Modelling Climate – Surface Hydrology Interactions in Data Sparse Areas

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The IHACRES rainfall-runoff model, which formed the basis of the rainfall-runoff model developed within, was originally developed by Prof. Anthony Jakeman. This work has not previously been submitted for a degree or diploma in any institution of higher education.

Some of the work presented in Chapter 4 has previously been published in Evans and Jakeman (1997, 1998); some of the work from Chapter 8 has been published in Evans et al. (1999); and some of the work from Chapter 9 has been published in Evans et al. (2000). Any contributions made by co-authors are indicated in the text.

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Abstract

The interaction between climate and land-surface hydrology is extremely important in relation to long term water resource planning. This is especially so in the presence of global warming and massive land use change, issues which seem likely to have a disproportionate impact on developing countries. This thesis develops tools aimed at the study and prediction of climate effects on land-surface hydrology (in particular streamflow), which require a minimum amount of site specific data. This minimum data requirement allows studies to be performed in areas that are data sparse, such as the developing world.

A simple lumped dynamics-encapsulating conceptual rainfall-runoff model, which explicitly calculates the evaporative feedback to the atmosphere, was developed. It uses the linear streamflow routing module of the rainfall-runoff model IHACRES, with a new non-linear loss module based on the Catchment Moisture Deficit accounting scheme, and is referred to as CMD-IHACRES. In this model, evaporation can be calculated using a number of techniques depending on the data available, as a minimum, one to two years of precipitation, temperature and streamflow data are required. The model was tested on catchments covering a large range of hydroclimatologies and shown to estimate streamflow well. When tested against evaporation data the simplest technique was found to capture the medium to long term average well but had difficulty reproducing the short-term variations.

A comparison of the performance of three limited area climate models (MM5/BATS, MM5/SHEELS and RegCM2) was conducted in order to quantify their ability to reproduce near surface variables. Components of the energy and water balance over the land surface display considerable variation among the models, with no model performing consistently better than the other two. However, several conclusions can be made. The MM5 longwave radiation scheme performed worse than the scheme implemented in RegCM2. Estimates of runoff displayed the largest variations and differed from observations by as much as 100%. The climate models exhibited greater variance than the observations for almost all the energy and water related fluxes investigated.

An investigation into improving these streamflow predictions by utilizing CMD-IHACRES was conducted. Using CMD-IHACRES in an “offline” mode greatly improved the streamflow estimates while the simplest evaporation technique reproduced the evaporative time series to an accuracy comparable to that obtained from the limited area models alone. The ability to conduct a climate change impact study using CMD-IHACRES and a stochastic weather generator is also demonstrated. These results warrant further investigation into incorporating the rainfall-runoff model CMD-IHACRES into a limited area climate model in a fully coupled “online” approach.

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Symbol	*Meaning*	**Units**
~	denotes an environmental value	-
α	represents an arbitrary variable; also absorptivity	-
α_c	cloud water radiation absorption coefficient	m^2g^{-1}
α_{cd}	cloud water downward radiation absorption coefficient	m^2g^{-1}
α_{cu}	cloud water upward radiation absorption coefficient	m^2g^{-1}
α_i	cloud ice radiation absorption coefficient	m^2g^{-1}
α_p	radiation absorption coefficient for precipitation	m^2g^{-1}
β	fraction of updraft condensate that re-evaporates in the downdraft	-
$\delta\theta$	soil moisture	mm
$\Delta = \frac{de^*}{dT}$	slope of the saturation water vapour pressure curve	mbK^{-1}
Δs	model gridpoint spacing	m
Δt	model time step	s
ε_d	downward emissivity function	-
ε_{tot}	total emissivity	-
ε_u	upward emissivity function	-
ε_{vapour}	water vapour emissivity	-
ϕ_0	soil water suction for saturated soil	m
ϕ_m	wind profile function	-
γ	psychrometric constant	mbK^{-1}
γ_ξ	correction to the local gradient that incorporates the contribution of large scale eddies to the total flux	-

η	fraction of transpiration from the top soil layer	-
μ	cosine of the zenith angle	-
$\tilde{\nu}$	wavenumber	m^{-1}
ν_a	annual frequency	s^{-1}
ν_{d}	diurnal frequency	s^{-1}
θ	potential temperature	K
θ_s	appropriate near surface temperature	K
θ_v	virtual potential temperature	K
θ_{va}	virtual potential temperature at the lowest model level	K
ρ	density	kgm^{-3}
ρ_a	density of surface air	kgm^{-3}
ρ_r	particle density	kgm^{-3}
ρ_s	density of the subsurface soil layer	$kgkg^{-1}$
ρ_w	soil water density	$kgkg^{-1}$
ρ_{wsat}	saturated soil water density	$kgkg^{-1}$
σ	terrain following vertical coordinate	
σ_f	fractional foliage cover for each grid point	-
σ_{SB}	Stefan-Boltzmann constant	$Wm^{-2}K^{-4}$
τ_c	cloud extinction optical depth	m
τ_q	quickflow time constant	days
τ_s	slowflow time constant	days
ω	particle single scattering albedo	
Ω_{r0}	maximum transpiration that can be sustained	$kgm^{-2}s^{-1}$
ξ	represents a prognostic variable	-
ψ_{w1}	diffusion of water from rooting zone to surface soil layer	mms^{-1}
ψ_{w2}	diffusion of water from total column to rooting zone	mms^{-1}
Ψ_w	rate of transfer of water by diffusion to the upper soil layer	mms^{-1}
a	Marshall-Palmer distribution parameter	-
A	surface area	m^2

$A_{\tilde{v}}$	absorptivity due to a given gas	-
ABE	buoyant energy available	J
ABE''	production of available buoyant energy by large scale motions during the time Δt	J
b	Marshall-Palmer distribution parameter	-
B	Plank function; also Clapp and Hornberger exponent	-
B	bias	mm/day
B_0	Bowen ration	-
C_D	aerodynamic drag coefficient over land	-
C_{DN}	drag coefficient for neutral stability	-
CMD	catchment moisture deficit	mm
C_p	specific heat of air	$Jkg^{-1}K^{-1}$
C_s	specific heat of the subsurface soil layer	$Jkg^{-1}K^{-1}$
C_{SOILC}	transfer coefficient between canopy air and underlying soil	-
D	diameter of droplet; relative drying power; also discharge from catchment	m; - ; mm
D_{db}	diurnal penetration depth	m
D_f	characteristic dimension of the leaves in the direction of wind flow	-
D_s	water diffusivity in the soil	m^2s^{-1}
D_w	rate of excess water dripping from leaves per unit land area	mm m^{-2}
E	evapotranspiration	mm
e_a	vapour pressure in near surface atmosphere	mb
E_a	total evaporative flux from the surface to the atmosphere	$kgm^{-2}s^{-1}$
E_A	drying power of the air	mm
E_f	evaporative flux from foliage	$kgm^{-2}s^{-1}$
E_f^{WET}	evaporation from wet foliage per unit wetted area	$kgm^{-2}s^{-1}$
E_g	evaporative flux from the ground	$kgm^{-2}s^{-1}$
E_p	potential evapotranspiration	mm
E_{p0}	evapotranspiration rate at which $E_p=E$	mm

E_{PT}	Priestly & Taylor potential evapotranspiration	mm
e_s^*	saturation vapour pressure at the surface temperature	mb
E_{tr}	transpiration	mm
E_{trmax}	maximum transpiration	$kgm^{-2}s^{-1}$
$F^{\uparrow}$	upward long wave radiation flux	Wm^{-2}
$F^{\downarrow}$	downward long wave radiation flux	Wm^{-2}
f_{cld}	probability of a cloud existing in a given atmospheric layer	-
f_{clear}	clear sky fraction of atmospheric column	-
$F_{clr}^{\downarrow}$	clear sky downward longwave radiation	Wm^{-2}
$F_{clr}^{\uparrow}$	clear sky upward longwave radiation	Wm^{-2}
f_g	wetness factor	-
F_H	horizontal diffusion effects	
F_q	moisture flux from ground to atmosphere	$kgm^{-2}s^{-1}$
F_{qm}	maximum moisture flux through the wet surface that the soil can sustain	$kgm^{-2}s^{-1}$
F_{qp}	potential evaporation	$kgm^{-2}s^{-1}$
F_{rr}	the unfrozen soil water	mm
F_s	atmospheric sensible heat flux	Wm^{-2}
F_V	vertical turbulent mixing effects	
g	gravity (ms^{-2}); also asymmetry parameter	-
G	net water applied to the surface in the absence of vegetation; also specific flux of heat into the ground	mm; Wm^{-2}
h	moist static energy; also height of PBL (m)	-
H_a	total sensible heat flux from the surface to the atmosphere	Wm^{-2}
H_f	sensible heat flux from foliage	Wm^{-2}
H_g	sensible heat flux from the ground	Wm^{-2}
h_l	meridionally varying, empirically derived local liquid water scale	-
h_s	surface heating	Wm^{-2}
I_1	amount of condensation integrated over the whole depth	-

	of the updraft normalised by the updraft mass flux	
I_2	evaporation in the downdraft normalised by the downdraft mass flux	-
J	relative evaporation; also Thornthwaite heat index	-
k	von Karman constant	-
K_ξ	the eddy diffusivity coefficient	m^{2}s^{-1}
k_{sb}	thermal diffusivity of soil for diurnal wave	m^{2}s^{-1}
K_{w0}	saturated hydraulic conductivity	ms^{-1}
K_{zm}	momentum diffusivity coefficient at height *z* above the surface	m^{2}s^{-1}
K_{zm}	eddy diffusivity for moisture at height *z* above the surface	m^{2}s^{-1}
K_{zt}	eddy diffusivity for temperature at height *z* above the surface	m^{2}s^{-1}
L	latent heat; Monin-Obukhov length scale; also daytime hours	Wm^{-2}; - ; 12 hrs
L_{AI}	leaf area index	-
L_d	fraction of foliage surface free to transpire	-
L_e	latent heat of evaporation	Wm^{-2}
L_f	latent heat of fusion	Jkg^{-1}
L_s	latent heat of sublimation	Jkg^{-1}
LS	denotes the large scale tendency	-
L_v	latent heat of vaporisation	Jkg^{-1}
L_w	fractional area of leaves and stems covered by water	-
M	moisture availability parameter	-
m_0	mass flux at the downdraft originating level	kgm^{-2}s^{-1}
m_b	mass flux at the updraft originating level	kgm^{-2}s^{-1}
MC	denotes the model calculated tendency	-
m_d	mass flux of the downdraft	kgm^{-2}s^{-1}
M_f	stomatal resistance dependence on soil moisture	-
m_u	mass flux of the updraft	kgm^{-2}s^{-1}
n	the displacement from the nearest boundary	grid points
N_0	Marshall-Palmer distribution parameter	m^{-4}

NA	rate of change of available buoyant energy per unit of mass flux	Js^{-1}
NSE	Nash-Sutcliffe efficiency	-
p	pressure	Pa
P	precipitation	mm
p^*	$p_s - p_{top}$	Pa
p_{clbk}	pressure level of the cloud base at k	Pa
P_{CON}	condensation of water vapour into cloud	$kgkg^{-1}s^{-1}$
P_{ID}	sublimation/deposition of cloud ice	$kgkg^{-1}s^{-1}$
P_{II}	initiation of ice crystals	$kgkg^{-1}s^{-1}$
P_{MF}	melting (freezing) of snow or ice (rain or cloud) due to atmospheric advection	$kgkg^{-1}s^{-1}$
Pr	Prandtl number	-
P_r	precipitation falling as rain	mm
P_{RA}	accretion of cloud by rain	$kgkg^{-1}s^{-1}$
P_{RC}	conversion of cloud to rain	$kgkg^{-1}s^{-1}$
P_{RE}	evaporation of rain	$kgkg^{-1}s^{-1}$
P_{RM}	snow melting to become rain	$kgkg^{-1}s^{-1}$
p_s	prognostic surface pressure	Pa
p_{top}	pressure specified to be the model top	Pa
q	specific humidity; also streamflow (observed)	$kgkg^{-1}$; mm
$\hat{q}$	modelled streamflow	mm
q_a	specific humidity of the lowest model level	-
q_{af}	water vapour specific humidity of the air within the foliage	-
q_c	mixing ratio of cloud water	-
q_g	saturated specific humidity at the temperature of the surface	-
Q_g	net outflow of ground water	mm
$q_{g,s}$	saturated specific humidity at soil surface temperatures	-
Q_n	available energy flux density	Wm^{-2}

q_r	mixing ratio of rain water	-
Q_s	net outflow of surface water	mm
q_v	mixing ratio of water vapour	-
$\mathfrak{R}$	residual of water balance	mm
r_e	effective of cloud droplets	m
R_f	stomatal resistance dependence on solar radiation	-
R_g	groundwater runoff	mm
Ri_B	surface bulk Richardson number	-
Rib_{cr}	critical bulk Richardson number	-
r_{la}	aerodynamic resistance to moisture and heat flux	sm^{-1}
R_{net}	net incident radiation at the surface	Wm^{-2}
r_s	stomatal resistance	sm^{-1}
R_s	surface runoff	mm
r_{smin}	minimum stomatal resistance	sm^{-1}
R_{ti}	fraction of roots in soil layer i	-
s	volume of water divided by volume of water at saturation	-
S	sources and sinks; also water volume stored in the system	- ; mm
S_0	solar constant	Wm^{-2}
S_a	clear air absorption of shortwave radiation flux	Wm^{-2}
S_{AI}	stem area index	-
S_{ca}	cloud absorption of shortwave radiation flux	Wm^{-2}
S_{cs}	cloud scattering of shortwave radiation flux	Wm^{-2}
S_d	downward shortwave radiation flux	Wm^{-2}
S_f	stomatal resistance dependence on temperature	-
S_g	solar flux absorbed over bare ground	Wm^{-2}
s_i	soil water in layer i	-
S_m	rate of snow melt	$kgm^{-2}s^{-1}$
SM	soil moisture	mm
S_{rw}	rooting zone soil water	mm
S_{rwmax}	maximum rooting zone soil water	mm
S_s	clear air scattering of shortwave radiation flux	Wm^{-2}
S_{sw}	surface soil water (upper layer)	mm

S_{swmax}	maximum upper soil water	mm
S_{tw}	total water in the soil	mm
S_{twmax}	maximum water in total soil column	mm
s_w	soil water for which transpiration essentially goes to zero	-
t	time	s
T	Temperature	K
T_a	air temperature of lowest model layer	K
T_{af}	temperature within the foliage layer	K
T_c	cloud water transmissivity	-
T_f	temperature of foliage	K
T_{g1}	surface soil temperature	K
T_{g2}	subsurface temperature	K
T_{g3}	deep soil temperature	K
T_p	precipitation transmissivity	-
T_v	water vapour transmissivity	-
u	cross front wind velocity	ms^{-1}
U	horizontal wind speed; also effective rainfall	ms^{-1}; mm
$\bar{u}$	mean wind speed	ms^{-1}
u_*	surface frictional velocity scale	ms^{-1}
U_a	horizontal wind above the canopy	ms^{-1}
U_{af}	wind velocity within foliage layer	ms^{-1}
u_c	cloud water path	gm^{-2}
u_g	geostrophic wind	ms^{-1}
u_p	effective water path	gm^{-2}
v	along front wind velocity	ms^{-1}
V_f	fall speed of rain or snow (ms^{-1}); also stomatal resistance dependence on vapour pressure deficit	-
V_q	relative volume of flow that travels through as quickflow	-
V_s	relative volume of flow that travels through as slowflow	-
w	vertically integrated cloud water path length; also a weighting function for the lateral boundary conditions	gm^{-2}

W_{dew}	total water stored by canopy per unit land area	mm m^{-2}
W_{DMAX}	maximum water the canopy can hold	mm m^{-2}
W_{LT}	soil dryness (or plant wilting) factor	-
w_s	mixed layer velocity scale	-
$x^{(q)}$	quickflow	mm
$x^{(s)}$	slowflow	mm
z	height above the surface	m
z_0	originating level of downdraft; also the roughness length	m
z_1	height of lowest model level	m
z_b	originating level of updraft	m
Z_r	depth of soil rooting layer	m

List of Acronyms

Acronyms	*Meaning*
ABRACOS	Anglo-Brazilian Climate Observation Study
AMIP	Atmospheric Model Intercomparison Project
ARI	Average Recurrence Interval
ARPE	Average Relative Parameter Error
ASCE	American Society of Civil Engineers
BALTEX	Baltic Sea Experiment
BATS	Biosphere-Atmosphere Transfer Scheme
BOREAS	Boreal Ecosystem-Atmosphere Study
CMD	Catchment Moisture Deficit
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ECMWF	European Centre for Medium Range Weather Forecasts
EF	Evaporative Fraction
EFEDA	ECHIVAL Field Experiment in Desertification threatened Areas
ET	evapotranspiration
FIFE	First ISLSCP Field Experiment
GARP	Global Atmospheric Research Program
GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratories
GISS	Goddard Institute for Space Studies
GMT	Greenwich Mean Time
HAPEX	Hydrological and Atmospheric Pilot Experiment
HEIFE	Hei Ho River basin Field Experiment
IFC	Intensive Field Campaign

IHACRES	Identification of Hydrographs And Components from Rainfall, Evaporation and Streamflow data
IPCC	Intergovernmental Panel on Climate Change
ISLSCP	International Satellite Land Surface Climatology Project
IUH	Instantaneous Unit Hydrograph
LAM	Limited Area (climate) Model
LTER	Long Term Ecological Reserve
MM5	Penn State/NCAR Mesoscale Model version 5
MOBILHY	Modelisation du Bilan Hydrique
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research, USA
NCEP	National Center for Environmental Prediction, USA.
NOAA	National Oceanic and Atmospheric Administration
NOPEX	Northern Hemisphere Climate Processes Land Surface Experiment
NSE	Nash-Sutcliffe Efficiency
PAM	Portable Automatic Mesonet stations
PBL	Planetary Boundary Layer
PET	Potential evapotranspiration
PILPS	Project for Intercomparison of Land-surface Parameterisation Schemes
PIRCS	Project to Intercompare Regional Climate Models
RegCM2	NCAR Regional Climate Model version 2
SHEELS	Simulator for Hydrology & Energy Exchange at the Land Surface
SRIV	Simple Refined Instrumental Variable technique
SVAT	Soil-Vegetation-Atmosphere Transfer scheme
UTC	Coordinated Universal Time (GMT)