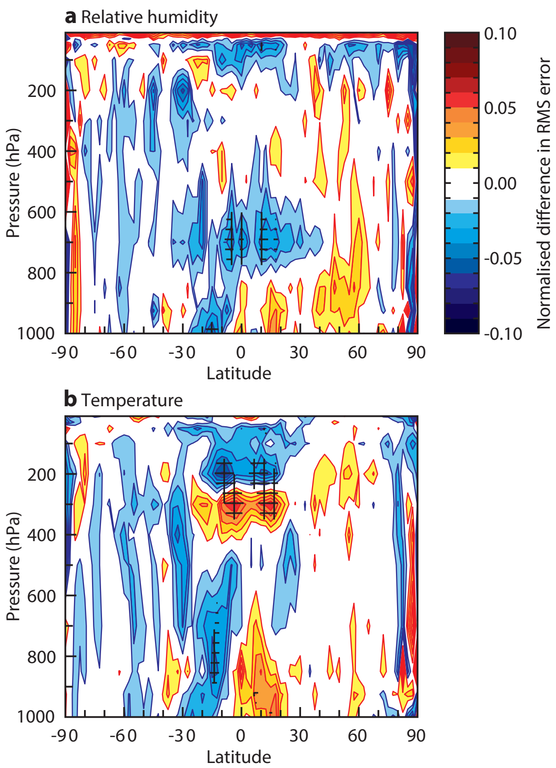

Figure 6 As Figure 5 from Cy31r1 EUCOS OSEs for 15 June to 15 August 2006.

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Future

Ten years ago, the idea of assimilating cloud and precipitation-affected satellite observations was deemed impossible. The results that are obtained with the current operational system at ECMWF on this area can be considered a big success. Already, research activities towards the assimilation of Atmospheric Infrared Sounder (AIRS onboard Aqua) and Spinning Enhanced Visible and Infra-Red Imager (SEVIRI onboard Meteosat Second Generation satellites) radiances are pursued at ECMWF that will be complemented by similar studies for microwave sounders (AMSU-A/B) in the near future. From this, it can be expected that the observational coverage of cloud-affected areas will greatly improve.

With regard to microwave imagers, there are three main areas of development for the period 2007–8:

- Extension of the 1D+4D-Var system. The extension of the 1D+4D-Var system to other microwave sensors such as AMSR-E, TMI and SSMIS. This will greatly improve data coverage along 6/12-hour assimilation windows and produce an impact that is geographically more balanced. Even redundant data coverage is of advantage in case of sensor failure. The inclusion of multiple satellites also allows observing system impact studies in preparation of the Global Precipitation Measurement (GPM) mission. GPM is a NASA/JAXA satellite constellation dedicated to precipitation observation from space planned for 2013.
- Assimilation of radiances over land surfaces. The assimilation of rain-affected (and clear-sky) radiances over land surfaces is currently exploited with the support of visiting scientists funded through the EUMETSAT Satellite Application Facilities (SAFs) for Numerical Weather Prediction (Fatima Karbou) and Hydrology (Chris O'Dell).
- Direct assimilation of radiances in 4D-Var. For optimizing the impact of rain-affected radiances in 4D-Var and to alleviate the side-effects of channelling this impact through a moisture pseudo-observation, the direct assimilation of radiances in 4D-Var is envisaged as done for all other clear-sky radiances. The technical implementation of this has already been carried out in 2006 and will be tested in 2007. Once successful, its activation in the operational system will mark another milestone of advanced data assimilation realized at ECMWF.

Other meteorological services are following similar routes.

- The Met Office will soon implement the assimilation of cloud-affected AMSU-A radiances.
- The Meteorological Service of Canada is preparing a 1D+4D-Var procedure using the ECMWF methodology.
- Météo-France is focusing on the assimilation of ground-based precipitation radar data in the regional Application de la Recherche à l'Opérationnel à Méso Échelle (AROME) project.

Further reading

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