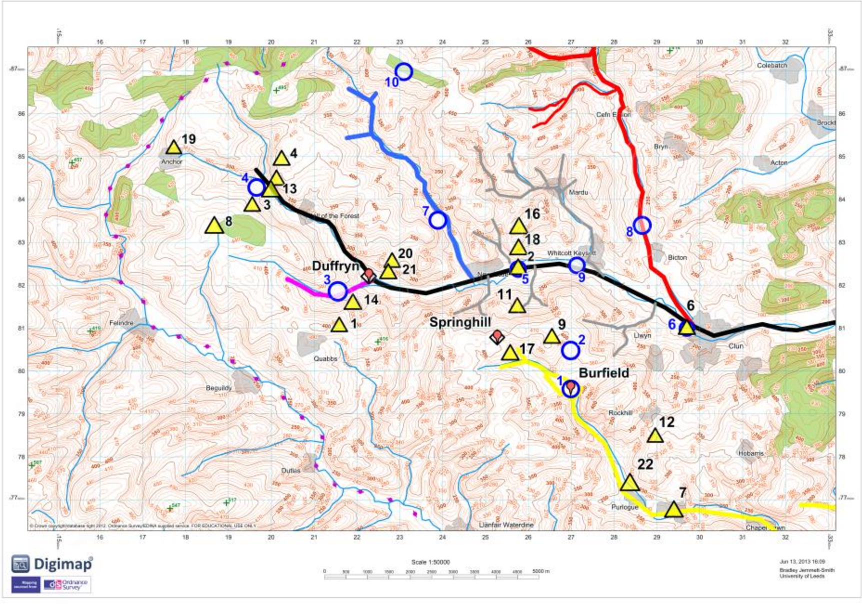
A CASE STUDY OF COLD AIR POOL EVOLUTION IN HILLY TERRAIN USING FIELD MEASUREMENTS FROM COLPEX

BRADLEY JEMMETT-SMITH[1]*, **ANDREW ROSS[1]***, PETER SHERIDAN[2], SIMON VOSPER[2], JOHN HUGHES[1]

[1]Institute of Climate and Atmospheric Science, University of Leeds, Leeds, UK
[2] Met Office, Exeter, UK
**b.jemmett-smith@see.leeds.ac.uk*
**a.n.ross@leeds.ac.uk*

Introduction

- A case study investigation of cold air pool (CAP) evolution in hilly is conducted using field measurements made during IOP 16 of the COLd air Pool EXperiment (COLPEX; ***Price et al.*, 2010; see map right**).
- Valleys of this size (~100-200m deep, ~1km wide) can exhibit temperatures up to 10°C cooler than surrounding hill tops (see **Fig 1**).
- Such temperature phenomena are difficult to forecast accurately using current operational models, which have resolutions on the order of 1 to 5 km (***Vosper et al.*, 2013a**; ***Vosper et al.*, 2013b**; ***Hughes et al.*, 2015**).
- Here we investigate a typical night where conditions are ideal for cold air pools to form (IOP 16); low ambient winds, high pressure, no cloud or fog.
- Despite these ideal conditions we find that the CAP evolution is not uneventful. On the contrary, we find a number of interesting phenomena that have an effect on the CAP, but do not completely erode it.
- Three episodes are highlighted using LIDAR measurements and the cause of CAP disruption attributed to; (1) wave activity, (2) rapid increases in the ambient wind and erosion of the residual layer, (3) the development of a nocturnal low level jet (NLLJ).



Above: Map showing instrumentation deployed during COLPEX, situated across the Clun valley region. Triangles are HOBOS, circles are AWS, balloons are flux tower sites.

Pictured right: AWS 2, one of 10 University of Leeds and NCAS Automatic Weather Stations (AWS) deployed during COLPEX .

Overview of IOP 16

- IOP 16 was one of the strongest CAPs observed during COLPEX (**Fig 1**), with temperature differences between the hill top and valley floor peaking at ~7°C around sunrise, following a rapid strengthening of the CAP (**Fig 3**).
- Skies remained clear during the night, and no fog formations were recorded (see **Fig 3** RH).
- Temperatures in hill top regions remained at or above freezing during the night, while frost formed in the valleys.
- Following sunset the CAP evolved uninterrupted; however, ~4 h after sunset (~10:30 UTC) the Environmental Lapse Rate (ELR) shows interruptions in the CAP evolution, which continue intermittently until CAP break up in the morning.

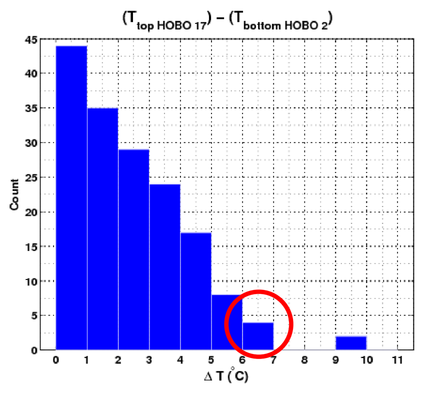


Fig.1. COLPEX climatology of Clun Valley CAP strength.

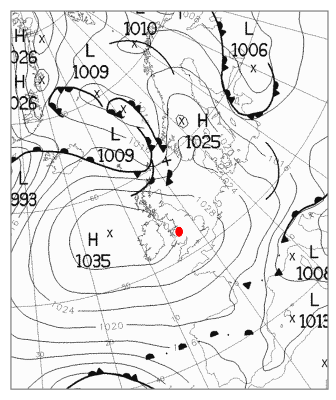


Fig.2. Analysis at 00:00 UTC 5 March 2010

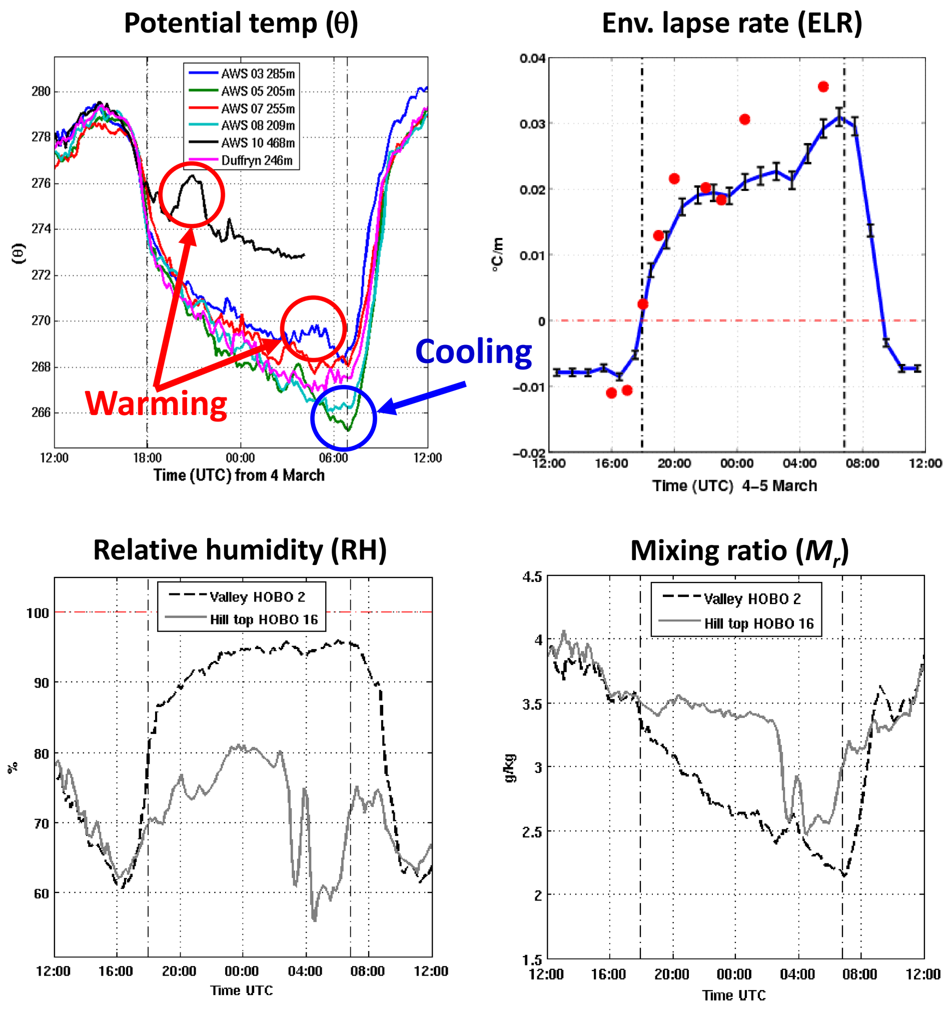


Fig.3. Time-series of θ, valley ELR, RH and M_r. Top right; valley ELR obtained using (1) radiosondes launched from Duffryn (red), (2) AWS and HOBO 2m temperature (blue).

Episode 1 – Wave activity

- Prior to Episode 1 there was sustained uninterrupted growth of the CAP; however, during Episode 1 the CAP is disturbed, highlighted by a change in behaviour of the ELR (**Fig.3**). Drainage flows also appear disturbed after Episode 1 (**Fig 4**).
- Episode 1 is characterised by between 6 and 8 intermittent increases and decreases in the LIDAR vertical velocity profile (referring to the LIDAR measurements, **centre figure**) that occur in the region at and above the hill tops near Duffryn (200 to 400m AGL).
- At ~22:30 a wave-like feature is seen at the top of the LIDAR profile and at ~23:00 UTC, a period of sustained downward vertical velocities are seen that extends throughout the LIDAR profile depth.
- Results of radiosonde ascent speed (**Fig 4**) suggest evidence of gravity wave activity.
- Bulk Richardson results (Ri_B **Fig 5**) suggest the region between hill tops and the Burfield valley are in transition between laminar and turbulent flow, despite ambient winds being relatively light (Springhill, **Fig 5**). Springhill to Duffryn (50m) is more stable (not shown).

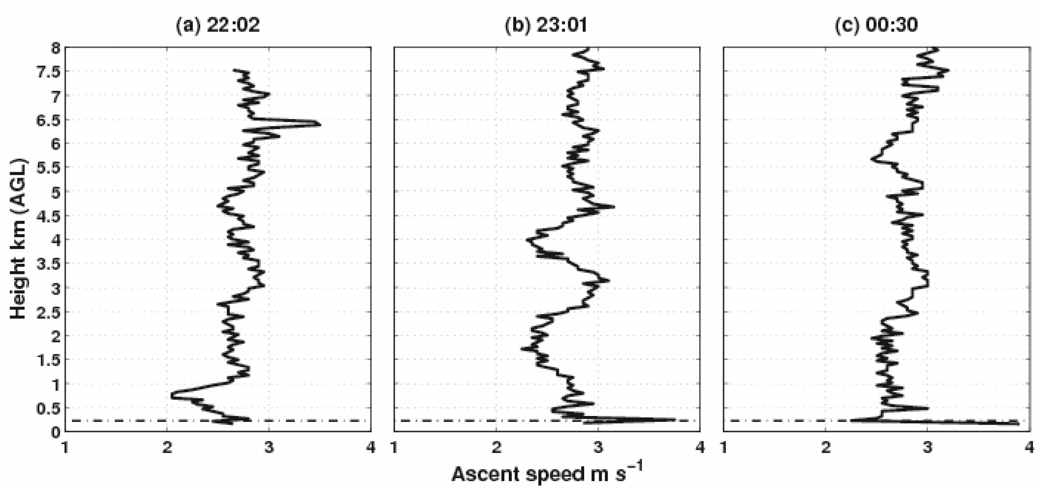


Fig.4. Radiosonde ascent speed profiles launched from the valley floor site Duffryn.

Episode 3 – NLLJ and CAP break up

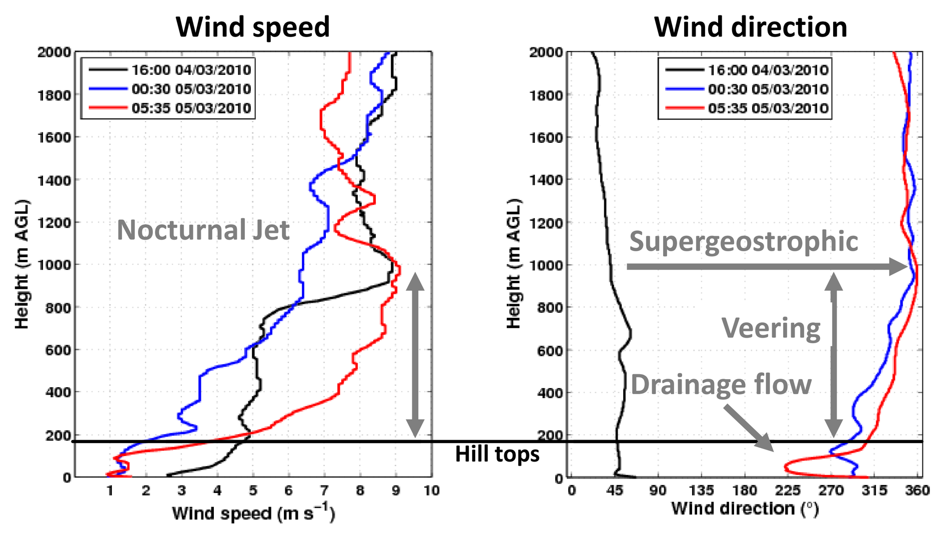
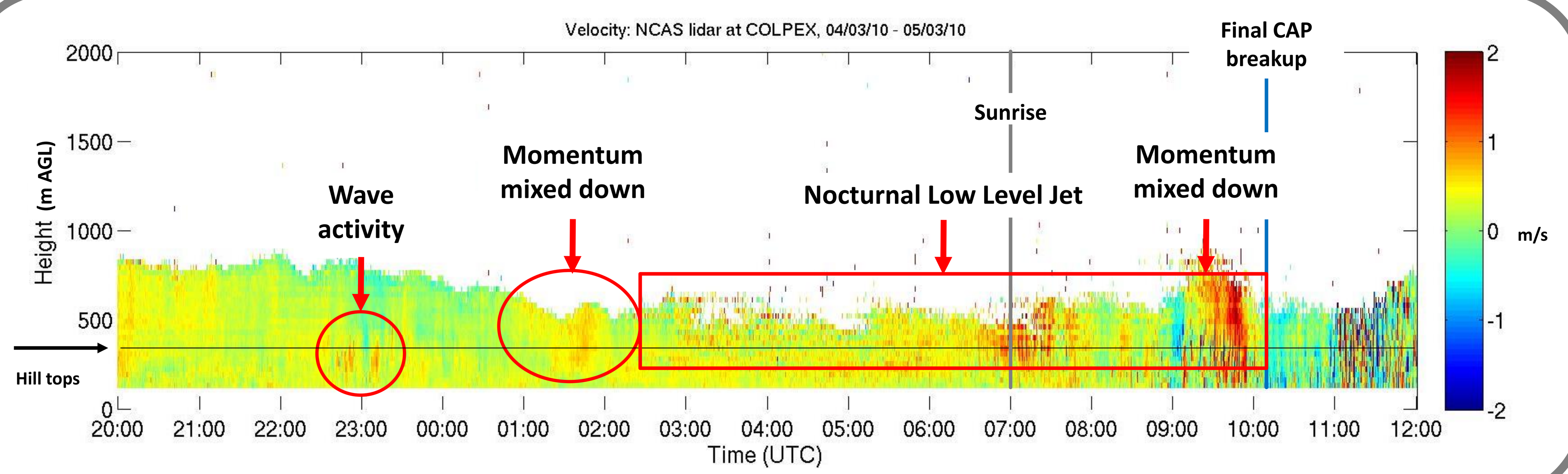


Fig.6. Radiosonde profiles launched from valley floor site Duffryn, showing wind speed and direction with height above ground level.

- During Episode 3 the LIDAR vertical velocities are distinctly different compared to any time previous, appearing characteristically more turbulent. This is further emphasised by the Ri_B profiles, which show the region between Burfield and Springhill to be persistently less stable than previous.
- Radiosonde profiles show the formation of a nocturnal jet during the night (**Fig 6;** 05:35 profile).
- Associated with this jet is a strong wind speed gradient and a veering of the wind direction with height ~1000 m AGL.
- CAP breakup occurs some 3hrs after sunrise between 10:00 and 10:30 UTC. Just prior to CAP breakup a region of increased vertical velocities descend with time (similarities to Episode 2).



Left, NCAS LIDAR measurements of vertical velocity, taken at Duffryn.

Episode 1 = 22:00 to 00:00
Episode 2 = 01:00 to 02:00
Episode 3 = 02:30 to 10:00

Episode 2 – Erosion of residual layer

- Episode 2 is characterised by a region of increased vertical velocities, that descend with time down to hill top regions (**centre figure**).
- The region of increased vertical velocities is first seen in the LIDAR around 01:00 UTC at ~800m AGL. By ~01:50 it descends below the surrounding hill tops and extends throughout the profile depth.
- Over the same time period the ambient wind at Springhill increases sharply over a 1 h period, accelerating from around 2 m/s to around 4m/s (**Fig 5**).
- After Episode 2 ambient winds remain higher than previous at around 4 m/s, with fluctuations between 3 and 5 m/s.
- The region between Springhill and Burfield is also changing from a stable laminar regime to a more laminar/turbulent regime (**Fig 5**).

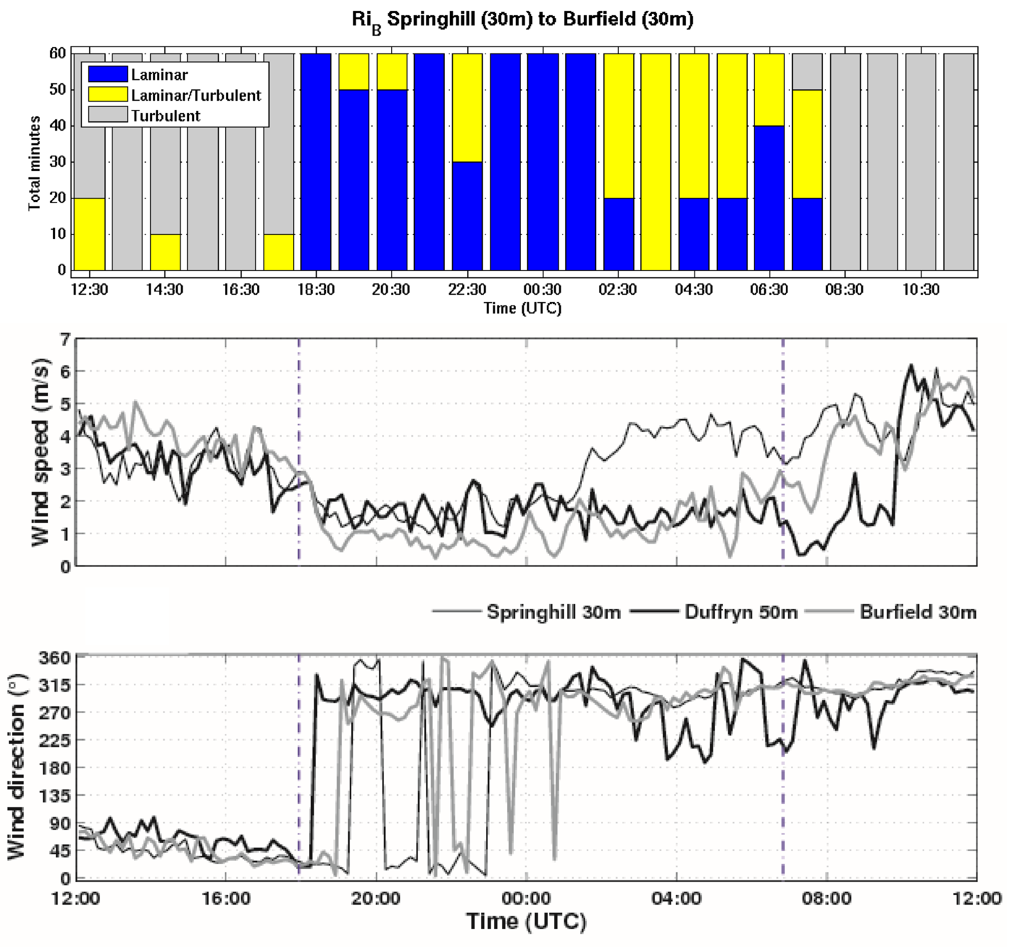


Fig.5. Top, bulk Richardson number (Ri_B) representing region between the hill top (Springhill, 30m AGL) and Burfield valley (Burfield 30m AGL).
Bottom. Time-series of wind speed and direction for three mast sites.

Discussion and conclusions

- A case study using a unique set of field investigations from COLPEX (***Price et al.*, 2010**), highlights a number of meteorological phenomena that occur during CAP evolution in hilly terrain.
- During the night three episodes highlight the phenomena, which are defined using LIDAR measurements of vertical velocity.
- Neither phenomena are significant enough to break up the CAP, but do affect its evolution.

Episode 1 – Radiosonde ascent rates suggest the presence of gravity wave activity in the atmosphere at 23:00 UTC. According to ***Lalas et al,* (1980)** this is one of one of the best methods to identifying gravity wave activity in the troposphere. In addition, according to Ri_B results, upper regions of the valley are in transition from laminar to laminar/turbulent flow, these conditions are ideal for HK instability and waves to form. Radiosonde profiles show a characteristic residual layer during this period.

Episode 2 and Episode 3 – Episode 2 is defined by a region of increased vertical velocities that descend with time and an increase in ambient winds. A pre-dawn radiosonde profile (05:35 UTC) shows the formation of a jet. This jet shares many of the characteristics of a Nocturnal Low Level Jet, as outlined by ***Thorpe and Guymer* (1977)**.

A summary of the night is given by **Fig 8**. The wave activity in Episode 1 may be attributed to either gravity waves or HK instability and occurs within a near neutral, residual layer. This residual layer is eroded during Episode 2 as momentum is mixed down from the developing NLLJ. The NLLJ gradually strengthens and maintains higher winds in hill top regions, but not strong enough to cause CAP break up. CAP break up finally occurs ~3 h after sunrise as momentum is mixed down from the decaying NLLJ.

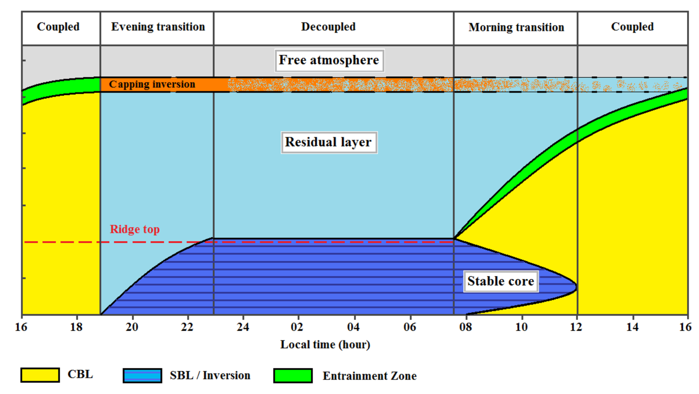


Fig.7. Typical textbook example of CAP and nocturnal boundary-layer evolution, adapted from Whiteman (2000).

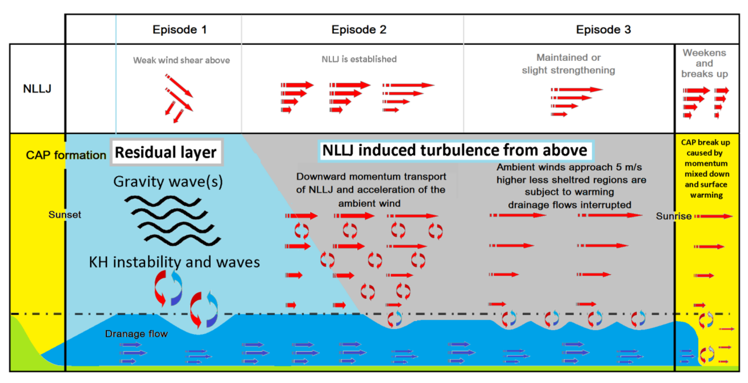


Fig.8. Generalised depiction of CAP evolution and associated phenomena during IOP 16 of COLPEX.

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