1. Working Group on Land Surface Modelling

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1.1. Working Group Discussion

The modelling working group discussed several topics following the Workshop survey of current research in several NWP and Climate Centres. The main question, which formed the basis for much of the discussions, was philosophical: 'Are the land surface model's good enough?' The working group agreed on the need of a context to judge the quality of the models, and it is referred to the 'Observation WG' to define the appropriate context (dependent on observations availability) for verification and benchmarking. In particular, it was felt that a driver for recommendations (in section 2) to ECMWF/GLASS is the relevance for NWP. Another criterion to determine a parametrizations adequacy is provided by the time and spatial scales for which the scheme is going to be used (Global-Mesoscale or Local Area Modelling [LAM] applications, medium-range/monthly forecasts, or seasonal prediction). It was acknowledged that ECMWF is moving towards high spatial horizontal resolution with the next planned implementation (CY36R1, T1279L91 ~16km, foreseen in January 2010). This resolution is an achievement for operational global models and it has been so far considered only in a LAM context. The land surface model is expected to better represent terrain heterogeneity at this resolution. Moreover model developments can take advantage of extensive research done in several NWP Centres. Current LAM systems, which are operational in several centres, are either considering comparable spatial resolutions (10-20km) for large domains (e.g. Western/Eastern Europe, US, Canada, etc.) or developing/running new very high resolution models (2-3km) for National/Regional domain forecasts.

1.1.1. The Tiling/Nesting approaches

Land surfaces are notoriously heterogeneous due to natural and man-made differentiation of land-use, vegetation, soils, snow and ice, water-bodies, town, etc. As a consequence, significant sub-grid surface flux (heat, mass and momentum) associated with heterogeneity has to be parametrized in a NWP model grid box. An increasingly popular method (largely owing to it's conceptual simplicity) to address this issue is to break the surface into sub-grid patches or tiles in order to better represent the (non-linearity of) processes associated with different surface types. All NWP models consider at least two resolved tiles: ocean/sea and continental surfaces, with different distinct parametrizations for each. The continental surface tile can be further decomposed into a number of sub-tiles depending on surface cover types and/or elevation. In this discussion we use the term 'continental tile' to encompass both inland water bodies (lakes) and the land surface (including so-called permanent ice). Such tiling can be done for multiple surface energy budgets overlying a single grid point soil column (currently the case for ECMWF), or the tiling can extend to the base of the soil profile. The aforementioned approaches can be applied to constant (in time) tile fractions (such as vegetation and bare soil) or can also be extended to include sub-tile patches (or tiles within tiles) for which the areal extent changes in time (e.g. for snow or flooded areas, frozen lake fractions, and canopy-intercepted water).

The tiling as a concept was discussed, and a basic question was posed: do we need tiling or are simpler 'effective parameter' approaches still efficient? Although the computational burden of a more sophisticated scheme is less of an issue nowadays, tiling is still a relatively low priority at some operational centres and for instance at Météo-France the effective parameter approach is still used in operational NWP. Likewise at NCEP, research on the stable PBL receives higher priority, because of the expected impact on bias in temperature and momentum, compared to tiling. However, research on sheltered snow and carbon/plant functional type modelling are clearly supporting the introduction of surface tiling. Nesting was also discussed as a type of tiling where the sub-grid tiles/patches are geo-referenced. In this case, the actual location and elevation of different land cover and soil types could be identified moving towards a scheme for which soil and vegetation processes can be physically treated rather than parametrized. Preliminary offline results were shown at the workshop from MSC-Canada. However it is highlighted that this method represents a significant increase in CPU and processing, while at present it remains uncertain how much it improves NWP predictions; we recommend a devoted study. The tiling approach, at least for the surface layer, is generally accepted to be of good scientific value (and computationally balanced) and should be recommended for use within the GLASS community, especially for cost-effective applications (e.g. seasonal forecasts).

The main conceptual issue to be addressed for both tiling and nesting approaches remains the validity of the blending height hypothesis, especially when applied to a very low first atmospheric vertical level (at ECMWF it is close to 10m). Can observations be helpful to establish if the blending height hypothesis could break? Under what circumstances is this likely to happen? What are the implications? Are drawbacks of the blending height approach outweighing benefits? The working group felt that some issues could be studied using single column model (SCM) simulations on contrasting neighbouring points. Issues related to the blending height hypothesis are highlighted as important research questions.

1.1.2. Land surface (vegetation and soil) parameter datasets

The importance of high resolution and high quality Land Use Classification that permits parameter association (e.g. ECOCLIMAP) was highlighted. Methods developed to make better use of satellite-based datasets in real time to correct model ancillary fields (such as leaf area index, LAI, and albedo for example) should also be investigated (the assimilation of 'anomaly' was suggested for fields such as LAI that have large uncertainties on the absolute value, which is similar to applying a strong bias correction). It is recognized that the adoption of new land datasets is a difficult issue for the NWP community, as their advantages compared to the old datasets are difficult to verify. In fact, several parametrizations depend on land use (roughness, vegetation types for evaportranspiration, carbon processes such as assimilation, respiration, etc...) and all depends on the chosen orography. However the adoption of up-to-date datasets should be pursued and implemented whenever this is possible (the example of vegetation roughness length sensitivity on snow accumulation in the ECMWF model was given).

1.1.3. Soil hydrology

A key research activity across the represented NWP centres is soil hydrology. Examples of very-high resolution (kilometre scale) simulations performed at NCAR were shown at the WS where lateral overland flow in the soil and interaction with soil moisture is shown to be relevant if terrain complexity (in particular slope) can be resolved. The horizontal redistribution of soil water owing to lateral surface flow during land surface spin-up cycles was shown at the workshop to have a minor, yet non-negligible, impact on the overlying atmospheric circulation for a short-term (on the order of a day) simulation.

For resolutions coarser than approximately 5 km, a sub-grid parametrization should be considered, as lateral flow can't be resolved. TOP-Model type approaches for sub-grid soil moisture redistribution or VIC schemes for sub-grid runoff (as currently adopted by HTESSEL) should be adopted. Mountainous regions still represent a challenge since smoothed orography limits a realistic representation of snow processes (as affected by temperature/height/radiation). The idea of using tile elevation bands in order to enhance the capability of modelling snow in mountainous areas is discussed. A first step could be simple and consider just elevation effects (for precipitation phase and air temperature). However, potential problems are that the lapse rate used in disaggregating the air temperature can have a geographical dependence (along with depending on the local meteorological conditions), and the blending height concept becomes more complicated when large sub-grid topographic variability exists. In addition, in theory, each elevation band in a grid box might contain multiple land surface cover types, thereby significantly increasing the computational burden for such a scheme. It also implies being able to identify which vegetation classes correspond to which elevations.

It is mentioned that UKMO has the intention of looking into elevation bands for the purpose of improving the effect of orography on snow model predictions. At NCAR, studies are ongoing which utilize an independent nested land grid approach that may have potential benefits particularly over runoff/discharges. WRF uses a terrain adjusted insolation and shading parameterization for topography. However for Colorado, studies have indicated that for grid spacings above 2 km there is not much of an effect. Météo-France (for NWP at 2.5 km) does not yet consider this level of detail (e.g. over the Alps).

1.1.4. Soil thermal properties and soil water phase changes

The most widely used thermal conductivity scheme is the Peters-Lidard scheme, however recent developments suggest that this approach can be improved. This concerns the shape of the dependence of thermal conductivity on soil moisture content and the calculation of dry and saturated thermal conductivity. In particular, schemes that explicitly consider ice content, this can provide a more realistic representation of soil heat propagation. Also, a better simulation of soil freezing can be achieved by considering recent advances in JULES and ISBA (diffusion version). The need of a prognostic ice (frozen soil water) was discussed, but no consensus was reached on the absolute necessity of this as prognostic variable. It was also recognised that porosity and cracks in the soils, caused by the freezing process, are important since water percolation chooses preferentially open paths (preferential flow). This counteracts (to some extent) the impedance of infiltration owing to ice. A model connection with root distribution to parameterize the effect of cracks seems feasible, although the parameteriation of roots in land surface models is still rather approximate (poorly constrained by data).

1.1.5. Variable soil depth and vertical resolution (soil layering)

Several NWP models consider a shallow top layer (approximately 1cm for ISBA, of the order of mm in ORCHIDEE) while other models implement a thicker first layer but then adopt an infinitesimally thin skin 'layer' (NCEP/ECMWF adopting 10/7 cm, respectively). However, the optimal number of layers and the vertical resolution are highly variable among models and there is no broad consensus in the modelling community (although numerical arguments can be made based on the important time scales). However, the capacity to increase from a few layers (4 in HTESSEL) to a finer discretization should be an option. It is suggested that more layers with finer resolution at the top of the soil may better represent:

1. More realistic propagation of wetting fronts
2. Deep root-zone storage in primary forests (Amazon presents an ET phase shift issue which seems to be sensitive to the presence of deeper soils)
3. Better vertical moisture transfer mechanisms: the Richard's equation is highly non-linear and typical NWP time steps are fairly large so numerical issues arise at low vertical resolutions (e.g. interpolation of hydraulic conductivity to layer interfaces, proper handling of infiltration, etc.)
4. Permafrost/freeze-thaw modelling requires high near-surface vertical resolution (for accuracy) and deep soils
5. The ability to model the saturated zone and therefore feedbacks with surface fluxes

A multi-layer scheme configuration should be a balanced choice of

1. Assimilation aspects (SMOS/AMSR-E brightness temperatures are more realistic if soil moisture gradients can be accounted for: upper soil layers should be at most 3 or so cm thick)
2. Numerical aspects (linearised verses iterative approaches)
3. Evaporation realism (from bare ground; resolving the diurnal cycle)
4. Freezing realism: the vertical resolution is very important. For seasonal forecasts, soil depth can be an issue (for freezing)
5. Representation of possibly large near-surface soil water gradients
6. Algorithmic (in HTESSEL fluxes and the skin temperature calculation may not allow easy time-splitting methods)

A variable soil depth acts on the soil memory. For example, variable soil depth is important for Iberian Peninsula shallow soils. It also has a significant impact on hydrology and river forecasting (e.g. SIM hydrological forecasting operational at Météo-France). At NCAR, soil vertical discretization was shown to act on the Bowen ratio (improved diurnal partitioning). However it should be noted that soil depth datasets are of limited quality. Geomorphological approaches are promising alternatives for obtaining global parameter values. Some unresolved issues are: How deep the soil should be (2 to 3 m as in current schemes, or 8m to 10m)? How can global datasets of soil depth at relevant resolutions be derived? How to link soil depth, water-table and Aquifers? Reliable simulation of the water-table is recognized to be a difficult issue; this is very relevant for climate integration, although maybe of secondary importance for NWP.

1.1.6. Snow processes

Snow-MIP2 was acknowledged to provide a rich source of information for working on snow model improvements for NWP. Large-scale impact and interaction with the atmosphere may be considered in the follow-on study. The composite energy balance method is not well adapted for partial snow coverage (too sudden melting: very large dependence on snow fraction parametrization which is a weak link in such models). A separate tiled energy balance is a priority for UKMO (similarly to HTESSEL). An explicit canopy representation is probably needed: representation of snow underneath high vegetation showed benefits from the introduction of tiling which addressed large biases in the lower troposphere. Recent revision of the snow model at ECMWF has addressed a soil cold bias in snow-cover conditions and substantially improved the snow model (in particular the impact of liquid water in the snow-pack and a revised snow density were identified as effective)

Enthalpy provides a valuable integrated approach to represent snow (with only two prognostic variables being temperature and liquid water content). This could be incorporated into a single variable stored in memory.

A snow-on-canopy model could be also explored although the initialization might be an issue (canopy can intercept significant amounts of snowfall, and sublimation can result in large losses with consequent albedo effects), however incorporation snow interception processes puts strong weight on accuracy of snowfall prediction. Canopy and sub-canopy energy budget (short-wave radiation) is treated in a very simple manner, and forest sites are difficult to model. An open question is turbulence within the canopy. Tundra would need a separate canopy to be correctly represented in snow covered conditions: can this transition be modelled effectively? Is an explicit snow interception by the canopy needed? Is the interception capacity LAI-dependent for snow as it is for liquid water? And should the effective heat capacity be considered (and how) when snow is intercepted? More research within the SnowMIP2 will try to disentangle these contributions.

Global scale snow-cover and forest impact is really important for large grids used in climate/seasonal prediction model. However scale-dependence of snow fraction parametrizations is a big issue (especially for unified-models running at several resolutions). Schemes are rather empirical according to literature. This parametrization can effectively remove much of the benefit from using more realistic physics.

Large uncertainties in remote sensing of snow mass is a limiting factor for developing advanced parametrizations and the link between snow-mass and snow-cover is still poorly understood. Current products do best for snow cover (not mass or depth). Combined satellite and model approaches probably hold the most promise. Remote sensing requires snow layering information (and most of all grain size; snow crystal types might also be important). Albedo is a function of grain-size in JULES but has age as a proxy. Snow-MIP1 showed that snow-aging is slightly more preferable than temperature dependence. It is reminded that snow fraction and canopy masking are still dominant effects for the albedo.

It is a general conclusion in the literature that a 3-layer snow scheme may be a good compromise to have liquid water content gradient in the snow-pack and provide diurnal temperature oscillations. The layers are generally chosen in terms of relevant time scales (for NWP). Experimental versions of the multi-layer scheme in HTESSEL show some benefits but it is not issue-free (since other radical simplifications, e.g. in the canopy parametrization, may obscure full benefit). ISBA has an explicit snow-pack which is numerically robust for a sub-cm uppermost layer thickness and time steps up to 1 hour. The presence of a liquid water reservoir in the snow-pack allows interception of rainfall which increases snow mass and density. It also retards snow melt (due to refreezing of liquid water in the snow-pack). In addition, liquid water can impact night-time fluxes over the snow-pack.

Turbulence in the presence of snow is critical, as the atmosphere is most often stable above snow-packs and stable regimes are generally accepted to be a weak point of LSMs in NWP. Some models use a Richardson number limit to avoid too much land-atmosphere decoupling. Changes to the roughness length also have a similar impact since there is a large sensitivity of the snow to roughness parameters. A windless exchange coefficient seems a practical solution for inversions. FLUXNET data could be used to back-out the CH coefficient in stable/unstable conditions. Model experiments concentrating on freezing conditions (‘zero degree experiments’) can be used reduce uncertainties. It was agreed that stability aspects are probably more important than roughness parameters although the two are obviously inter-related. A separation between strong-wind or weak-wind conditions is necessary, perhaps by modifying the parametrization for these different regimes.

1.1.7. Lakes and flooded zones

FLake (lake+ice) is a common choice for NWP. There is insufficient research to comment on its performance. Is 1-D good enough for large lakes? Tests with optimized lake-depth showed reasonable results over the Caspian Sea (closed basin not included in ocean models) and over the American and European Great Lakes. Lake depth is a big issue for NWP implementation and indirect estimation methods are needed. It was also pointed out that rivers and marshes/wetlands can’t be distinguished from lakes and the quality of modelled evaporation fluxes is unknown. Some models parameterize flooded zones requiring a river routing mechanism. However initialization of river levels is an issue at global scale. Altimeter-derived river height changes at an approximately 50 m spatial resolution will be a major product of the new mission SWOT (Surface Water and Ocean Topography). Improvements in the parametrizations of flooded zones and interactions with rivers and lakes should help. Such zones have a significant impact on surface fluxes on NWP and probably also very important for SMOS assimilation applications.

1.1.8. Vegetation processes (towards a more physically based representation of photosynthesis and the Carbon cycle)

It is recognized that the Jarvis (1976) gs (stomatal conductance) equation (known as Big-Leaf) has an appealing simplicity that inherently suits NWP applications. However, this is limiting for the combined photosynthesis-stomatal conductance approach. The Jacobs (1994) approach (also known as A-gs model, where A stands for photosynthesis) is a simple widely accepted mechanistic alternative to Jarvis (1976). However, the large number of parameters required in such schemes is something to examine as the problem of equifinality could exist for Jacobs and Farquhar (1980) schemes. Measured values of stomatal conductance are often not available and top-down conductance estimation can lead to unreliable estimates of gs (due to non-linearities in the Penman-Montheith equation). Sensitivity analysis of such schemes is recommended prior to tuning (for NWP), and over-tuning should be avoided and particularly if parameters fall outside the literature-based dynamical range.

The implementation of more physically based gs-schemes that provide at least neutrality in NWP scores should be pursued. Physiological conductance is already considered in the JULES scheme that is also used for NWP. Data assimilation considerations are also important in the decision making (e.g. reasonable linearity of the soil moisture/evapotranspiration relationship). Bare ground evaporation, in particular how to model its surface conductance, is also identified as an important player, and the effect of approximations should be evaluated, particularly in dry-land areas where the neglected water vapour transfer may underestimate modelled extraction from soils. The use of wilting point in the bare-soil evaporation is somewhat questionable as this is a plant concept. Soil moisture values in arid or semi-arid regions are often observed to fall far below typical wilting point values. This is even more critical in light of soil moisture assimilation of satellite data such as SMOS.

1.1.9. Urban modelling

Urban areas are covering a very small fraction of continents (0.05%) but 50% of the global population lives in cities (70% in EU). Heat waves have proven to be high-impact weather events after the European summer of 2003 (more than 15000 casualties in Western Europe), where a long and severe drought caused sustained hot temperatures, particularly in urban areas. The implementation of a simple urban tile based on modified bare ground (roughness, albedo, soil heat and hydraulic conductivity) is suitable to represent daytime heat-island but has limits in representing night-time inertia. Canyon effects are included in the Météo-France operational NWP no-hydrostatic limited area model Applications of Research to Operations at the MEsoscale (AROME: 2.5 km), but it is not clear whether it would be relevant yet in near future resolutions (at 16km).

1.2. Recommendations

Hydrology is identified as top land surface priority for NWP models, and a improvement of schemes involved in the land water fluxes (both land-atmosphere and land-oceans) is recommended. This should devote attention to soil evaporation, vegetation transpiration/phenology, vertical discretisation of soil layers and roots as those areas of developments are anticipated to be crucial for reliable estimates of both atmospheric turbulent fluxes and river discharges at all time-scales and spatial-scales of interest at ECMWF. Sub-grid runoff and snow-cover are still weak points in models (and source of inter-model variance), despite recent progress.

A linked action with the above targets is the **increased realism of land surface heterogeneity** (via parametrization of lakes, urban area, snow in mountainous regions, etc.). This should be considered as a linked top priority since the omission of relevant surface processes can only result in overfitting models to compensate errors. The GLASS modelling community should aim at obtaining '*the right answer for the right reason*' and the concept of model **benchmarking** could make sure that improved performance in an area (e.g. evapotranspiration and near-surface temperatures) does not come at the expenses of other parts of the model (e.g. soil moisture or runoff). A more specific list of recommendations from the working group is reported below, separated into High Medium and Low priorities with indicative titles:

1.2.1. High Priority

- (*LAND-USE*) Improved land classification datasets are needed. This includes harmonized land-use datasets with NWP and more physically based photosynthesis and Carbon scopes (e.g. plant functional types need to be characterize to set carbon regimes). This is judged to be highly relevant and can be recommended to GLASS as an important research effort (as already done within IGBP at 1 degree resolution) since it has both modelling and assimilation implications. High-resolution land use (e.g. MODIS/IGBP, GLOBCOVER) and soil texture datasets (e.g. FAO HWSD) are identified as base for the entire land surface scheme and it should be ensured that these ancillary fields are state-of-the-art.
- (*SEASONALITY*) In order to represent the seasonal variability in evapotranspiration an annual vegetation phenological cycle (e.g. a seasonally variable Leaf Area Index or Green Vegetation

Fraction) is recommended, at least with a prescribed monthly climatology. LAI (GVF) and ALBEDO climatology, produced with satellite data (e.g. MODIS) should allow us to pursue studies on the impact of vegetation anomalies (e.g. European summer 2003). Main issues to address are: What does the satellite actually 'see' (i.e. Is it what the model uses?) Are there enough independent data?

- (*EVAPOTRANSPIRATION*) Due to scarcity of systematic validation studies inter-comparing Jarvis and Jacobs approaches for gs and hence ET (and) prediction it is recommended that more research should be done in this area (e.g. in the context of FLUXNET/CEOP) to extend a study to several sites (biome representative if possible) and establishing which approach (minimum stomatal resistance versus physiological conductance) is most adapted for NWP.
- (*SOIL PROCESSES*) It is recommended to re-consider soil vertical discretization in HTESSEL particularly in top layers (splitting the 7cm in 2cm and 5cm). This is beneficial for microwave forward operators (SMOS and AMSR-E sensors 'see' superficial soil moisture), as it will improve the course of the diurnal dry-down cycle of near surface soil moisture (requiring a thinner layer). For the same scope bare ground evaporation should be revisited (to avoid limitation to permanent wilting point) and the total depth of soil could be generally increased.
- (*ATMOSPHERIC COUPLING*) It is recommended to look at atmospheric-coupled versus offline-driven land surface experiments in order to check feedbacks (offline simulation may alter feedbacks due to fixed low-level atmospheric forcing) and blending height hypothesis. More research using coupled land-atmosphere modelling systems are needed and Single-Column-Models might be a valuable option to set intercomparison studies at well observed site locations (e.g. Cabauw, Netherlands or Lindenberg, Germany). Those experiments are now made accessible to a large science community thanks to generalized atmospheric couplers (Polcher et al. 1998; Best et al. 2004). It is recommended to both ECMWF and GLASS to provide an externalized SCM (as used in GABLS) to the land surface community in order to permit (affordable) coupled experiments.
- (*INTERCOMPARISON*) The importance of land surface intercomparison projects and a follow-on of GSWP2 is highly recommended to GLASS. Modern ERA reanalysis such as ERA-Interim could be a base for offline land surface modelling, albeit under the caveat of imperfect datasets (as was the case for GSWP2) particularly for precipitation. Higher spatial and temporal resolution forcing (more consistent with NWP) should be produced (to address in more detail issues related to the daily cycle for example). Three known areas of intercomparison in the near future are:
    - Lake model intercomparison project (contact: Viktor Stepanenko) is under construction with the probable name of LakeMIP looking at resolved Lakes.
    - Snow-MIP3 (contact: Richard Essery) is also to be considered and involves a small number of models performing several runs to verify parameters.
    - AMMA-ALMIP (contact: Aaron Boone) local studies on super-sites are planned in 2010. This will address semi-arid to tropical land surface processes. A wealth of observational data will be used at the local scale for several sites.

1.2.2. Medium Priority

- (*SNOW*) Snow has a large impact on global NWP systems and should be highlighted as top priority for climate models (within GLASS), however considering the recent snow model revision at ECMWF covering several aspects (albedo, ageing, density, water reservoir, etc.), further snow developments are here considered in medium priorities. Of particular importance is the fractional snow cover parametrization, which need work and validation. Current schemes are highly empirical and little consensus is found in the literature. A topographically-based approach should be explored; however, a recommendation is made (to the observation group) to increase observations of snow processes in mountainous areas (can FLUXNET be receptive on this and support installation of sites at high elevations?). A SNOWFLUX network would be highly recommended to increase knowledge. Eddy covariance data in stable cases have blending height issues and need dedicated sites (with a close-to-the-surface eddy covariance set-up). Elevation bands should improve snow modelling in mountainous areas (accumulation and melting processes), thereby also impacting surface temperatures, soil moisture and the corresponding fluxes. Liquid water in the snow pack was shown to be important (slowing melting) and relevant for NWP. It is recommended to compare the enthalpy (used in ISBA) and the capacity heat barrier approach (used in HTESSEL). For the snow albedo a simple ageing function is normally used, but in light of data assimilation it is suggested to explore grain-size or explicit grain-type parametrizations (grain size is a key parameter although its initialization is an issue).
- (*SOIL FREEZING*) It is advised that to model soil freezing follows the Gibbs-free energy concept (maximum liquid water content), as in JULES/ISBA-DIF. Frozen soil (snow-free and snow covered) data are needed to test. A revision of soil thermal properties according to recent literature is recommended.
- (*RUNOFF*) The current implementation of VIC implicitly incorporates sub-grid variability of soil water holding capacity, slope variations and, in essence, sub-grid precipitation. It also does not consider Hortonian runoff, which becomes increasingly important at higher spatial resolutions (and possibly for frozen soils). Some distinction between such processes should probably be developed at ECMWF (rather than lumping them all together since they have different dynamics and associated time scales)
- (*RIVER ROUTING*) Research activity on river routing should be pursued within the context of mass closure (discharge to an ocean model) in a seasonal forecast context, and also, on shorter time scales (medium range forecasts) to permit interactions between flooded zones and rivers and lakes for improved prediction of evaporative fluxes. It is recognized that river discharge is an integrated quantity affected by the entire land surface hydrology, therefore we recommended to use this variable in a land surface benchmarking exercise.

1.2.3. Low Priority

- (*VERY-HIGH RESOLUTION*) The adoption of a very-high land surface model is considered at present a low priority for operations at ECMWF and more research is recommended to have a proof-of-concept for the benefit of this approach in NWP models (in terms of meteorological and hydrological impact). This issue will become important in the longer term with horizontal grid resolutions finer than 10 km (and particularly in regions of high topographic variability/steep slopes). The NASA Land Information System (LIS) is mentioned since it could provide a valuable framework to explore high-resolution models and the infrastructure to run several schemes, including HTESSEL (up to kilometre resolution). Research on the potential of high-resolution modelling is recommended (to GLASS) for the promise it holds to establish process-oriented land surface schemes.

- (*URBAN*) For the cost-benefits, a simple urban modelling approach is recommended (modified natural surface with changed albedo, roughness etc..). Although this is listed as a low priority for global atmospheric general circulation, it is stressed that prediction of surface temperature extremes occurring during droughts and heat waves might improve. These large-scale phenomena are exacerbated in urban areas (e.g. European summer heat-wave in 2003) with higher daytime temperatures and reduced nocturnal cooling. Heat waves are recognized as 'high impact weather' for the population. A concrete buffer parametrization is also recommended (without an explicit urban canyon). This would require a single ancillary field (urban fraction, e.g. from ECOCLIMAP). The possibility of forecasting road temperatures can become relevant. More detailed urban treatment will be needed (e.g. TEB) in the long term as resolution increases.
- (*RADIATION*) Radiation separation of Visible and NIR into spectral bands could be used in land surface schemes but at present there are not enough observations to support this kind of studies. (A Recommendation is made to the Observation Working group). Also a canopy radiation model would allow producing FAPAR, which is an available EO data.

2. Working Group on Land Surface Data Assimilation

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2.1. Working Group discussion

2.1.1. Review of the existing land surface data assimilation systems

The working group discussion started with a review of existing land surface analysis systems for NWP applications.

First, soil moisture (SM) analysis systems were reviewed. ECMWF, Météo France, Environment Canada, ALADIN and HIRLAM consortia use an Optimum Interpolation (OI) data assimilation system of screen level variables (T2m and RH2m) for their operational soil moisture analysis. The UKMO uses also increments of screen-level variables but they are linked to soil moisture corrections by an analytical formulation (instead of a statistical one in the OI). The DWD uses a Simplified Extended Kalman Filter (SEKF) soil moisture analysis but, due to computing time issues, they would like to move away from this system in operations. In contrast, ECMWF recently developed an EKF to be implemented in operations in the next IFS cycle (36r3). Météo France and Environment Canada also investigate the use of EKF and EnKF (Ensemble Kalman Filter) techniques for soil moisture analysis. Concerning this analysis these two centres and ECMWF are currently performing research developments to enable the use of satellite data (soil moisture from ASCAT, brightness temperatures from SMOS at L-band or from AMSR-E at C-band). UKMO are investigating the use of ASCAT soil wetness measurements through both a nudging and direct insertion approach. Since results are promising they expect operational implementation of a nudging method to correct model soil moisture that uses screen level observations and ASCAT surface soil wetness measurements. Research developments are conducted at NASA/GSFC where an advanced LDAS has been developed based on an EnKF. This system is currently for research and will be integrated in the quasi-operational NWP and seasonal forecasting systems at NASA/GSFC. The GSFC LDAS enables the assimilation of brightness temperatures, surface soil moisture, land surface temperature, and eventually snow observations. It can also be used for the assimilation of vertically and horizontally integrated terrestrial water storage information from GRACE observations.

Snow analysis systems used for NWP and at NASA/GSFC were also reviewed. NASA/GSFC uses an EnKF to assimilate Snow Water Equivalent (SWE) in research experiments. ECMWF uses a Cressman snow depth analysis for operational NWP, based on SYNOP snow depth data and corrected by NOAA/NESDIS snow extent information. An OI system is used operationally at Environment Canada. Météo France does not perform any snow analysis in operations, but they are starting to develop an OI SWE analysis in collaboration with the HIRLAM consortium. UKMO uses a rule based method in which a depletion curve is used to convert snow cover fraction from the Interactive Multisensor Snow and Ice Mapping System (IMS) to a water equivalent. The resulting addition or removal of mass is directly inserted into the model.

Vegetation parameters analysis systems have also been reviewed. No operational NWP centre uses in real-time a vegetation parameters analysis. Also Skin Temperature and albedo are not analysed, although both have been identified as important parameters. Research at Météo France, ECMWF and at Environment Canada is performed to investigate LAI and albedo data assimilation for NWP.

2.1.2. Which parameters should be analysed and which observation are useful to assimilate ?

The working group agreed on the important parameters to analyse, by order of priority: soil moisture, soil temperature, snow depth, albedo, LAI.

There was some discussion concerning the observations and their usefulness with regard to their availability and relevance for NWP. There was a general consensus to recognise that surface soil moisture data from satellite is an extremely valuable source of information to be used for root-zone soil moisture analysis. ECMWF is recommended to use ASCAT surface soil moisture data as well as brightness temperature data from SMOS (L-band) and AMSR-E (C-band). It is recommended to use these data together with screen level variables in a multi-variate data assimilation system.

From 2015 SMAP (Soil Moisture Active and Passive) data will be available, although it is not clear whether the data latency will be short enough for NWP applications. ECMWF interests in SMAP rely on (1) the continuity of SMOS passive L-band measurements with those of the European SMOS mission (2) the new possibilities opened by SMAP to exploit the synergy between active and passive microwave L-band measurements. ECMWF is recommended to use SMAP data (when available) since current developments on SMOS will provide the suitable technical environment.

Skin temperature analysis poses some problems due to the fact that this variable has no memory. So it does not need to be analysed as a prognostic variable. However there are strong motivations to get accurate skin temperatures for multivariate data assimilation purposes. As a preliminary step, the working group recommended ECMWF to compare Meteosat surface temperature with the IFS to examine if the model has improved compared to Trigo and Viterbo 2002 (http://www.ecmwf.int/publications/library/do/references/show?id=83934).

Concerning snow data, the working group agreed that snow cover area (SCA) and albedo products are relatively robust, but the current suite of global snow water equivalent (SWE) products is unreliable. The working group recommended continued use of SYNOP snow depth data along with snow cover extent data such as the NOAA/NESDIS product until such time as a superior system is devised. Movement away from the current Cressman analysis and better use of now cover were seen as desirable for the data assimilation system. Suggestions regarding more sophisticated use of passive microwave data for snow inversions, or joint state-parameter updating for snow covered area assimilation are not yet mature; interaction with the broader community should continue on this matter. Greater potential may lie in future satellite missions such as ESA's CoReH20.

Some discussion focused on the use of land surface albedo data. Albedo is measured with a good accuracy and is available from several geostationary (MSG) and polar orbiting (MODIS) satellites. Albedo presents the advantage that no forward operator is needed and it could efficiently replace the climatology that is currently used at ECMWF. In addition, multi-spectral albedo data have a potential to be linked to future snow and vegetation analysis. Météo-France has conducted a study to combine a climatological albedo with the MSG LandSAF daily product using a KF to propagate errors (that increase with time when clouds are present). Although it was a preliminary study, positive impact of the albedo analysis on 2m temperature forecast scores were obtained. ECMWF is recommended to perform research studies on albedo analysis. MODIS product is of direct interest since it is provided globally.

The discussion revealed that different levels of products (e.g. radiances, physical products) will be used in the long term within the ECMWF data assimilation system (LAI, albedo, Tskin, ASCAT soil moisture, SMOS brightness temperatures etc...). Since this will result in a complex land data assimilation system, it is recommended to account for inconsistencies and synergies between the products through a multi-variate data assimilation approach.

2.1.3. What are the requirements for land data assimilation systems and what level of complexity is needed?

The working group discussed the choice of using an EKF compared to an EnKF and several recommendations were proposed to improve the current EKF system recently developed.

A discussion followed concerning the covariance matrix of background errors B. Currently, ECMWF and Météo France use constant background errors (both in time and space). It would be useful to account for spatial variations that could be provided by precipitation forecast fields (deterministic or ensemble). Such information could also be put in the covariance matrix of model errors Q when the B matrix is cycled in the assimilation system. ECMWF could take advantage of the EPS to address soil moisture uncertainties in the surface analysis which could in turn feedback on the EPS system initial conditions.

Quality controls have been highlighted to be of crucial importance in any data assimilation system and it is suggested to ensure a rigorous quality control in the surface analysis, possibly using dynamical quality checks. The importance of bias correction schemes was also discussed (dynamical approach and CDF matching).

ECMWF is encouraged to develop ‘a posteriori’ diagnostics on the land data assimilation system and to evaluate observation information content, i.e. the Degrees of Freedom for Signal (DFS). This last diagnostic provides the self-sensitivity of analysis to different observation types.

Screen level observations provide highly valuable information for the surface soil moisture and soil temperature analyses. ECMWF is recommended to work further on the screen level analysis (to account for surface inhomogeneities and anisotropies) and to investigate in particular the use of more ground data that are available at non-synoptic time to better constrain the diurnal cycle.

The working group discussed about the choice of using an EKF versus an EnKF. An important limitation of the EKF as developed at ECMWF is to neglect horizontal correlations on both model and observation sides. Due to computational requirements, soil columns within each grid point are assumed independent (only vertical transfers) and a nearest neighbour approach is to be used for projecting satellite data (SMOS and ASCAT) onto the model grid. However in the future, when lateral hydrology is included or when the model grid resolution is much higher than the satellite pixel size, it is recommended to use an EnKF approach.

Having the EKF inside the IFS model avoids input/output problems. However it is not flexible in order to use a different resolution for the surface data assimilation system. ECMWF is strongly recommended to develop a stand-alone EKF based surface analysis system. A stand-alone surface analysis is currently under development. It will be able to run within prepIFS without performing any upper air analysis. It will open the possibility to run the surface analysis at different resolutions and to perform surface re-analysis in an affordable computing time (useful for seasonal forecast and for re-analysis activities). In addition to the stand-alone surface analysis suite, ECMWF is also recommended to develop a fully offline surface analysis that would be portable and able to use observed forcing. This offline system would help in performing research and developments experiments at very low costs. In addition it would be suitable for intercomparison exercises as discussed later (section 1.6).

2.1.4. What are the requirements for Land surface modelling in the context of data assimilation?

The working group agreed that it is important to have a land surface modelling system as realistic as possible in order to reduce as much as possible model error compensations by the land data assimilation system. The description of ground water, as well as irrigation and flood plain parameterisations was recognised to be important for the assimilation of microwave radiances.

In particular, having a good representation of water fraction and flood plains is crucial for data assimilation activities. For the use of SMOS brightness temperature data in the surface analysis, water fractions are expected to strongly influence the first guess departures and so the efficiency of the data assimilation system. The working group recommended accounting for water fraction in SMOS data assimilation study. Water fractions (whether lakes or wet snow) can also disrupt microwave inversions of snow mass. It is agreed that from a data assimilation perspective it is important to identify wet surfaces. This can be done by model improvement or simply by using auxiliary information (e.g a satellite derived product globally estimating inundated areas already exist).

Some discussion followed concerning the interest of using a high resolution land surface model. There is a consensus that high resolution would be useful to better characterise the surface properties (e. g. orography, land use). The working group stressed that high resolution land surface modeling systems (e.g. around 1km) require a tiling system to account for non-dominant types fractions (e.g. vegetation, texture). However in contrast to tiling approaches, high resolution systems consistent with satellite observations resolution may provide explicit information on vegetation parameters. This makes them relevant for vegetation parameters data assimilation.

For data assimilation activities, it is noted that in a high resolution system the use of visible and infra-red measurements from satellite data would be interesting. In contrast, for the assimilation of microwave data, using a high resolution data assimilation system might lead to up-scaling issues with the EKF system as currently implemented at ECMWF (as pointed out in section 1.3). The group agreed that the stand-alone land data assimilation system will allow consideration of high resolutions at an affordable computing cost.

2.1.5. Use of data assimilation for parameter estimates

Use of data assimilation for parameter estimates has been addressed and it was agreed that this is a difficult issue (choices of relevant parameters, methodology and informative data sets).

Adjustment of the roughness length for infra-red skin temperature analysis could be investigated by extending the state vector.

Updating of parameters describing the relation between snow fractional cover and mass through an extended state vector has been shown to have promise in synthetic experiments.

Soil texture is also a very important parameter that is crucial for model soil moisture dynamics and range. However it is not clear whether we can retrieve soil texture from L-band. It is important to invest in research activities in these areas. Using a fully offline surface analysis system will help in these developments.

It is recommended to adjust vegetation optical depth in the assimilation of SMOS brightness temperature. Vegetation optical depth at L-band provides a direct link to vegetation water content and LAI. SMOS might be useful and complementary from other sensors to estimate LAI. Given the sensitivity of surface microwave emission models to surface roughness and the lack of objective estimation for this parameter, studies could be undertaken to adjust it in the data assimilation.

2.1.6. Intercomparison project for LDAS

Within the GLASS activity, NASA/GSFC, ECMWF and Météo-France are interested to set up an intercomparison of LDASs. Environment Canada would be interested but they would need manpower to adapt their CalDAS system which is not designed to easily perform an intercomparison experiment.

Such an intercomparison will be a good way to examine LDASs of various complexities (from direct insertion toward EnKF) using a variety of land surface models to get insight on what really matters for the final analysis (vertical discretisation, land surface model, data assimilation approach, ...). Questions on the required data assimilation system complexity (to be used at ECMWF) can be addressed in such an intercomparison exercise. ECMWF is recommended to participate once the fully offline EKF is ready.

The working group agreed to focus on a rather small area (a river basin over US), to work over a rather long period (possibly 10 years), to use synthetic observations (surface soil moisture, L-band brightness temperature), to perform their own experiments and by exchanging synthetic observations to recover root zone soil moisture.

A document describing the experiment design will be prepared by NASA/GSFC and Météo-France and will be circulated among the potential participants in 2010, for the intercomparison to start in late 2010.

2.2. Summary of recommendations for ECMWF

Before concluding, the working group recognised the pioneering research activities undertaken at ECMWF on the use of satellite soil moisture for land surface analysis in the NWP context. The Centre is encouraged to maintain such effort that is beneficial to its own numerical forecast activities and also to the scientific community. The working group focused on providing priorities in their recommendations, as summarised hereafter.

2.2.1. High priority

- A stand-alone land data assimilation system is recommended to reduce the computational cost and to perform the surface analysis at high resolution. This system (to be developed within the prepIFS environment) would take advantage of the efficient structure at ECMWF, and would benefit re-analysis and seasonal forecast activities.
- The development of a fully offline EKF system is also recommended. In contrast with the stand-alone version, it would be independent from the ECMWF prepIFS structure and portable. It would enable the use of observed forcing datasets and would be suitable for inter-comparison experiments.
- ECMWF is encouraged to ensure a rigorous quality control in the surface analysis, possibly using dynamical quality checks.
- ECMWF is also encouraged to develop 'a posteriori' diagnostics on the land data assimilation system and to evaluate observation information content, i.e. the Degrees of Freedom for Signal (DFS). This last diagnostic provides the self-sensitivity of analysis to different observation types.
- ECMWF is recommended to perform research studies on albedo analysis which has also a potential for snow and vegetation analyses.

2.2.2. Medium priority

- ECMWF is recommended to take part of the Project for Intercomparison of Land Data Assimilation System (PILDAS) within the GLASS activities.
- Assimilation of skin temperature needs to be investigated. In particular, it is suggested to compareMeteosat surface temperature with the IFS to examine if the model has improved compared to Trigo and Viterbo (2002).
- It would be useful to account for spatial variations that could be provided by precipitation forecast fields (deterministic or ensemble). Such information could also be put in the covariance matrix of model errors Q when the B matrix is cycled in the assimilation system. ECMWF could take advantage of the EPS to address soil moisture uncertainties in the surface analysis which could in turn feedback on the EPS system initial conditions.
- The working group recommended accounting for water fraction in SMOS data assimilation study. It is noted that from a data assimilation perspective it is important to identify wet surfaces. This can be done by model improvement or simply by using auxiliary information.
- ECMWF is recommended to assimilate operationally ASCAT surface soil moisture data as well as brightness temperature data from SMOS (L-band) and AMSR-E (C-band). It is noted that these data should be used together with the screen level variables in a multi-variate data assimilation system. ECMWF is also recommended to use SMAP data (when available).

- Parameter estimation is a difficult issue. It is recommended to adjust vegetation optical depth (and possibly surface roughness) in the assimilation of SMOS brightness temperature and heat roughness length for infra-red skin temperature.

2.2.3. Low priority

- ECMWF is recommended to work further on the screen level analysis and to investigate in particular the use of more ground data that are available at non-synoptic time to better constraint the diurnal cycle.
- For microwave measurements assimilation using a high resolution data assimilation system might lead to up-scaling issues with the EKF system as currently implemented at ECMWF. An EnKF would be necessary to address this issue, and also when lateral hydrology is considered. The group agreed that the stand-alone land data assimilation system will open the possibility of using high resolution at an affordable computing cost.
- The working group recommended continued use of SYNOP snow depth data along with snow cover extent data such as the NOAA/NESDIS product until such time as a superior system is devised. Movement away from the current Cressman analysis and better use of snow cover were seen as desirable for the data assimilation system. Suggestions regarding more sophisticated use of passive microwave data for snow inversions, or joint state-parameter updating for snow covered area assimilation are not yet mature; interaction with the broader community should continue on this matter.

3. Working Group on Observations Verification and Benchmarking

Participants: ***Pedro Viterbo*** *(Chair),* ***Souhail Boussetta*** *(rapporteur),*
Yann Kerr, Martin Best, Jean-Christophe Calvet, Matthias Drusch, Debbie Clifford, Nuno Carvalhais, Carlos Jimenez, Tomas Kral, Catherine Prigent, Anton Beljaars

Recommendations are labelled TIER 1 or TIER 2, where the former are deemed more urgent.

3.1. Forcing and point observations for validation, benchmark and verification

3.1.1. Forcing dataset

Precipitation data is of primary importance for LS research and its assimilation was considered to be beneficial for all LS applications. Despite previous workshops recommendations for getting, archiving and maintaining RT or NRT (i.e., a few days latency) continental wide precipitation data from a dense network of gauges and radar at major NWP centres, no major advances materialized. Transboundary timely sharing of surface based precipitation data remains the exception rather than the rule, with adverse consequences to the characterization of the surface water cycle. The group agreed this was one of the major, if not the major, gap in observations.

Land surface modelling is a key element to understand climate and weather. As demonstrated in some of the presentations to this workshop, good knowledge of the soil-vegetation-atmosphere interface and its interaction with the water in the root zone and recharge layer can improve the atmospheric predictability at different time scales (short to long range). Uncoupled land surface schemes (LSS) integrations forced by near-surface meteorology and radiation and precipitation fluxes are an efficient way to estimate the surface state needed for model initialization as well as contributing to better process understanding, a key step for model improvement. In this context, the GSWP project was established, with the release of global atmospheric forcing. However, the latest version of the GSWP is becoming outdated and the period spanned by the data does not extend beyond 1996. The GSWP3 initiative as well as the WATCH EU FP project are undergoing efforts to update global forcing datasets for land surface models. An effort to produce a long, continuous and consistent dataset, to be made available to the land surface research community, would be extremely useful. The ECMWF reanalysis product ERA-Interim does have appropriate accuracy for such uncoupled LSS applications, provided some known systematic biases can be corrected.

Recommendation 1: Forcing dataset for land surface applications **TIER 1**

ECMWF should create and maintain 2D forcing data for land surface applications, based on continuous and timely re-analyses, e.g. ERA-interim, with appropriate bias corrections, e.g., for precipitation. The dataset should be made available to the research community in lat-lon representation equivalent to the T255 ERA-interim resolution and at 3-hourly time intervals, spanning the whole ERA-I period.

3.1.2. Point Data

LS model development or validation in the last two decades depended crucially on the existence of high quality observations, associated to dedicated field campaigns. In-situ measurements are of crucial importance for process understanding. Surface data assimilation is another application of point measurements where representativeness of these data is resolved by blending them into the model to have a higher value product.

In the framework of the LS modelling, many local and regional in-situ experiments were performed, but only few programs attempted to assemble data covering most continents. Recently, the CEOP project attempted to gather data from different locations in the world and collocate them with global model outputs and satellite products in order to resolve the global water cycle. One additional useful aspect of this project is the structure of its database which is now becoming a prototype for the GEO community.

FLUXNET, another relevant project in this context, is a substantial effort to collect data on surface state and fluxes from different regions on the globe with different characteristics (climate, soil, vegetation..), and a clear focus on the surface carbon budget. Several issues, including but not limited to data policy, limited the use of FLUXNET data to the meteorological and NWP community.

Within the framework of ESA's Soil Moisture Network Study, soil moisture data from the SMOS cal/val stations and selected operational networks will be collected, quality controlled and made available to the community via a dedicated web portal (hosted by University of Vienna). A particular focus lies on data assimilation development, model development and verification.

Snow gauge observations are still essential for the few global data assimilation systems; such observations are used in conjunction with remote sensing snow cover products derived from IR and VIS reflectances. SNOTEL data on the presence of snow and snow mass was used by ECMWF during the development of its snow assimilation, but have not been used since then.

Recommendation 2: Point data

1. ECMWF should enrol on a dialogue with FLUXNET data managers in order to collect a significant number of site-year data. Significant work on closure of water and energy budgets and general quality control and gap filling procedures is needed before it can be used by the land surface community on validation and benchmark. The dataset to be created should be available to the entire LS research community. ***TIER 1***
2. ECMWF is encouraged to use SMOS cal/val data and other operational in-situ measurements for model verification, forecast evaluation and long term monitoring for the planning and development of future missions. In addition, L-band and C-band information fit to the background should be compared. Ideally, this activity would be carried out in close collaboration with ESA within the framework of the data assimilation study. ***TIER 1***
3. ECMWF is encouraged to acquire SNOTEL data in a systematic way, and to compare with collocated model and data assimilation results as well as remote sensing data. ***TIER 2***
4. Given the importance of the work on the 3 aspects above, ECMWF is encouraged to create a structured set of point data to verify land surface processes that can also be used by the LS research community. ***TIER 2***

The group discussed the usefulness of discharge data to validate land surface model results but recognized that proper attention needs to be devoted to: (i) the use of a routeing model appropriate to the spatial scales and hydrological characteristics and timescales of the basins; (ii) managed basins. Particularly difficult are boreal basins (e.g., the large Siberian basins), frozen for a substantial part of the year

The group noted that GRACE remains the only data source available on sub-seasonal variations of total water storage and encouraged the continued use of such data for model development and validation of reanalysis data.

3.2. Remote sensing products for validation, benchmark and verification

3.2.1. LSA SAF products

Many innovative land surface remote sensing products have emerged in the last 10 years and the current generation of some products is timely produced with very high time frequency (15-30 minutes) and good match to in-situ observations.

Recommendation 3: LSA SAF remote sensing products ***TIER 1***

Given their current level of accuracy, as demonstrated during the presentations, ECMWF is encouraged to acquire LSA SAF data on surface radiation fluxes and land surface temperature and compare those with their model equivalents as a routine verification effort. Issues on spatial up-scaling of the remotely sensed data to ECMWF resolution should be addressed beforehand.

3.2.2. Combining point data with remote sensing estimates

LandFLUX is an initiative of the GEWEX radiation panel to develop capabilities to produce a global, multi-decadal surface turbulent heat flux product. Two workshops, held in 2007 and 2009, collected requirements from the community and reviewed the methods currently in use. An inter-comparison of land surface heat fluxes is ongoing within the framework of LandFLUX. A comparison of monthly heat fluxes in 1993-95 was conducted with the aim of assessing the spread in the estimated fluxes; data collected includes reanalysis results and remote sensing products. Such inter-comparison exercises is evolving into a focused activity (LandFlux-EVAL), that will include multi-scale (spatial and temporal) data sets, assessment over longer time-periods, and identification of specific regions for focused analysis, with ETH Zurich and the Observatoire de Paris the contact institutions. It is recognized that reanalysis data or offline land surface model estimates suffer from deficiencies in the forcing while remote sensing data may be affected by calibration problems.

The group recognized that, in general, an optimal use of information comes from a combination of point data and remote sensing observations. For some variables (e.g. snow) this is best achieved via data assimilation, while for others (e.g. fluxes) it must be done using more ad-hoc merging.

Recommendation 4: Combining point data with remote sensing estimates ***TIER 2***

1. LANDFLUX intercomparison of ET products provides to the LS community a new opportunity to identify the large spread in the data. The usage of remotely sensed based estimations of ET for validation and verification should start once maturity of such products is proven.

2. In general, ECMWF should engage with the research community in the definition of suitable methods for merging remote sensing estimates and point data, in order to preserve the spatial distribution of the former and the accuracy of the latter.

3.2.3. Snow data

The group was of the opinion that the accuracy of current snow mass products derived from MW satellite instruments is still relatively poor. In the longer term, direct use of radiances to derive snow mass in a data assimilation context might improve on the current generation of products. MODIS snow cover product, based on VIS and IR reflectances, has been used in the past for model and data assimilation development, but not systematically for validation and verification.

Recommendation 5: MODIS snow cover data ***TIER 2***

ECMWF is encouraged to acquire MODIS data on a systematic basis, to compare with model and data assimilation results.

3.3. Observations for data assimilation

3.3.1. Asymptotic use of satellite radiances

Land surface data assimilation of satellite products has shown reasonable skills in improving land surface and atmospheric predictability. This is currently achieved in 2 ways: (1) inverse modelling of the satellite observations (e.g. ASCAT backscatter, AMSR-E brightness temperatures) to obtain model variables parameters (surface soil moisture), with errors arising arise from the empirical formulation of the inverse models and (2) forward modelling, where the observed brightness temperature(e.g. SMOS, AMSR-E, TMI..) is directly compared with its model counterpart, with errors arising from the radiative transfer model that transforms model state variable into brightness temperatures. Following what occurred to the atmospheric assimilation, the expected evolution of land surface assimilation will gradually lead to an increased direct usage of satellite radiances in detriment of satellite products.

3.3.2. Multi-variate land data assimilation

ECMWF new DA scheme for soil moisture, using the Extended KF, is able to combine MW and surface air temperature and humidity in a consistent way. Future testing of the method will reveal if it is possible to control forecast drift and, at the same time, reduce the role of land surface increments in the soil water seasonal evolution. In the future, the information contents linked to the LST rapid changes before noon should be explored in the same framework.

Recommendation 6: SMOS data reduction for data assimilation ***TIER 1***

ECMWF is encouraged to continue and reinforce the actual collaboration with ESA in order to come up with a rationale for SMOS data volume optimization by reducing non necessary data for the assimilation (e.g. averaging of similar viewing angles), without affecting the archiving of all the incoming data.

The group recognizes that accurate top soil temperature is crucial for assimilation of L-band radiances for soil moisture. Accurate skin temperature is also a pre-requisite to the continental usage of MW sounding data of channels that peak close to the surface; In order to exploit its full usage as a means of deriving atmospheric profiles of temperature and humidity an accurate estimate of surface emissivity.

Recommendation 7: Use of LST from LSA-SAF and GOES in the EKF for SM ***TIER 2***

ECMWF is encouraged to assess the information contents of morning evolution of LST in the MSG and GOES disks in the context of soil moisture assimilation and as a boundary condition to atmospheric assimilation of microwave sounder data.

3.3.3. Use of remote sensing vegetation data

In the longer term it is expected that TOA reflectances will be used more directly in data assimilation rather than using elaborated vegetation products. This would be done through a model operator that includes atmospheric effects and considers aerosol optical thickness derived from the observed signal (LSA-SAF is showing that aerosols can be a sub-product of the albedo chain). The group acknowledged that this will represent a change of paradigm, and will have consequences relevant for the long term planning and modus operandi of the space agencies. Nevertheless, vegetation products (e.g. LAI) will still be needed in the short term.

The seasonal evolution of vegetation is an important issue not only for carbon flux estimation but also for the surface water and energy flux estimation. It is therefore necessary to constrain LS models with the appropriate vegetation information on seasonal time scales. In this context, satellite derived LAI and/or FAPAR was proven to be a good proxy (e.g. from MODIS, AVHRR, VEGETATION…). In addition, and in order to be used in future reanalysis exercises, a long time series of observations is needed. This would require the use of a diversity of sensors over time (AVHRR from 1982 to present) with a proper a-priori inter-calibration.

Recommendation 8: Use of remote sensing vegetation data ***TIER 1***

Given the demise of several of the relevant missions in the near future it is important for ECMWF to establish a consistent path for using and eventually monitoring remote sensing of vegetation. The use of MODIS and VEGETATION data is encouraged now, in a broader perspective of a follow-on VEGETATION mission that will bridge the gap to SENTINEL-3 and VIIRS.

3.3.4. SYNOP snow depth

It is unlikely that the range of conventional observations used for surface data assimilation will be extended. Nevertheless, it would be highly desirable to alter coding practices for SYNOP snow depth, in order to resolve the current ambiguity of no snow and missing data information

4. Working Group on Contribution of the Land Surface to Predictability

Participants: ***Randy Koster*** *(co-chair),* ***Bart van den Hurk*** *(co-chair)****, Tim Stockdale*** *(rapporteur), Antje Weisheimer (rapporteur), Eric Jager, Yvan Orsolini, Ryan Teuling, Thomas Jung, Martin Leutbecher, Frederic Vitart*

The working group focused on drafting recommendations associated with three land-based sources of predictability: soil moisture, snow, and vegetation. Herein we present, for each recommendation, a summary of our discussions along with a rough priority rating.

4.1. Soil moisture

Recommendation: *Quantify the strength of land-atmosphere coupling and land-related potential predictability in the ECMWF model*. This was seen to be a straightforward exercise, given the experimental protocols already established for the GLACE experiments. The GLACE-1 experiment could be repeated several times, using different baseline years to ensure robust (and not year-specific) statistics. The GLACE-2 experiment, already performed, is already providing further information on land-related potential predictability for the ECMWF model. (GLACE-1 and GLACE-2 both focus on subsurface soil moisture.)

Priority: High. A basic understanding of land-atmosphere coupling strength in a given model is necessary for the proper interpretation of soil moisture impacts on forecast skill – where to look for impacts, where to focus initialization efforts, etc.

Recommendation: *Perform a surface reanalysis in which the stand-alone HTESSEL land model is driven with global precipitation-corrected (and possibly radiation-corrected) ECMWF reanalysis forcing*. The precipitation corrections would come from station data or merged station / remote sensing products; in data-rich areas, these corrections should improve the hydrological simulations significantly over those obtained through the use of reanalysis precipitation alone. (However, in data-poor data areas such as the Amazon or Central Africa, ECMWF expert analysis should determine whether to 'correct' the reanalysis precipitation prior to the surface reanalysis – in some regions, the reanalysis precipitation may be as good as the independent observational estimates.) The surface reanalysis would provide optimal land initial conditions for suites of hindcasts, and if the reanalysis is maintained in real time (e.g., using CMAP near-real-time precipitation observations), it could provide the initial conditions for operational forecasts.

Priority: High. This is a straightforward exercise that would optimize land initialization for forecasts.

Comment

Multiple working groups referred to this desirable land surface reanalysis, yet the exact purpose and outline seemed to vary among groups. A clear description of the current ECMWF plans should become part of the workshop recommendations.

Recommendation: *Perform this surface reanalysis at the resolution used in the forecast system*. If different forecasts are made using different resolutions, don't rely on interpolating a single surface reanalysis to the chosen grid; instead, perform the surface reanalysis at each grid resolution used. This will involve regridding the ECMWF reanalysis forcing data and making resolution-dependent lapse rate corrections to some of the forcings, but it will considerably simplify – and make more reliable – the use of the resulting land initial conditions.

Priority: High. This is a straightforward exercise that will improve the effectiveness of the initialization procedure.

Recommendation: *Assess the contribution of land surface model and forcing data uncertainty to predictive skill*. This can be achieved by performing forecast experiments in which the values of soil moisture content, land model parameters, and/or (precipitation, radiation) forcings are perturbed. The idea is to allow uncertainty in land model behavior to be reflected appropriately in the forecast ensemble spread.

Priority: High. It is important to ensure, for example, that the model is not too overconfident in its predictions given uncertainty at the land surface.

Recommendation: *Assess the effective soil moisture – evaporation relationship in the model*. One way to achieve this is to examine modeled relationships between seasonal precipitation (a surrogate for seasonal soil moisture) and seasonal air temperature (a surrogate for seasonal evaporation) against those quantified from observations, using techniques documented in the literature. Several U.S. models are poised to do such a study.

Priority: Medium. While understanding the behavior of a model is important for interpreting its successes and failures, the exercise is not as critical for ECMWF operations as those rated 'high priority' above.

Recommendation: *Interact with the community that assesses land-atmosphere coupling strength from observations*. Some in the community argue that such coupling strength can be quantified by examining, for example, lagged correlations between soil moisture and precipitation, with or without spatial filtering. If ECMWF keeps abreast of this work, they can better evaluate the coupling strength produced in their own model.

Priority: Medium. This activity does not constitute a new effort on the part of ECMWF; it requires mostly a familiarity with ongoing work.

Recommendation: *Explore the use of CDF (cumulative distribution function) scaling to transfer medium-range forecast HTESSEL data into seasonal forecast TESSEL data*. Such CDF scaling would be performed in lieu of running a special TESSEL analysis.

Priority: Low

Recommendtion: **Investigate alternatives to soil moisture 'nudging'**. This recommendation is geared in particular toward the seasonal forecast effort. Nudging in effect adjusts soil moisture so that simulated screen height variables agree better with observed values, and while this may be fine for shorter term forecasts, it may be detrimental to seasonal forecasts, which can particularly benefit from accurate soil moisture initialization. (The nudging may be adjusting soil moisture inappropriately given that a host of model variables and parameters, beyond just soil moisture, work together to affect the simulated screen height variables.) Potential alternatives to nudging include updating/calibrating parameters (e.g., stomatal conductance and hydraulic conductivity) and adjusting background error covariances to avoid strong increments.

Priority: Low. This may be important, but developing an alternative to nudging would require significant analysis, and available personnel-hours are limited.

4.2. 2 Snow

Recommendation: *Assess snowcover-atmosphere connections by analyzing existing archives of ECMWF model runs*. If a mechanism does exist for translating snow cover into forecast skill (e.g., through the 'stratospheric bridge' or through an impact on the monsoon), and if that mechanism is indeed captured by the ECMWF modeling system, then evidence for this mechanism should lie within archived model runs (e.g., 13-month reforecasts, ENSEMBLES and operational seasonal forecasts). Such a search should take place prior to the formulation of a GLACE-2 type snow initialization experiment.

Priority: High. A search for snow-atmosphere teleconnections within archived runs is straightforward and is a sensible first step in addressing the impact of snow initialization on forecast skill.

Recommendation: *Explore the mechanisms underlying any snow-atmosphere teleconnections found*. To explore the mechanisms, ECMWF personnel could perform transient response experiments. They might also consider a GLACE-1 analogue, paying attention to a more comprehensive set of variables (i.e., rather than just precipitation and air temperature, they might examine Z500 or snowmelt-season runoff).

Priority: Medium. Such studies would entail a substantial amount of work, and personnel-hours are limited. Naturally, if the ECMWF model does not show evidence of snow-atmosphere teleconnections through the analysis of archived runs (see recommendation above), the priority of the present recommendation is **Low**.

Recommendation: *Examine spring snowmelt predictability*. This analysis would be performed offline first, using multiple decades of data for proper statistics. (Only one snowmelt season occurs per year.) Potential forcing datasets include that produced by reanalysis or provided by the Princeton group. The offline analyses would be followed by a GLACE-2-type forecast experiment.

Priority: High, if the outside community establishes the experimental infrastructure. **Low**, if ECMWF needs to take the lead. Leading the experiment would put too large a strain on ECMWF resources.

4.3. Vegetation

Recommendation: *Keep abreast of GEOLAND2 developments*. The GEOLAND2 project is addressing the effect of seasonal LAI on forecasts, the implementation of a prognostic LAI model, and the evaluation of optimal LAI data assimilation strategies.

Priority: Low. In terms of ECMWF operations, the impacts of vegetation variations on predictability are considered, for now, to be of secondary importance to those of soil moisture and snow, except perhaps during strong climatological anomalies (droughts).

Recommendation: *Evaluate the impact of interannually-varying LAI on climate variability and predictability using a 'short cut' approach*. This can be achieved by comparing simulations using climatological LAI with those using interannually-varying LAI, as derived from observations. The results might indicate whether the assimilation of vegetation phenology information into the model would lead to any increases in forecast skill (perhaps especially for extreme conditions like the 2003 European summer).

Priority: Low (for now). The priority may increase as GEOLAND2 moves forward.

Recommendation: *Evaluate the time scales of LAI variations and their responses to extreme meteorological conditions*. This should in fact be done as part of GEOLAND2.

Priority: Medium. Await GEOLAND2 developments.