The role of the land surface in forecasting

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https://africanswift.org/

Outline

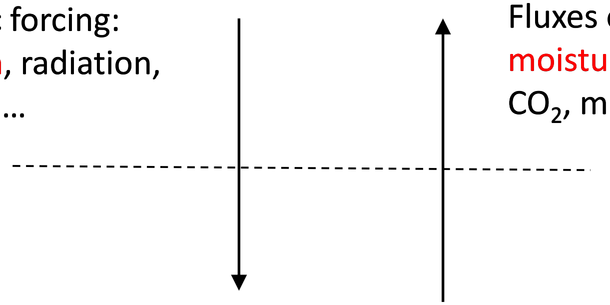
- Motivation
- Surface energy balance
- Impact of land surface on atmosphere at mesoscale
- Impact of land surface on atmosphere at synoptic scale

Early afternoon cloud development around flooding, Mozambique 25/3/19

Land-atmosphere feedbacks

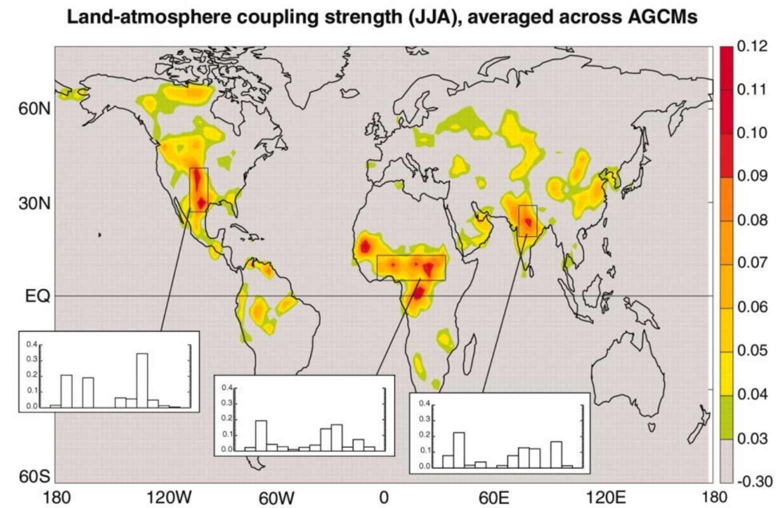
Atmosphere

Atmospheric forcing:
precipitation, radiation,
temperature…



Fluxes of heat,
moisture,
CO_2, methane…

Land surface properties
(soil moisture, snow, vegetation)



Soil moisture- precipitation feedbacks in climate models

GLACE-1 multi-model experiment:
Models show that soil moisture affects rainfall in certain parts of world - transition regions between arid and wet climates

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Koster et al, Science 2004

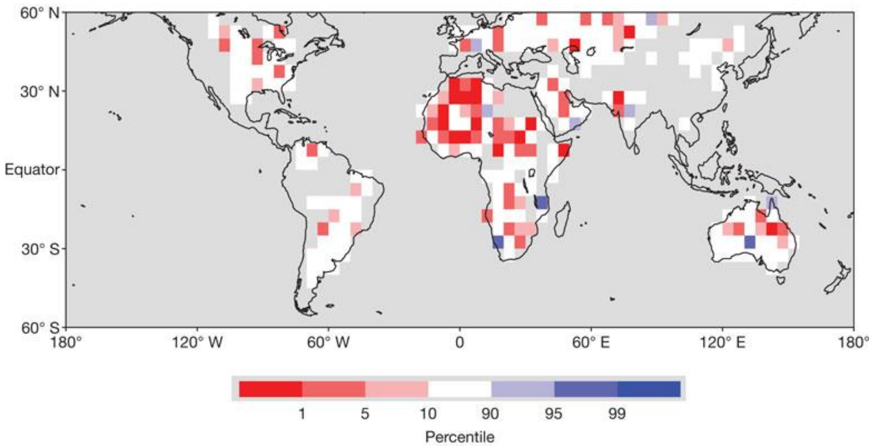
Soil moisture-precipitation feedbacks in observations

Observations confirm feedbacks clearest in transition regions

This example shows whether afternoon rain falls preferentially on wetter or drier soils locally (~100km)

Indicates that coarse resolution models (e.g. used for global forecasting) may not be reliable for in capturing this feedback

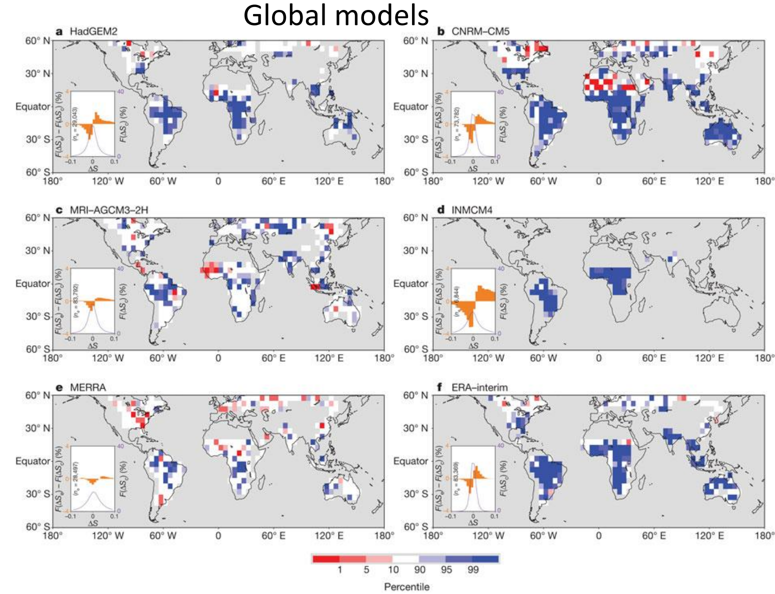
Satellite observations



Rain over drier soil

Rain over wetter soil

Global models



Taylor et al, Nature 2012

Surface energy balance

Strong function of T_{surf}

$$SW_{\downarrow} + LW_{\downarrow} = SW_{\uparrow} + \boxed{LW_{\uparrow} + LE + H + G}$$

SW : short-wave radiation, $\downarrow$ insolation, $\uparrow$ reflected
LW : long-wave radiation, $\downarrow$ downwelling, $\uparrow$ surface emission ($\varepsilon\sigma T_{surf}^{4}$)
LE (or λE): turbulent latent heat flux (evapotranspiration)
H: turbulent sensible heat flux
G: heat flux into soil

Land properties affect surface energy balance primarily through:

- albedo ($SW_{\uparrow}$)
- surface roughness length (turbulent fluxes [H+ LE] vs [$Lw_{\uparrow}$ + G])
- ability of surface to evaporate (LE vs H)
    - soil moisture
    - vegetation (root depth, leaf area)

Dry surface, LE= 0
Well-watered surface, LE= $LE_{potential}$ – evaporation is *energy-limited*
Transition zone, LE, H, T_{surf} are *water-limited*
In much of Africa, seasonality of water availability controls LE vs H

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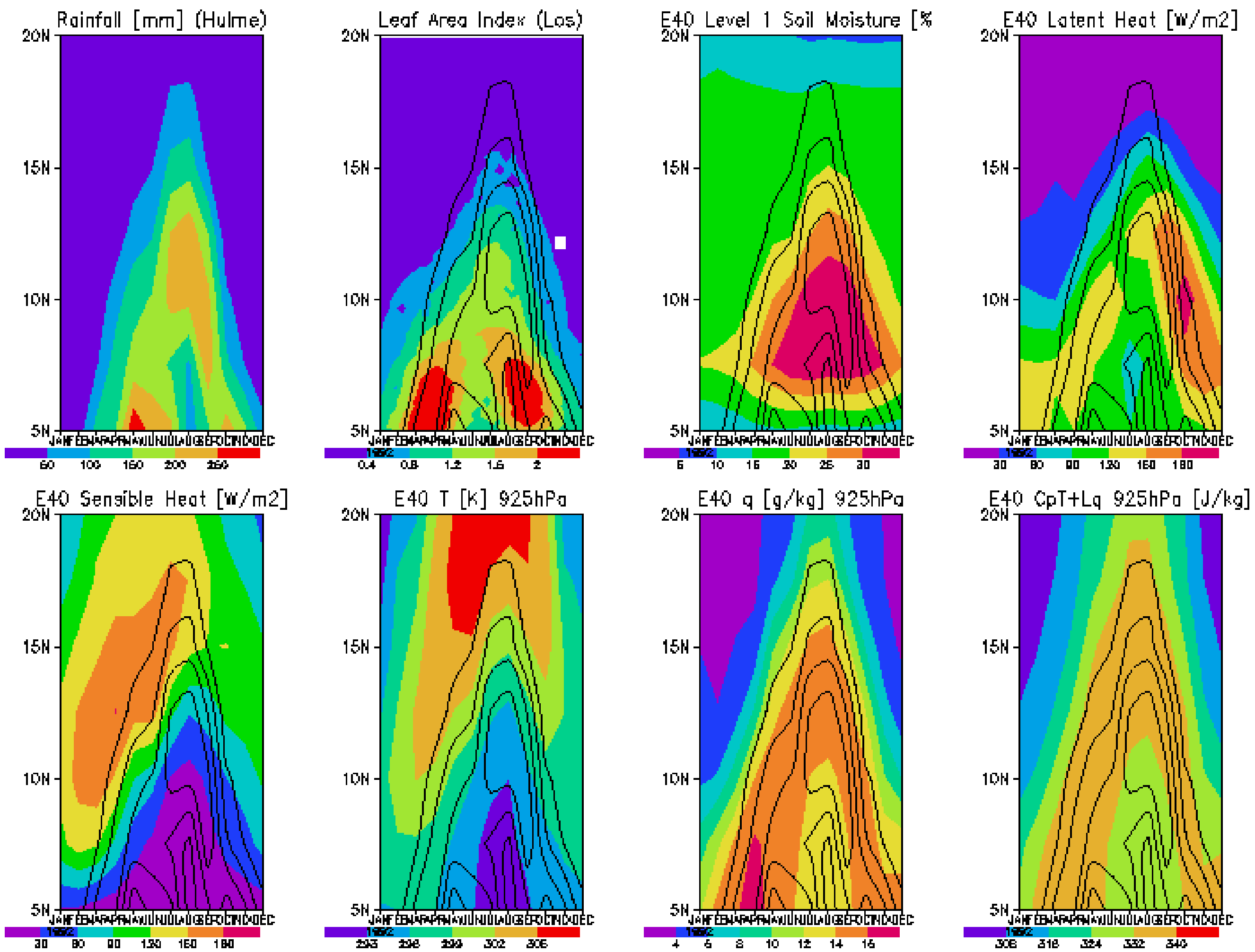
Seasonal cycle of the W. African monsoon



Note: surface fluxes in reanalyses like ERA40, ERA5 etc are NOT reliable compared to atmosphere

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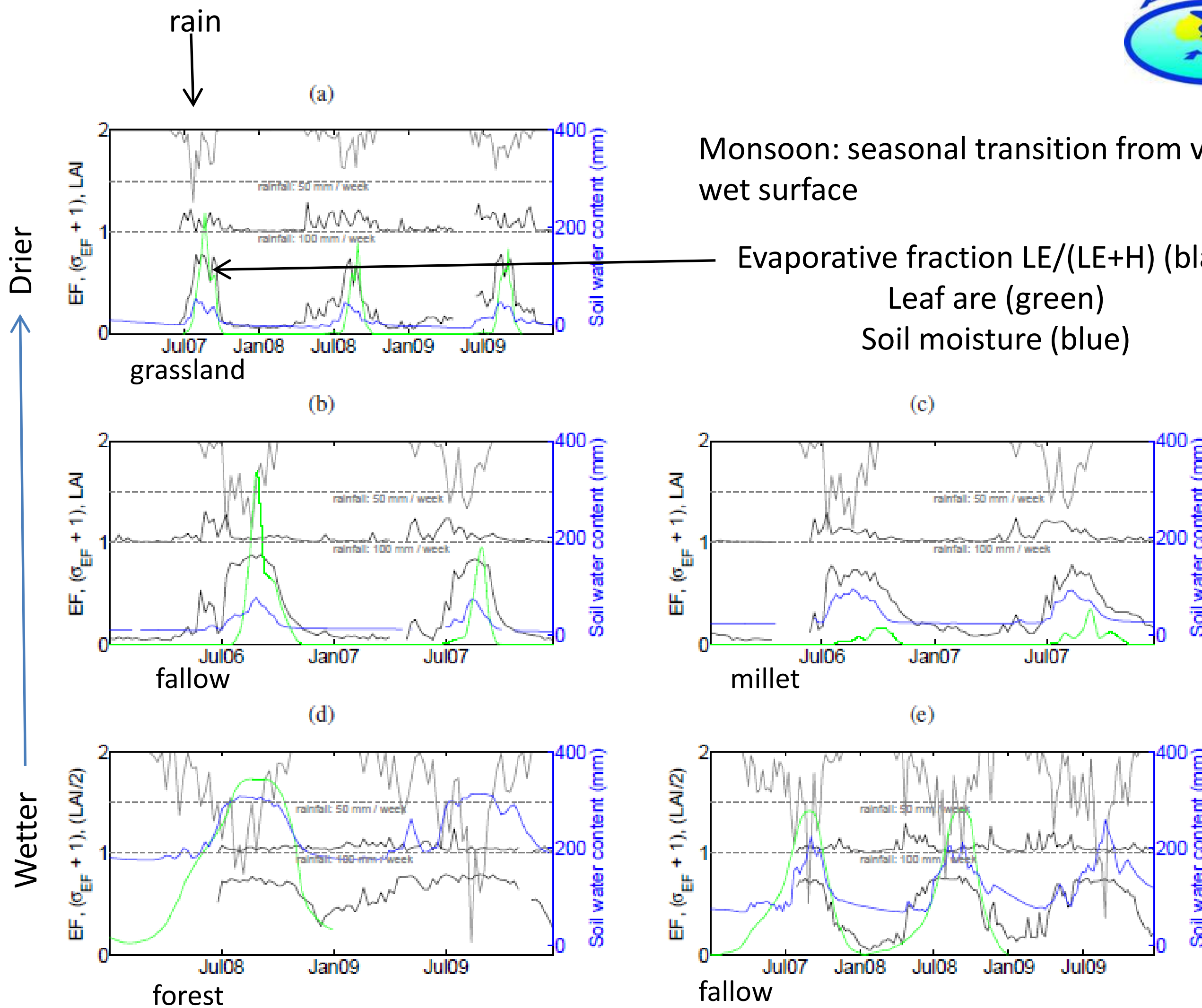
Seasonal cycle surface fluxes



Monsoon: seasonal transition from very dry to wet surface

Evaporative fraction LE/(LE+H) (black)
Leaf are (green)
Soil moisture (blue)

Observations from AMMA flux station network in N. Mali (top), SW Niger (middle) and N Benin (bottom)

Lohou et al ACP 2014

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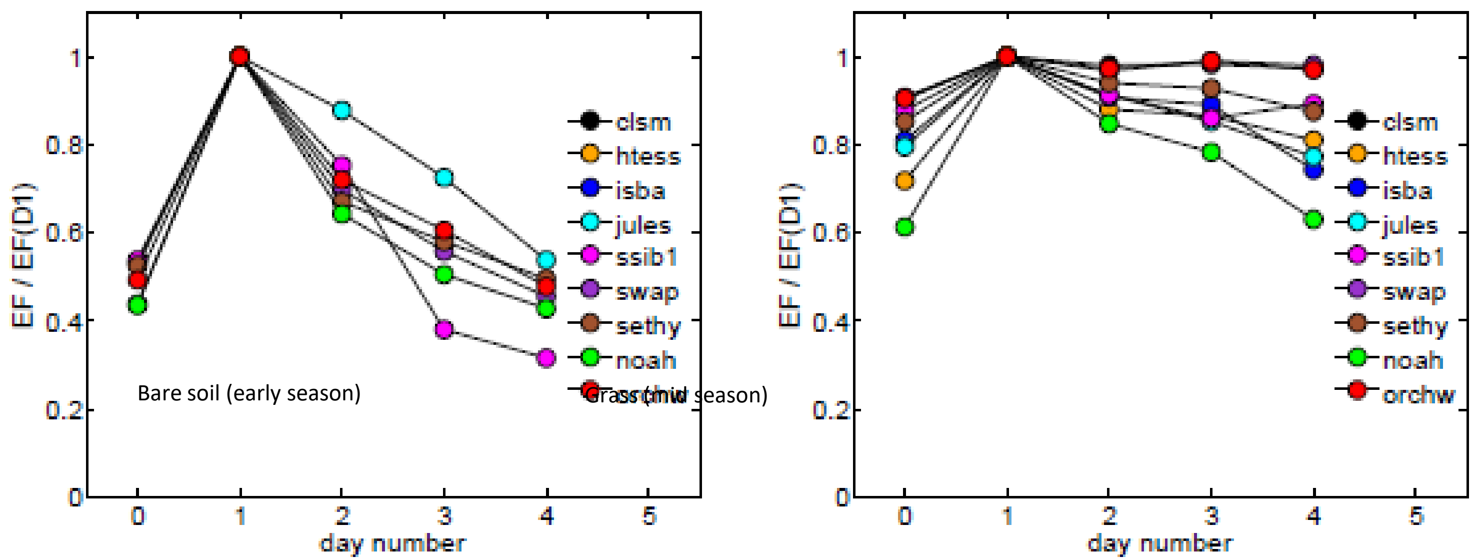
Day-to-day variations in surface fluxes

Land models forced by observed meteorology in Sahel

Rain event between day 0 and day 1

Evaporative fraction LE/(LE+H)
(Normalised)



Land surface schemes struggle to capture realistic flux dynamics in response to day-to-day rainfall variability, but these dynamics are important for the atmosphere

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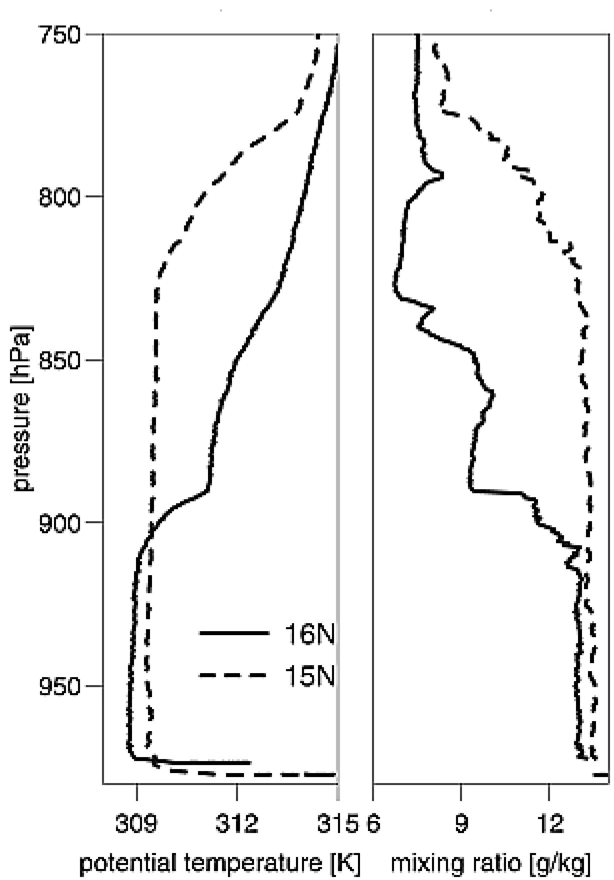
Lohou et al, ACP 2014

Impact of surface fluxes on the local Planetary Boundary Layer (PBL)

- Sensible heat flux drives daytime development of PBL
- Stronger H (weaker LE) means warmer, deeper (and drier) PBL



Vertical mid-afternoon profiles at nearby locations. Rain fell the previous day at 16N but not 15N

Taylor et al GRL 2007

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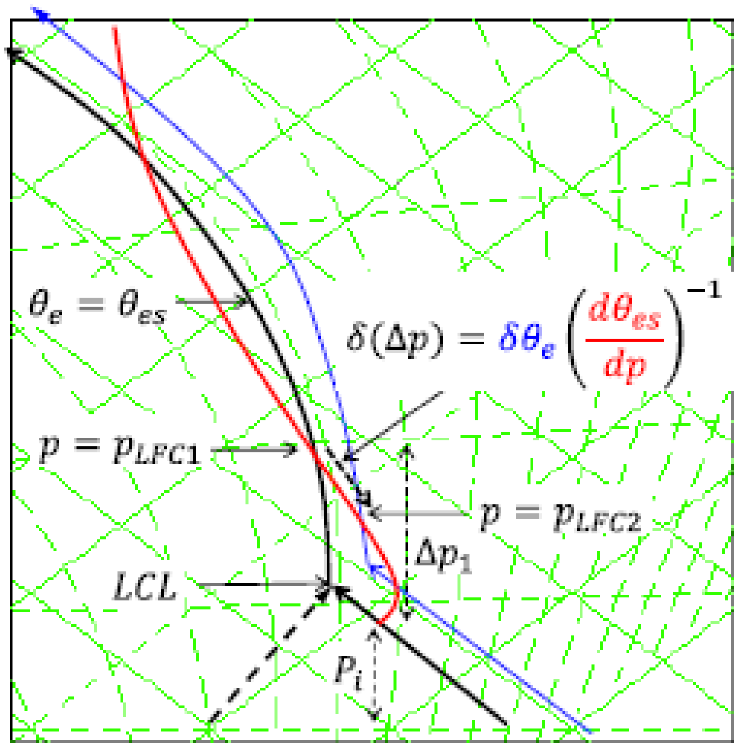
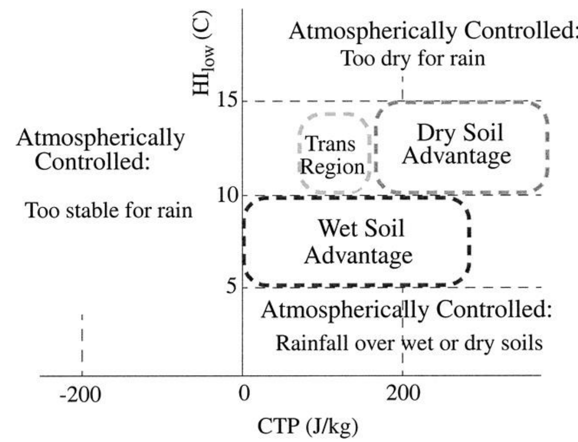
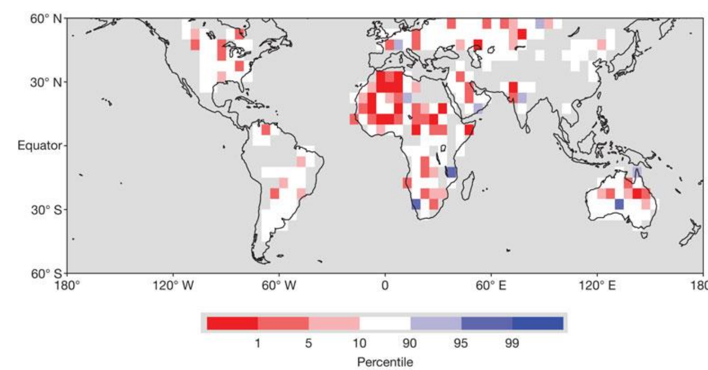
How does moist convection respond to surface fluxes (1D)?







Does a wetter or drier surface favour reaching the level of free convection?
Depends on the vertical profile

BUT we generally see afternoon rain over locally drier soils.
Is this really a 1-dimensional (thermodynamic) question?

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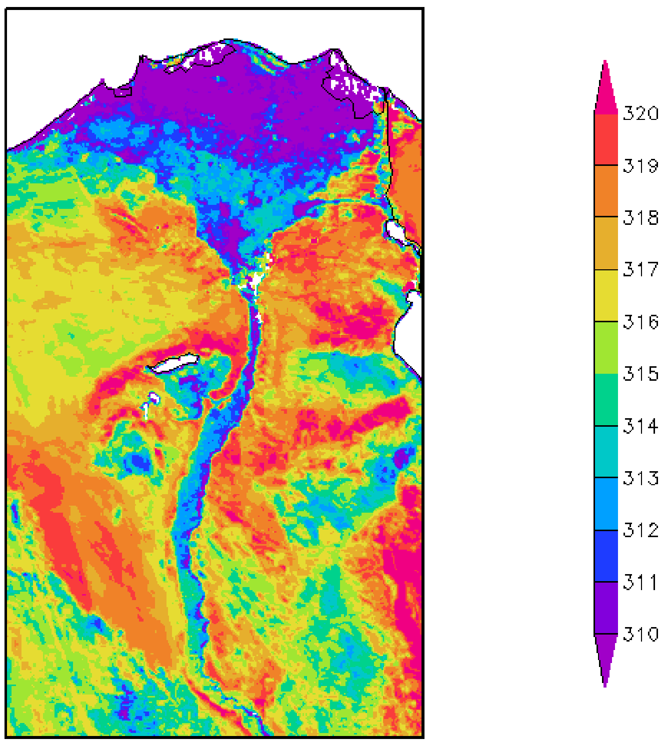
Bhowmick and Parker, QJRMS 2018, Gentine et al, JHydroMet 2013, Findell and Eltahir, JHydroMet 2003

How homogeneous is the landscape? Example #1

MODIS Terra climatological LST [K] month 6



$$SW_{\downarrow} + LW_{\downarrow} = SW_{\uparrow} + \boxed{LW_{\uparrow} + LE + H + G}$$

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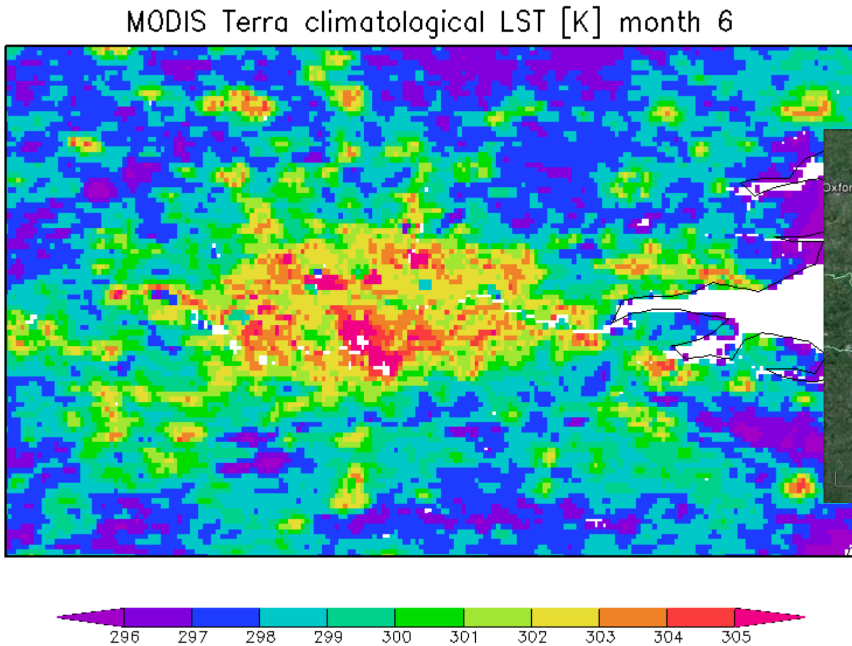
How homogeneous is the landscape? Example #2



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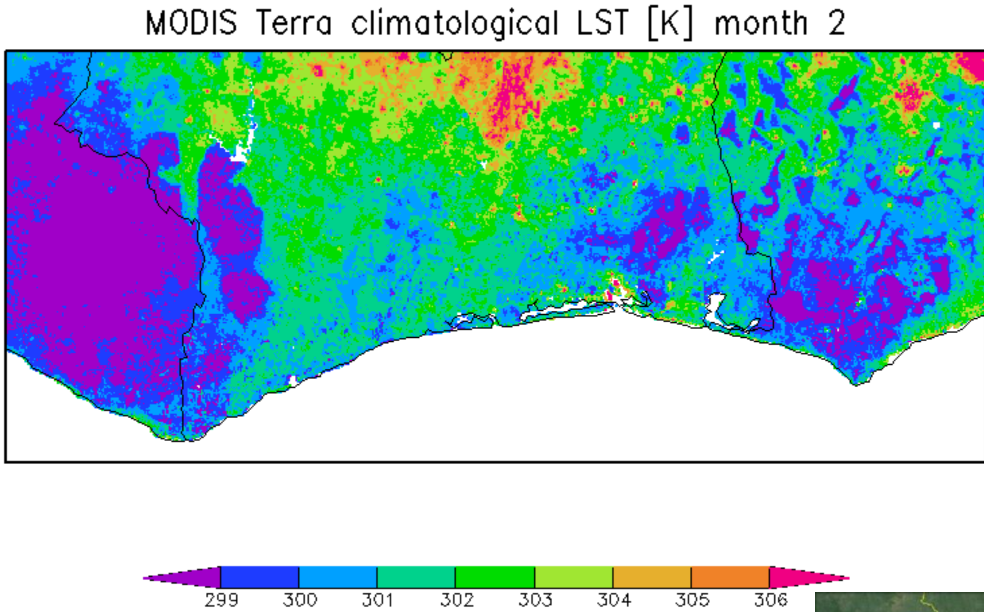
How homogeneous is the landscape? Example #3



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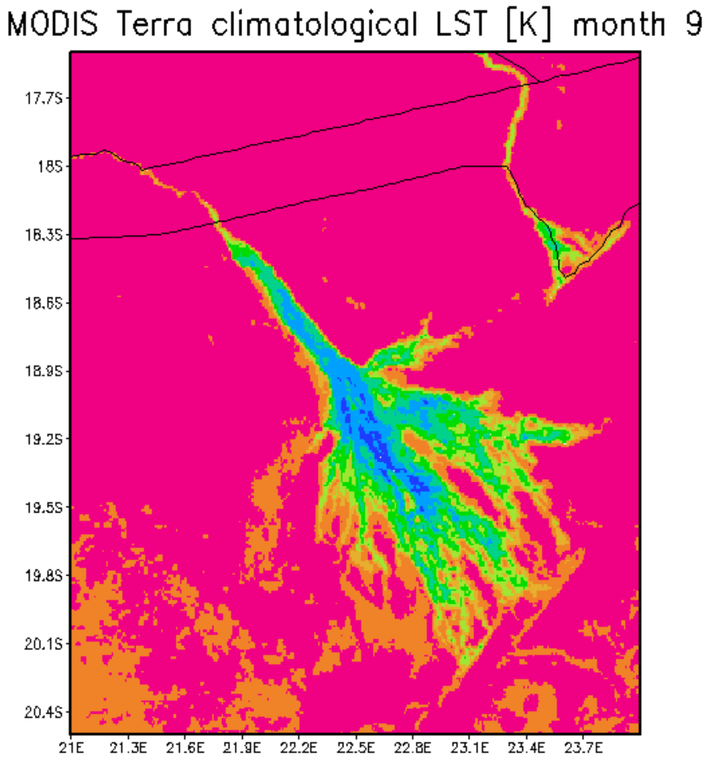
How homogeneous is the landscape? Example #4



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Atmospheric response to heterogeneity

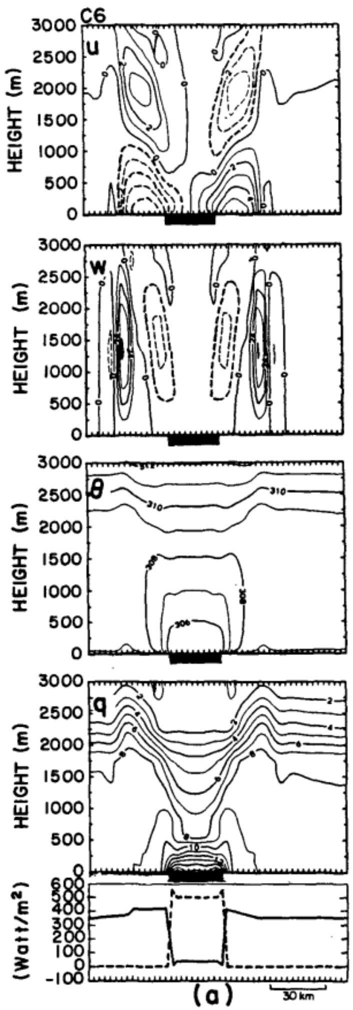
Horizontal wind

Vertical wind

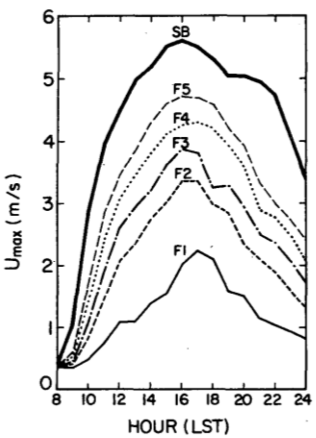
Potential temperature

Specific humidity

H (solid), LE (dashed)



Dense veg / bare soil



Temporal evolution of breeze (soil moisture-induced, Ookoutchi et al 1984)

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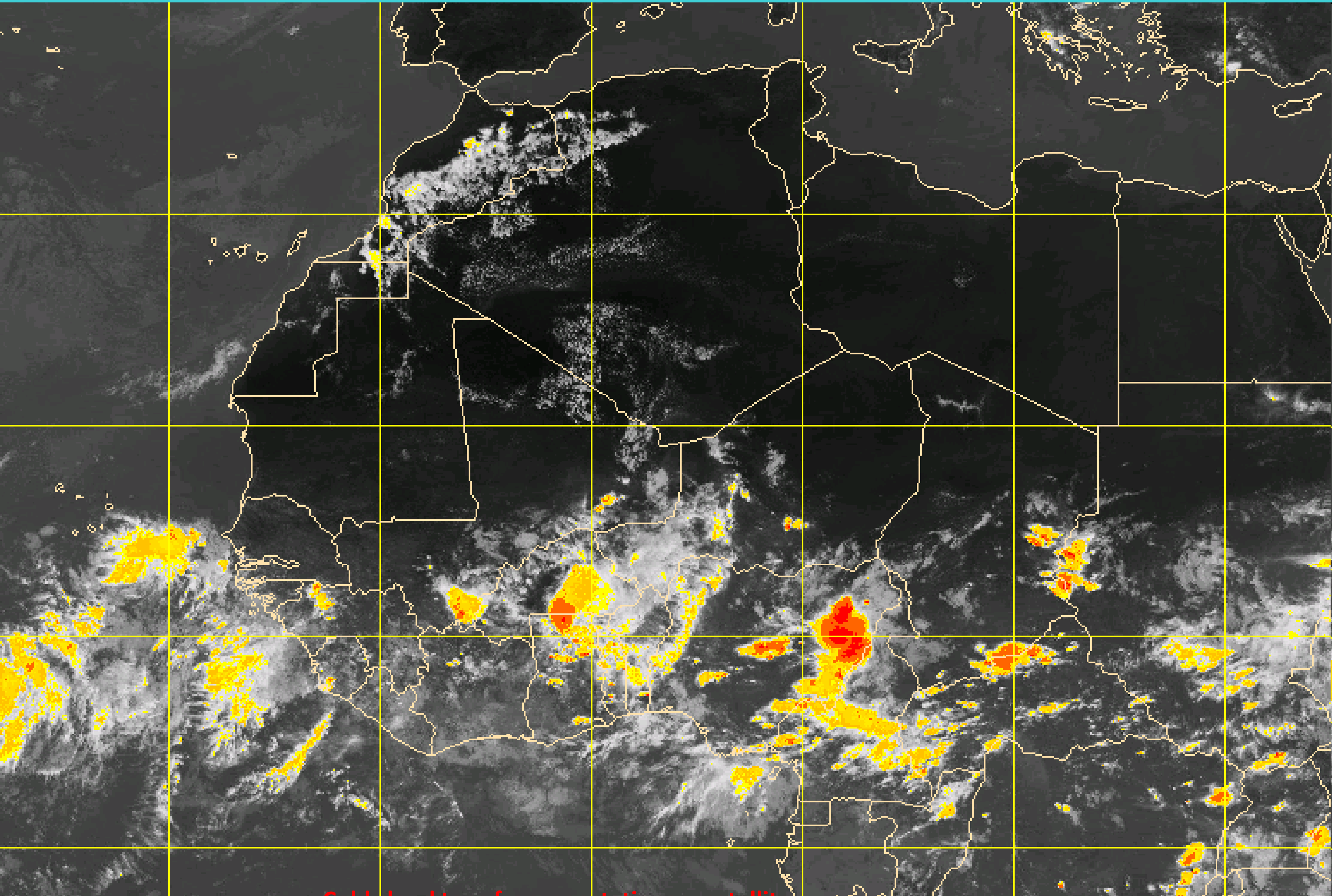
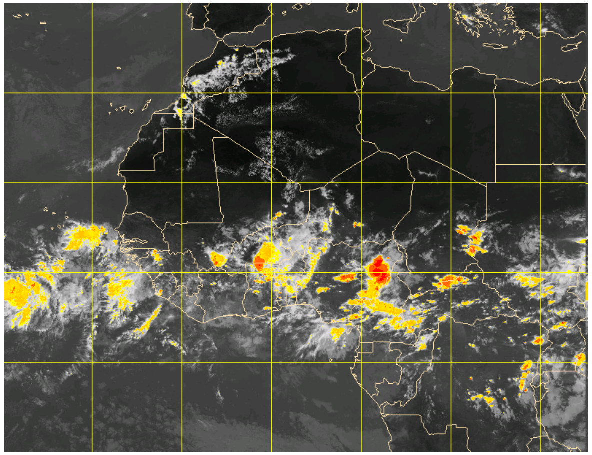
Segal et al, JAS 1988

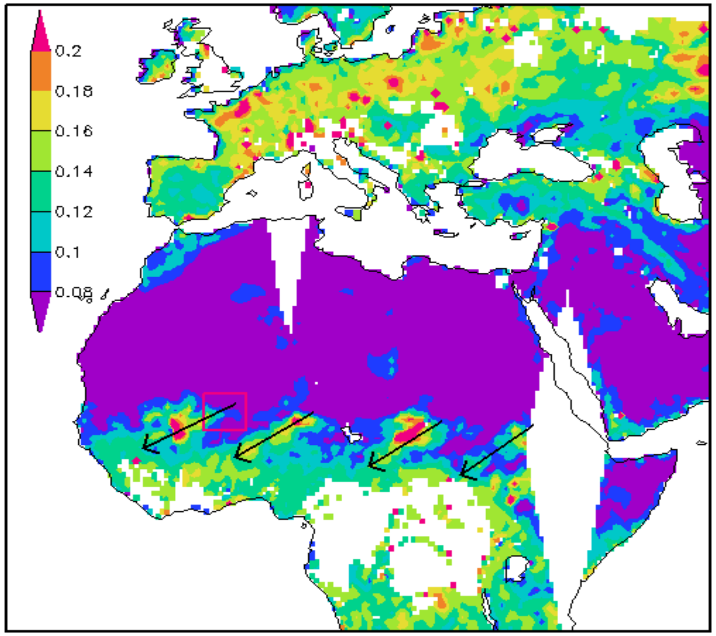
How does weather drive heterogeneity?



Spatial variability in soil moisture



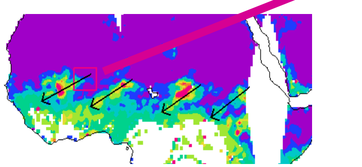
AMSR-E near surface soil moisture ($m^3\,m^{-3}$) Aug 1 2006

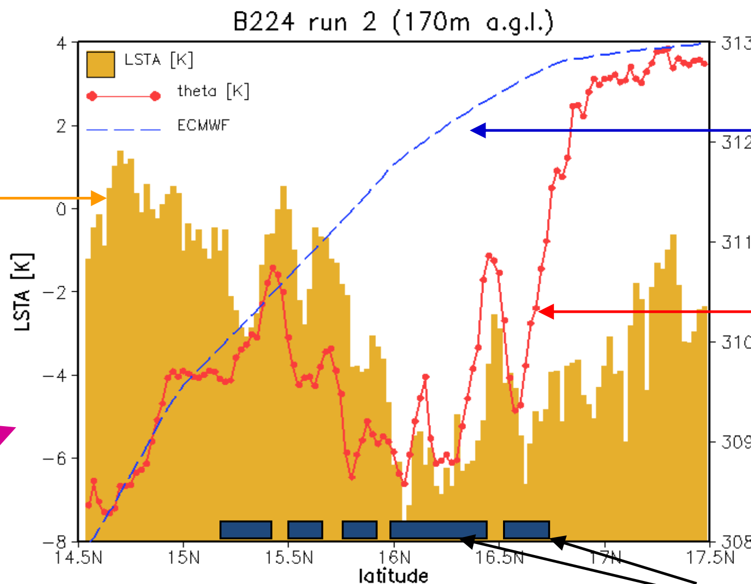


AMMA campaign 2006: aircraft flights targeted soil moisture gradients from rain in previous day

PBL response to land variability: aircraft data

Land surface temperature anomaly (Meteosat, LandSAF) Proxy for soil moisture



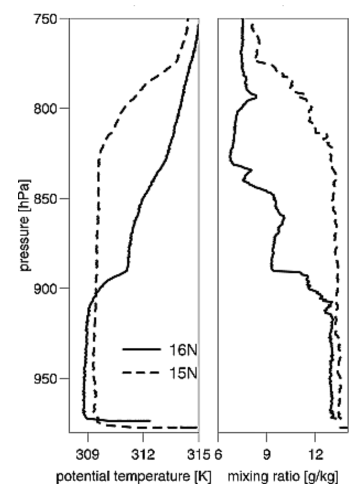


PBL temperature from ECMWF forecast model

Observed PBL temperature

Low LSTA → wet surface

wet patches ~10-60 km



PBL and surface temperature coherent down to λ~6km

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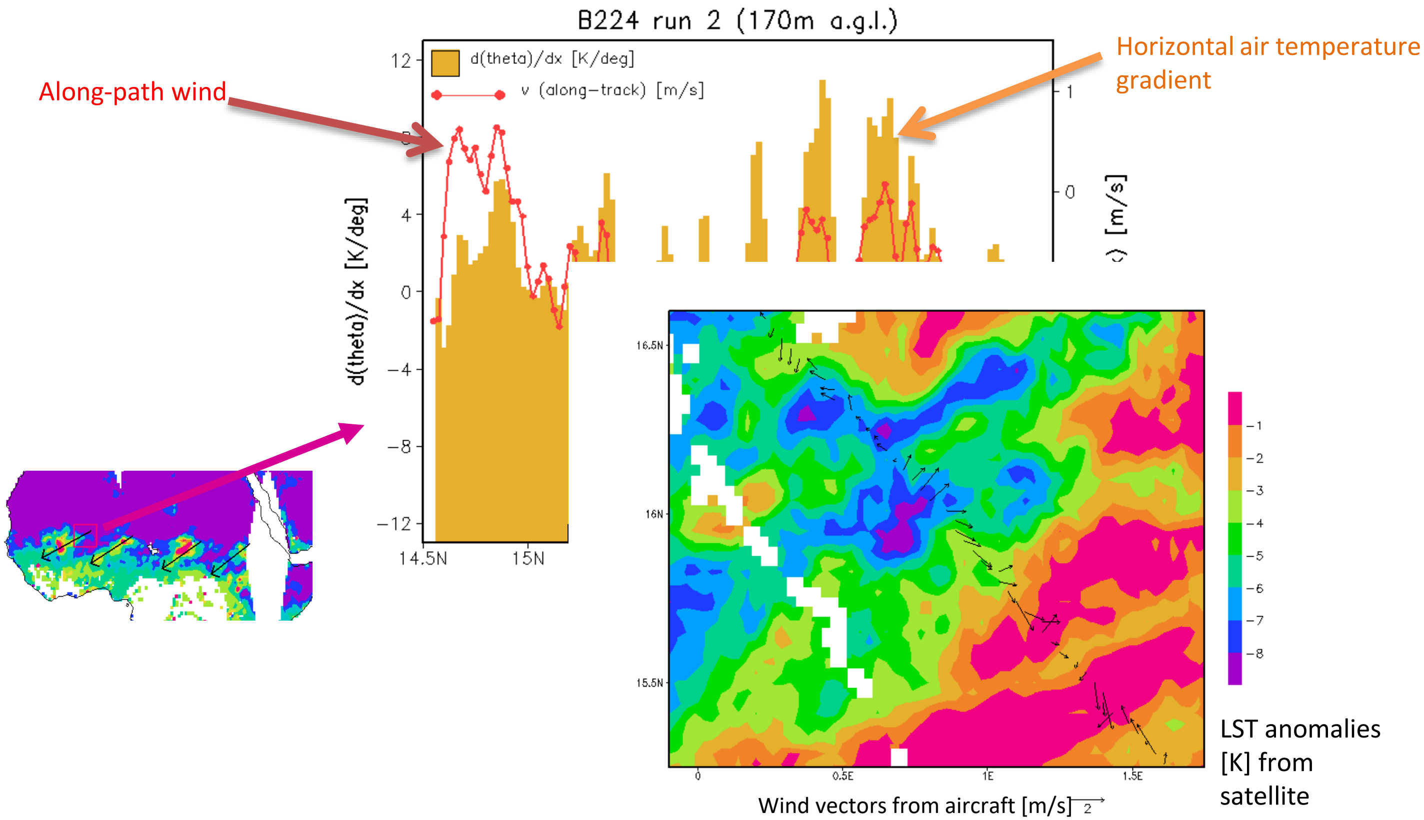
Taylor et al GRL 2007

Low-level wind response to patchy soil moisture: AMMA flight data



Wind and surface temperature coherent down to λ ~ 20km

Taylor et al GRL 2007

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Impact of heterogeneity on moist convection?

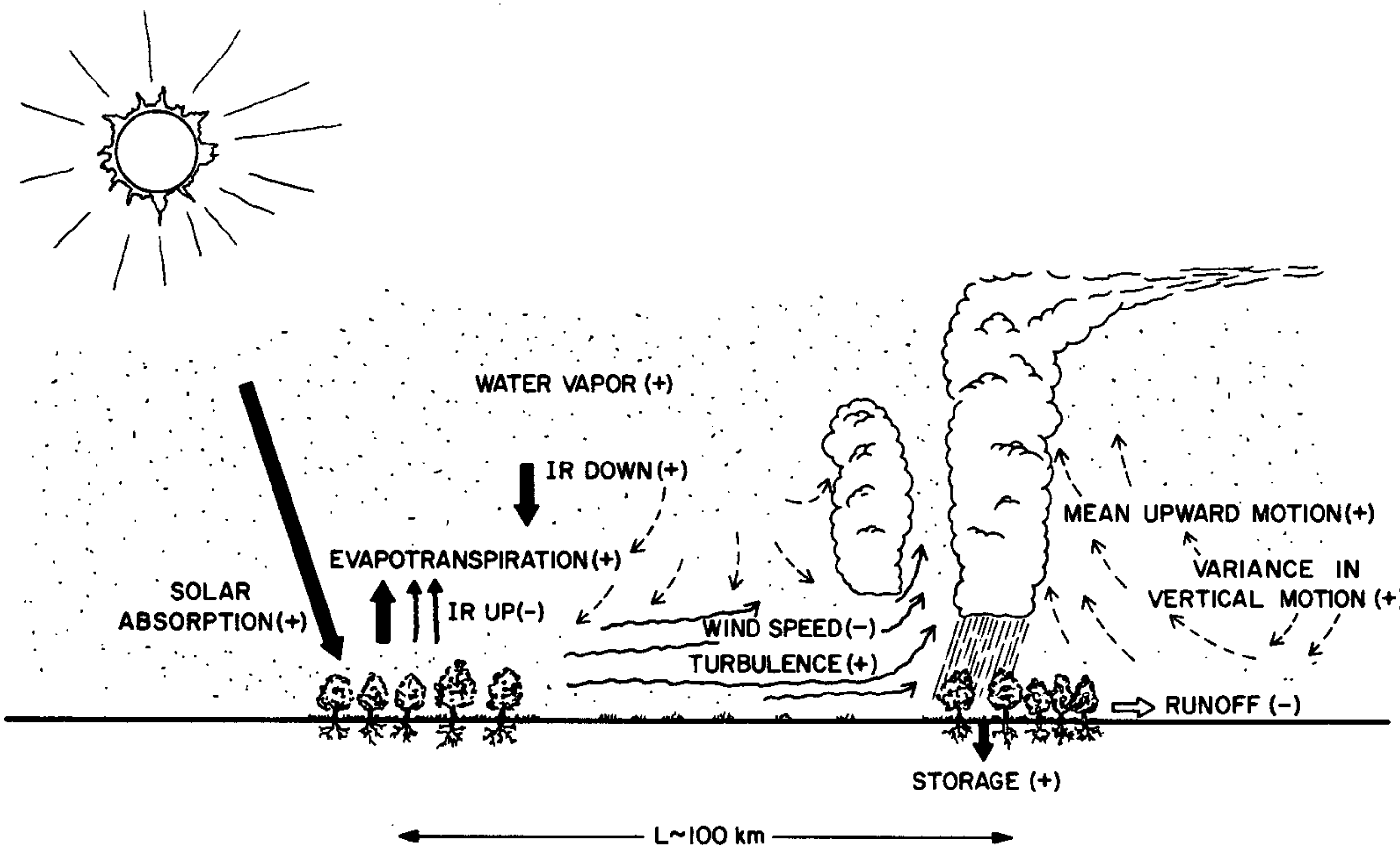

FIG. 4. Hypothesized effect of establishing bands of vegetation in a semiarid region of previously bare soil. Increases or decreases of an effect or process following the introduction of vegetation are indicated by pluses or minuses, respectively.

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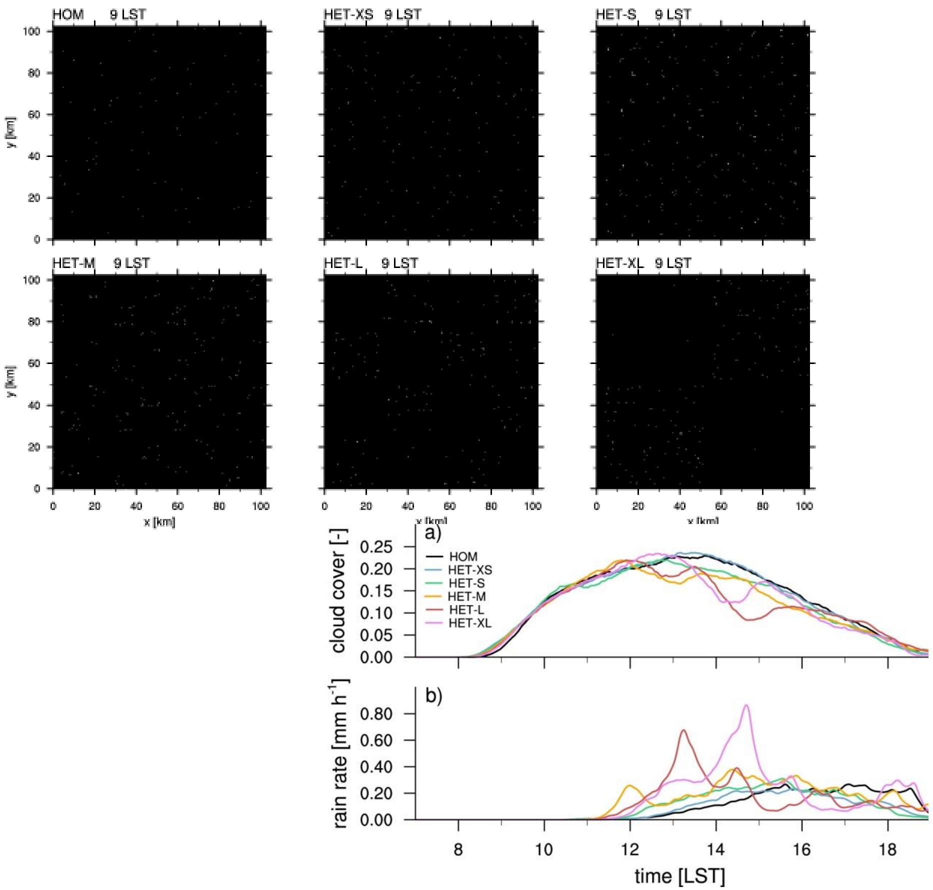
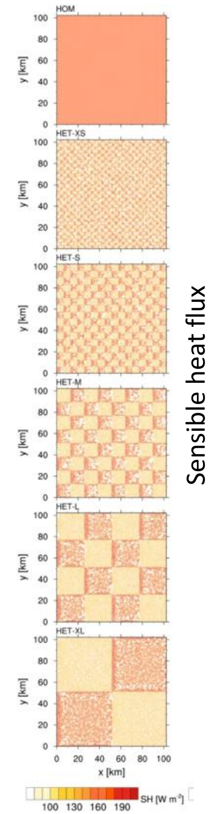
Anthes, J Clim and App Met 1984

Idealised large eddy simulations: sensitivity of deep convection to patch size

Total cloud liquid water





Sensible heat flux

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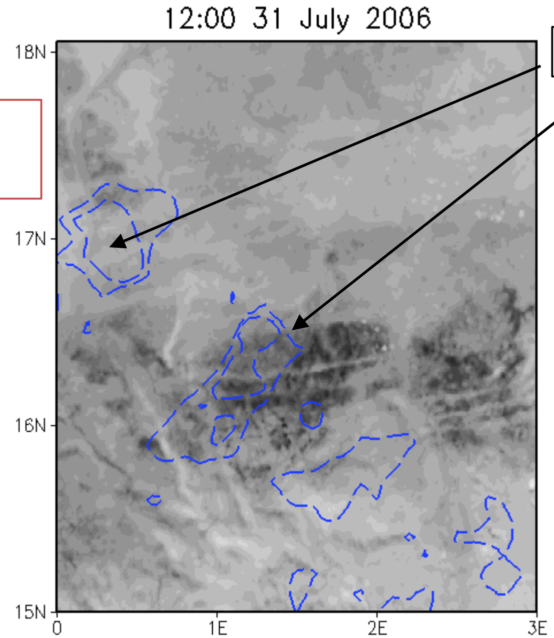
Rieck et al, MWR 2014

Observations from the Sahel

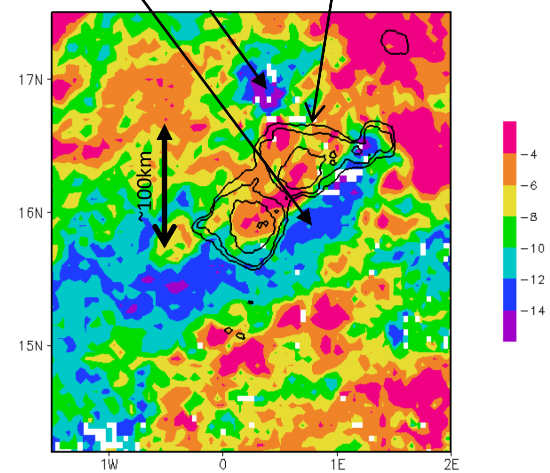
Cloud-top temperatures
(-40,-50,-60C)

Cold (wet) features

Blue contours: Land Surface Temperature anomalies (LSTA)



Visible Imagery from Meteosat



Land Surface Temperature anomalies (LSTA) at ~3km

Convective initiation along edge of wet-dry edge consistent with forcing by mesoscale circulation

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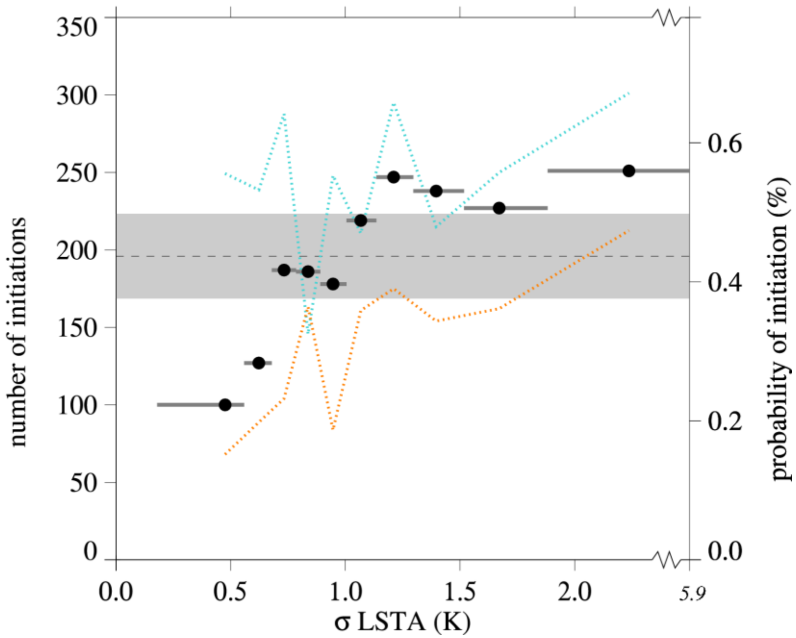
Taylor et al, QJRMS 2010
Birch et al QJ 2012, Klupfel et al QJ 2012, Gantner and Kalthoff QJ 2010

Analysis of multi-year observations:
Initiations more likely over variable surface

3000+ observed initiations from MSG
Land surface characterised by LST from MSG



Proxy for soil moisture variability

All atmospheric conditions

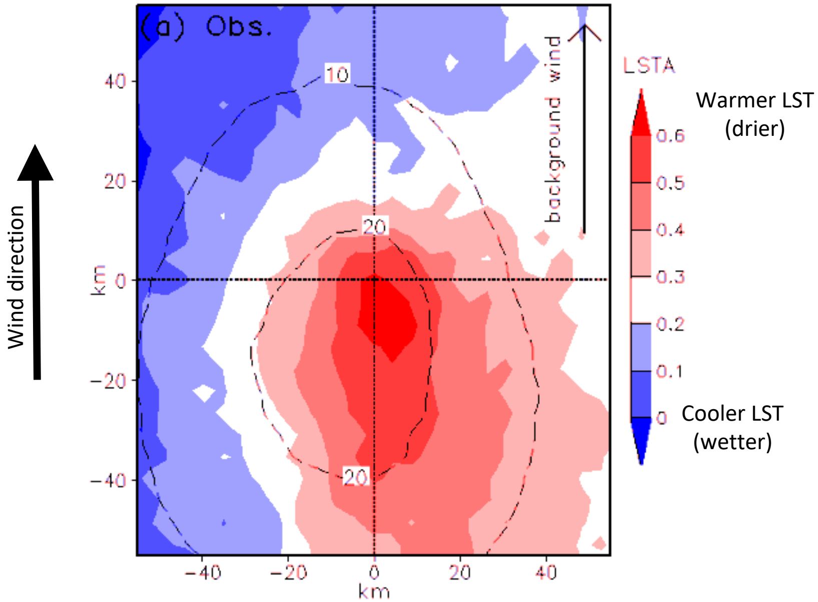
LFC<200hPa above surface

LFC>300hPa above surface

Taylor et al, Nature Geoscience 2011

Soil moisture patches and MCS initiation

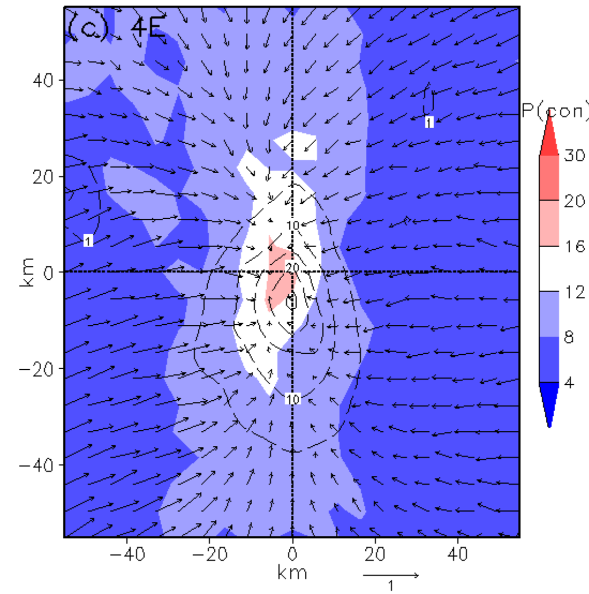
Observations



Shading: Land Surface Temperature Anomalies composited on initiation point (0,0). Contours: cold cloud frequency [%]

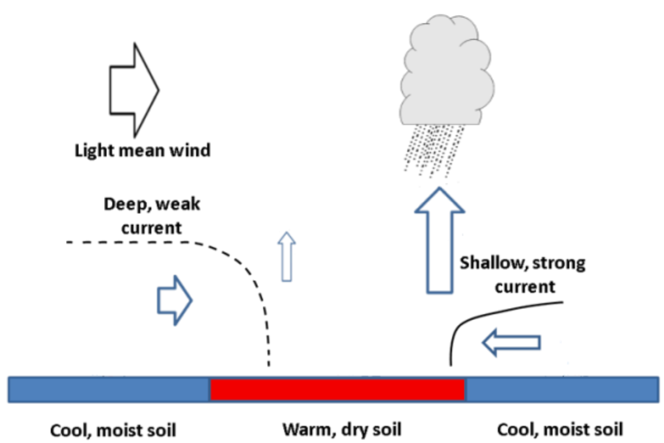
Pattern of H from soil moisture drives mesoscale circulation

Numerical simulation



Shading: Probability of strong convergence pre-initiation
Vectors: low level wind anomaly

Preference for initiation over locally drier surface close to (~10 km) LSTA gradient downwind



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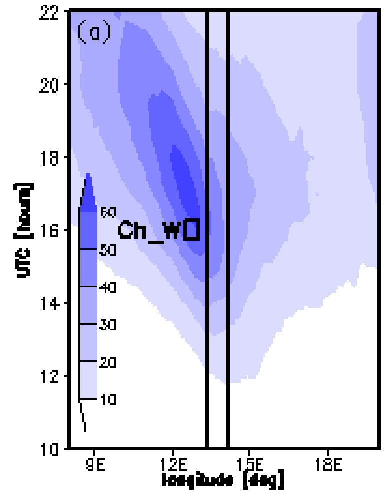
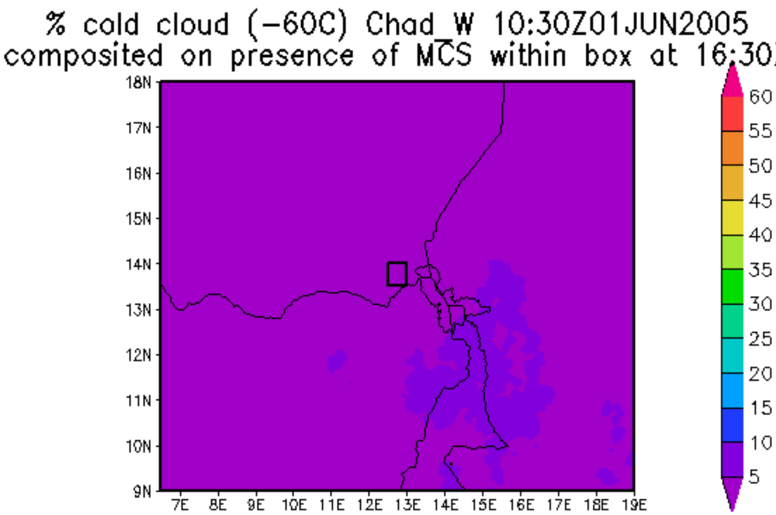
Taylor et al, Nature Geoscience 2011
Garcia-Carrerras et al JGR 2010

Impact of surface on pre-existing mesoscale convective systems (MCS)?



Composite Meteosat cloud-top temperature data for several hundred MCS in vicinity of Lake Chad (JJAS 1982-2005)



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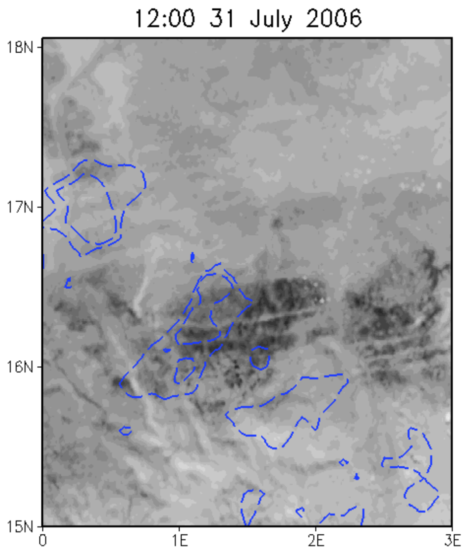
When MCS meet large wet surface, convection within MCS weakens

Taylor et al, QJRMS 2018
Lauwaet et al, QJRMS 2012

Relevance for forecasting



Triggering by mesoscale soil moisture gradients accounts for 1 in 8 storms in Sahel

Lakes, wetlands and deforested patches also trigger afternoon storms across Africa

In principle, knowledge of mesoscale land features can provide localised predictability

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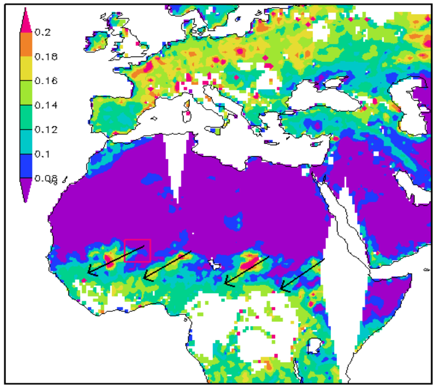
Problems for forecasting

Land surface conditions are just one effect. Without favourable atmospheric conditions, initiation won't occur



"knowledge of mesoscale land features" is not easy to acquire, especially for dynamic features.

- Satellite near surface soil moisture products (e.g. ASCAT SMOS, SMAP…) available typically once every 24 hours
- Land surface temperature provides information every 15 minutes if its not cloudy

Land schemes within NWP models are designed to compute fluxes which represent the diversity of landscapes across the world (soil and vegetation types, land use, soil moisture…). This is very challenging

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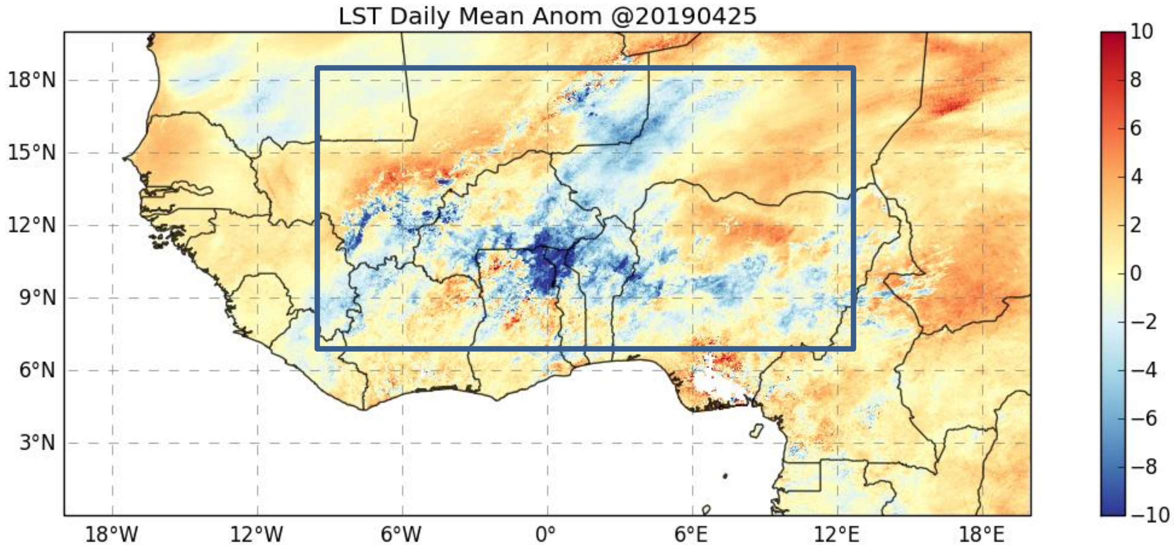
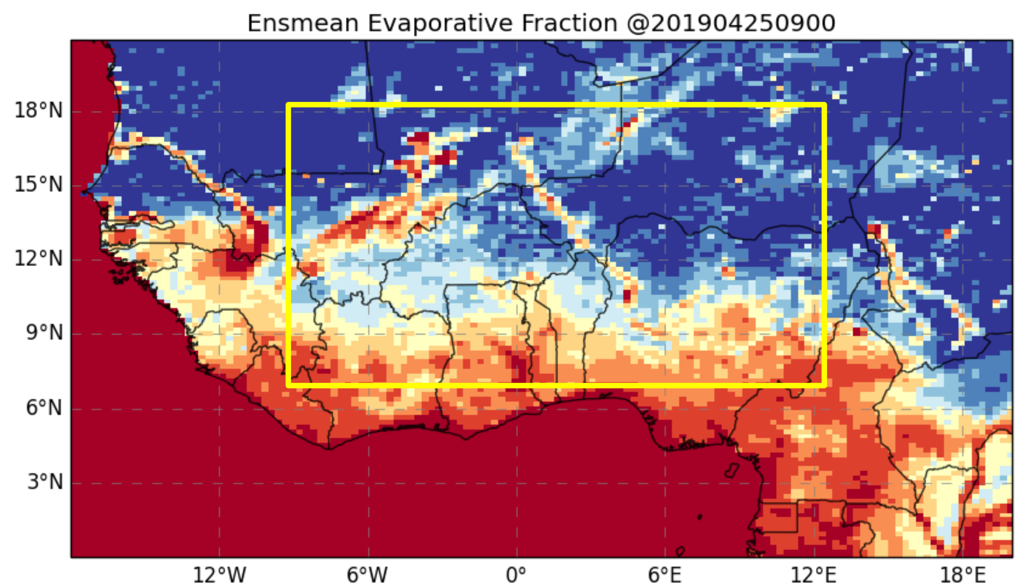
How soil moisture heterogeneity treated in 1 (unrepresentative?) model



Blue areas: soil moisture from rain in previous days cooling surface

Output from one operational global model
Red areas (high evaporation):
Guinea Coast (realistic)
Senegal/Niger rivers (unrealistic scale)
Model captures some of wet features from previous rain, but not others.
Depends on availability of satellite soil moisture data assimilated by model



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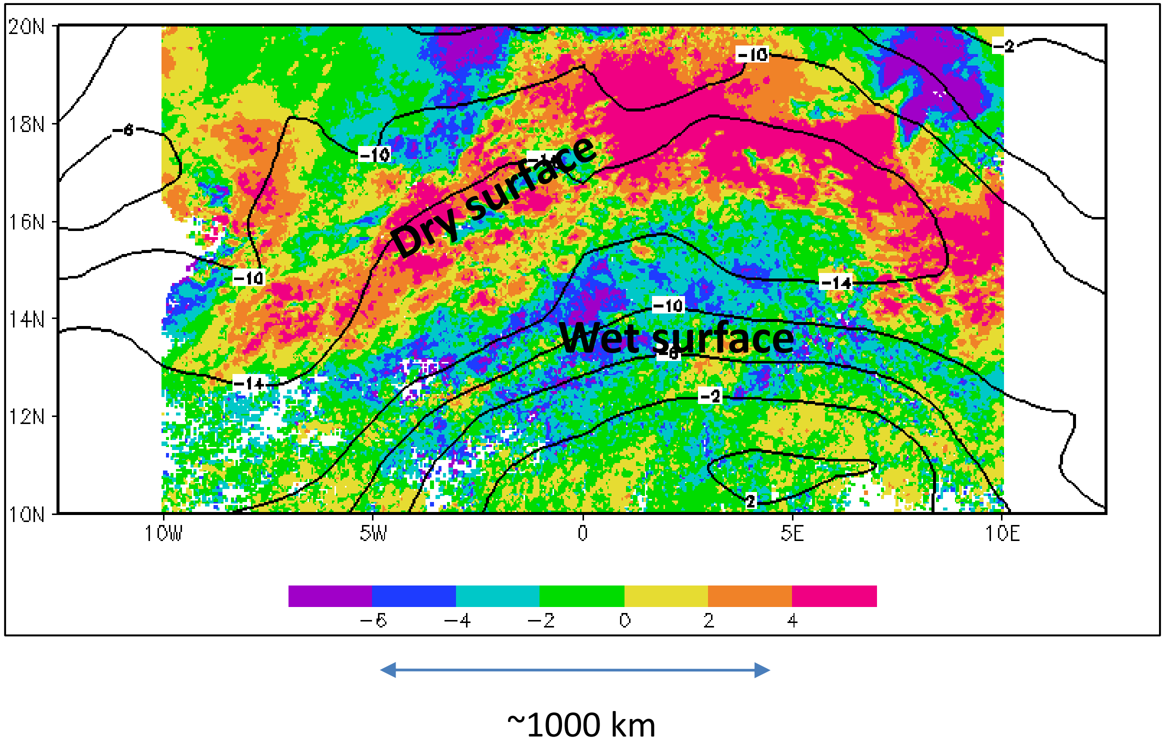
Semeena Shamsudheen Valitaveetil

Soil moisture variability at large scales (1)

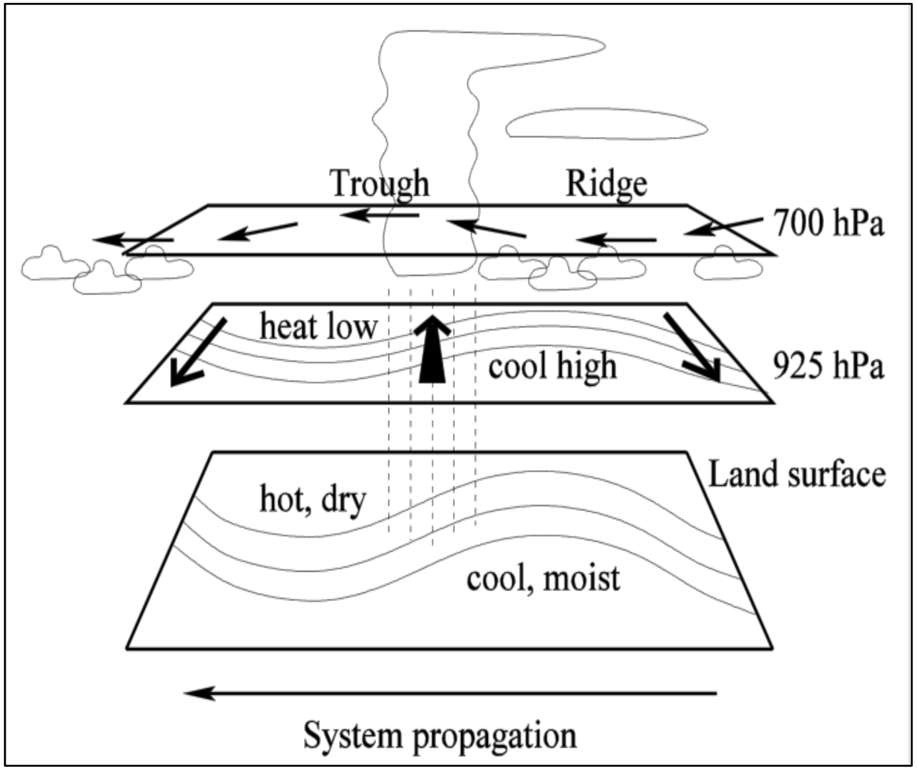


Shading: land surface temperature anomaly
Contours: zonal wind at 700 hPa

Synoptic systems e.g. AEWs can produce large-scale soil moisture patterns which provide “memory” of rainfall for several days

These patterns can spin up new synoptic-scale circulations

Soil moisture variability at large scales (2)



Land-atmosphere coupling within an AEW.

Wave-modulated convection creates synoptic variability in soil moisture

- wet soils favoured behind the trough.

Soil moisture pattern drives zonal gradients in sensible heat flux

- perturbs boundary layer (eg 925hPa) temperature
- Relatively low (high) pressure over drier (wetter) soil drives southerly flow between the dry and wet soils, enhancing new convection there

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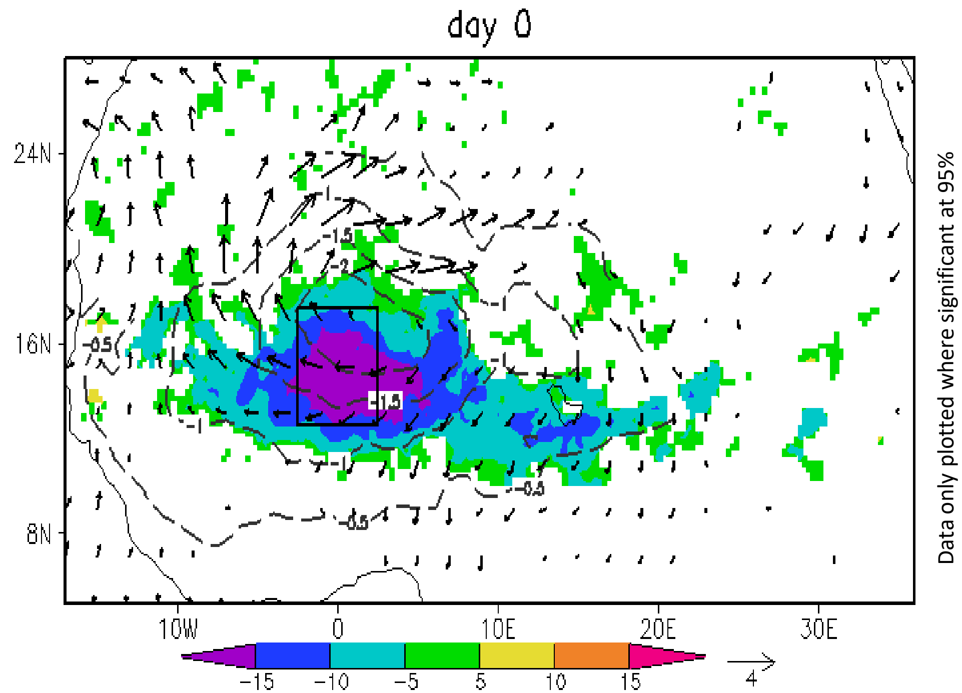
Taylor et al QJRMS 2005
Forecasters Handbook

Soil moisture variability at large scales (3)

Composite intra-seasonal soil moisture from observations

ECMWF analysis depicts "cool high" anomaly

- propagating vortex consistent with Sahelian mode of Sultan and Janicot
- Soil moisture-driven sensible heat fluxes reinforce westward propagation



Shading: Sensible heat flux anomaly
Contours: T (925hPa) 18Z
Vectors: u,v 925hPa 6Z day+1

Taylor, J Clim, 2008, Sultan and Janicot GRL 2001, Parker QJRMS 2008, Lavender J Clim 2010, Grodsky and Carton, GRL 2001

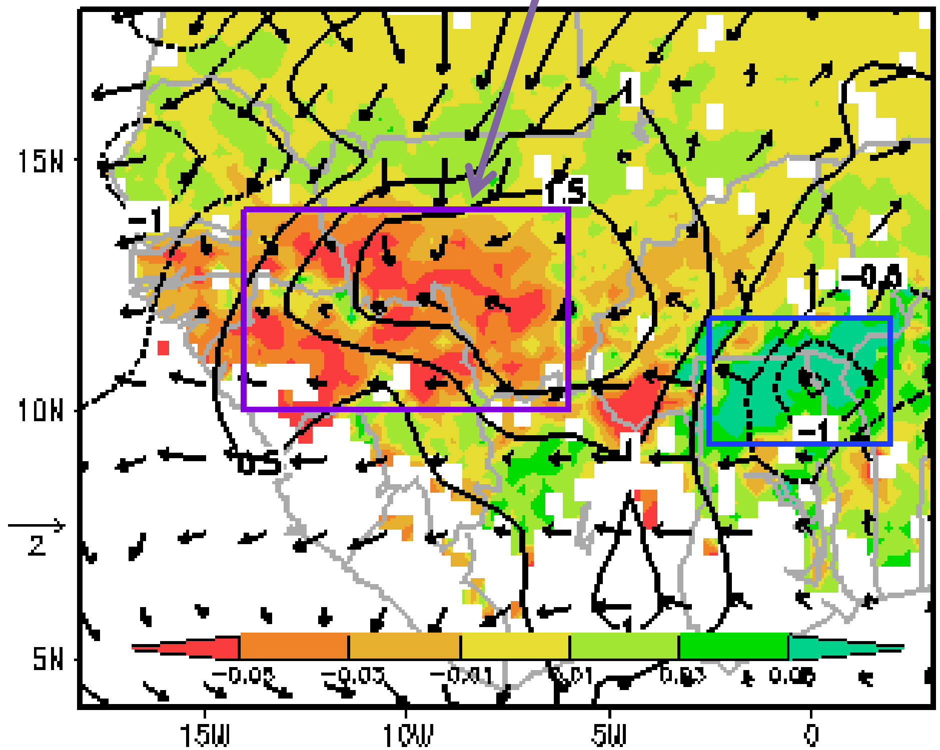
Soil moisture variability at large scales (4)

Surface soil moisture dries in few days in Sahel

BUT outside of core wet season, rainfall variability stimulates vegetation growth – longer memory

Vegetation anomalies *may* modulate monsoon circulation on time scales of weeks via enhanced evapo-transpiration

May rainfall deficit delayed seasonal vegetation development
Enhanced surface heating induced a persistent heat low anomaly in June.



NDVI and 925hPa T and wind anomalies June 2007

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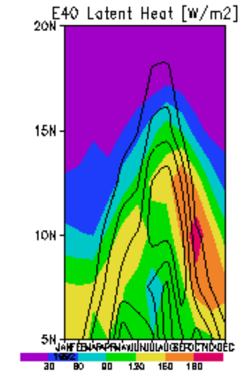
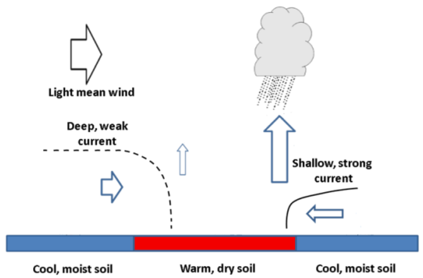
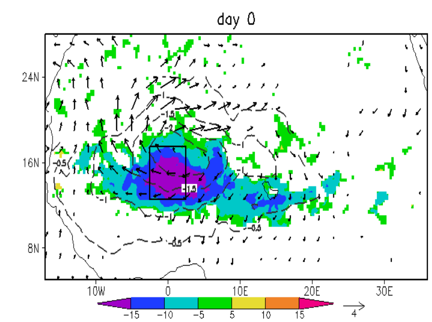
Summary

- Land affects atmosphere through variations in surface properties (e.g. albedo, roughness) controlling surface energy balance
  – availability of soil water for LE particularly important
  – Drives strong variations in H vs LE on daily to seasonal time scales
- Spatial variations in fluxes from previous rain
  – induce daytime mesoscale circulations which increase likelihood of storm initiation
  – feed back on synoptic circulations
- Numerical weather prediction models not always reliable at simulating surface fluxes







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