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Respecting the Drainage Divide:
A Perspective on Hydroclimatological Change and Scale

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Underlying any discussion of the long-term availability of fresh water supplies locally, regionally, and globally is the question of how climatic variability impacts precipitation and how this variability might change in the future. While national and political boundaries often create social, cultural, or technical barriers to water delivery, the free atmosphere ignores such boundaries. The delivery of its precipitation is determined by *physical* factors linked to how the atmosphere interacts with the geography of a watershed via features such as circulation patterns, moisture availability, storm tracks, drainage divides, topography, and lifting mechanisms. The role of these physical factors in relation to hydroclimatological change is the topic of this essay. Issues of spatial and temporal scale are of key importance in describing and modeling the processes involved in the delivery of precipitation to individual watersheds at the Earth's surface. A predominant theme in water-resources-related global climate change research has been the development of methodologies to link projected global-scale climatic variability to local-scale hydrologic responses in different parts of the world. One such methodology is *downscaling*: the interpolation of global general circulation climate model (GCM) results computed at large spatial scale fields to higher resolution, smaller spatial scale fields, and eventually to watershed processes at the Earth's surface. (Figure 1, right arrow).

The May 2003 issue of *Water Resources Update* tackled the question "Is global climate change research relevant to day-to-day water resources management?" In that issue, several authors addressed downscaling and cross-scale issues. Pulwarty (2003) discussed the importance of downscaling to make global-scale climate information useful for water resources management at the local level. He noted that recent advances have been made in downscaling to the watershed scale in some localities, but he also pointed out that regional scale predictive capability still needs improvement, especially in areas of complex topography. In addition, he highlighted the importance of clearly communicating the accuracy and precision of downscaled-model results (i.e., not overselling them). He emphasized that "scaling up from local data is as important as scaling down from

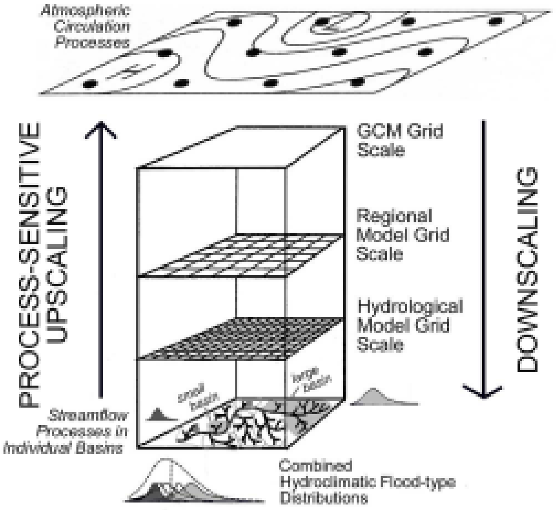

Figure 1. Traditional downscaling (right arrow) and process-sensitive upscaling (left arrow). The two approaches are complementary and when used together can provide a more comprehensive assessment of the relationship between atmospheric circulation and hydrologic response.

globally forced regional models." (Pulwarty, 2003, p 6). Chase et al. (2003) concluded that "present-day climate simulations as input to downscaling techniques designed for day-to-day operations should be used with caution" (p 32). In particular, they noted that "downscaling cannot improve errors in large scale forcing information" (p 33) and that downscaling cannot supply additional predictability by itself. They had major concerns about the use of downscaled results from current climate models for making water resources management decisions at the regional scale. Additional concerns have been raised elsewhere, as in the 2000 *Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change*, which stated that confidence is low in the model-based projections of precipitation for specific regions "because different models produce different detailed regional results." (Gleick, 2000, p 4). The inability of climate models to compute precipitation fields as accurately as they compute pressure, wind and temperature fields is one factor that underlies such warnings about the applicability of downscaled results in water resources applications. This essay provides some further insights on global climate change, water resources, and the limitations of downscaling, and it endorses Pulwarty's statement on the importance of scaling up from local data. It argues that attention to some very basic geographic elements at the local and regional scale—such as basin size, watershed boundaries, storm types, and geographic setting—provide a complementary cross-scale approach to linking global climate variability with local hydrologic variations, including extreme events such as floods.

Limitations of Spatial Downscaling in Hydroclimatology

In his essay "Conceptualization and Scale in Hydrology," Klemeš (1983) states, "in nature, scales of things are not arbitrary but arise as a function of their material substance and of the balance between the interacting forces. . . . we cannot impose scales but have to search for those which exist and try to understand their interrelationships and patterns" (p 1). If nature does indeed operate this way, downscaling from global or regional scale atmospheric processes to watershed-scale hydrologic responses, whether it be statistical or dynamical, must be sensitive to the scales at which naturally occurring atmospheric and hydrologic processes operate. Traditional downscaling approaches link information at one predefined scale of resolution to another through either statistical models, which use empirical techniques to define relationships between scales, or process-based nested models, which compute results at progressively higher resolutions, using coarser data as boundary conditions (see Hewitson and Crane, 1996). If, as Klemeš suggests, the preferred scales at which processes in nature operate tend to "have concentrations around discrete states which seem to be rather far apart" (p 2), downscaling techniques may or may not be able to resolve or disaggregate these discrete states in a manner that accurately represents the process. An example is the difficulty that meso-scale models have in forecasting the specific locations within a watershed at which smaller-scale convective thunderstorm precipitation cells may develop, e.g., Li et al. (2003).

Other limitations may occur at the point when downscaled precipitation results are used as input to a hydrologic rainfall-runoff model to estimate mean streamflow and/or the relative contribution of short-duration or high-magnitude flood peaks to mean streamflow. Many storm-related characteristics (e.g., rainfall intensity; storm shape, trajectory or speed) that are critically important to the timing of runoff and the resulting shape of the hydrograph cannot be resolved by the finest mesh grid in the downscaling procedure. Further limitations in downscaling's ability to capture variations in the rainfall-runoff process take place when grid-based estimates of precipitation are distributed over a watershed to produce a runoff estimate. Numerous studies have shown that basin morphometric factors—such as shape, size, relief, drainage density and drainage hierarchy—each influence the spatiotemporal distribution of precipitation in a basin (e.g., Horton, 1945; Ward, 1978; Patton, 1988). This fact means that, in nature, the location, timing, and rate of precipitation delivery within a specific watershed can have a significant impact on the resulting streamflow. As a result, downscaled precipitation values that are distributed over a watershed in gridded format will not exhibit the same runoff response as an actual rainfall event of the same magnitude that is organized in clusters of thunderstorm cells which interact selectively with the watershed's drainage hierarchy and topography. Another factor that downscaling has difficulty addressing, due to errors and uncertainty in estimates of soil moisture, is the antecedent condition of a watershed prior to a precipitation input. Because of these limitations, hydroclimatic downscaling is more successful in large (e.g., 50,000 – 100,000 sq. km) drainage basins and when model runoff is estimated over monthly, seasonal, or annual time scales. Furthermore, low flow extremes and drought conditions can be more successfully downscaled than short-term flood extremes. For managing long-term water quality and supplies into the future, low flows are of more concern to water resource managers. However, the ability to assess the magnitude and variability of future flooding is a management issue as well, especially in arid and semi-arid regions, where flood events contribute a large percentage of the annual discharge. Because GCMs more accurately model temperature changes than precipitation, researchers have the most confidence in downscaled assessments of hydrologic responses to global climate change in large watersheds that are dependent on snowmelt from seasonal snowpacks for their water supply. For example, basins in mountainous areas of the Western United States that rely on seasonal snowpacks are expected to be quite vulnerable to shifts in the timing of runoff and increases in early Spring flooding because projected warmer temperatures promote an earlier snowmelt season and more precipitation falling as rain instead of snow (Gleick, 2000). Despite its limitations, GCM-based downscaling of climatic information to the watershed scale is one means of defining relationships between varying climatic scenarios, their associated circulation patterns, as well as local and regional streamflow responses. However, traditional approaches to precipitation downscaling based on nested sets of gridded data *by definition* impose their own predetermined scales of resolution and analysis upon the climate-streamflow relationship. To "search for the scales which exist" in nature and "try to understand their interrelationships and patterns" (Klemeš, 1983), an alternative approach is needed.

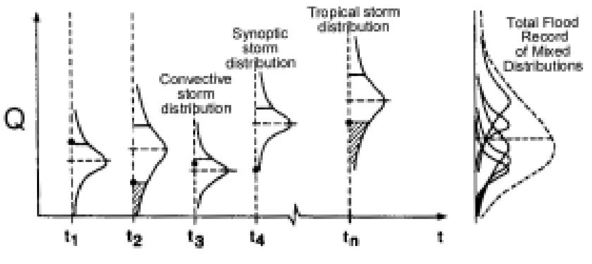

Figure 2. Schematic diagram depicting likely probability distributions for peak discharge events (Q) arising from different hydroclimatic causes at various times, t. Based on an analysis of 40 years of peak flows in the southwestern United States (see Hirschboeck, 1988 and Hirschboeck et al., 2000).

Respecting the Drainage Divide: Process-Sensitive Upscaling from within the Watershed

In regions of the world where precipitation is delivered by distinctly different atmospheric circulation patterns and storm types, annual streamflow hydrographs will be composed of flows having multiple hydroclimatic causes. This result can occur, for example, in extratropical or subtropical regions that are affected by synoptic-scale disturbances (extratropical cyclones and fronts) in winter, spring, and fall, a predominance of convective thunderstorms in summer, and an occasional tropical storm event in late summer or fall (Hirschboeck, 1991; Hirschboeck et al., 2000). Under these conditions, the probability of a flow of a given magnitude produced by a specific storm type (e.g., a tropical storm) is driven by the hydroclimatically defined mixed distribution that underlies the overall probability distribution function for the flow record (Figure 2) (see Hirschboeck, 1987, 1988). The assumption of stationarity (i.e., that events in a hydrologic time series behave as independent and identically distributed random events with constant mean and variance) underlies many analytical approaches in water resources research. Flood frequency analysis is a typical example. Separating out a flow record into mixed distributions on the basis of hydroclimatic cause provides a process-based understanding of the variations in the times series, as opposed to a blind assumption of statistical stationarity.

Dominant streamflow-producing meteorological events in most parts of the world tend to exhibit a distinct seasonal variability. They also vary spatially in relation to drainage basin size (e.g., the peak flow of record is more likely to be generated by heavy rainfall from a convective thunderstorm event in a small drainage basin, than in a large drainage basin)

(Hirschboeck, 1991; Michaud et al., 2001). Projected climatic changes that manifest themselves as latitudinal shifts in typical seasonal storm tracks, or as changes in the intensity, timing, or frequency of certain types of storms on an inter-annual, decadal, or multi-decadal basis will have a profound impact on the overall probability distribution of flows through temporal adjustments in the underlying mix of distributions.

A watershed's gaged streamflow record can be used to separate out mixed distributions by identifying flow events arising from different types of hydroclimatic causes at various spatial scales in the drainage basin (Hirschboeck 1987, 1988). From this information, a probabilistic link between climatic variability and streamflow response can be established that is sensitive to the natural scales of flow-producing processes within the basin. Upscaling that includes information on the probability distributions of basin-scale hydrometerological processes can link these processes to the meso- or synoptic-scale circulation patterns that generate them (Figure 1, left arrow). Furthermore, the imprint of the drainage basin's morphometry, topography, and characteristic mode of intercepting precipitation and distributing it through the drainage hierarchy as runoff will have been incorporated into the statistics of the streamflow probability distribution as it is "scaled up" or correlated with a specific flow-generating circulation pattern. As a result, the distinctive circulation patterns linked to a basin's hydrology through process-sensitive upscaling will reflect the physical features and hydroclimatological processes delimited by the basin's drainage divide in a manner than cannot be easily accomplished via a grid-constrained downscaling approach. Upscaling in this manner (i.e., defining the circulation patterns that are correlated with specific types of hydroclimatically distinct streamflow events) has limitations as well. Once a flow-generating circulation type is identified, the recurrence of that circulation type over a given region does not guarantee that another similar streamflow event will occur in the same basin. Rather, it increases *the probability of occurrence* of that particular type of flow event as long as that circulation type is influencing the region. It has been hypothesized that the shape of a hydroclimatically defined mixed distribution will have some physical meaning derived from the nature of the flood-generating process itself (Hirschboeck, 1988). For example, the probability distributions of flood peaks generated by tropical storms tend to be highly positively skewed with larger means and higher variance than distributions of other flood types due to the rarity of such events, the erratic nature of tropical storm tracks, and the huge discharges that can occur from the rainfall associated with such storms. Hence, linking local streamflow events to the storm types and/or circulation patterns that produce them via upscaling may contribute an important mechanistic understanding to the probability of occurrence of such events. The process-sensitive circulation patterns defined through the upscaling approach can then be matched with similar circulation patterns produced at various points in the downscaling process to develop a complementary cross-scale methodology for linking global climate variability and local hydrologic responses.

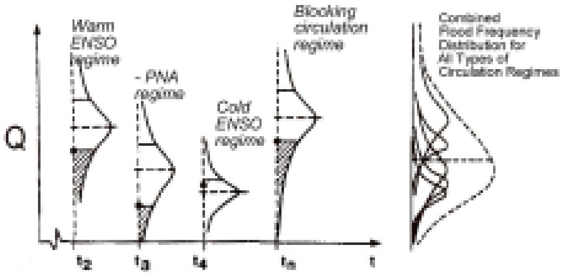

Figure 3. Schematic diagram depicting likely probability distributions for peak discharge events (Q) occurring during different circulation regimes at various times, t. Based on the results of several flood-climate studies in the southwestern United States (e.g., Hirschboeck, 1988, Ely et al., 1993, 1994, Hirschboeck et al., 2000).

Climatic changes themselves can be conceptualized as time-varying atmospheric circulation regimes that generate a mix of shifting streamflow probability distributions over time (Hirschboeck, 1988), as depicted schematically in Figure 3. A regime, defined as a regular pattern of occurrence or the characteristic behavior of a natural process, can manifest itself as a recurring teleconnection pattern (Pacific/North American Pattern PNA, North Atlantic Oscillation NAO, etc.), a persistent synoptic circulation pattern (blocking, cutoff lows), or the joint occurrence of one phase of a multi-decadal pattern (e.g., Pacific Decadal Oscillation PDO) with that of a more frequently recurring pattern (e.g., El Niño Southern Oscillation ENSO). Using the upscaling approach, the likely streamflow probability distributions associated with different types of circulation regimes (Figure 3) or combinations of regimes provide new insights into the range of hydrologic variability that can be expected should that circulation regime develop, recur frequently, and/or persist for a series of days, months, years, or even decades. Conceptualizing the hydrologic time series as emerging from a set of time-varying mixed distributions linked to different types of circulation regimes is another way to develop a process-sensitive understanding of climate-water interactions as they impact water resources.

Conclusions

This essay argues that when searching for linkages between global climate change and local streamflow responses, process-sensitive upscaling defines relationships that may not be detected via precipitation downscaling. The approach outlined here is directed toward developing a better representation of streamflow-climate relationships by using within-basin streamflow events to identify the significant storm types and circulation patterns to which they are linked at other scales. Events generated by similar storm types or circulation patterns can be separated into mixed probability distributions to provide a mechanistic understanding of the hydroclimatic causes of variability in the streamflow time series. In addition, this streamflow-sensitve upscaling approach allows the imprint of a drainage basin's characteristic mode of interacting with precipitation in a given storm type to be incorporated into the statistics of the flow event's probability distribution as it is "scaled up" and linked to a meso- or synoptic-scale flow-generating circulation pattern. Hence process-based upscaling fosters a sensitivity to the basic physical geography of drainage basins at the local and regional scale that may be difficult to resolve through gridpoint-based precipitation downscaling. Together the two approaches provide a complementary cross-scale approach to linking global climate variability with local hydrologic variations.

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