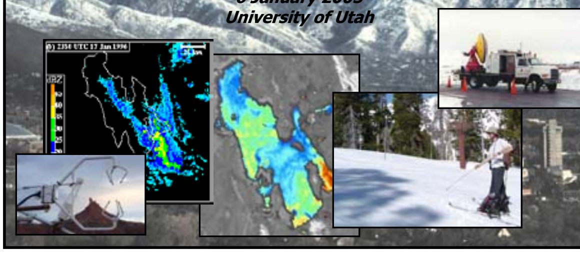
Initial Plans for the Study of Precipitation and Evapotranspiration in the Great Salt Lake Hydrologic Observatory

Preliminary Atmospheres Group notes for the GSLBHO Planning Meeting
6 January 2005
University of Utah



Planning Methodology

Concentrate on science topic areas from Neuse prototype

- Linking hydrologic and biogeochemical cycles
- Sustainability of water resources
- hydrologic and ecosystem interactions
- Hydrologic extremes (e.g,. droughts and floods)
- fate and transport of chemical and biological contaminants

Emphasize cross-cutting themes

- forcing, feedbacks, and coupling
- scaling
- prediction and limits to predictability

Leverage four basic properties of a catchment

- stores, residence time, fluxes, flowpaths

Core Science Drivers and Questions

How do hydrologic processes (stores, fluxes, flowpaths, residence times) vary across topographic and climatic gradients?

How are hydrologic processes influenced by natural and human-modified landscape heterogeneity (e.g., large water bodies, urbanization)?

How do hydrologic processes respond to natural and anthropogenic climate variability and change?

How can we better predict hydrologic extremes (e.g., droughts and floods) and evaluate critical factors for future policy alternatives?

How do hydrologic processes vary across topographic and climatic gradients?

Science Question: What processes control the distribution, amount, phase, and isotopic/chemical composition of precipitation over complex terrain?

- What is the relative importance of large-scale vs. orographic precipitation processes?
- How do precipitation processes, distribution, amount, phase, and composition vary from hours to days (within storms) to seasons (dominated by a few storm cycles) to years (ENSO, PDO, anthropogenic warming)?
- How does precipitation vary on scales from 10's to 1000's meters?
- To what degree does the isotopic composition of precipitation vary spatially and temporally over regions of complex terrain?

How do hydrologic processes vary across topographic and climatic gradients?

Science Question: How does the ratio of precipitation (P) to evapotranspiration (ET) vary over complex terrain?

- How do physical and biological controls on ET vary over complex terrain?
- How does ET vary seasonally and respond to critical atmospheric, hydrologic, and biological processes (e.g., snowmelt, leafout, summer precipitation vs. winter precipitation)
- Does snowpack sublimation lead to substantial water loss?
- What fraction of water is recycled within hydrologic basins?

How are hydrologic processes influenced by natural and human-modified landscape heterogeneity?

Science Question: How are hydrologic processes modified by land-surface change?

- How are surface roughness and fluxes, temperature, humidity, local wind patterns, cloud processes, and precipitation patterns modified by urbanization, agriculture, forest management, fire, and ecological change?
- How do urban and point-source (e.g., power plant) pollution modify cloud processes, precipitation, and chemical deposition?
- How do the above effects and their impact on P & ET vary within storms, seasonally, and interannually?
- Does land-use change have a greater impact on hydrologic processes than regional and global climate change?
- How is the frequency and severity of hydrologic extremes, including droughts and floods, altered by land-surface change?

How are hydrologic processes influenced by natural and human-modified landscape heterogeneity?

Science Question: How do large continental water bodies (e.g., Great Lakes, Aral Sea, Great Salt Lake) influence regional hydrologic processes?

- To what degree is water recycled within terminal basins? Is there a positive feedback loop linking lake area/elevation/temperature to precipitation and runoff (i.e., high water years more precipitation)?
- How is this feedback loop modified by humans through water transfers, land-surface change, and altered lake chemical composition (e.g., salinity)?
- How does lake-effect precipitation and evaporation vary with lake size, surface temperature, and salinity, as well as temporally (hours to years?

How do hydrologic processes respond to climate variability and change?

Science Question: How do climate variability and change affect precipitation amount and phase (snow vs. rain)?

- Can anthropogenic forcing & climate change be detected more readily in regions where natural climate variability related to ENSO, PDO, etc. is relatively weak?
- To what extent do natural climate variations and anthropogenic forcing affect the ratio of precipitation resulting from large-scale vs. orographic processes?
- How do low-frequency alterations in the planetary-scale circulation affect the characteristics of the few winter-season storms that are responsible for much of the seasonal snowpack and hydrologically significant precipitation?
- How will climate change alter hydrologic processes as a result of changes in the elevation of the freezing and melting levels?

How do hydrologic processes respond to climate variability and change?

Science Question: How do climate variability and change affect evapotranspiration?

- How do alterations in seasonal snow cover, sublimation rates, soil moisture and surface temperature affect ET as a function of elevation across mountain ranges?
- Will changes in the summer/winter distribution of precipitation influence vegetation distribution and subsequently alter ET?
- Is the amount of water recycling within basins affected by natural and anthropogenic climate variations?
- To what extent do global climate change, regional human modifications of the land surface, and policy decisions in response to natural and global climate change feedback upon one another?

How can we better predict hydrologic extremes and evaluate critical factors for future policy alternatives?

Science Question: What is the optimal mix of observations and models to best analyze and predict hydrologic processes and their impacts, including droughts and floods?

- What instrumentation is required to specify the hydrologically relevant vertical and horizontal structure of the atmosphere and land-surface (including soil moisture and snowpack), as well as determine precipitation rates, amounts, and phase?
- What improvements and capabilities are needed for existing hydrologic, land-surface, and atmospheric models to better predict hydrologic extremes (e.g., droughts and floods)?
- What improvements and capabilities are needed for data assimilation systems to better utilize existing and future observations and initialize coupled hydrometeorological modeling systems?

Testable Hypotheses

Annual precipitation (snowfall and SWE) cannot be predicted by elevation alone, but also depends on proximity to local moisture sources, airmass transformation by upstream topography, and local topographic effects

- At a given elevation, windward catchments near the Great Salt Lake (e.g., the Ogden Valley) receive more annual precipitation and snowfall than interior catchments (e.g., the upper Weber).
- Locations with topographic configurations that produce local precipitation enhancement (e.g., Ben Lomond Peak) receive anomalously heavy precipitation for their elevation

Testable Hypotheses

The magnitude of orographic precipitation enhancement is not constant, but varies in time and space and depending on the precipitation processes operating during and within storms

- Orographic enhancement is smallest when precipitation processes are dominated by large-scale atmospheric processes, such as cold-frontal lifting
- Orographic enhancement is largest when precipitation processes are dominated by orographic processes, such as the release of potential instability by terrain-induced flows and hydrometeor sublimation/evaporation over valleys
- Changes in the large-scale circulation arising from natural climate variability and anthropogenic forcing affect the ratio of precipitation from large-scale vs. orographic processes

Testable Hypotheses

The isotopic composition of precipitation is not controlled solely by the well-known effect of Rayleigh distillation, but reflects the evolving isotopic characteristics and precipitation processes of individual storms

Deposition rates of ammonium, nitrate, sulfate, etc. are a function of atmospheric processes and cannot be predicted based on precipitation amount alone.

- Deposition rates are largest in catchments that receive heavy precipitation in flow regimes that transport such chemical species from urban areas and coal-fire powered plants.

Testable Hypotheses

Annual snowfall cannot be predicted solely from precipitation and must consider freezing level and the large-scale flow

- Annual snowfall is sensitive to interannual temperature variability and is anomalously low during warm winters in lower-elevation catchments near the mean cool-season freezing level (e.g., the Ogden Valley)
- Annual snowfall is less sensitive to interannual temperature variability in upper-elevation catchments that are well above the mean cool-season snow level (e.g., the upper Weber)
- Climate change alters hydrologic processes as a result of changes in precipitation and the elevation of the freezing and melting levels
- Large-scale circulation changes arising from natural climate variability and anthropogenic forcing affect the ratio of snowfall to rainfall

Testable Hypotheses

Annual precipitation and snowfall cannot be predicted solely from known climate signals (e.g., ENSO, PDO) or the time-mean large-scale atmospheric flow

- Low-frequency alterations in the planetary scale circulation affect the characteristics of the limited number of hydrologically significant storms that dominate seasonal snowfall and precipitation
- Annual precipitation and snowfall cannot be predicted solely from known climate signals (e.g., ENSO, PDO) or
- The likelihood of detecting regional climate change due to anthropogenic forcing is larger in basins where precipitation is poorly correlated with known interannual and interdecadal climate signals (e.g., the GSLB)
- Paleoclimate data is needed to extend knowledge and improve the predictability of hydrologic extremes such as drought and floods

Testable Hypotheses

The ratio of precipitation to ET varies strongly across the basin, within storms, seasonally, and annually. Regions that receive similar precipitation amounts and experience similar seasonal climate will differ in P/ET based upon vegetation type.

The timing of snowmelt leads to differences in the seasonal timing of ET in forests at different elevations with similar precipitation (e.g., Ogden Valley vs upper Weber). Lower elevation forests begin and end transpiring earlier and experience substantial summer drought relative to higher elevations.

Testable Hypotheses

Seasonal ET peaks as a function of elevation lead to differences in chemical transfer fluxes to streams (nitrate, sulfate, DOC, etc)

Warm season precipitation does not lead to enhanced ET in the Basin since most plants do not heavily use summer rains.

Testable Hypotheses

Urbanization affects the hydrologic cycle not only by directly altering surface moisture fluxes, but also by indirectly affecting cloud dynamics and processes

- Pollution related to urbanization, as well as point-source emissions, alters the availability, size distribution, and composition of cloud nuclei and precipitation efficiency within storms
- Increased urbanization within the Basin changes local wind flows and the distribution of precipitation as a result of changes in surface roughness and evapotranspiration

Vegetative changes produced by land use and fire management activities increase the likelihood of flash flooding produced by sporadic warm season precipitation

Testable Hypotheses

There is no significant water recycling within midlatitude semi-arid terminal basins

- Although precipitation produced by small terminal lakes can be locally heavy, its spatial coverage is too small to have a significant impact on basin integrated runoff
- Lake-effect storms produced by small terminal lakes is comprised primarily of water vapor that was advected into the region rather than fluxed from the lake surface
- There is limited ET during the winter when a majority of the precipitation falls

Existing Infrastructure

MesoWest Cooperative Networks

- Integration of existing meteorological networks including SNOTEL, RAWS, CUP, NWS, U of U, ski areas etc.
- Roughly 250 surface stations and 60 precipitation stations
- Reflects considerable cost sharing with government agencies and private companies
- Extensive MySQL database with all observations and available metadata since 1997

National Weather Service (NWS) Radar on Promontory Point

- Inadequate for many of our applications because:
  - Suffers from terrain blockage – coverage east of Wasatch very poor
  - Doesn't provide reliable precipitation estimates
  - Resolution may not fine enough to capture local orographic enhancement
  - Not polarized (useful for precip estimates) but will be by end of decade

Existing Infrastructure

NWS cooperative observers (daily and event precipitation)

3-4 flux towers in Rush Valley (west of Oquirrh Mountains)

- run by Larry Hipps, USU
- juniper, sagebrush, crested wheatgrass
- Measure ET and CO_2 fluxes

Potential Infrastructure from Pending Foundation Grant

U of U GSL Environmental Communication Network

- to be installed 2005-2006
- spread spectrum communication enabling point to multipoint Ethernet communication
- includes enhancements and upgrades to existing Francis Peak communication infrastructure
- Upgrades to met stations around GSL
- in partnership with National Weather Service, Federal Aviation Administration and Utah Department of Natural Resources and Air Quality agencies

ET Flux tower in upper Weber or Ogden River area, subalpine forest

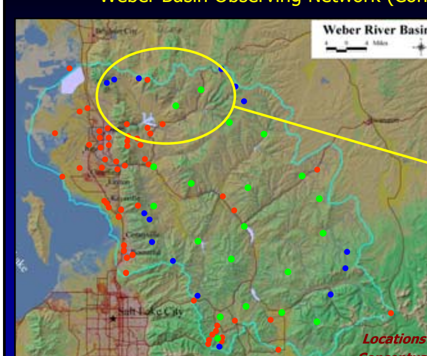
- to be installed 2005-2006
- includes tunable diode laser to measure oxygen isotopes in water vapor

Potential Infrastructure from Foundation Grant

Buoy or platform on the GSL

- In cooperation with NOAA National Buoy Data Center
- Vertical profiles of temperature and salinity
- Air temperature, humidity, atmospheric pressure, solar radiation, wind, and fluxes
- Wave height and surface currents

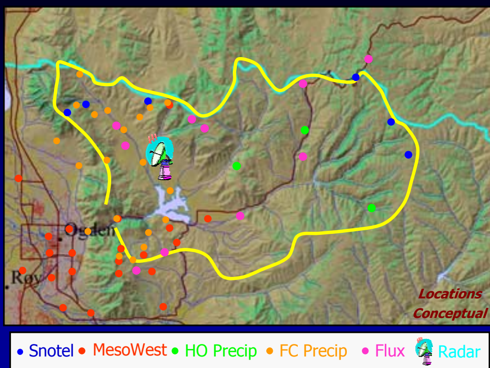
Weber Basin Observing Network (Conceptual)



- Snotel
- MesoWest
- HO Precip

Ogden Valley Focus Catchment

Ogden Valley Focus Catchment (Conceptual)



Strengths and Weaknesses of Ogden Valley

Strengths
- Variable influence of Great Salt Lake from west to east
- Wettest region of entire GSLB at many elevations
- Considerable spatial and temporal variability within storms
- Large elevation (1500-2950 m), climate, precipitation, ecosystem gradients
- Undergoing rapid development
- Reasonable access
- Private land at upper elevations
- Gradual terrain for ET flux towers
- Low elevation cuts through Wasatch Mountains
- NEXRAD Radar coverage "as good as it gets" in Weber; probably could site a scanning radar in or around Ogden Valley
- Access to Wasatch Crest at Snowbasin Ski Resort

Weaknesses
- See above
- Difficult to access Wasatch Crest except at Snowbasin
- Limited amounts of high alpine coniferous forest

Basin-Wide Precipitation Network

Supplements existing SNOTEL/MesoWest stations which sample a limited range of elevations, aspects, and climate zones

Station design analogous to SNOTEL
- Snow water equivalent instrumentation for daily, monthly and annual precipitation and snowpack SWE
  - Optional monthly or annual sampling for isotopic/chemical composition
- Ultrasonic snow-depth sensor
- Temperature
- Spread-spectrum communications
- Collocate with snowpack & surface hydrology measurements where advantageous

10-20 stations distributed throughout Weber *at various elevations and aspects*

$15,000/site

Focus Catchment Precipitation Network

Measures precipitation and other atmospheric hydrologic drivers (e.g., temperature) at high resolution within catchment basin

High frequency precipitation, land-surface, and weather observations
- Yankee Total Precipitation Sensor (high frequency precipitation)
- Snow water equivalent instrumentation for monthly or annual sampling of isotopic/chemical composition
- Disdrometer (precipitation type, selected locations)
- Ultrasonic snow-depth sensor
- Temperature, RH, wind speed and direction
- Solar radiation
- Soil Moisture and temperature
- Snow surface temperature
- Spread spectrum comms

20 stations distributed throughout Ogden Valley focus catchment

$30,000/site + $5,000/disdrometer

Water Flux and Energy Balance Network

Quantifies evapotranspiration and the surface energy balance over Weber Basin (emphasis on focus catchment)

Needed to validate land-surface models and remote sensing algorithms

Surface flux & energy budget stations consisting of level 2 instruments supplemented with
- 3D sonic anemometer
- krypton hygrometer
- closed-path infrared gas analyzer
- four-component radiation (short and longwave both up and down)
- photosynthetically active radiation
- full energy balance (including soil heat flux, soil T, bole T, etc)
- sapflow (tree transpiration)

10 stations throughout Weber Basin, but concentrated in the Ogden Valley focus catchment (cannot be used in complex local terrain)

$75,000/site

Tree Transpiration Network

Used to measure transpiration rate of trees and shrubs
- co-located with micrometeorology stations and surface flux stations
- CAN be used in complex terrain – critical to extend transpiration measurements to sites where flux towers will not work

30 stations throughout Weber Basin, but concentrated in Forks of Ogden Valley Focus Catchment

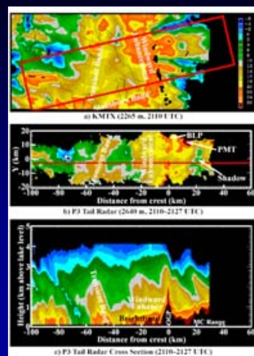
$7,000/site

Distributed Precipitation Radar Network

Estimates precipitation rates and phases (e.g., rain, snow) across focus catchment and possibly across Weber Basin

Critical for studies of precipitation processes

- 1-2 scanning polarimetric Doppler radars (S, C, or X-band)
- 1-2 vertically pointing Doppler radars
- High ticket item
  - Cost dependent on final scientific objectives
  - Could be permanent or portable and deployed for field campaigns



Radar Wind Profiler

Provides vertical profiles of wind direction and Doppler Velocity to better understand orographic precipitation processes, estimate precipitation rates, and determine snow levels

- $125,000 each

Integrated Atmospheric Precipitable Water Network

Needed to measure atmospheric water vapor transport and airmass transformation by GSL and topography

~10 GPS-based stations situated at existing or proposed weather stations throughout the GSLB

$10,000 per station

GSLB Land-Atmosphere Data Assimilation System

Example of a possible first-publication dataset

Integrates all available observations in 3 dimensions from atmosphere as well as surface and near subsurface

Used for hydrologic process studies and as input to hydrometeorological models

Horizontal grid spacing of .5-1km

Hourly forecast-data assimilation cycle

3D Atmospheric variables

- temperature, dewpoint temperature, wind, wind gust, pressure, precipitation, cloud cover and composition (ice, water, snow)

Surface variables

- lake surface temperature and salinity, land surface and subsurface temperature, snow cover and depth

First look (Level 0) data set could be provided in near-real time with archive-quality data (Level 1) provided after a week

Thoughts on Operations

Observing instrumentation and siting must be planned for maximum flexibility and expandability to accommodate evolving scientific needs

Must not be run as an extension of existing research labs

Critical to hire an experienced, full-time, *Facilities Manager* immediately after notice of funding

Partner with NCAR to broaden participation of scientists and insure early success of HO

- 30 y of instrumentation deployment and scientific experience on the atmospheric side of the water cycle
- Long record of scientific research through its Water Cycles Across Scales initiative
- Assistance of Earth Observing Lab for design, construction, and implementation of atmospheric facilities
- Participation of scientists from EOL and Water Cycle Initiative in HO design and development of scientific hypotheses
- Also a PI on Rio Grande Proposal

Integration

Work to develop our science drivers and hypotheses so they are closely coupled with the snowpack hydrology, stream hydrology, and paleohydrology groups

Design of met, snowpack, & land-surface networks should be complimentary

- Co-location *where desirable*
  - NOTE: It is not always optimal to colocate!
- Instrumentation should not be viewed strictly as “atmospheric”

Prioritize of core instrumentation based on consultation with other groups

Next Steps

Adjourn to Squatters Brew Pub

Increase interactions with other groups

Reassess priorities and budget

Locations of Critical Processes

Mountains
- Precipitation enhancement during most events
- Roughly 4 times valley precip, most as snow
- sublimation of snowpack
- timing of snowmelt influences timing of ET peak from transpiration

Valleys
- Precipitation suppression in some events from hydrometeor sublimation and evaporation

Over and upstream of windward slopes (precipitation enhancement processes)

Over and downstream of leeward slopes
- Hydrometeor spillover into immediate lee
- Reduced precipitation farther downstream advection and downstream

Over the GSL
- Heat, momentum, and moisture fluxes

Downstream of GSL
- Lake-effect precipitation

Location of snow level during precipitation events

Location of freezing level
- mean and variability during cool season

Critical Temporal Events

Cool Season
- Snowpack is primary driver of the GSL Hydrologic System

Warm Season
- Flash flood events due to slow moving convective systems

Major storm cycles (10-20% of cool-season precipitation can fall in a single event)
- Occur in a variety of synoptic patterns and favorable flows for precipitation vary across basin

Persistent cool-season anticyclones (high-pressure systems)

Lake-effect snowstorms
- For some catchments

Cool-season warm events
- the "January thaw" (may occur in other months)
- "Hatu Wind" events (strong, warm, dry southerlies for snowpack melting and sublimation)

Rainstorms prior to first snowfall
- soil moisture

Winter cold air pools
- Precipitation can develop as a result of lift over cold pools
- Venting of pollution at end of cold pool event may affect precipitation processes

Phenomenon affecting local climate variability
- ENSO, PDO, etc.
- NOTE: Climate drivers for GSLB now well understood