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Research Article

Using NHDPlus as the Land Base for the Noah-distributed Model

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Abstract

The National Elevation, Hydrography and Land Cover datasets of the United States have been synthesized into a geospatial dataset called NHDPlus which is referenced to a spheroidal Earth, provides geospatial data layers for topography on 30 m rasters, and has vector coverages for catchments and river reaches. In this article, we examine the integration of NHDPlus with the Noah-distributed model. In order to retain compatibility with atmospheric models, Noah-distributed utilizes surface domain fields referenced to a spherical rather than spheroidal Earth in its computation of vertical land surface/atmosphere water and energy budgets (at coarse resolution) as well as horizontal cell-to-cell water routing across the land surface and through the shallow subsurface (at fine resolution). Two data-centric issues affecting the linkage between Noah-distributed and NHDPlus are examined: (1) the shape of the Earth; and (2) the linking of gridded landscape with a vector representation of the stream and river network. At mid-latitudes the errors due to projections between spherical and spheroidal representations of the Earth are significant.

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A catchment-based "pour point" technique is developed to link the raster and vector data to provide lateral inflow from the landscape to a one-dimensional river model. We conclude that, when Noah-distributed is run uncoupled to an atmospheric model, it is advantageous to implement Noah-distributed at the native spatial scale of the digital elevation data and the spheroidal Earth of the NHDPlus dataset rather than transforming the NHDPlus dataset to fit the coarser resolution and spherical Earth shape of the Noah-distributed model.

1 Introduction

Hydrology is concerned with both the vertical exchanges of water between the land surface and the atmosphere, and the horizontal movement of water over and through the landscape in surface and groundwater systems. Over the past several decades, both vertical and horizontal water movement have been studied extensively though, generally, in relative isolation from one another (cf. Lyon et al. 2008). Specifically, the land surface models (LSMs) used as lower boundary conditions for numerical weather prediction models and global climate models focus on the vertical exchanges of entities including water (Yang 2004). In LSMs, horizontal exchanges of water at the grid or subgrid scales are not usually considered. The vertical interaction of the land surface and atmosphere is reasonably well described by gridded models of the landscape. However, many basin scale studies of stream and river flow, such as the national FEMA Flood Map Modernization effort (see http://www.fema.gov/plan/prevent/fhm/mm_main.shtm for additional details), apply the equations of one-dimensional open channel hydraulics to mapped river and stream reaches treated as distinct linear entities or vector objects. Additionally, highly irregular objects such as stream channels, groundwater basins, watersheds, lakes and reservoirs may be significantly mis-represented or wholly absent within comparatively coarsely-resolved gridded modeling domains whose grid sizes lack sufficient horizontal resolution to properly define the boundaries of important hydrographic features. The main objective of this article is to present a modeling framework using a standardized LSM for numerical weather prediction at the continental-scale with a high-resolution hydrographic database as its land information base. Issues related to the coupling of regular gridded modeling domains used in LSMs with spatially irregular river systems represented as vector objects are investigated on the Guadalupe River Basin in Texas as a case-study example (see Figure 1).

1.1 Geometry of Surface Routing in Hydrologic Modeling

In this study, we focus on those types of hydrologic models which emphasize coupling to a river hydraulics, river dynamics, or, more commonly, a river routing module. Many existing hydrologic models do not use vector-based mapped rivers for their hydraulic modeling, opting for a gridded representation of the river network instead. Such models include CASC2D (Julien et al. 1995), LISFLOOD (De Roo et al. 2000), MODCOU (Ledoux 1980), NWSRFS (NOAA 2005) and MIKE-SHE (Sahoo et al. 2006). Another class of 'watershed' models, such as TOPMODEL (Beven and Kirkby 1979) and those of Maidment et al. (1996) or Olivera and coworkers (Olivera and Maidment 1999, Olivera et al. 2000) typically route water across and through the landscape to a river basin outlet and do not explicitly model channel flow processes.

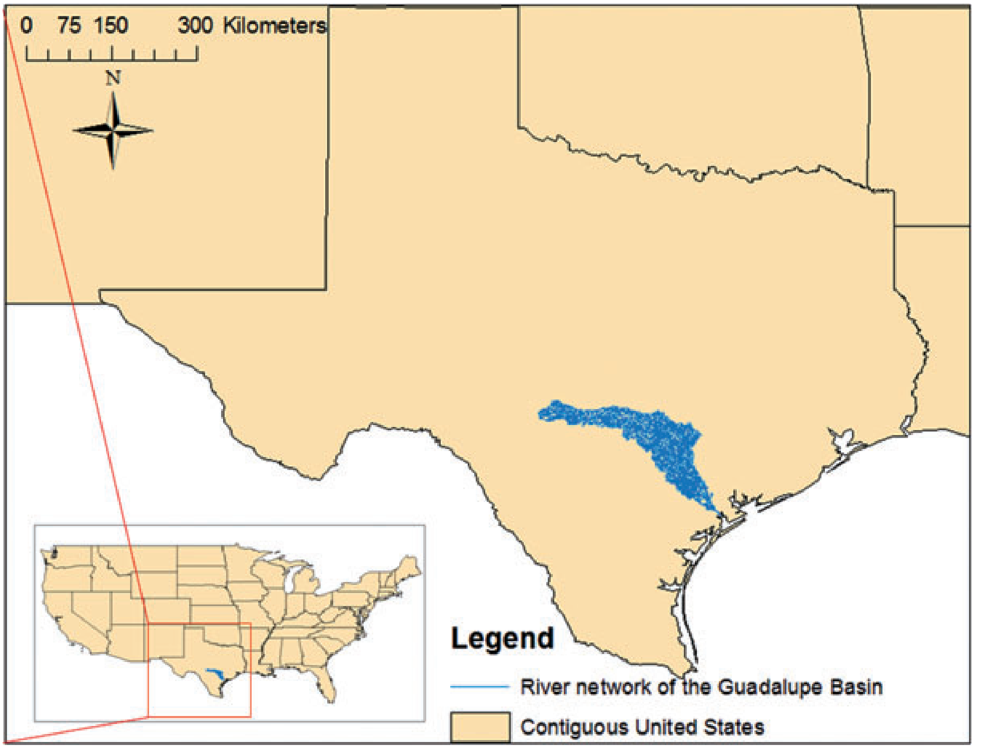

Figure 1 The Guadalupe Basin, located in southeast Texas

Although gridded representations of the land surface are most common, they are not the only representation employed. Triangular cells, such as those within triangulated irregular networks (TINs), are also sometimes used to characterize the land surface (e.g. the tRIBS model, Ivanov et al. 2004); triangular edges may be used to represent river links as in the coupled river network and groundwater flow model developed by Gunduz and Aral (2005).

In all of the models listed above, hydrographic features have been adapted to match model frameworks. However, recent development of high resolution vector-based hydrographic databases on a continental-scale such as NHDPlus (USEPA and USGS 2007) or on a global-scale such as HydroSHEDS (Lehner et al. 2006) offer the potential for improved accuracy in the mapping of hydrographic features across continental domains. The focus of the present study is on issues related to using these vector-based hydrographic datasets within hydrologic models. As shown subsequently, we suggest that retaining the spatial and geographic accuracy of underlying hydrographic data is advantageous to reducing potentially large georeferencing errors resulting from coupling hydrographic and meteorological data representations.

1.2 Coordinate Systems for Hydrologic Modeling

Hydrologic models require both land-base information (terrain elevation, hydrographic features and networks) and atmospheric forcing (precipitation, specific humidity, temperature, air pressure, wind speed, downward radiation, etc.). Provided with these data, hydrologic models calculate evaporation, surface radiation exchanges, soil moisture, lateral overland and subsurface flow and streamflow. Commonly, and for mathematical simplicity, a Cartesian (x,y,z) coordinate system is used over the region of interest. Therefore, horizontal projections of geospatial data from a geographic coordinate system in latitude, longitude (λ, φ) to a projected coordinated system (x,y) are needed in order to transform the curved surface of the Earth into the Cartesian coordinate system. A projected coordinate system consists of an Earth datum and a projection to transform the globe to a Cartesian coordinate system on a flat map; these transformations are typically performed within a geographic information system (GIS).

Hydrologic modeling has mainly been performed either at the small watershed-scale or at the larger continental-scale, and the geographic coordinate systems for data at these two scales are different. As high-resolution datasets become increasingly available, the geo-referencing of data becomes important in ways that have not been as apparent earlier.

In watershed scale models, land surface data usually come from local high-resolution databases and atmospheric data are interpolated from local point measurements, which are more resolved (spatially and temporally) than results from atmospheric circulation models at these scales. In this case, the high-resolution land-base is readily available in projected coordinates of a spheroidal Earth datum and meteorological stations are located using geographic coordinates on the same spheroidal Earth datum.

Another class of regional or continental hydrologic models is sometimes referred to as 'macro' scale hydrologic models following Shuttleworth (1988). These include ISBA (Noilhan and Planton 1989), Noah (Ek et al. 2003), and the Community Land Model (Dickinson et al. 2006) and have been developed by the atmospheric science community for coupling with atmospheric circulation models. The VIC model (Liang et al. 1994, 1996) also falls under this category although it is typically run in an uncoupled mode for hydrologic simulation and prediction. The purpose of these models is to provide an atmospheric circulation model with lower boundary conditions for energy and water balances at the surface. However, at regional or continental scales, streamflow calculation has rarely been a principal objective for macroscale hydrologic models (with the exception of VIC), but streamflow data are used to verify or improve the volumetric water balance of land surface and atmospheric circulation models. Because these regional/continental-scale models are coupled to atmospheric models, their grids are typically cast in a coordinate system which utilizes a spherical Earth datum (see Section 3.1), as opposed to the more appropriate spheroidal datum.

Datum issues and associated spatial errors in geographic transformations have not been focused upon in coupling land surface/atmospheric circulation models, perhaps because the grid resolution of atmospheric models has been much coarser than the positional errors associated with geographic transformations. However, atmospheric models and spatially continuous data products are now available for the continental U.S at very high spatial resolutions. For instance, results from real time runs of the Weather Research and Forecasting model are available on a 12 km grid (http://motherlode.ucar.edu:8080/thredds/catalog.html) and remotely sensed NEXRAD precipitation is available on a 4 km grid (Stage IV NEXRAD data are available at http://nomads.ncdc.noaa.gov/thredds/catalog.html). The increased geospatial resolution and quality of available atmospheric datasets suggests that datum and projection issues should not be neglected.

Therefore datum issues become important as high resolution atmosphere and land surface modeling is merged with high resolution hydrographic datasets, as is demonstrated in this study.

2 Framework Description

A hydrologically-enhanced form of the Noah LSM (Noah-distributed, Gochis and Chen 2003) has been developed that allows for cell-cell routing of flow across and through the landscape. In this study, the NHDPlus dataset is used as the land-base for Noah-distributed. NHDPlus is a GIS dataset that links the National Hydrography Dataset description of the mapped streams and water bodies of the nation with small catchments delineated around each stream reach. The Guadalupe Basin in Texas has about 3,000 river and stream reaches and their surrounding catchments in the NHDPlus dataset (Figure 2). This basin was chosen for study because it has significant contributions to surface water flow from groundwater sources, because it has a large reservoir, Canyon Lake (surface area of 33 km^2), where the effect of reservoir releases on downstream flow dynamics has to be considered, and because it flows out into an important estuarine system at San Antonio Bay. Figure 3 shows three components of the geospatial framework used in this study. A schematic of processes in Noah LSM (Chen et al. 1996) is presented in Figure 3a, the overland and subsurface routing functionalities of

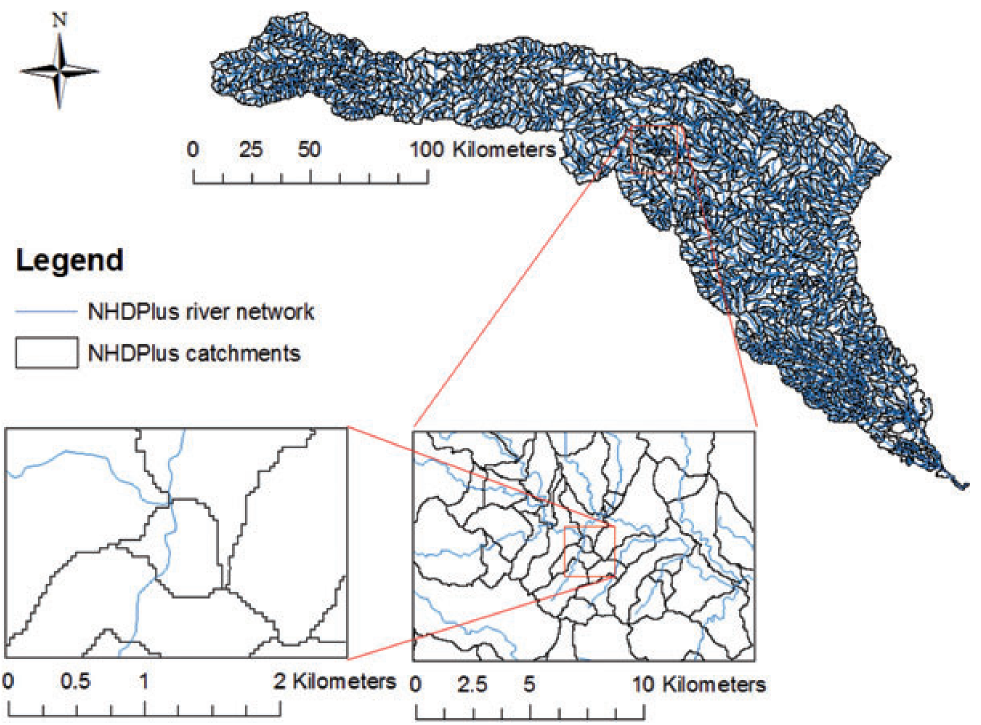

Figure 2 River and stream reaches and their surrounding catchments as defined in NHDPlus for the Guadalupe Basin

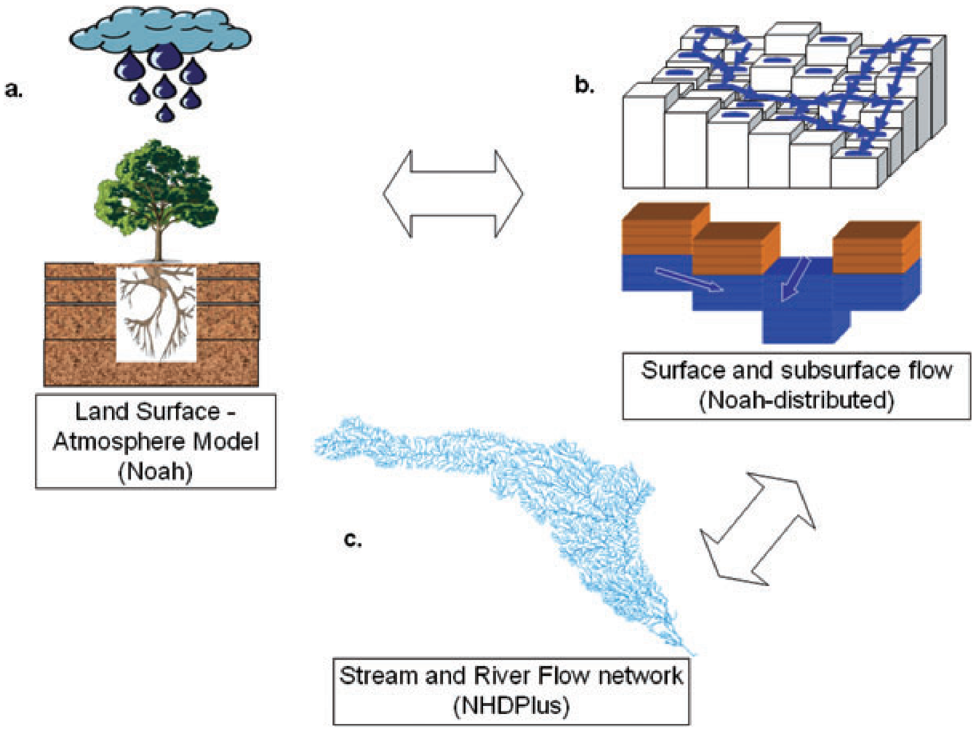

Figure 3 Components of the geospatial framework used in this study

Noah-distributed (Gochis and Chen 2003) are in Figure 3b, and the river network as defined in NHDPlus for the Guadalupe River Basin in Texas is in Figure 3c.

2.1 NHDPlus as the Land Base for Noah-Distributed

NHDPlus (USEPA and USGS 2007) is a hydrologically enhanced land database that incorporates many of the best features of the National Hydrography Dataset (NHD), the National Elevation Dataset (NED), the Watershed Boundary Dataset (WBD) and the national Land Cover Dataset (NLCD). NHDPlus includes a stream network based on the medium resolution NHD (1 : 100,000 scale), explicit stream networking, feature characterization, and a number of additional attributes such as divergence, network connectivity, stream order, and mean annual flow. Therefore, NHDPlus is a geospatial dataset that connects the land and water systems of the United States. A higher resolution NHD stream network at 1:24,000 scale exists for the U.S. but is not connected to the landscape by reach catchments as is NHDPlus. Within NHDPlus, the continental U.S. is divided in 18 regions, with their corresponding two-digit Hydrologic Unit Code (HUC, from 01 to 18). Data for Alaska are not available. Data for Hawaii are available within region 20. The Texas Gulf, within which the Guadalupe River Basin resides, is region 12 in NHDPlus.

In NHDPlus, the Digital Elevation Model (DEM) has been modified from the national elevation dataset to conform to the river network and the watershed boundary. Using the AGREE-DEM method (Hellweger and Maidment 1997) for the river network, DEM walls are created at known watershed boundaries from the watershed boundary dataset similarly to Moore et al. (2004). As a result, river and watershed delineation based on the modified DEM and its associated flow accumulation and direction grids conforms to available vector stream and watershed data. The spatial resolution of the raster datasets is 30 m in the NHDPlus DEM, flow direction and flow accumulation grids. NHDPlus rasters use the USGS national Albers projection with a spheroidal Earth, defined by the North American Datum of 1983 (Schwarz and Wade 1990).

NHDPlus uses connected river reaches, and for each reach a catchment is defined to delineate its local drainage area. This reach catchment is assigned a unique identifier, the COMID, and all features and attributes pertaining to this reach and its catchment are labeled similarly. Within NHDPlus, the river network value-added attribute table includes FromNode and ToNode fields that can be used to specify how streams and reaches are connected to form the river network. The NHDPlus dataset also has an estimated slope and mean annual flow for each river reach. For the continental U.S., the NHDPlus dataset has about 3 million stream and river reaches of average length 2 km, and the average catchment size defined around them is 3 km^2 in area. The Guadalupe River Basin has about 3,000 stream and river reaches of average length 3 km and the average catchment size is 5 km^2 in area.

NHDPlus also has integrated the National Land Cover Dataset (NLCD) and has as attributes the calculated percentage of coverage of each classified NLCD land cover (water, developed, barren, forested shrub land, etc.) for each catchment. While important, land cover is not the focus of the present study.

2.2 *The Noah-Distributed Model*

Within our framework, the core physical model governing the one-dimensional (1D) vertical fluxes of energy and moisture is the Noah LSM. The one-dimensional Noah model simulates liquid and frozen soil moisture, soil temperature, skin temperature, snowpack depth and water equivalent, canopy water content, and energy and water fluxes at the Earth's surface (Mitchell 2005). The Noah model has a long history, with successive versions extensively tested and validated, most notably within the Project for Intercomparison of Land surface Parameterizations (Henderson-Sellers et al. 1993), the Global Soil Wetness Project (Dirmeyer et al. 1999), and the Distributed Model Intercomparison Project (Smith et al. 2004). Existing gridded versions of the 1D Noah model are coupled to real-time weather forecasting models such as the NCAR/Penn State University (NCAR/PSU) MM5, the advanced Weather Research and Forecasting (WRF) numerical weather prediction model, and the NCEP North American Model (an alternate version of WRF), which is used for performing operational weather prediction for the U.S.

In Noah-distributed, a flow-routing-capable version of Noah (Gochis and Chen 2003), the overland flow routing is calculated as a fully unsteady, explicit, finite difference, one- or two-dimensional diffusive wave flowing over the land surface, similar to that used in the CASC2D model of Julien et al. (1995). 'Shallow' groundwater flow (down to 2 m depth) is also explicitly modeled using a quasi-steady state saturated flow model adapted from Wigmosta et al. (1994). The horizontal flow into a stream network calculated by Noah-distributed is then a combination of surface runoff and shallow groundwater flow. More recently a baseflow module was also implemented within Noah-distributed which employs a simple bucket model to estimate time-evolving baseflow in perennial streams. Flow from the stream back to the landscape or aquifer is currently neglected. Although Noah-distributed also has the ability of routing water within river networks and through reservoirs, these calculations are not used in the present study.

The spatial resolution of the 1D Noah model is currently limited by the spatial resolution of land surface characterization (e.g. soils and vegetation) datasets. Therefore a subgrid modeling approach is used in which the vertical fluxes and land-atmosphere exchanges within Noah are calculated using gridcells on the order of 1 km × 1 km while a much finer grid, on the order of 100 m, is typically used for routing runoff over and through complex landscapes. This subgrid routing functionality is intended to build upon highly-resolved terrain datasets, such as the NHDPlus, and the need for adequately resolving terrain slopes.

3 Linking a Land Surface Model with a Vector-Based River Network

3.1 Shape of the Earth

Most large scale atmospheric datasets that are available for North America are referenced on a Cartesian coordinate system projected from a spherical Earth. Such is the case for the Rapid Update Cycle and the North American Mesoscale model outputs, as well as for the North American Regional Reanalysis and the national aggregation of NEXRAD data. These data are all available online at http://nomads.ncdc.noaa.gov/thredds/catalog.html and http://motherlode.ucar.edu:8080/thredds/catalog.html. Most hydrologic datasets use a more accurate spheroidal Earth geometry. Vector data in NHDPlus are presented in geographic coordinates using the spheroidal NAD83 datum. This datum and the USGS national Albers projection is used for the NHDPlus rasters (DEM, flow direction and flow accumulation). The spheroidal or ellipsoidal shape used in NAD83 is that of the Geodetic Reference System 1980 (GRS80, Moritz 1980). To distinguish between a spherical and spheroidal Earth, two types of latitudes are needed: geocentric and geodetic as shown in Figure 4.

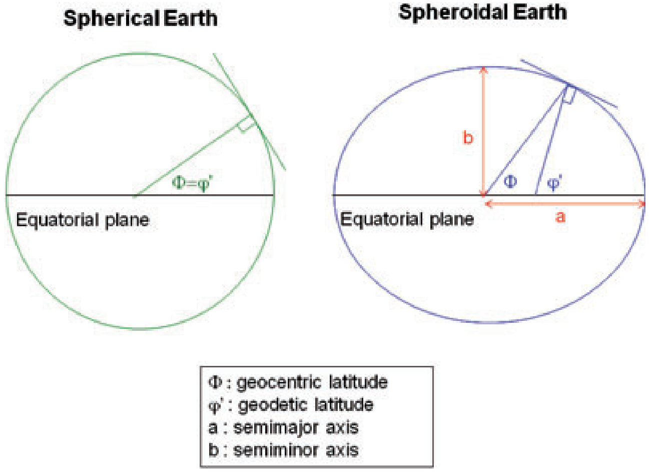

Figure 4 Geometry of spherical and spheroidal representations of the Earth

Longitudes are not affected by this difference in Earth shape because it only involves North-South flattening. The geocentric latitude Φ is the acute angle measured between the equatorial plane and a line joining the center of the Earth and a point on the surface of the sphere or spheroid. The geodetic latitude φ' is the acute angle between the equatorial plane and a line drawn perpendicular to the tangent plane of a point on the reference sphere or spheroid. Normal map coordinates are given in longitude and geodetic latitude. On a sphere, geocentric and geodetic latitudes are equal. For the GRS80 spheroid, the semimajor axis is a = 6,378,137 m, the semiminor axis is b = 6,356,752.3141 m and the mean radius is $\mathrm{R1} = \frac{2\mathrm{a}+\mathrm{b}}{3} = 6371008.7714\ \mathrm{m}$ (Moritz 1980). Gates (2004) derived the equations of atmospheric motion in spheroidal coordinates and gave the following expression for the difference between geocentric and geodetic latitudes:

$$\delta = \varphi' - \Phi = \tan^{-1}\left(\frac{\sin(\varphi)\cdot\cos(\varphi)}{\sinh(\xi)\cdot\cosh(\xi)}\right) \tag{1}$$

where

$$\varphi = \tan^{-1}(\tan(\varphi')\cdot\tanh(\xi)) \tag{2}$$

and

$$\tanh(\xi) = \frac{b}{a} \tag{3}$$

where φ is the angle of the cone that is asymptotic to the hyperboloid orthogonal to the spheroid, and ξ is a dimensionless parameter.

Equations (1) through (3) applied to the GRS80 spheroid at mid latitude ($\varphi' = 45°$) give $\delta = 0°11'33''$, which corresponds to 21.4 km on the surface of a sphere (with the radius being the mean radius of the GRS80 spheroid). Therefore, at mid-latitudes, the degree of error that results from ignoring the different shapes of the Earth is on the order of 20 km. This error is 18.5 km at $\varphi' = 30°$, 18.6 km at $\varphi' = 60°$ and goes to zero at the equator and at the poles. Figure 5 shows the distance between points having the same numerical value for latitude depending on whether it is geocentric-based or geodetic-based, as a function of geodetic latitude. For each geodetic latitude, the corresponding geocentric latitude was calculated using the GRS80 spheroid and Equations (1–3). The angular difference was then multiplied by the mean radius of the GRS80 spheroid to determine a distance in kilometers. Comparable values were given by Van Sickle (2004).

Using the geocentric latitude of the sphere as the geocentric latitude on the spheroid is equivalent to performing a geocentric projection. Figure 6 shows the principle of the geocentric conversion, where the geocentric latitude on a sphere is taken as the geocentric latitude on a spheroid allowing the projection of a point M_{sphere} at the surface of the sphere to the corresponding location $M_{spheroid}$ on the surface of the spheroid. Two domains resulting from two interpretations of latitudes are shown in Figure 7. These two domains were created using the same numerical values for longitude and latitude, but

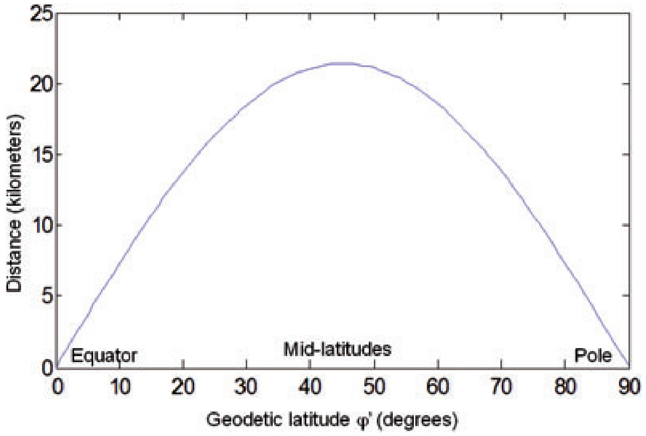

Figure 5 Distance between points having the same numerical value for latitude depending on whether it is geocentric- or geodetic-based, as a function of geodetic latitude

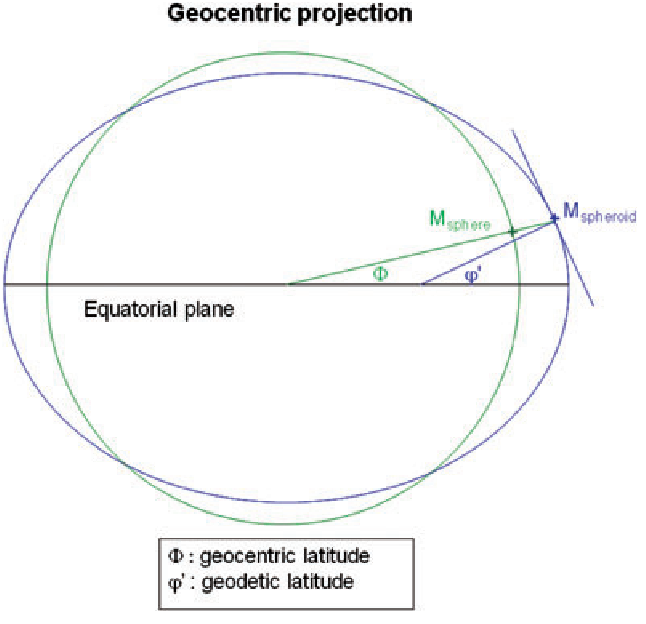

Figure 6 Geocentric projection of a sphere to a spheroid

assigning the latitudes either to the geodetic latitudes ($\varphi' = 28.3°$ and $\varphi' = 30.4°$ for domain a) or to the geocentric latitudes ($\Phi = 28.3°$and $\Phi = 30.4°$ for domain b). The shift is on the order of 20 km in the North-South direction. As illustrated in Figure 7, errors of these magnitudes can be particularly important for terrestrial hydrological applications such as flood prediction where positional errors of a few kilometers can produce pronounced differences on catchment scale runoff response.

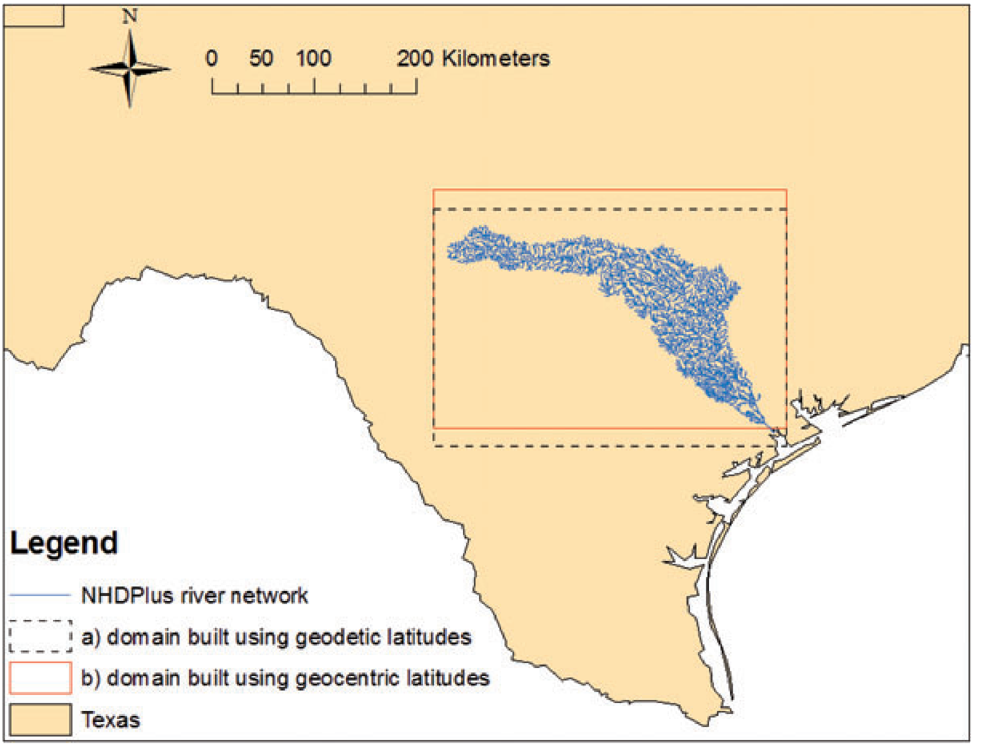

Figure 7 Different interpretations of latitude for the Guadalupe River Basin can lead to shifted locations of the same domain

3.2 Spatial Discretization in Noah-Distributed and NHDPlus

In several current applications of the Noah-distributed model, the computational grid has been set up using 100 m DEM and flow direction grids and a 1 km atmospheric data forcing. This means that the vertical water balance computations are done on a 1 km grid and the horizontal flow routing is performed on a nested 100 m grid. The native resolution of NHDPlus rasters is 30 m, which provides better explicit representations of topographic features, terrain slopes in particular, and is therefore capable of better representing hydrologically important terrain gradients than a coarser 100 m grid.

When a 30 m DEM is re-sampled to a coarser resolution of 100 m, the correspondence of the DEM, and its flow accumulation and flow direction fields with the original river reaches and catchment boundaries hydrologic features is lost, thereby requiring a re-definition of surface hydrographic features. The resulting catchments also change shape and, potentially, location, and the associated basin outlets or pour points also change location. The reprocessing of the raster data along with the re-specification of hydrographic features to coarser grids is very time consuming. The same arguments hold for projecting of the NHDPlus raster data from its spheroidal Earth coordinates to the spherical Earth coordinates used in Noah-distributed. Thus, from a hydrographic data perspective, there are distinct advantages to directly utilizing an integrated DEM-hydrography data set such as the NHDPlus which avoids reprocessing all of the geospatial data to a different spatial resolution. The principal disadvantage of using the native 30 m grid of the NHDPlus dataset is the need for substantially greater computing resources and longer model run times for Noah-distributed, particularly for large simulation domains. Such highly resolved domains also create a burden for data storage, analysis and visualization.

Given these considerations we recommend that, from a spatial accuracy standpoint, it is advantageous to adopt the NHDPlus spatial framework and to adapt the Noah-distributed model to execute on the NHDPlus grid, rather than to resample the NHDPlus land surface dataset to a coarser resolution. Thus, for studies of the Guadalupe River Basin, Noah-distributed utilizes a 30 m resolution DEM for overland and subsurface routing. The corresponding resolution for the one-dimensional Noah model was chosen as 900 m instead of the previous 1 km to allow for integer conversion between the two grids. Therefore, each 900 m land-atmosphere cell is constituted of 30×30 surface routing grid cells. The methods by which soil moisture and ponded water are disaggregated from the Noah-distributed land model grid onto the routing subgrid are described in Gochis and Chen (2003).

3.3 Catchment Pour Points

A "pour point" technique is used to link NHDPlus catchments to the vector-based stream network. This requires determining the outlet location of the catchment corresponding to each river reach of a basin. This location is taken as the point with the highest flow accumulation value on the raster DEM grid within the catchment. This connection is facilitated by the presence in the NHDPlus raster dataset of a catchment raster whose zone identifier is the COMID value of the catchment. By searching within this zone for the cell of maximum flow accumulation, the pour point cell is identified at the catchment outlet, as shown in Figure 8 where the same catchment is shown in both the gridded and vector environments of NHDPlus. Following the flow direction grid, water is allowed to flow on and below the land surface of each catchment within the calculations of Noah-distributed and is accumulated at the pour point. This water is then specified as the inflow to the corresponding river reach.

Figure 8 shows how vector data (river reaches) are connected to the pour point of the NHDPlus catchment, thus achieving a conceptual translation between vector-based and raster-based environments. Therefore, the pour point method allows the use of the gridded landscape of NHDPlus within the Noah-distributed model to simulate the horizontal movements of water, while remaining compatible with the NHDPlus streams and reaches that can then be used for routing within a vector-based river network. Hence, this study presents a way to provide lateral inflow of water from the land surface to the river network.

4 Conclusions

In this study, the advantages and disadvantages of alternatives for spatially connecting atmospheric model grids with those from catchment and river models using a standardized national GIS vector river and raster terrain dataset (NHDPlus) and a standard land surface/atmospheric model (Noah) are discussed. The different shapes of the Earth that are used in atmospheric science (spherical) and hydrology (spheroidal) can lead to two

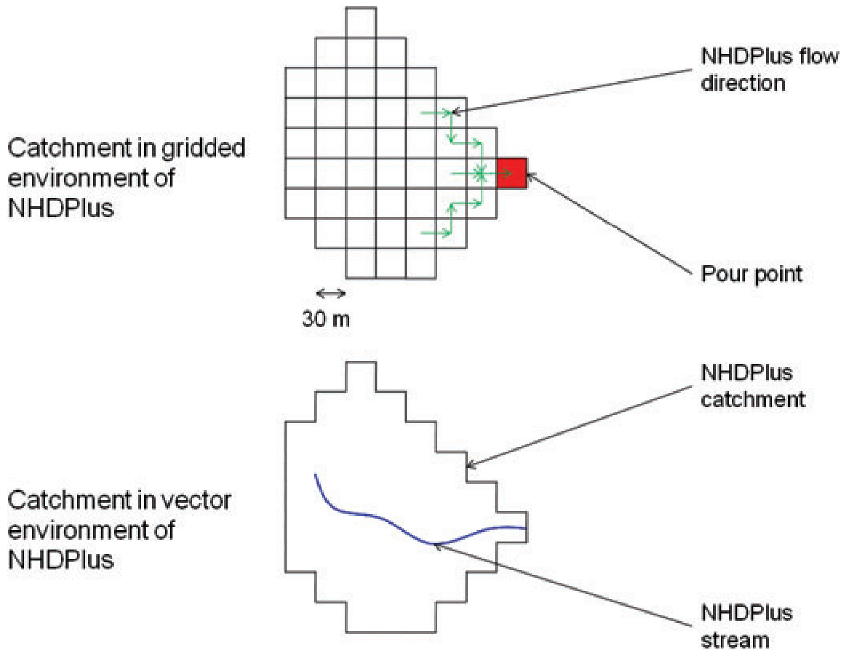

Figure 8 Connection between grid and vector environments of NHDPlus using pour points

different interpretations of latitudes: geocentric or geodetic. A shift in the North-South direction on the order of 20 km at mid-latitudes results from these two interpretations. The magnitude of this shift is comparable to the grid cell size of high-resolution atmospheric datasets available today. This discrepancy must be avoided by projections from one datum to another. It is advantageous to keep the original spatial resolution and datum of the NHDPlus, and to project and resample atmospheric data instead when using NHDPlus as the land base for the Noah-distributed model. In doing so, the original spatial resolution of the terrain rasters, the shape of hydrographic features, and the connectivity between catchments and river reaches from the NHDPlus dataset are preserved. The spatial resolution of the domain used for computation of the movement of water through the landscape to the river reaches is higher than that used in previous Noah-distributed studies, hence requiring a more intense computational demand. However, this demand can be met through recent advances towards petascale computing architectures now underway at major modeling centers around the world.

Acknowledgments

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