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Haboobs: Convectively generated dust storms in West Africa.

Introduction

Haboobs are a type of dust storm produced by precipitating convective clouds over regions where surface particles are easily lifted by the wind. Haboobs take the form of imposing, churning walls of lifted sand and dust that propagate steadily forward in a series of constantly developing lobes and clefts (Figure 1). Their leading edges are usually over a kilometre in height and between tens and hundreds of kilometres in length (Ross et al., 2004; Simpson, 1997). The passage of the leading edge produces very rapidly changing conditions at the surface: visibility can drop to a few metres, temperature usually drops by a few degrees, and wind speeds and gustiness increase dramatically to potentially structure damaging strengths.

In the last year there has been an unprecedented level of news and media coverage of haboobs due the occurrence of three spectacular events that hit Phoenix, Arizona, USA, in July and August 2011 (Figure 1). Drier than usual soil caused by drought conditions allowed more dust to be lifted than in previous years. Despite the locally impressive nature of the storms produced in Arizona, their sizes of ~ 150 km and vigour were well within typical ranges (Buckle, 2004). In comparison there are rare occasions when haboobs in West Africa reach over 1000 km in length and propagate a similar distance (Figure 2). The behaviour of these particularly large events in the Sahara is not well understood. This article aims to (a) discuss the processes responsible for the formation of haboobs in general, (b) provide a description of their formation in West Africa, (c) motivate why it is important to study them and (d) outline future research on this topic.

How are haboobs formed?

Haboobs occur when downdraughts from convective storms reach the ground and spread out. The cold air spreading away from its parent storm is known as a cold pool, which often develops a turbulent gusty leading edge (gust front). When cold pools flow over surfaces with light, easily lifted material, the gust front whips up dust from the surface into a towering wall that forms the leading edge of a haboob.

Convective clouds are capable of producing huge amounts of ice crystals and water droplets within a short period of time (Atlas & Williams, 2003). The interaction between ambient air and the hydrometeors produces strong downdraughts. As they fall through sub-saturated air water droplets start to evaporate, ice crystals will sublimate and at temperatures over 0 °C ice will start to melt. These phase changes play an important role. The energy required to melt and evaporate ice and water is supplied from the surrounding air (Atlas & Williams, 2003). This cooling makes the air denser and therefore negatively buoyant. In addition, frictional drag exerted by falling precipitation helps to drive downward motion (Byres, 1949; Rotunno et al., 1988).

The presence of downdraughts within a convective storm can lead to the disruption of updraughts to an extend that the continued production of hydrometeors is prevented, causing the storm to dissipate within a matter of hours. In this case the collapse of a single convective cell can produce a microburst that can cause a small, short-lived haboob. However, if the updraughts and downdraughts are separated from one another, multi-cellular convective storms can be produced that persist for days and become much larger. To produce a multi-cellular system such as a squall line or mesoscale convective system (MCS), vertical wind shear is needed (Rotunno et al., 1988). A cold pool generated by the initial storm propagating in a sheared environment will have enhanced gust front height along the edge propagating downshear (the edge moving in the same direction as the change in wind with height). The taller leading edge lifts environmental air more vigorously and new cells are preferentially triggered along this part of the cold pool's edge (Liu and Moncrieff, 1996). Continuous or repeated triggering of new cells produces long-lived systems with separated updraughts and downdraughts as well as the characteristic linear structure of MCSs (Houze, 1993, Johnson and Mapes 2001). This produces larger and longer-lived downdraughts, which subsequently leads to a cold pool spreading over much larger areas.

The colder and therefore denser air formed below precipitating clouds spreads out horizontally, driven by a pressure gradient caused by hydrostatic imbalance. As it flows, the cold air takes on the shape of a gravity current, as seen in many different naturally occurring phenomena (avalanches, pyroclastic flows, turbidity currents and many more). Studies of gravity currents (Benjamin, 1968; Simpson, 1997) have explored the structure of these flows under laboratory conditions to provide a basis for researching their behaviour in nature and as an analogue for convective storm outflows. The main features of these flows can be seen in Figure 3, the most notable of which is the turbulent nature of the leading edge of the flow. This explains the strong winds and gustiness that allow for uplift of so much dust into the atmosphere. It is clear by comparing Figures 1 and 3 that gravity currents in the laboratory and haboobs have very similar structures as they both clearly display similar lobes, clefts, billows and nose structures.

Haboobs in the Sahara

Generally, the convective storms needed to produce haboobs that propagate north into the Sahara and dusty northern Sahel are very seasonal and only occur during the West African summer monsoon (WAM) season (Buckle, 2004) (Figure 4).

During the northern hemisphere (NH) winter the mean winds over the Sahara are northeasterly (Buckle, 2004). This dry wind that blows over the desert is known as the Harmattan.

As the year progresses into summer the position of the most intense insolation moves northwards over West Africa and large scale convective circulation allows moist, monsoonal air to be advected over the African continent. The surface boundary between the monsoonal air and the north-easterly Harmattan flow is known as the inter-tropical discontinuity (ITD). The ITD is not bound to the position of greatest insolation but is a dynamic interface affected by both synoptic and mesoscale conditions. Its position determines how far over the dry African continent moist air reaches, and subsequently, along with middle and upper level dynamics has a strong influence on the positioning of deep convective storms and their associated cold pool outflows.

Production of MCSs relies upon a number of different factors, including: (1) an adequate level of atmospheric instability, where near surface air has an elevated potential temperature or moisture content (Laing and Fritsch, 2000; Johnson and Mapes, 2001), (2) an initial convective trigger capable of overcoming convective inhibition (CIN), such as low-level convergence forced by large- or meso-scale meteorology, topographical flow deflection or thermals caused by surface inhomogeneities (Johnson and Mapes, 2001), (3) shear to help separate updraughts and downdraughts producing long-lived and organised storms as discussed earlier (Johnson and Mapes, 2001). In the northern Sahel and southern Sahara the conditions for MCS production are only met under specific meteorological conditions. Often this is when northward excursion of the ITD occur due to: westward propagating synoptic-scale waves along the mid-level African easterly jet (AEJ) known as African easterly waves (AEWs), upper level troughs in the subtropics or modification by prior cold pools. This allows low-level moist air to intrude to latitudes which are usually very dry producing conditions of high convective available potential energy (CAPE) and high CIN. Once triggered, convective cells can sometimes develop explosively and due to the sheared environment, develop into MCSs.

The vertical shear present over the Sahel and southern Sahara during the NH summer produces MCSs that tend to propagate westward across this region of Africa (Figure 4). This is mainly as a result of the low-level south-westerly monsoonal flow and the mid-level AEJ (Laing et al., 2011). The shear supports the initiation of new cells on the western side of the storms, such that the system as a whole will propagate westward. The presence of westward propagating AEWs, also controls the direction and speed of propagation (Laing et al., 2011). There is often a southward component of motion also observed in these storms, which is likely driven by the greater availability of moisture at lower latitudes where the monsoonal air is deeper. As these MCSs propagate, cold air flowing away from the edges of these systems can reach the arid desert and produce haboobs, as seen in the particularly large event from 09/06/2010 shown in Figure 2.

The vertical structure of the atmosphere in the Sahara and Sahel also provides the perfect conditions for the creation of strong downdraughts. The intense solar heating and lack of surface moisture creates a very deep, hot and dry well mixed boundary layer (sometimes as deep as 5km) and high cloud bases. A storm's precipitation must pass through this layer and inevitably a large amount of water will evaporate before it reaches the surface.

As mentioned earlier, in some rare instances the haboobs produced in the Sahara are far bigger than those seen elsewhere in the world. The factors that allow for the creation of dust storms in the Sahara with fronts over 1000 km long and able to propagate a similar distance are not well understood. Cold pools, as their name suggests, are driven by the difference in temperature between thunderstorm outflow and the surrounding air. Therefore it is the rate at which the cold air warms due to surface fluxes of heat or mixing with the ambient air that determines their lifetime and horizontal extent (Ross et al., 2004). In the Sahara the strong sensible heat flux and entrainment can weaken a cold pool significantly over the course of a day, reducing its propagation speed and curtailing extent. The reason for the extreme propagation distances seen in some Saharan haboobs is not well understood. It is even unknown whether the dust plumes seen in satellite imagery that look like haboobs are driven solely by density perturbations. This suggests the possibility that when haboob dust plumes propagate over such large distances the analogy of a gravity current is no longer valid. As the distances over which the cold pool spreads increases, the Coriolis effect becomes more significant and steers the flow to the right (in the NH, see Box 1). This suggests that even in an idealised case, where there is no exchange of heat between the surface and the cold pool, it would not continue to propagate as a gravity current. Instead it would behave like a meso- to synoptic-scale cold high.

Why study haboobs?

There are numerous reasons why research into the production and behaviour of haboobs is an important endeavour. These include impacts on the climate system, the biosphere and numerous human impacts.

The Sahara is widely recognised as the largest source of airborne mineral dust on the planet. Estimates of the amount of dust exiting the continent range from 500 to 1000 Tg per year (Engelstaedter et al., 2006). Haboobs provide only one mechanism for dust uplift in the Sahara; others include phenomena such as dry convective plumes, dust devils and low-level jets. These processes, haboobs included, are poorly understood both in their dynamics and the proportion of dust that they lift into the atmosphere. However, it has been shown that there is a strong seasonality of dust uplift in West Africa that is likely caused by haboobs in the summer months (Marsham et al., 2008) and that haboobs might be responsible for as much as 50% of dust uplift in West Africa during summer (Marsham et al., 2011). Without a greater number of observations and knowing more about the dynamics of haboobs we are unable to make estimates on either the quantity of dust they raise or how efficiently they lift material away from the surface and into the Saharan air layer (SAL). Once in the SAL, dust is available for long-range transport away from the African continent, usually out over the Atlantic Ocean where it will either be deposited or transported further.

Atmospheric mineral dust has significant effects on the climate system. Absorption and reflection of incoming solar radiation and interactions with outgoing longwave radiation by aerosols are known as the direct aerosol effects. These effects can change the radiation balance of the planet as well as modifying the vertical temperature profile of the atmosphere (Shao et al., 2011). Also, aerosols can act as cloud condensation nuclei (CCN) and ice nuclei (IN) modifying the way that clouds behave. Examples of this are: increased droplet concentrations due to a greater number of CCNs increases the cloud albedo, while it can also lead to suppression of precipitation and changes to cloud duration (Shao et al., 2011). The number of INs modifies the speed of cloud glaciation, which can affect the intensity and timing of convective precipitation. These so-called indirect aerosol effects, like the direct effects, have a large impact on the radiation balance of the planet (Shao et al., 2011). The effects caused by mineral dust are thought to be largely natural perturbations to the climate system. However, if we are not able to understand the natural state of the climate it is much more difficult to make accurate predictions about the effect humans are making and will make in the future.

Dust deposited in the world's oceans can have a significant fertilization effect. Areas where iron availability is a limiting factor for primary production cover vast areas of the oceans (Jickells et al., 2005). The insolubility of iron in the usually slightly base oceanic waters means that the riverine iron flux is rapidly deposited close to land. Areas away from the coast therefore become iron deficient and iron rich minerals in Saharan dust become an important source. Oceanic lifeforms (phytoplankton) that can utilise this deposited iron show population explosions after large deposition events, resulting in algal plumes (Shao et al., 2011). These organisms form the base of the food chain, and abundances provide food for organisms higher up the trophic order. Planktonic lifeforms in such numbers also create plumes visible from satellite imagery. These can significantly affect surface properties of the ocean, changing nitrogen fixation, absorption of atmospheric CO_2 and surface albedo (Shao et al., 2011).

Lifted dust can have several significant impacts on humans. Despite the low population densities in regions where haboobs are most frequent, the suspended dust in the atmosphere is easily transported to more populated areas and can cause or exacerbate a number of health problems. If fine material is inhaled and becomes embedded in the lung tissue, it can cause silicosis leading to lung cancer, a higher risk of contracting tuberculosis and damage to the immune system (Derbyshire, 2007). Mineral dust has also been associated with the transport of pathogens and allergens, specifically the link between the dusty season in the Sahel and Sahara and the spread of meninoccocal meningitis (Sultan et al., 2005). Increased dustiness also causes increased occurrences of conjunctivitis, as dust in the atmosphere provides both a risk of damage to the eye and a source of infection (Goudie, 2009).

In addition to impacts on human health airborne dust can have a significant impact on agriculture. In the Sahel approximately 90% of the population is rural, largely depending on subsistence farming (Sterk, 2003). Therefore, any negative effects of airborne dust on plants or livestock have a huge impact on the local populace. The problems for local farmers include undesired sedimentation such as silting up of drainage and irrigation ditches, crop damage due to sand blasting, retarded growth in plants with leaves coated with dust and soil degradation where the loss of fine sediments over time results in nutrient poor soils with an abundance of coarse particles (Sterk, 2003).

High levels of airborne dust can also make travel particularly difficult and dangerous. Road travel under such conditions becomes almost impossible due to reduced visibility. Similarly, airborne dust can create danger for a wide range of aircraft. The lack of visibility coupled with turbulent flow structures with strong vertical shear found in thunderstorm outflows mean that aircraft can lose lift without warning greatly increasing the risk of crashes during low-level flight, take off and landing (Fujita & Byers, 1977). Also, exposure of jet engines to heavy dust loads has the potential to cause significant damage to the internal workings. Despite these issues, airborne mineral dust rarely poses a significant danger to aviation due to the scarcity of dust at altitudes reached when planes are in transit.

Studying the production and behaviour of haboobs and the role they play in global dust transport will enable a better understanding of the impact both on the climate system and people's lives. Reducing these uncertainties will not only allow for greater understanding of our climate but will also allow for the production of adaptation strategies to reduce the human impacts of haboobs.

Future work

In order to better understand and model the behaviour of haboobs in the Sahara more research is needed. A PhD project being undertaken at the University of Leeds is focused on the modelling of large convective events and their associated cold pools in the Sahel and Sahara using the Weather Research and Forecasting (WRF) model. By modelling the production of cold pools and their behaviour in WRF, information can be gleaned about what allows some Saharan haboobs to reach such large sizes and propagate so far into the Sahara desert. The specific case study chosen for investigation is that of a very large convectively generated dust event that occurred during the period 8th - 10th June 2010 (Figure 2). The MCS that produced this large haboob was initiated over the Aïr and Hoggar Mountains in Niger and Algeria, respectively, and propagated south-westward before turning westward. The cold pool appears to have propagated for almost two days and produced a massive expanse of deflated dust that covered large areas of Algeria and Mali bigger than the area of Spain.

One of the hypothesised mechanisms for production of haboobs over such large areas of the Sahara is the interaction between convectively generated cold pools and mid-latitude weather systems. It is suspected that variations in the synoptic-scale pressure field due to mid-latitude systems and upper and mid-level wave influences allow for movement of the ITD into an extreme northward position and the formation of haboobs in the Sahara and northern Sahel. It is also possible that north-south pressure gradients help to advance haboobs and previously deflated dust further north than would normally be expected. Other possible mechanisms include interaction between haboobs and baroclinic zones along the ITD, and diurnal effects on the vertical structure of the lower atmosphere. Information on these mechanisms can be gathered through numerical weather prediction (NWP) modelling and should allow conclusions to be drawn about the driving forces behind the behaviour of Saharan haboobs and explain why some haboobs behave in a way unexpected from simple theory.

Other research in connected parts of meteorological science is also needed. The meteorology of Africa is generally not as well understood as in other parts of the world (Europe or USA for example). More fieldwork and measurements would be especially valuable due to the extremely sparse nature of observations in West Africa, particularly in the Sahara.

Also our understanding of cold pool production is not complete. The microphysical processes between different water phases and the effect of different CCNs and INs are not fully understood. Research into the behaviour of ice crystals and water droplets within clouds is a rapidly developing area of meteorological science. The better our understanding of these processes, the better our understanding of the production of cold pools due to evaporation of precipitation. Another effect of the lack of certainty associated with CCN and IN is that modelling the production of downdraughts and cold pools in numerical models becomes more difficult. This issue is compounded by the fact that the processes within convective storms are usually on a scale smaller than the resolution used in NWP models. Therefore sub-grid-scale processes are not reproduced explicitly and there is a reliance on parameterizations, which currently do not represent convection realistically, particularly the organisation from single cells to MCSs. Therefore continued research is needed in both microphysics as well as the improvement of model parametrizations.

In addition to this, gravity currents have long been used as an analogy for haboobs. However, the turbulent structure of gravity currents is not particularly well understood, so that there is a need for further modelling (either computer or laboratory) of gravity currents and the complex turbulence of their leading edges. As well as this, there needs to be further research into the changes in gravity currents when their scales tend towards their Rossby radius of deformation (see box 1), and their behaviour changes to be dominated by rotational rather than inertial forces.

Summary

Saharan/Sahelian haboobs are potentially a very large source of atmospheric dust from the African continent. They are usually produced by MCSs that propagate westwards along the southern side of the ITD during the summer monsoon season. They are capable of reaching sizes far in excess of haboobs seen elsewhere in the world. Haboobs are partly responsible for various health and social impacts on the local human populace while dust deflated by them has the potential to impact on the global climate and the biogeochemical systems.

In order to fully understand the behaviour of Saharan haboobs it is necessary to explore various different areas of meteorological science. Specifically improvements in: (1) understanding West African meteorology and climatology, for example by increasing the number of observations in the Sahel and Sahara; (2) understanding the dynamics and thermodynamics of gravity currents and haboobs; (3) understanding the microphysics of convective clouds and how this affects downdraught and cold pool production and (4) making improvements to NWP models such as new parameterizations and modelling at finer resolutions.

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Box 1

Rotational effects on gravity currents.

To establish if the Coriolis force is a significant factor in the behaviour of a flow, it is common to calculate its Rossby number (*Ro*), equation 1. *Ro* is a dimensionless number that gives a measure of the ratio of inertial and rotational forces, where U is the characteristic velocity of the flow, L is its length scale and f is the Coriolis parameter. If a flow has $Ro \ll 1$ then rotational forces dominate and a flow will be deflected to the right (in the northern hemisphere), whilst if *Ro* >> 1 then inertial forces dominate and a flow follows the pressure gradient force.

$$Ro = \frac{U}{Lf} \qquad (1)$$

A cold pool can be thought of as the instantaneous release of a column of denser fluid, which then collapses and spreads out radially away from the centre of the column. Given that the flow is in a rotating frame of reference it is subject to the Coriolis effect. As the flow propagates, *Ro* decreases because *U* decreases whilst *L* increases. This change in *Ro* shows that the rotational forces become more significant over time. The fluid's direction of motion will increasingly turn towards the right (in the NH). Eventually the flow will reach a gradient wind balance where the pressure gradient force is matched by the Coriolis and centrifugal forces (figure 5). Under these circumstances the flow no longer has a radial component but is dominated by rotational motion.

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Figure 1. A photograph of a haboob near Maricopa, AZ, USA on 5th July 2011. This haboob was approximately 1500m high and had a front length of nearly 150km. Note the raised nose of the flow, where environmental fluid is trapped under the advancing cold pool, and the turbulent lobes and clefts along the leading edge. (Reproduced by permission of Chris Voyles, http://cv-photozz.smugmug.com/keyword/storm3)

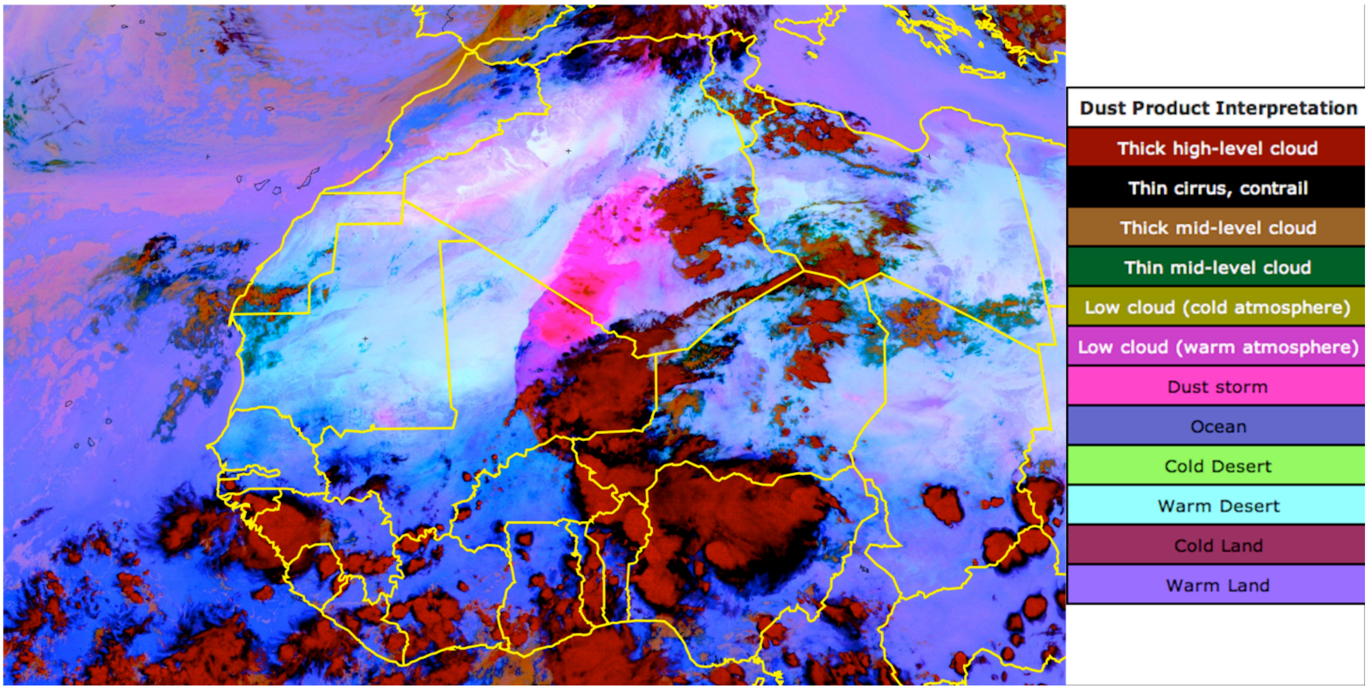

Figure 2. A false-colour satellite image showing a large MCS and its associated haboob propagating into the Sahara desert. Note the front length of the dust storm is over 1000km, much greater than haboobs in other parts of the world. Adapted from a SEVIRI RGB dust image from 1800 UTC 9th June 2010 (copyright © 2011 EUMETSAT).

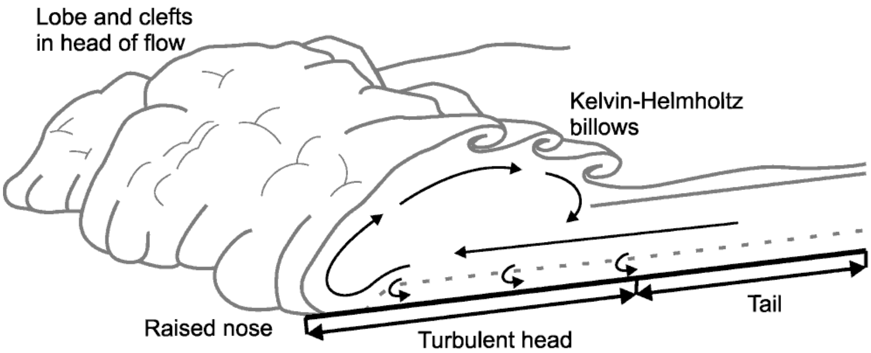

Figure 3. A schematic showing main features observed in gravity currents. Notably a turbulent leading edge with well defined head region with lobe and cleft structures thought to be produced by overrun environmental fluid rising through the head. Also shown is the laminar flow of the tail region, the raised nose of the gravity current and Kelvin-Helmholtz billows created by strong shear. The arrows within the flow denote the circulations that are generally assumed within the head. (Adapted from figures 2.6 and 11.3 from Simpson 1997)

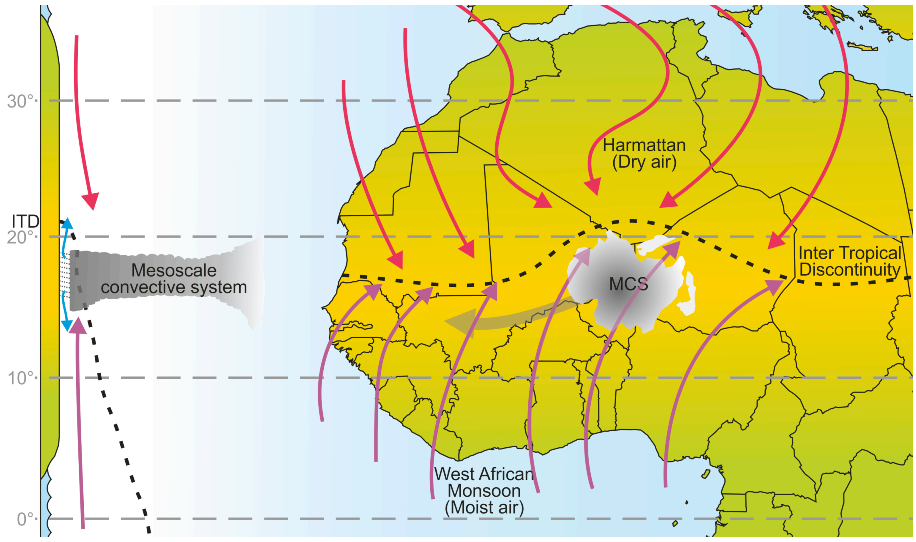

Figure 4. A schematic of the near-surface winds associated with the West African Monsoon, showing a realistic position of the Intertropical Discontinuity where the dry Harmattan air from the north meets the moist monsoon air from the south, the Harmattan/monsoon interface then slopes back to the south. Note the production of Mesoscale convective systems (MCSs) south of the ITD producing cold pools that propagate into the Sahara.

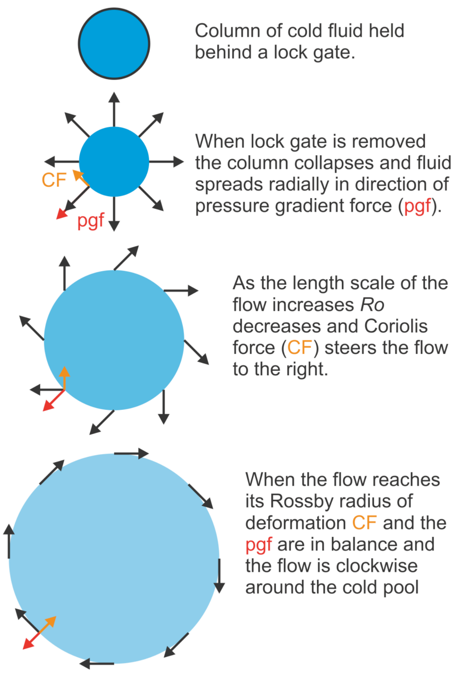

Figure 5 A schematic showing the change in behaviour of a gravity driven flow between radial spreading after release, to a point where the pressure gradient force is matched by the Coriolis and centrifugal forces and flow is perpendicular to the pressure gradient. Note that the strength in colour denotes the depth of the fluid where lightening indicates thinning. Also note that in the northern hemisphere flow is turned to the right whilst in the southern hemisphere it is turned to the left.