Report of LANDFLUX Workshop

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Rationale: One of the major goals of the World Climate Research Program's Global Energy and Water Experiment (GEWEX) is to obtain a quantitative description of the weather-scale variations of the global energy and water cycle over a period of at least 20 years to allow for diagnostic studies of the causes of these variations and to develop predictive capability. Towards that end the GEWEX Radiation Panel (GRP) conducts several global data analysis activities to complete the description of the energy and water cycle: all components are now being worked on either by GRP or other projects (clouds, aerosols, radiative fluxes, precipitation, ocean surface turbulent fluxes, water vapor, temperature, ozone) except the determination of the turbulent sensible and latent heat fluxes over land (and snow-ice) surfaces. In addition, some of the leading sources of uncertainty in the surface radiative flux products now being produced come from uncertainties of land surface and near-surface atmospheric properties. Although there is a lot of work on remote sensing of land properties and numerous studies of land processes, there is no systematic data analysis activity underway to produce complete, physically consistent, global, multi-decadal land property and energy-water flux data products. Two recent efforts took some steps towards fulfilling this need. The International Satellite Land Surface Climatology Project (ISLSCP) produced a decade-long (1986-1995), global compilation of land-surface-process-relevant data products; however, some of the key quantities were actually model outputs. The Global Soil Wetness Project (GSWP) not only produced soil wetness distributions but also produced consistent land surface temperature and turbulent fluxes using land surface process models forced by surface radiation, precipitation and other meteorological data, much of which came from the ISLSCP collection.

An additional motivation for systematic analyses of newer satellite observations with a land focus is that one of the major consequences of climate change is likely to be a chance in the water availability. Newer satellite measurements, when analyzed in combination, may begin to provide enough information for monitoring budgets of ground hydrology in the more traditional sense (the discussion above refers to an atmospheric energy and water cycle with the land and ocean providing boundary fluxes). Hence, obtaining a systematic and quantitative description of the land surface turbulent fluxes sets the stage for a more complete hydrological analysis.

Objectives: The GEWEX Radiation Panel (GRP), in collaboration with the GEWEX Land Surface Study (GLASS), is launching an activity, called LandFlux, to develop the needed capabilities and to produce a global, multi-decadal surface turbulent flux data product. There are (at least) three pathways to determining these fluxes: (1) using satellite and other measurements to infer the physical properties of the atmosphere and surface needed to calculate turbulent fluxes using a "bulk formula" approach, (2) forcing/constraining a land surface model using observations as was done for GSWP, or (3) employing a full assimilation approach with a land process model or even a coupled land-atmosphere model and observations. This workshop reviewed the status of current land surface property data products, discussed possible methodologies for determining the turbulent fluxes **and** for verifying their accuracy, and considered how the combination of surface energy and water fluxes with newer satellite measurements of water could be used to obtain detailed land-water budgets.

Sessions:

Session 1A: The first session introduced the topics of the meeting in the form of three overview talks. The first by W. Rossow gave the background for interest in systematic land surface turbulent (and radiative) flux data products from the perspective of GEWEX's goal to complete a quantitative description of the global energy and water cycle and its variations from weather to decadal time scales. Within the next couple of years, global, long-term data products for all the components of the energy and water cycle will be available except for the land (and ice) surface turbulent fluxes. J. Roads reviewed the current status of the land surface fluxes and continental energy and water budgets reported from the main global reanalysis products, emphasizing the lack of verification data for land surface turbulent fluxes. Y. Kerr provided an overview of the forthcoming SMOS mission that will add a more direct soil moisture mapping capability to the existing satellite observation suite.

Session 1B: The second session reviewed progress on understanding the land surface processes made by past programs and planned work for future programs. F. Hall reviewed the goals and accomplishments of the International Satellite Land Surface Climatology Project (ISLSCP), which included both field campaigns (the precursors to the GEWEX Continental Scale Experiments) and a major compilation of data products relevant to the study of land surface processes. The emphasis of the previous studies was on characterizing land surface vegetation properties (based on NDVI) and their controls of the surface fluxes (driven by FaPar). The data product compilations supported extensive land surface process model studies, including the Global Soil Wetness Project (GSWP) that provides one estimate of these fluxes (and soil moisture) by applying observation-based atmospheric forcing to stand-alone land models. A. Reissell provided an overview of the Integrated Land Ecosystem-Atmosphere Process Study (ILEAPS), which plans to continue work on land-atmosphere exchange processes focusing on vegetation controls of gas exchanges, especially water vapor and carbon dioxide. These plans complement the GEWEX LandFlux plans by focusing more on the chemical processes at the land surface, whereas LandFlux is focusing on the physical processes.

Session 2A: E. Wood contrasted two ways to determine the land surface fluxes, using one of the classic (bulk) formulae with observational inputs (Penman-Montieth) and a more elaborate model solving the instantaneous surface energy balance with observational inputs (forcing). In the latter case, the model emphasizes a detailed treatment of the turbulent atmospheric boundary layer with the land surface as a boundary condition specified by the inputs. Alternate ideas were presented later where the model emphasizes more the treatment of the land surface properties and processes and specifies the atmospheric properties from observations. He raised three critical questions: what are the (spatial) scales at which the inputs and processes must be represented, what is to be the source of validation (can tower data serve) and what further algorithm developments are needed (especially assimilation approaches)? B. Lin proposed a new remote-sensing based procedure to estimate land surface evapotranspiration (ET flux) based on a microwave spectral emissivity index that represents the variations of the vegetation canopy. Early tests over a deciduous forest encouraged further testing of this idea. The following discussion expanded on the topic of different approaches to estimating the fluxes: in addition to the already-mentioned techniques (using various formulae with observational inputs and using a variety of surface process models using observations as forcing), the idea of using assimilation techniques was also outlined. Several later talks in the workshop presented additional ideas.

Session 2B: P. de Rosnay opened the discussion of possible sources of *in situ* data that could be used for verification of remote-sensing-based flux estimates by describing efforts with the African Monsoon Multidisciplinary Analysis project to collect relevant observations on the ground and from satellites. This region had been identified as one where the interaction of the atmosphere and surface seems particularly strong. Observations were collected over a three year period (2005-2007) with intense activities in 2006. Of special interest besides the meteorological and precipitation measurements is an array of 12 surface flux sites covering a strong latitudinal gradient in surface properties. There were also 24 soil moisture stations. The AMMA program also includes a large number of modeling studies, where the observations are used to force a variety of land surface process (and other types of) models (a model comparison activity involves a dozen models). Available data include all surface fluxes, meteorology and precipitation, as well as various characteristics of the vegetation and soil moisture. J. Roads (on behalf of T. Koike) described the relevant datasets being collected by the Coordinated Enhanced Observing Project (CEOP), a component of GEWEX. The main subset of data of interest for surface fluxes is the set of observations collected at 36 sites over 2003-2004 (there is also data from 2002), including site characteristics (including soil temperature and moisture profiles), surface fluxes, meteorology and flux tower measurements, as well as satellite observations covering the surrounding region out to a distance of about 125 km. In addition output from a number of global weather models for the same region are archived. The collection of sites cover a very wide range of climate and surface conditions. The following discussion raised concern about the availability of verification data, in particular whether extensive (many sites, long time periods) flux-tower data from FLUXNET could actually be obtained. This concern was considered important, even though doubts exist as to whether such “point-like” data can really provide adequate verification of broad-scale determinations of surface fluxes.

Session 3A: A. Beljaars described the land surface scheme used in the version of the ECMWF model for the ERA-40 reanalysis, as one example of the current state of the art in operational assimilation and weather forecast models. The land component of this model has explicit treatments of the transports of energy and water in multiple soil and vegetation layer (also snow), as well as hydrological processes. The data assimilated are meteorological quantities (wind, temperature, humidity profiles, surface pressure and winds, as well as satellite infrared radiances. Comparisons with an extensive number of field experiment datasets show that the analysis-model-based inferences of soil moisture and surface fluxes exhibit quite realistic features for diurnal, synoptic, seasonal and longer-term variations. A key feature of this reanalysis is the adjustment of soil moisture and temperature using boundary layer budgets. Current issues are the quantitative accuracy of the surface fluxes and needed improvements in the soil moisture, but adequate verification datasets are lacking. He also suggested one possible scheme for obtaining land surface fluxes based on a weather-reanalysis-type system, but this required independent observations of net radiation and evaporative fraction. A. Beljaars also presented diagnosis ideas on behalf of A. Betts. Based on his analyses of field experiment measurements, he finds it possible to infer the net shortwave (SW) flux from cloud data (using a "cloud albedo" concept), net longwave (LW) flux from cloud and surface relative humidity data, and a "water availability" parameter (which can be related to precipitation and/or soil moisture) to obtain evaporative fraction. This approach can be constrained by measurements of the surface skin temperature and its diurnal amplitude. These relationships and constraints need much more testing in different regimes but they provide additional insights that can help infer surface fluxes from observations. S. Seneviratne presented a number of modeling studies of land-atmosphere coupling effects on climate change. Study of the changes in the Mediterranean and southern Europe region shows that climate change can also appear as a change in the magnitude of temperature variability in addition to changes in the average value, which can also be associated with increasing extremes of precipitation. In this area, such a change occurs in the modeled climate changes because of strong land-atmosphere coupling (feedbacks). Indeed, the strength of the coupling can also change with climate. The mechanism is a shift from a regime where the seasonal variations of soil moisture remain above the plant wilting point to one where the summertime soil moisture falls below this level, prompting a shift of the partitioning of energy between latent and sensible heat fluxes. She also outlined basin energy-water budget studies using global weather reanalyses, land surface models and *in situ* measurements. These studies highlighted the importance and lack of information about the water holding capacity at each location on land.

Session 3B: P. Houser began a discussion about improving modeled land surface fluxes by increasing the number (and quality) of observational constraints employed. As part of this topic, he reviewed the Global Soil Wetness Project (GSWP), conducted under the auspices of the GEWEX Land-Atmosphere System Study (GLASS), which produced a number of results using land models "forced" by atmosphere observations. In addition to soil moisture, the models also produced estimates of the turbulent fluxes. He also reviewed the Global Land Data Assimilation System (GLDAS), which employs many of the same observations in a direct assimilation involving a land surface process model. This led to discussion of advanced assimilation concepts using coupled land-atmosphere models with the observations augmented to include more hydrological information (not just meteorological information), particularly information coming from or soon to come from newer satellite instruments. As examples, he showed the improvements obtained by assimilating soil moisture, snow water equivalent and vegetation leaf area index information in such systems. In summary, three possible model-based approaches to estimating land surface fluxes are: semi-coupled model constrained by many observations allowing temperature and water to evolve, uncoupled-coupled assimilation (constrain off-line assimilation, run then assimilate land surface states into a coupled model) and fully-coupled assimilation (still allowing temperature and water to evolve).

Session 4A: M. Rodell described the NASA Global Land Data Assimilation System, focusing on the input observations and the fluxes determined by the system. The particular approach uses satellite observations to specify the offline (atmospheric) forcing of the model processes (precipitation, radiation) and to provide information about the land surface state that is assimilated: the latter emphasized new experiments assimilating snow cover from MODIS, water storage from GRACE and soil moisture (currently from field experiments). The experiments with the GRACE data were notable for suggesting that a complete partitioning of land water might be possible by combining information about surface water (snow, flooding and lakes, river discharge), soil moisture and total water from GRACE. The output of the assimilation includes evapotranspiration (and sensible heat flux). This approach to estimating surface fluxes has advantages of “filling in” missing information in a physically consistent way but does not include the effects of land-atmosphere feedbacks. D. Entekhabi outlined a new approach to estimation of evaporation that might overcome problems with current formulations (lack of remote sensing information on near-surface humidity and turbulence as well as vegetation “resistance”). The new formulation uses evaporative fraction to separate contributing factors of the surface properties, turbulence and thermal contrast between the surface and atmosphere. The proposal is that these different factors have different characteristic time scales, so that an analysis of the remotely sensed thermal contrast and its diurnal cycle can provide an estimate of evaporative flux at high time resolution. In this approach the ground storage is also solved for explicitly with a diffusion equation. Some test cases from field experiments showed encouraging results. In the following discussion, it was proposed that some combination of the analysis by A. Betts and this one might prove useful. M. Bosilovich described a land surface data assimilation system using a coupled land-atmosphere model where the land state properties and atmospheric characteristics are assimilated together. As example of the results, he showed the improvement of the results, particularly of diurnal variations, when surface skin temperature observations are assimilated. The verification data came from several GEWEX Continental Scale Experiments and CEOP. Not only the temperature results but also the evaporation variations are improved. Also illustrated were experiments assimilating higher space-time resolution precipitation data. He also presented a summary of the current state-of-art of global analyses from seven models based on CEOP inputs, showing the large (of order 50%) range of precipitation, evaporation and sensible heat flux produced by these analyses. A. Boone described a model intercomparison project based on AMMA datasets, involving a dozen off-line land surface models covering different-sized domains from local to regional scale. The forcing included atmospheric parameters from an operational meteorological analysis and surface radiation and precipitation from satellite observations. These models showed a range of land surface evaporation of more than 50% of the model-average value. Large differences in other hydrological parameters were also exhibited. The combination of model, satellite and *in situ* information is being used to construct a land-surface climatology for the west African monsoon regime.

Session 4B: F. Papa presented several studies exploiting new satellite (mostly) microwave measurements to estimate land surface flooding and river discharge. The global multi-instrument analysis obtains monthly estimates of flooding extent (including permanent lakes and rivers, wetlands and episodic floods). The relationship of annual cycles of flooding with variations of precipitation in the tropics and snowmelt at high latitudes demonstrated an excellent correspondence. Combining flood extent with water level determined from satellite altimeters provides estimates of total water volume; the first study of the Rio Negro system shows qualitative agreement of the annual variations of water volume when compared with GRACE total water estimates, total precipitation and *in situ* river discharge measurements. These results suggested the possibility that the total water variation from GRACE could be separated into a flooding component using this method and a total ground water, where the latter could be further separated employing results from a soil moisture measurement. Encouraged by these early results, future work will focus on decreasing the time scale of the determinations of flooding and water volume. Y. Zhang illustrated the large sensitivity of the net surface longwave radiative fluxes and their diurnal variations to small and subtle changes of surface skin and air temperatures. Comparison of many of the global data products for air temperature show rms differences of 2-3 K, but this is equivalent to longwave flux differences of 15-20 Wm^{-2}, a significant error. In particular, none of the available atmospheric temperature products exhibits an accurate diurnal amplitude of near-surface air temperature. Satellite-based land surface skin temperature products are limited by cloud cover to a biased subset and many newer products lack sufficient time resolution. Hence, current reconstructions of the longwave radiative fluxes over the land surface remain uncertain by significant amounts.

Session 5A: C. Prigent presented a new analysis approach that combines satellite measurements from infrared and microwave instruments to overcome the limitations of infrared-only products. Although infrared-based land surface skin temperatures that resolve the diurnal cycle can be obtained by combining polar orbiting and geostationary measurements, these measurements are not available under cloudy conditions. A combined analysis method can obtain “cloudy-sky” surface skin temperatures, but the passive microwave measurements are only available at two times per day in previous the previous decade (more recently, more frequent measurements are available). A method for completing the diurnal cycle from sparse measurements is proposed. However, since there is no systematic *in situ* verification data for skin temperature, the large differences among satellite products has not been resolved as yet. X. Zeng examined the consistency of surface skin temperature, soil moisture and turbulent fluxes in land surface models. He emphasized the difference between the equilibrium and transient values of these quantities and that accounting for this difference improved model representations of them, even over much longer seasonal time scales. He also illustrated the sensitivity of these quantities to assumed properties of vegetation and examined the effects on the skin – air temperature difference in the models. Additional experiments showed the effects of differences in snow albedo on model air temperature determinations. S. Gupta described the treatment of skin and air temperatures in the GEWEX Surface Radiation Budget (SRB) surface radiative flux product. Comparisons with the Baseling Surface Radiation Network (BSRN) dataset showed an systematic overestimate of the downwelling longwave fluxes at the high end of the range. The cause is that the calculations assume a specific relationship between skin and air temperatures in the lower atmosphere that is not correct over arid locations where the skin temperature during the day can be much larger than the air temperature.

Session 5B: E. Njoku reviewed the situation regarding global, long-term observations of soil moisture using satellite passive microwave measurements. Although there have been space-borne measurements made as far back as 1972, none of the instruments was specifically designed for remote sensing of soil moisture (very few had low enough frequency measurements): the forthcoming SMOS and HYDROS missions will be the first. At frequencies greater than 5-10 GHz, the scattering by vegetation dominates the signal from soil moisture. The most recent instrument available is AMSR-E, which has a 6.7 GHz channel that can be useful despite interference from cell phones and other communication devices. Multi-frequency analyses attempt to remove the scattering signature of the vegetation to isolate the emission signature of soil moisture variations. A key task required to allow construction of a long-term soil moisture data record (from the late 1970's onward) is to cross-calibrate the various microwave sensors that have been used. Y. Kerr reviewed various definitions of soil moisture as well as different methods for measuring it, including remote sensing approaches. Field studies have long illustrated the complexity of soil moisture behavior both spatially and temporally; these studies are key to understanding the radiation physics (both active and passive microwave) necessary to interpret satellite measurements. At frequencies above about 20 GHz, the atmosphere and surface roughness dominate the signal; between about 7 and 20 GHz, vegetation dominates; and below 7 GHz, soil moisture dominates. Some other issues with these measurements, which are often not considered, are the effects of topography (both large-scale changes of angle of incidence and small-scale roughness), saturation effects (surface flooding) and freeze/thaw effects. He also mentioned other new satellite measurements relevant to land-water studies: scatterometer, altimetry, gravity measurements and active SAR. C. Prigent outlined multi-sensor approaches to determining the properties of the land surface using soil moisture as an example. The problem is that, although the land surface is complex (topography, varying vegetation, variable amounts of liquid and frozen water, varying soil) and spatially heterogeneous, there are no satellite missions truly dedicated to unraveling these complexities and elucidating the processes. Hence the retrieval problem is ill-posed so measurements from many instruments have to be combined to try to limit the uncertainties. More advanced and detailed radiative transfer models of the land surface covering a much larger portion of the electromagnetic spectrum are needed. As an illustration, the relationships among satellite-measured microwave emissivities (four wavelengths, two polarizations), radar backscatter, thermal infrared surface temperature diurnal amplitude and vegetation color indices and soil moisture are analyzed together, showing that none of these pieces of information, alone, is well-related to soil moisture. Advanced mathematical methods for such multi-variate analyses can also be used to check the statistical consistency of current global models.

Session 6A: G. Schaepman opened the session on land surface albedo by reviewing the different terminology and usages in the literature. Because the land surface reflectivity is a function of wavelength and illumination geometry, the total amount of incident solar radiation that is not absorbed by the surface, even if the properties of the surface are constant, depends on the condition of the atmosphere (composition and cloudiness, which control the spectral and angular distribution of the illumination), time of day, latitude and season. Previous estimates of land surface albedos have generally lacked comprehensive information about these aspects and have, consequently, treated them with a range of simple approximations. Currently, we have a combination of instruments that provide more coverage of angle dependence (MISR, POLDER), but without complete spectral coverage, and that provide nearly complete spectral coverage (MODIS, MERIS, SEVERI), but without much angle coverage. Analysis of this combination of measurements should provide the best determination of land surface albedoes. Illustration of many of these issues was provided by a case study of changes in tundra albedo with changing vegetation and snow cover and characteristics. J-L. Roujean described a number of separate and combined analyses of the different satellite measurements available today based on advanced radiative models of the surface interaction with solar irradiance. In addition to illustrating the different information obtained from different instruments and comparing the various products, he showed the variety of detail included in some current GCMs. The activities of the EUMETSAT Land Satellite Application Facility (SAF) were also described: key products being produced of concern to the workshop participants are albedo and surface temperature. Y. Zhang illustrated the sensitivity of surface and top-of-atmosphere shortwave flux calculations to various aspects of the land surface albedo by comparing different available products. The effects of the atmosphere on total clear sky albedo are illustrated by differencing surface and top-of-atmosphere values; the overall global mean difference is a little more than 4% but differences reach more than 20% at high latitudes. By way of illustration, the visible and near-infrared albedoes used in the ISCCP-FD radiative flux product are compared with the surface albedo product from MODIS and the top-of-atmosphere (clear sky) albedo from CERES. The primary result is that the visible surface albedos agree quite well (in part because the ISCCP-FD values are based on visible reflectances) but the near-infrared albedos from ISCCP-FD are about 10-20% smaller than those from MODIS. However, comparison of the top-of-atmosphere clear sky albedos from CERES with those obtained using both the ISCCP-FD and MODIS surface albedos shows, as expected, that these large differences in near-infrared albedos are not quantitatively very important because the atmospheric water vapor absorbs most of the solar radiation in this wavelength range. This is not true, however, at high latitudes where water vapor abundances are very low. In general, comparison of the radiative flux products shows that there are still significant disagreements over snow/ice-covered locations and over un-vegetation land areas.

Session 6B: C. Schaaf summarized the analysis methodology and properties of the MODIS land albedo product. The MODIS product is based on measurements at six wavelengths covering the range from about 650 nm to 2150 nm; angle dependence is accounted for using an advanced model together with measurements over a 16-day period during which a range of viewing-illumination geometries are obtained. The wide range of uses for the MODIS albedo products were then described and illustrated. Validation efforts have been extensive, including an international study coordinated by CEOS. C. Schaaf, on behalf of E. Vermote, presented an summary of efforts to connect the longer AVHRR-based record of land albedo to the new MODIS-based record. This description included the method used for correcting for atmospheric absorption and scattering effects; the variation of polarization of the signal is also accounted for. The new analysis uses the MODIS-based aerosol product to correct for aerosol effects. Activities are now underway to merge the MODIS albedo products with AVHRR-based products by making the retrieval procedures as similar as possible (given the differences in spectral information available). B. Pinty reported on a number of studies to improve model treatments of surface albedo in complex situations. The first case described is snow on vegetation, especially forests: current-day weather forecast models generally under-predict near-surface air temperatures by more than 10°C because their snow-related albedos are too high in boreal regions. Although MISR and MODIS albedo products generally agree, there are some notable types of surfaces where the MODIS values seem to exhibit too little variability. He also considered in more detail the partitioning of sunlight absorbed at the ground between the vegetation layer and the ground. The 3-D structure and heterogeneity of the vegetation canopy significantly increases the effective transmission of sunlight; this can be accounted for by an "structure factor" that modifies the true leaf area index (optical depth) to an effective value (similar to what is done for clouds). In the case of snow on the ground under a forest canopy, these issues become very important to obtaining the correct albedo. Finally, he considered the consistency requirements for assimilating remotely sensed land surface properties into surface models: the same radiative transfer assumptions have to be used for retrieval and assimilation so that the "effective" values retrieved have the same meaning in the land surface model.

Session 7A: The current status of global, long-term data products that are relevant to studies of land-atmosphere exchanges (fluxes) and are systematically produced is as follows. Land surface albedo, especially recent products based on combined analyses of MODIS/MERIS and MISR/POLDER, appear to be in good shape, but the length of record is limited to less than 10 years. However, work is underway to connect this record to the longer AVHRR-based record by using modern angle and spectral models. Although several land surface temperature datasets exist, they are all incomplete in one way or another: most of the products are limited to clear-sky conditions, none covers the complete diurnal cycle for both cloudy and clear conditions. These products are all “research” products not currently in routine production. Near-surface atmospheric conditions (winds, temperature, humidity) are available from the extensive network of surface weather stations with 3-hourly time sampling, but there are notable areas not covered. Operational weather analyses (and reanalyses) provide systematic and complete coverage for these quantities, but the diurnal amplitudes are known to be inaccurate and the general quality of boundary layer treatments needs improvement. Two systematic surface radiative flux products (and one FPAR product) are available with useful accuracy, at least one (the GEWEX Surface Radiation Budget product) actively being produced. General compilations of information about the properties of the land surface and its vegetation are available with a wide range of quality: topography is well-described but small-scale roughness (and canopy structures) are not, various vegetation indices (implying qualitative values) are available but those related to multi-spectral measurements (such as leaf area index) appear to useful quantitatively.

Several approaches to estimating land surface turbulent fluxes were proposed and discussed: (1) eddy correlation measurements from flux towers, (2) bulk formula approaches (different formulations were presented) where the input quantities are measured *in situ* or inferred from satellites, (3) fluxes determined from land surface process models “forced” by meteorology and downwelling radiative fluxes (these models generally calculate much more than the turbulent fluxes, including surface temperature and soil moisture), (4) fluxes from numerical weather model-based assimilations of observations and (5) fluxes determined from land surface models or coupled atmosphere land-atmosphere models that are constrained by many observations of the state of the atmosphere and land surface (land surface assimilation). The first approach is done only at a small number of sites, usually as part of field experiments; however, efforts are underway by FLUXNET/ILEAPS to organize the collection of these results that could be used to verify the other approaches. The second approach (the one proposed by the GEWEX Radiation Panel) is one practical way to produce a global product employing satellite observations to determine the needed inputs. The third approach, as done by GSWP, is another practical way to obtain global products, where the land surface process model calculates the fluxes as its response to the forcing (this is similar to the GEWEX SRB calculations of surface radiative fluxes). The fourth approach produces products available now, but these systems do not currently assimilate information about the atmospheric boundary layer and land surface as yet. The fifth approach uses a land surface model in assimilation mode like GLDAS; this approach becomes equivalent to the fourth approach, especially if using a coupled land-atmosphere model, but using many more observations about the atmospheric boundary layer and land surface states than currently done in fourth approach.

Another approach that can be used as a constraint at large scales is to determine the land surface budget of water exchanges from observations of precipitation and atmospheric moisture convergence, if river discharge information is available.

Issues Raised in Discussion:

(1) The several turbulent flux methodologies have not yet reached a state of maturity to satisfactorily address the scientific questions that are the focus of GEWEX; how are the Earth's energy and water cycle changing and why?
(2) The formulations of the flux dependence on atmosphere and land surface properties need further work to cast them in terms of measurable quantities.
(3) Global information about vegetation structures and functions is not generally available in the needed detail. One response to this situation is to employ more constraints from the carbon (and other biospheric chemical) cycle, but more work is needed to identify possible new satellite measurements that would be needed.
(4) The contents, organization and access to an extensive collection of flux tower results from a large number of sites (in different climate regimes) and covering many years is critical to verification of turbulent flux products and land surface process models. A concern is whether these data are as useful in the absence of coincident high quality radiative flux, soil moisture and other hydrological measurements.
(5) The lack of a global survey of canopy structure (radar, lidar) was noted as important to progress (some results are available from ICESAT).
(6) The issue of space-time scale mismatches between atmospheric and surface properties was raised as needing more attention.
(7) The question was raised of whether other sources of verification are available but the only alternative to augmented flux tower datasets that was discussed would be creation of a network of sites specifically designed to determine complete energy and water fluxes.
(8) More development of flux-parameter relationships is needed using *in situ* experimental data. The question was raised as to the capabilities of FLUXNET/ILEAPS and CEOP to take on this task.
(9) All of the approaches for estimating land surface turbulent fluxes are immature and need further development work.

Needed Actions:

(1) Re-calibration of two long-term satellite radiance datasets are crucial to producing long-term land flux products covering more than a decade or two: AVHRR visible (for albedo, NDVI, FPAR) and infrared (for surface skin temperature, cross-calibration of the geostationary satellite radiances is also needed to resolve diurnal variability) and SSM/I (also SMMR, for surface skin temperature, vegetation properties and soil moisture). These records also be connected to more current records from MODIS/MERIS and SSMIS/AMSR.
(2) Finish the ongoing evaluation and comparison/revision of the newer albedo products based on combined analyses of MODIS, MISR, POLDER and connect them to an AVHRR-based record (CEOS is planning a workshop next year for this purpose).
(3) Finish a prototype global surface skin temperature product that resolves diurnal variations for clear and cloudy conditions by a combined analysis of satellite infrared and microwave measurements (many different instrument combinations can be tried but the longest record would be obtained using weather satellite infrared imagery and SSM/I – AMSR).
(4) Continue development and verification of all the different approaches to estimating surface fluxes. For satellite-observation-based approaches this requires more testing of the formulae that relate measurable state parameters to fluxes and development of more comprehensive multi-instrument analysis retrieval methods. For model-based approaches this requires revision of the

models to use more observational constraints and to improve the internal physical consistency of the model parameters.
(5) To stimulate that development, plan another LANDFLUX workshop in 18 months (joint with GSWP and ILEAPS) to compare global land flux products. Before the workshop, select a common time period (probably 2003-2005) and identify common diagnostics. Also attempt to identify and acquire verification datasets. Set up a website with description of tasks, common resources and datasets.

Session 7B: Recommendations and Plans

(1) The participants recommend to (support the intention of) FLUXNET/ILEAPS that they provide an international coordination of "landflux" sites (following the BSRN model) but hope that at least some of the sites can be augmented to add BSRN-quality radiative flux measurements and hydrological (soil moisture, snow water equivalent, river discharge) measurements (in addition to meteorology). This activity would benefit from the model verification experiences from PILPS, GSWP and GLDAS. The participants further recommend that GRP/GEWEX urge CEOP to participate significantly in this effort.

(2) The participants endorse the plans for an Albedo workshop to provide a "final" evaluation of current-day products and to set the stage for connecting these to the longer AVHRR record (to be forwarded to CEOS, TOPC/GCOS).

(3) The participants supported GEWEX Radiation Panel efforts to stimulate progress on multi-satellite analyses and are willing to participate in further studies of data-model analyses of land surface fluxes and hydrology (to be forwarded to GRP/GLASS/GEWEX).

(4) The participants recommend to GLASS (supported by CEOP and GRP) to focus more attention on improving large-scale hydrological parameters used in models.

Actions:

(1) Write a meeting report, distribute for comment to participants (and invitees), revise and submit to GEWEX Radiation Panel.
(2) Write short meeting report for GEWEX NEWS.
(3) Conduct an international Albedo workshop to evaluate the current products and to set the stage for connecting them to the longer-term AVHRR record. The evaluation of current products should specifically focus on spectral and angular dependence as these play a key role, beyond determining the net solar flux at the surface, in determining the partitioning of the absorbed solar energy between the ground and vegetation.
(4) To stimulate further progress on the various flux-estimate methodologies, organize and conduct and second LANDFLUX workshop in about 18 months where a coordinated comparison of flux products will be done.

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Agenda

28 May

0930-1100	Session 1A:	Overviews of Key Land Science Issues W. Rossow: Key Land Science Issues for GEWEX J. Roads: Budget Evaluations of GLDAS and Reanalysis Fluxes Y. Kerr: Overview of SMOS Mission
1130-1300	Session 1B:	Overview of ISLSCP and ILEAPS F. Hall: ISLSCP A. Reissell: ILEAPS Discussion
1430-1600	Session 2A:	Methods for Determining Surface Turbulent Fluxes E. Wood: Comparison of ET Retrieval Algorithms over the Mississippi Basin and Implications for LANDFLUX B. Lin: ET Flux Estimates using Combined Satellite Measurements Discussion
1630-1800	Session 2B:	In Situ Measurements of Surface Turbulent Fluxes P. de Rosnay: AMMA Land Surface Flux Estimates over West Africa: From Field Measurement Networks to Integrated Land Surface Modeling Approaches J. Roads: CEOP Datasets Discussion

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29 May

0930-1100	Session 3A:	Interaction of the Land Surface and Atmosphere A. Beljaars: Surface Fluxes over Land in ERA-40 S. Seneviratne: Land-atmosphere Coupling, Climate Change and Extreme Events Discussion
1130-1300	Session 3B:	Land Hydrology, Vegetation and Latent Heat Fluxes P. Houser: Improving Modeled Land Fluxes through Observational Constraints Discussion
1430-1600	Session 4A:	Land Surface Modeling Issues M. Rodell: Land Fluxes Simulated by NASA's Global Land Data Assimilation System D. Entekhabi: Mapping of Surface Turbulent Flux, Evaporative Fraction and Flux Roughness Length Scale using Sequential Assimilation of Thermal Remote Sensing Observations M. Bosilovich: Land Surface Fluxes in Coupled Land/Atmosphere Analysis Systems
1630-1800	Session 4B:	Land Surface Modeling Issues, Hydrology and Radiation A. Boone: AMMA Land Surface Model Intercomparison Project (ALMIP): Construction of Multi-model Surface Flux Climatology F. Papa: Multi-satellite Remote Sensing of Global Inundated Surfaces over a Decade Y. Zhang: Diurnal Variations of Skin-Air Temperature Differences

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30 May

0930-1100	Session 5A:	Land Skin-Air Temperatures, LW Radiative and Sensible Heat Fluxes C. Prigent: Surface Skin Temperatures Observed from Combined IR and Microwave Satellite Measurements X. Zeng: Treatment of Land Skin Temperature, LW Radiative and Sensible Heat Fluxes in Land Models S. Gupta: Computation of Surface Longwave Fluxes – Effect of Skin-Air Temperature Differences
1130-1300	Session 5B:	Soil Moisture, Vegetation and Latent Heat Fluxes E. Njoku: Long-term Passive Microwave Observations of Soil and Vegetation Water Variability Y. Kerr: Soil Moisture Retrieval from Satellite Data C. Prigent: Toward New Satellite Methodologies to Estimate Land Surface Variables: Soil Moisture as an Example
1430-1600	Session 6A:	Land Albedo and SW Radiative Fluxes G. Schaepman: Standardizing Terminology and Description of Satellite-derived Land Surface Albedo Products J-L. Roujean: Recent Advances in Albedo Generation from European Satellite Sensors (POLDER, Vegetation, MSG) Y. Zhang: Factors Affecting the Direct/Diffuse SW Flux Ratio
1630-1800	Session 6B:	Land Albedo and SW Radiative Fluxes C. Schaaf: MODIS Reflectance Anisotropy and Albedo C. Schaaf: Atmospheric Correction in the Reflective Domain of MODIS and AVHRR Data: Uncertainties Analysis and Evaluation of AERONET Sites B. Pinty: Exploitation of MODIS and MISR Surface Albedos in Support of SVAT Models

31 May

0930-1100	Session 7A:	Discussion of Data Product Status and Needed Actions
1130-1230	Session 7B:	Recommendations and Plans
1230		Adjourn