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Development of Two-Way Coupled Atmospheric Hydrological Models

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Abstract

The last two decades have witnessed a surge in the development of two-way coupled atmospheric and hydrological models, opening up hitherto unattainable potential to better comprehend hydrology-atmosphere interaction and enhance hydrometeorological forecasting. This study discusses recent advances in the display of hydrological data in Land Surface Models (LSMs) and climate models, as well as the two-way coupling of atmospheric and hydrological models.Fully coupled models have been widely used to identify the impact of lateral surface and subsurface water transport in a land-atmosphere coupled system, and hydrometeorological simulations have been used to improve model accuracy using techniques such as parameter calibration, data assimilation, and hydrology model structure revision.

Keywords: Coupled atmospheric hydrological models • Two-way coupling • Hydrometeorological Forecasting • Hydrology atmosphere coupling

Introduction

On global to regional dimensions, the water cycle is a critical component of the earth system, integrating land, atmosphere, ocean, and subsurface processes. The impact of human activities on the water cycle has progressively surfaced as populations and economic development have grown over the last several decades. Meanwhile, catastrophic hydrological events like floods and droughts are becoming more often as a result of global climate change and human activities. One of the fundamental challenges in water-related studies has been the interactions and feedbacks between regional climate change and hydrological processes .Coupled atmospheric and hydrological models are strong and useful instruments for studying scientific topics involving complex systems such as the atmosphere, land surface, and continental hydrosphere. Simple land surface parameterization techniques (for example, a leaky bucket parameterization [15]) were originally introduced into climate models in the 1960s, and were gradually expanded to include more complex representations. Launched in the 1990s , the Project for Intercomparison of Land-surface Parameterization Schemes (PILPS) revealed that three-generation land surface models (LSMs) such as the Biosphere-Atmosphere Transfer Scheme and Community Land Model (CLM). International projects such as the World Climate Research Program (WCRP), International Geosphere Biosphere Program (IGBP), and Global Energy and Water Cycle Experiment (GEWEX) have emphasised coupling hydrology models and regional climate models as an important topic since the beginning of the twenty-first century. Recently, two-way linked atmospheric and hydrological models have been developed.

Representation of hydrological processes in lsms and climate models

Because of their distinct foci and aims, climate models and hydrological models have been developed independently for decades. Climate models have evolved progressively to integrate comprehensive representations of biogeophysical, biogeochemical, and hydrological processes in land surface schemes. Hydrology models have evolved from lumped to distributed, statistically empirical to physically based, and from basic rainfall-runoff models to models with complicated land surface processes (e.g., VIC, TOPMODEL).

Application of two-way coupled atmospheric and hydrological models

Hydrological enhancement in fully coupled atmospheric and hydrological models primarily includes the explicit representation of lateral surface and subsurface water transport, with the possibility of moisture redistribution to neighbouring soil columns and re-infiltration of routed surface water , in addition to some one-way modelled processes such as channel routing and baseflow. As a result, fully connected atmospheric and hydrological models enable simulation of the whole regional water cycle, from the top of the atmosphere to the land surface, the unsaturated zone, and the flow in river beds.

Hydro meteorological simulations and forecasts

The WRF-Hydro model is one of the most widely used two-way coupled models for weather research and hydrological forecasting across the world. Its advantages include:

- WRF is an integrated modelling platform with an open source, detailed technique guide, and rich practical experience accumulated from users;
- the extension hydrological model is easily coupled with WRF as a physically based, fully distributed, multi-parameterization modelling system; and
- it has potential for flood forecasting in small and medium catchments with high spatial resolutions (typically 1 km or less).

Many researchers have employed the WRF-Hydro model for hydrometeorology modelling and forecasting, particularly in areas where data is scarce . For example, Gu et al. used the WRF Hydro model to simulate floods in the Qingjiang River Basin (at a resolution of 1 km in LSM and 100 m in hydrological model) using ECMWF reanalysis data; with calibrated parameters, the Nash-Sutcliffe Efficiency (NSE) of simulated floods ranges from 0.50 to 0.94.

Groundwater-atmosphere interactions

The impacts of groundwater tables and/or aquifers on the atmosphere have been widely researched in recent decades by modelling aquifers and/or groundwater tables in LSMs and climate models. The interaction between aquifers and the atmosphere is based mostly on the fact that groundwater in aquifers can interact with the surface soil profile vertically, increasing soil moisture and local water supply to the atmosphere. Liang et al.for example, discovered that a simulation incorporating surface and groundwater interactions resulted in wetter soil moisture in the lower soil layer.

The primary effect when describing groundwater dynamics and lateral subsurface flows in LSMs is that subsurface flows can rearrange the spatial pattern of soil moisture, possibly affecting surface atmospheric processes. For example, Seuffert et al. discovered that in a local climate model, lateral soil water movement across adjoining soil columns can redistribute soil moisture and alter evaporation and precipitation. In a linked simulation, Maxwell et al. discovered spatial and temporal connections between atmospheric variables (at the surface and lower altitudes) and water table depth.

The impacts of water table dynamics on regional climatic function are caused by local aquifer-atmosphere interactions; however, circulation variations are controlled by ambient aquifer-atmosphere interactions. Jr. Gutowski et al. discovered through numerical simulations that water redistributed by the aquifer-river network can sometimes elevate the water table to the plant root zone and boost evapotranspiration. Instead of just reflecting subsurface flows, the incorporation of groundwater models (e.g., ParFlow, MODFLOW) in climate models adds to clearly characterising lateral subsurface water transport and the additional interaction between surface water and soil water.

This allows us to evaluate the impact of lateral groundwater movement on total water cycling. Butts et al. used the HIRHAM-MIKE SHE dynamically linked climate-hydrological modelling system in a one-year simulation in a controlled groundwater-dominated catchment, the Skjern River, Denmark. The seasonal changes between linked and uncoupled models are large, notably for summer precipitation and evapotranspiration, but net precipitation was small.

Terrestrial water flows to the atmosphere

It was discovered that depicting surface runoff may significantly alter soil moisture, surface water, and energy balance in LSMs; however, without overland and channel routing, the created runoff disappears from LSM grids. The fully connected atmospheric and hydrological models can replicate lateral surface water flow and its feedback to the atmosphere due to the incorporation of hydrology models.The influence of hydrological augmentation on the atmospheric boundary layer was studied using two-way coupling atmospheric-hydrological simulations over short time periods (e.g., convective precipitation) Researchers discovered that terrestrial water flows can modify water cycle and influence regional climate at seasonal or longer time periods by comparing coupled and solo long-term hydrometeorological models.

Difficulties and challenges

- Hydrological parameters are being calibrated. Some hydrological parameters in hydrology models are derived by calibration, which is rather straightforward for statistical empirically based hydrology modelling. However, parameter calibration for coupled atmospheric and hydrological models is largely computational and time-consuming, and obtaining global- or continental-scale parameter datasets for high-resolution hydrology models remains difficult, despite the fact that some hydrological parameter datasets are available for large-scale hydrology models (e.g., the macro-scale VIC model).
- Physical mechanisms are described at great resolutions. At high or super-high resolutions, today's fully linked atmospheric and hydrological models are often used (less than 1 km). As a result, it is critical to comprehend the physical mechanisms through high-resolution monitoring of the underlying surface, such as interactions between atmospheric and hydrological processes, as well as interactions between the surface and the subsurface.
- The simulation domain and timeframe have limits. High- or superhigh-resolution hydrometeorological simulations are important research areas, but they necessitate substantial computer capability and a vast quantity of datasets. High-resolution hydrometeorological models were performed in this situation mostly for small domains/watersheds or short time spans.
- Schemes for parameterization are being improved. One goal for building connected atmospheric and hydrological models is to improve parameterization methods for water cycle processes, which will ultimately increase the accuracy of simulation and forecasting. Some human activities, such as reservoir impoundment and management, groundwater extraction, and irrigation, have the potential to drastically change hydrological processes and the water cycle.

Opportunities

Two-way linked atmospheric and hydrological models are physically based and employ parameters with clear physical meanings, as opposed to statistical empirically based hydrology models, which must be calibrated using data. Hydrological models in coupled models are focused on modelling two- and three-dimensional hydrological processes using high-resolution meteorological and underlying surface variables, as well as hydrological characteristic factors. RCMs, for example, can accurately replicate some localised atmospheric processes, such as orographic and convectional rain, as well as the locations, assisting in the forecasting of violent storm occurrences and the resulting hydrological processes.

Fully connected atmospheric and hydrological models mimic atmospheric processes as well as lateral surface and subsurface water flow in a dependent manner, and variables are exchanged between atmospheric and hydrological models. Unlike the one-way coupling strategy, which requires hydrology models to be externally driven by forced meteorological conditions, the two-way coupling approach allows climate models to simulate catchment-scale hydrological processes and changing water cycle-related variables. These occur throughout the simulation duration and over the whole simulation domain. This helps to improve the accuracy of hydrometeorological forecasting and revise modelling atmospheric processes, which has significant promise in forecasting floods and droughts in the future.

The anthropogenic implications on the terrestrial water cycle have received growing attention as anthropogenic disruption has increased. Anthropogenic water resource redistribution can impact hydrological processes (e.g., change in flood amplitude and timing due to reservoir impoundment and management, reduction in groundwater table due to groundwater extraction) as well as land surface processes (e.g., increase in evapotranspiration and alteration of energy exchange by irrigation).

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