Land surface climate analysis

– along the rainfall-runoff chain –

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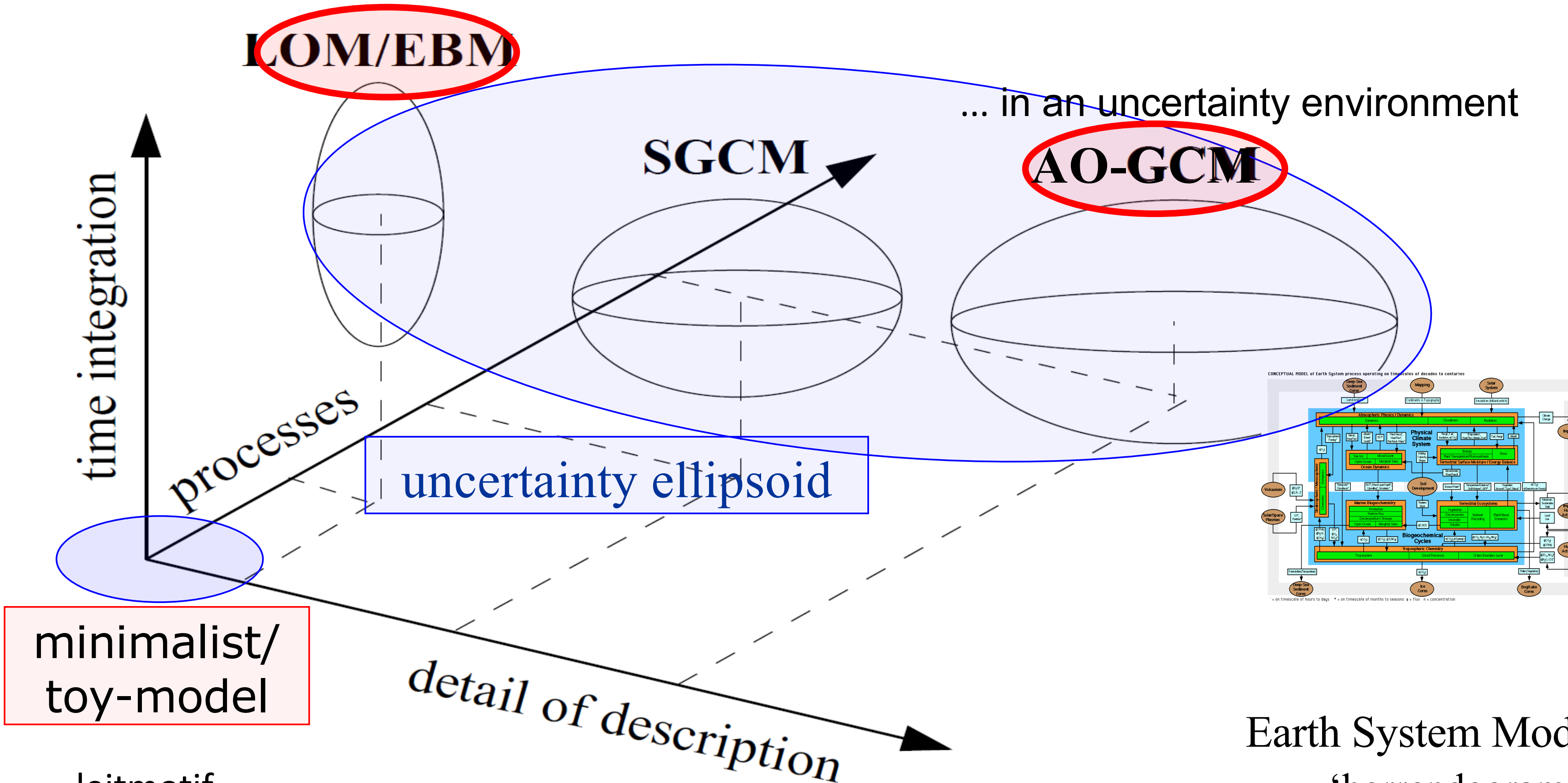
1. Introduction — *from models to toys*
2. Water Supply and Demand — *minimalist models*
3. System Analysis — *equilibria & trajectories, attribution & causality*
4. Outlook — *criticality, sustainability etc*



leitmotif

Earth System Models

'horrendogram'
(copyright: Michael G)

Source (KF et al 2005): General Circulation Models of the Atmosphere: Encyclopedia of Nonlinear Science

Model Complexity from models to toys

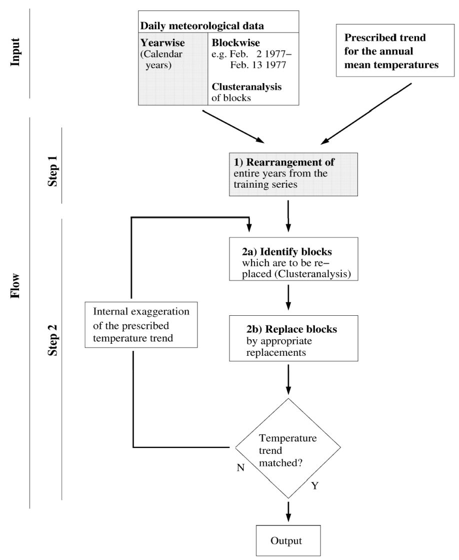
statistic

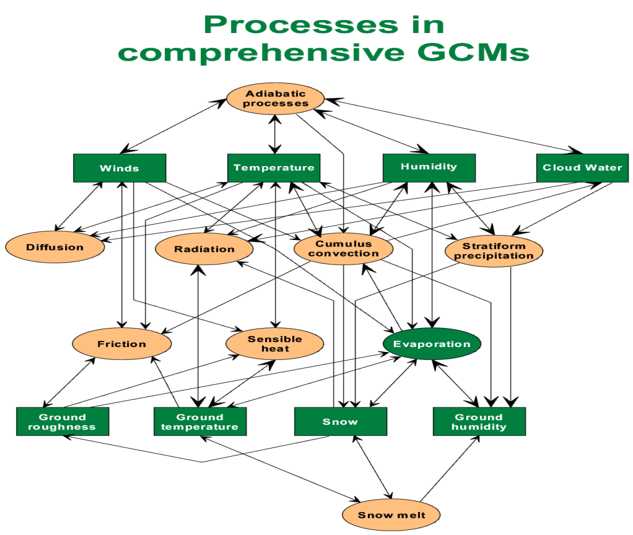
deterministic

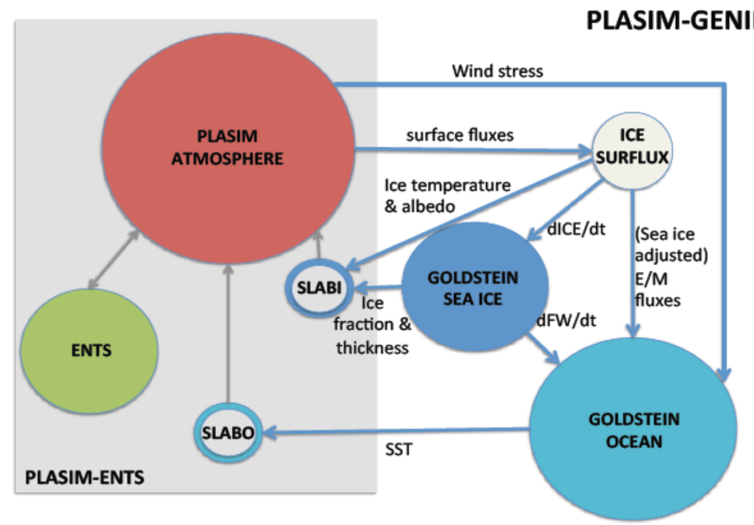
Weather Generators for regional climates

General Circulation Models (GCMs)

Global Climate Models (GCMs)







Statistical regional climate model (STAR)

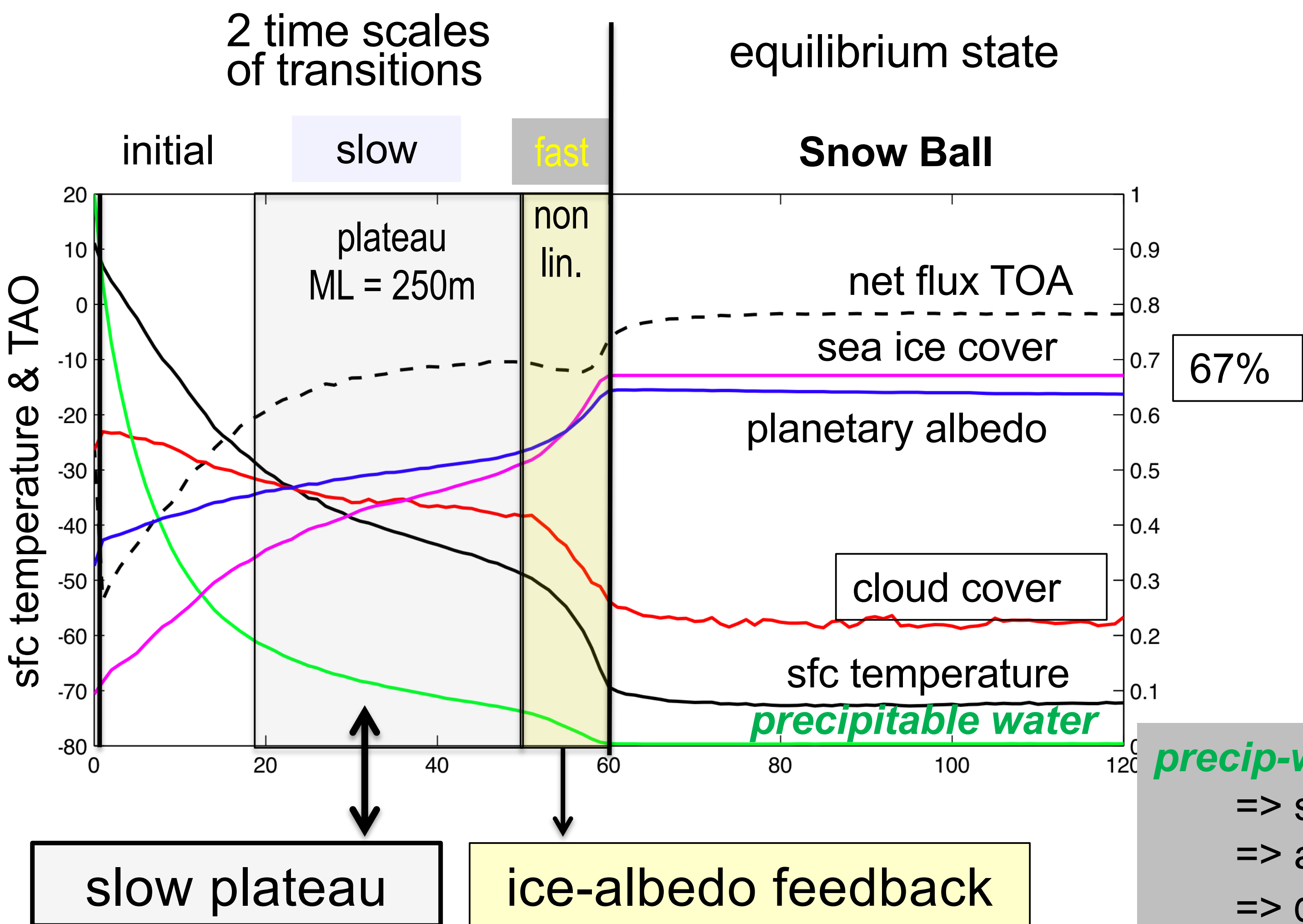
Planet Simulator (PlaSim)

PlaSim – Genie

Zhu, X., KF, and W. Wang, 2013: Future climate in the Tibetan Plateau from a Statistical Regional Climate Model. J. Climate 24, 10125-10138.
KF., H. Jansen, E. Kirk, U. Luksch, and F. Lunkeit, 2005: The Planet Simulator: Towards a user friendly model. Meteorol. Zeitschrift, 14, 299-304
KF., 2012: A suite of user-friendly global climate models: Hysteresis experiments. Eur. Phys. J. Plus, 127, doi: 10.1140/epjp/i2012-12053-7
Holden, P.B., N.R. Edwards, KF, E. Kirk, F. Lunkeit, and X. Zhun 2016: PLASIM-GENIE: a new intermediate complexity AOGCM. Geosci. Model Dev. 9, 3347-3361.
Holden, P.B., N.R. Edwards, P.H. Garthwaite, K. Fraedrich, F. Lunkeit, E. Kirk, M. Labriet, A. Kanudia, and F. Babonneau, 2014: PLASIM-ENTSem: a spatio-temporal emulator of future climate change for impacts assessment. Geosci. Model Dev. 7, 433-451
Holden, P.G., N. R. Edwards, A. Ridgwell, R. D. Wilkinson, K. Fraedrich, F. Lunkeit, H. E. Pollitt, J.-F. Mercure, P. Salas, A. Lam, F. Knobloch, U. Chewpreecha and J.E. Viñuales 2018: Climate-carbon cycle uncertainties and the Paris Agreement. *Nature Climate Change*, 8, 609–613

Simulation (time series) atmos. water content

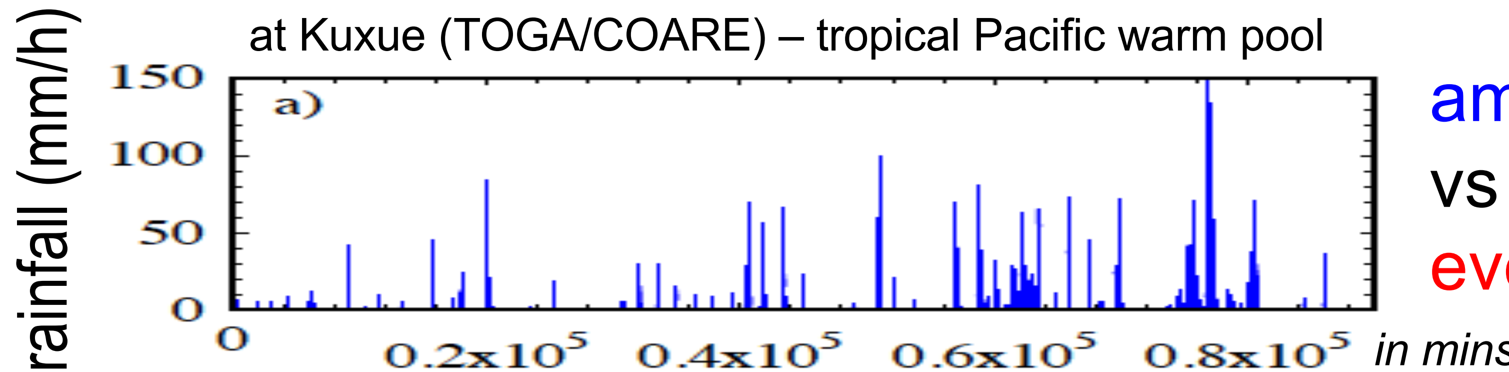
abrupt into a snowball Earth: CO_2 & O_3 = 0



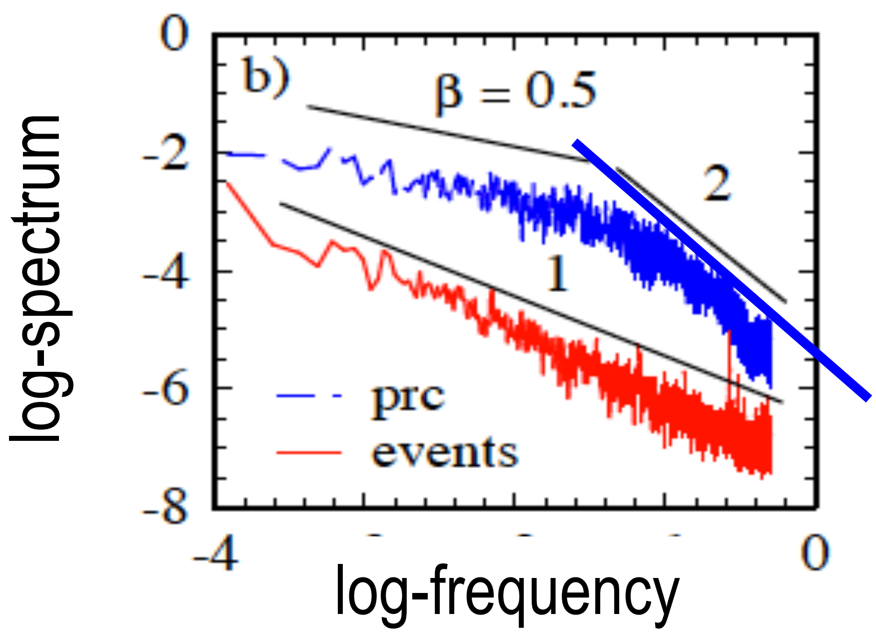
Planet Simulator
global response
transient experiment
ocean: ML = 250m

***precip-water:* most rapid decrease**
=> sea ice growth
=> albedo increase
=> global scale ice-albedo feedback
=> fast transition to snowball

Observation (time series) local rainfall



amount
vs
event



… and scaling $f^{-ß}$

blue: rainfall amount *ß ~ 2*
=> *AR(1)-process plus Long Term Memory (LTM)*

red: binary events *ß ~ 1*
=> *intermittency ~ Flicker noise*

toy: censored AR(1) – process

Hannachi, A., 2012: Intermittency, autoregression and censoring: a first-order AR model for daily precipitation. Meteorol. Appl.

2. Water Supply *and* Demand toy-models

Jennings‘ rain (1955)

Linacre‘s potential evapotranspiration (1977)

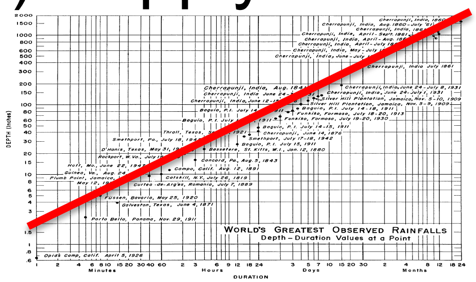
Schreiber‘s run-off (1904)

State spaces (Budyko frame work)

KF., F. Sielmann, D. Cai, X. Zhu 2016: Climate dynamics on watershed scale: along the rainfall-runoff chain. In: *The Fluid Dynamics of Climate*, Intern. Centre for Mech. Sci. (CISM), Springer, 183-209

from Supply *to* Demand — minimalists' toys geogr. space

i) Supply: Rainfall event/extreme

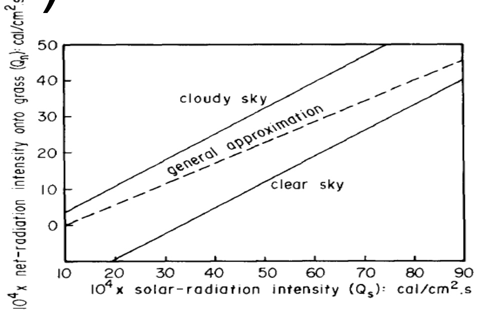


$$\boldsymbol{P}(d) \approx d^{1/2}$$

Scaling & Jennings' (1950) law

- a censored *AR(1)* – Intermittency

ii) Demand: Pot. Evapotransp. *N*

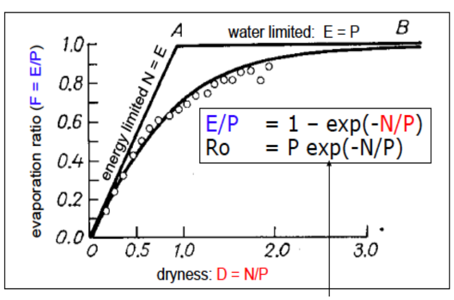


$$\boldsymbol{N} = \tfrac{1}{2}\, Solar$$

Linacre (1977), Abtew (1996)

- max entropy production (*MEP*)

iii) Rainfall – Runoff Chain



$$Ro = \boldsymbol{P} \exp(-\boldsymbol{N}/P)$$

Rainfall *P and* Net radiation *N*

Schreiber's (1904) formula

- a biased coin-flip Ansatz -

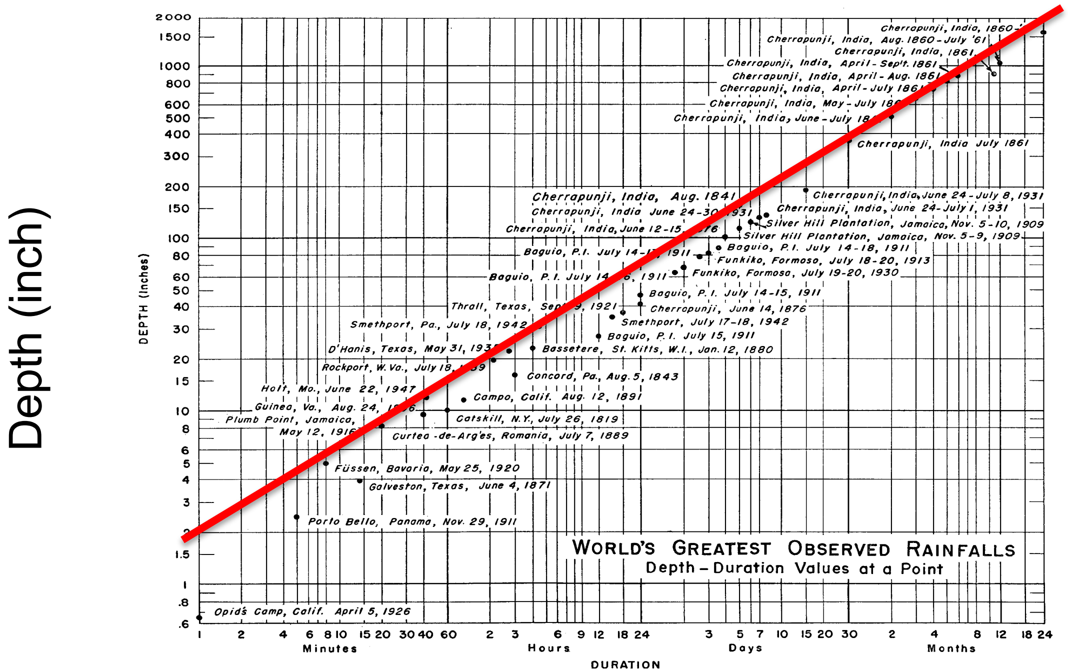
i) Water supply… world's greatest point rainfall

and Jennings' (1950) scaling law

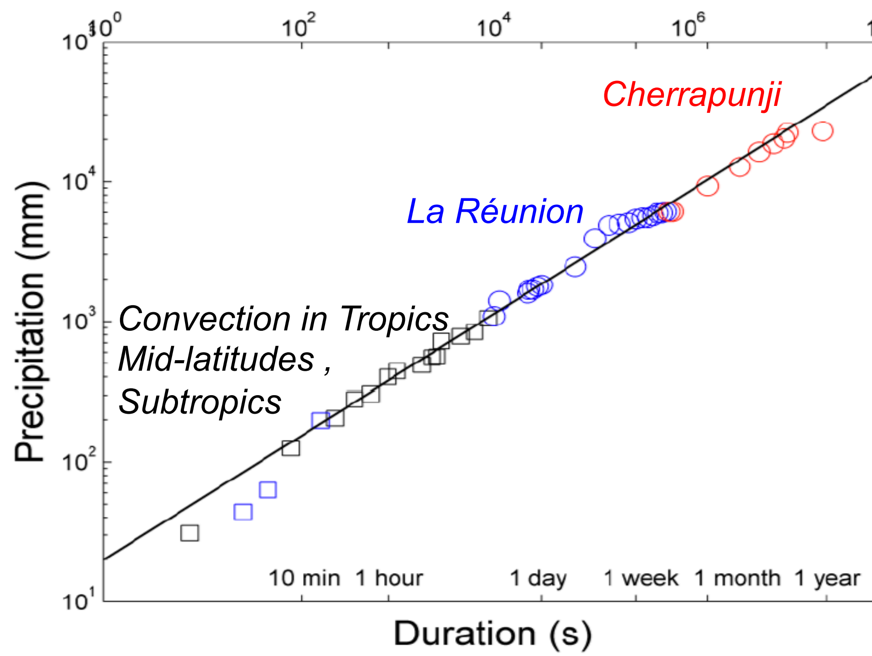
MONTHLY WEATHER REVIEW

WORLD'S GREATEST OBSERVED POINT RAINFALLS

ARTHUR H. JENNINGS



Reproduced with updated data (2013)



empirical

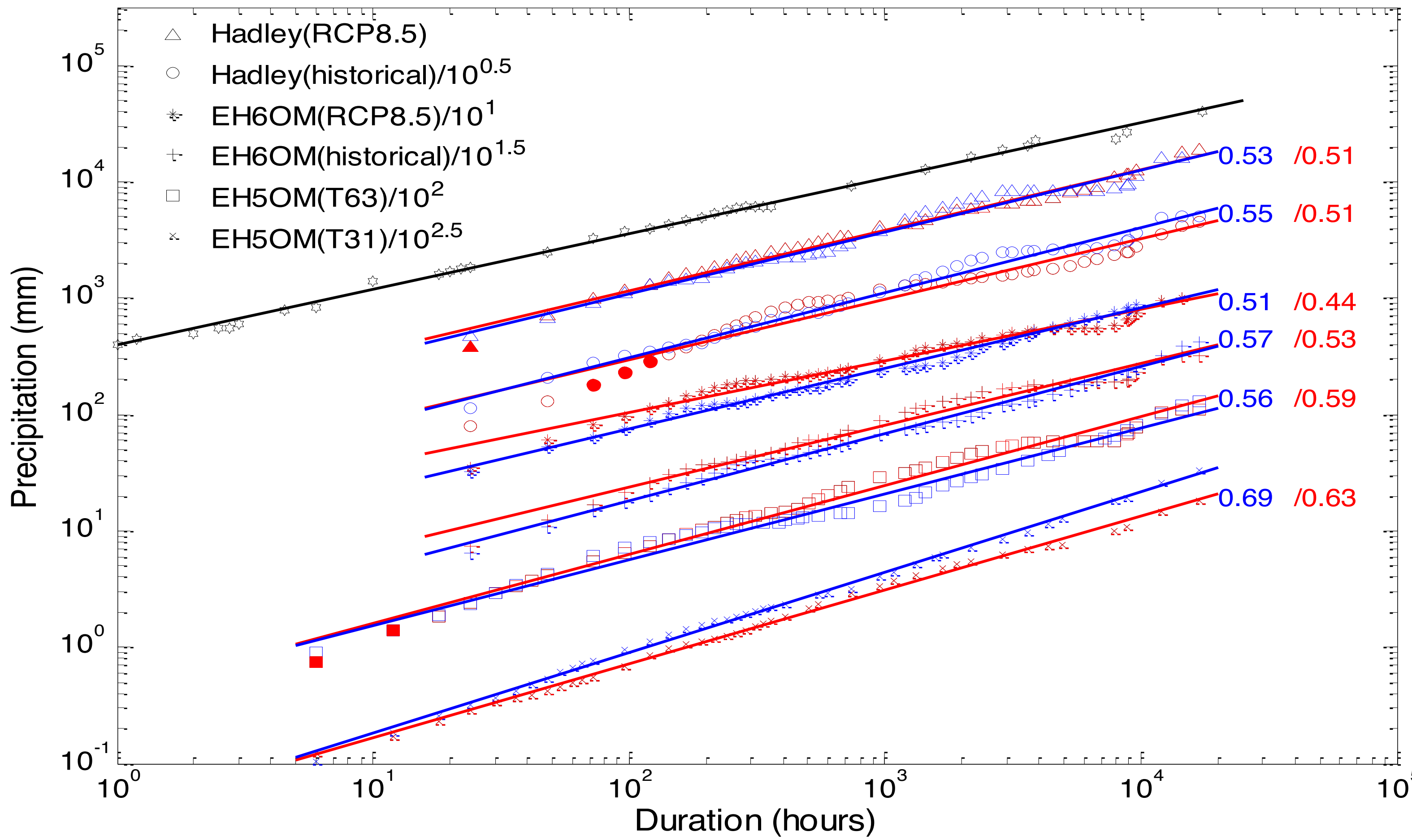
Jennings' Scaling Law (1951)

$$P(d) \approx d^{1/2}$$

P max local precipitation

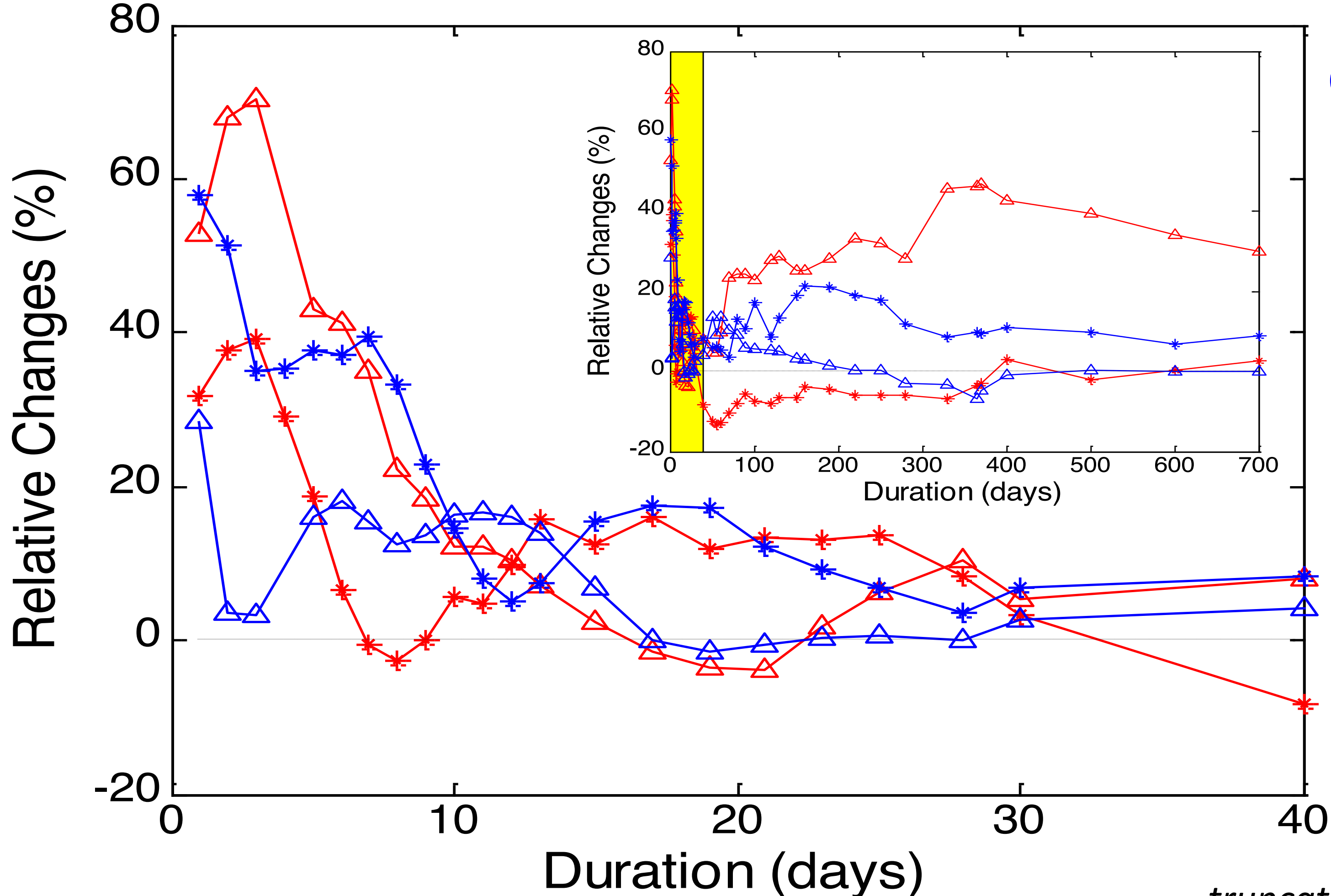
d duration

GCMs (sim.) Greatest point rainfall vs. time duration
land, ocean, and world wide observed



Water supply Jennings scaling law – present / warmer future

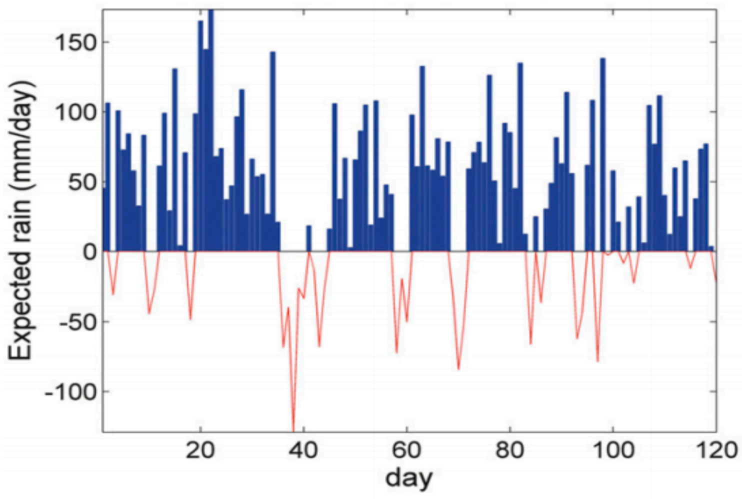
warmer climates: rainfall extremes become more severe at shorter duration time scales



Ocean and Land
triangle: HadGEM
star: ECHAM6OM

… truncated AR(1) follows

Water supply … a minimalist model



Toy model censored AR(1)

Interpretation: vertical water flux
rainfall-efficiency = 1
Data: daily 850hPa, ERA, Fangcheng

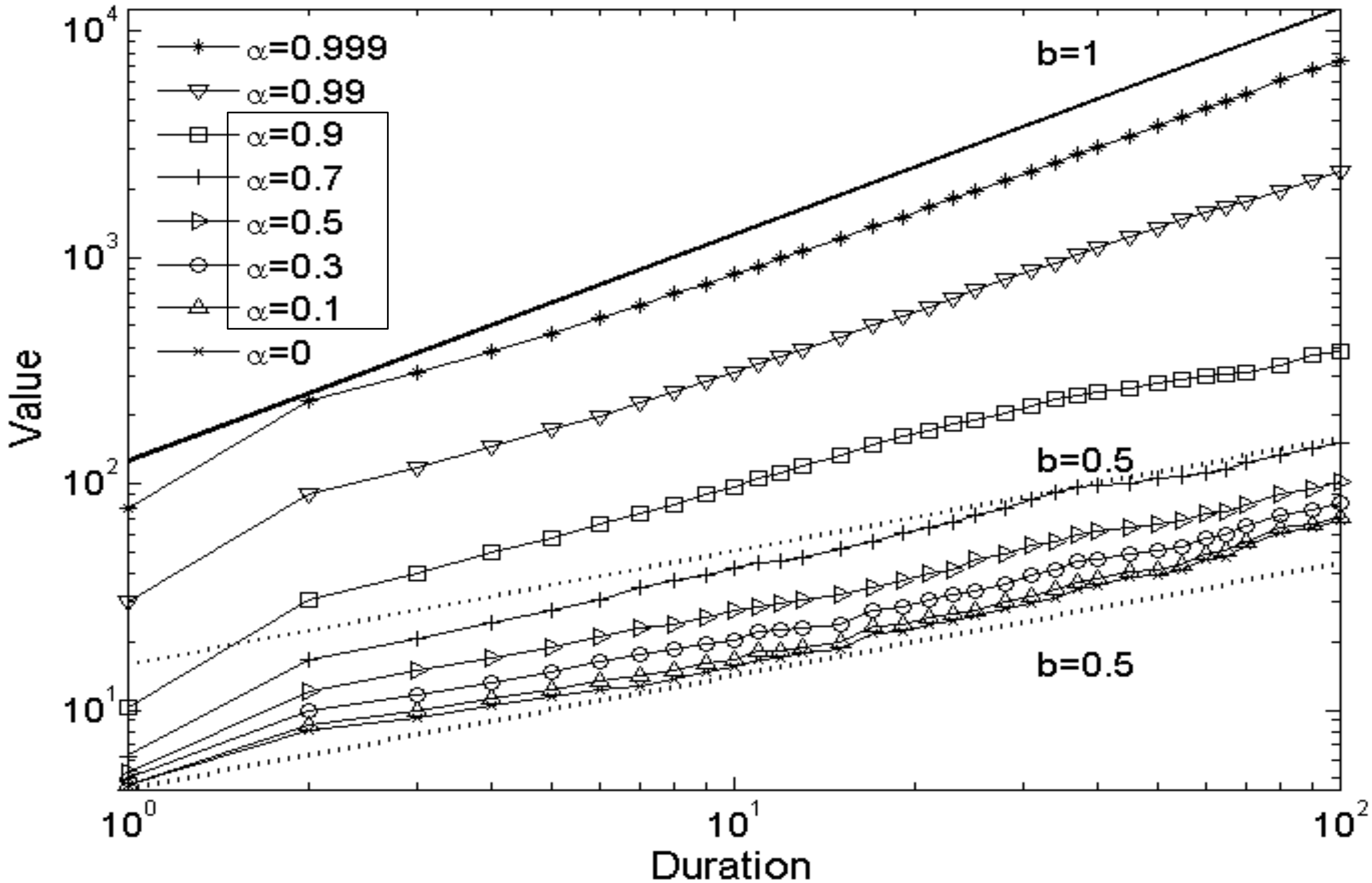
$$m(t) - M = a\,(m(t-1) - M) + \varepsilon$$

vertical water flux ***m***
mean ***M***
time ***t***

autocorrelation ***a = 0.31***
memory (integral time scale) ***1/(1-a)***
random noise ***ε***

Water supply truncated AR(1): $m(t) = a \cdot m(t-1) + r$

Gaussian noise with zero mean and unit variance



Zhang, H., K. Fraedrich, R. Blender, and X. Zhu 2013: Precipitation extremes in CMIP5 simulations on different time scales. *J. Hydromet. 14, 923-928*

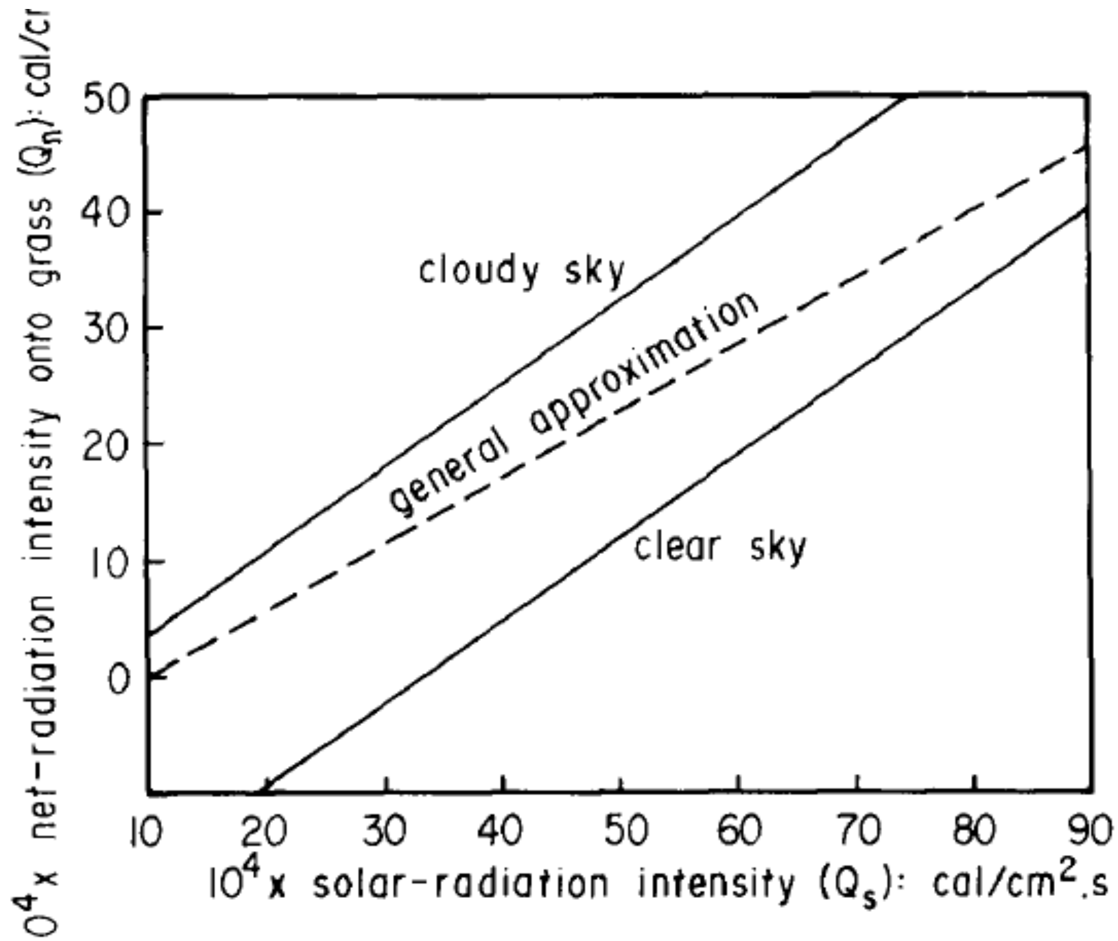
Zhang, H., K. Fraedrich, X. Zhu, and R. Blender 2013: World's greatest observed point rainfalls: Jennings (1950) scaling law. *J. Hydromet. 14, 1952-1957*

ii) Water demand *N* catchment scale pot. evapotranspiration

Linacre-77 Net rad = ½ Solar

Abtew-99 PET = 0.53 Solar

Linacre: Net & solar radiation with cloudiness extremes: Dashed: intermediate relationship assumed applicable generally.



Abtew W. 1996. Evapotranspiration measurement and modeling for three wetland systems in South Florida. Water Resources Bulletin 32, 465-473.
Linacre E.T. 1977. A simple formula for estimating evaporation rates in various climates, using temperature data alone. Agricultural Meteor. 18: 409–424

Water demand N … and on continental scale

Table 1b. Surface components of the annual mean energy budget for the globe, global land, and global ocean, except for atmospheric solar radiation absorbed (Solar absorb, left column), for the ERBE period of Feb 1985 to Apr 1989 (W m^{-2}). Included are the solar absorbed at the surface (Solar down), reflected solar at the surface (Solar reflect), surface latent heat from evaporation (LH evaporation), sensible heat (SH), LW radiation up at the surface (Radiation up), LW downward radiation to the surface (Back radiation), net LW (Net LW), and net energy absorbed at the surface (NET down). HOAPS version 3 covers 80°S–80°N and is for 1988 to 2005. The ISCCP-FD is combined with HOAPS to provide a NET value.

Global	Solar absorb	Solar down	Solar reflect	LH evaporation	SH	Radiation up	Back radiation	Net LW	NET down
KT97	67	168	24	78	24	390	324	66	0
ISCCP-FD	70.9	164.9	24.0	-	-	395.9	344.8	51.1	-
NRA	64.4	161.9	45.2	80.2	15.3	395.5	334.1	61.5	4.9
ERA-40	80.7	155.8	23.1	82.3	15.3	394.8	340.3	54.4	3.8
JRA	75.0	168.9	25.6	85.1	18.8	395.6	324.3	71.3	−6.3
Land									
ISCCP-FD	69.9	147.2	42.9	-	-	377.8	318.7	57.5	-
NRA	59.1	155.2	68.9	52.0	27.1	369.7	295.9	73.8	2.3
ERA-40	86.0	134.3	42.9	40.9	25.8	370.3	304.9	65.3	2.3
JRA	72.2	154.9	51.5	39.5	27.3	372.7	286.7	86.0	2.1
Ocean									
ISCCP-FD	71.4	171.5	17.0	-	-	402.7	354.5	48.2	10.4
NRA	66.3	164.3	36.7	90.3	11.0	404.9	347.9	57.0	6.0
ERA-40	78.8	163.5	15.9	97.3	11.5	403.6	353.1	50.5	4.2
JRA	76.0	173.9	16.2	101.5	15.8	403.9	337.9	66.0	−9.4

<Net rad> ≈ <½ Solar>

Trenberth K.E., J. T. Fasullo, and J. Kiehl 2009: Earth’s global energy budget, Bull. American. Meteor. Soc. 90, 311-323

Water demand *PET ≈ N = ½ Solar*

quantitative

reversible

Radiation balance **N** = **S**olar – **L**ong

terr. rad flux **L**ong = K (T_{sfc} – T_{atm})

linear with K = d $(\sigma T^4)/dT\,|T_0$

heat flux **J** = N = E + H

thermodyn feedback **J** = **S** – K (T_{sfc} – T_{atm})

(T_{sfc} – T_{atm}) = (S – J) / K
small grad T if J large
=> thermod. limit of max power prod

KE-Generation **G** = dissipation D

steady state

G = (heat flux **J**) x (efficiency **η**)

Efficiency **η** = (T_{sfc} – T_{atm}) / T_{sfc}

Carnot (reversible)

=> G = J (T_{sfc} – T_{atm}) / T_{sfc}

= J (S – J) / (KT_{sfc})

G = (J **S** – J^2) / (KT_{sfc})

Optimizing **dG/dJ** = 0

0 = **S** – 2 **J**

=> **S = 2 J = 2 N** **or** ***N = ½ S***

Renner M., S.K. Hassler, T. Blume , M. Weiler, A. Hildebrandt, M. Guderle, S. J. Schymanski, and A. Kleidon 2016: Dominant controls of transpiration along a hillslope transect inferred from ecohydrological measurements and thermodynamic limits. Hydrol. Earth Syst. Sci., 20, 2063–2083

iii) Water supply P & demand N catchment scale

Schreiber's (1904) equation

Meteorologische Zeitschrift. Oktober 1904.

Über die Beziehungen zwischen dem Niederschlag und der Wasserführung der Flüsse in Mitteleuropa.

Von Dr. Paul Schreiber.

empirical

$$y = x \cdot e^{-\frac{k}{x}}$$

jährliche Abflußhöhe y

Niederschlagshöhe x

minimalist model

$$Ro = P \exp(-N/P)$$

Supply P rainfall
Demand N net rad (pot. evapot)
Loss Ro runoff

$D = N/P$ = dryness

theor. underpinning

Supply & demand
blue – green water

‘ideal *rainfall–runoff* chain’

from a *biased* coinflip stochastic model
to an equation of state (P, N, Ro)

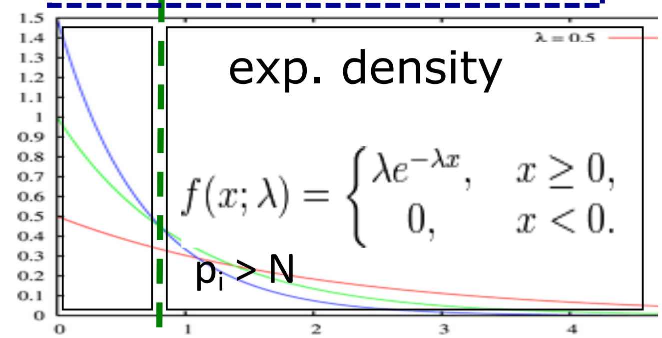
‘upper world’ forcing — ***random*** atmosphere

‘bias’ — ***fast*** ‘bias’-sphere

‘under world’ response — ***slow*** soil

2 time scales:
fast t => 0
slow t => ∞

supply P
daily biased coinflip
‘dry’ ‘wet’



daily rainfall

start

end

demand N
net rad ~ pot. evap.

waste Ro
runoff

Climate mean runoff

Ro = P exp(-N/P)

Schreiber 1904: eq. of state
Dryness = N/P

KF. 2010: A parsimonious stochastic water reservoir: Schreiber's 1904 equation. J. Hydrometeorology, 11, 575-578

‘ideal rainfall–runoff chain‘ *quantitative*

random atmosphere

water supply	exponentially distributed daily rainfall p_k $prob(p_k \leq p^*) = 1 - exp(-p^*/P)$
water demand	biased coin-flip daily rainfall threshold $p^* = N$

fast biosphere

interception	water in transit: short residence $t \sim 1day$
capacity	~ water equivalent of net radiation $n_k \sim N$

slow soil

no supply $\Rightarrow ro_k = 0$	$q_0 = prob(p_k \leq N) = 1 - exp(-N/P)$ $evapo\ e_k = p_k$, $sens.\ heat\ h_k = N - e_k$
supply $\Rightarrow ro_k = p_k - e_k$	$q_1 = prob(p_k > N) = exp(-N/P)$ $evapo\ e_k = n_k = N$

	Supply $p_k > N$	minus	demand $n_k = N$
Ro =	${}_N\int^{\infty} p_k\, exp(-p_k/P)\, dp_k/P$	minus	${}_N\int^{\infty} N\ exp(-p_k/P)\, p_k/P$
	$(P + N)\, exp(-N/P)$	minus	$N\, exp(-N/P)$

‘ideal rainfall-runoff chain’

equilibrium

water balance

energy balance

$$0 = P - (E + Ro)$$
$$0 = N - (E + H)$$

plus

eq. of state

$$Ro = P \exp(-N/P)$$

$D = N/P$
= dryness

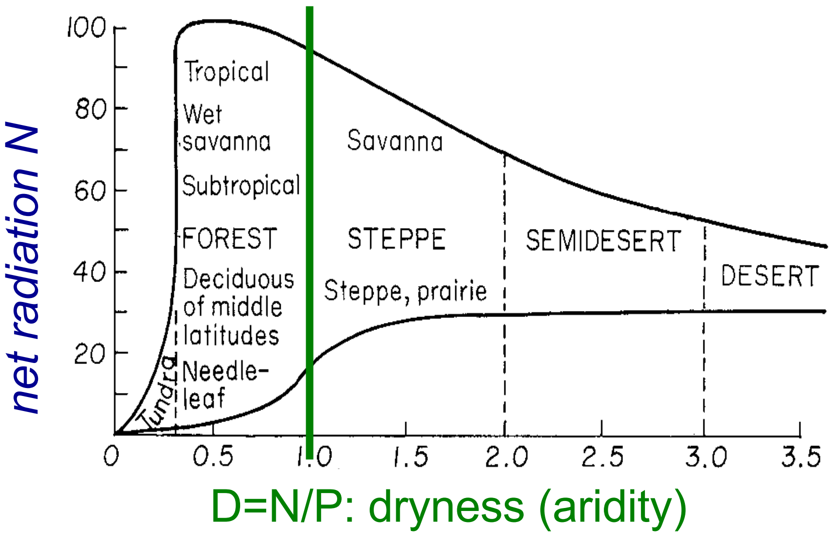
validation

1st,2nd moment, predictab., sensitivity

KF, Sielmann, Cai, Zhang, Zhu 2015: Validation… *Water Res. Manag. 29*, 313
KF, Sielmann 2011: An equation of state … *Int. J. Bifurc.Chaos* 21, 3577

... and eco-hydrological state spaces

eco-hydrological state spaces fluxes

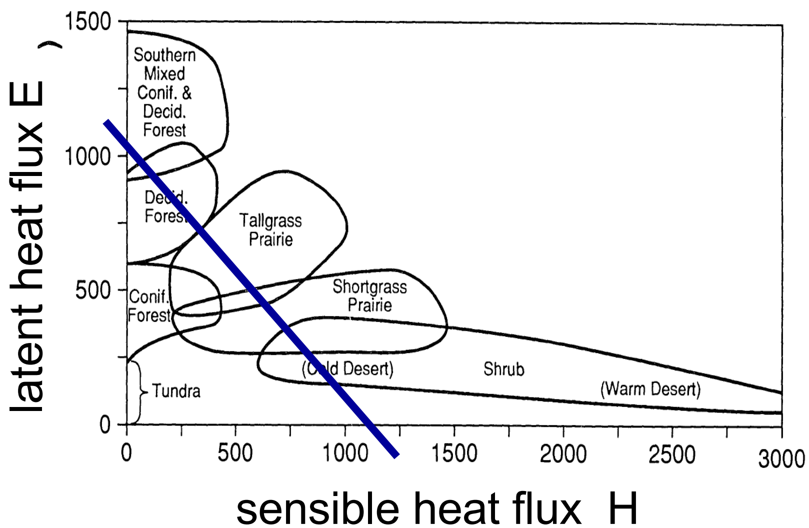


(N,D) - space

N: pole-equator meridionality (vertical axis)
D: dryness (aridity): geo-botanic climate state

Budyko, M. I. (1974): Climate and Life, 508 pp

Application: embedding vegetation



(E,H) - space

N = E + H = const: zonality
latent & sensible heat flux: E & H

Stephenson, NL (1998): J Biogeogr. 25, 885-870

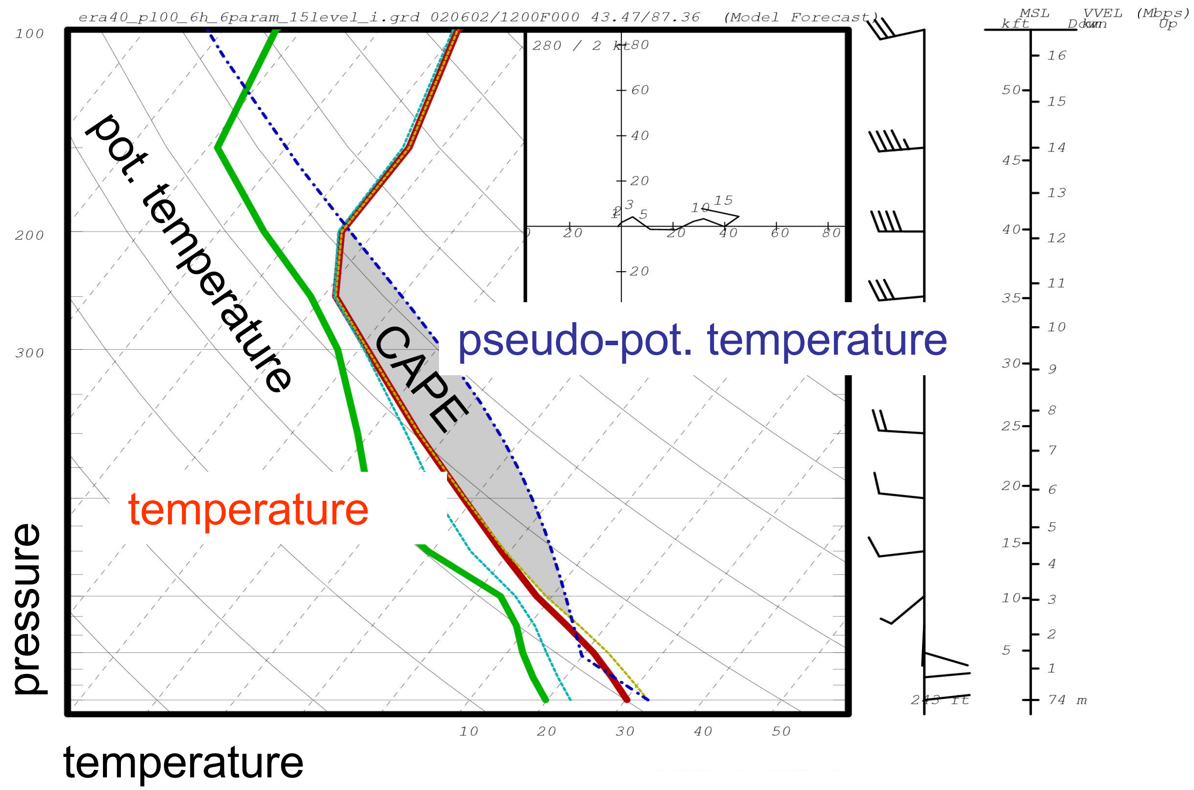
Application: embedding animals

an analogy… thermodynamic diagram

Equation of state

plus
Energy balance
Moisture balance

CAPE: energy available for conv. overturning



towards system analysis equilibria – trajectories – criticality

rainfall runoff chain			
special trajectories	equilibrium	finite trajectories	criticality
dynamic model state space diagnostics	ideal rainfall-runoff chain validation	attribution of change external-internal causes	index model life systems

Vegetation Greenness – NDVI

Vertebrates – Species Richness

Humans – Urbanization – Nighttime Light

S-America & Tibetan Plateau

Conclusion

3. System Analysis equilibria and trajectories

(i) Equilibria and state space coordinates

Vegetation – Greenness – NDVI

Vertebrates – Species Richness

(ii) Trajectories attribution of change (internal – external)

Tibetan Plateau & Qinghai Lake

South-America & Lake Titicaca

Humans & Urbanization – Nighttime Light

Cai, D., K. Fraedrich, Y. Guan, S. Guo, C. Zhang, X. Zhu 2019: Urbanization and climate change: Insights from eco-hydrological diagnostics. Science of the Total Environment (STOTEN) 647, 29-36

Zhang, X.X., S. Guo, Y. Guan, D. Cai, C. Zhang, K. Fraedrich, X. Han, Z. Z. Tian 2019: Urbanization and spillover effect for three megaregions in China: Evidence from DMSP/OLS nighttime lights. Remote Sensing 11,

Cai, D., Fraedrich, K., Guan, Y., Guo, S., Zhang, C. (2017): Urbanization and the thermal environment of Chinese and US-American cities. Science of the Total Environment (STOTEN), 589, 200–211

Cai, D., K. Fraedrich, F. Sielmann, Y. Guan, S. Guo 2016: Land cover characterization and aridity changes of S. America (1982 to 2006): An attribution by eco-hydrological diagnostics. J. Climate 29, 8175-8189.

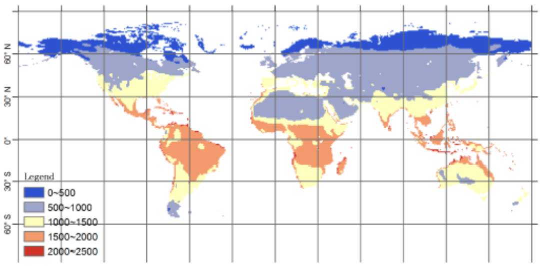
Cai, D, K. Fraedrich, F. Sielmann, L. Zhang, X. Zhu, S. Guo, Y. Guan, 2015: Vegetation dynamics on the Tibetan Plateau (1982 to 2006): An attribution by eco-hydrological diagnostics, J. Climate 28, 4576-4584.

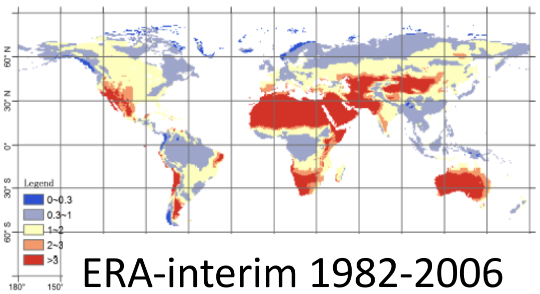
Cai, D., K. Fraedrich, F. Sielmann, Y. Guan, S. Guo, L. Zhang, X. Zhu 2014: Climate and vegetation: An ERA-1 Interim and GIMMS NDVI Analysis, J. Climate 27, 5111-5118.

KF., F. Sielmann, D. Cai, X. Zhu 2016: Climate dynamics on watershed scale: along the rainfall-runoff chain. In: *The Fluid Dynamics of Climate*, Intern. Centre for Mech. Sci. (CISM), Springer, 183-209

Vegetation greenness (NDVI) (*N*,*D*) – state space

Geographical Space





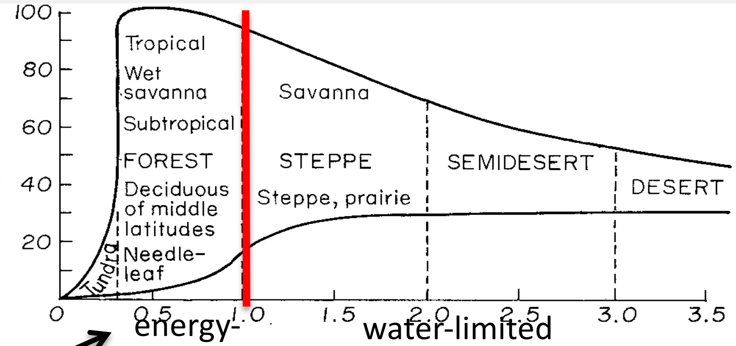
ERA-interim 1982-2006

Net radiation N
y-axis

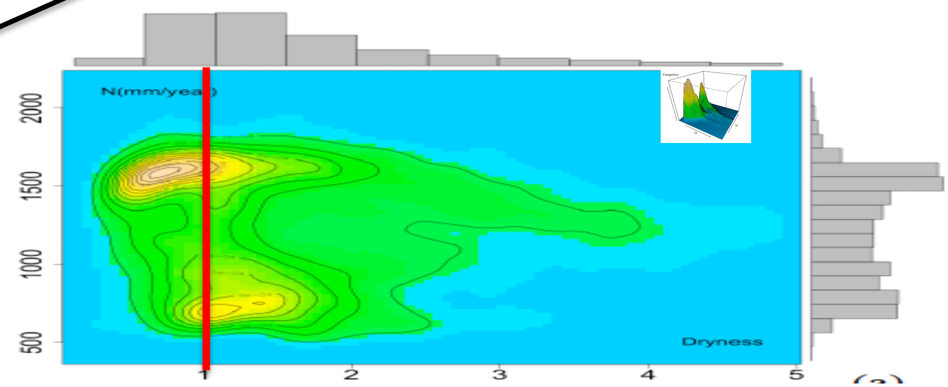
~ latitude

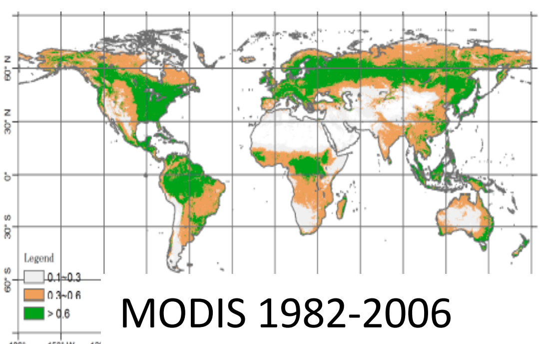
Dryness D = N/P
x-axis

~ biomes



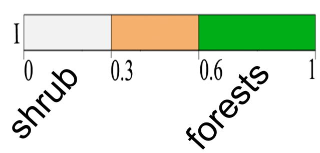
Dryness D

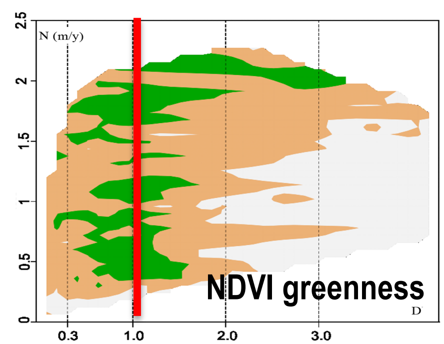


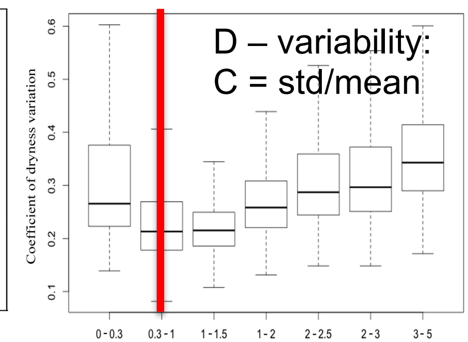


MODIS 1982-2006

NDVI greenness





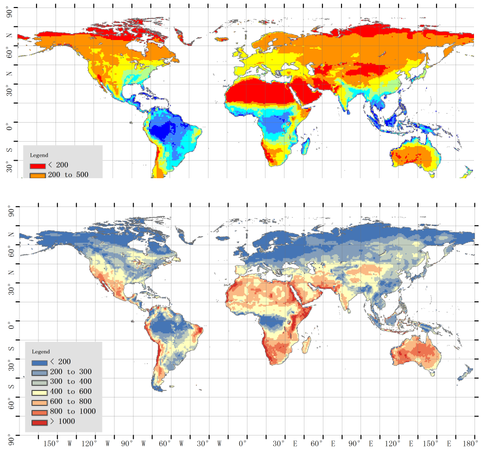


D – variability:
C = std/mean

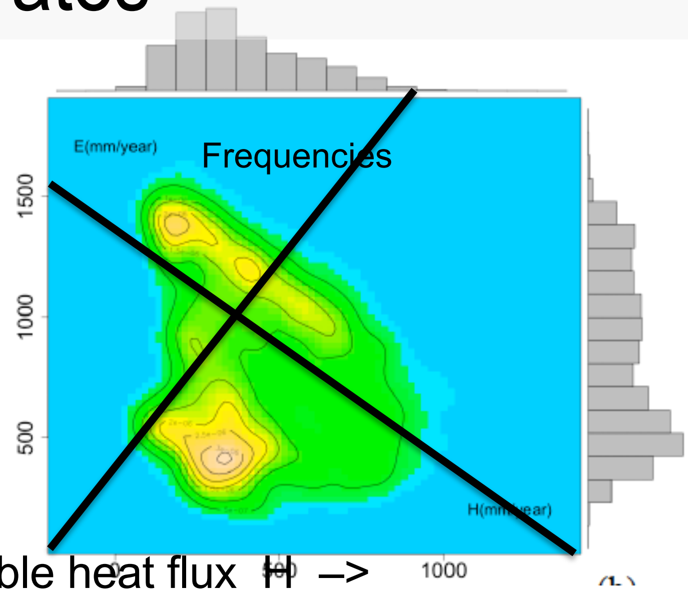
D ~ 1: max NDVI-greenness <–> min D-variability

Animals – vertebrates (*E*,*H*) – state space

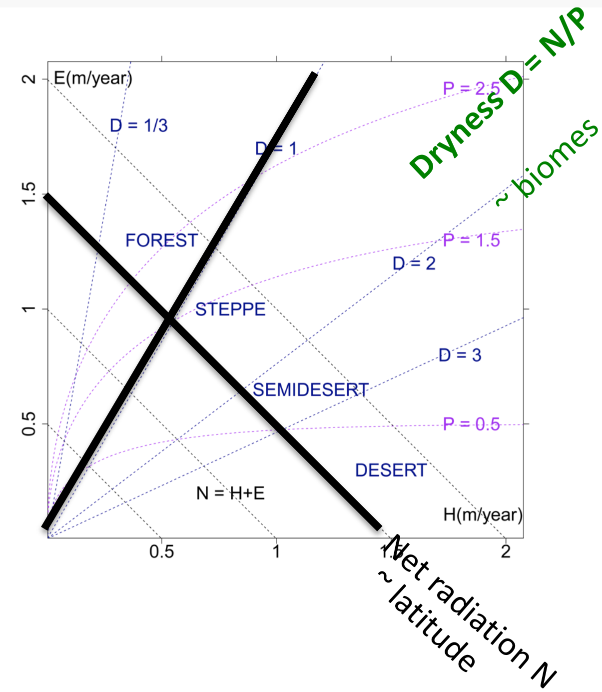
Geographical Space

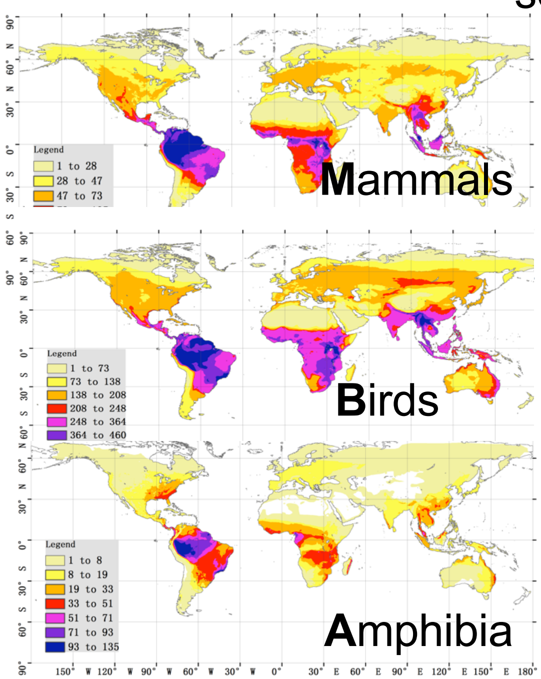


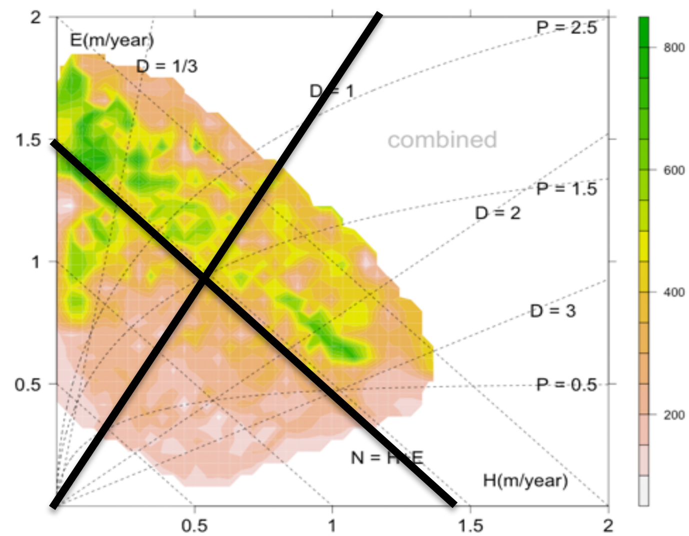
latent heat flux E



sensible heat flux H –>







ERA-interim 2001-2013

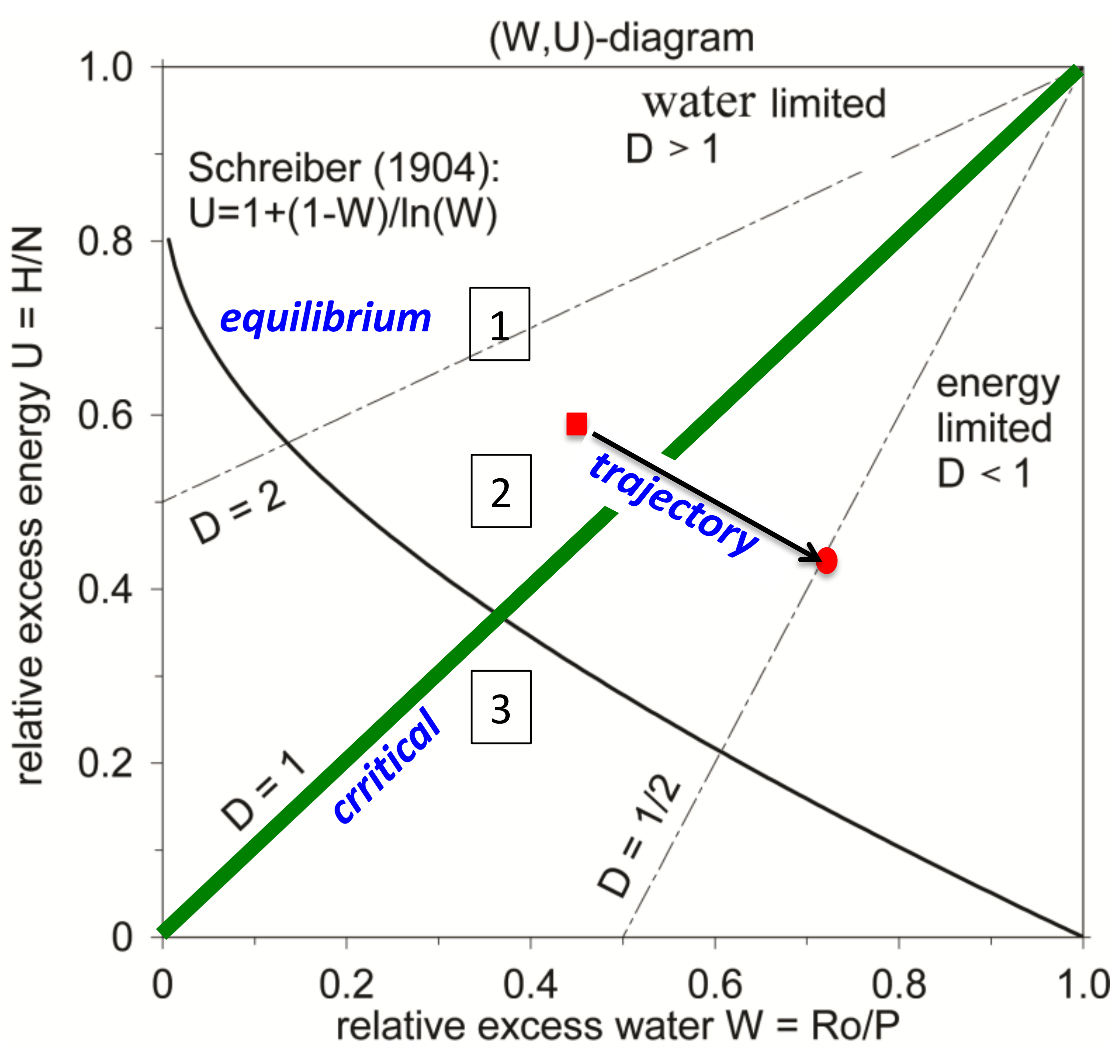
species richness

census 2013: types per 10x10km^2

richness thresholds:

D = 1 and N = PET ≈ 1.5 m/yr

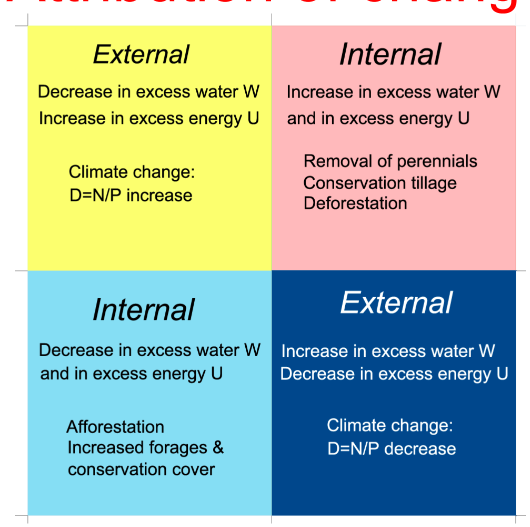
eco-hydrological state spaces (*U*,*W*) – state space



flux ratios

W = Ro/P runoff (water excess)
U = H/N energy excess
D = N/P dryness

Application: Attribution of change



Attribution of change

Causes of change

external: climate induced change of flux input *N* & *P*

natural variability, climate change

versus

internal: basin induced change of flux partitioning

E & N land use, irrigation, grazing
E & Ro water recycling
regional/local human activity

Separation – Ansatz

separation possible in (U,W)-space

external

$$N = H + E$$
$$P = E + Ro$$

internal

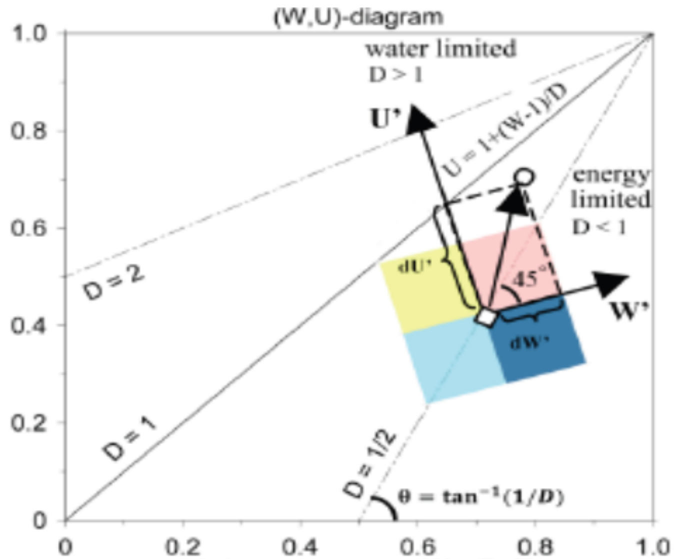
related to catchment

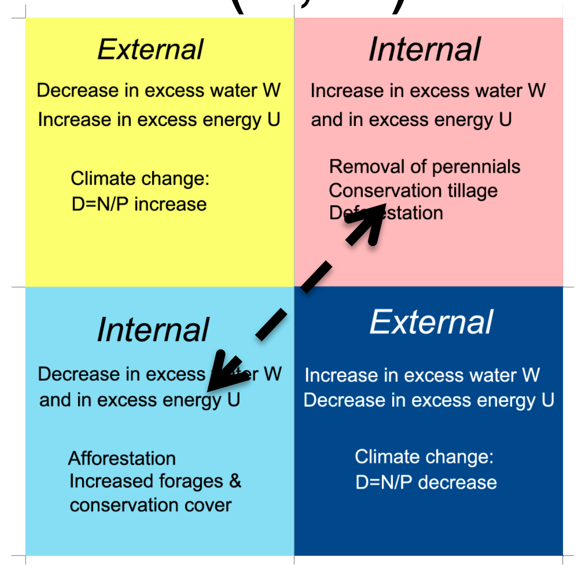
Qualitative arguments

Tomer, M, Schilling, K. 2009: A simple approach to distinguish land-use and climate-change effects on watershed hydrology, J. Hydrol., 376, 24–33.

Attribution – 1

(U,W) – state space





Gedanken Experiment with **U = H/N = 1 – E/N; W = Ro/P = 1 – E/P**

Internal ('human') affecting evaporation E (but not P or N)

Change

energy-excess | water-excess

dU = – dE/**N** | dW = – dE/**P**

for example:
fix external **N,P**
but change **E**: dE

dU > 0 | dW > 0 (dE < 0)

dU < 0 | dW < 0 (dE > 0)

in (U,W)-diagram changes along **main-diagonal**

Attribution – 2 cont'd (U,W) – state space

$$\begin{bmatrix} dW \\ dU \end{bmatrix} = \begin{bmatrix} W_2 \\ U_2 \end{bmatrix} - \begin{bmatrix} W_1 \\ U_1 \end{bmatrix} = \begin{bmatrix} W_2 - W_1 \\ U_2 - U_1 \end{bmatrix} \quad (1)$$

$$D = N/P = (1 - W) / (1 - U) \quad (2)$$

$$S = E/N = 1\text{-}U \quad (3)$$

$$\begin{bmatrix} dW' \\ dU' \end{bmatrix} = \begin{bmatrix} cos(\theta - 45°) & sin(\theta - 45°) \\ -sin(\theta - 45°) & cos(\theta - 45°) \end{bmatrix} \times \begin{bmatrix} W_2 - W_1 \\ U_2 - U_1 \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} CT \\ AT \end{bmatrix} = \begin{bmatrix} cos(\theta - 90°) & sin(\theta - 90°) \\ -sin(\theta - 90°) & cos(\theta - 90°) \end{bmatrix} \times \begin{bmatrix} W_2 - W_1 \\ U_2 - U_1 \end{bmatrix} \quad (5)$$

$\tan\theta = 1/D$, $\theta \in [0,90°]$, when $D = 1, \theta = 45°$

$$\begin{bmatrix} dW_A' \\ dW_c' \\ dU_A' \\ dU_c' \end{bmatrix} = \begin{bmatrix} dW' \\ dU' \end{bmatrix} \times \begin{bmatrix} sin45° & cos45° & 0 & 0 \\ 0 & 0 & sin45° & cos45° \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} dS_A \\ dS_c \end{bmatrix} = \begin{bmatrix} \text{-}dU_A' \\ \text{-}dU_c' \end{bmatrix} \quad (7)$$

time-period selection

Updated trends: Temp & SPI & NDVI

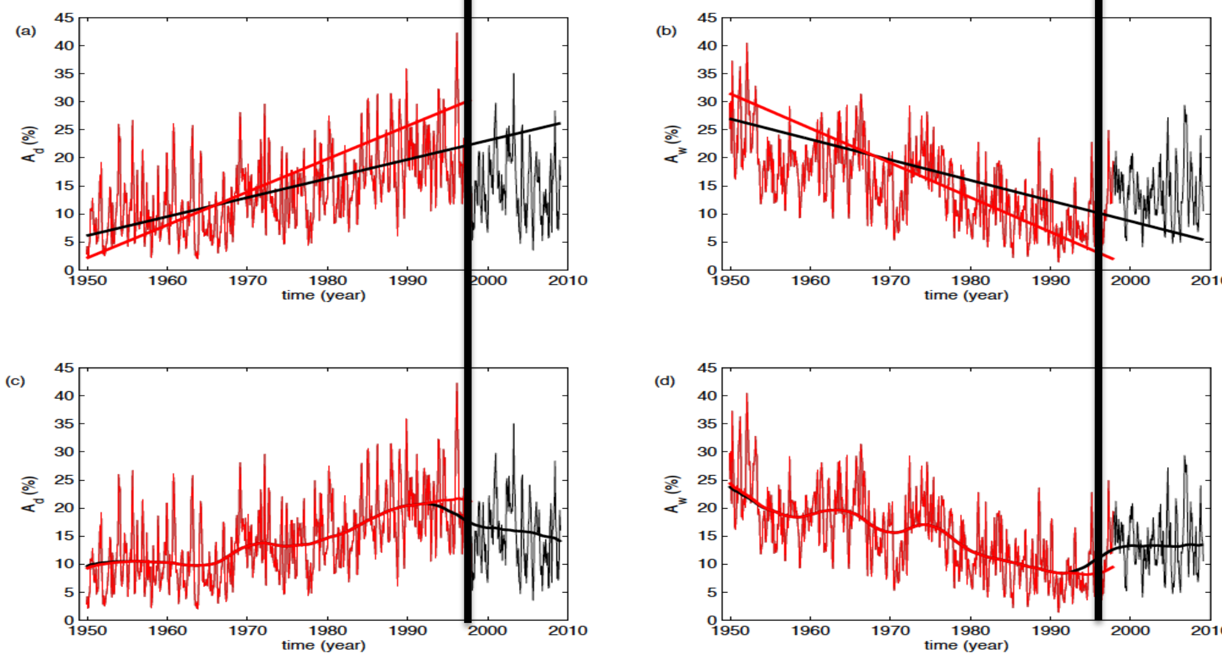
selection of
climate periods
1973 – 1993
1994 – 2008

Temperature-rise 1973– 1993 | stagnation 1994–2006

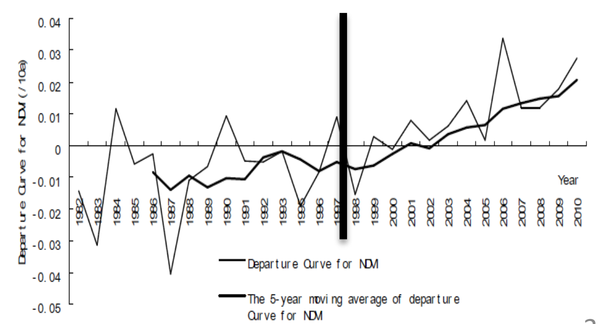
SPI-decline 1973– 1993 | stagnation 1994–2006

linear trends Europe

non-linear trends Europe

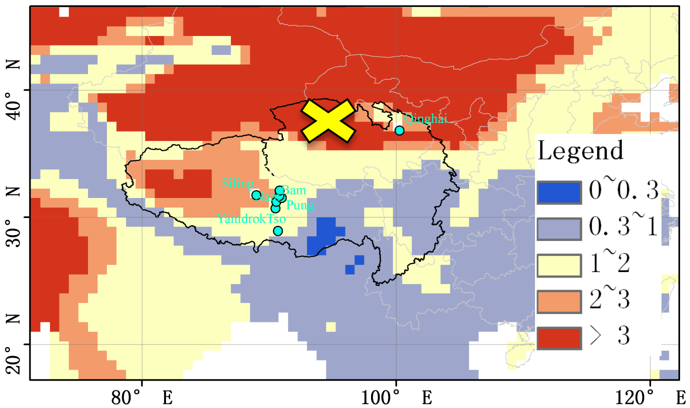


NDVI-trend 1982– 2010
Qinghai-Tibet

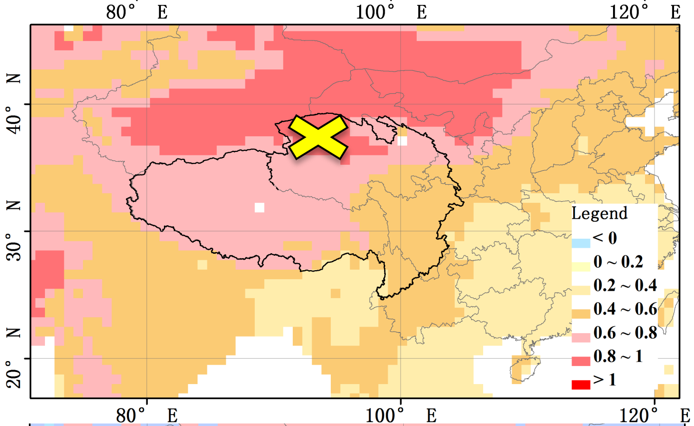


Bordi, I., KF, A. Sutera, 2009: Observed drought and wetness trends in Europe: an update. Hydrology and Earth System Sciences 13, 1519-1530

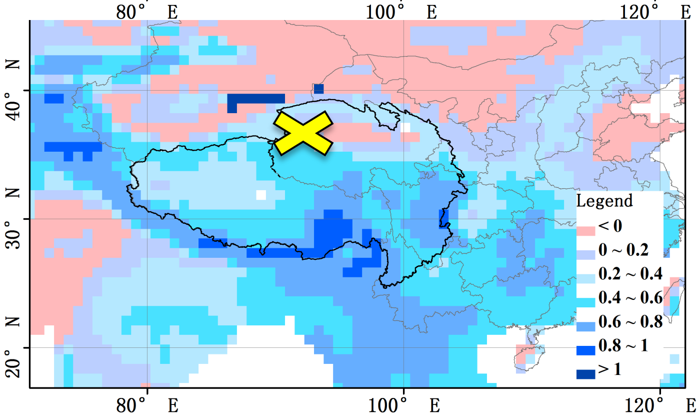
U(lat,long), W(lat,long) => (U,W)-scatter plot



Dryness ratio
D = N/P = (1–U) / (1– W)

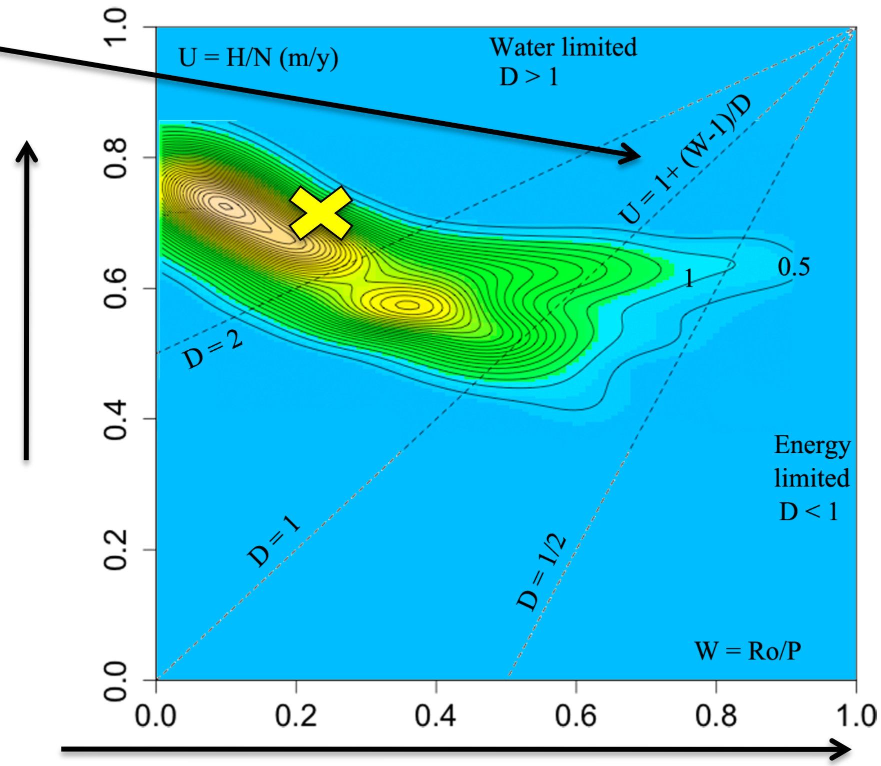


Excess Energy
U = H / N



Excess Water
W = Ro/P

(U,W)-frequency distribution

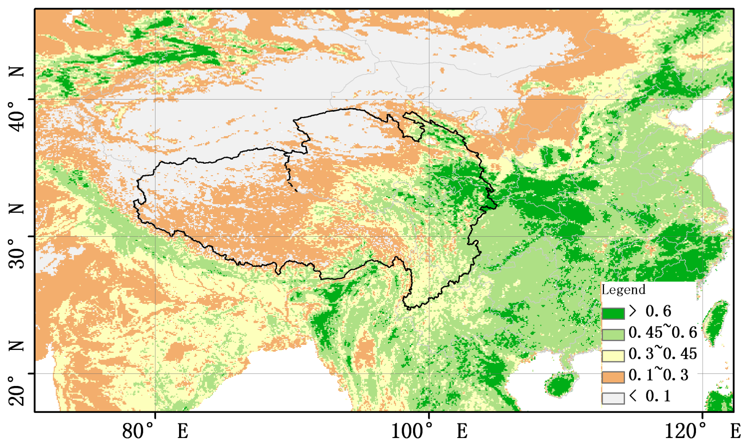


grid-point

add vegetation (NDVI-greenness) => (U, W, NDVI)

…. as ‘passive tracer’ in physical state space

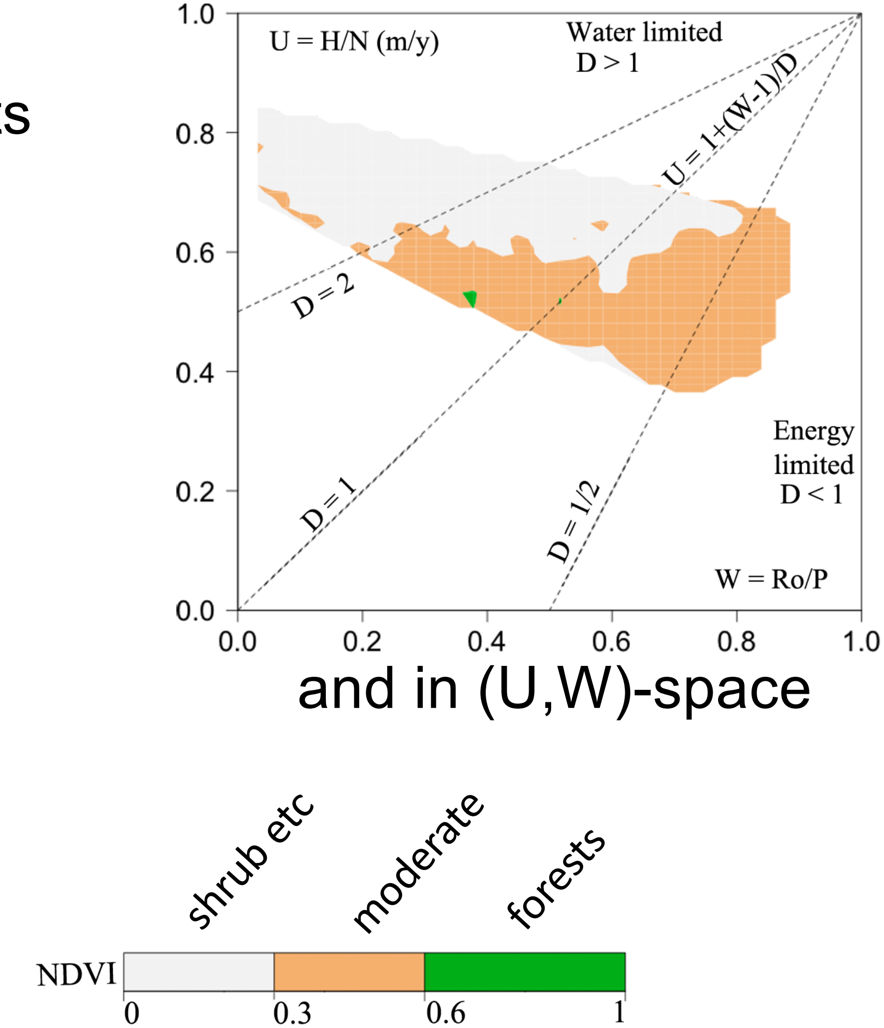
at gridpoints
from 2 variables (U,W)-pairs
to 3 variables (U, W, NDVI)-triplets



NDVI in geographical space

Period-1: 1982 - 1993

coupling biotic & abiotic processes

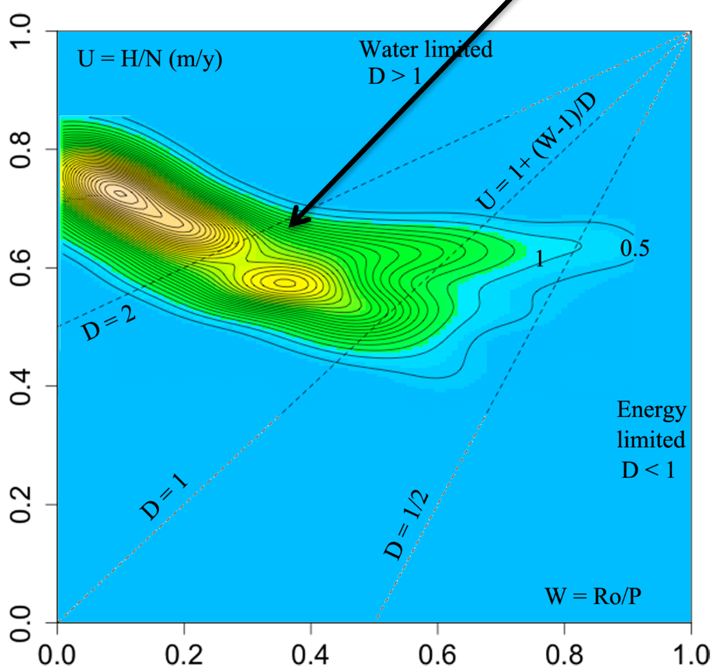


and in (U,W)-space

(U,W) and (NDVI) climates

(*U,W*) - state space

Period-1: 1982 - 1993



Frequencies in (U,W)-space

Notes

at D = 2: Bimodality gap

semidesert <=> steppe

NDVI-shrub <=> transition

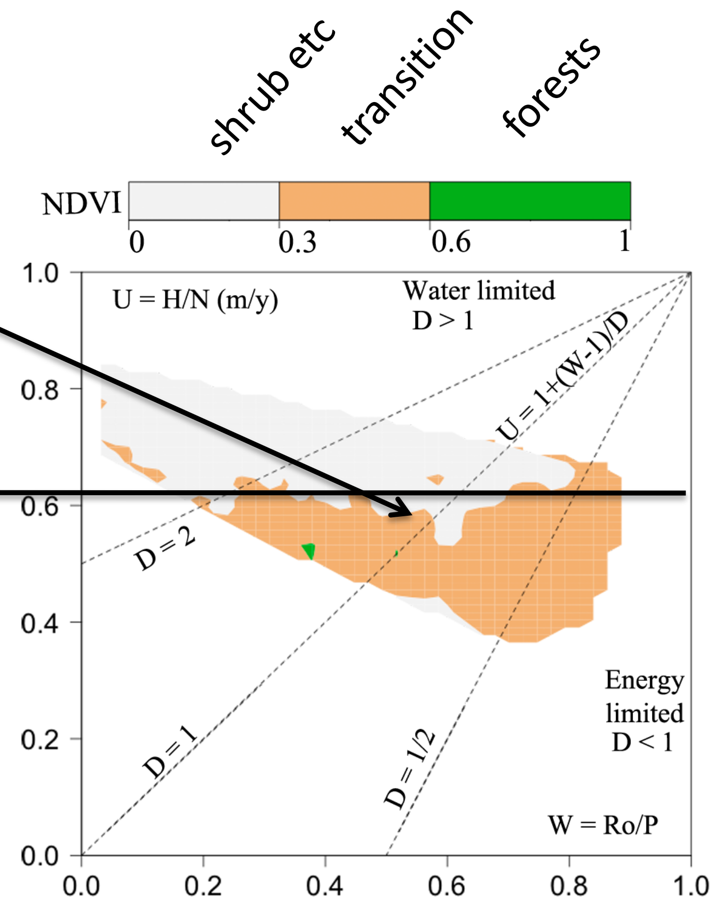
D < 1: energy ltd

NDVI-moderate

U ~ 0.6 NDVI-separation

changes with U

independent on W



NDVI in (U,W)-space

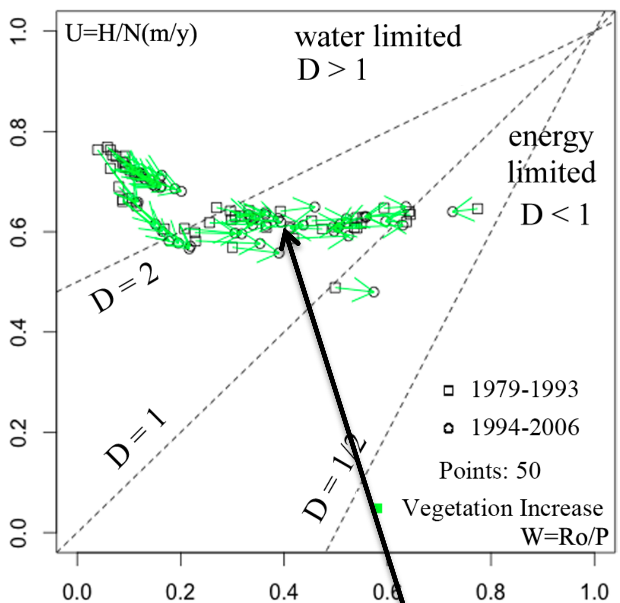
Attribution of change

Tibet-only trajectories

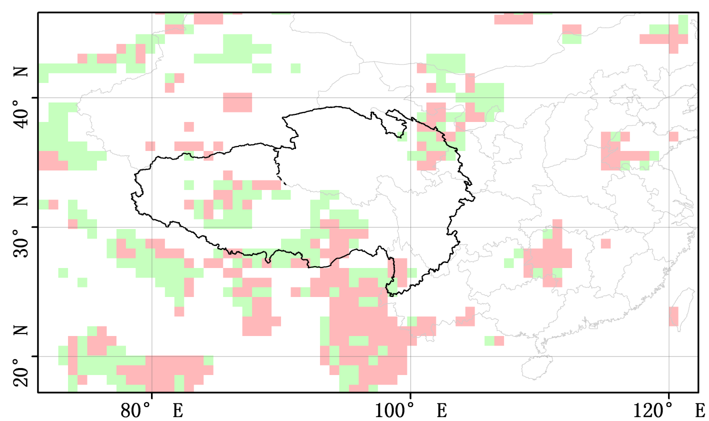
d(NDVI) > 0

d(NDVI) < 0

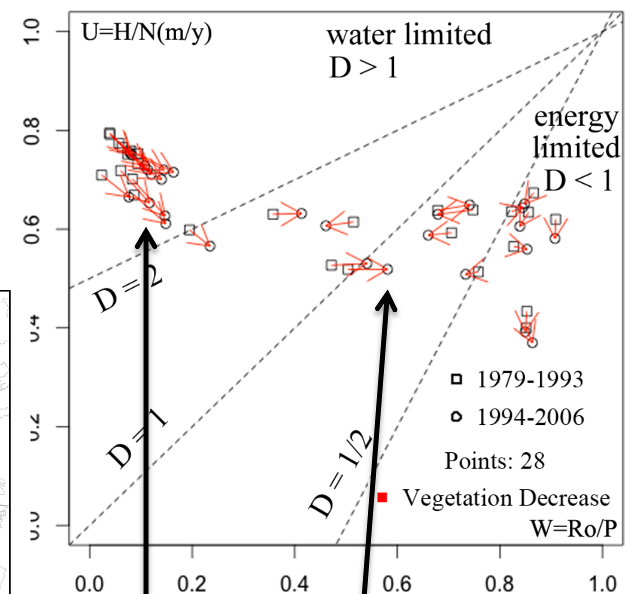
from period-1 to period-2



Significant ERA-size pixels: 78 (373)



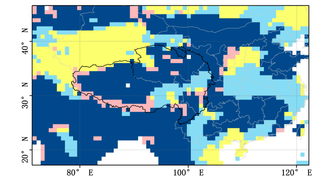
from period-1 to period-2



Notes:
50 sign. pixels: dNDVI > 0
in water ltd regimes D = N/P > 1
low NDVI becomes greener:
<=> D decreases <=> wetter climate

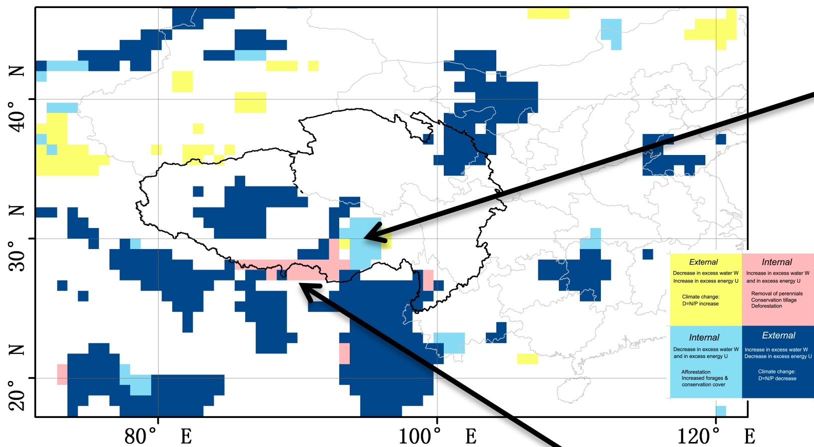
Notes:
28 sign. pixels: dNDVI < 0
in water & energy ltd regimes
barely vegetated NW &
well forested SE

Attribution of change (on ERA-scale)

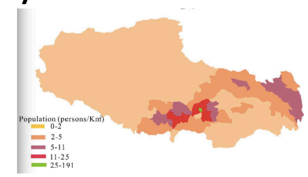


1. **external causes** (dark blue):
Mostly wet tendencies controlled by dynamics

significant: > 1 std-dev of U or W

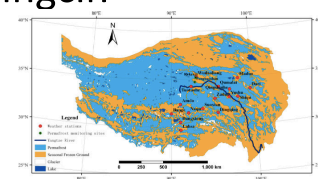


2. **internal** (light blue): population density increase
1990 - 2000 by ½ million to 2 616 300

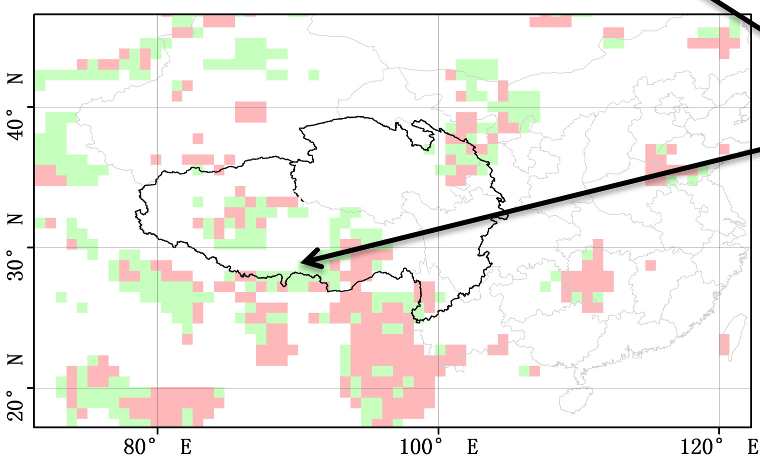


3. **NDVI changes**

Increasing excess water dW > 0 => d(NDVI) > 0
melting ice/permafrost => moisture supply
Decreasing excess water dW < 0 => d(NDVI) < 0
Steppe: Cona, Shannan, Medog, Nyingcin



Vegetation-NDVI at **significant** ERA-pixels



NDVI-greenness relevant for interpretation

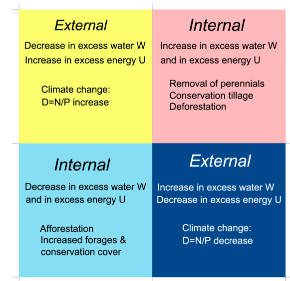
Himalaya: (pink) & ground heatflux G = 0
BUT: d(NDVI) > 0: vegetation increase
=> ground flux reduced (G1 > G2)
=> semidesert excess energy U2 reduced
$U1 = H/(N - G1) > U2 = H/(N - G2)$
=> Himalaya external (dark blue & not 'pink')

Attribution of change

NDVI-scale pixels

downscaling

Vegetation (NDVI)	Attribution (percentage)			
Region	Entire		Significant	
	External	Internal	External	Internal
Increase	3.8	7.7	2.0	8.5
Decrease	3.1	7.0	0.6	7.7
	Internal	External	Internal	External
Increase	8.4	41.4	7.2	44.1
Decrease	4.8	23.8	6.8	23.1



21% Sign. large scale (U,W)- & area average NDVI-change:
70% external (46% in- vs. 24% decreasing NDVI) – d-blue/yellow
30% internal (15.5% increase vs. 14.5% decrease) – pink/l-blue

Chen et al. (**2014**): Net Primary Prod. Model for alpine Tibetan grassland (1982 - 2011)

Area of grassland change attribution
68.5% due to changing climate
31.5% due to **human** activities

Cai, D., KF, F. Sielmann, L. Zhang, X. Zhu, S. Guo, Y. Guan **2015**: Vegetation Dynamics on the Tibetan Plateau (1982-2006): An attribution by eco-hydrological diagnostics, J. Climate 28, 4576-4584

Climate change and human activities
Impact on land surface dynamics: Tibetan Plateau

Attribution Analysis: First and second periods (1982 – 1993 and 1994 – 2006, ERA-Interim)

State space climates: bimodal distribution with two distinct geobotanic regimes
(semidesert and Steppe) of low and moderate vegetation-greenness
Gaps at dryness D = 2 (net radiation over precipitation) and greenness NDVI**=**0.3

Total Area of signif. changes (first / second period): external (70%) and internal (30%)
21% sign. large scale (U,W)-change ***and*** area average NDVI-change; (dU, dW) > (std(*U)*, std(*W*))
70% external (46% in- vs. 24% decreasing NDVI)
30% internal (15.5% increase vs. 14.5% decrease)

Areas of significant (U,W)-changes :
(i) 36.2% (63.8%) of significant NDVI changes show NDVI decrease (increase)
(indep. of vegetation type & aridity)

Attribution conditioned joint distributions of NDVI vs NDVI-change: 38.2% decreasing (61.8% increasing) coverage with low (moderate) NDVI; high NDVI-areas slightly reduced.

Water surplus regions: benefit from climate change (vegetation greenness growth)
Energy surplus regions (Himalayas): ambiguous change attribution as internal
but heat storage deficit due to increasing vegetation being neglected

The End – 1

Thank You