Global maps of Local Land-Atmosphere coupling

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Land-atmosphere coupling takes place at all conceivable spatial and temporal scales. Obviously, the state of the land is determined largely by the forcings it receives from the atmosphere, but a reverse impact of the land state on the overlying atmosphere is also evident. The atmosphere gets moistened or heated by fluxes originating from the land surface. Convection may be triggered, or precipitation may be formed. The radiative properties vary in time and place. The fluxes of momentum, heat, moisture and radiation between the land and the atmosphere are in fact an expression of land-atmosphere interaction. It involves many physical processes simultaneously. Because of the large scope of land-atmosphere coupling, it is useful to define a subset for study. The LoCo theme of the GLASS panel aims to look at just 'local' land-atmosphere coupling. For instance to identify conditions or areas where land-atmosphere interaction has a significant impact on the local climate. Or to define proper diagnostics expressing the degree of coupling. Or to design model intercomparison experiments in order to evaluate the coupling across modelling systems.

During the WATCH/LoCo workshop on local land-atmosphere coupling, held in De Bilt (Netherlands) in June 2008, an excellent selection of presentations and discussions helped considerably in defining the topic, and to propose a "proof of concept" diagnostic and model experimental design to nail down the subject. At the outset it was realized that any definition of a sub-component of the complex climate system needs consideration of the "adjacent" components. For instance, during the land model intercomparison projects carried out under the auspices of PILPS it was already recognized that the land models probably behave differently under conditions of offline atmospheric forcing than when fully coupled to the atmosphere. But this experimental set-up of offline forcing did not prevent major positive developments in the area of land surface modelling and calibration.

During the workshop we came to the conclusion that a good conceptual definition of "local land-atmosphere coupling" would involve the temporal and spatial scale of all land-surface related processes that have a direct influence on the state of the Planetary Boundary Layer (PBL). Specifically, these processes include (see figure):

- the direct moistening/drying and heating/cooling of the PBL, and the feedback exerted by this PBL change on the surface fluxes
- the impact of the change of the PBL depth or thermodynamic state on the formation/disappearance of PBL clouds (shallow cumulus) induced by land surface fluxes
- the triggering and fuelling of shallow or deep convection
- the accumulation of hydrological anomalies in the soil water or snow reservoir, and the subsequent impacts of these surface states on the surface energy balance.

It was also recognized that many expressions of land-atmosphere coupling are not easily tied to the local scale, like the precipitation response to changing soil moisture in Randy Koster's GLACE experiments. Also large scale atmospheric circulation is under certain conditions clearly affected by the state of the land surface, but both these examples are considered to be beyond the immediate scope of the "LoCo" theme.

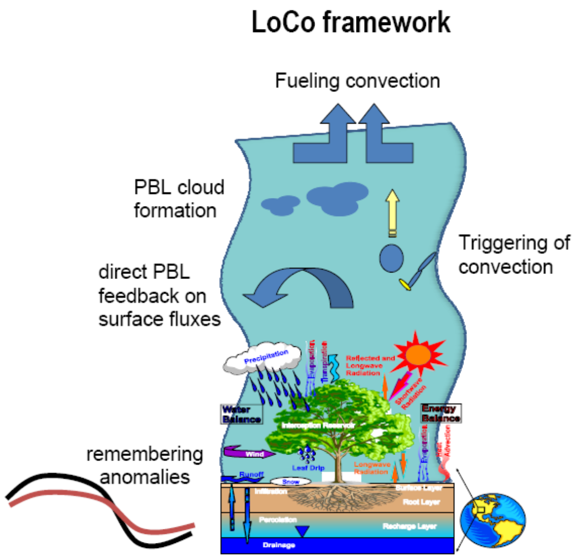

Figure: conceptual framework of the realm of the "LoCo" theme

Each of the processes listed above are briefly discussed below, guided by the presentations and discussions that emerged during the workshop. It was jointly organized with the EU project WATCH (WATer and global CHange, see http://www.eu-watch.org), as in this project due attention is paid to land-atmosphere feedback and its consequences for the assessment of current and future water resources impacts. For more information we refer to the workshop website at http://www.knmi.nl/~hurkvd/LoCo_workshop_2008.html.

Direct land-PBL feedback

Evaporation moistens the atmosphere. Clear. But vice versa, evaporation (partly) depends on the atmospheric demand for water, depending on the moisture condition. A straightforward feedback loop is evident. However, the state of the (well-mixed dry) PBL is not only dependent on the surface fluxes of heat and moisture; also the interaction with the overlying free atmosphere via entrainment plays an important role. During the course of a day PBL drying can occur due to mixing in of dry air, in spite of an upward surface moisture flux. This feedback needs to be considered when trying to estimate surface evaporation from simple environmental variables, like available energy (A) or vapour pressure deficit (D). A number of diagnostics and concepts have been discussed. *Jim Shuttleworth* used definitions of a "climatological resistance" (defining the ratio between A and D) and the "area average surface resistance" to give a theoretical explanation for differences in trends between open water and actual evaporation rates, depending on the aridity of the climate. Compared to earlier concepts of e.g. the Priestly-Tailor coefficient or McNaughton's coupling coefficient a clear role of PBL feedback in the characterization of the surface state is included. Likewise, *Joe Santanello* expanded on earlier work by e.g. Alan Betts by decomposing the diurnal evolution of the surface temperature and humidity into a surface driven and an entrainment driven component. Pilot studies with NASA's Land Information System (LIS) were carried out to identify the impact of switching between a suite of land surface models or PBL models, which is a first indication of which component governs the degree of land-atmosphere coupling. The diagnostic is also built into the Single Column Model (SCM) testbed environment developed by *Roel Neggers*, and used more and more in GCSS and GABLS model intercomparison studies.

Cumulus formation

Michael Ek casted the relative contribution of land wetness versus atmospheric entrainment nicely in an expression for the PBL relative humidity tendency, another useful diagnostic expressing the possible consequences of changing the land surface state on the overlying atmosphere. He performed SCM studies for a few special cases where PBL cloud formation appeared to be highly sensitive to both surface evaporation and the atmospheric stability above the PBL. However, cloud formation (and its obvious impact on surface radiation and conditional stability) are not well embedded in the diagnostics above (climatological/area resistance, diurnal cycle of T/q near surface), and these feedbacks need to gain more attention in diagnostic studies.

Triggering and fuelling convection

Although not present at the workshop, it was felt that *Kirsten Findell's* earlier work towards creating maps of areas and conditions where soil moisture values do affect the formation of convection is a valuable component of the LoCo theme. In her work (already published some years ago) SCM models forced with observed atmospheric profiles were used to determine when/where different soil moisture states do give rise whether or not convection is triggered. Although in many cases convective triggering is not determined by the local soil moisture state, many cases can be found where convection is preferably triggered over either moist or dry soils. *Craig Ferguson* expanded on this concept by calculating the Convective Triggering Potential (CTP) and the atmospheric dewpoint depression from AIRS satellite data, as a first promising step to create land-atmosphere feedback maps from spaceborne observations. In addition, he explored the correlations between soil moisture and Lifting Condensation Level (LCL) using AMSR-E data (expanded with VIC simulations), a diagnostic explored before by Alan Betts and expressing the effect of soil moisture on the surface relative humidity (closely related to LCL). On a somewhat smaller scale *Chris Taylor* studies the formation and dynamics of Mesoscale Convection Systems in the Sahel region depending on the spatially varying surface temperature pattern induced by earlier rain storm. He argues that convective triggering often takes place at the interface between wet and dry soil patches, where both a sufficient surface heating and further fuelling of the convective system with moisture occur. His work clearly points at the need to consider spatial variability as a contributor to convective activity and land-atmosphere feedback within the scope of LoCo.

Accumulation of anomalies

The (hydrological) land state has a long memory. Many observational and modelling studies have shown the importance of hydrological anomalies in the past to explain extreme conditions in the present. Local land-atmosphere interaction may turn into long-lasting positive feedback loops when critical thresholds are exceeded. *Sonia Seneviratne* for instance used a plot of monthly mean surface evaporation/sensible heat versus soil moisture index to demonstrate a clear difference in memory (causing hysteresis in the plot) for a Northern and Southern European fluxnet site. This type of analysis can also be used to evaluate the realism of land-atmosphere coupling representation in current climate models.

Global maps and remote sensing

One of the ultimate goal of the LoCo community is to produce comprehensive global distributions of where and when the land surface and the atmosphere have a strong mutual feedback, either positive or negative. The importance of this is demonstrated by *Stefan Hagemann*, who reviews the various pathways of land-atmosphere coupling and their representation in GCMs used for present-day and future climate calculations. *Bernie Bisselink* made clear from his precipitation recycling analysis that on relatively short mutual distance within Europe strong recycling is favoured under very different climatological conditions. Since multiple diagnostics and processes are involved, multiple maps already exist. *Randy*

Koster provided observational support of the earlier defined "hotspots" of land atmosphere coupling by identifying places where the correlation between temperature and precipitation express regimes where evaporation is both highly variable (by a variation in the degree to which it is controlled by radiation or soil water content) and highly coherent (expressing a strong surface control on the evaporation). Such hot spots regions are highly dynamic and are expected to be geographically shifted with climate change, as highlighted by *Sonia Seneviratne*. *Richard de Jeu* used satellite imagery of surface soil moisture to plot the global distribution of typical time scales of changes in soil moisture, another way to express the potential soil control on evaporation variability. Together with the remote sensing based maps of *Craig Ferguson* a suite of coupling products is becoming available, but all highlighting different aspects of the coupling: the PBL feedback (Betts' soil moisture – LCL diagram), convective triggering (CTP), soil memory (satellite soil moisture), or pathways possibly including large scale processes (Koster's coupling coefficient).

To reach the goal of creating comprehensive maps of local coupling significance a single observable diagnostic that represents all relevant processes (PBL feedback, cloud formation and its radiative consequences, convective triggering) would be preferable. This is not straightforward, as the nature of the processes is very different and requires different observations to pin them down. However, a common feature of the various diagnostics is the sensitivity of the atmosphere to the surface state, either soil moisture content or heat content. Koster's coupling coefficient, Findell's analysis of US CTP, Ek's relative humidity tendency, and Betts' relation involving the LCL all contain a sensitivity to soil moisture (either explicit or implicit via surface evaporative fraction or surface resistance). In all these cases modelling experiments are used to quantify this sensitivity to soil wetness. Although this is not a direct observation of the coupling strength, we can perhaps rely on the models which are well capable of stratifying our understanding of the conditions that lead to strong coupling, and provide a useful laboratory to explore these sensitivity ranges.

A global map with coupling strength diagnostics needs to incorporate the various coupling mechanisms. As a start, we propose to apply a hierarchy approach, where the coupling pathway may be associated with an index, which is subsequently plotted. The first level of coupling is the direct PBL feedback, which may be expressed as the degree to which evaporation is sensitive to soil moisture or not, expressed for instance with the correlation between evapotranspiration and temperature. A positive feedback may emerge when low evaporation/high sensible heat flux may enhance PBL growth that leads to further drying and a higher bowen ratio. A second level of feedback is the formation of PBL clouds and its radiative consequences. A positive feedback here may be a case where at high moisture contents clouds develop, that reduce surface radiation, surface heating and PBL growth, allowing for a further build-up of PBL humidity. The third level is the triggering of convection, which may show positive or negative feedbacks via the likelihood of generating precipitation that moistens the soil, as detailed by Findell and Taylor. And finally, level 4 expresses an overall hydrological feedback signature, which is the impact of land surface on precipitation, for instance diagnosed from the coupling coefficient detailed by Koster.

What would such a map look like? Starting from the 1st level coupling, areas will be highlighted where changes in soil moisture do have a pronounced effect on the daytime PBL. For instance, the ratio between the surface and entrainment Bowen ratio diagnosed from Santanello's framework changes strongly for small soil moisture perturbations. Where this is not the case, a strong impact of land surface on the atmospheric state cannot be expected, and further analysis is not necessary. For areas where index 1 is significant, the second and third feedback via cloud formation or convective triggering can be tested. Likewise, a small soil moisture perturbation leads to cloud formation which is either shallow without rain (index 2) or deeper with possible rainfall (index 3). And the formation of rainfall will at the end be labelled as index 4. If somewhere in the chain this feedback appears weak or even negative, a strong impact of (local) land state on (local) precipitation is not expected.

This framework is still maturing. A proof of concept will be examined using the NASA Land Information System coupled to the WRF atmospheric model, which features a suite of land, PBL and conviction parameterization schemes. For a number of different climate regimes a set of snap shot experiments will be set up, and perturbation experiments will be applied to determine the hierarchy of coupling indices. If proven successful, a way will be sought to extend this set-up to the multi-year global scale.