Examination of the Bouchet–Morton Complementary Relationship Using a Mesoscale Climate Model and Observations under a Progressive Irrigation Scenario

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ABSTRACT

The complementary relationship between actual and potential evaporation over southeastern Turkey was examined using a mesoscale climate model and field data. Model simulations of both actual and potential evaporation produce realistic temporal patterns in comparison to those estimated from field data; as evaporation from the surface increases with increasing irrigation, potential evaporation decreases. This is in accordance with the Bouchet–Morton complementary relationship and suggests that actual evapotranspiration can be readily computed from routine meteorological observations. The driving mechanisms behind irrigation-related changes in actual and potential evaporation include reduced wind velocities, increased atmospheric stability, and depressed humidity deficits. The relative role of each in preserving the complementary relation is assessed by fitting a potential evaporation model to pan evaporation data. The importance of reduced wind velocity in maintaining complementarity was unexpected, and thus examined further using a set of perturbation simulation experiments with changing roughness parameters (reflecting growing cotton crops), changing moisture conditions (reflecting irrigation), and both. Three potential causes of wind velocity reduction associated with irrigation may be increased surface roughness, decreased thermal convection that influences momentum transfer, and the development of anomalous high pressure that counteracts the background wind field. All three are evident in the mesoscale model results, but the primary cause is the pressure-induced local wind system. The apparent necessity of capturing mesoscale dynamical feedbacks in maintaining complementarity between potential and actual evaporation suggests that a theory more complicated than current descriptions (which are based on feedbacks between actual evaporation and temperature and/or humidity gradients) is required to explain the complementary relationship.

1. Introduction

It is widely accepted that regional evapotranspiration from land surfaces is difficult to estimate and remains one of the most poorly understood components of the hydrologic cycle (Entekhabi et al. 1999). In part, this difficulty stems from lack of reliable data on soil moisture, especially in highly variable surfaces. Additionally, most routine methods to estimate evapotranspiration require hard-to-obtain parameters such as turbulent transfer coefficients and stomatal conductances. Thus, evaporation estimation methods that avoid the use of rarely available soil moisture data and are simple enough to be used with routinely available meteorological data are highly desirable.

One such method is the complementary relationship (hereafter CR) first proposed by Bouchet (1963) and further developed by Morton (1965). Originally based entirely on heuristic arguments, the theory of complementarity has found wide support in the literature both through comparison to other methods that estimate evapotranspiration (Parlange and Katul 1992; Qualls and Gultekin 1997) and through analysis based on meteorological observations and/or modeling results (Hobbins et al. 2001; Sugita et al. 2001; Ozdogan and Salvucci 2004; Hobbins et al. 2004). Other recent research is focused on finding a more physical foundation for the CR (e.g., Kim and Entekhabi 1997; Szilagyi 2001).

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The purpose of the study presented herein is to investigate the validity of the CR in southeastern Turkey with the help of a mesoscale climate model as well as with meteorological data. The CR was evaluated within the climate model by performing 10-day midsummer simulations to determine the changes in hydrologic fluxes under a progressive irrigation development scenario. The model, which forecasts regional meteorological and surface conditions, implicitly captures the feedbacks between potential and actual evaporation by updating the temperature and moisture fields, both at the surface and in the overlying atmosphere, which subsequently moderates the interaction between the two. This makes the model a reasonable forecasting tool for this region and a reasonable tool for supporting or contradicting the theory of complementarity. The CR was further analyzed by estimating the terms of the Penman equation [including the Monin–Obukhov (1954) (M–O) stability parameters] that was calibrated to measured pan evaporation. Because M–O characterization requires specification of the sensible heat flux (H), a simple land surface energy balance was computed to estimate H in conjunction with the potential evaporation equation.

By combining the results from the climate model and meteorological data, it was possible to (i) test the CR purely in the mesoscale model; (ii) compare potential evaporation estimates between the climate model, pan evaporation data, and calibrated potential evaporation equations; (iii) estimate the M–O scaling variables (which include instability) for comparing environmental variables such as wind speed and humidity between the climate model and observations; (iv) have a calibrated potential evaporation equation with which sensitivity analyses could be performed to explore the relative importance of variables like humidity and wind speed for maintaining complementarity; and (v) explore the larger-scale, dynamical feedbacks controlling the wind speed decreases reported in Ozdogan and Salvucci (2004). As an example of a unique long-running experiment, the data collected throughout the extensive irrigation development projects in southeastern Turkey provide an opportunity to perform and evaluate each of these tasks.

8. Conclusions

The present study was designed to evaluate the complementary relationship between potential and actual evaporation using a mesoscale climate model as well as meteorological data. The gradual expansion of irrigated land area in southeastern Turkey forms the natural setting for such a task. The results indicate that model-simulated potential evaporation decreases as a function of increased irrigated land area and that this decrease is at the same rate as the actual evaporation increase, lending support to the complementary relationship. Given appropriate representations for potential and wet-environment evapotranspiration—for example, through observed pan evaporation or other empirical methods suggested by Brutsaert and Stricker (1979) it becomes a simple matter to compute actual evapotranspiration from routine meteorological observations under complementarity theory. The simulated fluxes of potential evaporation also agree well with the re-estimated potential evaporation equation that includes M–O stability corrections, and with the measured pan evaporation data. Such agreement, in turn, leads to confidence to using the RSM model as a numerical laboratory for studying the meteorological feedbacks (e.g., wind speed decreases with nonclassical mesoscale circulations).

Research using this model output also presents a unique opportunity to find physically meaningful explanations for the CR. The importance of dynamic feedbacks is one such finding. According to the model results, irrigation causes increased surface pressure, which generates localized pressure gradients across which the air flows. This locally generated flow of air is generally in the opposite direction of background wind field. This "counterflow" leads to a decrease in wind speed over irrigated areas, which acts to reduce potential evaporation.

Another effect is thermodynamic in origin and is related to the atmospheric stability. Irrigation, when practiced extensively, increases latent heat flux at the expense of sensible heat flux and this influences the stability of the atmosphere. The resulting increasingly stable conditions reduce mixing in the lower atmosphere (similar to creating a smoother surface), thus further lowering potential evaporation. With stability effects included, potential evaporation calculated over an area is smaller than what it otherwise would be.

Results of this study also lend credibility to the evaporation prediction skill of the RSM model. The model, which forecasts regional meteorological conditions and soil moisture, accurately captures the feedbacks between E_a and E_p even without the use of a detailed land surface/biota component, making it a reasonable forecasting tool for this region.

As stated above, one of the goals here was to find a physical explanation for the CR, for example, through a conservation principle. However, the results from climate simulations and meteorological data used in a coupled SEB/calibrated Penman equation indicate that the complementarity arises from a combination of mechanisms including feedbacks from dynamics (through wind speed), atmospheric stability (through sensible heat flux), and humidity. This is contrary to some of the earlier work, which suggested the feedbacks from humidity are the only necessary explanation for the complementary relationship (e.g., Szilagyi 2001). The unexpected—and previously unreported—findings of this research related to the feedbacks on partitioning of water between surface and the atmosphere are exciting and form the basis for future research in further evaluating the complementary relation in southeastern Turkey and elsewhere.