MODULE DESCRIPTION

17. Hurricane Boundary Layer Entrainment Flux Module

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Primary IFEX Goal: 3 - Improve understanding of the physical processes important in intensity change for a TC at all stages of its lifecycle

Motivation and Background: Tropical cyclones interact with the ocean through the boundary layer, obtaining heat and moisture as the enriched fuel, and transferring momentum to the ocean in the form of currents and waves. An improved knowledge of mechanisms underlying air-sea exchange across the boundary layer is essential for interpreting physical, dynamical and thermodynamical processes, and hence for the development of models with realistic prognostic capabilities forecasting or simulating tropical cyclones. Unless model parameterizations of surface fluxes, vertical mixing and entrainment processes are complete and well founded, the models will have limited predictive capability under hurricane intensity change.

The equivalent potential temperature (θ_e) of the eyewall column has been directly related to the minimum sea-level pressure or intensity that a tropical cyclone achieves (Riehl and Malkus 1960, Emanuel 1986, Betts and Simpson 1987). The source of the air for the eyewall updraft is primarily the inflow layer that has its lower boundary at the sea surface. It is well established that the increase of θ_e is chiefly due to the flux of sensible and especially latent heat at the air-sea interface. However, the flux at the sea surface is but one part of the energy budget that determines the θ_e of the inflow, and ultimately the eyewall column. The fluxes through the top of the inflow layer, a result of convective scale motions or entrainment, can remove as much energy as was gained through the sea surface. In the right environmental conditions convective-scale downdrafts, merging at the surface to form a cooler, drier outflow in the subcloud layer, can reduce θ_e of the inflow layer and have a negative impact on TC intensity (Powell 1990b).

In contradistinction to this scenario there is evidence for situations, especially in the annulus adjacent to the eyewall, where the θ_e in the layer above the inflow can be warmer than that found in the inflow (Barnes 2008). This annulus is where surface wind speeds are increasing rapidly and where the stratiform rain and weakly subsiding air found in this region (Houze and Marks 1984) may serve to inhibit energy loss through the deeper troposphere by suppression of convective clouds. Radial-height cross-sections of θ_e from observations (e.g., Hawkins and Imbembo 1976, Jorgensen 1984, Wroe and Barnes 2003) and from numerical simulations (e.g., Rotunno and Emanuel 1987) reveal that θ_e increases substantially in this annulus adjacent to the eyewall. Entrainment of this warmer θ_e can result in an additional energy source to the inflow (Barnes and Powell 1995, Wroe and Barnes 2003). The overarching point is that the vertical profile of the total enthalpy flux divergence is what is required for the determination of the θ_e budget for the inflow, and the θ_e of the eyewall column.

Losses or gains through the top of the inflow have been argued to be an important but poorly measured component of the energy budget (Barnes and Powell 1995, Wroe and Barnes 2003). Recent flux measurements demonstrate that there is a downward sensible heat flux contributing to the energy content of the inflow (Zhang et al. 2008, 2009). Accurate determination of the fluxes at the top of the inflow layer, coupled with the change in the energy content within the inflow layer estimated with the GPS sondes, would allow us to determine the surface fluxes as a residual of the energy budget. The experiment is designed to estimate these fluxes directly by utilizing the GPS sonde observations at 10 m, and the AXBT data. To date the challenging conditions found within a TC has prevented the community from accurately determining the surface fluxes so vital to hurricane thermodynamics. Accurate determination of the changes in the energy content of the inflow and of the losses or gains at the top of the inflow allows us to circumvent the problem of measuring the surface fluxes directly.

Objectives

- Estimate the energy content of the inflow to the eyewall;
- Determine the sensible and latent fluxes through the top of the hurricane boundary layer;
- Determine the air-sea fluxes both as a residual to an energy budget and via the bulk aerodynamic formulae;
- Investigate the effect of turbulent transport processes near the top of the inflow layer on the hurricane intensity change.

Module overview: This is a multi-option, single-aircraft module that is designed to directly measure momentum and enthalpy fluxes near the top of the inflow layer, as well as the energy of the inflow layer. This module can be included or linked with any of the following missions: Genesis experiment, or NHC-EMC-HRD Three-dimensional Doppler Winds Experiment missions, or Arc cloud experiment, or TC Landfall and Inland Decay Experiment, or UAS Experiment. A combination of data sources from GPS sondes, AXBTs, high frequency turbulence sensors and Doppler radar on NOAA-42RF are applied to determine the quantities listed in the above objectives. Turbulence sensors need to be calibrated at the start of the field season as described in the turbulence calibration module. The stepped-descent module and the box module are also described below.

Turbulence Calibration Module (2-3 hours)

The calibration module only needs be executed on separate flights at beginning of the field season. The following maneuvers are requested for turbulence sensors calibration:

1). Dynamic Yaw--2 sets:

First set, vary sideslip angle (beta) by +/- 4 degrees. This maneuver requires 5 full sinusoids, with one consisting of left 4 degrees, back through center, right 4 degrees, back to center--one sinusoid. Second set, set angle variation, and perform faster roughly +/- 2.5 degree variation with 25 sec period.

2). Acceleration/Decceleration (AC/DC) run--1 set: Start at normal flight speed, slow to minimum sustainable flight speed, increase to maximum flight speed, slow minimum flight speed, return to normal speed. Try to maintain constant altitude (vary angle of attack).

3). Wind Circles: Two 360° standard rate turns: first clockwise, then counter-clockwise. We need 360° of data to be in a coordinated turn, so after the pilot enters the turn and it is coordinated, only then 'start the clock'.

4). Wind box: Straight and level box, 2 min on each side, standard rate 90° turn on the corners. The box consists of 4 two-minute legs, with 90 degree standard rate turns after the completion of each leg. The box should be set up to fly one leg into, the next cross, the third out of, and the fourth cross wind direction. Indicated airspeed should be 210-220 kt.

5). Pitch (angle of attack) maneuvers--2 sets of 5: Five sinusoids with angle attack variations of +/-5 to 7 degrees. One complete sinusoid should have a period of 15 to 20 seconds. Upon completion of one set, fly straight and level roughly 2 minutes and begin second set.

All of these maneuvers should be aligned with the wind. The boxes should have legs parallel and perpendicular to the wind. The calibrations should be completed at the mean radar altitude where the measurements were conducted or roughly 1,000 ft (300 m). The maneuvers should be conducted in smooth air (as smooth as possible).

Stepped-descent module (40 minutes):
The module is flown between the eyewall and an outer rainband by NOAA-43, which is equipped with the turbulence sensors. It does not require any penetration of convective cells, the eyewall or convective rainbands. Preference is for a region that is either rain-free or stratiform rain only. For the simplest experiment 5 legs would be flown, each about 40 km or 5 minutes in duration (Fig. 17-1 and 17-2). The pattern would begin with a pass at 3 to 4 km altitude rapidly jettisoning 4 GPS sondes spaced approximately 10 km apart. During this pass 2-3 AXBT's would also be deployed to determine the SST. Airborne radiometers (SFMR) would also provide an estimate of surface wind speeds, and if there are enough scatterers in the volume the Doppler radar can be used to determine mesoscale wind and divergence. The first leg (at ~ 3 km altitude) can be done in conjunction with the standard figure-4 patterns.

The GPS sondes are used to estimate the boundary layer height to the eyewall and the mean conditions of the boundary layer and the lower portion of the layer above. Because it is difficult to determine the height of the inflow layer at real time, the height of the maximum wind speed is defined to be top of the boundary layer, which is around 500 – 1000 m. The inflow layer top is expected to be 1-2 km in height.

We can use the dropsonde data at the end of outbound radar leg to diagnose the boundary layer height. Then we turn back into the storm to do the stair-step. The aircraft would descend to 600 m above the inflow top (about 2400 m) and fly toward the eyewall along an approximate radial. This leg will cover 40 km or require about 5 minutes. The aircraft will then turn and descend ~500 m and fly out-bound for 5 minutes. Two more legs will be completed, each another 500 m below the previous pass. The last pass will be 700 to 800 m above the sea. If the aircrew deems it safe a final pass could be flown 400 to 500 m above the sea. All legs will finish with a turn upwind to keep the legs nearly vertically aligned and in the same portion of the TC. Time to complete the module is about 40 min including descents and turns.

These five passes and the GPS sondes will allow for a determination of the sensible and latent heat fluxes (total enthalpy flux) as a function of height and radial distance adjacent to the eyewall or a convective rainband from the top of the inflow layer to 500 m altitude. The combination of the vertical profiles of equivalent potential temperature (θ_e) and the determination of the fluxes at the top of the inflow layer will allow an estimate of the air-sea fluxes as a residual and directly through the application of the bulk aerodynamic formulae applying AXBT, SFMR, and 10 m observations obtained from the GPS sondes. The scheme will allow us to infer the magnitude of the transfer coefficients necessary to achieve energy balance, provide insight to the role of dissipative heating, and determine the role of entrainment of warmer θ_e through the top of the inflow layer.

Box Module (20-25 minutes):
If we wish to estimate divergence and there are too few scatterers to obtain this estimate from the Doppler radar we would like to execute a box pattern (Fig. 17-3) near the top of the inflow layer (1 – 2 km); this may add about 20-25 minutes to the module. This additional stage is beneficial, but not essential to estimate the fluxes or to complete the energy budget. It allows us to avoid

constraining assumptions about the flow (we would have to assume no divergence due to the tangential wind component).

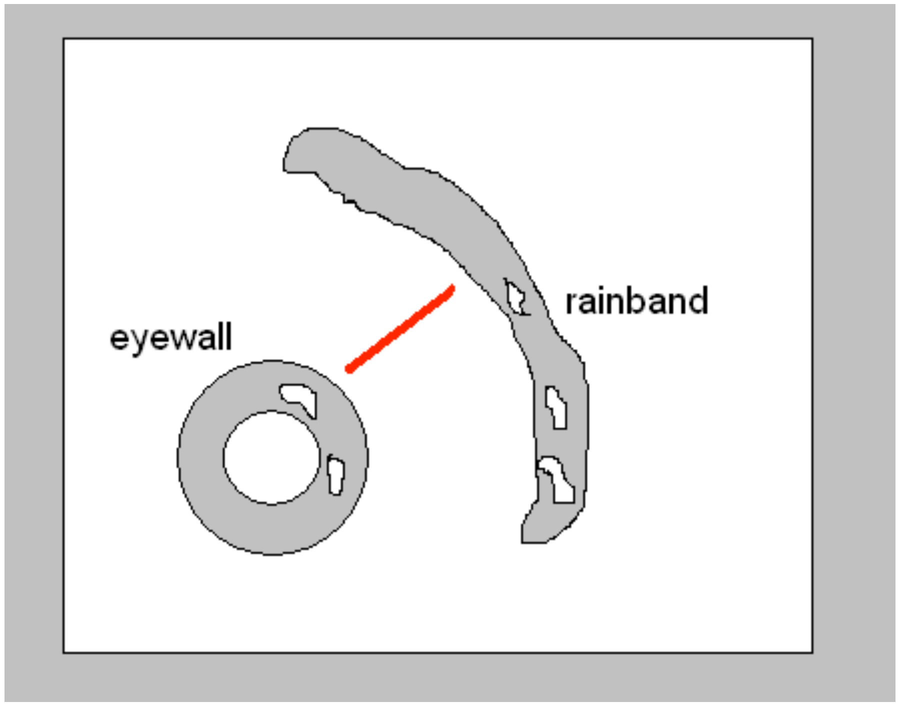

Figure. 17-1. Plan view of the preferred location for the stepped-descent module. Red line shows aircraft track.

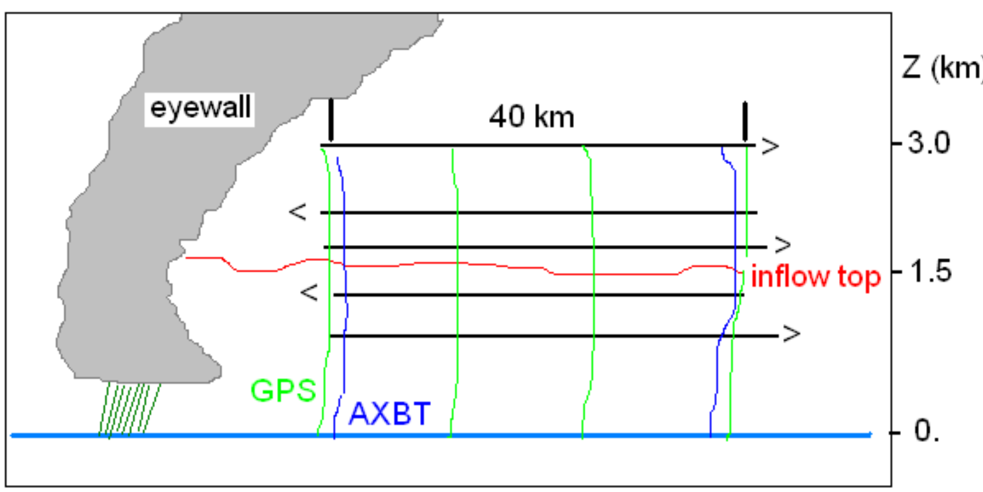

Figure17-2. Vertical cross-section of the stepped-descent module.

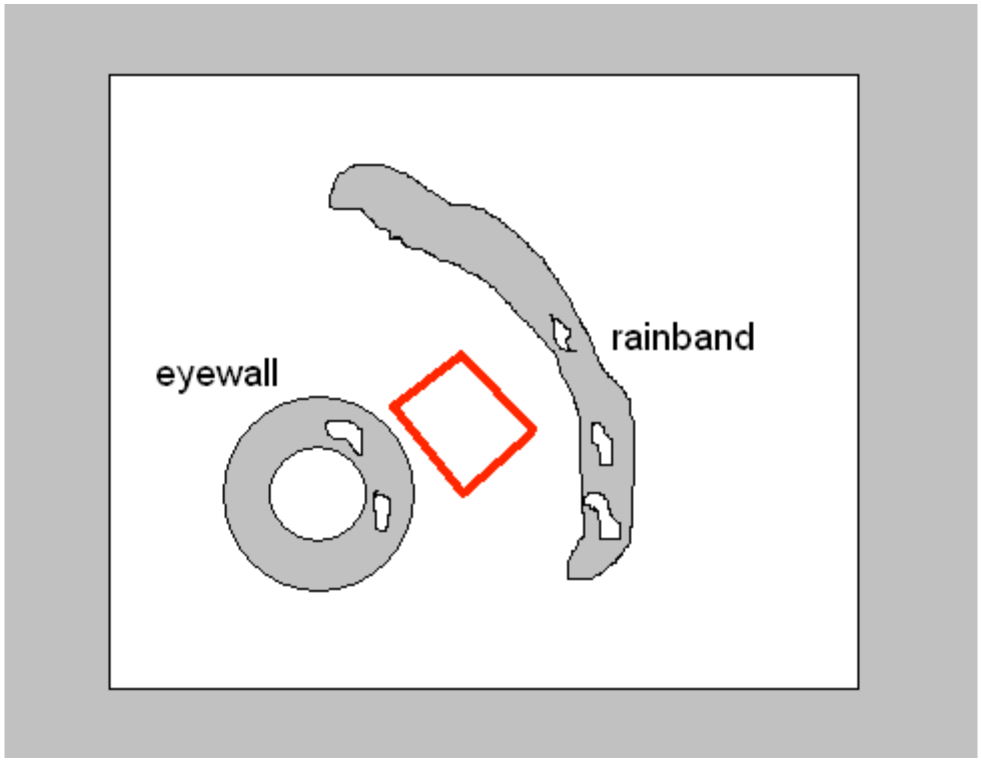

Figure17-3. Box module used to calculate divergence if no scatterers exist in the volume.