Addressing Hydrologic Extremes and Dealing With the Stationarity Assumption in Water Resources Systems Operations & Planning

Soroosh Sorooshian

Center for Hydrometeorology and Remote Sensing

University of California Irvine

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University of California Irvine (UCI) and Arizona (UA)

CHRS & Affiliates: A truly International Team

Climate – Hydrology - Extremes

Nothing new about the occurrence of hydrologic Extremes

What is new:

- The recent predictions (i.e., IPCC) that with the intensification of hydrologic cycle (due to warming), we will experience more hydrologic extremes - invalidating the stationarity assumption ?

- With the increase in population & urbanization, impacts of extremes will be more severe on society (resources, infrastructure, etc.)

Challenges Posed by Hydrologic Extremes:

- ***Floods: The Primary Hydrologic Hazard***
  - ***Heavy Precipitation***
  - ***Rapid melting of snow***

- ***Droughts: Major impact on water supply availability***
  - ***Lack of precipitation***

Hydrologically-Relevant Climate Variables

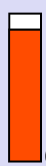
What Do "Instrumental" Records Tell Us?

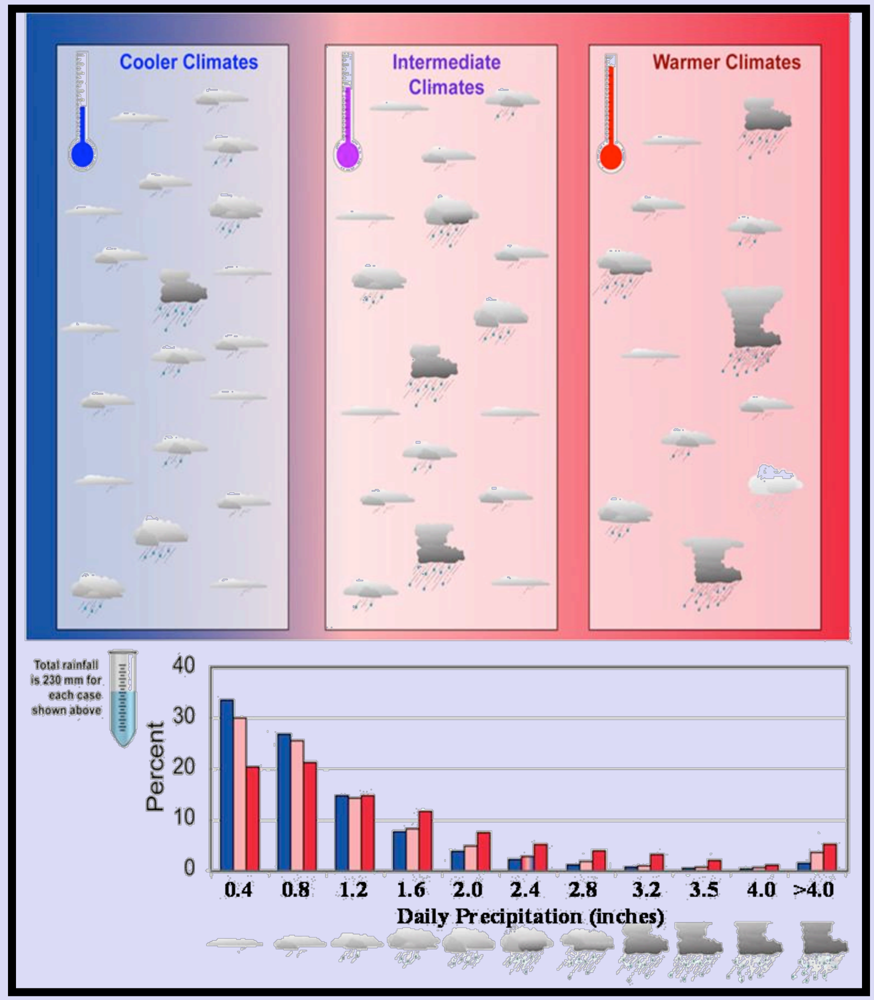
Changes in Precipitation: U.S.A

Facts from Observations

- From 1908-2002:
  - Total annual precipitation across the contiguous U.S. increased 7%
  - Heavy daily Precipitation events have increased by 20%

- Rainfall associated with warmer climates are more due to extreme events compared to colder climates



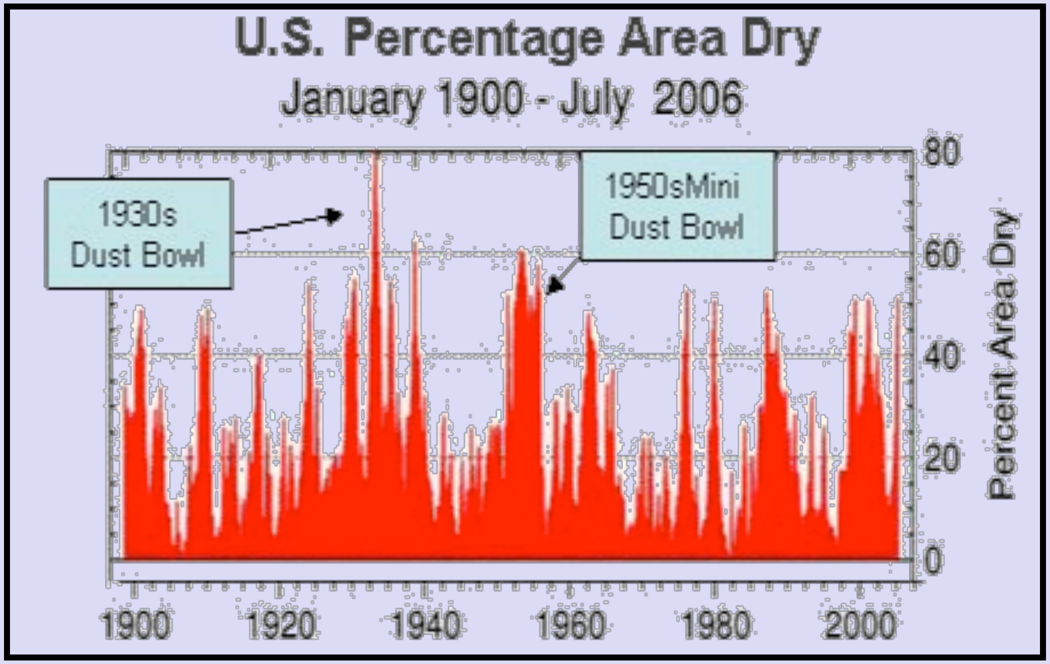


Source: Tom Karl NCDC-NOAA 2007

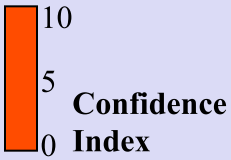
Observed changes: Drought

Drought activity during the 20th and early 21st Century

- U.S. droughts show pronounced multi-year to multi-decadal variability, **but no convincing evidence for long-term trends toward more or fewer events.**

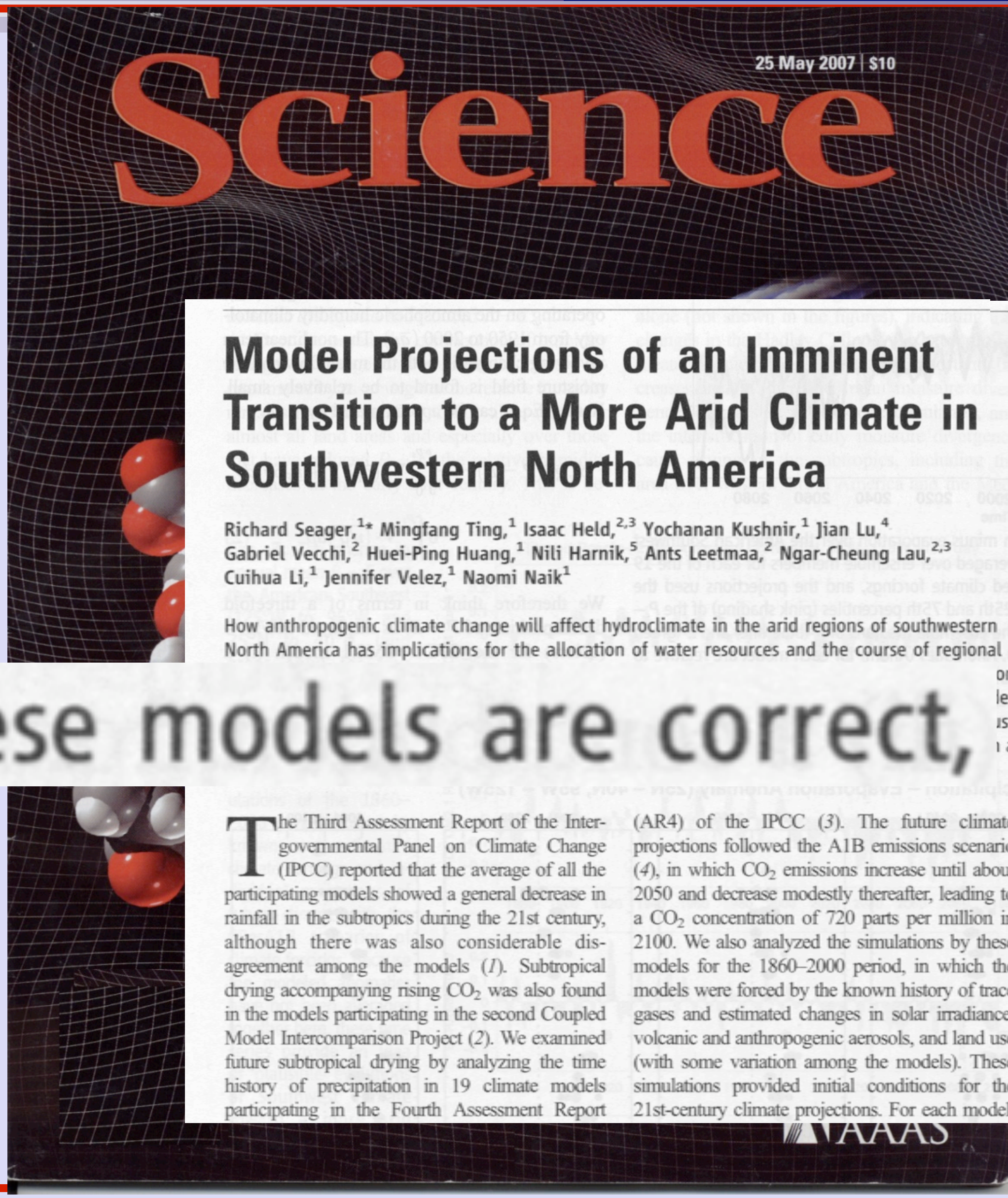


Based on Palmer Drought Index
Moderate to Extreme Drought



Source: Tom Karl NCDC-NOAA 2007

A Dryer Future for Southwest US?



Model Projections of an Imminent Transition to a More Arid Climate in Southwestern North America

Richard Seager,[1*] Mingfang Ting,[1] Isaac Held,[2,3] Yochanan Kushnir,[1] Jian Lu,[4] Gabriel Vecchi,[2] Huei-Ping Huang,[1] Nili Harnik,[5] Ants Leetmaa,[2] Ngar-Cheung Lau,[2,3] Cuihua Li,[1] Jennifer Velez,[1] Naomi Naik[1]

How anthropogenic climate change will affect hydroclimate in the arid regions of southwestern North America has implications for the allocation of water resources and the course of regional

If these models are correct,

The Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) reported that the average of all the participating models showed a general decrease in rainfall in the subtropics during the 21st century, although there was also considerable disagreement among the models (*1*). Subtropical drying accompanying rising CO_2 was also found in the models participating in the second Coupled Model Intercomparison Project (*2*). We examined future subtropical drying by analyzing the time history of precipitation in 19 climate models participating in the Fourth Assessment Report (AR4) of the IPCC (*3*). The future climate projections followed the A1B emissions scenario (*4*), in which CO_2 emissions increase until about 2050 and decrease modestly thereafter, leading to a CO_2 concentration of 720 parts per million in 2100. We also analyzed the simulations by these models for the 1860–2000 period, in which the models were forced by the known history of trace gases and estimated changes in solar irradiance, volcanic and anthropogenic aerosols, and land use (with some variation among the models). These simulations provided initial conditions for the 21st-century climate projections. For each model,

precipitation minus the evaporation ($P - E$), averaged over this region for the period common to all of the models (1900–2098). The median, 25th, and 75th percentiles of the model $P - E$ distribution and the median of P and E are shown. For cases in which there were multiple simulations with a single model, data from these simulations were averaged together before computing the distribution. $P - E$ equals the moisture convergence by the atmospheric flow and (over land) the amount of water that goes into runoff.

In the multimodel ensemble mean, there is a transition to a sustained drier climate that begins in the late 20th and early 21st centuries. In the ensemble mean, both P and E decrease, but the former decreases by a larger amount. $P - E$ is primarily reduced in winter, when P decreases and E is unchanged or modestly increased, whereas in summer, both P and E decrease. The annual mean reduction in P for this region, calculated from rain gauge data within the Global Historical Climatology Network, was 0.09 mm/day between 1932 and 1939 (the Dust Bowl drought) and 0.13 mm/day between 1948 and 1957 (the 1950s Southwest drought). The ensemble median reduction in P that drives the reduction in $P - E$ reaches 0.1 mm/day in midcentury, and one quarter of the models reach this amount in the early part of the current century.

The annual mean $P - E$ difference between 20-year periods in the 21st century and the 1950–2000 climatology for the 19 models are shown in Fig. 2. Almost all models have a drying trend in the American Southwest, and they con-

Hydrologically-Relevant Climate Variables

What are the hydrologic predication requirements and how well are we satisfying them?

Required Hydrometeorologic Predictions

Short Range - > Long Range

hours - - - - > days - - - - > weeks - - - > months - - > seasons - - > years - - - - - - > decades

Flash Flood Warning

Flash Flood Guidance

Headwater Guidance

Flood Forecast Guidance

Reservoir Inflow Forecasts

Spring Snow Melt Forecasts

Water Supply Volume

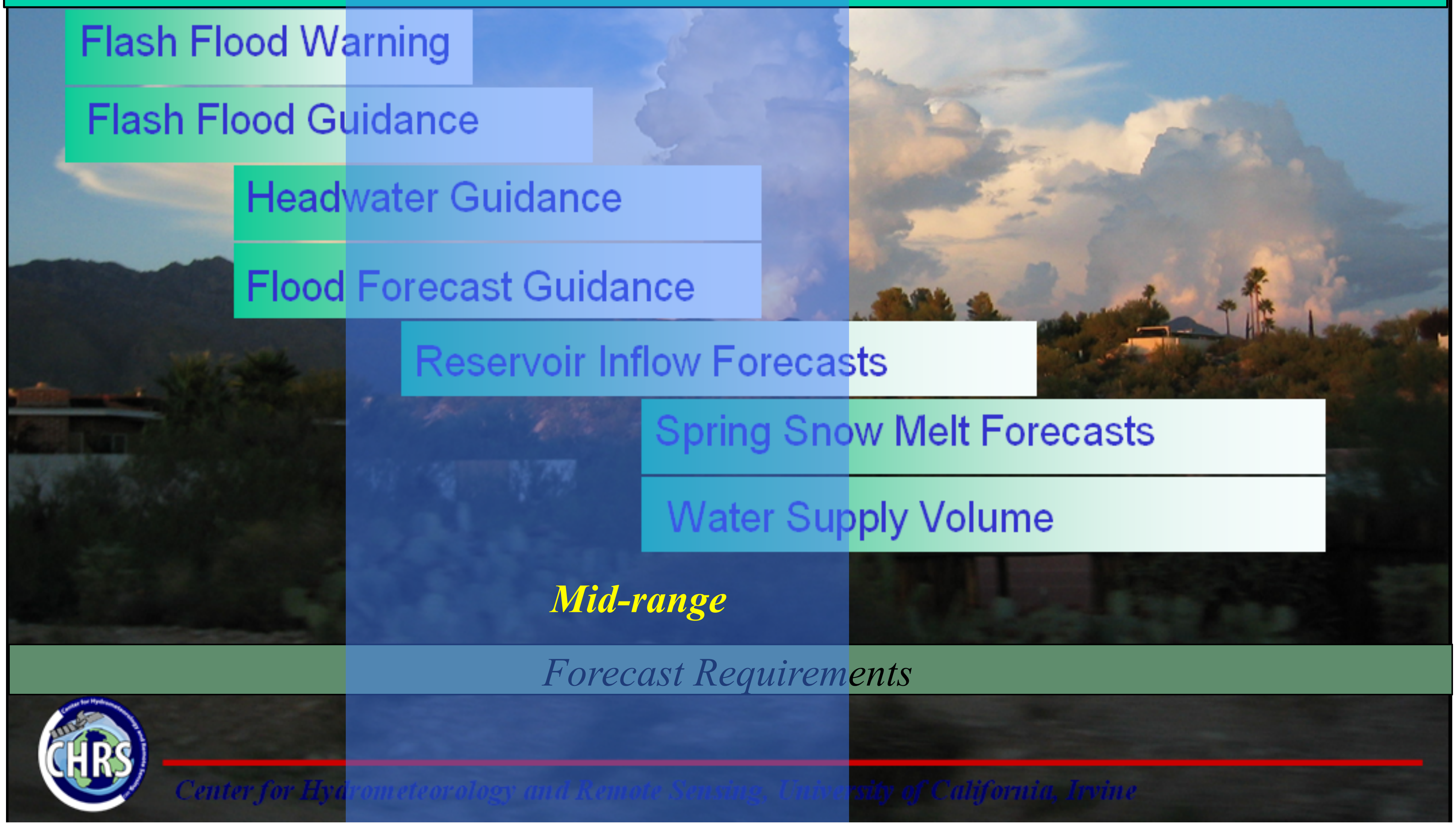
Short-range ***Mid-range*** ***Long-range***

Forecast Requirements

Required Hydrometeorologic Predictions

Short Range - · - · - · - · - · - · - · - · - · - · - · - · - · - ->Long Range

hours - - - -> days - - - -> weeks - - -> months - -> seasons - -> years - - - - - -> decades



Flash Flood Warning

Flash Flood Guidance

Headwater Guidance

Flood Forecast Guidance

Reservoir Inflow Forecasts

Spring Snow Melt Forecasts

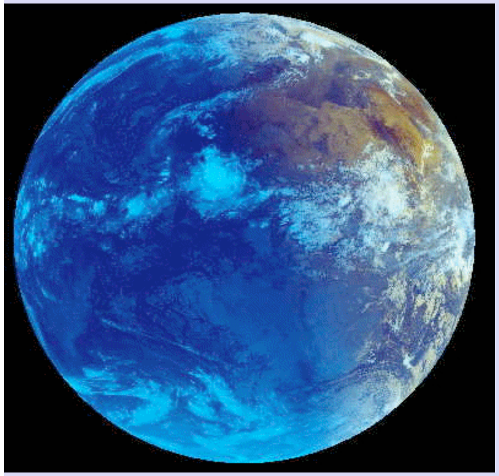
Water Supply Volume

Mid-range

Forecast Requirements

Recent Assessment of Seasonal Climate Forecasts

Quoting from Science, Vol. 321, 15th August 2008



- ***" of the dozens of forecast techniques proffered by government, academic, private-sector climatologists, all but two are virtually useless, according to a new study"*** *Livezey &Timofeyeva - BAMS, June 2008.*
- ***"About the only time forecasts had any success predicting precipitation was for winters with an El Nino or a La Nina"***

Climate-Scale approaches to addressing hydrologic extremes

Short Range - · - · - · - · - · - · - · - · - · - · - · - · - · - · -> Long Range

hours ----> days ----> weeks ---> months --> seasons --> years ------> decades

- ***Use of climate models: down-scaling and ensemble schemes***

- ***Traditional statistical hydrology methods:***

Climate-Scale approaches to addressing hydrologic extremes

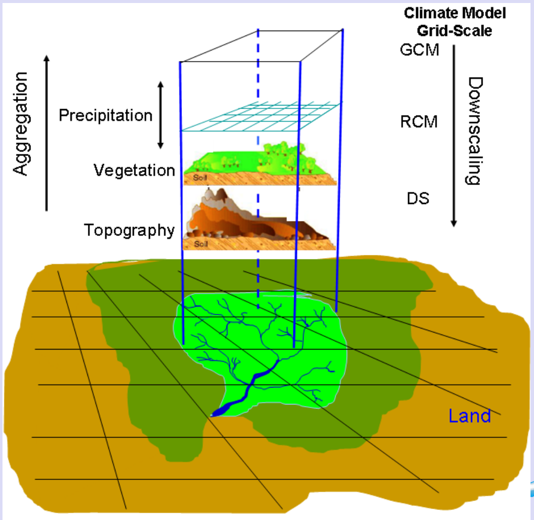
Short Range -> Long Range

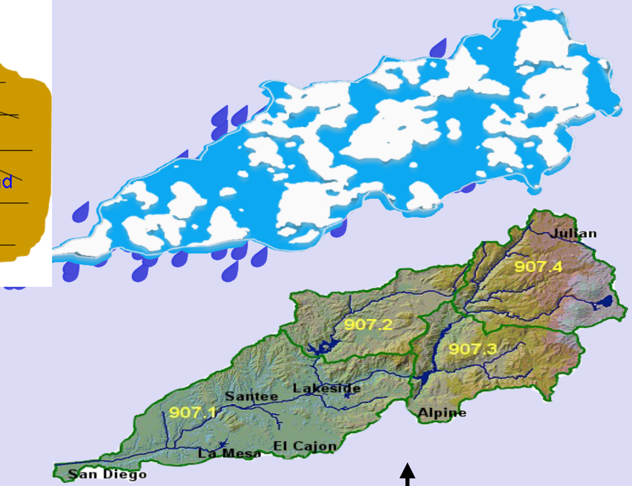
hours - - - -> days - - - -> weeks - - -> months - -> seasons - -> years - - - - - -> decades

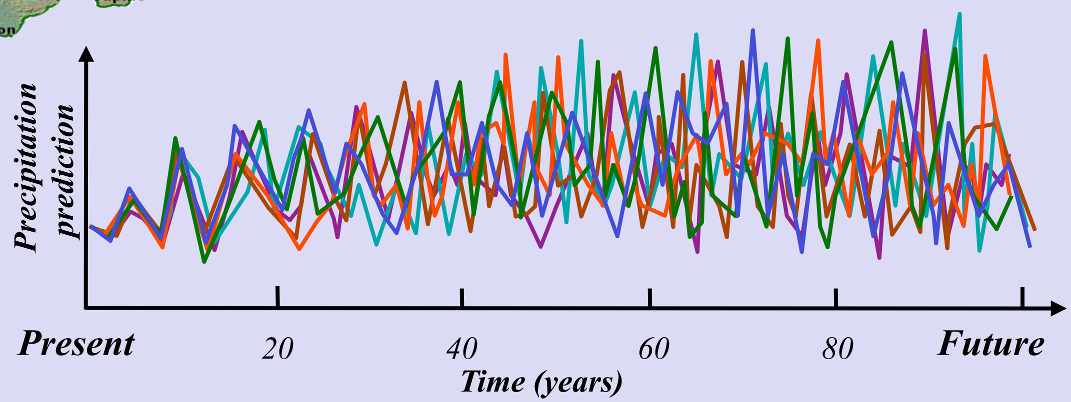
- ***Use of climate models: down-scaling and ensemble schemes***

Climate Model Downscaling to Regional/Watershed Scales

Generation of Future Precipitation Scenarios

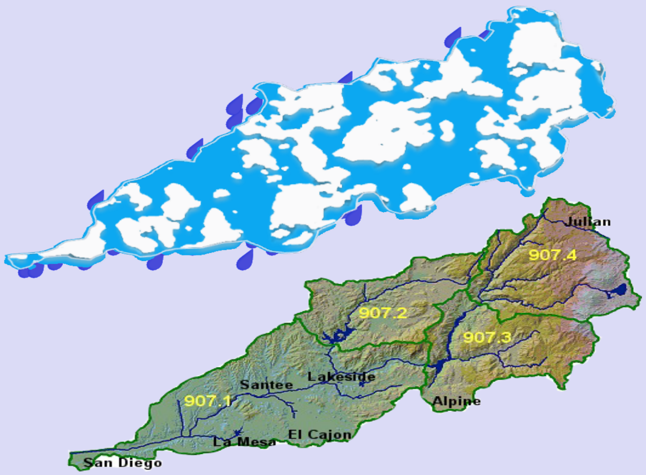


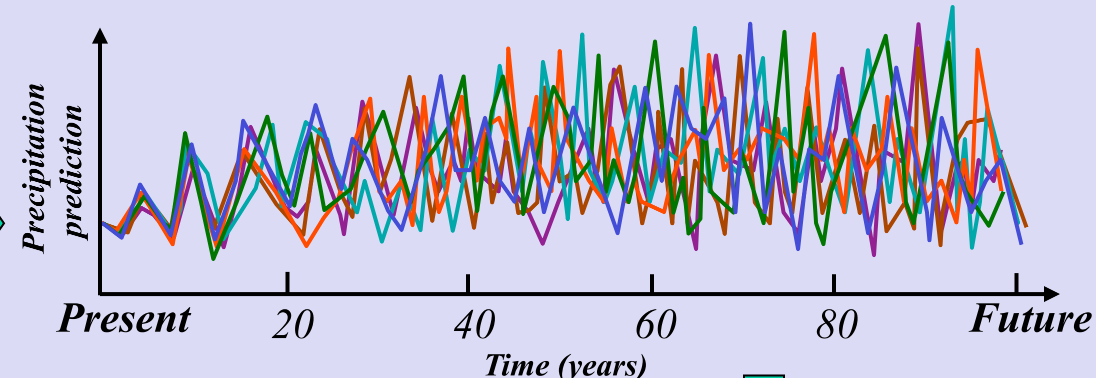


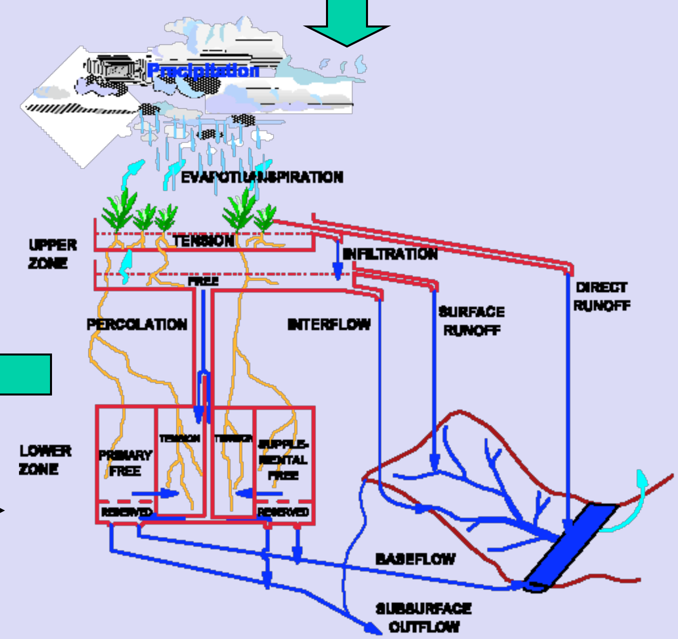


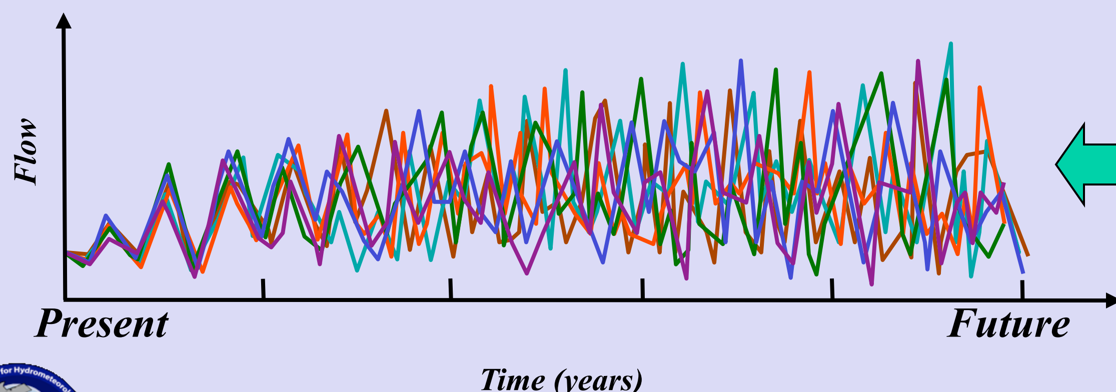
Downscaled Precipitation to Runoff Generation

Generation of Future Runoff Scenarios



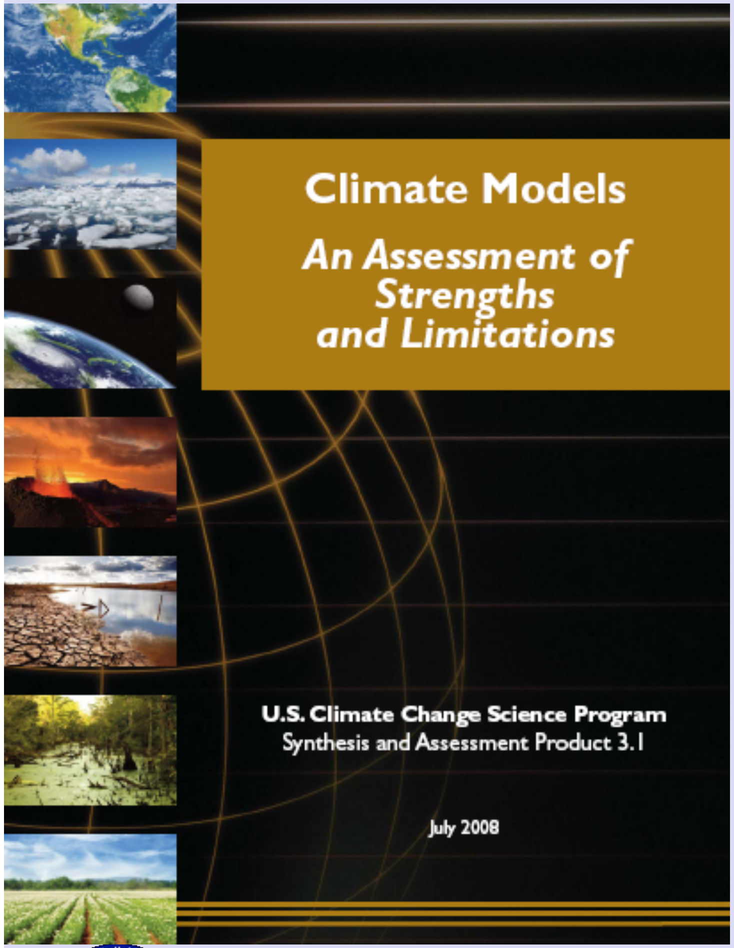






Recent Assessment of Climate Models

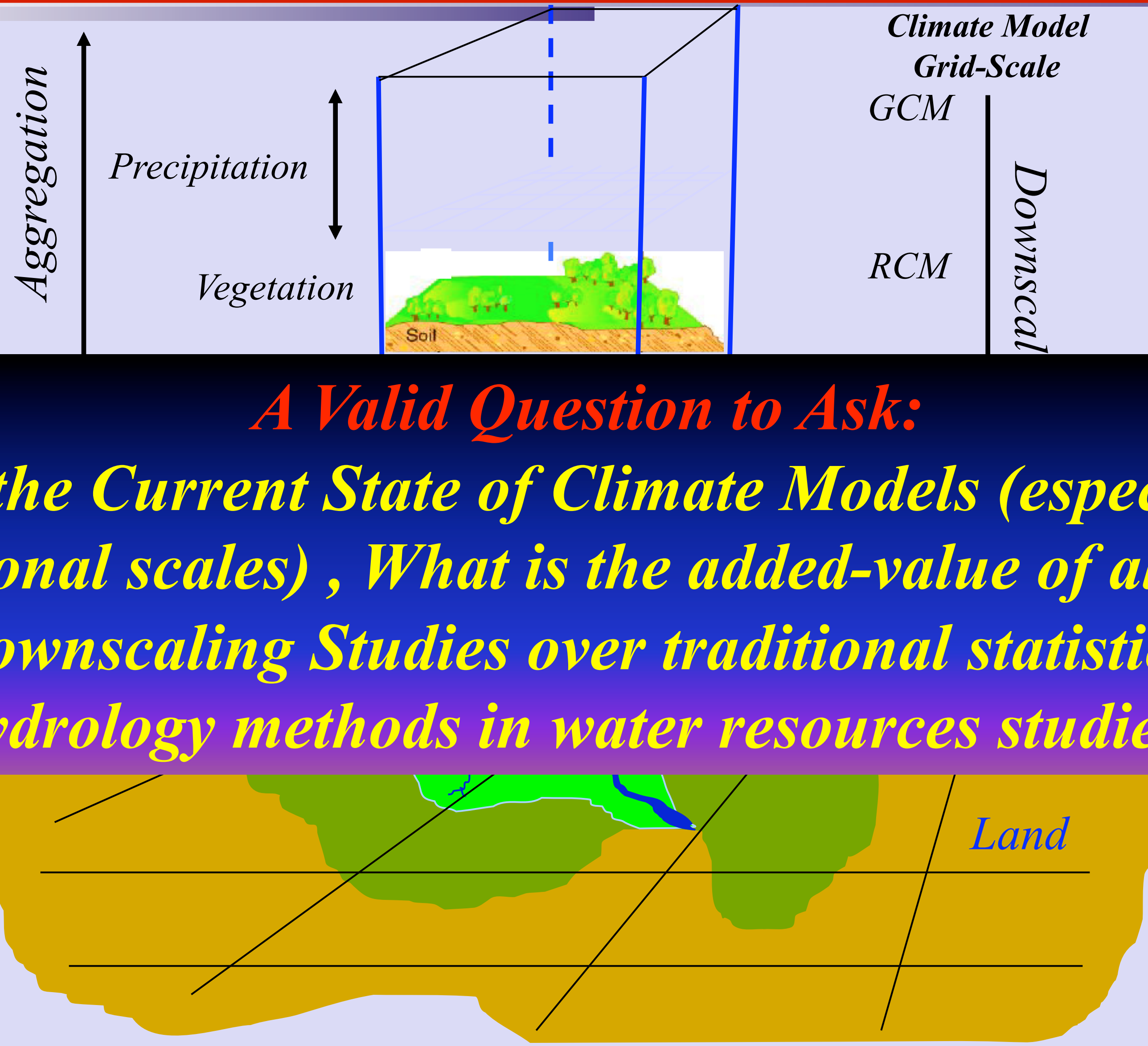
How Accurate Are Global Climate Models?



- Regional trends in extreme events are not always captured by current models

- It is difficult to assess the significance of these discrepancies and to distinguish between model deficiencies and natural variability

Climate Model Downscaling to regional/watershed Scale



A Valid Question to Ask:

Given the Current State of Climate Models (especially at regional scales) , What is the added-value of all the Downscaling Studies over traditional statistical hydrology methods in water resources studies?

Climate-Scale approaches to addressing hydrologic extremes

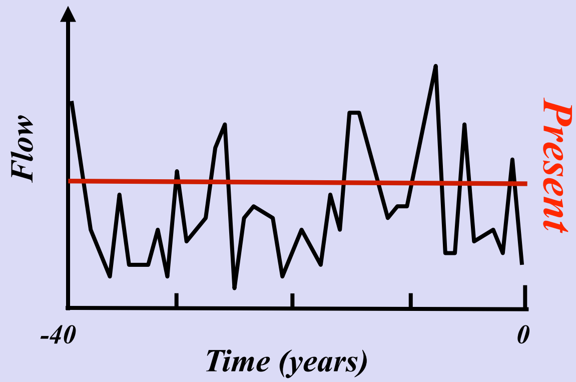
Short Range - · - · - · - · - · - · - · - · - · - · - · - · - · - · ->Long Range

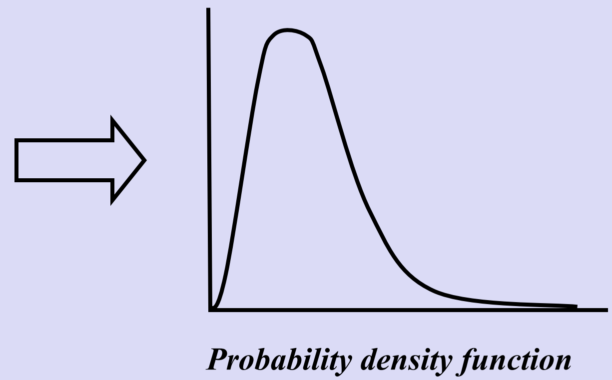
hours ----> days ----> weeks ---> months --> seasons --> years ------> decades

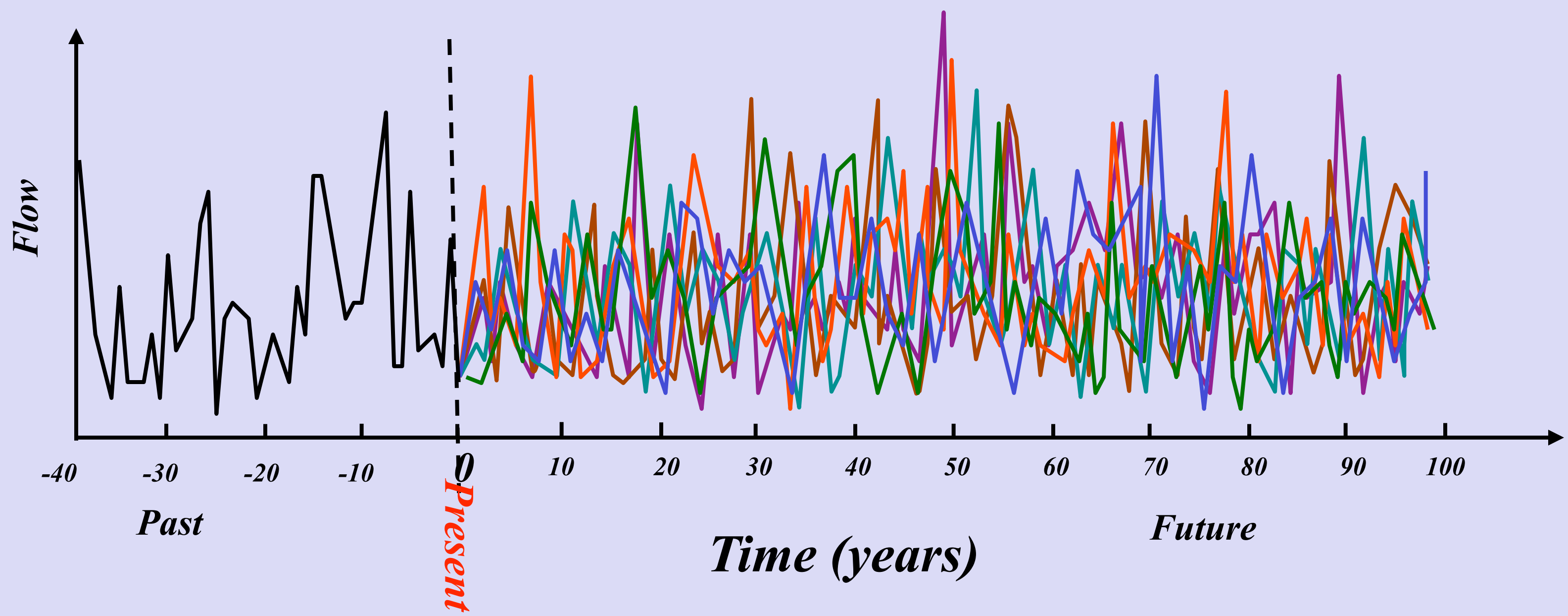
- ***Use of climate models: down-scaling and ensemble schemes***

- ***Traditional statistical hydrology methods:***

Statistical Hydrology: "synthetic" streamflow Generation







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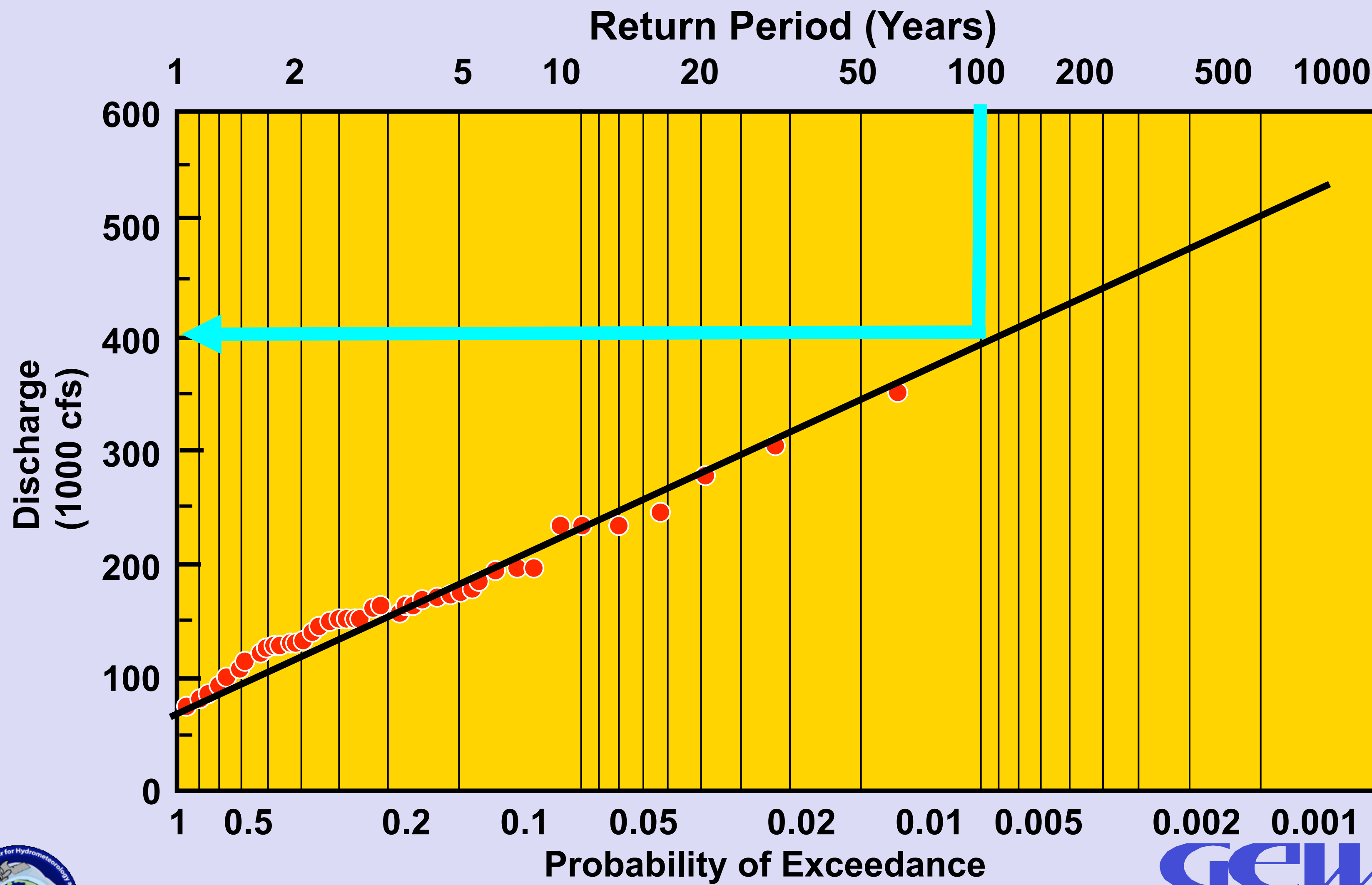
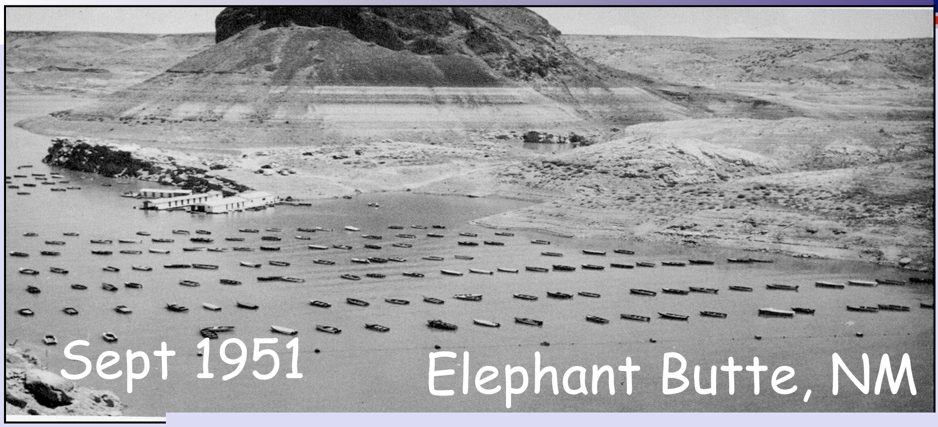
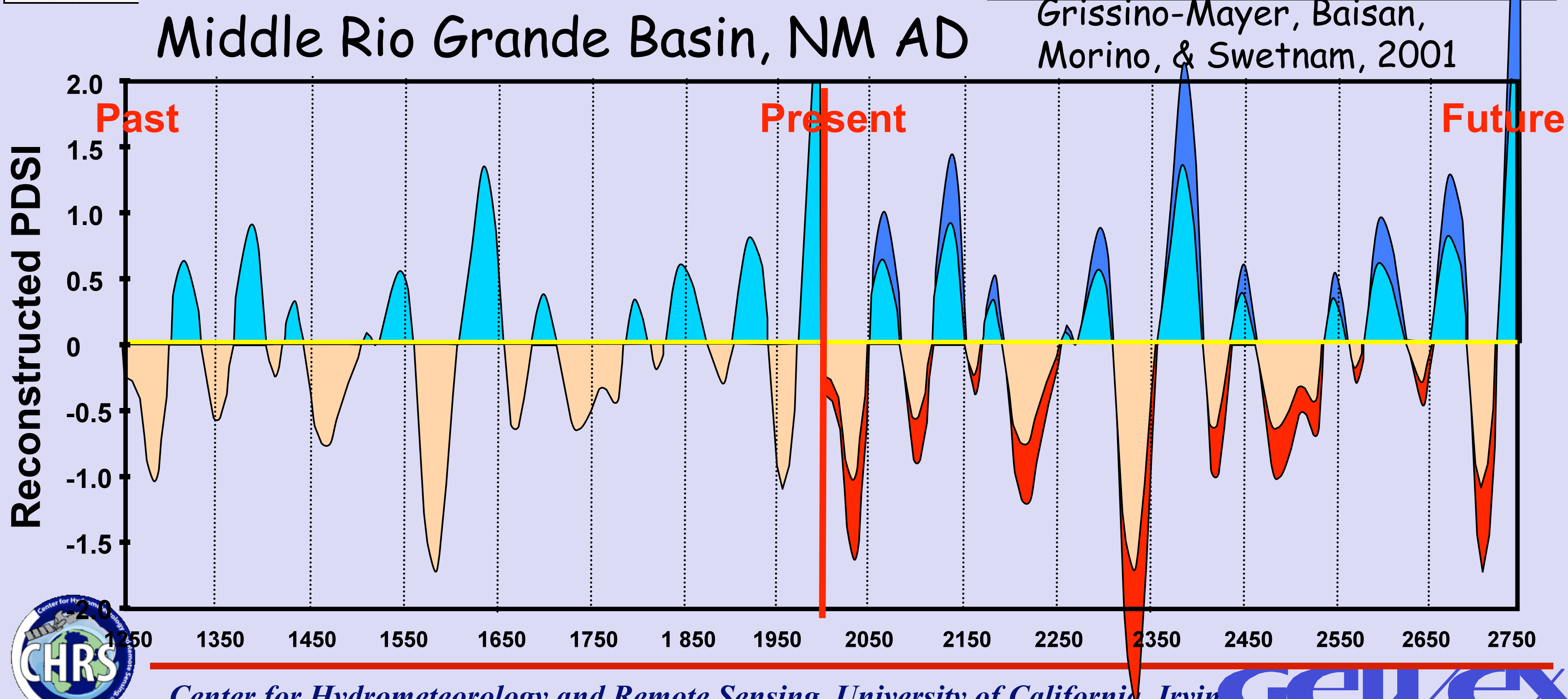
Potential Hydrologic Scenario: Stationarity!



Statistical Hydrology Developed Based on Stationarity Assumption





Impact of Nonstationarity on Water Resources

POLICYFORUM

CLIMATE CHANGE

Stationarity Is Dead: Whither Water Management?

Climate change undermines a basic assumption that historically has facilitated management of water supplies, demands, and risks.

P. C. D. Milly,[1]* Julio Betancourt,[2] Malin Falkenmark,[3] Robert M. Hirsch,[4] Zbigniew W. Kundzewicz,[5] Dennis P. Lettenmaier,[6] Ronald J. Stouffer[7]

Systems for management of water throughout the developed world have been designed and operated under the assumption of stationarity. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering. It implies that any variable (e.g., annual streamflow or annual flood peak) has a time-invariant (or 1-year–periodic) probability density function (pdf), whose properties can be estimated from the instrument record. Under stationarity, pdf estimation errors are acknowledged, but have been assumed to be reducible by additional observations, more efficient estimators, or regional or paleohydrologic data. The pdfs, in turn, are used to evaluate and manage risks to water supplies, waterworks, and floodplains; annual global investment in water infrastructure exceeds U.S.$500 billion (*1*).

The stationarity assumption has long been compromised by human disturbances in river basins. Flood risk, water supply, and water quality are affected by water infrastructure, channel modifications, drainage works, and land-cover and land-use change. Two other (sometimes indistinguishable) challenges to stationarity have been externally forced, natural climate changes and low-frequency, internal variability (e.g., the Atlantic multidecadal oscillation) enhanced by the slow dynamics of the oceans and ice sheets (*2*, *3*). Planners have tools to adjust their analyses for known human disturbances within river basins, and justifiably or not, they generally have considered natural change and variability to be sufficiently small to allow stationarity-based design.

An uncertain future challenges water planners.

In view of the magnitude and ubiquity of the hydroclimatic change apparently now under way, however, we assert that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning. Finding a suitable successor is crucial for human adaptation to changing climate.

How did stationarity die? Stationarity is dead because substantial anthropogenic change of Earth's climate is altering the means and extremes of precipitation, evapotranspiration, and rates of discharge of rivers (*4*, *5*) (see figure, above). Warming augments atmospheric humidity and water transport. This increases precipitation, and possibly flood risk, where prevailing atmospheric water-vapor fluxes converge (*6*). Rising sea level induces gradually heightened risk of contamination of coastal freshwater supplies. Glacial meltwater temporarily enhances water availability, but glacier and snow-pack losses diminish natural seasonal and interannual storage (*7*).

Anthropogenic climate warming appears to be driving a poleward expansion of the subtropical dry zone (*8*), thereby reducing runoff in some regions. Together, circulatory and thermodynamic responses largely explain the picture of regional gainers and losers of sustainable freshwater availability that has emerged from climate models (see figure, p. 574).

Why now? That anthropogenic climate change affects the water cycle (*9*) and water supply (*10*) is not a new finding. Nevertheless, sensible objections to discarding stationarity have been raised. For a time, hydroclimate had not demonstrably exited the envelope of natural variability and/or the effective range of optimally operated infrastructure (*11*, *12*). Accounting for the substantial uncertainties of climatic parameters estimated from short records (*13*) effectively hedged against small climate changes. Additionally, climate projections were not considered credible (*12*, *14*).

Recent developments have led us to the opinion that the time has come to move beyond the wait-and-see approach. Projections of runoff changes are bolstered by the recently demonstrated retrodictive skill of climate models. The global pattern of observed annual streamflow trends is unlikely to have arisen from unforced variability and is consistent with modeled response to climate forcing (*15*). Paleohydrologic studies suggest that small changes in mean climate might produce large changes in extremes (*16*), although attempts to detect a recent change in global flood frequency have been equivocal (*17*, *18*). Projected changes in runoff during the multidecade lifetime of major water infrastructure projects begun now are large enough to push hydroclimate beyond the range of historical behaviors (*19*). Some regions have little infrastructure to buffer the impacts of change.

Stationarity cannot be revived. Even with aggressive mitigation, continued warming is very likely, given the residence time of atmospheric CO_2 and the thermal inertia of the Earth system (*4*, *20*).

A successor. We need to find ways to identify nonstationary probabilistic models of relevant environmental variables and to use those models to optimize water systems. The challenge is daunting. Patterns of change are complex; uncertainties are large; and the knowledge base changes rapidly.

Under the rational planning framework advanced by the Harvard Water Program (*21*, *22*), the assumption of stationarity was

[1]U.S. Geological Survey (USGS), c/o National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory, Princeton, NJ 08540, USA. [2]USGS, Tucson, AZ 85745, USA. [3]Stockholm International Water Institute, SE 11151 Stockholm, Sweden. [4]USGS, Reston, VA 20192, USA. [5]Research Centre for Agriculture and Forest Environment, Polish Academy of Sciences, Poznań, Poland, and Potsdam Institute for Climate Impact Research, Potsdam, Germany. [6]University of Washington, Seattle, WA 98195, USA. [7]NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ 08540, USA.

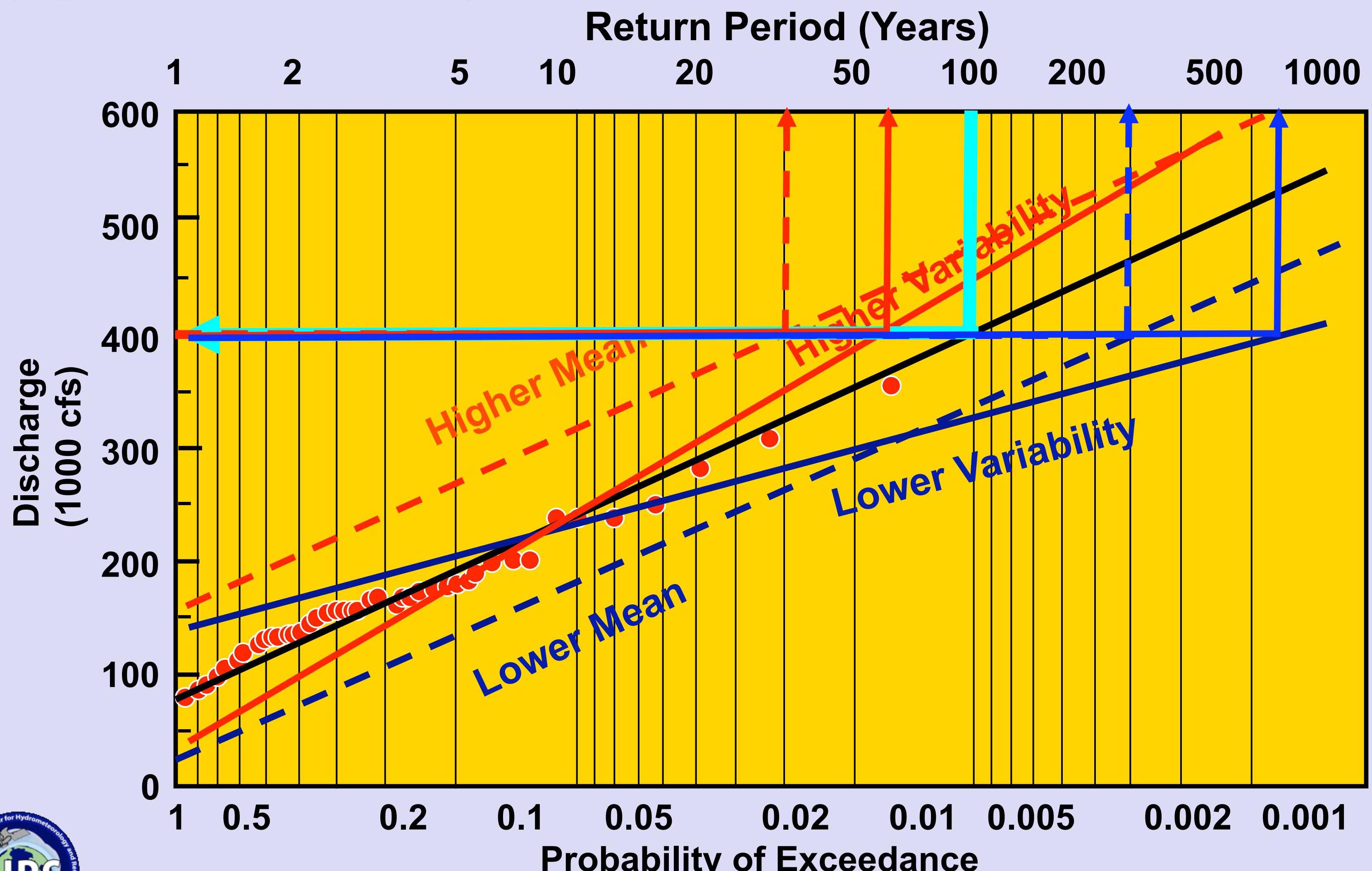
*Author for correspondence. E-mail: cmilly@usgs.gov.

Downloaded from www.sciencemag.org on February 4, 2008

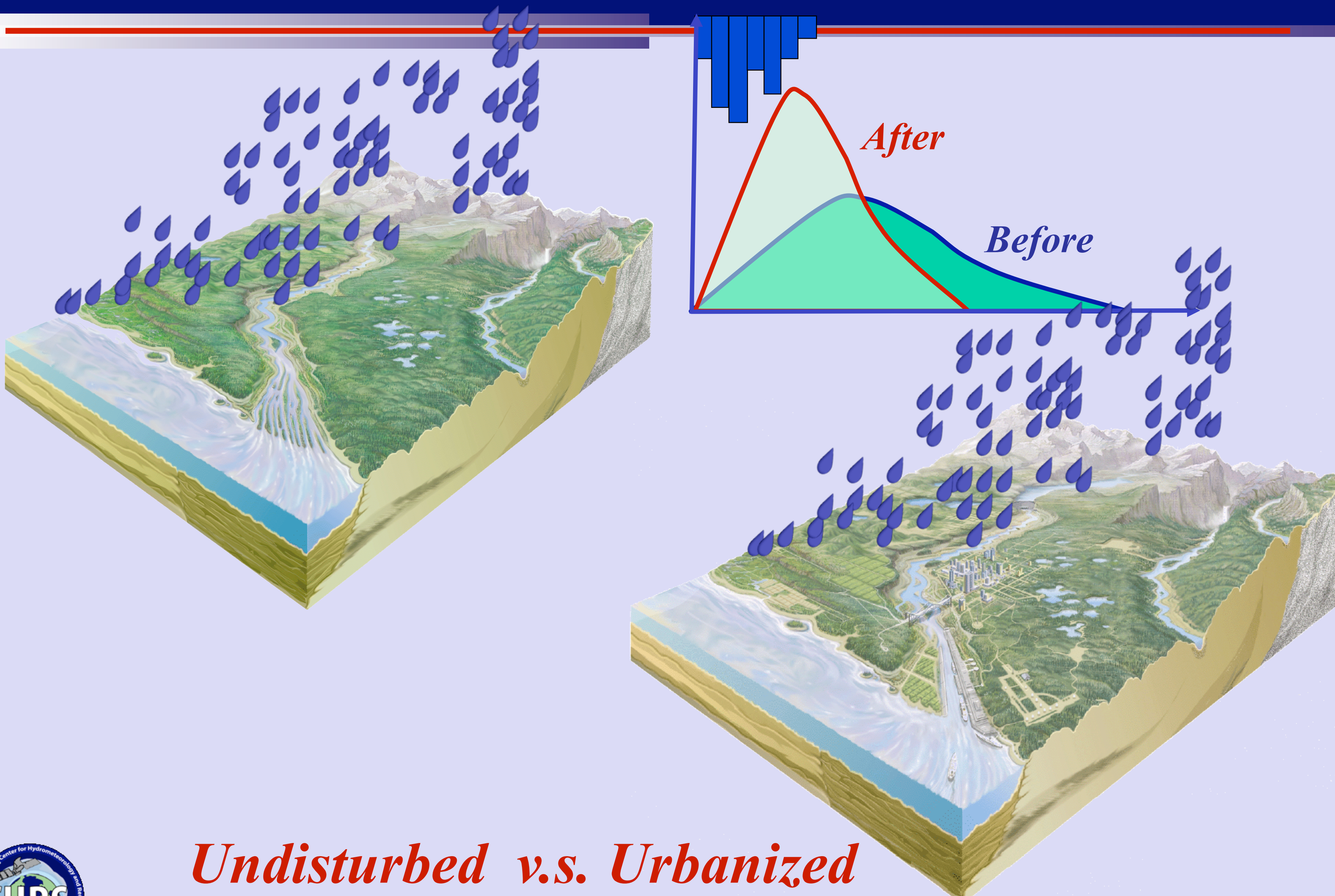
Potential Hydrologic Scenarios

1. Precipitation and Runoff Trends
(e.g. increase/decrease)

2. Hydrologic Variability
(e.g. magnitude/severity/duration)



Increase in Runoff not always due to Increase in Precip.



Undisturbed v.s. Urbanized

What is the Message?

•Presently, the accuracy of regional-scale climate model fall short of meeting the requirements of water resources planning.

Factoring in Resiliency in water resources systems design and planning is still the safest approach!

•Th… hydrology methods should not be … Research is required to advance their capability to address non-stationarity.


Thank You For Listening
08/14/2009
Somewhere in New Mexico, USA - Photo: J. Sorooshian

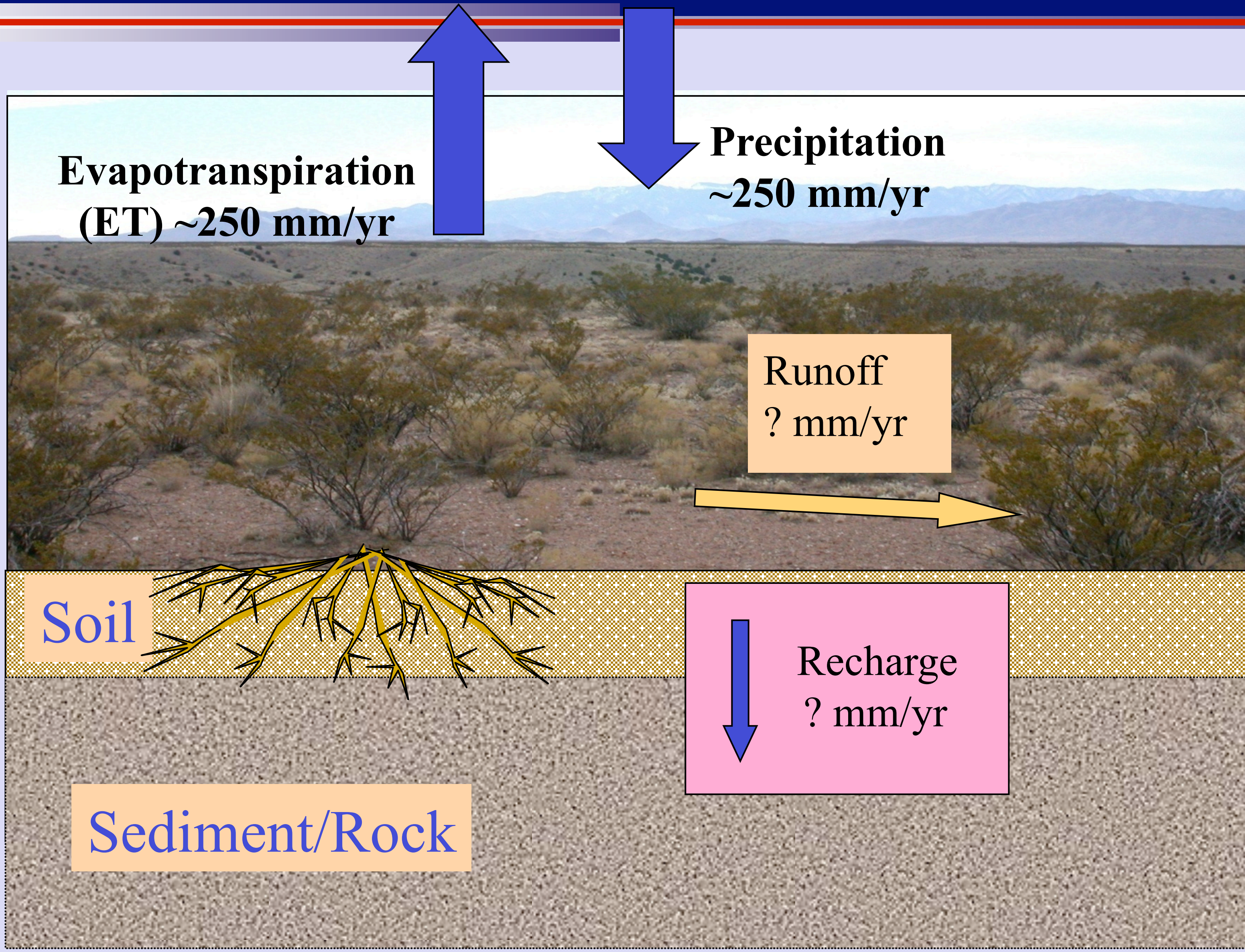
Back up slides

Some of the Issues facing the Arid & Semi-Arid Regions:

Implications of Hydrologic Variability

(Extremes)

Water balance in Semi Arid Regions



Source: Eric Small, NMT now at CU Boulder

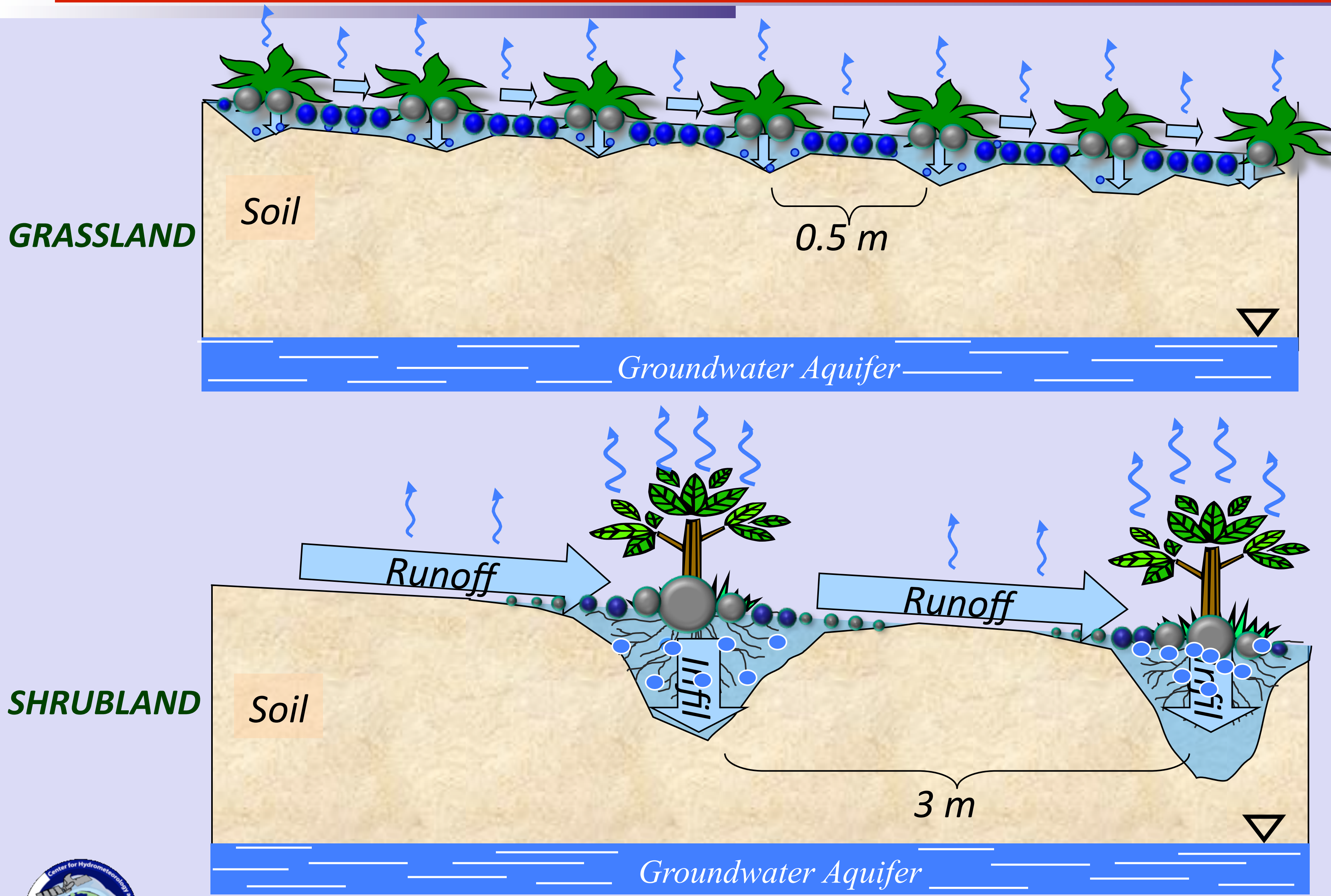
Interspaces are sources of runoff, Canopies are sinks for runoff

grasslands

deep rooted shrubs.

Source: Eric Small, NMT now at CU Boulder

Impact of Vegetation Cover Change on Infiltration



Animation Assisted by: ***Wei Chu and Gi-H. Park***

Study by: Eric Small, NMT now at CU Boulder

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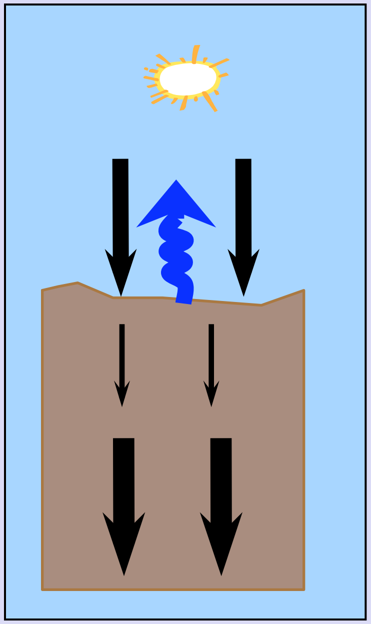
Recharge through semiarid soils

Conventional hypothesis:

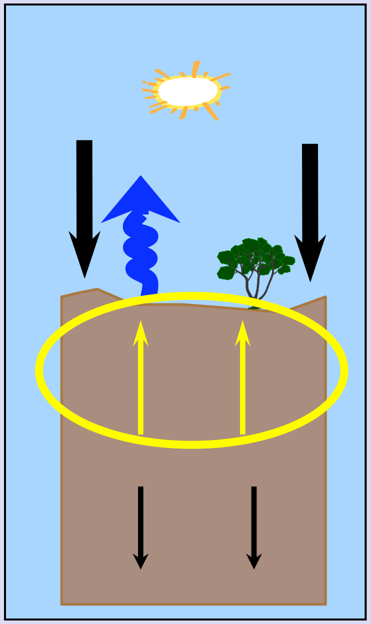
Net water fluxes always *downward, regardless of climate*



Recharge ~ 2 mm/yr
= gw for 400,000 households

New hypothesis:

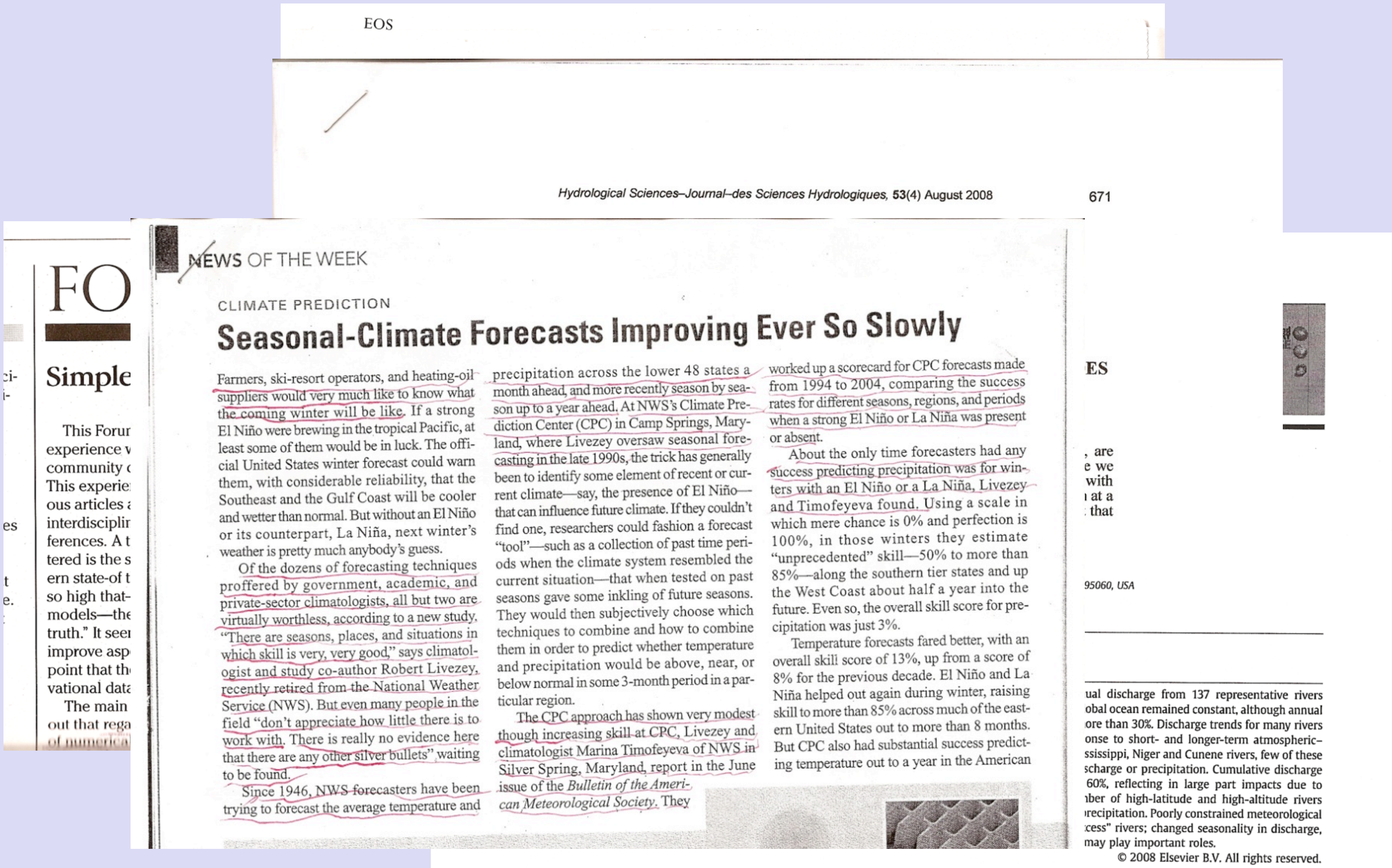
Xeric vegetation maintains net *upward* moisture fluxes



Recharge ~0.02 mm/yr
= gw for only 4,000 households

Slide contents from Walvoord & Phillips 2002, NMT

Recent Articles About the efficacy of climate models



EOS

Hydrological Sciences–Journal–des Sciences Hydrologiques, 53(4) August 2008 671

NEWS OF THE WEEK

CLIMATE PREDICTION

Seasonal-Climate Forecasts Improving Ever So Slowly

Farmers, ski-resort operators, and heating-oil suppliers would very much like to know what the coming winter will be like. If a strong El Niño were brewing in the tropical Pacific, at least some of them would be in luck. The official United States winter forecast could warn them, with considerable reliability, that the Southeast and the Gulf Coast will be cooler and wetter than normal. But without an El Niño or its counterpart, La Niña, next winter's weather is pretty much anybody's guess.

Of the dozens of forecasting techniques proffered by government, academic, and private-sector climatologists, all but two are virtually worthless, according to a new study. "There are seasons, places, and situations in which skill is very, very good," says climatologist and study co-author Robert Livezey, recently retired from the National Weather Service (NWS). But even many people in the field "don't appreciate how little there is to work with. There is really no evidence here that there are any other silver bullets" waiting to be found.

Since 1946, NWS forecasters have been trying to forecast the average temperature and precipitation across the lower 48 states a month ahead, and more recently season by season up to a year ahead. At NWS's Climate Prediction Center (CPC) in Camp Springs, Maryland, where Livezey oversaw seasonal forecasting in the late 1990s, the trick has generally been to identify some element of recent or current climate—say, the presence of El Niño—that can influence future climate. If they couldn't find one, researchers could fashion a forecast "tool"—such as a collection of past time periods when the climate system resembled the current situation—that when tested on past seasons gave some inkling of future seasons. They would then subjectively choose which techniques to combine and how to combine them in order to predict whether temperature and precipitation would be above, near, or below normal in some 3-month period in a particular region.

The CPC approach has shown very modest though increasing skill at CPC, Livezey and climatologist Marina Timofeyeva of NWS in Silver Spring, Maryland, report in the June issue of the *Bulletin of the American Meteorological Society*. They worked up a scorecard for CPC forecasts made from 1994 to 2004, comparing the success rates for different seasons, regions, and periods when a strong El Niño or La Niña was present or absent.

About the only time forecasters had any success predicting precipitation was for winters with an El Niño or a La Niña, Livezey and Timofeyeva found. Using a scale in which mere chance is 0% and perfection is 100%, in those winters they estimate "unprecedented" skill—50% to more than 85%—along the southern tier states and up the West Coast about half a year into the future. Even so, the overall skill score for precipitation was just 3%.

Temperature forecasts fared better, with an overall skill score of 13%, up from a score of 8% for the previous decade. El Niño and La Niña helped out again during winter, raising skill to more than 85% across much of the eastern United States out to more than 8 months. But CPC also had substantial success predicting temperature out to a year in the American

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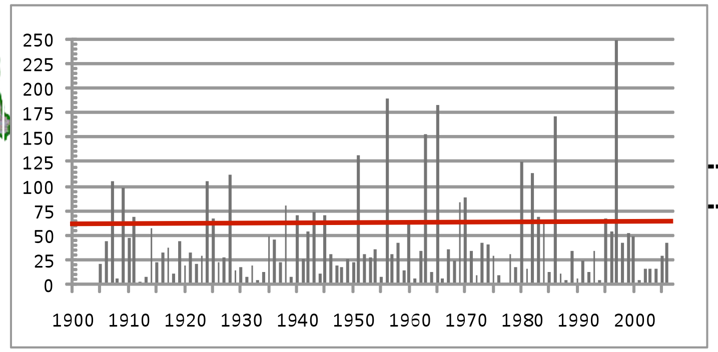
How About Drought Frequency Analysis Methods?

Not to my Knowledge. No comprehensive program until recently.



Probability density function