1. Working group 1: Data requirements

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1.1. Precipitation

The use of the 15-month high resolution rainfall database in the framework of ELDAS Project has clearly indicated that NWP model performance may strongly benefit from the assimilation of precipitation data. This may be particularly important for the forecasting of natural hazards, such as flooding, or drought, but also for air pollution, runoff modelling, and crops modelling.

For such purpose, it is essential that a (global) network of gauge and radar data are available for NWP centres in real time (RT). Currently ECMWF uses the following precipitation data for validation purposes only: STAGE IV Radar-gauge, received with 1-month delay; and European synop-gauge data, received with 6-month delay.

The European Weather Services should be mobilised, under the co-ordination of WMO, to provide RT precipitation, in complement to the already existing US STAGE IV network. The NWP centres should then have access to precipitation data from the European Rain Radar network – Opera (1.1) - and to rain gauge data in RT (1.2).

1.1.1. European Rain Radar network – OPERA

The OPERA Project aims building a combined European Radar network, within the time frame of 2-3 years.

1.1.2. National gauge online

The European Countries should be able to provide about 5-times more rain gauge data, preferable within the next 2-years, than that available from synop stations. The stochastic nature of the precipitation field would greatly benefit from a higher coverage in space and in time (1-to-3-hourly data would be preferred).

Problems regarding the QC (quality control) of such rain gauge data might be risen. The poor spatial correlation of precipitation makes it virtually impossible to assign quality flags, though the combination of gauge data and Radar data may compensate this problem.

Recommendation 1: Use of rainfall observations

i) ECMWF should evaluate the impact of rainfall (gauges and/or Radar) in the land assimilation system; improvements are likely to be expected in, e.g., forecasted T2m. Previous studies in the USA have shown that there is no longer the need to nudge for soil moisture (SM) when observed precipitation is used.

ii) Gridded precipitation fields obtained from the currently available synoptic stations should only be compared with higher resolution rainfall data after aggregation in space and time is carried out. The 15-month ELDAS precipitation should be used for an evaluation of the relevant spatial and temporal scales and precipitation regimes at which such comparison is meaningful.

1.2. Thermal Infra Red Observations

In this paragraph we focus on the retrieval / usage of surface parameters under cloud free situations.

1.2.1. Land surface temperature

Geostationary derived Land Surface Temperature (LST) products are already available, as is the case of GOES-LST with a 30-min time resolution. MSG-retrieved LST will soon (January 2005 for Europe, end of 2005 for the remaining land pixels within MSG disk) start to be provided by the Land SAF with a 15-min time sampling. The merging of these two products may be a useful tool for the validation of NWP, particularly where radiative ground flux measurements do not exist.

Recommendation 2: Use of LST observations

LST retrieved from geostationary satellites is a powerful tool for the validation of NWP models. The large area coverage and high-frequency sampling make such products particularly suitable for the diagnostic of models diurnal cycle. Comparison of retrieved and modelled LST may also provide information on the performance of land surface schemes, and on the possible range of surface parameters, such as roughness length for heat. Realistic LST model values are a pre-requisite to the atmospheric assimilation of sounding channels peaking at the lower troposphere.

1.2.2. Emissivity Product

The validation (or assimilation) exercises, using the LST products mentioned in the previous point, requires a better description of surface emissivity in NWP models, consistent with the Land Cover and Vegetation parameters prescribed in models.

Recommendation 3: Emissivity

It is recommended that ECOCLIMAP-2 should include global emissivity, for relevant bands. ECOCLIMAP could make use of the Land SAF emissivity database for SEVIRI channels, based on GLC2000 – also the land cover data planned for the global dataset of ECOCLIMAP-2.

1.2.3. Geostationary versus High Latitudes

Products provided by the current constellation of geostationary satellites have a very reasonable global coverage, missing only latitudes higher than about 55°. Polar-orbiters provide a higher temporal sampling over the polar regions, than that typical for lower latitudes, which may be useful when merging with geostationay data to have global products. There are plans to start using AVHRR/METOP (to be launched in 2005) and AVHRR/NOAA to complement geostationary products on high latitudes (e.g., Land SAF EPS-delta development for the initial operational phase).

1.3. Microwave remote sensing

Recommendation 4: Protected frequencies

This working group supports all activities related to the protection of frequencies as specified in Space Frequency Coordination Group (www.sfcgonline.org) from unwanted emissions for current and planned spaceborne earth observation missions.

1.3.1. Precipitation over land

At NWP centres, satellite radiances are operationally used for parameter retrieval/assimilation and direct assimilation. This is almost exclusively done in cloud-free areas and mostly over oceans. Only recently, model resolution, moist physical parameterizations and radiative transfer models have reached sufficient accuracy and computational efficiency to investigate the introduction of cloud and rain affected satellite observations for model validation and data assimilation. Therefore, several NWP centres have begun to pursue, e.g., the assimilation of rain (related) observations over oceans (ECMWF, NCEP, JMA, MSC).

Operational satellite programs (e.g., NOAA, US-Navy, EUMETSAT) maintain and prepare satellites that provide global coverage of rain-affected microwave observations within about 3 hours (e.g., DMSP SSM/I's and AQUA AMSR-E). These are complemented with spaceborne visible/infrared radiometers (VISSR, SEVIRI) on geostationary satellites.

In general, it is recommended that modelled radiances over land should be produced and compared to satellite observations on a (more) routine basis.

1.3.2. Soil moisture

1.3.2.1. Active sensors

The Hydrology SAF (H-SAF), foreseen to start its development phase in 2005 will address the use of some of the data. However, the existence of a consistent/long-term network of SM observation sites is essential for a proper validation of the retrieved SM products. The existing sites are often short-term and not linked to the meteorological community (see section 7).

1.3.2.2. Passive sensors

The value of L-band passive microwave brightness temperatures for the soil moisture analysis has been demonstrated within ELDAS. However, observations at this frequency will not be available before 2007. With increasing frequency and decreasing penetration depth the impact of vegetation and atmosphere become more important. Consequently, the potential for soil moisture retrieval decreases. However, results from regional field experiments show that soil moisture can be retrieved from observations at 6.9 and 11 GHz over semi-arid and sparsely vegetated areas and soil moisture data sets from AMSR-E and TMI have become available recently.

1.3.3. Snow

Currently available data have not been fully explored. A significant number of observations (e.g. the US SNOTEL sites) are not available through the GTS. In addition to the operational real-time data used by ECMWF (snow depth gauges and NESDIS snow cover), the US Air Force snow depth analysis could be evaluated. Although the accuracy of snow depth is probably not very high, NESDIS snow cover (derived from a blend of imagery from geostationary satellites and AVHRR, but also station data) is supposed to be accurate. Snow water equivalent and snow cover derived from passive microwaves have been available for more than two decades. However, the data have hardly been used in operational applications because of their limited accuracy.

Recommendation 5: Use of remote sensing observations for rainfall, soil moisture and snow

In general, it is recommended that modelled radiances over land should be produced and compared to satellite observations on a (more) routine basis. This recommendation comprises the entire spectral range covering VIS, IR, and MW. The specific recommendations on the individual parameters focus on passive microwave, since the required technical framework is available at many NWP centres.

i) The evaluation of model performance with respect to cloud/rain affected satellite observations in radiance space will greatly support the analysis of the quality of the model's moist physical parameterizations (within the limits of the forward model's accuracy); it will facilitate and prepare the possible assimilation of such observations over land, leading to remote sensing-based precipitation estimates.

ii) Implementation of the ELDAS soil moisture data assimilation system into ECMWF's operational integrated forecast system. The observation operator should be a 'community' land surface microwave emission model (merge LSMEM and L-MEB), which should ideally be coupled to ECMWF's atmospheric radiative transfer model. Once the system is in place, assimilation experiments based on TMI and AMSR-E data, which have been available since 1998 and 2002, respectively, could be carried out.

iii) Since most of the retrieval algorithms are based on empirical relationships between brightness temperature and snow water equivalent it is recommended to evaluate the potential of physical retrieval methods. Within the framework of a revised soil moisture analysis (Extended Kalman Filter, land surface emission model, and microwave brightness temperatures) it is recommended to produce 19 and 37 GHz brightness temperatures for snow covered areas. Differences between modelled and observed values will lead to a better understanding of the spatial and temporal structure of errors. To model and analyze brightness temperatures over snow covered areas a parameterization for the grain size distribution has to be implemented.

1.4. Radiative Forcing

1.4.1. NWP versus available radiation products

Satellite derived radiative forcing are (will be) available from GOES (MSG from 2005 onwards). The comparison of such products with NWP forecast, and also with their equivalent re-analyses fields is likely to give insight on a number of cloud-related problems.

Recommendation 6: Model vs. remote sensing surface radiation

Surface short wave fluxes retrieved from Geostationary satellites should be compared with both forecasts and re-analyses fields, with the purpose of validating/identifying error sources from model cloud cover and optical depths, aerosol, or total column water vapour.

1.5. Reanalysis

The lack of consistency in time and space of Snow Data, which often miss large areas in Northern America, strongly limits the quality of the reanalyses snow-related fields. Although there is little doubts such data should be better represented, currently there are no new/better data available. To partially overcome these problems, the next version ERA-40 should include NESDIS data on snow extent, available since the mid-80s (with complementary data going back to 1966).

1.6. ECOCLIMAP

1.6.1. Static data

The static data available at ECOCLIMAP database consists of a land cover classification, which will be based on GLC2000 at global scale and CORINE 2000 for Europe for ECOCLIMAP-2.

1.6.2. Semi static data

A set of soil and vegetation surface parameters (e.g. FVC, LAI, albedo), updated with 10-day frequency based on SPOT/VEGETATION data.

1.6.3. Emissivity

It is recommended that ECOCLIMAP should have an emissivity product fully compatible with its land and vegetation cover (see Recommendation 3) and become part of its semi-static data.

1.6.4. Irrigation

Information on the fraction of irrigated crops may be extremely valuable for the quality of SM products. This is already available in the ECOCLIMAP database, through the fraction of vegetation cover (semi-static data) of its irrigated crops land cover (static data).

Recommendation 7: Update of ECOCLIMAP

> There is a need to update and improve the existing surface parameters database for vegetation and soils at 1km resolution (ECOCLIMAP-2) using new land cover maps (GLC2000, CORINE2000), new soil maps (STATSGO) and new sensors (SPOT/VEGETATION, MODIS), and to compare and validate the surface parameters fields (LAI, albedo, fraction of vegetation, ...) available through different projects such as the Land SAF, UMD LCF, Cyclopes, MODIS.

1.7. Hydro-Meteorological Observations

For the purpose of data-assimilation and validation of models, the forcings and the performance of land-surface DA systems, there is a need for an extensive, long-term hydro-meteorological observation network, in which measurements of soil moisture, turbulent fluxes, radiative fluxes and precipitation are tightly linked. Furthermore, systematic observations of in situ physiographic properties should be performed. The observation sites in such a network could also serve as reference stations for remote sensing observations.

Recommendation 8: Surface hydrometeorological observations

> This working group supports the establishment of a hydro-meteorological network, where measurements should be performed according to worldwide, standardized protocols, and quality control. Existing infrastructure, protocols and quality-control mechanisms of present-day networks, such as the Euroflux network in Europe, should be gradually extended and where necessary improved. For maximum benefit and spin-off, the hydro-meteorological network might also be linked with other networks, such as ecological and air-quality observation networks, and more specifically with the Baseline Surface Radiation Network. Priority should be given to the implementation and link of soil moisture observations to existing networks.

1.8. Discharge

For large and medium-sized river basins, the annual surface water budget together with observed river discharge and observed runoff ratios (runoff/precipitation) provides a powerful diagnostic tool for evaluating the annual surface evaporation and precipitation in ECMWF model and 4D DA systems. To a good approximation, the total annual storage change (mm) of water in the soil column and snowpack is negligible compared to the annual accumulation of precipitation (P), evaporation (E) and runoff (R), and hence to good approximation the annual water budget can be expressed as

$$E = P - R \qquad (2)$$

The above approximation of the annual surface water budget holds even better if applied over multiyear periods and if the annual period is defined with respect to the typical date of minimum snowpack (e.g. Oct 1 in the N. Hemisphere; the annual period between Oct 1 and Sep 30 is commonly known as the "water year' in hydrological applications).

If observations of basin mean annual runoff and precipitation are known, then Eq. (1) yields good estimates of the basin mean annual evaporation. This provides a powerful alternative to surface flux stations for evaluating model evaporation, albeit at annual time scales, as demonstrated by the North American Land Data Assimilation System (NLDAS) project, the Global Soil Wetness Project and PILPS-2c. Since annual evaporation is dominated by warm season evaporation over the bulk of extra-tropical regions, then systematic biases in model annual evaporation likely arise from the model's warm season evaporation. Additionally, Eq. (2) offers an effective tool for regional evaluation of model evaporation, which is difficult to accomplish using typically sparse surface flux stations.

Recommendation 9: Use of river discharge observations

The workshop recommends that

i) ECMWF acquire observed river discharge and observed precipitation for many river basins around the globe in order to regionally assess model surface evaporation using Eq. (2). From river discharge, basin mean runoff (R) can be derived knowing the basin area. The Global Runoff Data Center (GRDC) is a central source for observed river discharge. The Global Precipitation Climatology Project (GPCP) is a recommended source for global gridded data sets of observed precipitation. Other institutions (e.g. USGS and NCEP in the U.S.) and land data assimilation system projects (ELDAS, NLDAS, GLDAS, GSWP) should be contacted as additional sources for observed river discharge and gridded precipitation data sets.

ii) Additionally, observed runoff ratios (R/P) provide another useful tool in the context of Eq. (2) for evaluating evaporation, runoff, and precipitation in ECMWF modelling and assimilation systems. Observed annual runoff ratios, as well as their multi-year climatologies, are often available from the same institutions that provide observed river discharge.

2. Working group 2: Data assimilation and model infrastructure

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2.1. Data assimilation Methodology

2.1.1. Considerations on feasibility

With the (simplified) Extended Kalman Filtering (EKF) technique and a coupled surface and atmospheric model, the computer cost of the initialisation of the land surface state increasingly becomes a substantial component of the forecasting system. Addition of new control variables will increase further the cost. Methods exist that may reduce this cost (adjoint development, relaxation of upper levels to analyses) but possibly require massive software development. A pragmatic approach is advisable, where such software development is not started at short term.

Recommendation 1: Operational implementation of ELDAS

> The working group recommends a swift operational implementation of ELDAS, with pragmatic choices for parameters.

2.1.2. Combination of multiple time scales

With a project as GEOLAND at hand, land surface data assimilation systems are being designed that combine multiple time scales in dual-cycle systems (24 hour assimilation window for soil moisture combined with 2-3 weeks window for LAI). For the LAI estimation, the EKF method can be applied using an offline land model, at virtually no computer cost.

Recommendation 2: Realism of model LAI

> It is recommended to check the existence of correlation between modelled and observed LAI prior to starting the DA system development. If insufficient correlation is found, model improvements should be implemented first.

In future (GMES) applications a combination of temporal and spatial scales is necessary to link inverse flux retrievals from atmospheric concentration measurements and surface flux estimates from the land cover data assimilation. A blueprint for such a combined system has been developed in the context of the CAMELS project.

2.1.3. Penalization of deviation from large scale or local budget conservation

Lack of budget closure in (re)analysis systems is problematic when results are used for hydrological budget studies. However, including penalty functions for violation of this budget in the cost function is not realistic, as it requires very long time scales and too complex correction algorithms.

In principle penalty functions could be designed that limit soil moisture increments to within realistic constraints. Disadvantages of these penalty functions is that (a) the objective of the data assimilation (remove drifts from the system) may not be met due to inability to put in large enough increments, and (b) model deficiencies that are the cause of unrealistic (systematic) increments will be obscured. Alternatively, increments may be reduced by re-analysing offline the surface state with a monthly to seasonal time window, with the intention to smooth the increments.

2.2. Surface model improvements

2.2.1. How to learn from (systematic) model increments?

The existing systematic soil moisture increments during the summer season are undesirable, since they are no longer a small correction to assumed errors in the forcing.

An optimal way to reveal the origin of the systematic bias is to use parameter optimisation techniques on a retrospective analysis period, where the parameter optimisation is conditioned on minimisation of increments given perfect forcing conditions. The ELDAS data set is a useful test-bed for this exercise.

Even with optimised parameters, additional degrees of freedom in the parameter settings may remain necessary in order to continuously minimise systematic model biases. This surely applies to parameters that are assumed fixed, but in reality are conditioned by environmental conditions (e.g. hysteresis in hydraulic conductivity, or cases where the transpiration stress to limited soil water availability depends on environmental conditions such as radiation). This opens the way to a new research area of online parameter estimation in combination with state variable adjustment as applied in classical data assimilation. Research into this direction is recommended.

Recommendation 3: Soil moisture increments

i) To analyse soil moisture increments with a view to (land surface) model improvements.

ii) Use of both a DA cycle and a control suite (same model without land data assimilation) is recommended in order to attribute the increments to specific terms in the water balance.

2.2.2. Anticipated model improvements

The following model improvements are deemed necessary to comply with (near-)future data assimilation requirements:

- The parameters responsible for the systematic positive soil moisture increments (notably hydraulic conductivity, soil and root depth, canopy stress formulation) should be optimised or re-parameterised;
- For snow assimilation the introduction of orographic elevation bands and a parameterisation of snow cover fraction as function of SWE that allows hysteresis is recommended;
- For the possible assimilation of TIR, a refinement of the aerodynamic coupling of the skin layer to the atmosphere is needed, possibly by adopting a (calibrated) z0h-map;
- For the assimilation of TIR and m-wave T, introduction of an extra 1cm soil layer may help improve the dynamics of the skin temperature and the representation of sub-layer vertical profiles of soil moisture and temperature.

2.3. Boundary conditions

2.3.1. Specification of rooting depth and texture

Many parameters derived from ancillary databases are highly parameterised according to the host model properties, and the use of ancillary data is not purely "objective". Yet, the pragmatic way of putting in fields of rooting depth and soil texture – as already planned by ECMWF – and the subsequent evaluation of their added value in forecasts and data assimilation experiments is highly supported.

2.3.2. Observed precipitation

The use of observed precipitation as a driver for soil wetness is – obviously – highly recommended. Recommendations on mobilisation of European organisations are included elsewhere in this document.

The EKF approach assumed gaussian error statistics, which in the case of precipitation is clearly not a valid assumption. It is unknown whether this may play a role in the systematic nature of the soil moisture increments. The ELDAS database provides a good tool to explore the consequence of this assumption. It is recommended to use this database to explore the assumption of Gaussian precipitation error statistics.

However, as long as near-realtime observations are lacking, the use of a forecast product with not affected by spin-up (e.g., 12-36 hour forecast) is recommended above using a short-range 6-hour forecast.

Recommendation 4: Observed precipiation

> Use of observed precipitation, where available, as a driver for soil wetness in data assimilation is recommended.

2.4. Snow assimilation

Apart from the proposed model revisions further development of advanced data assimilation techniques to include both snow cover and snow depth is highly recommended. The LandSAF snow cover products are an interesting source of high-resolution information that may be combined with existing global coverage products.

2.5. New and synergetic observations

2.5.1. Using multiple observations simultaneously

Biased observations and/or model deficiencies may increasingly lead to conflicting information about the state of the model. This implies that the use of multiple observations puts additional constraints on the model physics, and warrants a close relation between model improvement and use of observations. Research into synergetic assimilation of various data sources (T, RH, remote sensing data) is highly encouraged.

2.5.2. Assimilation of fAPAR

fAPAR is an interesting source of information, which may be very informative on soil moisture and vegetation dynamics on seasonal time scales. Developments in this area should be taken step by step, and the introduction of LAI-assimilation in GEOLAND is a useful first step.

2.5.3. Information content of LCL/low level cloud data

Although low level cloud data and LCL seems to be very informative on the surface evaporative fraction, direct observation of these parameters is less straightforward than near-surface relative humidity, a strongly related quantity. Systematic errors in PBL entrainment and shallow convection may lead to overestimation of surface evaporation and thus enhance the drying problem; research in this field is highly encouraged.

2.5.4. Detection or assimilation of irrigation

Irrigation can either be provided as an extra artificial forcing, or could be diagnosed from systematic data assimilation increments. Assimilation of fAPAR may help to detect green vegetation that can only exist because of irrigation. Techniques developed in climate modelling are based on a overlaying land use maps, irrigation practices and atmospheric moisture demand. National weather services (e.g. INM) are highly encouraged to carry out research efforts to quantify and routinely include irrigation amounts in NWP.

2.6. Assimilation of thermal infrared and microwave brightness temperature

2.6.1. Thermal infrared radiances

Assimilation of thermal infrared radiances (either direct or via its rate of change) is – given the present systematic biases in modelled skin temperatures – not yet feasible.

Recommendation 5: Use of thermal infrared radiances

> Additional research is needed to remove these biases via model improvement, possibly in combination with bias removal by calibration of the aerodynamic transfer properties using observed skin temperatures.

A 3D-feasibility study of assimilation of heating rates has not yet been carried out, and is recommended.

It is noted that the NWP-SAF has created adequate RT models and an emissivity product that should be used in combination with the data assimilation of skin temperatures or heating rates.

2.6.2. Assimilation of radiance or retrieved soil moisture from m-wave satellite platforms

The large signal/noise ratio of in particular L-band data makes use them very useful for soil moisture assimilation. In general, assimilation of m-wave radiance data into the NWP system is a preferred practice, as it is more straightforward to establish a model state that is consistent with other assumptions in the model (e.g., it avoid the problem of transferability of retrieved soil moisture to the model soil moisture). However, two aspects favour the evaluation of using retrieved soil moisture data instead:

- The retrieval generally include observed information on the vegetation structure (by multi-angular observations and/or ancillary data), which may be incompatible with the vegetation assumptions made in the host model.
- Quality checking on retieved products may be more straightforward than on observed radiances, which facilitates removal of invalid observations.

Recommendation 6: SMOS assimilation study

> It is strongly recommended to ESA to facilitate a data assimilation feasibility study to explore the merits and technicalities of future assimilation of SMOS and/or HYDROS data.

3. Working group 3: Applications and future developments

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3.1. Introduction

Applications of land data assimilation systems include now-casting, initialisation of NWP and sub-seasonal forecasts, and process studies in the context of retrospective analyses. Variables of interest in forecasts include surface meteorology, primarily screen-level temperature and precipitation over land, land surface states such as soil moisture, soil temperature, and snow, as well as associated parameters such as crop yield, fire risk, and hydrological (runoff, streamflow) prediction – all of which are affected to a varying degree by how well we can determine the land surface state and its interactions with the atmosphere. Processes of interest in retrospective analyses cover the partitioning of available water and energy into latent and sensible heat, runoff generation, land-atmosphere feedbacks and memory of soil moisture and snow that might be the source of predictability of weather and seasonal climate variations. While the community has achieved much in the past decade (e.g. improved understanding of soil moisture memory and associated predictability) there are many obstacles that need to be overcome – primarily related to soil moisture transferability, cold land processes, green biomass/carbon, groundwater, and irrigation – before new applications of land data assimilation can be successful.

3.2. Subseasonal-to-seasonal predictability and land data assimilation

Seasonal prediction at ECMWF, like elsewhere, has traditionally focused on the predictability of climate variations associated with tropical ocean initialization and prediction, primarily El Niño. A growing body of recent findings, however, suggests that in some subtropical and mid-latitude regions the memory of soil moisture together with land-atmosphere interactions provide a further degree of predictability of surface air temperature and precipitation over and above what tropical ocean phenomena may induce. Soil moisture has been the key variable targeted by the ELDAS project. Consequently, the working group encourages ECMWF to focus more strongly on land in its seasonal prediction efforts.

Fresh water storage in the form of snow during the winter season strongly impacts spring and summer runoff and hydropower generation (see Hydrological Applications below). Moreover, snow may also affect seasonal climate variations. Unlike the role of soil moisture, however, the role of cold land processes such as snow and permafrost, in the predictability of the climate system is poorly understood. Modelling studies have linked early season snow cover extent variations in Eurasia with dominant modes of wintertime variability at mid-latitudes of the Northern Hemisphere. In addition, observational studies have shown relationships between antecedent winter precipitation and summer monsoon intensity (both over Asia and North America). Attempts to model this phenomenon have seen limited success. More experimentation similar to the warm season work on soil moisture is urgently needed to assess the potential predictability associated with cold lands and cold season processes. Such experiments need to move beyond gross sensitivity studies designed around the specification or initialisation of extreme and unrealistic snow conditions.

These efforts at ECMWF would be facilitated by involvement in community experiments such as the GEWEX Global Land Atmosphere Coupling Experiment (GLACE) or the Global Soil Wetness Project (GSWP). Finally, in connection with the GEOLAND project, predictability associated with the carbon cycle is worth exploring as it is inexorably intertwined with the surface water and energy cycles that link the land and atmosphere on climatic time scales.

Recommendation 1: Land surface and seasonal prediction

> Seasonal prediction efforts at ECMWF should accentuate land processes, land memory, and associated predictability.

3.3. Hydrological applications, crop yield, and fire risk

3.3.1. Hydrological applications

Predictions of drought and flooding periods are of utmost concern for hydrological applications that affect society in terms of hazard and the management of water resources. Precipitation is the dominant variable for such applications; nevertheless, products from the land surface assimilation and forecasting system may prove useful, as soil and vegetation conditions can affect the character and severity of hydrologic extremes.

To date, the analysis of the soil state from land surface models has not shown to be useful for flood prediction. The hydrological models themselves have well-proven soil moisture parameterisations that are presently more appropriate for runoff prediction. In cold regions, analysis of the state of the snow pack and permafrost could provide beneficial inputs to flood prediction as they are closely linked to 2m temperatures. Alternatively, better prediction of 2m temperature would improve the prediction capability of the snow modelling components of rainfall runoff models. Better representation of snow and frozen soils in the land surface model are necessary for improving the near-surface meteorology and surface state.

Regarding drought, both the forecast and statistics from re-analysis of the combination of soil moisture state and 2m temperature should provide added value to precipitation outputs. Drought is a response to the combination of the short time scale of precipitation and the longer time scale of soil moisture deficit. It is therefore particularly sensitive to the representation of soil moisture memory in land surface models. Improvements to representation of the soil processes over seasonal scales would help quantify this. Additionally, there are distinctions between meteorological, agricultural and hydrological drought which represent, among other differences, a progression of integrative time scales from short to long. Different user communities have specific interests in these distinct types of drought, and improved land surface modelling can extent forecast skill benefit to the longer time scales.

Validation efforts and inter-comparison studies that address cold region processes and drought would benefit model development. These studies should capitalise on using the datasets from previous and ongoing international model inter-comparison projects (e.g. the Project to Intercompare Land-surface Parameterization Schemes (PILPS) studies including the Torne and San Pedro, and the Rhône-AGG experiment of GSWP).

At longer time scales and larger spatial scales, estimates of changes in terrestrial water storage from atmospheric moisture convergence in combination with runoff observations might be valuable for assessment and prediction of drought conditions. Moreover, a new type of satellite observations (from the NASA GRACE mission) based on the gravity signal can detect changes in terrestrial water storage at large spatial and long temporal scales. Such observations might be useful for constraining the water budget.

3.3.2. Fire risk prediction

A good prediction of conditions that are conducive to the occurrence of forest fires is needed for many Mediterranean countries, subtropical, semi-arid and boreal forest regions. The risk of ignition is strongly correlated with the presence of dried vegetation mass (litter), and soil moisture may be used as a proxy for the moisture state of litter. Both the quality of the land surface model and of the soil moisture assimilation will determine the realism of those predictions in the weekly to sub-seasonal range. Moreover, development and further propagation of fires are conditioned by variables (for example wind, precipitation, and air temperature) whose prediction might be improved with advances in land data assimilation. Forest fires also represent a relevant process in the carbon budget. Including carbon/green biomass into the modelling and assimilation system should improve our ability to assess fire risk conditions (see Carbon section below). Finally, the release of CO2 to the atmosphere caused by natural fires is non-negligible and for some regions is a relevant source of emissions.

3.3.3. Crop yield forecasting, groundwater, and irrigation

Current crop yield-forecasting methods based on statistical analogues require medium-range predictions of vegetation stress. This implies that soil moisture values must be transferred between the crop modelling system and the land surface scheme used in the land data assimilation system. A demonstration study is needed to verify if the current soil moisture levels in the ELDAS outputs can be converted into realistic vegetation stress levels (see Soil Moisture Transferability section). These studies could be carried out for selected areas with relatively homogeneous crop types (e.g. Seine basin, northern Netherlands, Po basin, southern France, southern Spain). In the longer term, the community is interested in sub-seasonal to seasonal predictions of surface air temperature, radiation, and precipitation in order to integrate the crop model for extended forecasts periods and provide dynamical, end-of-year yield predictions based on meteorological forecasts.

Crop yield models today take the output of weather and climate forecast models as their input. However, the phenology of crop variations (and for that matter the phonological variations of natural vegetation systems) in response to temperature and precipitation anomalies could be incorporated into the prediction equations of the land surface model (see the section on interactive vegetation below). At the very least, the mean annual cycle of vegetation phenology (LAI, greenness and vegetation cover fraction) must be included in operational land surface schemes.

Studies indicate that soil moisture levels can play a role in deepening a local drought that was initiated by large-scale weather patterns. However these soil moisture levels can be altered by local irrigation practice. We suggest that reanalysis can be used to study if the geographical distribution of the data assimilation increments corresponds to either irrigated areas or areas with shallow groundwater levels or deep root systems. It is also possible that GRACE measurements may be used to monitor the total water change (including ground water) due to irrigation. In addition, the IGRAC (International Groundwater Resources Assessment Centre) database can be used to analyse groundwater feedbacks. These results will help to decide if the closure of the water balance may be improved by incorporating terrestrial water storage terms in the ELDAS water balance.

Recommendation 2: Hydro-ecological applications

> ECMWF is encouraged to explore forecasts of hydrological and ecological variables, including runoff, fire risk, and crop yield.

3.4. Carbon and interactive vegetation

Advances in the identification of natural carbon sources and sinks may be possible even before green biomass and carbon processes are included into the land surface model that is currently part of the land data assimilation system. In fact, the identification of natural carbon sources and sinks using traditional "inverse" methods depends on the accurate description of the land surface state – notably soil moisture and soil temperature – that is the focus of current ELDAS products.

Nevertheless, improving the description of photosynthesis and including soil respiration into the land surface model is the key to future progress. Vegetation controls transpiration of water from all soil layers and influences surface albedo. On the wide range of time scales of interest (minutes to a few months), the processes involved are (i) stomatal control as a trade-off between photosynthesis and plant water loss, (ii) phenology (time evolution of LAI), and (iii) rooting strategy. None of these are described in traditional (non-carbon) SVAT models such as ECMWF's operational Tessel land surface scheme but are currently being addressed in the new version C-Tessel.

The expected benefits from the inclusion of carbon and interactive vegetation include: (i) improved process description within the forecasting system and for applications, (ii) addition of processes at time scales up to seasonal predictions, and (iii) use of satellite-based observations (e.g. fractional absorbed photo-sythetically active radiation, or fAPAR) in assimilation mode.

Research needs that are partly addressed by the development of C-Tessel include:

- Better understanding and simple descriptions of rooting strategies and their interaction with water/energy balance and soil texture/depth;
- Better phenology models;
- Improved models describing surface albedo as a function of surface soil texture, moisture, plant cover and snow;
- Improved representation of land cover and fraction of various vegetation types;
- Better parameter estimation and data assimilation techniques to improve the description of the land surface state including vegetation, snow and irrigation, possibly fire;
- Development of adequate sequential data assimilation techniques that are able to include fAPAR and vegetation in addition to traditional DA observations and state variables;
- Development of soil respiration parameterizations.

Model inter-comparison projects (MIP's) are an integral part of model development. In addition to C4MIP (~100 yr time scale carbon/climate interactions) and C-PILPS (surface CO2 and water fluxes), there is a potential for a "green forecast MIP" that looks specifically at the potential of atmospheric models coupled to interactive vegetation models (including snow and rooting strategies) for improving medium-range, sub-seasonal and seasonal predictions.

There are close links between carbon processes and the applications discussed above. Interactive vegetation-SVAT models are very similar to crop models, so their results may be transferred to crop forecast applications. Moreover, it may be possible that the assimilation of fAPAR can detect irrigation and may be used to quantify the impact of irrigation on the atmosphere. In semi-arid regions with significant winter snow, fAPAR may respond to snow mass anomalies. Finally, fire risk is intimately linked to vegetation status, and fire influences surface albedo in addition to vegetation, snow and soil moisture.

Recommendation 3: Surface carbon fluxes

> Continue the incorporation of carbon/green biomass processes into C-Tessel and assess the impact on medium-range to seasonal predictions and applications.

3.5. Retrospective analysis and process studies

The group realizes that it is a very challenging problem to develop a land data assimilation scheme producing analysed soil moisture that conserves water and energy within the analysis. The soil water increments in ERA-40 systematically reduce the amplitude of the annual soil water cycle, typically with negative increments in spring and positive increments in summer. At the seasonal timescale, and for sub-continental scales, increments in summer are a sizeable fraction of the change in soil water storage. Conceptually, the presence of the increments creates a problem for users of ERA-40 surface water budget: A user would like to be able to attribute the analysis increment to evaporation, runoff or precipitation. The size of the increments should be reduced with improvements in the land-surface models and precipitation and radiation forcing from the short-range atmospheric forecast, as well as better assimilation systems. It is also hoped that the use of more (and more importantly, more diverse) observations, sampling several aspects of the physics of land-atmosphere interface, would avoid aliasing of information into soil moisture, and decrease the size of the increments. In this context, the group encourages ECMWF to continue looking into the potential of microwave observations sampling top soil moisture and VIS/NIR information sampling the vegetation state. For future reanalyses efforts, the overall size of the soil moisture increments should be assessed. If it is anticipated that they will remain a sizeable fraction of seasonal rate of change, consideration should be given to methods that drift away from the current atmospheric (weather) oriented land surface assimilation, operating on short time intervals, to focus on longer (sub-seasonal) timescales. A smoother approach (looking into the future and past) for the land surface could be considered, dependent on its computational costs. A cheaper option could be a parallel effort of forcing an off-line version of the surface model with the best possible estimation of precipitation, surface downward radiation and near-surface meteorology, covering the entire period of the reanalysis, in the vein of GSWP. With this option, users would have access to a complete and closed energy and water cycle (albeit not entirely compatible with the atmospheric reanalysis).

Recommendation 4: Land surface assimilation in re-analysis

> For re-analysis, reformulate the land data assimilation algorithm as smoother (rather than a filter) to improve water & energy balance estimates.

3.6. Transferability of soil moisture

It is well documented that different land surface models (LSM) generally do not produce the same surface and root-zone soil moisture values because of differences in their parameterisations that result from the lack of knowledge about the correct soil parameters and ultimately the true soil moisture climatology. Variations among models also arise because different schemes have been developed for diverse applications, and form (e.g., vertical structure and resolution in the soil column) follows function. This is reflected in differences in the total depth of the soil layer, field capacity, wilting point, distribution of active roots and the parameterisation of plant water stress.

However, soil moisture values produced by land surface models that are scaled (e.g. between wilting point and field capacity) can be compared more easily. There is at least a correlation between the values produced by different LSMs and the observations. In the context of the assimilation of remote sensing data that provide information about surface soil moisture (e.g. SMOS, HYDROS), a prerequisite for assimilation is that a bias reduction is performed (tantamount to rescaling the model outputs through fitting minimal and maximum values, means and variances, or using more refined probability distribution functions.)

Differences in the way soil moisture is addressed in LSMs pose the problem of transferability of soil moisture from one application to another (e.g. NWP, hydrology, crop monitoring, and carbon monitoring). The most obvious solution is to use the same LSM for different applications, which is the strategy adopted by the NWP community. But it will be difficult to establish the dialogue between the meteorological community and other disciplines. One of the objectives of a space mission like SMOS is to reconcile the different LSMs by providing a climatology of surface soil moisture which should help reconcile the models. However, root-zone soil moisture will not be observed by SMOS and must be retrieved by assimilation techniques. Since the assimilation of SMOS data will likely be performed by the meteorological community, the LSMs used in the data assimilation system will both attract and require more attention.

Depending on the application at hand, optimal communication between models might be achieved by exchanging information in terms of (and hence scaling) evaporative stress, runoff, or soil moisture indices, rather than soil moisture.

There also exists the problem of transferability of parameters within any given LSM. Data do not exist to calibrate a LSM at more than a few dozen locations around the globe, yet the grid of discrete land surface points in a global model numbers in the thousands. The demonstrated lack of transferability of tuneable parameters to unmonitored grid points is another source of error in LSMs that can affect weather and climate forecasts as well as land surface analyses. Again, remote sensing may be able to provide global information (e.g. fAPAR) that can be used to constrain LSM parameters and improve simulations.

Recommendation 5: Soil moisture transferability

> Differences in soil moisture and associated variables between models, observations, assimilation products, applications and locations must be documented. Further research is needed to determine how such differences can best be overcome.