A Density Current Parameterization Coupled with the Emanuel’s Convection Scheme

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Observation of cold pools in the Sahel  
(Lothon et al. 2011, Dione et al. 2013)

Niamey and vicinity (mesoscale):

MIT C-band Doppler Radar

ARM mobile facility

AMMA Catch meteo & flux stations, and raingauges

well defined very circular gust front emerges from reflectivity fields (backscattering insects, debris...)

very low wind speed in BL round shape consistent with Parker (1996)
Observation of cold pools in the Sahel

Lothon et al. (2011): analysis of a case-study of locally-initiated deep convection (10 July 2006)

Dione et al. (2013): analysis of the month of July 2006 (24 days with data)

- locally-initiated convection with formation of a cold pool observed on 8 days i.e. this is frequent!

- These are distinct (smaller) from the wide cold pools & gust fronts associated with mesoscale squall lines, also observed as propagating MCSs (e.g. Chong 2010)
Observation of cold pools in the Sahel

mesoscale dynamics: retrieval of 3D wind components

Lothon et al. (2011)
Observation of cold pools in the Sahel

Another example: 11 July 2006

Dione et al. (2013)
MCSs Tracking Climatology over 25 years

West Africa

- High CIN and dryness → Convection
  Triggering is difficult
- Triggering mainly in mountainous areas
- Other forcings (soil moisture, breezes, AEWs…)

- More zonally homogeneous distribution of rain, due to propagation systems
- Favourable factors:
  - CAPE
  - PW
  - Mid-level dryness
  - Shear (AEJ)

Fast-moving type C3+C4 → 80% of precipitation over Sahel
Outline

1. **Introduction**: observation evidence
2. **New physics at LMD including Wakes**
   - Wake model
   - Triggering & closure: ALP and ALE concept
3. **1D test**
4. **Current works and further steps**
2. New physics at LMD

- In most GCMs deep convection is function only of LS variables (quasi-equilibrium hypothesis)
  ⇒ elementary convective structures (MCS, Squall Lines…) do not exist in climate simulations

- Observed self-sustaining behaviour of deep convection (diurnal cycle and propagation…) shows that there is a memory somewhere.

- Proposition: convective wakes (= cold pools) are key elements of this memory ⇒ to be represented
The Wake model

Lifting

Cold pool
Density current
Wake

Gust front

Convective Part

Stratiform Part

Wake

D

H

Conceptual model

Mali, August 2004
F. Guichard, L. Kergoat
**Basic assumptions**

- **Population of homogeneous circular wakes:**
  - height \( h_w \), radius \( r \), density \( D_{wk} \) (*simpler than in Qian et al. 1998*)

- **Prognostic variables (+3):**
  - Fractional surface \( \sigma_w \)
  - Vertical profiles \( \delta \theta(p) \), \( \delta q(p) \)

- **Spreading speed:**
  - Wake Available Pot. Energy
  
  \[
  C_x = k_x \sqrt{2 \text{ WAPE}}
  \]

  \[
  \text{WAPE} = -g \int_0^{h_w} \frac{\delta \theta_v}{\theta_v} dz
  \]

  Spreading differential speed: \( \delta \omega(p) \rightarrow \text{advection} \)

- **Conservation laws** (mass, energy, water)

- **Feeding by a convection scheme (KE)** with a partitioning of heat and moisture sources (Q1, Q2) between
  - **Wake zone:** unsaturated downdrafts (cooling) \( \sigma_w \)
  - **Outside the wake:** convective drafts (1- \( \sigma_w \))

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*Grandpeix and Lafore 2010 (JAS)*
Large scale variable tendencies

Potential temperature:

\[
\begin{aligned}
\partial_t \bar{\theta} &= (\partial_t \bar{\theta})_{LS} + \frac{Q_R}{C_p} + \frac{Q^{bl}_{1}}{C_p} + \frac{Q^{cv}_{1}}{C_p} + \frac{Q^{wk}_{1}}{C_p} \\
\frac{Q^{wk}_{1}}{C_p} &= + (\partial_t \sigma_{w} - e_{w}) \delta \theta \\
-\sigma_{w} (1 - \sigma_{w}) \delta \omega \delta p \delta \theta &= \text{Differential vert. advection}
\end{aligned}
\]

Specific humidity: idem.
Wake variable tendencies

Potential temperature difference:

\[
\partial_t \delta \theta = -\bar{\omega} \partial_p \delta \theta + \frac{\delta Q_{1}^{cv}}{C_p} + \frac{\delta Q_{1}^{wk}}{C_p} \frac{k_{gw}}{\tau_{gw}} \delta \theta
\]

where \( \tau_{gw} = \frac{\sqrt{\sigma_w (1-\sqrt{\sigma_w})}}{4Nz \sqrt{D_{wk}}} \)

is the damping time by gravity waves

\[
\frac{\delta Q_{1}^{wk}}{C_p} = -\frac{e_w}{\sigma_w} \delta \theta
\]

: Entrainment

\[-\delta \omega \partial_p \bar{\theta} \]

: differential advection of \( \bar{\theta} \)

\[-(1 - 2\sigma_w) \delta \omega \partial_p \delta \theta \]

: differential advection of \( \delta \theta \)

Specific humidity difference: idem (except for the gravity wave term).
**Coupling convection with sub-cloud processes: ALE & ALP**

At least two variables:

**Available Lifting Energy**

**ALE**

The **shower is triggered** when \( K > gh \) (\( K = \text{ALE} \))

**Available Lifting Power**

**ALP**

Convection is triggered when the maximum kinetic energy \( K \) (\( K = \text{ALE} \)) of air impinging on the gust front exceeds the convective inhibition:

\[
\text{ALE} > |\text{CIN}|
\]

**Closure**

Wakes provide a power \( P_w \).

A fraction \( k \) (the wake lifting efficiency) of \( P_w \) is used to lift at a mass flow rate \( M \):

- overcoming inhibition \( \Rightarrow \) power \( M |\text{CIN}| \)
- velocity at LFC = \( w_B \) \( \Rightarrow \) power \( \frac{1}{2} M w_B^2 \)
- dissipation \( \Rightarrow \) power \( \frac{3}{2} M w_B^2 \)

**Closure:** stream power \( M K = k P \) (\( = \text{ALP} \))
Coupling convection with sub-cloud processes: ALE & ALP

Different contributions to ALE & ALP

- PBL (Rio et al 2009)
- Orography
- Density currents...

\[
ALE = \max (ALE_{PBL}, ALE_{ORO}, ALE_{WK})
\]

\[
ALP = ALP_{PBL} + ALP_{ORO} + ALP_{WK}
\]

**ALE (Available Lifting Energy) (J/kg)**

ALE = order of magnitude of the kinetic energy of the strongest updraughts (scale ≈ km).

- Boundary layer: \( ALE \approx (\frac{1}{2}w^2)_{max}, \approx (\frac{1}{2}w^2)_{Thermals} \).
- Orography thermal effect: ALE estimated from the potential energy of the surface layer.
- Density currents: \( ALE = \frac{1}{2}C^*w^2 \), \( C^* = \) gust front velocity.

**ALP (Available Lifting Power) (W/m²)**

- PBL:

\[
ALP = \frac{1}{2}\rho w^3 \quad (\approx \text{qq } 0.01 \text{ W/m}^2)
\]

- Density currents:

\[
ALP = h_w \Gamma_w \frac{1}{2} \rho C^*^3 \quad (\Gamma_w = \text{gust frt lgth / unit area})
\]  

\( (\approx \text{qq } 0.1 \text{ W/m}^2) \)

- Orography:

\[
ALP = - \int_{\text{top}}^{\text{base}} \vec{D} \cdot \vec{V} \, dp \quad (\approx \text{qq } 0.1 \text{ W/m}^2)
\]
**1D tests against CRM simulations African SL case – HAPEX 92**

Turbulence is prescribed from the CRM simulation

→ Only the wake coupling with the convection is tested
Simulated wake properties

HAPEX92: 21 Aug 1992 squall line case

TOGA-COARE: 22 Feb 1993 squall line case
Time evolution
Only the coupling with “wakes” gives the good cooling close to the surface as simulated by the CRM.

Not enough drying ~700 hPa
Sensitivity study – $\theta$ & $q_v$ profiles

- **e**: CRM

**Without the wake**
- PBL stays too well-mixed

**Good stratification only for the wake**
- Emanuel standard...
- Alp Strong............
- Alp weak.............
- Emanuel+Wakes...

**Profiles**
- $\theta(18h)$
- $q_v(18h)$
Sensitivity to Dw

- To the Density Dw \(\rightarrow\) Key factor
- Dw = 2 \(\rightarrow\) 10 / 1000 km square
Conclusion

- **Density currents = key element** of the life cycle of deep convection

- The wake model implemented in the new version of LMD yields *wake properties in agreement with observations* (although a little overestimated)

- The Emanuel convection scheme with the **ALE & ALP closure**, coupled to the thermal plume and the wake parameterizations, yields an **improved diurnal cycle** of deep convection → See Romain’s talk

- **LESs and CRMs** are powerful tools to help to develop and validate parameterizations
Current works and further steps for the LMD new physics (1/3)

Present shortcomings
- Too intense wakes growing too fast
- Population of uniform circular wakes...

Wake parameterization improvement (1)
- Wake erosion by surface fluxes enhancement → See Romain’s talk
  - Due to temperature and humidity anomalies in the wake,
  - and to the wind increase (gusts)
- Gravity wave term impact on humidity → positive impact → to be implemented
- Test entrainment/detrainment in and above the wake: (only entrainment above the wake now)
Current works and further steps for the LMD new physics (2/3)

Wake parameterization improvement (2)

- Evolution of the wake density $D_{wk}(t)$
  - **Now**: $D_w$ is constant and Mixing when the wake fraction reaches $\sigma_w \approx 0.5$
  - **Different regimes**: shear and humidity dependent
    - “Pop corn” high density, weak/small wakes $\rightarrow$ early stage, oceanic cases
    - Organized convection (MCSs): low density, intense and large wakes $\rightarrow$ mature stage, continental
  - **Different processes**:
    - Wake collapsing, merging
    - Destruction by surface fluxes and PBL processes
    - Initiation by 1st convective cells $\rightarrow$ link with the triggering (cloud density at the precipitation onset)
  - Set of equations has been developed for different regimes $\rightarrow$ to be tested

- **Propagation** (key step)
  - Allows convection in region of high CIN, interaction with waves (AEWs)
  - Physically well understood: shear dependent
  - Sets of equations have been derived
  - How to transport convection and wakes from one cell to the other? Not decided

- **A framework** for Q3 and dust lifting parameterization?
  - Important for organized MCS such as fast-moving SL
  - Linked to the circulation associated to the wakes, anvils and convective parts.
  - Important for AEWs (Poan et al 2013 to be submitted)
Wake coupling

**Triggering** \[ ALE > |CIN| \]
- Accounting for orography through ALE: developed \( \rightarrow \) to be further tested and implemented
- Other subcloud and surface forcings (breezes, soil moisture heterogeneities…)
- Link with the dry and shallow convection stages \( \rightarrow \) Stochastic triggering (Rochetin et al 2013a, b)

**ALP Closure** \[ M_b = \frac{ALP}{CIN| + 2w_b^2} \]
- \( W_b \) dependents now on the cloud base: important to separate continental/oceanic regimes (Rio et al 2012)
- Accounting for the shear effect on the ALP efficiency

In short:

*The object approach is physically very attractive but implies many complications. Is it necessary?*
Some References


Squall line arrival over Niamey on 26 June 2012 – Courtesy Laurent Labbé
Shear impact on DC

a) No-Shear case: the density current spreads in all directions. Forced ascents are weak and not localized

b) Case with shear: the density current is dissymmetric. Convergence is localized on the downshear side, better

**RULE Nr 1**

In case of shear the Density Current, DC, is dissymmetric. Convergence is stronger and localized on the downshear side of the DC

Symmetric solution

Spreading of the convergence $\rightarrow$ weaker

Gust (Cold) Front

Top view

Gust (Cold) Front

Top view

Zone of convergence, localized and intense
$\rightarrow$ Easier new cell triggering
Fig. 3. Expected vertical profiles of $\delta \theta$ and $\delta \omega$ in a case where $e_w - d_w = 0$ below wake top. Both profiles are linear below wake top (pressure $p_w$); the $\delta \omega^{\text{ev}}$ profile is a sketch of the vertical velocity difference resulting solely from the convective mass fluxes.
MIT
10 Jul
0851 UTC
h=400 m
Chong et al. 2008
MIT
10 Jul
0931 UTC
h=400 m
MIT
10 Jul
1101 UTC
h=400 m

matin:
rotation
MIT
10 Jul
1151 UTC
h=400 m

rouleaux:
augmentation des échelles
MIT
10 Jul
1241 UTC
h=400 m
MIT
10 Jul
1331 UTC
h=400 m
Évaluation AERES 15
- 17 janvier 2008

MIT
10 Jul
1451 UTC
h=400 m

aprem:
cellules
seconde traces d'un système plus au nord

MIT
10 Jul
1531 UTC
h=400 m
MIT
10 Jul
1541 UTC
h=400 m
cellules:
fusion à l'est
Évaluation AERES 15
15 janvier 2008

MIT
10 Jul
1601 UTC
h=400 m

1 “macro” cellule
(10 km)
MIT
10 Jul
1611 UTC
h=400 m
MIT
10 Jul
1621 UTC
h=400 m
MIT
10 Jul
1631 UTC
h=400 m
MIT
10 Jul
1641 UTC
h=400 m
MIT
10 Jul
1701 UTC
h=400 m
MIT
10 Jul
1711 UTC
h=400 m
MIT
10 Jul
1721 UTC
h=400 m
MIT
10 Jul
1731 UTC
h=400 m
MIT
10 Jul
1741 UTC
h=400 m
MIT
10 Jul
1751 UTC
h=400 m
MIT
10 Jul
1801 UTC
h=400 m
MIT
10 Jul
1811 UTC
h=400 m
MIT
10 Jul
1831 UTC
h=400 m
MIT
10 Jul
1841 UTC
h=400 m
MIT
10 Jul
1851 UTC
h=400 m
Observation of Cold Pools over Sahel

10 July 2006 event: daytime sequence

- At noon, there is no deep convection over a wide zone.
- By 18h, a convective event develops, focusing on a relatively small and short-lived convective event (such events are frequent).
- Development of daytime deep convection.
Observation of cold pools in the Sahel

Direct estimate of the speed of the cold pool spreading: ~ 5-6 m/s consistent with the formulation of Grandpeix and Lafore (2010)

Lothon et al. (2011)
Observation of cold pools in the Sahel

Gust front from surface time series:
Change in wind direction, gust wind
Sharp drop in temperature
especially when during the afternoon
More varied in humidity and θ e, they sometimes
drop, sometimes jump...
especially during the early and late monsoon periods
they often jump