

JOINT WMO TECHNICAL PROGRESS REPORT ON THE GLOBAL DATA PROCESSING AND FORECASTING SYSTEM AND NUMERICAL WEATHER PREDICTION RESEARCH ACTIVITIES FOR 2006

European Centre for Medium-Range Weather Forecasts

1. SUMMARY OF HIGHLIGHTS

Major changes in the operational data processing and forecasting system in 2006:

1 February: Implementation of Cycle 30r1. This was a significant increase in resolution of the medium-range forecast system: T799 (25 km), 91 level global model; data assimilation with T255 (80 km) inner loop; T399 (50 km), 62 level EPS. A tighter dissemination schedule and harmonised product access were introduced on the same date.

12 September: Implementation of Cycle 31r1. This included various changes to the model physics (revised cloud scheme, implicit convective transports, revised orographic drag) and variational satellite bias correction.

28 November: Operational implementation of VarEPS, extending range of EPS to 15 days with reduction in resolution from T399 (50 km) to T255 (80 km) after day 10. Introduction of 15-day EPSgram.

12 December: Implementation of Cycle 31r2. This introduced the assimilation of new satellite data: winds from MTSAT, and GPS radio occultation data from CHAMP, GRACE and COSMIC.

On 31 October, distribution by EUMETSAT of data from AMSU-A on the MetOp-A satellite started. On 2 November, exactly 2 weeks after the launch of MetOp-A these data were operationally monitored by ECMWF, followed by the Microwave Humidity Sounder (MHS) and High Resolution Infrared Sounder (HIRS). Operational monitoring statistics are available on the ECMWF website.

ECMWF was designated a WMO Global Producing Centre of Long-Range Forecasts at the WMO/CBS meeting in Seoul in November.

2. EQUIPMENT IN USE

The main change during 2006 was the upgrade of the HPCF, replacing the POWER4+ clusters with POWER5+. This system gives approximately 1.8 times the sustained performance of the POWER4+ system.

The computer equipment in use at the end of 2006 is summarised in Table 1. More information can be found on the ECMWF website <http://www.ecmwf.int/services/computing/>

Table 1: Computer equipment in use for operational activities (end of 2006)

Machine	Processors	Memory (GB)	Storage (TB)	Tape Drives
2 IBM Cluster 1600	2x2480 (1.9GHz Power5+)	2x4960	2x50	
4 HPrx4640	4x4	4x8	3	
11 IBM p-series	52	100	120	100

3. DATA AND PRODUCTS FROM GTS IN USE

A summary of data received through the GTS and other sources and processed at ECMWF is given in Table 2. Data coverage maps for most of these data are available from:

<http://www.ecmwf.int/products/forecasts/d/charts/monitoring/>

Table 2: Number of GTS products processed (December 2006, mean daily counts)

Data type	Mean	Data type	Mean	Data type	Mean
SYNOP	64171	AMV-GOES10	253005	HIRS-NOAA17	623686
SHIP	7735	AMV-GOES12	212643	AMSUA-NOAA15	365446
METAR	43521	AMV-MET5	172116	AMSUA-NOAA16	352067
DRIBU	29637	AMV-MET7	703235	AMSUA-NOAA18	412168
MOORED	854	AMV-MET8	765962	AMSUA-AQUA	289936
AIREP	22623	AMV-TERRA	16167	SSMI-F13	22809
AMDAR	83479	AMV-AQUA	16326	SSMI-F14	21494
ACARS	105947	GRAD-MET5	287484	SSMI-F15	0
TEMP-LAND	1198	GRAD-MET7	721157	SCAT	200140
TEMP-ASAP	14	GRAD-MET8	574634	SCAT-ERS	117325
PILOT	799	GRAD-GOES9	0	OZONE-ERS	5259
DROPSONDE	2	GRAD-GOES10	281819	OZONE-NOAA14	0
PROFILER-USA	696	GRAD-GOES12	318713	OZONE-NOAA16	1287
PROFILER-EU	627	HIRS-NOAA14	0	OZONE-NOAA17	1166
PROFILER-JAP	736	HIRS-NOAA15	26048	OZONE-MIPAS	0
AMV-GOES9	88125	HIRS-NOAA16	26371	AIRS	266631

4. FORECASTING SYSTEM

4.1 SYSTEM RUN SCHEDULE AND FORECAST RANGES

Major changes to the forecasting system in 2006 included a significant increase in resolution of the medium-range forecast model (February) and the extension of the Ensemble Prediction System (EPS) from 10 days to 15 days (November).

The following forecasts are produced operationally at ECMWF (December 2006):

Medium-range: global atmospheric model coupled to ocean wave model

- Forecast to ten days from 00 and 12 UTC at T799 (25 km) resolution and 91 levels
- 50-member ensemble forecasts to 15 days from 00 and 12 UTC at variable resolution - T399 (50 km) to day 10, then T255 (80 km) to day 15; 62 levels
- Global ocean forecast to ten days from 00 and 12 UTC at 0.36° resolution; European waters wave forecast to five days from 00 and 12 UTC at 0.25° resolution

Extended range (monthly): atmosphere-ocean coupled model

The monthly forecast is run once per week from 00 UTC Thursday, as a 50-member ensemble with a forecast range of 32 days. The atmospheric resolution is T159 (125 km), 62 levels; the ocean model has horizontally-varying resolution (1/3° to 1°), 29 levels.

Long range (seasonal): atmosphere-ocean coupled model

The seasonal forecast is run once per month as a 41-member ensemble with a forecast range of six months. The initial conditions are for the 1st of the month; the forecast is released on 15th. The atmospheric resolution is T95 (200 km), 40 levels; the ocean model has horizontally-varying resolution (1/3° to 1°), 29 levels.

4.2 MEDIUM RANGE FORECASTING SYSTEM (4-10 DAYS)

4.2.1 Data assimilation, objective analysis and initialization

4.2.1.1 In operation

The operational data assimilation is four-dimensional variational multi-variate analysis (4D-Var) for wind, temperature, humidity, surface pressure and ozone. Increment minimisation (inner loop) is run at T255 (80km) resolution on 91 model levels. The operational configuration comprises two 6-hour 4D-Var analyses, centred at 00 and 12 UTC, from which the main deterministic and EPS forecast are initialised. In addition there is a continuous 12-hour 4D-Var analysis (DCDA) cycle (observations from 09–21 UTC and 21–09 UTC) that runs with a delayed cut-off time to allow the maximum possible number of observations to be used. Short forecasts from the DCDA analyses are used as the background fields for the operational 00 and 12 UTC 6-hour assimilation.

Surface parameters: Sea surface temperature from NCEP Washington analysis; sea ice from SSM/I satellite data; soil moisture (Optimum Interpolation); snow depth; screen level temperature and humidity.

4.2.1.2 Research performed in this field

The ongoing developments in data assimilation reported here include long-window, weak-constraint 4D-Var, ensembles of assimilations, humidity analysis, improved usage of observations in general, and the use of satellite data in the surface analysis in particular. Diagnostic capabilities have been improved to facilitate troubleshooting, long-term performance monitoring, and observation impact assessment. Migration to the new IBM Phase-4 system and the general-purpose linux cluster has been successfully carried out.

(a) Data assimilation system

T255/L91 analysis increments. In the implementation of the high-resolution forecasting system (February 2006), the analysis resolution was increased to T255 (80 km) for the second inner loop, and to T799 (25 km) for the outer loops. The number of levels was increased from 60 to 91, and the domain was extended to include the lower part of the mesosphere (to 0.1 hPa). Analysing the new top-most levels is very challenging, given that there is virtually no observational information there and extrapolation from the stratosphere can be problematic. Instabilities due to large-amplitude gravity waves in the lower mesosphere caused ill-conditioning of the analysis solution algorithm in some cases. Work-around solutions were developed to enable successful implementation, but several issues remain.

Modified configuration of 4D-Var. A modified configuration of 4D-Var that comprises three rather than two outer loops (at T95, T159 and T255 resolution rather than T95 and T255) and fewer inner-loop iterations has been proposed (Trémolet, 2005) and tested. Full tangent-linear physics is used in the final two iterations. The change enhances the ability to deal with non-linearities, for example in cloud and precipitation observation operators and in variational quality control. There is a positive impact of the change even with current operational data usage. The modified configuration is cost-neutral in 12-hour 4D-Var, and is scheduled for implementation in 2007.

Analysis of tropical cyclones in the high resolution system. The assimilation of tropical cyclones in the ECMWF 4D-Var system has been investigated with special emphasis on resolution issues. The main conclusions from this work are that T799/L91 with T255/L91 analysis increments improves the representation of tropical cyclones compared to the previous T511/L60, T159/L60 configuration. The storms are more intense, the gradients near the centre and the rain band structures surrounding the storms are more realistic. The forecasts from T799 analyses retain the intensity of the tropical cyclones better. In almost all cases the analysed position of the tropical cyclones are very close to the observed location. Regarding their intensity, the 2–5 day forecasts are often more intense and realistic than the analyses, though almost always with an inferior

position. The tendency for weaker tropical cyclones in the analyses is partly because the structure functions are broad in the tropics and do not represent tropical cyclone background errors well. It may now be possible to address this issue building on the flexibility of the wavelet Jb. There are some indications that certain satellite data, like HIRS, has a detrimental impact on tropical cyclone analyses. This too will be investigated further. The use of flow-dependent background statistics based on an ensemble data assimilation system has shown encouraging results (Kucukkaraca and Fisher, 2006) and will be further explored in combination with improved quality control based on the Huber norm.

Ensembles of data assimilations. In future it will be possible to run low-resolution data assimilation ensembles in real-time. It will then be possible to link the ensemble spread with the background term, thus providing the assimilation scheme with flow-dependent 'errors of the day' (Kucukkaraca and Fisher, 2006); there is also the potential to improve the initial perturbations for the EPS. Currently a streamlined, efficient and user friendly configuration of the forecast system is being developed to run such an ensemble data assimilation system in experimental mode. The first version of this system is now in place. The system will provide estimates of the uncertainty in ECMWF analyses and short-range forecasts.

(b) Humidity analysis

Coupling with dynamics. Work has progressed on coupling the humidity more tightly with the dynamics in the analysis. The humidity control variable is normalized relative humidity, which has contributions from specific humidity and temperature increments. This provides a link from humidity to the dynamics through temperature. In the present implementation (Hólm et al., 2002) use is made of the unbalanced instead of the total temperature increments in the definition of the humidity control variable. When using the total temperature increments, as originally intended, the temperature changes associated with humidity observations become considerably larger, with balancing vertical and horizontal flows. Investigations will take place into whether it is possible to further enhance the humidity-dynamics coupling by including diabatic effects in the omega equation.

Humidity observation impact on analyses and forecasts. The global analysis and forecast impact of humidity observations has been assessed by means of observing system experiments with the ECMWF's 4D-Var data assimilation system (Andersson et al., 2006). It was found that humidity data have a significant impact extending into the medium range (5–6 day forecasts), with a marked impact also on the wind and temperature fields. This contradicts some recent papers that have shown insignificant impact of such observations. The current, greater benefit of the humidity analysis may be due to improvements to the model and data assimilation methods, and vastly increased availability of moisture observations. The study has also shown that each tested data type provides some benefit to the analysis and forecast performance, which indicates that the humidity analysis is effective in extracting information from a wide variety of humidity observations. Data from the microwave sounding instruments (SSM/I and AMSUB) dominates the humidity analysis over sea, whereas information from radiosondes, surface stations (SYNOP) and AMSUB dominates over land. The infrared sounders (GEOS, HIRS and AIRS) dominate in the upper troposphere, at 200–300 hPa.

(c) Surface analysis

Additional data for the SST, sea ice, snow and soil moisture analyses. There is a general emphasis on introducing additional observational data sets in the SST, sea ice, snow and soil moisture analyses such as satellite radiances (e.g. from future L-band microwave data from SMOS), derived products (e.g. ASCAT soil moisture) and mapped data sets (e.g. NCEP high-resolution SST and ice). The technical work for this includes the development of a new surface analysis suite. This will provide a computationally cheap test bed for forthcoming changes in the surface analysis and for the land surface model that will require long model integrations for evaluation through several seasonal transitions.

New soil moisture analysis scheme. A new soil moisture analysis scheme is currently being developed. The new system is based on the extended Kalman filter prototyped for Europe within the ELDAS project, which is now being implemented globally within the IFS. Compared to the current operational Optimum Interpolation scheme the main advantage of the Kalman filter approach is the capability to include satellite observations in the analysis.

Operators for the assimilation of satellite-derived soil moisture products. Observation operators for the assimilation of satellite-derived soil moisture products have been developed (Drusch et al., 2005; Gao et al., 2006) for TRMM, TMI and AMSR-E. The potential impact of satellite observations on the forecast system has been assessed through nudging experiments using the TMI Pathfinder data set over the Southern USA (Drusch and Viterbo, 2006; Drusch, 2007). The results show improved soil moisture analyses over a 2-month period, suggesting an improved representation of seasonal soil moisture variations. In collaboration with NASA, the methodology has been adopted for the global AMSR-E soil moisture data set and a multi-year data assimilation study has been performed within the framework of ECMWF's visiting scientist programme.

(d) Observation usage

Static TEMP bias correction scheme. The current operational TEMP temperature bias correction scheme was introduced some ten years ago. The scheme is static and based on assumed (rather than reported) sonde types. For each assumed sonde type there are 12 bias coefficients on 16 pressure levels accounting for the dependence on solar elevation and a 13th coefficient for the mean bias, stored in ad hoc files. The scheme has been given a complete technical overhaul in order to make regular updating and maintenance easy. An ODB (Observational Data Base) structure has been developed to store all the associated coefficients, lists and data. Using the new database in place of the old files gives identical results, and this has been implemented as a first technical stage. In 2007, the scheme will be merged with that used in ERA-40 and recalibrated.

Dynamic TEMP bias correction scheme for re-analysis. The radiosonde temperature bias correction scheme used for re-analysis (ERA) is a dynamic system based on observation minus background departures. Bias coefficients are computed monthly and averaged yearly. The ERA tables have also been converted into a single database structure. The IFS code has been modified to use this database in future reanalyses and as an option alongside the operational scheme. A one-month experiment has been run comparing (a) the ERA-40 bias correction, (b) the operational one and (c) no bias correction. Initial results confirm the utility of the ERA scheme. An adaptation of the ERA scheme, but based on the reported sonde type (where available) and applicable to both temperature and humidity, is now being developed for operational use.

ADM Level-2B processor development. Preparations are being made for the arrival of wind profile measurements from the ADM-Aeolus satellite (Tan and Andersson, 2005a, 2005b), with expected launch in 2008. ESA has placed a contract with ECMWF to develop the software to produce and deliver to ESA two of the mission's official data products: (a) the retrieved wind profiles (level 2B data products), and (b) the ADM-assisted wind analyses (level 2C data products). Part of the software will be portable and made available to the meteorological community at large; this is to facilitate widest possible use of the ADM-Aeolus data soon after they first become available. Observation processing software for ADM-Aeolus has been written in collaboration with Météo-France/GAME, KNMI, DLR and LMD/IPSL. Earlier simulation results of Aeolus analysis and forecast impact have been published (Tan et al., 2006).

Doppler wind lidar. In autumn 2003, as part of THORPEX, targeted field campaigns were carried out in the North Atlantic. The main objective of the Atlantic THORPEX Regional Campaign (A-TReC) was to reduce the 1–3 day forecast error over Europe and north-eastern America (Cardinali and Buizza, 2005). The airborne Doppler wind lidar (DWL) of the DLR was used to observe wind in predicted sensitive regions. In total, 1,600 measured wind profiles from eight flights have been assimilated and the impact of DWL measurements over Europe has been assessed (Weissmann and Cardinali, 2006). DWL observations have a significant impact on the analysis as well as on the

forecast due to their high accuracy and high spatial resolution. The measurements reduce the errors of the 1–4 day forecasts of geopotential height, wind, and humidity over Europe throughout the troposphere. On average, the 2–4 day height forecast error decreases by ~3% or more. Dropsondes, released in the same area where the Doppler lidar was operating, show good agreement with the lidar-measured winds, but smaller analysis impact and less reduction of the forecast error for forecast ranges beyond day 1. It is concluded that DWL data show great potential for future use in targeting campaigns.

Accounting for observation error correlation. Work has started on incorporation of observation error correlations in the ECMWF analysis system, following the ideas of Fisher (2005). The proposed algorithm uses an approximation of the observation error covariance matrix R that is constructed from the leading eigenvectors of the matrix. The correlation model itself is a combination of a convolution in the model space by the square-root of an isotropic correlation function and an interpolation from model to observation space. The modelled R is block-diagonal: only the observation errors in a given block (typically observations of the same kind) are assumed to be correlated. The feasibility of this construction of the correlation model has been demonstrated for highly reduced observation sets and hypothetical correlation functions. It is planned to test the scheme in a real 4D-Var configuration first for SATOB wind observations, where observation error correlation is well known and documented (Bormann et al., 2003).

(e) Diagnostics

The value of targeted observations. In support of the THORPEX programme and the initiative of EUCOS to set up an operational targeting activity, experiments have been carried out to assess the value of targeting sensitive areas over the Pacific and Atlantic Oceans to improve the 48-hour forecasts over North America and Europe respectively. Sensitive areas have been computed every 12 hours for two different seasons, winter 2003/04 (three months) and summer 2004 (two months), using dry energy norm singular vectors. Different experiments have been performed, denying the use of all observations either in sensitive areas or in randomly selected areas. The differences in the forecast errors between these two experiments provide an estimate of the value of dry-energy singular vectors in determining the areas where observations are most useful. For reference, an upper bound forecast degradation has also been computed by denying observations over the whole ocean area, while the operational system (with all the routine observations assimilated) provides the forecast error lower bound. It is found that for 48-hour forecasts over North America, the forecast degradation is larger when observations are denied in sensitive areas over the Pacific than when they are denied over randomly selected areas. For 48-hour forecasts over Europe, the difference between the two experiments is smaller, although sensitive areas of the Atlantic still seem to carry more information content than randomly selected areas.

ODB graphical user interface. The data assimilation system utilizes the Observational Data Base (ODB) for both input and output of observational data, quality control flags, et cetera. The contents of the ODB are invaluable for study of data assimilation performance, data monitoring, case studies and troubleshooting. An interactive visualisation tool has been developed to provide convenient access to the data. There is a graphical user interface that allows the user to browse the contents of the data base and to make selections of subsets of data for graphical presentation. Full graphical interactivity through an interface to Metview is under development. With this tool it is easy to generate data base requests without prior knowledge of the ODB contents and structure.

(f) Long-window and weak-constraint 4D-Var

Model error in 4D-Var. A weak-constraint formulation of 4D-Var has been developed and implemented in the IFS (Trémolet, 2003). It is not feasible to implement a global weak-constraint 4D-Var without simplifications in the representation of model error, and its covariance statistics Q . The approach we have taken is to consider model error to be constant by time intervals. The two extreme cases are thus: (a) having only one interval which means that model error is constant for the whole assimilation window, and (b) having an interval as short as a model time-step (Trémolet, 2006). The latter is in principle the full weak-constraint 4D-Var. Experimental results show that

taking model error into account greatly reduces the mean observation departure for the stratospheric channels of AMSU-A on NOAA-16. The statistics of the fit to radiosonde data over Antarctica show that the vertical oscillations in temperature are reduced and that the standard deviation is reduced above 50 hPa for both the background and analysis. The weak constraint formulation gives 4D-Var more freedom to fit the data without causing spurious oscillations in increments, which shows the importance of specifying different error covariances (**B** and **Q**) for the initial-condition and model-error control variables.

Long-window 4D-Var. Fisher et al. (2005) demonstrated the benefits of extending the length of the analysis window in a weak-constraint 4D-Var system for a simple one-dimensional model. Work has begun on applying this idea in the IFS. Initially, emphasis will be put on extending the current analysis window to 24 hours, rather than the several days envisaged, since this configuration is relatively inexpensive to run, and already demonstrates sensitivity to the representation of the effects of model error on the analysis. Although these preliminary results are encouraging, it is likely that improvements in the representation of the covariance structure of model error will be needed if the 24-hour window is to match and eventually exceed the performance of the current system.

(g) Satellite data – Operational Activities

Monitoring ATOVS radiances. ATOVS radiances (HIRS, AMSU-A and MHS) from NOAA-18 have been monitored operationally since 12 July 2005. Departures for AMSU-A were stable and within specifications, and operational assimilation started on 8 September 2005. This restored the use of four AMSU-A instruments in the operational system. In contrast, HIRS radiances from NOAA-18 show too large temporal variations in the departure statistics, so NOAA-18 HIRS is currently considered not suitable for assimilation. HIRS on NOAA-17 remains the only HIRS instrument used in operations. The MHS (the new Microwave Humidity Sounder) flying on NOAA-18 replaces the AMSU-B instrument currently flying on NOAA-15, -16 and -17, and will also fly on the three MetOp satellites. Monitoring the data from MHS confirmed that its radiometric performance was much better than that of AMSU-B and MHS data have been assimilated operationally since November 2005.

MetOp – ATOVS instruments. The EUMETSAT MetOp-A satellite was successfully launched on 19 October 2006, the first of a series of three polar-orbiting satellites forming the space segment of the EUMETSAT Polar System, and carries an ATOVS instruments suite (HIRS, AMSU-A and MHS). Data from AMSU-A was first made available to NWP users via EUMETCast on 31 October. These were immediately processed by ECMWF and were being monitored operationally by 2 November, followed shortly by the Microwave Humidity Sounder (MHS) and High Resolution Infrared Sounder (HIRS). Since then all three instruments have been monitored operationally providing invaluable feedback on instrument quality to EUMETSAT. An initial analysis of the monitoring statistics suggests the noise characteristics of the three instruments are well within specifications and comparable to similar instruments onboard NOAA satellites.

MetOp – ASCAT instrument. The Advanced Scatterometer (ASCAT) uses triplets of back scatter to estimate surface vector winds over the global oceans, soil moisture over land and the extent of land and sea ice. The access to a few orbits on 17 November 2006 allowed an early validation of the instrument, with wind inversions at ECMWF indicating a high quality product within specifications when compared with the ECMWF surface winds.

Microwave radiances. Technical work to include clear-sky radiances from three conically scanning microwave sensors (SSMIS on DMSP-16, AMSR-E on EOS Aqua, and TMI on TRMM-1) in the IFS has been completed. SSMIS combines channels similar to AMSU-A, AMSU-B and SSMI with a three-channel mesospheric sounder, whereas AMSR-E and TMI are microwave imagers similar to SSMI. After SSMIS, AMSR-E is particularly attractive for future assimilation as EOS Aqua's orbit provides coverage complementary to that of SSMI. Monitoring and assimilation experiments have been performed to estimate bias characteristics, to assess the quality of the radiances from these three sensors and evaluate their impact in terms of forecast skill. An operational implementation is scheduled for summer 2007.

Assimilation of rain-affected satellite observations. Several modifications to the first operational version of the 1D+4D-Var assimilation of rain-affected passive microwave radiometer data from SSMI (Bauer et al., 2006a, 2006b) have been introduced in Cy31r1 of the IFS. Firstly, as surface winds have a strong influence on sea surface microwave emissivity, these winds have now been included in the 1D-Var control vector to help prevent any errors in the background winds from being aliased into the temperature and humidity retrieval. Secondly, biases are now corrected individually for each of the three SSMI sensors from which data are assimilated, replacing use of a single correction for the data from each sensor. This sensor-based approach eliminates inter-satellite biases that previously could be seen in the TCWV increment field. Finally, retrievals are rejected when the model background profile includes more than 30% frozen precipitation. Applying this tighter quality control essentially reduces observation numbers in areas of tropical convection and at high latitudes.

Height assignment for Atmospheric Motion Vectors. One of the two height-assignment methods used operationally for Meteosat-8, the CO₂ slicing technique, uses a channel centred in the CO₂ absorption band at 13.4 µm, together with a second IR channel. The choice for this second channel was the subject of a change in the operational setup at EUMETSAT for which ECMWF provided pre-operational evaluation. The aim of the change was to reduce a slow bias created by assigning upper-level winds to too great a height. An impact trial carried out at ECMWF showed a reduction in speed bias in the extratropics but the development of a positive tropical bias. Whilst forecast score differences showed no statistically significant improvement, some evidence was nonetheless found to suggest that, overall, high level winds over the Met-8 region were being assigned to better levels. The modifications to the CO₂ slicing technique were implemented operationally by EUMETSAT on 1 December 2005.

Other developments affecting Atmospheric Motion Vectors Other developments include the following.

- The Japan Meteorological Agency switched MTSAT-1R (140°E) into operation in June 2005. MTSAT winds have been passively monitored operationally and assimilation trials have been carried out, leading to an operational implementation in December 2006.
- The acquisition of FY-2C AMVs has begun. However, their quality does not match yet the requirements for considering them as a candidate for operational use.

Monitoring and assimilation of ozone. The monitoring of ENVISAT near-real-time (NRT) products from SCIAMACHY and GOMOS has continued.

- The monitored GOMOS products are ozone and temperature. Owing to a major failure in the instrument telescope in January 2005 and later to problems in the ESA's data conversion, monitoring of GOMOS data was possible again only from February 2006 onwards. Good agreement (within 1%) was found between GOMOS and ECMWF analysed temperatures, at least below 1 hPa. The quality of the GOMOS ozone profiles has not improved, with differences still as large as 50% or more in places.
- The total ozone column products from SCIAMACHY are generated by KNMI (TOSOMI product) and assimilated operationally at ECMWF. In general, these products depict well the seasonal cycle of total ozone column, such as high ozone values in the northern hemisphere during the late northern winter and early northern spring, and low ozone in the tropics.

- Nadir ozone profiles from SBUV onboard NOAA-16 are assimilated operationally. The quality of similar products from NOAA-17 and NOAA-18 has been assessed throughout 2006 and their implementation in the ECMWF operational suite is planned for 2007.

Bias correction. Development of the variational bias correction system (VARBC) for satellite radiances has reached maturity (McNally et al., 2006). The scheme has demonstrated an ability to distinguish between systematic errors in the observations (or observation operators) and the assimilating model. Corrections generated by the adaptive scheme have been implemented statically in operations in February 2006, significantly improving the fit of the assimilation system to radiosonde temperature data in the lower stratosphere (where previously a large proportion of the correction applied to the satellite data was compensating for and thus reinforcing a model temperature bias). Implementation of the fully evolving VARBC has taken place on 12 September 2006. Efforts continue on establishing the best possible parametric form for the satellite bias correction to guarantee the longer-term stability of the VARBC correction system. Considerable technical effort has gone into display and monitoring of time series of observational biases and more generally the performance of the new bias correction scheme.

(h) Developments for the assimilation of data from advanced sounders

Preparations for the arrival of IASI data. In preparation for the arrival of IASI data, the bulk of the required technical infrastructure has been installed and tested with simulated observations. The EUMETCAST system has been exercised and a full end-to-end test with IASI simulations should be completed by the end of summer. The cloud detection algorithm that has been successfully applied to AIRS data has been improved and extended to handle IASI spectra. It has also been recoded for export to the wider NWP community as part of our NWP-SAF contribution. Within the SAF framework and in collaboration with DWD, studies have been carried out to validate the performance of the cloud detection scheme using the on-board AQUA visible imager. While these studies have confirmed that the scheme is generally effective at identifying even very small amounts of cloud contamination, a number of areas where the algorithm may be improved have been highlighted and these will be pursued in an ongoing collaboration with DWD.

Radiative transfer developments. A research version of RTTOV has been developed that includes the science of RTIASI. RTTOV can now simulate IASI and AIRS radiances with CO, CH₄, N₂O and CO₂ as profile variables and a solar term to evaluate the solar radiance reflected by a land or a wind-roughened water surface. The accuracy of the line-by-line (LBL) spectra on which the RTTOV fast transmittance model is based has been improved by including four more molecules in the LBL computations and by using a more recent release of the HITRAN molecular database. The treatment of the angular dependence of the optical depths has also been improved by introducing an altitude-dependent value of the local zenith angle that takes into account the curvature of the Earth and its surrounding atmosphere. A major new feature of RTTOV is the inclusion of a parametrization of multiple scattering in the presence of aerosols and clouds that is performed by scaling the optical depths by a factor derived by including the backward scattering in the emission of a layer and in the transmission between levels.

Aerosol detection for AIRS and IASI. Exploiting the ability to simulate the spectral signature of aerosol with the new RTTOV radiative transfer model, a scheme has been developed to detect the presence of aerosol contamination in spectra measured by AIRS and IASI. It follows similar principles to the cloud detection algorithm and will be distributed with the NWP-SAF cloud detection software to the wider NWP community. In its current form it should be regarded as a prototype, but it has already demonstrated an ability to detect significant aerosol loading events over sea (e.g. from desert dust and volcanic ash). The potential will be explored for this aerosol detection scheme to be used for quantitative aerosol estimation. If so it may allow AIRS and IASI radiance data to constrain aerosol concentrations within the GEMS assimilation context.

Direct assimilation of MIPAS limb radiances. Developments for the assimilation of emitted infrared limb radiances from MIPAS have been completed as part of the EU-funded ASSET project.

MIPAS radiances can now be assimilated either with a one-dimensional observation operator which assumes local horizontal homogeneity for the radiative transfer calculations, or with a two-dimensional observation operator which takes into account horizontal gradients along the limb-viewing plane. Assimilation experiments with the two operators have been performed to assess the impact of MIPAS radiances on stratospheric analyses of temperature, humidity, and ozone over a six-week period. The experiments are also used to compare the impact against results obtained from assimilating MIPAS retrievals of temperature, humidity, and ozone. The experimental stratospheric humidity analysis was activated for the study, following developments by Hólm et al. (2002). The results demonstrate the feasibility of direct assimilation of emitted infrared limb radiances. The assimilation of MIPAS radiances leads to considerable differences in the mean stratospheric analyses, without a significant degradation of the fit to other observations used in the assimilation. For ozone, the assimilation causes an increase in the tropical ozone maximum in the analysis, and a reduction of ozone over the poles.

(i) Direct assimilation of GPS radio occultation bending angles

Experiments assimilating CHAMP GPS radio occultation measurements. The first set of experiments assimilating CHAMP GPS radio occultation (GPSRO) measurements with two-dimensional bending angle observation operators has been completed. The two-dimensional operators improved the bending angle departure statistics in the lower troposphere by around ~5% compared with a one-dimensional bending angle operator, although this did not translate into a clear, statistically significant improvement in the forecast scores. The results with the one- and two-dimensional operators are extremely similar in the upper troposphere and lower stratosphere, with both approaches substantially reducing the stratospheric oscillation problem over the South Pole.

Monitoring and assimilation of GPSRO measurements. The IFS and associated software have been modified to enable the monitoring and assimilation of GPSRO measurements from CHAMP, GRACE-A, the GRAS and COSMIC missions during 2006. A substantial effort has then been dedicated towards the operational exploitation of GPSRO bending angle measurements currently available (CHAMP, GRACE-A and COSMIC constellation). Temperature information can be inferred from these measurements with a unique vertical resolution, improving considerably the thermal structure of the stratosphere of the model. All the preparatory work has been done for ECMWF to join the EUMETSAT GRAS Satellite Application Facility (SAF), the objective of which is to develop operational radio occultation products from the Global Navigation Satellite System Receiver (GNSS) for Atmospheric Sounding onboard MetOp, in its Continuous Development and Operational Phase (CDOP). RO measurements from CHAMP, GRACE-A and COSMIC were introduced operationally on 12 December 2006.

(j) EUCOS/EUMETSAT Observing System Experiments

Contribution of the components of the terrestrial Observing System. Observing System Experiments (OSEs) coordinated by EUCOS have been performed to examine the various components of the terrestrial Observing System, in the presence of the current satellite-based Observing System. The study involves Member-State partners to whom ECMWF provides boundary conditions for their own regional OSEs. The experiments have been run for a 43-day period in winter. Results from a summer period (46 days) are currently being assessed. The winter studies indicate a large impact of the radiosondes (wind and temperature) and aircraft (wind and temperature), a marginal impact of radiosonde humidity information, and a contrasted impact (with negative spells) from the wind profilers. Wind information alone from sondes does not seem sufficient to impact noticeably the forecast skill. In contrast, coupled temperature/wind information from the radiosondes provides a large and statistically significant improvement in the forecasts well within the medium-range.

Contribution of the components of the satellite-based Observing System. An assessment of the relative contribution of the various components of the satellite-based Observing System has been performed in collaboration with EUMETSAT, using the same periods and version of the assimilation system as used for the EUCOS study. A “baseline” scenario has been defined, where

only conventional observations have been assimilated. Satellite sensors have then been added individually or in combination to the “reference” to document their intrinsic contributions. Among all sensors, AIRS and AMSU-A (and to a lesser extent HIRS) appear to be the main contributors to forecast skill for both hemispheres. It is reassuring to confirm that all the space-based sensors contribute positively to the overall improvement of the ECMWF forecasting system. In particular, the impacts of AMSU-B (or MHS), CSRs from geostationary orbit and SSM/I on the global humidity analysis and short-range forecasts, and of scatterometer data on the surface wind forecast for the southern hemisphere, have been clearly demonstrated within these OSEs. A particular focus on the impact of the MODIS AMVs confirmed that this product is now a major component of the Global Observing System.

4.2.2 Model

4.2.2.1 In operation

All components of the ECMWF data assimilation and forecasting system use the Integrated Forecasting System (IFS). The medium-range data assimilation and deterministic and ensemble forecast systems both use the same model cycle (31r2 at December 2006).

Specification

- **Variables (recalculated at each time-step):** Wind, temperature, humidity, cloud fraction and water/ ice content, ozone content, pressure (at surface grid-points).
- **Numerical scheme:** Semi-Lagrangian, semi- implicit time-stepping formulation.
- **Horizontal grid:** wind and temperature are held as spectral fields. The grid for computation of physical processes is a reduced, linear Gaussian grid
- **Vertical grid:** hybrid levels
- **Physics:** Orography (terrain height and sub-grid-scale characteristics); four surface and sub-surface levels (allowing for vegetation cover, gravitational drainage, capillarity exchange, surface and sub-surface runoff); stratiform and convective precipitation, snow-fall, snow-cover and snow melt; radiation (incoming short-wave and out-going long-wave); sub-grid-scale orographic drag, gravity waves and blocking effects; evaporation, sensible and latent heat flux; simplified ozone chemistry.

The high resolution 10-day forecast runs at T799 (25 km) horizontal resolution with 91 levels (top at 0.01 hPa). The EPS uses 62 levels (top at 10 hPa) and runs at T399 (50 km) resolution to day 10, then at T255 (80 km) to day 15.

4.2.2.2 Research performed in this field

(a) Radiation and Aerosols

Surface albedo. A new surface albedo derived from four-years of MODIS measurements processed by Boston University has been introduced in the IFS as a monthly climatology. It distinguishes the ultraviolet-visible (0.25–0.7 microns) from the near-infrared (0.7–4.0 microns) parts of the spectrum and is given for both direct and diffuse radiation. The differences with the currently operational albedo show a complex geographical and seasonal pattern. The overall tendency is a reduction of the surface albedo by a few percent. The impact on standard large scale forecasts scores is small.

Monte Carlo Independent Column Approximation. A Monte-Carlo representation (McICA; Pincus et al., 2003) of the radiation using both RRTM-LW (with 140 grid points) and RRTM-SW (with 112 grid points) is now under test. At present, the cloud generator is used in the "operational" configuration, assuming a maximum-random overlap of the cloud layers on the vertical. The important elements in this new radiation package are:

- RRTM-SW with absorption coefficients for all gases derived from more recent spectroscopic data, and with increased spectral resolution.

- The McICA approach which guarantees a similar treatment of the clouds in both the longwave and shortwave parts the spectrum and can easily accommodate different cloud overlap and inhomogeneity assumptions through a cloud generator external to the radiation schemes.
- A revision of cloud optical properties adapted from the more recent data from Fu et al. (1998) in the shortwave and Fu et al. (1999) in the longwave.

In year-long simulations as in ten-day forecasts at TL159 L60, this radiation configuration shows a marked improvement in the overall balance between longwave and shortwave radiation at the top of the atmosphere.

Revised numerics and ice-phase microphysics. A new prognostic cloud scheme has been developed which is designed to tackle the vertical resolution sensitivity that exists in the current operational scheme, while taking the opportunity to enhance and improve the treatment of the ice phase microphysics. The new package consists of the following changes.

- The numerical solver was changed to a fully implicit upstream scheme.
- The sedimentation of ice crystals is now formulated as a pure ‘advective’ process i.e. ice crystals that fall below cloud base are no longer converted to snow.
- A new autoconversion parametrization was added to convert ice to snow.
- A new parametrization was implemented that allows supersaturation with respect to ice to occur in the cloud-free part of the grid box at temperatures colder than 250 K.

This significant upgrade produced a substantial impact on the model cloud climatology, which naturally influences the other model fields.

Further cloud scheme developments. A long-standing aim has been to introduce enhanced ice microphysics into the IFS by the implementation of a prognostic ice variable. Although it would be possible to modify the operational scheme to include this, the structure of the scheme is not able to cope with the solution of multiple pathways between multiple prognostic microphysical variables. This would hamper future development of the code, such as the introduction of prognostic equations for rain, snow, graupel and ice, as well as number concentrations for these variables. Therefore efforts have been expended this year to develop a replacement for the operational scheme. The scheme will be developed and implemented in two stages:

- *Stage 1:* Introduction of multiple prognostic microphysics equations for snow, ice and rain mass mixing ratios.
- *Stage 2:* Replacement of the Tiedtke treatment of a prognostic cloud cover variable with a statistic cloud scheme with prognostic skewness and variance of total water.

Convective transport for momentum, humidity and temperature. Operational implementation in Cy31r1 of the implicit formulation of the convective transport for momentum, humidity, and temperature was a major activity. The motivation behind this development comprise a better numerical stability of the integrations, smoother convective profiles avoiding overshoots leading to negative humidity, and a more flexible specification of the convective fluxes in the subcloud layer (linear flux profiles are no longer imposed, but the draught values are specified). The main impact of the implicit formulation is on momentum, and to a lesser extent on humidity and upper-tropospheric temperature,. In addition, the integration of the humidity tendencies from all physical processes along the semi-Lagrangian trajectory has been corrected to preserve positive humidity, which is particularly important for the coming interim reanalysis. The main effects of these developments are a reduction of the model’s negative 10 m wind speed bias over convective oceanic areas, an improvement of the tropical upper-tropospheric winds that are affected by both the momentum and temperature tendencies (through quasi-geostrophic adjustment), and a slight increase of precipitation over the Amazon region, as well as a northward shift of precipitation over Africa toward the Sahel region. Both precipitation features seem to verify well against synoptic data and climate maps from the GPCP.

Improved and simplified entrainment formulation. Work has started on an improved and simplified entrainment formulation that aims to drop the undesired dependency of the convective mass fluxes on the large-scale moisture convergence, and aims to address the lack of sensitivity of the current convection scheme to environmental moisture. The difficulties of the current model to simulate the Madden-Julian Oscillation are possibly related to the latter deficiency. So far the results, based on a simple entrainment rate that is a sum of a pressure-scaled “constant” term and a buoyancy-dependent term, are promising as a significant reduction in tropical rainfall over the central Pacific and Indian Ocean is obtained (regions were currently the main positive precipitation biases are located). However more work is necessary to correctly simulate the land-sea contrast in convection, and to correctly simulate the cloud tops and the upper-level mass fluxes (detrainment) that are critical to the upper-level tropical winds.

(b) Boundary layer

New PBL scheme. The combined eddy diffusivity mass-flux framework (EDMF, Siebesma et al., 2006) which forms the basis for the new PBL scheme was implemented in 2005 and was applied to heat and moisture in situations with dry convection and stratocumulus. Work is progressing on the extension of this EDMF framework to include momentum transport by mass flux and to include shallow convection. At the same time the operational EDMF stratocumulus scheme was evaluated using observations for a winter stratus case over Europe (Köhler, 2005), the stratocumulus off California (DYCOMS-II, Stevens et al., 2006), the GCSS Pacific cross-section II, and GLAS space lidar over oceans. The latter study of collocated space lidar/model data is particularly interesting as it measures cloud top height with about 70 m resolution. This showed that the PBL height is generally too low and that the stability based regime transition criteria is too conservative for stratocumulus. The sensitivity to parcel entrainment and the stability criteria is under study.

EDMF – momentum. The EDMF framework is being extended to include momentum transport by the mass-flux term, which will represent so-called counter-gradient effects. Without this non-local mass-flux component, the surface winds are too weak during day time over land and over the ocean. Two key design decisions are involved namely (a) the relative importance of mass fluxes transport and K-diffusion transport near the surface and (b) the momentum deficit to be assigned to the updraughts.

- Surface layer similarity theory is well tested and should be built into the parametrizations, particularly with respect to momentum transport. Yet, when adding a mass-flux term to the K-diffusion term in the flux equation, one risks over-estimating the fluxes near the surface. K is therefore reduced to exactly offset the added flux by the mass flux term at the surface. This can be done because the mass flux M and the updraught properties are known as they are specified from the tail of a Gaussian PDF.
- The updraught momentum deficit is scaled with friction velocity u^* according to surface layer similarity, and the pressure gradient term is specified following Kershaw and Gregory (1997) as a function of vertical shear.

The scheme is currently being tested in single column mode and compared to LES results from an idealized parameter study by Brown et al. (2006).

EDMF – shallow convection. Extensive evaluation against observations at land sites of the Atmospheric Radiation Measurement (ARM) programme and the European CloudNet project has exposed serious deficiencies in the shallow convection scheme such as representing the diurnal cycle over land (Cheinet et al., 2005). Because of the close coupling with the surface, it appears natural to consider shallow cumuli as boundary layer clouds and to include their parametrization in the boundary layer scheme. This project is also an opportunity to update the associated physics with recent new scientific insights into shallow cumulus convection. The new scheme is designed as an extension to the Eddy Diffusivity Mass flux framework that forms the current PBL scheme, which already accounts for the dry convective and stratocumulus-topped PBL. In brief, the extension consists of two new components: a dual mass flux scheme and a bimodal statistical cloud scheme. To evaluate and optimize the EDMF scheme, offline single column model (SCM) tests have been performed for a range of idealized cases, as developed by the GEWEX Cloud

System Studies (GCSS) boundary layer working group. In addition, a routine SCM evaluation project has started for some ARM and CloudNet sites with near real time observational data.

(c) Orography

Changes to the parametrization of subgrid orography effects in Cy31r1. Cy31r1 includes a major change to sub-grid scale orography (SSO) parametrization with the replacement of the effective roughness scheme by the Turbulent Orographic Form Drag (TOFD) scheme (Beljaars et al., 2004a). A revised vegetation roughness table is also introduced. These changes are implemented in conjunction with an 'effective' mountain height in the parametrization of gravity wave drag, in order to reduce the velocity deficit at high altitude downstream of orography.

Momentum tendencies over orography. Momentum tendencies over orography computed by the TOFD scheme and the Lott and Miller (1997) SSO scheme (i.e. due to low-level blocking and gravity wave drag) are computed with implicit numerics and the increments can be very large for long time steps (at the lowest resolution a time step of one hour is used). In order to avoid dependencies on the time step it is important to have good balance between processes during the implicit computations (Beljaars et al., 2004b). Moreover, to some extent the processes are coupled, leading to a time step sensitivity as each scheme evaluates its tendencies independently. To obtain good balance for large time steps and to reduce time step dependency, Cy31r1 solves for turbulent diffusion, turbulent orographic form drag and for the subgrid scale orography scheme simultaneously in a single implicit calculation. This results in a decrease in sensitivity of surface stress and gravity wave stress (and to a lesser extent low-level velocity) to time step over orography.

(d) Land surface

Soil hydrology. Three major changes to the operational land surface scheme TESSEL have been prepared and are currently under test:

- A new dataset for soil type; sand and clay fraction is used to define for each grid point the dominant hydrological class: coarse, medium, medium-fine, fine, very fine or organic. The data is based on the Digital Soil Map of the World.
- The empirical formulation for hydraulic diffusivity and the hydraulic conductivity for the six hydrological classes according to Van Genuchten (1980) are introduced.
- A parametrization of sub-grid surface runoff, based on Dümenil and Todini (1992), which takes into account the unresolved orography/heterogeneity effects, is introduced. Ideas from a more recent implementation from Hagemann and Gates (2003) are included.

The implications of these changes are still under investigation, but the expected effect is to generate more surface runoff (currently negligible), to reduce the speed of vertical soil water transport, and to increase the dynamic range of the soil moisture reservoir. The last two characteristics will result in increased memory of soil moisture at the seasonal time scale.

GEOLAND. The EU-Funded GEOLAND project aims at preparing an operational system for the estimation of consistent water vapour and biospheric CO₂ fluxes. The vegetation modules of ISBA-A-gs have now been successfully coupled to TESSEL. The coupled version, called C-TESEL, has two major improvements: (a) transpiration is coupled to photosynthesis which is explicitly computed by the model and (b) carbon assimilated by the vegetation is allocated to different plant compartments (leaves and trunks). The carbon allocated to leaves control the foliage development (growth and decline) often expressed in terms of LAI (Leaf Area Index). This means that the seasonal evolution of LAI is a function of the relevant meteorological conditions, thus accounting for the interannual variability in vegetation. C-TESEL is now able to estimate the CO₂ fluxes in the vegetation. These CO₂ fluxes will be tested as boundary condition for the GEMS atmospheric CO₂ assimilation.

(e) Physics in data assimilation

Developments in tangent-linear and adjoint physics. The separation of the tangent linear (TL) and adjoint (AD) vertical diffusion code from the scheme that is used in the full nonlinear model has been finalized. All parametrizations of surface processes have been moved to the library dedicated to the surface, in a consistent way with the nonlinear code. In addition, the TL and AD versions of the surface routines that were not previously available have been coded for the purpose of obtaining larger increments near the surface (especially temperature over land). Additional experimentation has aimed at a partial inclusion of perturbations of the exchange coefficients at the surface and in the atmosphere. Indeed, the current total absence of perturbations of the turbulence exchange coefficients in the TL and AD seems to be too conservative. Experiments including all these modifications have shown a slight systematic improvement of the TL approximation with respect to the nonlinear model, especially at low levels.

Replacement of the current linearized longwave radiation. An investigation on the possible replacement of the current linearized longwave radiation (a combination of neural network and mean Jacobians) by a linearization of an earlier version of the full longwave radiation code (Morcrette, 1989) has started. The motivation for this work is that the cost-advantage of the current approach seems to be reduced as a result of the recent increase in vertical model resolution (from 60 to 91 levels). Maintenance of the neural network code is also becoming increasingly difficult. Frequent re-training of the neural network and re-calculation of the Jacobians every time the resolution is changed and after each substantial modification of the model code is impractical. Finally, the current approach does not include sensitivity with respect to such parameters as aerosols and gases. This would be desirable for the prospect of their assimilation as part of the GEMS project. As a first step, the nonlinear code for longwave radiation has been optimized and its TL version has been coded. The integrity of the TL code is being checked and the accuracy of the TL approximation for finite-size perturbations will then be tested.

Improvements to the linearized cloud and convection schemes. Several improvements to the linearized cloud and convection schemes have been implemented in Cy31r1. The tangent linear and adjoint versions of the tracer transport by vertical diffusion and convection have been provided to the GEMS group for further evaluation. The TL and AD versions of the radar reflectivity model have been coded and tested and will be useful in feasibility studies on the assimilation of reflectivity measurements from satellites (e.g. CloudSat, TRMM) or ground-based radars. Previous preliminary studies of this kind were based on very expensive computations of Jacobians, which prohibited any long experimentation.

Tests of new linearized moist physics in 4D-Var. The evaluation of the new linearized cloud and convection schemes in 4D-Var has been pursued using the most recent model cycle (the current 4D-Var uses only a very simple convection scheme in which no perturbations to the udraught properties and strength are allowed). Assimilation experiments have been run for a winter period (December 2005) with high vertical resolution (91 levels) in Cy30r2. As in previous experiments, more observations are used and at the same time the observation and the background terms of the cost function are systematically reduced. The fit of analyses to the observations is also improved. The impact in terms of objective scores is positive in the northern hemisphere and close to neutral in the southern hemisphere. The largest improvement is found over North America.

Assimilation of SSM/I rainy radiances. Substantial effort has been devoted to the development of the TL and AD versions of the new microwave brightness temperature operator to be used in the future direct 4D-Var assimilation of SSM/I rainy radiances. A study of model errors in daily precipitation using European rain gauge data (ELDAS) has indicated that the correlation length of these errors remains within 150 km, even less during summer where convective situations dominate. This work should be repeated for shorter accumulation periods and will help to specify error statistics for the assimilation of precipitation.

Assimilation of hourly surface precipitation observations. 1D+4D-Var assimilation experiments using hourly surface precipitation observations from the combined radar (NEXRAD)

and rain-gauge 4-km resolution analyses produced by NCEP in quasi-real time over the USA have been run over a month (late spring 2005). Preliminary results indicate that the impact of the additional 1,200 observations per 12-hour cycle is mainly neutral in terms of standard global scores (geopotential, temperature) and slightly positive for precipitation scores over the USA for short forecast ranges (up to 18 hours). Further diagnostics and validation are required to finalize this study. Besides, large uncertainties remain about the specification of observation and background error statistics (standard deviation and correlations), about the optimal temporal and spatial frequency of the observations (incl. the accumulation period), and about the degree of consistency between the precipitation observations and other more conventional moisture measurements (e.g. radiosoundings). Further experimentation should address these specific issues, the final objective being the direct 4D-Var assimilation of this type of observations.

AMMA project. The EU-funded AMMA project (African Monsoon Multidisciplinary Analysis) started at ECMWF in January 2006. ECMWF has provided support with the monitoring of the enhanced radiosonde network in the AMMA region. Also work on forecast verification for the last monsoon season of 2005 was started during April 2006. Preliminary results obtained by comparing analysis with 1-day, 2-day and 3-day forecasts show that the African Easterly Jet (AEJ) core is quite well predicted up to day 3. The easterly wave troughs are well predicted up to 48 hours. However, at 72 hours the predicted troughs are sometimes weak and slow. The short-range forecasts of precipitation over the Sahel are not good enough to be of use to the forecasters in Africa. However, 700 hPa relative humidity thresholds at 70% for lowland and 80% for highlands match quite well the NOAA/NCEP/CPC/FEWS precipitation estimates over West Africa. One of the main problems with precipitation is a systematic southward shift of approximately 4 degrees on the predicted position of the maximum precipitation band associated with the ITCZ over Africa for the short-range forecasts (D+1 to D+3). This systematic shift is also present in the 2004 West African wet monsoon season. A comparison of monthly total precipitation for observations from a very dense network of rain gauges over the Sahel with rainfall forecasts at day 1, day 5 and day 10, shows that this systematic shift becomes smaller with forecast range.

(f) Numerical aspects

Operational change in horizontal and vertical resolution. The high-resolution system T799L91 and T399L62 EPS (Cy30r1) became operational on 1 February 2006. Better representation of the orography and increased vertical resolution led to more observations being accepted in the analysis. The mean scores are in general better than the control scores with T511L60 and Cy29r2, with the largest gain and highest statistical significance in the southern hemisphere. This new forecast system leads to improved forecasts of tropical cyclones and of other severe weather events.

Non-interpolating semi-Lagrangian version. The accuracy of the semi-Lagrangian advection scheme depends crucially on the quality of the interpolations at the departure points of the trajectories. In the operational configuration, cubic Lagrange interpolations with quasi-monotone limiters are used for the advected quantities and linear interpolations are used for the right-hand side of the equations. An alternative to more accurate interpolation to improve the quality of the semi-Lagrangian advection may be a “non-interpolating version” that does not require interpolations at the departure point. A non-interpolating algorithm in three dimensions has been coded. The nearest grid point to the semi-Lagrangian departure point is found and the semi-Lagrangian method is applied with this grid point as departure point, while the remaining or “residual” advection is computed in an Eulerian way. Several options for treating this residual advection have been coded and are being evaluated. This non-interpolating semi-Lagrangian scheme is expected to have less damping of the smallest scales than the operational scheme, and hence produce a more realistic kinetic energy spectrum.

Non-hydrostatic version of the IFS. The non-hydrostatic model developed by the ALADIN community for the limited area version and incorporated into the global ARPEGE/IFS model by Météo-France has been interfaced with the ECMWF physical parametrizations. Its performance in terms of stability and accuracy is being evaluated in global forecast mode.

Interface of physics and dynamics. An option of integrating the model with the physical parametrizations at a different resolution from that of the dynamics has been coded in the IFS. Preliminary results indicate that the verification scores, for a given dynamics resolution, improve progressively with increased physics resolution.

Simulation of the MJO by means of idealized IFS simulations. The ability to simulate the MJO by means of idealized IFS simulations has been investigated. An eastward propagating signal in the equatorial region has been found in Held-Suarez type (dynamical core) simulations with two distinct periods of 39 and 66 days, indicating an entirely dynamical mode selection in the MJO frequency band. IFS climate simulations forced by observed SSTs and relaxed towards a 50 day zonal mean zonal flow oscillation in the lowest equatorial troposphere (below 970 hPa) stimulate upper level (200 hPa) variability in the 20-day averaged stream function and substantially improve the prediction of MJO events. This variability is characterized by strong gradients of the averaged stream function contours close to the equator, which are absent in the IFS control climate simulations. Likewise, there is no such variability with an enforced constant zonal mean zonal flow in the tropical troposphere where essentially all wave motions are suppressed. Further experimentation with a revised entrainment closure in the convection scheme showed similar variability in the averaged stream function and an equally improved simulation of the MJO.

(g) Diagnostics

Sensitivity of the life cycle of extratropical cyclones. Previous work on the sensitivity of the life cycle of extratropical cyclones to horizontal resolution (Jung, Gulev et al., 2006) has been extended. There is a pronounced underestimation of extratropical cyclones by the semi-Lagrangian version of the TL95L60 model in high-latitudes, the major baroclinic zones in the Gulf Stream and Kuroshio region, over the North Pacific and in lee of the Alps. It has been speculated that these errors are due to the excessive amount of dissipation associated with the use of the semi-Lagrangian advection scheme. In order to test this conjecture two additional experiments have been carried out using a semi-Lagrangian scheme without monotonic interpolation and the Eulerian scheme. These experiments reveal that it is not the use of the semi-Lagrangian scheme, which leads to the underestimation of cyclone activity in the above mentioned regions.

New automatic cyclone tracking procedure. So far, the cyclone tracking has been carried out using a scheme developed by S Gulev and co-workers (P.P. Shirshov Institute of Oceanology, Moscow, Russia). Recently, the automatic tracking procedure developed by K. Hodges (Reading University) has been implemented. One advantage of this method is that a variety of features (e.g. extratropical weather systems, hurricanes and easterly tropical waves) can be tracked (not just local sea level pressure minima).

Greenland's influence onto the atmosphere. Aspects of Greenland's influence onto the atmosphere have been studied together with P Rhines (University of Washington). The strength of the interaction has been described by the zonal pressure drag across Greenland. It turns out that high pressure drag events are associated with a large number of high-impact weather events such as rapid cyclogenesis, down-slope wind storms, tip jets and vertically propagating gravity waves. The high-resolution ECMWF model (TL799L60) appears to be capable of realistically simulating these small-scale features. Furthermore, the possible influence of Greenland on the skill of medium-range weather forecast further downstream has been investigated. Although high pressure drag events across Greenland are accompanied by increased forecast errors in the short-range (in the wake of Greenland), no evidence has been found for any significant influence of Greenland on forecast skill in the medium-range over northern Europe.

Predictability of the northern hemisphere stratospheric circulation. The predictability of the northern hemisphere stratospheric circulation has been investigated. It turns out that useful predictions are feasible well beyond day 10. The improvement in the predictive skill during the ten years, however, has been rather modest compared to that found for the troposphere. The largest improvement occurred in autumn 2000, when the resolution of the deterministic high-resolution system was increased to TL511L60. This improvement, however, did not show up in the control

forecast of the EPS (TL255L40) and, therefore, a gap in the predictive skill between the two systems developed.

Stratospheric climate. The stratospheric climate of the IFS has been investigated. Seasonal integrations reveal a high sensitivity of stratospheric planetary wave activity over northeast Canada to horizontal resolution. Moreover, it has been shown that the observed statistical properties of the stratosphere-troposphere link (“downward propagation” of zonal mean zonal wind anomalies) are successfully simulated by the IFS (at various resolutions). This is reassuring given that this link might be one of the sources of extended-range predictability in the Euro-Atlantic region.

Simulation of the QBO. The capability of the IFS in simulating the QBO has also been investigated. Seasonal integrations with two different vertical resolutions (L40 and L60) reveal considerable sensitivity to vertical resolution. However, even the L60 version of the IFS fails to simulate the strong bimodality of the distribution of zonal-mean zonal winds at the 20 hPa level. Finally, it turns out that the QBO has weakened already substantially after only 10 days into the integration (the QBO is realistically represented in the initial conditions), suggesting that the successful simulation of the QBO is not just an extended-range forecasting problem.

Assessment of model physics using initial tendencies. The systematic tendency of the model during the first few forecast timesteps can be used to assess model physics. The methodology of Klinker and Sardeshmukh (1992) has been refined further by making a more accurate integration over the diurnal cycle. The initial tendency method has been used for two investigations.

- A new cloud physics package has been implemented in the operational model. The initial tendencies indicate improvements to the initial temperature tendencies in the upper troposphere and also to the day-5 temperature bias. There is a slight degradation in the corresponding humidity tendencies.
- An assessment of the perturbations to the turbulent convective entrainment coefficient has been made. The strong initial tendencies found suggest that the physics of these perturbed models are poor and that these models should not be used in the assessment of climate change uncertainty.

Importantly, it has been shown that the initial tendency methodology is much less computationally expensive than century-long climate assessment simulations and also benefits from a degree of linearity that could make the assessment of climate change uncertainty a manageable proposition.

4.2.3 Operationally available Numerical Weather Prediction Products

All numerical products generated by the operational forecast suites are archived in the Meteorological Archive and Retrieval System (MARS). ECMWF forecast products are disseminated to Member States and Co-operating States using a scheduled dissemination system. A flexible interface provides appointed contacts in Member States with a wide range of numerical products to be disseminated in GRIB or BUFR.

Numerical products are also disseminated via the Global Telecommunications System (50 to 64,000 bits per second) operated under WMO/WWW. The horizontal resolution is 2.5x2.5 degrees (dissemination in GRIB). These products are also made available to WMO NMHSs in graphical format via the ECMWF web site. Additionally, dissemination through EUMETSAT MDD is arranged via METEOSAT to Africa. Special dissemination agreements have also been agreed with NCEP, JRC, EUMETSAT and ESA.

A catalogue of ECMWF products available via the GTS is available from the following web page:
<http://www.ecmwf.int/products/additional/>

A selection of products is available to WMO NMHSs in graphical format via the ECMWF website at:

<http://www.ecmwf.int/products/forecasts/d/charts>

Details of how to access these products are given at:

4.2.4 Operational techniques for application of NWP products (MOS, PPM, KF, Expert Systems, etc.)

4.2.4.1 In operation

No activity in this area

4.2.4.2 Research performed in this field

No activity in this area

4.2.5 Ensemble Prediction System (EPS)

4.2.5.1 In operation

Two major changes were made to the ECMWF EPS during 2006. In February the resolution forecast model was increased from T255 (80 km) to T399 (50 km) and from 40 to 62 levels. In November the range of the EPS forecast was extended from 10 days to 15 days; the last five days are run at lower horizontal resolution of T255. The EPS runs twice per day (from 00 and 12 UTC).

The EPS uses the same forecast model as used for the deterministic forecast (see section 4.2.2.1), but at lower resolution. The ensemble comprises one control forecast (run from the operational analysis) and 50 perturbed members. Initial perturbations are generated by multi-dimensional Gaussian sampling from 50 singular vectors (SV) selected at T42 resolution in the extratropics, plus up to 30 SV (5 per Tropical Cyclone) selected in the vicinity of Tropical Cyclones that have been reported on the GTS. Random perturbations of the physical tendencies (stochastic physics) are applied to the perturbed forecasts.

4.2.5.2 Research performed in this field

(a) VAREPS (VARIABLE Resolution Ensemble Prediction System)

Implementation schedule. On 1 February 2006, the EPS resolution was increased to TL399L62, with T42L62 singular vectors. This change is the first of a three-phase upgrading process that will lead to the implementation of the ECMWF Variable Resolution Ensemble Prediction System (VAREPS):

- *Phase 1* (February 2006): resolution increase of the 10-day EPS from TL255L40 to TL399L62.
- *Phase 2* (November 2006): extension of the forecast range to 15 days using the VAREPS system, with TL399L62(days 0–10) and TL255L62(days 10–15).
- *Phase 3* (planned for 2007): weekly extension of VAREPS to one month, with a TL255L62 atmospheric resolution and ocean coupling introduced at day 10 (the precise configuration of this final stage of VAREPS is still to be finalized).

Strategic aim of VAREPS. VAREPS aims to provide better predictions of small-scale, severe-weather events in the early forecast range, and skilful large-scale guidance in the medium forecast range. The strategy used to achieve these goals is to resolve small-scales up to the forecast time when they are predictable and their inclusion has a positive impact on the forecast accuracy. This strategy leads to a more cost-efficient use of the computer resources, with most of them used in the early forecast range to resolve the small but still predictable scales.

(b) EPS verification

New climatology. A new climatology for each day of the year based on ERA-40 analyses is being developed, with a view to replacing the current climatology for verifying deterministic and probabilistic forecasts. Monthly ACC for 500 hPa geopotential height have been computed for 2005

using both climatologies. The use of the new climatology tends to reduce the ACC in particular for months with ACC lower than 70%.

EPS performance at different spatial scales. The EPS performance has been analysed at different spatial scales. Four wavenumber bands have been defined with zonal wavenumber 0, 1–3, 4–12 and 13–63. In the mid-latitudes, these correspond to the zonal mean, planetary scales, synoptic scales and sub-synoptic scales, respectively. It is found that the ratio of spread to error depends clearly on the spatial scale. In the short-range, the ensemble is over-dispersive at all scales; the mismatch between spread and error is largest in the synoptic scales, where the spread is 40% larger than the ensemble mean error. If one considers all scales and the entire northern hemisphere extra-tropics, the spread is too large by 22%. Significant over-dispersion at day-2 in the northern hemisphere mid-latitudes and synoptic scales is also diagnosed for geopotential at 1000 hPa (27%), meridional wind at 700 hPa (24%) and 200 hPa (26%) but not for temperature at 850 hPa (6%). Experimentation with the backscatter scheme under development at TL255L40 resolution (Cy30r1, 46 cases) indicates that the over-dispersion at day-2 in the synoptic scales can be significantly reduced by reducing the amplitude for the initial perturbations and using more active tendency perturbations without decreasing the spread in the later forecast ranges and with neutral to positive impact on probabilistic scores of 500 hPa geopotential.

(c) Initial perturbations

Moist singular vectors. The impact on singular vectors and the EPS of using the new moist physical parametrization package and the new radiation scheme in the tangent linear and adjoint (TL/AD) model was further tested together with the impact of increasing the horizontal resolution and shortening the optimisation time. The following three experiment configurations were compared for a sample of 39 cases spanning one year (Cy29r2, TL255L40 resolution, 50+1 member):

- A: Operational configuration with T42, 48-hour optimisation time singular vectors, TL/AD model: dry in extra-tropics and old moist physics for tropical cyclones.
- B: TL95, 24-hour optimisation time singular vectors; TL/AD model: dry in extra-tropics and old moist physics for tropical cyclones.
- C: TL95, 24-hour optimisation time singular vectors, TL/AD model: new moist physics and new radiation for all regions.

The scaling of the initial perturbation amplitude in B and C was adjusted to obtain a similar spread as in A at day-2 for 500 hPa geopotential. B and C exhibit equal performance in terms of probabilistic scores for the 500 hPa geopotential indicating a neutral impact of the change in the representation of physical processes in the TL/AD model. However, B and C are moderately worse than A in terms of the area under the relative operating characteristic curve for 500 hPa geopotential while Brier scores are similar for all three experiments. This degradation is attributed to the shortening of the optimisation time (as earlier experimentation has shown that the impact of increasing the horizontal resolution alone in the singular vector computation is neutral).

Hessian singular vectors, and sensitivity of EPS performance on choice of initial time norm.

The ensemble prediction system was run in model Cy29r2 (with singular vectors resolution T42L60 and forecast resolution TL255L60) using the leading 25 initial singular vectors based on total energy (TESV) and the Hessian (HSV) to generate 50 initial perturbations for a ten-day forecast. This was performed for 12 cases at equally-spaced intervals from July–December 2005. A perturbation scaling factor, Γ , was applied to both TESV and HSV ensembles where $\Gamma = 0.027$. In a further experiment to address an under-dispersive HSV ensemble spread, denoted HSVinf, this factor was inflated by 15% to obtain similar ensemble spread as in the TESV ensemble at day 2. If the spectrum of wavenumbers is narrowed to consider just 'synoptic-scale' zonal wavenumbers 4–12, then the TESV ensemble displays larger spread than the ensemble mean error up to day 3, particularly in the mid-latitudes. Under these circumstances, the reduced spread exhibited by the HSV ensemble provides comparatively good spread-skill at short time ranges, but as it is consistently less than the TESV ensemble spread over the entire forecast range, the HSV ensemble becomes more under-dispersive (than the TESV ensemble) beyond day 3. Further

experimentation to incorporate a suitable model error representation may assist in correcting both the TESV and HSV ensemble spread for these scales. There is consistency of these results to the associated area under the ROC curves for these scales, where the skill of the TESV ensemble is greater than that of the HSV (or HSVinf) beyond short time-scales.

(d) Simulation of model uncertainties

Stochastic Physics and Model Error in the Ensemble Prediction System. The cellular automaton stochastic backscatter scheme (CASBS) aims at simulating model error by generating a pattern with correlations at the near-grid-scale which are weighted by the local dissipation rate stemming from numerical dissipation, convection and gravity/mountain wave drag. Improvements were made in both aspects: the pattern generator was improved and a new method to calculate the dissipation rates from shallow and deep convection based on a mass-flux formulation introduced. Results based on a 50 member ensemble at TL255L40 in Cy30r1 for 46 cases throughout the year indicate a small, but robust increase in skill of the ensemble prediction system. The improvement is partly due to the fact that having a better representation of model error allowed for a reduction of the initial perturbation amplitudes without decreasing the ensemble spread in the medium-range. This is reflected by a better agreement between ensemble spread and ensemble mean error. Experiments testing CASBS in higher resolution TL399L62 and in the newest model cycle are under way.

Stochastic physics and systematic model error on seasonal to inter-annual timescales. The impact of a stochastic representation of unresolved processes on systematic model error was assessed using (a) CASBS and (b) a stochastic-super-cluster (SSC) scheme run at TL95L60 for 40 winters. The CASBS improves blocking, reduces the systematic error over the North Pacific and greatly improves the precipitation in the tropics. The SSC scheme aims at representing the dynamical signature of organised convection in a stochastic manner and is only active in the tropical band. First results indicate that the introduction of the signature of cloud-super-clusters not only improves tropical precipitation but more importantly increases the activity of the model in the MJO-band of 30–60 days. Experiments are also underway replacing the cellular automaton scheme with a spectral stochastic Markov process..

(e) Applications of ensemble forecasts

PREVIEW. The generation of a high-resolution, high-frequency data-set required by the PREVIEW partners has been completed (Prevention, Information and Early Warning, an EU FP6 project). This data-set provides the initial and boundary conditions required to drive limited-area ensemble systems and hydrological models (either directly using VAREPS input data, or indirectly using limited-area data). The data-set has been generated using ensemble forecasts run in a prototype of the VAREPS configuration planned for operational implementation, with resolution with a TL399L40 resolution up to forecast day 7, and a TL255L40 resolution from day 7 to day 13, have been run for the PREVIEW special period (20 July to 31 August 2002), with a high-frequency post-processing of 3 hours, and saving model levels up to forecast day 6.

Health applications. Efforts on promoting the use of EPS forecasts for health applications have been intensified. Extreme weather events, like the 2003 heat wave over Europe, have shown that increased collaboration between governmental health agencies and the meteorological community can be beneficial. ECMWF has pioneered such collaborations already some time ago (e.g. in the EU-funded DEMETER project), and work on establishing new partnerships is underway. ECMWF will be part of a WMO initiative to form a health/climate partnership for Africa using meteorological information to mitigate health epidemics. In addition, the use of EPS in EU-projects on health applications has been supported for currently running projects, and intensified collaborations in new projects have been proposed.

(f) Other developments

Calibration of ensemble forecasts. The investigations on the potential benefits of using re-forecast data to calibrate the EPS have been continued. After the first tests with a re-forecast dataset consisting of only control forecasts, the experiments have been extended to also include perturbed members. This enabled the test of a more advanced calibration method (logistic regression). The newly produced re-forecast dataset consists of 280 cases (i.e. 14 start dates times 20 years) covering the period from September to November 1982–2001. ERA-40 re-analyses have been used as initial conditions. Preliminary results indicate the potential of the logistic regression method to improve certain EPS scores. In the initial tests, the calibration coefficients have been derived comparing forecasts and analyses in both the training and test period. However, it is expected that the scores can be improved even further when using station data instead of analyses as verifications. It also seems that there is more scope for improving near-surface weather parameters rather than upper-air fields.

Combined Prediction Systems. Present ECMWF medium-range forecast products include a single high-resolution “deterministic” forecast and a 50-member lower-resolution ensemble prediction system (EPS). Each forecast system is useful in its own right but here an attempt has been made (see Rodwell, 2005) to harness the strengths of both systems in a single “combined prediction system” (CPS). The CPS methodology produces a probability distribution based on an optimally weighted average of a set of forecast systems. The weights are considered to be spatially invariant and derived to maximise the Brier Skill Score for the prediction of European precipitation when verified against SYNOP rain-gauge data. These weights could be used to assess our forecast products and help optimise their configuration in terms of resolution, number of ensemble members etc.

4.2.5.3 Operationally available EPS Products

Products are disseminated using the same dissemination as for the deterministic model (see section 4.2.3). A selection is available to WMO NMHSs in graphical format via the ECMWF website at:

<http://www.ecmwf.int/products/forecasts/d/charts>

Details of how to access these products are given at:

http://www.ecmwf.int/about/wmo_nmhs_access/index.html

4.3 SHORT-RANGE FORECASTING SYSTEM (0-72 HRS)

No short-range system is run at ECMWF.

4.3.1 Data assimilation, objective analysis and initialization

4.3.1.1 In operation

"[information on Data assimilation (*if any*), objective analysis and initialization,]" (*Indicate boundary conditions used*)

4.3.1.2 Research performed in this field

"[Summary of research and development efforts in the area]"

4.3.2 Model

4.3.2.1 In operation

"[Model in operational use, (*domain, resolution, number levels, range, hydrostatic?, physics used*)] "

4.3.2.2 Research performed in this field

"[Summary of research and development efforts in the area]"

4.3.3 Operationally available NWP products

"[brief description of variables which are outputs from the model integration]"

4.3.4 Operational techniques for application of NWP products

4.3.4.1 In operation

"[brief description of automated (formalized) procedures in use for interpretation of NWP output]"
(MOS, PPM, KF, Expert Systems, etc.)

4.3.4.2 Research performed in this field

"[Summary of research and development efforts in the area]"

4.3.5 Ensemble Prediction System

4.3.5.1 In operation

"[Number of runs, initial state perturbation method, perturbation of physics?]" (Describe also: time range, number of members and number of models used: their domain, resolution, number of levels, main physics used)

4.3.5.2 Research performed in this field

"[Summary of research and development efforts in the area]"

4.3.5.3 Operationally available EPS Products

"[brief description of variables which are outputs from the EPS]"

4.4 NOWCASTING AND VERY SHORT-RANGE FORECASTING SYSTEMS (0-6 HRS)

4.4.1 Nowcasting system

No such system is run at ECMWF.

4.4.2 Models for Very Short-range Forecasting Systems

No such system is run at ECMWF.

4.5 SPECIALIZED NUMERICAL PREDICTIONS

4.5.1 Assimilation of specific data, analysis and initialization (where applicable)

4.5.1.1 In operation

Altimeter wave heights (from ENVISAT and Jason) and ASAR spectra (from ENVISAT) are assimilated in the ocean wave model (See section 4.5.2.1)

Tropical cyclone observations reported on the GTS using BUFR format are used as seeds for the tracking and of tropical cyclones in the medium-range deterministic and ensemble forecast systems.

4.5.1.2 Ocean wave modelling research

See section 4.5.2.2.

4.5.1.3 GEMS Project

See section 4.5.2.3.

4.5.1.4 Reanalysis Project

(a) Introduction

ERA-Interim. A new ECMWF reanalysis, ERA-Interim from 1989 onwards, began in summer 2006 and has reached mid-1995. ERA-Interim is a major upgrade of ERA-40 and will address the main deficiencies of ERA-40 for this period. Adaptive bias correction techniques will, for the first time in the reanalysis context, be used for satellite radiances. ERA-Interim will be continued in near-real time as a Climate Data Assimilation System. It will be an evolutionary step between ERA-40 and the next major ECMWF reanalysis.

(b) Configuration of the ERA-Interim data assimilation system

Model configuration for ERA-Interim. The ERA-Interim system uses IFS Cy31r1/2, with model resolution T255L60. In addition to the increased spatial resolution and improvements in the model physics, the main differences with respect to ERA-40 are:

- Use of 4D-Var with a 12-hour time window.
- Better formulation of background error constraint.
- New humidity analysis.
- Data quality control that draws on experience from ERA-40 and JRA-25.
- Rain assimilation using 1D retrievals of rain-affected SSM/I radiances.
- Variational bias correction of satellite radiance data and of SHIP and SYNOP surface pressure data.
- Use of a homogenised radiosonde temperature dataset and improved bias correction tables.
- Use of reprocessed Meteosat winds.

Improvements in the monitoring system. Monitoring the performance of the data assimilation is an essential part of reanalysis production and there are several complementary ways to do this. Under normal circumstances, 10–15 days of analyses are produced every actual day. Statistics are needed over quite long periods, and have to be examined regularly. Based on experience with ERA-15 and ERA-40, comprehensive monitoring diagnostics with routine web-based display have been further developed for ERA-Interim. They include:

- Time series and monthly-means (maps and cross-sections), for quantities such as basic analysed and forecast variables, and their differences from ERA-40.
- Means and standard deviations of the analysis-minus-background increments and the observation-minus-background and observation-minus-analysis departures for all assimilated observations.
- Number of used, blacklisted and rejected conventional data.
- Radiosonde bias correction statistics.
- Predictors and corrections from the VarBC scheme for radiances.

A variety of monthly mean plots are also produced (e.g. of surface fluxes, analysis fields, zonal mean analysis increments), and in many cases the differences of these quantities with respect to ERA-40 are included. All plots are automatically generated by the system and stored on the web for easy access.

General quality of the new analyses. The new radiance bias correction scheme and results on the representation of the hydrological cycle are described below. The general quality of the new analyses shows a substantial improvement of the preliminary ERA-Interim analyses over ERA-40, which in turn showed improvements over ERA-15 and ECMWF operations for 1989 and 1990.

(c) Adaptive bias correction of satellite radiances

Adaptive system for handling biases in satellite data. The adaptive system for handling biases in satellite data is based on a variational bias correction scheme, in which bias parameters associated with each radiance channel are treated as additional degrees of freedom in the 4D-Var minimization. The system is self-contained and does not require any external information about the biases. It has been shown to perform well in numerous preparatory ERA-Interim experiments, as well as in the operational context. It solves most of the technical problems associated with manual bias tuning, smoothly corrects bias drifts, handles data gaps, and can quickly develop bias corrections for new sensors. Variational bias correction of radiance data simultaneously with the adjustment of the model state appears to remove many of the detrimental side effects of suboptimal and/or conflicting bias corrections seen in ERA-40. The radiance biases are adjusted for all channels except for the top SSU channel. As a result, the fit to conventional data improves as well, and the system is able to assimilate larger numbers of observations overall and the upper stratospheric temperatures have realistic evolution.

Stability of the adaptive scheme. The stability of the adaptive scheme depends on the amount of information about the biases available from other observations. To test and illustrate this, a simple experiment was performed in which all observations were withheld from one of two otherwise identical assimilations during a period of two weeks, causing the two systems to drift apart considerably. It was found that there was divergence of the global mean analysed temperatures in the two systems followed by a re-convergence after the reintroduction of observations. Re-convergence in the upper stratosphere is relatively slow, consistent with the lack of unbiased observations there.

(d) Other developments

Preliminary results on the hydrological cycle. Precipitation in the new system is more realistic than ERA-40 (as judged by the comparison with GPCP data, for example) both in the tropics and in mid-latitudes. It is too early to determine the extent to which the spurious temporal trend in total column water vapour and precipitation seen in ERA-40 will be reduced, but indications are promising. Precipitation spin-up has been reduced, and global P-E is in good balance. The new system produces more stratus over upwelling regions in the subtropical oceans. Revisions to the humidity analysis formulation and the cloud/radiation parametrizations have led to substantial changes in the energy balances at the top and bottom of the atmosphere. Top-of-atmosphere energy exchange has improved with respect to ERA-40, but surface energy exchange has deteriorated somewhat. The Saharan soil is drier and warmer in the recent experiments.

Examination of the SSU radiances used in ERA-40. With the objective of improving the handling of early stratospheric observations in the next major reanalysis, work has begun on examination of the SSU radiances, which were for the first time directly assimilated in ERA-40. Large biases and inadequate bias corrections contributed to the deficiencies of the stratospheric temperature analysis in ERA-40. It is found that inter-satellite biases are quite large and not completely removed by the bias-correction. Some jumps in the time series occur when the satellite observing system changed (or for NOAA-6 early in 1981 when the bias correction was changed). There is a small increasing trend in the time series for NOAA-7, which is believed to be due to high leakage rates in the pressure modulator cell. The fast radiative transfer model (RTTOV), which is used to model the assimilated radiances has a single coefficient file for all SSU instruments from TIROS-N to NOAA-14 and changes of atmospheric CO₂ concentrations and cell pressures in time are not taken into account. Information on the characteristics such as the leakage rates has been systematically collected. It is foreseen that these imperfections can be taken into account in RTTOV leading to improved adjustments to the inter-satellite biases of SSU radiances in future reanalyses.

4.5.2 Specific Models

4.5.2.1 In operation

An ocean wave model is integrated (two-way coupling) in all operational configurations of the ECMWF atmospheric model (IFS). The model is based on the WAM cycle 4 model, with various enhancements as documented in ECMWF Technical Memoranda 478 and 509 (available from the ECMWF website <http://www.ecmwf.int/publications>). The wave model resolution is 40 km for the deterministic forecast; 110 km for the EPS; 170 km for the monthly and seasonal forecasts. In addition, a limited area European shelf version is run at 28 km resolution to 5 days.

4.5.2.2 Research associated with ocean wave modelling

(a) Operational Developments

Support continues to be given for the operational running of the wave model. The wave forecasting system is currently part of the global medium-range forecast suite, the limited area European shelf, the boundary conditions suite, the EPS, and the monthly and seasonal forecast systems. On 1 February 2006, together with the IFS increase of resolution, the wave model resolution was increased from 0.5° to 0.36°. In addition, the assimilation of Jason Altimeter wave height data and ENVISAT ASAR data were introduced.

(b) Verification of analysis and forecast

The wave model performance during 2005–2006 has been monitored extensively. Forecast validation against buoy data and against the verifying analyses shows that the quality of the wave forecast continues to be very high. There has been an increase in forecast skill in wave height and surface wind (obtained by determining the rms error against buoy data) over the past 14 winter seasons. In addition, the comparison of performance with other operational centres continues, with the ECMWF wave model maintaining a clear lead over the other centres.

(c) Monitoring and assimilation of satellite observations

Bias and random error as function of the relevant parameter. A triple collocation method (usually applied to satellite, model and buoy data) was developed, which allows for each of the three collocated data sets to obtain bias and random error as function of the relevant parameter (e.g. wind speed or wave height). Using this method the CMOD5 bias and random error as a function of wind speed was established, and will result in a recalibration of the CMOD5 model parameters. In the context of the interim reanalysis, the same method was also applied to Altimeter wave height data from ERS-1 and ERS-2, demonstrating that bias correction of the Altimeter wave height data is required.

Dependency of radar backscatter on surface stress. Since there are physical arguments for the radar backscatter being dependent on surface stress and the sea state, a next step for improvement is to develop an inversion algorithm along these lines. Additional experiments using the assimilation of neutral winds are under way.

Improvement to the Altimeter wind retrieval algorithm. Work was carried out to improve the Altimeter wind retrieval algorithm in order to obtain smoother wind speed distributions and get better agreement with buoy measurements, in particular for low wind speeds. The improved Altimeter wind algorithm was introduced operationally by ESA in the ENVISAT processing chain in October 2005. This new Altimeter wind product performs in a satisfactory manner as expected.

Huber norm in the altimeter wave height OI assimilation. Observation minus first-guess statistics show clear deviations from the normal distribution. This has led to the introduction of the Huber norm in the altimeter wave height OI assimilation which gives a better description of the non-Gaussian altimeter and model error statistics, and serves as a replacement for the first-guess check.

(d) Modelling developments

Prediction of extreme sea states. Three years ago, a theory for the prediction of freak waves was developed at the ECMWF. These extreme events result in large deviations of the normal

probability distribution of surface elevation as expressed by the kurtosis. According to theory the kurtosis depends on the cube of the wave spectrum, and it is therefore straightforward to make probabilistic statements on the occurrence of freak waves in the open ocean. A number of consequences of this approach have been validated in the laboratory. The next step is a validation against in-situ buoy data. However, normally operational buoys do not report observed kurtosis of the sea surface elevation, except a number of non-governmentally-owned buoys around Japan. A recent validation against these buoy data was reported by Mori and Janssen (2006). The results suggest that, as expected from theory, the kurtosis is a good predictor for extreme sea states.

Development of shallow water physics and numerics of the wave model. In the context of a coastal version of the wave prediction system the shallow water physics and numerics of the wave model have been modified and extended. The new elements are bottom-induced wave breaking and an improvement of the representation of the nonlinear transfer in shallow water. Tests of a number of different model configurations are under way.

4.5.2.3 Research associated with GEMS

(a) Introduction

Aim of GEMS. GEMS is an EC Framework-6 Integrated Project that is developing global modelling and data assimilation for greenhouse gases, reactive gases and aerosols, and regional modelling and data assimilation for reactive gases and aerosols. The aim is to improve global monitoring of atmospheric composition, estimation of surface fluxes of CO₂ and other species, and regional air-quality forecasting. Aside from overall project management and technical support, ECMWF's main tasks within GEMS are to:

- Develop the modelling and assimilation of greenhouse gases (initially CO₂, followed by methane and N₂O) within the IFS.
- Couple the IFS forecast model with global chemical transport models (CTMs), carry O₃, CO, NO₂, SO₂ and CHOH in the IFS and develop assimilation of retrievals for these species.
- Incorporate externally-produced aerosol parametrizations in the IFS, and develop assimilation, first of retrievals, then of radiances.
- Integrate the above components into a pre-operational system and run assimilations for recent years.
- Provide boundary conditions and technical support for the regional air-quality prediction component of the project.

Overview of progress. Project work began in the spring of 2005. Since then, an initial version of the greenhouse gas, reactive gas, and aerosol assimilation system has been built, and the observational data necessary for initial testing have been acquired. Extra model fields for the greenhouse and reactive gases and several aerosol species have been included in the IFS, and the 4D-Var assimilation system has been extended to allow the assimilation of data for each constituent. The extension of the data assimilation system required extensive coding and testing, because the IFS did not have the facility for tracers other than humidity and ozone. Generic interfaces between model and observations have been changed to allow the inclusion of GEMS variables. These interfaces include several routines to interpolate model fields both vertically and horizontally to the observation locations. The code changes from the various strands of work have been merged and incorporated in Cy31r1 of the IFS. Good progress has been made on developing the web interface and the reporting, monitoring and verification tools.

(b) Greenhouse Gases

Introduction of CO₂ as a tracer. CO₂ has been introduced as a tracer in the IFS. Prescribed climatologies are used to describe the exchange between the surface and the atmosphere. The introduction of surface fluxes in the IFS requires climate fields at all model resolutions. For that purpose interpolation routines have been modified for coastal areas to maintain consistency with the land sea mask and to satisfy conservation. Diagnostics have been introduced in the IFS to check tracer mass conservation. Budgets are computed regularly during the forecast model runs.

Separate tracers have been connected to the different CO₂ surface fluxes (land biosphere, ocean and anthropogenic) to allow an assessment of the relative contribution of the different modelled processes to the simulated CO₂ concentration.

Assessment of model quality. Long integrations have been carried in 12-hour intervals to assess model quality. Each 12-hour forecast starts from the analysed meteorological fields, but the tracers are taken from the previous 12-hour forecast. This enables the simulations to be compared to observations in a deterministic way. Model outputs were compared on a monthly basis to in situ measurements both in the PBL and in the upper troposphere. Unfortunately, many ground observations are on remote islands and coastal areas giving little information about anthropogenic sources. Globally, the model showed reasonable agreement with observations. The “missing sink” in the northern hemisphere was manifested in underestimation of the latitudinal gradient at the surface during the growing season. On an annual basis, simulations showed higher north-south gradients at the surface than in observations, suggesting shortcomings in the prescribed fluxes (emissions from biomass burning are still missing) or in the transport model (slow inter-hemispheric exchange, excessive vertical trapping).

Experiments using both monthly mean fluxes and diurnally resolved fluxes. Various types of atmospheric CO₂ observations are and will be available in the future, constraining different parts of the atmosphere. In view of the requirement to assimilate different observation types, there has been an investigation of the impact of resolving the diurnal cycle of CO₂ exchange with the natural biosphere. Experiments were carried out using both monthly mean fluxes and diurnally resolved fluxes from the CASA climatology. As expected, the impact of ignoring the diurnal cycle is large in the PBL close to the local forcing, negligible in the marine boundary layer and moderate for the high troposphere and total column. However, the effect on the latitudinal gradient (about 0.8 to 1 ppm) is non negligible, given that a 1 GtC/year northern hemisphere carbon sink may decrease the north-south column CO₂ gradient by about 0.4 ppm (Olsen and Randerson, 2004). The primary reason for the impact is that vertical mixing in summer has a strong diurnal cycle which is correlated with the diurnal cycle of biospheric activity. It has thus been decided to use three-hourly fluxes rather than monthly values for the natural biosphere, despite the additional computational burden.

Experiments using hourly observations. The forward modelling of atmospheric CO₂ concentration has been assessed using hourly observations located both in the land and in the marine boundary layer. These measurements are valuable because they resolve the diurnal cycle of atmospheric processes and the carbon exchange with the surface. The main findings are:

- The correlation between the model and observations drops during night-time for most of the stations, a result that was expected given that respiration is poorly represented in most models. The correlation is low when CO₂ is strongly controlled by the boundary layer height which suggests a further contribution from modelling of the nocturnal boundary layer. The verification of CO₂ with surface observations over land will be an interesting diagnostic to help improve the parametrization of the nocturnal boundary layer.
- Modelled and observed mean diurnal cycles are in better agreement for flat areas than for hilly areas where the boundary layer is likely to be misrepresented due to limited (currently T159) model resolution.

Data assimilation. Radiance data from the Atmospheric Infrared Sounder (AIRS) are being used to infer information about atmospheric CO₂ mixing ratios in the same way as is done for temperature and humidity. The RTTOV fast radiative transfer model has been extended to include variable CO₂ and is used as the observation operator. For initial tests a background covariance matrix based on the operational ozone background covariance matrix was used with estimated standard deviations representing the expected uncertainty in the CO₂ model fields. The assimilation experiments produced CO₂ increments consistent with the specified observation and background errors. A more CO₂-specific background covariance matrix is now being derived using the NMC method (already adopted for aerosol) including perturbation of the climatological CO₂ surface fluxes used in the IFS

forward model. Together with a more careful selection of AIRS channels and bias correction, this will lead to more realistic results from the assimilation.

(c) Global Reactive Gases (GRGs)

Coupling of the IFS with the CTMs. The coupling of the IFS with the CTMs is a key challenge for GEMS. The OASIS4 coupler has been adopted, and following extensive testing and dialogue with the developers (the PRISM group) is now running on the IBM with almost full functionality. The problem remaining to be solved is the global search across processors for the points needed in the interpolations. The interfaces from the IFS to the coupler have been developed and tested and the preIFS software has been expanded to allow submission of coupled forecast experiments.

Global CTMs. Two of the three global CTMs included in GEMS, namely MOZART and TM5, are now running on ECMWF's IBM HPC system. The output of chemical tendencies to the coupler is still under development, however. This is needed by the IFS to provide the sources and sinks of the chemical species that it carries for the purpose of data assimilation. Progress in this area is largely dependent on progress by the GEMS partners responsible for the CTMs.

UV-radiation processor. In a separate contribution to GEMS, a UV-radiation processor has been implemented in the IFS. It allows the spectral distribution of UV radiation between 280 and 400 nm to be computed with a user-defined spectral resolution. This code has been shown to provide UV diagnostics in good agreement with other UV-reference codes. However, as it is quite expensive in computer time, it might not be used routinely within ECMWF.

Data assimilation developments. The observation operator currently used for the GRGs calculates the model equivalent of the reactive gas retrievals as vertically integrated columns. An observation operator is also being developed that makes use of the averaging kernels often provided by data producers. A major task in the assimilation of satellite observations is the design of the background error covariance matrix, B. For initial tests of the GRG assimilation system simple diagonal B matrices with prescribed horizontal correlations have been constructed for the reactive gases. However, more work will be needed to refine the background statistics.

Test the performance of the GRG assimilation system. Initial data assimilation experiments were carried out to test the performance of the GRG assimilation system. In these experiments, the assimilating IFS model was not coupled to a CTM. Firstly, single observation experiments assimilating simulated total column GRG observations were performed. These experiments confirmed that the magnitude of the analysis increments was consistent with the specified observation and background errors. Secondly, test experiments were carried out assimilating total column CO retrievals from the MOPITT instrument and total column NO₂ retrievals from SCIAMACHY. These experiments show that the first version of the GRG data assimilation system is working properly.

Reanalysis for the year 2003. In addition to developing the GRG assimilation system, a reanalysis for the year 2003 has been carried out. The primary reason for this was to meet a need identified at the GEMS kick-off meeting, namely for a common dataset for use in driving the participating CTMs for the purpose of comparing their performance. It also served to identify and resolve a few issues relating to the meteorological component of the data assimilation. The ECMWF reanalysis system already includes assimilation of data on stratospheric ozone, for which profile retrievals are available from both GOME on ERS-2 and MIPAS on ENVISAT for part of 2003. Improved representation of the Brewer-Dobson circulation and hydrological cycle make these reanalysis fields more suitable for driving CTMs than the fields provided for earlier years by ERA-40.

(d) Aerosol

Modelling development. A representation of sea-salt and desert aerosols, using three categories for each with limits 0.03, 0.5, 5 and 20 microns for sea-salt and 0.03, 0.55, 0.9 and 20 microns for

desert-dust, has been introduced into the IFS. This has been tested in the same way as for CO₂ by running a simulation in which the aerosols evolve under physical processes including sources, transport by advection, sedimentation, and wet and dry deposition, within a series of consecutive 12-hour forecasts initiated from operational analyses. The results show a reasonable agreement between model and AERONET surface observations when the optical thickness is dominated by desert aerosols. Tests have also been carried out with a 10-bin representation, showing no real improvement. A new model (Huneeus, 2006), with four prognostic variables to represent the fine and coarse modes of dust (separation at 10 µm), the coarse sea salt, and all other aerosols combined (all assumed to be below 10 µm), is being introduced in the IFS. This is an alternative approach that would represent not only sea salt and dust, but also the effect of DMS, black carbon, and organic matter.

Pathway through the IFS for observations of aerosol optical depth. The pathway through the IFS for observations of aerosol optical depth has been established along with a preliminary background error covariance matrix for aerosol mixing ratio (Benedetti and Fisher, 2006). These are two of the main building blocks of the analysis system. Six months of aerosol forecasts have been used to build background error statistics based on the difference between 48-hour and 24-hour forecasts (the NMC method, Parrish and Derber, 1992). A first aerosol background error covariance matrix was constructed based on these statistics using the wavelet-Jb approach proposed and implemented by Fisher (2003, 2006). Benedetti and Fisher (2006) showed that this error covariance matrix describes well the vertical and horizontal error correlation characteristics of the total aerosol variable and can be used to produce realistic analysis increments. This result is especially valuable considering the fact that the observations of aerosol optical depth represent a vertically integrated quantity, and the vertical distribution of the increments is thus dictated by the background error correlations for the control variable, here the profile of aerosol mixing ratio.

Observation operator for total optical depth. The observation operator for total optical depth has been developed and implemented, along with its tangent linear and adjoint. This operator is flexible and can be applied to total optical depth retrieved from various sensors at different wavelengths. For now, the chosen wavelengths are those of the MODIS instrument on board the Aqua and Terra satellites (0.47, 0.55, 0.66, 0.87, 1.24, 1.63, 2.13 µm). Consideration is now being given to including optical-depth retrievals from other sensors.

Difference between model aerosol optical depth and observations. Preliminary results using MODIS data, over oceans only, for one assimilation cycle show that the analysis is able to reduce the difference between model aerosol optical depth and observations through realistic increments. The model configuration for this experiment used the three-class representation of sea-salt and desert-dust, initialized from climatology. The control variable was total aerosol mixing ratio defined as the sum of mixing ratios for all species and classes. The optimization in terms of this variable was done by assuming that the relative contribution of the mass in a given class and for a given species does not change over the assimilation window (6 hours). This is a strong assumption in the sense that the increments in total mixing ratio mainly come from heavier aerosols whose contribution to the total mass is dominant. However, it is a necessary assumption given that not all aerosol species and classes can be included in the control vector to keep the cost of the minimization at a reasonable level for eventual applications in operations and reanalysis.

(e) Other developments

Technical processing of observations. For many of the observational data sets to be used in GEMS there were no suitable BUFR tables entries to describe entities such as concentration of chemical species or various aerosol related parameters. New BUFR table entries have thus been proposed to the WMO. Key satellite data sets have been acquired covering the period of 2003–2004 to be used in the initial GEMS reanalysis runs. These data sets include aerosol products from the MODIS instruments on the Terra and Aqua satellites, nitrogen dioxide retrievals by KNMI from the SCIAMACHY instrument on ESA's ENVISAT and carbon monoxide retrievals from the MOPITT instrument onboard NASA's Terra satellite. Other data acquisitions include GOME O₃ profile

retrievals by RAL for 1995–2003, GOME HCOH retrievals by KNMI for December 2001 and TES CH₄ and CO from NASA's Aura satellite for July 2005.

Web interface and verification tools. The basic structure of the GEMS web site has been put in place and a set of collaboration tools developed. The objective was to design a central web page to enhance collaboration between the project managers and each of the five GEMS sub-projects. A web-based framework for writing progress reports has been developed and a suite of tools for consequent extraction, consolidation and reformatting of the reports was assembled and tested. A discussion board, a document repository and a news system were also developed and integrated into the GEMS web pages.

4.5.3 Specific products operationally available

4.5.2.1 Ocean wave products

Products from the ocean wave forecasts include significant wave height, peak period, mean periods and mean direction. Probabilities of mean periods and significant wave height are generated for the EPS wave forecasts.

4.5.2.1 Tropical cyclone forecast products

Tropical cyclone products are generated from the deterministic and EPS forecasts. Tropical cyclones reported on the GTS are identified and tracked forward in the forecasts using wind, pressure, vorticity and temperature fields. The forecast tracks are disseminated on the GTS and products are available to WMO members via the ECMWF website

<http://www.ecmwf.int/products/forecasts/d/tccurrent>

Details of how to access these products are given at:

http://www.ecmwf.int/about/wmo_nmhs_access/index.html

4.6 EXTENDED RANGE FORECASTS (ERF) (10 DAYS TO 30 DAYS)

4.6.1 Models

4.6.1.1 In operation

ECMWF has run a monthly forecast system in operational mode since October 2004. The system uses the same atmospheric model as the medium-range forecasts (see section 4.2.2.1), coupled to a 29 level ocean model that is also used for seasonal forecasts (section 4.7.1). The atmospheric model is runs at T159 (125 km) with 62 levels; the ocean model has a zonal resolution of 1.4° and a meridional resolution varying from 0.3° at the equator to 1.4° at midlatitudes.

The system is run once a week (from 00 UTC Thursday) for 32 days in ensemble mode. The ensemble has 51 members using the same atmospheric perturbation method as for the medium-range EPS (section 4.2.5.1). Hindcasts are updated each week for the same week over the last 12 years (5 members only) for calibration purposes. More details on the monthly forecast system can be found on the ECMWF website:

http://www.ecmwf.int/research/monthly_forecasting/Documentation.html

4.6.1.2 Research performed in this field

(a) Assessing skill

Skill of the monthly forecasting system to predict an MJO event. In collaboration with S Woolnough from Reading University, several sensitivity experiments have been performed to assess the skill of the monthly forecasting system to predict an MJO event. Last year, it was shown that an improved representation of the mixing processes in the ocean model improved the skill of the monthly forecasting system to predict an MJO event (Woolnough et al., 2006). This year, additional experiments have been performed using the same experimental framework. Results

suggest that the horizontal resolution of the model has only a small impact on the skill, compared to changes in the model physics. The quality of the atmospheric and oceanic initial conditions and the ensemble generation method seem also to have an important impact on the skill of the model to predict an MJO event. Results are summarized in Vitart et al. (2006).

Skill in predicting stratospheric sudden warming events. According to Baldwin et al. (2003), the stratosphere plays an important role in the monthly time-scale. In particular, stratospheric sudden warming have a significant impact on the tropospheric circulation a couple of weeks later and this stratosphere-troposphere interaction is a very important source of predictability for the monthly forecasting system. Jung and Barkmeijer (2006) have shown that the IFS is able to simulate such propagation. The model showed indeed some skill in predicting the strong January 2006 sudden warming event more than ten days in advance, and a study using composites of all the observed sudden warming events and their forecasts since 1990 suggest that the model has in general skill in predicting stratospheric sudden warming events more than two weeks in advance. Further studies will evaluate their impact on the troposphere in the monthly forecasting system. Collaboration with Jan Barkmeijer from KNMI is taking place to evaluate the impact of stratospheric singular vectors on the forecasts of stratospheric sudden warming events.

(b) Future implementation of the VAREPS-monthly unified system

Plans include merging the monthly forecasting system with VAREPS in 2007. In this future configuration, the atmospheric model will be integrated forced by persisted SST anomalies (instead of persisted SSTs) till day 10 with a TL399L62 resolution. After day 10, the atmospheric model will be coupled to the ocean model till day 32. In order to prepare the oceanic initial conditions, the ocean model will be run for the first 10 days, starting from the accelerated ocean analysis and forced by fluxes from each ensemble member of the VAREPS integration. A similar configuration has been tested in research mode with Cy30r1. Results from 48 5-ensemble member hindcasts (12 years, 4 times a year) suggest a slight but statistically significant improvement in the performance. This is presently evaluated with Cy31r1, along with the skill to predict an MJO event. Technical work also includes porting all the products of the current monthly forecasting system to the new environment.

4.6.2 Operationally available NWP model and EPS ERF products

Products from the monthly forecast system are generated as anomalies relative to a model climatology. Most products are 7-day means for calendar weeks (Monday-Sunday). Probabilities are produced for 2m temperature and precipitation; thresholds are defined as terciles of the climate distribution. In 2006 additional products were introduced for the Madden-Julian Oscillation.

4.7 LONG RANGE FORECASTS (LRF) (30 DAYS UP TO TWO YEARS)

4.7.1 In operation

Seasonal forecasts are produced monthly at ECMWF using a version of the ECMWF atmospheric model (IFS), coupled to 29 level version of the Hamburg Ocean Primitive Equation (HOPE) model developed at the Max Planck Institute. The coupling between the two components is operated by the OASIS (Ocean, Atmosphere, Sea-Ice, Soil) interface from the Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique (CERFACS). In 2006 System 2 of the seasonal forecast system was operational. In this system, the atmospheric model ran at T95 (200 km) with 40 levels (cycle 23r4 of the IFS); the ocean model has a zonal resolution of 1.4° and a meridional resolution varying from 0.3° at the equator to 1.4° at midlatitudes. The forecasts are run monthly for the next 6 months in ensemble mode (40 members).

A major upgrade of the seasonal forecast system, System 3, will be introduced in March 2007. More details can be found at <http://www.ecmwf.int/products/forecasts/seasonal/documentation/>.

4.7.2 Research performed in this field

(a) Developing and finalising System 3

Choice of Cy31r1 for System 3. Various versions were tested both in the medium-range system and in the seasonal system, culminating in the creation of Cy31r1. Tests of this model version suggest that it is the best cycle to date in terms of SST anomaly forecasts, and that the model climate has also improved. It was therefore adopted for System 3. The coupling of the surface currents with the atmospheric boundary layer, discussed last year, is now included in the forecast system – tests showed that with the recent model improvements, the impact is no longer detrimental.

Structure of System 3. The structure of “System 3” has several important changes. Firstly, the period over which the calibration integrations are made will be 1981–2005 (compared to 1987–2001 for System 2). This extended 25 year calibration period will give users more information on the skill of the system, and allow better estimation of forecast products calibrated using actual past performance. Note that although the mean model bias can be estimated reasonably with 15 years of data, estimates of for example reliability of probability forecasts need as many past cases as possible. In fact, 25 years is still a long way short of what is desired, but corresponds roughly to the period for which reasonably accurate SST and wind fields are available to initialize the coupled model forecasts. The ensemble size of the System 3 calibration integrations will be 11 members every month. This differs from System 2, which has only 5 member ensembles, but augmented to 41 members for forecasts starting in November and May. This change is cost-neutral, but allows better operational characterization of forecast performance and fits better with planned developments of EUROSIP.

Length of forecasts. Following the users’ request, System 3 forecasts will be 7 months long rather than 6 months. Additionally, once per quarter a modest ensemble will be run to 13 months, in order to give an “ENSO outlook”. Tests with Cy29r3 gave an encouraging level of forecast performance for Nino SSTs over this forecast range, and the model version used for System 3 is expected to have similar characteristics. The archived output of the model runs has been modestly upgraded. Of particular note is the inclusion of model level output for a subset of the integrations (and for a limited forecast range) to facilitate dynamical downscaling work by interested parties.

Climatology of the atmospheric component of System 3. The climatology of the atmospheric component of System 3 shows substantial improvements with respect to System 2. Systematic errors in geopotential height, sea-level pressure and lower-tropospheric temperature have been substantially reduced in both the tropical and the northern extra-tropical regions. Internal atmospheric variability is generally higher in System 3 than in System 2; a notable improvement is found in the amplitude of tropical intraseasonal variability in the 20-to-70-day frequency range, which includes the Madden-Julian Oscillation.

Rainfall over the tropical oceans. Both the seasonal mean and the interannual variability of rainfall over the tropical oceans is generally reduced compared to System 2 values, bringing the model climatology in closer agreement with GPCP (Global Precipitation Climatology Project) observational data. The spatial distribution of modelled rainfall is notably improved in the tropical Pacific during the boreal winter. While in System 2 rainfall in the eastern Pacific ITCZ exceeds observations by (at least) a factor of 2, System 3 simulates a more correct ratio between rainfall in the western and eastern parts of the ocean. The improvement in the mean field is reflected in the distribution of rainfall interannual variability. While the System 2 variability shows two distinct maxima (with similar amplitude) in the western and eastern tropical Pacific, System 3 simulates a single variability maximum located just west of the dateline, in closer agreement with observations. Also the improved distribution of tropical rainfall in System 3 is reflected in the patterns of rainfall anomalies associated with ENSO events. On the other hand, the meridional extent of the region with positive rainfall anomalies is still underestimated in System 3 compared with GPCP data, and the area-averaged heat-source anomaly appears to be reduced with respect to System 2.

(b) Ocean analysis for System 3

New ocean analysis. A new ocean analysis system has been developed to provide initial conditions for System 3 and for monthly forecasts. It consists of an ocean re-analysis and a real time ocean analysis. Unlike the atmospheric re-analysis, that covers a fixed period of time, the ocean re-analysis is continuously updated on a daily basis, although with a delay of 12 days. The ocean reanalysis goes back to 1959 and provides initial conditions for System 3 seasonal forecasts (real time and 1981–2005 calibrating hindcasts). In addition, a real time ocean analysis is performed daily to bring the delayed product to real time. The real time ocean analysis provides initial conditions for the monthly forecasts (once a week), and in the near-future it will also be used on a daily basis by the VAREPS forecasting system. Details about the timing and the dependencies between the reanalysis and real time products are given Balmadesa et al. (2005). The System 3 ocean reanalysis will also provide initial conditions for the ENSEMBLES integrations, both for the seasonal and the multi-year forecasts runs, and will contribute to the CLIVAR/GODAE ocean reanalysis inter-comparison project.

Ocean data assimilation system. The ocean data assimilation system for System 3 is based on HOPE-OI, as for System 2, but major upgrades have been introduced. The first-guess is given by the HOPE ocean model forced by ERA-40/OPS fluxes (ERA-40 fluxes from the period January 1959 to June 2002 and NWP operational analysis thereafter). In System 2 the fluxes were from ERA-15/OPS. The OI scheme, previously two-dimensional (i.e. the analysis was carried out on each level independently), is now three-dimensional, the analysis being performed at all levels simultaneously. The horizontal and vertical decorrelation scales have been revised, and it is possible to spread the information along isopycnals. In addition to subsurface temperature, the OI scheme now assimilates altimeter derived sea-level anomalies and salinity data. All the observations in the upper 2000 m are assimilated (in System 2 only the observations in the upper 400 m were used). For the period 1959–2004, the observations come from the quality controlled data set prepared for ENACT and later updated for ENSEMBLES (Ingleby and Huddleston, 2006), and from the GTS from 2005.

Ensemble of ocean analyses. There is an ensemble of five ocean analyses (as in System 2), which are created by perturbing the wind stress forcing. The wind perturbations have been revised in System 3 to represent the uncertainty in ERA-40/OPS wind stress. The spread of the ensemble can be taken as a measure of the uncertainty, which may be underestimated, since only wind error is accounted for, and there is no representation of errors in the heat or fresh water flux, in the model or the analysis procedure.

Reference climatology for the seasonal forecasts products. The variability in the upper ocean temperature is dominated by the upward trend, starting around the mid 1980s. The presence of this trend should be taken into account when considering the reference climatology for the seasonal forecasts products. Salinity variations occur mainly on decadal time scales, and they seem to be correlated with variations in the thermohaline circulation (THC). Although there is broad agreement with the estimates by Bryden et al. (2005), the System 3 ocean analysis show that the decadal variability is large and therefore sampling is an issue when drawing conclusions about the slowing down of the THC. The System 3 ocean analysis will provide initial conditions for the decadal ENSEMBLES forecasts, where the capability of the coupled models to reproduce changes in the THC will be explored.

Information from the ARGO network. Observing system experiments have been carried out to determine the information provided by the recently developed ARGO network, how it interacts with the information given by the altimeter and the impact of the observing system in the climate variability. Results indicate that the observing systems for the ocean are not yet redundant. Even in the presence of ARGO and TAO data, the altimeter information can improve the vertical temperature structure in the far Eastern Pacific. In the Indian and Atlantic oceans the contribution of altimeter and ARGO is similar, and the best results are obtained when both observing systems are included. ARGO has a large impact on the salinity field on a global scale.

(c) Other developments

Multi-model system run in an operational mode. All three components of the multi-model system have run in an operational mode throughout the last year. Separate suites produce graphical products from each of the models. A further multi-model processing suite produces combined multi-model products. Procedures are in place to allow easy upgrading of any component model. The Met Office introduced a new version of their forecasting system in the spring of this year – essentially an upgrade to fix problems with some of the ocean initial condition files. The change has a minimal impact on overall forecast skill. The partners have agreed to work towards a longer base period of 1981–2005 for the back integrations, as will be used for ECMWF System 3.

Implementation of NEMO. Work has started on the implementation of NEMO (i.e. OPA9) as the future ocean model for the ECMWF activities (ocean analysis and coupled forecasts). The effort during 2006 has concentrated on the development/implementation of the NEMOVAR system, a variational data assimilation based on OPA9. The work on NEMOVAR is an ongoing collaboration with CERFACS and INRIA. The starting point for NEMOVAR is the OPAVAR system which is based on the OPA 8.2 version. OPAVAR supported the ORCA2 configuration only (i.e. a resolution of 2°, but with equatorial refinement). The goal is now to construct a modular analysis system with separated inner and outer loops that can support different ocean resolutions.

Implementation of NEMOVAR. Work during 2006 has targeted implementation of the observation operator in the outer loop, inner loop based on OPAVAR supporting 3D-Var and 4D-Var assimilation and inner loop based on NEMO supporting 3D-Var assimilation. To facilitate collaboration with external partners it has been necessary to merge the script system of OPAVAR with that of NEMO, in a way that is compatible with the SMS structure used at ECMWF while still being usable outside, without the SMS software.

4.7.3 Operationally available EPS LRF products

Products from the seasonal forecast system are generated as anomalies relative to a model climatology and are calculated as 3-monthly mean fields. Probabilities are produced for parameters including sea-level pressure, 2m temperature and precipitation; thresholds are defined as terciles of the climate distribution. In addition a number of indices are available as timeseries, including sea-surface temperature averaged over areas of the tropical Pacific (Nino indices and Southern Oscillation index).

In November 2006, ECMWF was designated a WMO Global Producing Centre of Long-Range Forecasts. A selection of products is available to WMO NMHSs in graphical format via the ECMWF website at:

<http://www.ecmwf.int/products/forecasts/d/charts/seasonal/forecast/>

Details of how to access these products are given at:

http://www.ecmwf.int/about/wmo_nmhs_access/index.html

5. VERIFICATION OF PROGNOSTIC PRODUCTS

5.1 WMO/CBS standard scores

Averages of the monthly WMO/CBS standard scores for 2006 are summarised in Tables 3, 4 and 5.

Table 3: Annual scores against analyses

VERIFICATION AGAINST ANALYSIS in 2006 (2005)							
		24 hr		72hr		120hr	
		2006	2005	2006	2005	2006	2005
N Hemisphere	500-hPa height RMS (m)	7.6	7.8	22.7	23.1	45.0	46.0
	Wind RMSVE 250 hPa (m/s)	4.1	4.0	8.6	8.6	13.6	13.7
S Hemisphere	500-hPa height RMS (m)	9.1	9.3	27.3	28.8	53.0	55.9
	Wind RMSVE 250 hPa (m/s)	4.1	3.9	8.9	9.1	14.2	14.8
Tropics	Wind RMSVE 850 hPa (m/s)	2.1	1.9	3.0	2.9	3.5	3.5
	Wind RMSVE 250 hPa (m/s)	3.8	3.7	6.2	6.3	7.8	8.0

Table 4: Annual scores against radiosondes measurements

VERIFICATION AGAINST RADIOSONDES in 2006 (2005)							
		24 hr		72hr		120hr	
		2006	2005	2006	2005	2006	2005
Asia	500-hPa height RMS (m)	13.3	13.1	22.9	23.0	40.0	39.1
	Wind 850 hPa (m/s)	4.0	3.9	5.2	5.2	6.7	6.7
	Wind 250 hPa (m/s)	5.6	5.7	8.6	9.1	12.6	15.6
Australia/NZ	500-hPa height RMS (m)	10.5	10.6	20.4	20.4	38.0	38.7
	Wind 850 hPa (m/s)	3.9	3.9	5.0	5.0	6.5	6.5
	Wind 250 hPa (m/s)	5.7	6.0	8.3	8.7	12.4	12.9
Europe	500-hPa height RMS (m)	10.0	10.3	22.0	24.0	44.9	51.3
	Wind 850 hPa (m/s)	3.8	3.8	4.9	4.9	6.8	6.9
	Wind 250 hPa (m/s)	5.1	5.2	9.0	9.1	14.4	15.6
North America	500-hPa height RMS (m)	10.9	10.7	23.4	24.5	44.4	46.9
	Wind 850 hPa (m/s)	4.0	4.0	5.4	5.5	7.4	7.6
	Wind 250 hPa (m/s)	5.8	5.9	9.8	10.0	14.9	15.2
N Hemisphere	500-hPa height RMS (m)	11.9	12.0	24.8	25.8	48.0	50.5
	Wind 850 hPa (m/s)	4.0	4.0	5.3	5.3	7.2	7.3
	Wind 250 hPa (m/s)	5.4	5.5	9.2	9.4	14.2	14.8
S Hemisphere	500-hPa height RMS (m)	12.8	12.6	24.6	24.7	45.5	47.2
	Wind 850 hPa (m/s)	4.3	4.2	5.5	5.4	7.3	7.3
	Wind 250 hPa (m/s)	5.9	6.1	9.0	9.3	13.8	14.3
Tropics	Wind 850 hPa (m/s)	3.7	3.8	4.2	4.3	4.6	4.7
	Wind 250 hPa (m/s)	5.1	5.2	6.7	7.0	8.2	8.5

Table 5: Annual scores against analyses (Ensemble Prediction System)

EPS VERIFICATION AGAINST ANALYSIS in 2006 (2005)								
			72 hr		120 hr		192 hr	
			2006	2005	2006	2005	2006	2005
N Hemisphere	500-hPa height	Ensemble mean RMSE (m)	23.4	24.5	42.7	44.6	68.2	68.6
		Spread/EM error (%)	90.5	90.9	81.8	80.1	77.3	77.4
	850-hPa temperature	Ensemble mean RMSE (m)	1.6	1.6	2.3	2.4	3.2	3.2
		Spread/EM error (%)	75.6	77.3	79.3	78.7	80.9	80.8
S Hemisphere	500-hPa height	Ensemble mean RMSE (m)	28.2	30.2	50.9	53.0	78.5	79.5
		Spread/EM error (%)	88.5	90.2	79.9	81.9	78.4	80.8
	850-hPa temperature	Ensemble mean RMSE (m)	1.6	1.6	2.3	2.3	3.1	3.1
		Spread/EM error (%)	78.5	82.8	82.1	84.0	84.0	86.3

5.2 RESEARCH PERFORMED IN THIS FIELD

Verification procedures for severe weather are being investigated in liaison with Deutscher Wetterdienst. Work has focussed on precipitation events, using data from the high resolution rain gauge networks in Europe. These data have been used to create gridded precipitation fields to use as verification. An initial study has been made using this gridded data as a “perfect” forecast which is then verified using the original station observations. The skill of such a “perfect” system is significantly less than 100% because the gridded data represents an area-average value while there can be substantial variability between point values within each grid box. Although this is an obvious difference between model and observation, the quantitative effect on skill measures can often be overlooked. Work will continue using the gridded observational data to investigate appropriate scores for severe events and to investigate further the difficulties associated with verification of model precipitation (gridded data) against point observations.

Developments in verification of the Ensemble Prediction System are reported in section 4.2.5.2(b).

6. PLANS FOR THE FUTURE (NEXT 4 YEARS)

6.1 DEVELOPMENT OF THE GDPFS

6.1.1 Major changes in the Operational DPFS which are expected in the next year

- New moist physics in TL/AD.
- RRTM-SW + McICA + MODIS albedo.
- Retuned ice particle size and retuned subgrid-orography scheme.
- Improved parametrization of the heterogeneous ozone chemistry.
- 3rd inner loop for 4D-Var.
- Revised convergence criteria for 4D-Var.
- Assimilation of AMSU-A and MHS from METOP.
- Introduction of Seasonal Forecasting System 3, and implementation of new web products and validation statistics.
- New formulation of convective entrainment.
- New soil hydrology/runoff.
- New radiosonde temperature and humidity bias correction.
- Jb statistics from Cy31r1 DA-ensemble.
- Modified humidity analysis with Jb statistics from new ensemble including ice super-saturation and better T-q coupling.
- RTTOV-9 implementation.
- Assimilation of HIRS from METOP.
- Increase usage of RO from COSMIC.
- Assimilation of AMSR-E, TMI and SSMIS data.
- Stochastic Backscatter Scheme in VarEPS.
- Assimilation of GRAS RO.

- Assimilation of Met-9 AMVs and CSRs.
- Assimilation of SBUV (N-17, N-18) and OMI.
- Improved trajectory interpolation.
- VarQC with Huber Norm, relaxed BgQC.
- Enable use of radiosondes in WMO BUFR format (true lat/long/time).
- Introduce new ocean wave advection scheme.
- Introduce ASCAT data assimilation.
- Assimilate scatterometer winds as neutral winds.
- European Shelf model: include bottom-induced wave breaking, new nonlinear transfer and higher resolution (probably a 0.15 deg model).
- Prognostic ice, rain and snow.
- New shallow convection/boundary layer scheme.
- Mass flux momentum transport in boundary layer + new PBL parcel solver.
- C-TESSEL.
- Variational soil moisture analysis.
- Assimilation of a reduced set of IASI channels.
- Assimilation of sounding channels from SSMIS.
- Implementation of (new method) aggregated NCEP SST fields (from 1/12deg).
- Assimilation of GOME-2 products from METOP.
- Implementation of VAREPS extension from d15 to d32 including a re-forecast suite (configuration to be decided), and a replacement of SST with SST-anomalies in the 12 UTC 15-day VAREPS.

6.1.2 Major changes in the Operational DPFS which are expected in the next four years

Major changes in 2008

- Direct assimilation of rain-affected radiances in 4D-Var.
- Assimilation of cloud-affected radiances from AIRS, IASA and MSG.
- Improvement of assimilation of microwave data over seas-ice and land.
- Improvements in the assimilation of IASI data.
- Representation of observation error correlations for satellite data.
- Initial operational implementation of ensemble data assimilation
- Comprehensive evaluation of long-window, weak constraint 4D-Var.
- Operational use of re-forecasts for calibration of the EPS spread.

Major changes in 2009/10

- Preparation of operational use of NNP instruments (ATMS, CRIS, OMPS, VIIRS).
- Optimization of the number of satellite data used as a function of the local flow properties.
- Monitoring and then assimilating ADM-Aeolus and SMOS data.
- Initial operational implementation of long-window, weak constraint 4D-Var.
- Preparation and implementation of the next resolution upgrade.
- Major upgrade of ocean wave model in coastal zones (coupling with a storm surge model).
- Coupling the ocean and sea-ice in all forecast systems.
- EPS initial perturbations based on ensemble data assimilation.

- Implementation of System 4 for seasonal forecasting, using the NEMO ocean model and NEMO-Var ocean data assimilation.

6.2 PLANNED RESEARCH ACTIVITIES IN NWP, NOWCASTING AND LONG-RANGE FORECASTING

6.2.1 Planned Research Activities in NWP

Data assimilation

- Investigate long-window, weak-constraint 4D-Var.
- Assess forecast error sensitivity with respect to observations.

Satellite data

- Assimilate cloud-affected radiances.
- Introduce direct 4D-Var assimilation of rain-affected radiances.

Reanalysis

- Continue with the on-going production of the interim reanalysis.
- Seek long-term funding of the reanalysis activity with the EU and various funding agencies in the Member States.

Numerical aspects

- Test the IFS non-hydrostatic approach of Météo-France and propose various improvements
- Investigate more conservative semi-Lagrangian scheme.
- Assess the physics and dynamics at different resolutions.

Physical aspects

- Develop further the linearized physics.
- Start running a “cloud resolving model” driven by IFS on situations of interest to diagnose weaknesses of our parametrizations.

Ocean waves

- Study and introduce interaction between ocean currents and ocean waves.
- Validate freak wave products.

Diagnostics and EPS

- Carry out experiments with relaxation towards analysis in the tropics and/or in the stratosphere.
- Assess the impact of resolution on various aspects of the model climate.
- Assess Combined Prediction Products (with MetOps).
- Investigate calibration and verification methods for the EPS.
- Explore skill of multi-model ensembles using TIGGE data.

Monthly and seasonal forecasts

- Collaborate on mixed-layer modelling and MJO skill.
- Continue with ENSEMBLES and MERSEA projects.

Tools

- Continue to improve the ODB, ODBTk, OBSTAT/SATMON, PrepIFS, etc.

GEMS

- Consolidate and develop the aerosol analysis system and produce a one-year reanalysis.
- Upgrade the aerosol model and assess the surface fluxes of CO₂ of C-TESSSEL.
- Refine Jb, develop additional observation operators and produce a one-year reanalysis for GHG and GRG.
- Finalize coupling between IFS and CTMs and start reanalysis.
- Assess impact of biomass burning on all aspects of GEMS.

6.2.2 Planned Research Activities in Nowcasting

No activities planned.

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