PBO meteorology miniproposal

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A prime rationale for the PBO is that the consistent and persistent collection of data over extended time periods often underpins key new insights into how physical systems work. This motivation is, however, no less true for hydrology and meteorology than it is for geodesy. Thus, networks with extended lifespans that make homogeneous suites of observations on environmental conditions can be of great value to environmental scientists as well as to geodetic studies. The development of both backbone and dense arrays of continuous GPS sites creates an opportunity to gather real-time meteorological and hydrological data that will be integral to answering fundamental environmental questions. We propose, therefore, to utilize the PBO geodetic networks to make observations of atmospheric and very shallow subsurface conditions. One ultimate goal is to share GPS-site telemetry to achieve real-time, internet-accessible data collection at these many sites across western North America. Whereas some of the proposed observations will be directly relevant to improved geodetic accuracy, others will primarily benefit atmospheric and hydrologic sciences. By promoting the active collaboration of researchers from these fields in order to achieve scientific objectives that have national relevance, the mandate for PBO can be further strengthened.

Below we discuss some key objectives that observations tied to the PBO network could address. For most of these disciplines, these represent a limited sampling of potential ways to exploit this network. We recognize that the network configuration has yet to be agreed upon. As a consequence, site-specific meteorological proposals are premature. All of the research problems discussed below can be addressed in the context of the ultimate array. We also do not attach a cost estimate to this proposal. Although the overall PBO budget requests ~$2M for meteorological equipment, we think it is premature to attempt allocate these resources. Our expectation is that, by the time the network is implemented (2004 at the earliest), technological advances will drive down the costs, provide new unanticipated options, and make real-time, internet access a viable option. Moreover, the specific instrumentation is dependent on the network configuration and the problems that are best suited for these arrays. Nonetheless, in general terms, we envision ~600 sites where temperature, relative humidity, barometric pressure, soil moisture, and precipitation are measured, and ~40 sites where these measurements are enhanced by more elaborate vertical profiles.

Geodesy

• ***Key problem:***

Atmospheric delays. It is well established that characteristics of the neutral atmosphere and ionosphere , including integrated water vapor and total electron content, commonly introduce phase delays of ≥2 m in GPS signals. Dual-frequency GPS receivers permit effective correction for the ionospheric delays, but the delays due to atmospheric moisture remain as a limiting source of error (Chen and Herring, 1997). When an azimuthally homogeneous atmosphere is assumed, an average zenith delay and correction can be estimated from surface atmospheric pressure. The atmosphere is, however, not azimuthally homogeneous: moisture content is both spatially and temporally variable. Consequently , there are significant differences in moisture and consequent phase delays along the “slant paths” travelled by GPS signals coming in from differing azimuths. Such variations introduce a temporally and spatially varying source of error into calculations of geodetic positions. Clearly, when averaged over time, such variability diminishes in importance with respect to a mean position. But, to the extent, the geodetic data at short time intervals, such as in the days weeks prior to an earthquake, are to be relied on for scientific insights, it is of fundamental importance to reduce the sources of error attributable to the atmosphere.

• ***Proposed approach.*** Observations of barometric pressure at permanent GPS sites will permit the slant-path precipitable water to be modeled (Ware et al., 2000). Measurements at multiple sites will enable spatially and atmospherically consistent corrections to be applied to geodetic position estimates.

Hydrology

• ***Key problems:***

Groundwater recharge. Water is a vital resource in the region of the planned deployment of the PBO. As ever expanding demands are placed on this limited resource, an improved scientific basis for decision making with respect to water-resource allocation attains increased importance. Today, continental, river-basin, and small watershed-scale groundwater recharge represents the largest unknown factor in hydrologic water balances, despite the fact that recharge makes a larger contribution to this balance than do factors like evapotranspiration. The spatial variability of recharge as a function of terrain features (slope, aspect, altitude, roughness, etc.), climatic zones, and physiographic or ecological regions is poorly documented within the study area. For example, it is presently unknown how recharge varies across the Great Basin, and this will remain poorly estimated until soil moisture and precipitation are better defined. Whereas the regional signal is most important in the large-scale water balance, the catchment-scale signal is key to attaining a better understanding of physical hydrologic processes. Interactions among precipitation, runoff, permeability, vegetation, evapotranspiration, and recharge are best understood in smaller catchments where variability in each parameter can be better documented.

Dynamic mountain-front hydrology. For many years, orographic precipitation along mountain fronts has been recognized as a fundamental control on the distribution and intensity of precipitation, flood susceptibility, groundwater recharge, and erosion processes. Unfortunately, around the globe, most meteorological observations are collected in valley bottoms where the population is concentrated. Even in populous states like California, the available data on orographic gradients within mountains, such as the Sierra Nevada, are remarkably sparse. Surprisingly, even well populated mountain fronts, such as the Wasatch front, lack well distributed arrays of topographically dependent climatic observations. Most mesoscale climate models, including the most widely used ones, only account for topography at rather coarse spatial scales (>25 km). Consequently, the predictions of spatial variations in precipitation and all of the consequences of those variations are tenuously calibrated. Without dense arrays of climatic observations that sample the 3-D topographic variability of range fronts, i.e., both the altitudinal variations and the shape of the topography that focuses storm tracks or distributes moisture, orographic precipitation will remain poorly understood.

Hydrologic dynamics of closed basins. Topographically closed basins dominate much of the topography between the Rockies and the Cascade-Sierra ranges. In recent years, the influx of new inhabitants to this region has rapidly expanded the pressure on scarce water resources. At present, the distribution of meteorological observations across this region is sparse, and the knowledge of the magnitude of evaporative losses, groundwater recharge, groundwater pumping, and runoff is poor. Nonetheless, reliance on local sources of water is expected to increase dramatically in the coming decade. Rational resource planning is predicated on a scientifically based understanding of the hydrologic dynamics of these closed basins. At the present time, such an understanding is severely limited by the sparse data on many of the crucial controlling variables.

Catchment-scale flood forecasting. Flood prediction during severe storms is based on a combination of predicted rainfall, previous observations of the response to similar rainfall, and antecedent conditions in a catchment. The movement of a floodwave through a catchment results from an integration of discharge from successive tributaries, each of which has individual hydrographic characteristics. Thus, the distribution, intensity, timing, and duration of precipitation events within each tributary affect how runoff is cumulatively integrated along large catchments. Uncertainties arise in runoff predictions due to the undocumented variability in where, when, and how hard rain is actually falling in different tributary catchments and also from the effects of bank storage and groundwater-stream relationships. The present density of meteorological observations commonly precludes discharge forecasts that are based on the actual rain that fell in tributary basins. The effects of delayed storage are often unknown. As a consequence, surprising and sometimes disastrous discharges of long duration occur when the actual precipitation distribution is not reasonably well matched by the model predictions of rainfall or of groundwater bank storage.

Hydrology of plateaus Due to their high elevation and low relief, plateaus are both topographically and climatically anomalous. Large plateaus, such as the Tibetan Plateau, drive major weather systems in South Asia (the monsoons) and have significant impact on global climate (Kutzbach et al., 1993). Other smaller in scale, plateaus in the western US, such as the Yellowstone plateau, also create unique climatic and hydrologic conditions. Snow retention, spring melt characteristics, and climatic gradients on plateaus are fundamentally different from those observed in typical mountain ranges. Yet, because these plateaus commonly occupy sparsely populated regions, their hydrology is less well known than in many other regions. Most such plateaus have never been studied as an integrated climatic-hydrologic entity, but rather as an amalgam of potentially unrelated individual catchments.

• ***Proposed approach.*** The solution to many of the hydrologic problems posed above lies in the acquisition of vertically integrated arrays of hydrologic data, beginning in the subsurface and continuing through the surface to the atmosphere. In the subsurface, the spatial and temporal variability in the amount of soil moisture and in gradients of moisture in the upper 2 m needs to be known to define groundwater recharge, as well as antecedent conditions relevant to runoff. At the surface, measurements of local precipitation serve to document the water flux, whereas measurements of relative humidity and temperature help calibrate evaporative moisture fluxes.

Regional problems that span broad climatic gradients require observations spread over 100s to 1000s of kilometers, whereas improved understanding of physical processes requires observations at the scale of small catchments. The proposed geometry of the geodetic arrays is well suited to addressing both of these problems: the backbone array will be used to document climatic gradients and hydrologic conditions across broad areas, whereas dense arrays will permit observations of relatively small catchments. Given that many hydrologic experiments run for one season or a few years at most, the relatively long interval of planned operation (10 years) would provide an unprecedented data set, particularly in the dense arrays. Although the same equipment would not be installed at every site, the primary observations would be collected with rain gauges (commonly 2 at a site) and with temperature, relative humidity, and soil moisture sensors.

Given that many meteorological observations are already made in the western US, the justification for collecting additional measurements might be questioned. We would argue that the coordinated array of observations, the uniformity of instrumentation, the concentration of observations in dense arrays, the sampling of presently undersampled areas, and the real-time data access constitute an unequaled opportunity to make a quantum leap forward in understanding the physical underpinnings of hydrologic processes. Given the importance of water in the western US, the value of such an understanding is self-evident.

Geomorphology

• ***Key problems:***

Tectonic-climate interactions and surface processes. It has long been recognized that rates of deformation exert important controls on range-front topography (Bull and McFadden, 1977). But many unresolved questions persist: how does that topography evolve under contrasting climatic regimes? How does the spectrum of topographic characteristics of the mountain fronts across the Basin and Range reflect the influence of both variable strain rates and climatic contrasts? If the growth of folds were sustained at a similar rate among two areas, how would the evolution of the geomorphic surface vary as a function of the spatial variation in climate? Alternatively, if folds are growing in the same climatic regime, but at different rates, how do their surfaces evolve? In general, these questions can be distilled as: how do the interactions between growing structures and climate influence the evolution of the geomorphic surface? Such questions can be applied at the local scale, for example, along the San Andreas system, as well as at regional scales, but are difficult to answer, given the existing data sets.

Catchment-scale processes. Catchments are complex physical systems in which erosion, deposition, and sediment transport are driven by variations in topography, hydrology, vegetation, lithology, soils, and climate. Considerable progress has recently been achieved via dense monitoring of very small catchments. The need to understand the behavior of larger catchments has motivated new research initiatives within the USGS and ones such as the "Source to Sink" Margins focus area. Only two sites, neither in North America, have been targeted by the latter initiative. Consequently, the need remains for understanding mesoscale catchment processes in temperate to arid, mid-latitude climates.

• *Proposed approach.* Dense networks provide opportunity to gather mesoscale gradients (10-200 km) in climatic and soil parameters. For geomorphologists, the power of these data will lie in combining them with the present strain field, the Quaternary growth of structures, and high-resolution (submeter) digital topography in order to facilitate a new quantification of landform evolution that will underpin the use of landforms to calibrate long-term rates of deformation. Furthermore, such data provides a vital ingredient in understanding sediment routing processes within these catchments.

Climatology

• *Key problems:*

Calibration of mesoscale to global climate models. Climate models rely on the surface energy balance that is commonly expressed in terms of four components, sensible (H) and latent heat (LE), net radiation (NR), and the heat flux (G):

$$H + LE = NR - G.$$

One of the most fundamental calculations of climate models is the partitioning of the available energy between sensible and latent heat. Although models are highly sensitive to this partitioning, actual measurements that would serve to calibrate this partitioning are scarce.

Absent such data, progress in understanding the physical processes and the complex interactions resulting from energy partitioning will be restrained.

• ***Proposed approach.*** In order to calibrate the energy balance, the four variables listed above need to be measured. This can be accomplished with radiometers to measure NR, soil moisture and temperature gradients to measure the heat flux, and vertical arrays of temperature, relative humidity, and wind speed that can be used to calculate latent and sensible heat. We propose that, at a subset of sites, 10-m towers be erected that would collect T, RH, and wind speed at 2-m intervals. In addition to the soil moisture measurements proposed above, soil temperature data in vertical profiles will permit calibration of the heat flux across the surface. These data will be used to calibrate and significantly enhance the present generation of climate models.

Meteorology

• ***Key problems:***

More reliable forecasting of severe weather at time scales of 1 day to a week. The ability to predict severe weather is of immense social value. Despite significant infrastructure, forecasting in the western US is difficult because storms approach via the relatively unmonitored Pacific. Several current and proposed research initiatives are underway to address this shortcoming. Their main strategy is to ascertain what additional measurements are most effective in enhancing the success of weather prediction. Two of these initiatives [i) Pacific Landfalling Jets Experiment (**PACJET:** www.etl.noaa.gov/programs/pacjet) and a Long-term Effort to Improve 0-24 h West Coast Forecasts; and ii) The Hemispheric Observing System Research and Predictability Experiment (**THORPEX:** www.Nrlmry.navy.mil/~langland/ THORPEX document)] will deploy radiosondes and numerous other atmospheric sensors across the Pacific with the intent of tracking storms on their approach to the coast. Whereas PACJET is most concerned with coastal weather in California (up to 200 km inland), THORPEX seeks a more continental view.

• ***Proposed approach.*** In the context of the planned dense arrays, particularly in California, we propose to take advantage of the data that will be obtained from these other meteorological experiments. They will provide a unique density of measurements of atmospheric conditions, including moisture, and will, therefore, permit an optimal calibration of the phase delays caused by atmospheric moisture. As such, these will enhance the accuracy of the geodetic estimates.

Global gravity

• ***Key problem:***

Calibration of soil- and groundwater on observed gravity. The launch of the GRACE (Gravity Recovery and Climate Experiment) satellite by NASA will yield global gravity observations that will be used to estimate global models for the mean and time variable Earth gravity field approximately every 30 days for the 5-year lifetime of the mission. Over land, the most rapidly changing variables effecting gravity are soil moisture and groundwater. Unfortunately, these are rather poorly documented at present, and there are no systematic, regional observations of these variables.

• ***Proposed approach.*** The proposed collection of soil-moisture content and fluxes (see above) in both regional arrays and dense arrays will provide valuable calibration data that will assist in a more accurate interpretation of remotely sensed gravity variations.

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