TROPICAL CONVECTIVE BOUNDARY LAYERS: A NEW APPROACH TO SCALING

R. Narasimha [roddam caos.iisc.ernet.in]
Engineering Mechanics Unit, Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore, India

ABSTRACT: The tropical atmosphere is characterized by strong convective systems and low winds. It has been well known for some time that an enhancement of the fluxes at low winds, over the values given by classical Monin-Obukhov theory, improves the simulation of the Indian monsoons substantially. Two atmospheric experiments, the MONTBLEX90 carried out in India, and BLX83 carried out in the United States, provide valuable observational data on convection at low winds. A recent analysis of these data suggests that classical theory is not valid close to the free convection limit. The data further suggest that it is useful to define a regime that may be called *weakly forced convection*, in which the heat flux is independent of wind speed and the drag varies linearly with wind speed. It is argued that these results may be understood by introducing a velocity scale determined by the heat flux in the atmosphere rather than by the wall stress as in classical theory. Applications of this argument have given encouraging results in cyclone track prediction in the Bay of Bengal and elsewhere in the tropical regions of the world.

1. INTRODUCTION

A large number of turbulent shear flows in nature as well as in technology are strongly affected by stratification. In the oceans and the atmosphere stratification arises from temperature and/or admixture (salinity or humidity) gradients. The most widely used approach for taking into account the effect of such stratification on a turbulent boundary layer is based on classical Monin-Obukhov (M-O) similarity theory. In the limit of highly unstable stratification the flow should tend towards natural or free convection.

Now it is well known that the tropical atmosphere is characterized by strong convective systems and generally low winds. Miller *et al.*[1] showed that simulations of tropical circulation, in particular the monsoons, were considerably improved if eddy fluxes at low winds were enhanced over the values given by classical models such as e.g. Monin-Obukhov theory. Various methods of doing this have been suggested by Hack *et al.*[2], Godfrey & Beljaars[3] , Beljaars[4], Stull[5] , etc.

2. THE ATMOSPHERIC DATA

A major field experiment carried out in India, called MONTBLEX90 (for the Monsoon Trough Boundary Layer Experiment, 1990) provides data that shed considerable light on low-wind convection. An account of the Experiment and the first conclusions from an analysis of the data are contained in a volume edited by Narasimha, Sikka and Prabhu[6]. A detailed description of the tower instrumentation, the associated data acquisition system and the various quality checks adopted to ensure the reliability of acquired data is available in Rudrakumar *et al.*[7]. The sensors providing the data were mounted on a 30 m high guyed uniform triangular lattice structure, with booms fitted at 6 levels (1, 2, 4, 8, 15, 30 m above the surface). Horizontal arms were attached to these booms at a distance of about 1.3 m from the body of the tower. The booms could be partially rotated about the vertical and horizontal axes to facilitate orientation of the sensors towards the general direction of the prevailing wind and to ensure horizontality of the instrument posts. The sensors consisted of a sonic anemometer placed at a height of 4m above the surface, cup anemometers at six heights (1, 2, 4, 8, 15 and 30 m), and platinum wire resistance thermometers at four heights (1, 8, 15 and 30 m). The sonic anemometer provides wind and virtual temperature fluctuations to a frequency response of 8Hz at hourly intervals during intensive observation periods[8], otherwise at three-hourly intervals continuously for 10 min (15 min) from 15 June to 7 July (6-14 June and 8 July-20 August). The data used in the present analysis were acquired at Jodhpur ($26^0 18$ N, $73^0 04$ E) over a period extending from 9 June to 20 August. The tower was installed in a farm field, which at the time of the observations reported here was covered with small pebbles or patches of grass. A detailed description of the tower site, including estimates of roughness length and description of prevailing weather, is given by Rao[9]. The total number of data sets acquired during the period was 676.

Important supplementary data come from the boundary layer field experiment BLX83 carried out between 26 May and 18 June 1983 near Chickasha, Oklahoma ($35^0 02$ N, $97^0 51$ N) using the NCAR aircraft ueenair[5]. The terrain was generally flat, with average roughness length of 5 cm. As 24 out of the 28 data points are characterized by wind speeds less than 10 ms ^{1} under highly unstable conditions, BLX83 provides some valuable data on the low-wind convective regime. The mixed layer depth (or equivalently, the height of the capping inversion) was defined as the height at which there is a 50-50 mixture of the free atmosphere and mixed layer air, and was obtained from ground-based lidar during scans along the aircraft track. Eddy correlation measurements of heat, moisture and momentum fluxes were made during the near-surface legs of the aircraft track. Skin parameters were obtained by a downward-looking radiometer and by an NCAR portable Automated Mesonet Station.

3. RESULTS

Based on M-O theory (assuming it is valid), it is possible to estimate both momentum and sensible heat flux using measured velocity and temperature profiles and appropriate stability functions such as those proposed e.g. by Businger *et al.*[10]. Rao *et al.*[11] found that while the high-wind, low-instability data agree well with M-O theory, the low-wind high-instability data (flux Richardson number Rf 1.0) show substantial departures, sometimes amounting to as much as 30% in the friction velocity u (and about 70% in the drag coefficient).

Rao *et al.*[12] found instead that, if the cross-wind was sufficiently low (5 ms ^{1}), the sensible heat flux was directly proportional to $\Delta T^{4/3}$, where ΔT is a characteristic temperature differential (e.g. between 1 and 30 m above ground). This suggests that the heat flux obeys the free convection law, even in the presence of some cross wind.

Raju and Narasimha[13] examined available engineering heat transfer data acquired in the laboratory, and came to the same conclusion. They further showed that the limiting cross-wind velocity above which the free-convection law did not apply was characterized by a critical value of the densimetric Froude number.

The drag was found to increase linearly with wind speed at low winds. Such linearity is usually associated with Stokes flow, which of course is not relevant to the atmospheric conditions under consideration.

At the 9th Asian Congress in Isfahan, a preliminary account of a new analysis was presented, proposing that the above results may be best understood by introducing a new velocity scale determined by the heat flux, abandoning the friction velocity that forms the basis of classical M-O theory[14]. Something like this cannot in fact be avoided, because in pure free convection the spatially averaged wall stress will vanish (for reasons of symmetry), although the velocity fluctuations do not in turbulent convective flow. Rao & Narasimha[15] have recently made a detailed analysis with several possible velocity scales, including one proposed by Grachev[16]. Their overall conclusion is that it is useful to define a flow regime they call weakly forced convection, in which a low cross-wind velocity acts as a *linear* perturbation on free convection. This proposal provides plausible arguments for the observed linear dependence of drag on wind speed, and the observed lack of dependence of the sensible heat flux on wind speed.

4. APPLICATION

These ideas have recently been incorporated into a new atmospheric general circulation model (called *Varsha*), written by Venkatesh *et al.*[17] at the National Aerospace Laboratories. This code has shown very encouraging results in cyclone track prediction; e .g. the Orissa super-cyclone of 1999 was tracked by the code with an error of less than 200 km, integrating for 5 days from a specified initial condition[17]. Other cyclone/hurricane tracks have also been predicted well by the code.

5. CONCLUSION

We conclude that much of the tropics is often in a weakly forced convection regime, and heat-flux scaling promises to provide a rational approach to understanding the behaviour of eddy fluxes in the regime. Much further work needs to be done, however, to confirm the more general usefulness of the proposed heat-flux velocity scale in describing the fluctuating motion.

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