Hints that proteins that must act together will be induced or repressed in a coordinated manner in individual cells, possibly even generating phenotypic diversity among cells (Fig. 1). So how might this long-term action occur, and what are the probable physiological consequences? One proposed model is that random fluctuations in regulatory components are amplified as a signal cascades down a pathway. Alternatively, long-lived responses may result from self-reinforcing mechanisms, such as positive feedback, that lead to slow rates of conversion between distinct activation states of gene networks.

Harder to gauge is the phenotypic impact of this extrinsic variation. A possible benefit of coherent variation could be to ensure that processes that are energetically expensive, such as protein secretion, are restricted to a few cells, rather than having many cells incur a high fixed cost to produce a set of proteins that are underused. Also, by analogy to microorganisms, where variation is postulated to generate phenotypic heterogeneity, one might speculate that noise could allow a subpopulation of cancer cells to evade endogenous or exogenous attempts to inhibit unrestrained cell growth.

At least three issues await further investigation. First, to what extent do the tissue-culture conditions reflect what occurs in vivo? Although tissue culture is an artificial environment that might generate noise that doesn’t occur in vivo, cells typically divide much more slowly in vivo, which could cause deviations to persist for even longer timescales than Sigal et al. report. Second, to what extent will the observations reported here prove general? As the authors point out, the set of proteins they examine are biased (for example, by their abundance and accessibility for YFP integration). Third, do variations in protein concentrations lead to proportional changes in their activities? After all, cells have many mechanisms for controlling activities. These include modifying a protein after it has been made, and regulating the protein’s cellular localization and the availability of key partners, all of which might act to suppress variation. More broadly, can we link heterogeneity in protein concentrations or activities to phenotypic differences? Although these questions show that much remains to be done, it is clear that these and related topics can now be explored in the cells of multicellular organisms.

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**HYDROLOGY**

**Water from on high**

Dennis P. Lettenmaier and James S. Famiglietti

Data on changes in water storage in the Congo basin show how GRACE, a pair of satellites designed to record variations in Earth’s gravitational field, is benefiting the study of the planet’s water cycle.

Hydrologists yearn above all to close Earth’s water balance. This is essentially a housekeeping task: to measure precisely where and in what quantities Earth stores water, and how the water moves between those stores. Constant changes, both natural and anthropogenic, to the global water cycle make this calling especially exciting, and particularly important. Writing in *Geophysical Research Letters*, Crowley et al. further the cause with measurements of land water storage in the Congo river basin in central Africa. Their observations provide further evidence of a ‘see-saw’ anti-correlation with similar measurements in the Amazon basin of South America. Most significant of all, however, is how these data were acquired: through sensitive space-based measurements of Earth’s gravitational field, courtesy of the Gravity Recovery and Climate Experiment, or GRACE for short.

On Earth’s land surfaces, the main moisture fluxes are precipitation, evaporation and transpiration (evaporation from plants, often lumped together with evaporation as evapotranspiration) and run-off. The balance of these fluxes is reflected in changes in moisture storage in both surface and subsurface stores; not only lakes, reservoirs, wetlands and rivers, but also snow and glaciers, and groundwater and soil moisture. Measuring each of the flux and storage terms presents its own challenges. But evapotranspiration — for which little more than model estimates exist, despite various efforts to tie these to local observations — and changes in storage are the most problematic of all.

A strategy that has been used to sidestep these problem terms and estimate the terrestrial water budget over large areas is to perform averages over many years. In this case, the effect on the overall balance of interannual variations in terrestrial storage is small; but on
NASA and the German Aerospace Center, the VIC model, capacity (VIC) model, month deviation of moisture storage from the annual mean as calculated from the variable infiltration capacity (VIC) model. The VIC model and GRACE data agree closely on the variability of terrestrial moisture storage between years; an earlier study (R&Y) based on the atmospheric moisture budget put this variability much higher. (Figure courtesy of J. Adam, Univ. Washington; GRACE data processing by T. H. Syed, Univ. California, Irvine.)

The GRACE satellites were launched by NASA and the German Aerospace Center, DLR, in March 2002, and provide a new source of information to assist in unravelling the complexities of the terrestrial water balance. The two satellites measure month-to-month changes in surface and subsurface water storage through the effect of these parameters on Earth’s gravitational field. Although GRACE’s spatial resolution (nominally around 300,000 km²) is coarse, it provides observations that are independent of atmospheric and surface conditions. Errors are thus globally consistent.

Crowley et al. use GRACE data to assess variations in terrestrial moisture storage in the Congo basin of central Africa between 2002 and 2006. Their results show that interannual variations were out of phase with those in the Amazon basin during this period, confirming an anti-correlation inferred earlier from precipitation and streamflow anomalies. This see-saw behaviour is thought to be related to the so-called Gill mechanism, which holds that, near the Equator, persistent atmospheric uplift (and associated vapour condensation, and so precipitation) in one area will be compensated by atmospheric subsidence, and so precipitation deficits, in another.

Crowley and colleagues’ data also show a downward trend in Congo terrestrial storage over the short period surveyed. This might well be just a manifestation of decadal-scale variations in precipitation already indicated by streamflow records, but also indicates the relatively high magnitude of interannual variations in terrestrial storage when compared with seasonal variations.

Other researchers have also started to use the GRACE record to estimate seasonal and interannual variations in the terrestrial water cycle. The data have been applied to evaluating whether global climate models can capture the seasonal cycle of continental moisture storage. Comparison with observed soil-moisture and groundwater levels in Illinois has shown that the GRACE record tracks moisture levels, and that the interseasonal and interannual variations in it are due roughly equally to soil moisture and shallow groundwater. The atmospheric and land–surface water budgets from GRACE have been combined to estimate the run-off from large river basins, assuming that this is the residual term once atmospheric moisture convergence and terrestrial and atmospheric storage changes have been taken into account. And seasonal variations in moisture storage in 53 river basins covering most of the global land area have been estimated, along with sources of error and their variations with basin area, latitude and shape.

The Mississippi river basin provides an interesting case study for the use of the GRACE data. Soil moisture and groundwater — rather than lakes and other forms of surface storage — dominate terrestrial water storage in the Mississippi basin. But in this region, high-quality climatological data offer an opportunity to estimate the terms in the terrestrial water budget using land-surface models. A comparison of seasonal and interannual variations from model calculations and GRACE data throws up some interesting disparities (Fig. 1). First, model estimates of seasonal variability in soil moisture and snow storage are greater than those from the GRACE data for the same period. This might indicate that the groundwater contribution is modest over the Mississippi basin, as land-surface models do not represent groundwater explicitly. But this remains conjecture, as other researchers have suggested that groundwater may contribute substantially to interannual moisture-storage variability, over at least part of the Mississippi basin. Second, the mean interannual variability inferred from the atmospheric water budget is several times that obtained from either the GRACE data or model soil–moisture results, possibly through accumulated error in the estimated atmospheric convergence.

At this point, the GRACE period of record is too short to answer questions about the relative contributions of soil–moisture and groundwater (or perhaps other) effects to terrestrial-storage variations. The data do, however, provide a viable means of understanding the sources of these variations, with their various scientific and practical implications. Their role in pinpointing as-yet poorly understood curiosities such as Crowley and colleagues’ Amazon–Congo anti-correlation could also prove invaluable. Our insight into such phenomena will no doubt improve as the GRACE record is extended.

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