Blending field studies, wind tunnel models and theory to understand and predict stable flows on forested hills

John Finnigan and Dale Hughes
CSIRO Marine and Atmospheric Research, Australia

In this talk I want to take you through a narrative to show how the three ways of accessing knowledge listed in the title reinforce each other to increase our understanding of a complex atmospheric flow.

1. Problems of measuring turbulent exchange of carbon dioxide over forests at night first became too large to ignore when anomalously high values of NEE were reported from LBA towers in the Amazon. Soon, experiments in other forests were suggesting strongly that the problem was lateral advection of CO2 by stable gravity currents so the tower flux instruments missed most respiration. What was not understood was why the effect was so severe and why it occurred at tower sites that were apparently flat and homogeneous.
2. Serendipitously, it became possible to perform a small wind tunnel experiment with a model canopy over a hill with a heated surface. The model was mounted upside down, reversing gravity and generating a stable flow. To our surprise, it was clear that turbulence within the canopy collapsed even though the flow above was fully turbulent, although stable. Above the canopy the gradient Richardson Number Ri~O[0.1] while within the canopy Ri~O[10.0]. Within the canopy, the flow was downslope on both sides of the hill whilst in the boundary layer above it was over the hill as in neutral conditions.
3. This prompted a theoretical investigation where it became clear that the different mechanisms of heat and momentum transfer across canopy element surfaces were responsible for this effect. Heat transfer across the element boundary layers relies ultimately on molecular diffusion whereas momentum transfer is effected mainly by pressure. As a result, air temperatures in the canopy approach canopy surface values much more slowly than the velocity tends to the surface value of zero. It follows that continuity of velocity, and temperature and momentum flux and heat flux across the canopy top ensures that as the canopy cools, moderately stable Ri values above the canopy must be accompanied by very stable values within the canopy. This causes turbulence collapse within the canopy and in real forests after sunset, accelerates radiative cooling.
4. Furthermore, examining the momentum balance for a stable canopy showed that, once turbulence has collapsed, the force balance within the canopy is between the hydrodynamic pressure gradient (generated as wind flowed over the hill), the hydrostatic pressure gradient (directed always downslope and generated by the density difference between cool canopy air and the ambient air at the same geopotential height) and the aerodynamic drag (which always opposes the net flow). When the hydrostatic pressure gradient exceeds the hydrodynamic, the air flows downhill. Unexpectedly, the momentum balance showed that on low hills, the onset of downslope flow was controlled by a Froude Number, Fr that depends on slope length but not on slope steepness!
5. A detailed field experiment that used a clever experimental design to construct a direct mass balance confirmed that at a site where CO2 advection was negligible by day, it was large by night and that the within-canopy velocity profile at night showed the characteristic wall jet form of a gravity current.
6. Results from 4 and 5 prompted the construction of a properly scaled wind tunnel model with a properly simulated boundary layer. Both canopy elements and floor could be heated independently and, as before, the model was mounted upside down to reverse gravity. Also as before this model generated some surprises:

    a. First, the within-canopy gravity current penetrated onto flat ground in front of the hill for a considerable distance (~3 hill widths). This current was driven by the thermal wind term, in effect, the net slope of the gravity current surface. This slope was generated in turn because the downslope gravity flow on the upwind side of the hill was opposed by advection, resulting in a deepening of the stable layer in front of the hill. This was a completely unexpected phenomenon.
    b. Second, increasing the effect of stability by decreasing the effective Fr caused the gravity current to appear first in a thin layer near the ground, deepening to fill the canopy as Fr fell.
    c. Third and also completely unexpectedly, although shear stress collapsed in the stable canopy, there was a good deal of turbulent motion. This must be inactive irrotational turbulence driven by the pressure field of the active turbulence above the canopy.
7. We are now at the stage of theoretical analysis of these results, attempting to quantify:
    a. what controls upwind penetration of the gravity current,
    b. why we observe a sharp peak in heat flux where the gravity current terminates
    c. what the inactive turbulence in the canopy means for nighttime lateral diffusion
    d. How the onset of downslope flow depends on Fr and what this means for the timescale of onset of downslope flow after sunset.
8. To do this we are enlisting different types of theoretical approach ranging from simple closure models to rapid distortion theory. We are also planning a large scale field experiment as well as an extension of the Wind Tunnel experiment including repeating it with a 3D hill model.

Summary

This tale of discovery illustrates the powerful role that can be played by abstracting complex flows from the field and reproducing their essential features in the wind tunnel. To model these flows physically we are forced to consider carefully which physical features are essential and which can be traded off to allow us to reproduce the flow in the tunnel. In turn we are rewarded by insights from the controlled environment that natural variability in the real environment together with the much lower measurement density that is possible there usually obscure. The real message though is that using field measurements, laboratory simulations and theoretical analysis in a synergistic way vastly increases the value of each approach. .