Geophysical Research Abstracts
Vol. 12, EGU2010-7059, 2010
EGU General Assembly 2010
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Why does poleward latent heat flux have an upper limit?

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Poleward atmospheric energy transport plays a key role in the climate system by helping set the mean equator-pole temperature gradient. The mechanisms controlling the response of poleward heat flux to climate change are still poorly understood. Recent work (Caballero and Langen 2005, O'Gorman and Schneider 2008) shows that midlatitude poleward latent heat flux in atmospheric GCMs generally increases as the climate warms but saturates at high temperature, reaching an upper limit and decreasing with further warming. The reasons for this behavior have remained unclear. The simplest scaling theory suggests that the latent heat flux $F_\ell \sim v_{ref}q_{ref}$, where v_{ref} is a typical meridional velocity in the baroclinic zone while q_{ref} is the typical humidity of poleward-moving air (Pierrehumbert 2003). This scaling works well at lower temperatures, but fails to capture the high-temperature saturation of F_ℓ. We study this problem using a series of simulations employing NCAR's CAM3 GCM coupled to a slab-ocean aquaplanet and spanning a wide range of CO_2 concentrations. We find that the main flaw of the simple scaling is its neglect of the humidity carried by equatorward-moving air. The latent heat flux can be expressed exactly as $F_\ell = V\Delta q$, where V is the total poleward mass flux and Δq is the difference between the flux-weighted humidities of poleward- and equatorward-moving air. Evaluation of these quantities in the simulations shows that humidity in the poleward-moving air increases at the Clausius-Clapeyron rate (about 7%/K), but humidity in the equatorward-moving air increases even faster, resulting in a net drop in Δq which coupled to the observed decrease in V leads to the saturation of F_ℓ. Using a Lagrangian back-trajectory algorithm and associated diagnostics, we show that this behaviour is related to the asymmetric shortening of mixing lengths as temperature increases.