Observational evidence of the complementary relationship in regional evaporation lends strong support for Bouchet’s hypothesis

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[1] Using independent observations of actual and potential evapotranspiration at a wide range of spatial scales, we provide direct observational evidence of the complementary relationship in regional evapotranspiration hypothesized by Bouchet in 1963. Bouchet proposed that, for large homogeneous surfaces with minimal advection of heat and moisture, potential and actual evapotranspiration depend on each other in a complementary manner through land-atmosphere feedbacks. Although much work has been done that has led to important theoretical and conceptual insights about regional actual evapotranspiration and its relation to regional potential evapotranspiration, never before has a data set of direct observations been assembled that so clearly displays complementarity, providing strong evidence for the complementary relationship hypothesis, and raising its status above that of a mere conjecture. Citation: Ramírez, J. A., M. T. Hobbins, and T. C. Brown (2005), Observational evidence of the complementary relationship in regional evaporation lends strong support for Bouchet’s hypothesis, Geophys. Res. Lett., 32, L15401, doi:10.1029/2005GL023549.

1. Bouchet’s Hypothesis

[2] Bouchet [1963] proposed that, for large homogeneous surfaces with minimal advection of heat and moisture, potential evapotranspiration (ETp) and actual evapotranspiration (ETA) are strongly coupled through land-atmosphere feedbacks. Thus, ETa is not an independent forcing function as usually assumed. If moisture at the surface is not limiting (i.e., under purely energy-limited conditions), \( ET_a = ET_p = ET_w \), where ETw is the wet-environment evapotranspiration. The hypothesis states that when ETa falls below ETw as a result of limited moisture availability, an amount of excess energy becomes available for sensible heat flux that warms and dries the atmospheric boundary layer thereby causing ETp to increase; similarly, if ETa increases because more moisture becomes available, less energy is available for sensible heat flux, causing ETp to decrease. If the energy budget remains otherwise unchanged and all the excess energy goes into sensible heat, a complementary relationship of the form \( ET_a + ET_p = kET_a \) develops such that k equals 2, as illustrated in Figure 1. In this expression, ETw is a constant for the prevailing atmospheric conditions and energy availability. As in the traditional Budyko approach

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2. Observational Evidence

[3] No absolute theoretical proof of the complementary relationship hypothesis has been given, except for proofs based on heuristic arguments [e.g., Morton, 1983] or on restrictive simplifying assumptions [e.g., Szilagyi, 2001], and some theoretical arguments suggest that, in principle, the hypothesis of a 1:1 compensation of ETA and ETp around ETa is only partially fulfilled [e.g., Kim and Entekhabi, 1998; McNaughton and Spriggs, 1989; Sugita et al., 2001]. However, models based on the complementary relationship hypothesis have been successfully used to make predictions of regional ETa on different temporal scales, therefore providing indirect evidence of its validity [e.g., Brutsaert and Stricker, 1979; Hobbins et al., 2001; Kim and Entekhabi, 1998; Morton, 1983]. But, by and large, the hypothesis has remained a conjecture, both from observational and theoretical points of view.

[4] Figures 2 and 3 present evidence of the complementary relationship hypothesis in the form of independent measurements of ETa and ETp. Figure 2 contains 192 data pairs from 25 basins across the U.S. [Hobbins et al., 2004], each pair consisting of an annual measure of pan evaporation (ETpan) (a surrogate for ETp) and an annual measure of ETA* (a water-budget based surrogate for ETa) from the basin containing the pan. For each available measure of annual ETpan in the period WY 1953–1994, ETA* was computed for the basin surrounding the pan as the difference between precipitation and runoff: The highest values of ETpan occur at the left of the graph, in water-limited environments, and are matched with the lowest values of ETA*. Moving to the right as precipitation increases, the limitation of water gives way to a limitation of energy, and ETpan decreases as ETA* increases. In general, ETpan and ETA* converge toward ETw in the wettest basins. Figure 2 closely matches the theoretical shape of the complementary relationship between regional ETp and ETa.
covering such a large geographical area and long temporal span. Furthermore, noting that the observations in Figures 2 and 3 have fundamentally different scales ($ET_p$ and $ET_a$ are point observations at pans or meteorological stations, whereas $ET_{aw}^*$ is an areal observation) this agreement is all the more remarkable, and raises the possibility that improved data could reveal even more precisely the complementarity of $ET_a$ and $ET_p$. If better data were available, exceptions to the complementarity might be revealed, but at this point it must be concluded that the complementary relationship hypothesis has substantial empirical support.

[6] Figures 2 and 3 correspond to a composite of 192 pans in 25 different basins over the continental U.S., spanning the full climatic range from arid to humid. Lumping basins from widely different environments into one graph allows one to depict the full range of humidity but takes us beyond the strict interpretation of Bouchet’s hypothesis. A more rigorous description of the behaviour of the evaporation fluxes for a fixed region is presented in Figures 4–6, showing the complementary relationship behaviour for three individual basins. Using the climate classification of Eagleson [1978b], the basin shown in Figure 4 (Peace River at Arcadia, central Florida) corresponds to a climate spanning a range from semi-arid to humid, that is, a climate with a potential humidity ratio between 0.7 and 1.2; the basin shown in Figure 5 (Salt River near Roosevelt, eastern Arizona) corresponds to a semi-arid climate spanning the range between arid and semi-arid; and the basin shown in Figure 6 (Guadalupe River near Spring Branch, central Texas) corresponds to a semi-arid climate. Although the data plotted in Figures 4–6 correspond to different years, each plot can be considered as showing the expected instantaneous response of $ET_p$ and $ET_a$ to changes in moisture availability. This is so because the magnitude of $ET_{aw}^*$ is relatively constant. Clearly, Figures 4–6 show that the complementary relationship is also observable for each individual basin (i.e., for a fixed region).

3. Concluding Remarks

[7] To summarize, using independent observations of actual and potential evapotranspiration combined with an
adjustment for the pan coefficient, we have offered the first large-scale direct observational evidence of the complementary relationship in regional evapotranspiration, and have shown that the relationship is evident at individual basins. Although much work has been done that has led to important theoretical and conceptual insights about regional ET and its relationship with ET [e.g., Brutsaert and Parlange, 1998; Brutsaert and Stricker, 1979; Hobbins et al., 2001; Kim and Entekhabi, 1998; Morton, 1983; Ozdogan and Salvucci, 2004; Sugita et al., 2001; Szilagyi, 2001], never before has a data set of direct observations been assembled that so clearly displays complementarity.

The complementary relationship has important applications in the field of water management [e.g., Hobbins et al., 2001; Ozdogan and Salvucci, 2004] and in explaining observed trends in climate variables associated with climate change. For example, the complementary relationship was recently invoked in the context of the so-called pan evaporation paradox [Brutsaert and Parlange, 1998; Ohmura and Wild, 2002; Roderick and Farquhar, 2002; Hobbins et al., 2004]. The pan paradox refers to the seemingly paradoxical observation of a decreasing trend in ETpan over the past half-century concurrent with an increase of global average surface temperatures. Our result supports arguments explaining the pan paradox as simply a manifestation of the complementarity between ET and ET [Brutsaert and Parlange, 1998; Hobbins et al., 2004].

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References

Figure 4. Pan ID 84707–Basin ID 02296750ID: Peace River at Arcadia, Florida, in HUC 03100101 (WRR 3: South Atlantic-Gulf) [data source: Slack and Landwehr, 1992].

Figure 5. Pan ID 27281–Basin ID 09498500: Salt River near Roosevelt, Arizona, in HUC 15060103 (WRR 15: Lower Colorado) [data source: Slack and Landwehr, 1992].

Figure 6. Pan ID 411429–Basin ID 08167500: Guadalupe River near Spring Branch, Texas, in HUC 12100201 (WRR 12: Texas-Gulf) [data source: Slack and Landwehr, 1992].

Figure 7. Pan ID 411429–Basin ID 08167500: Guadalupe River near Spring Branch, Texas, in HUC 12100201 (WRR 12: Texas-Gulf) [data source: Slack and Landwehr, 1992].

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