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Contents

The Rise and Fall of Monin-Obukhov theory

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1. Introduction

The Monin and Obukhov similarity theory (Monin and Obukhov, 1954) and the Deardorff (1970) convective scaling theory have together provided conceptual and practical foundations for almost all modeling of the unstable atmospheric boundary layer for the past four decades. Neither theory was scienctically conclusive but any doubts were swept aside by the results of two great field experiments: the 1967 ‘Kansas’ experiment (Haugen *et al*., 1971) and the 1973 ‘Minnesota’ experiment (Kaimal *et al*., 1976). The experimenters themselves were so impressed by the support they provided for the Monin-Obukhov similarity theory that Kaimal (1973) was able to claim that “*with proper nondimensionalization, all spectra and cospectra in the surface layer can be reduced to a set of universal curves*”. Most scientists have agreed with him since that time.

The problem is that Kaimal was overly optimistic, confusing good progress in bringing empirical order to wind and scalar profiles, spectra and other turbulence statistics, with a final solution to that problem. The purpose of this article is to point out some of the problems with Monin-Obukhov theory and to provide a brief introduction to an alternative approach for convective boundary layers (CBLs).

2. The Monin-Obukhov similarity model

Most text books present the Monin-Obukhov similarity theory as a dimensional argument based on the set of governing parameters, z, u_*, and gq/T, where symbols have their usual meanings and q is heat flux at the round, but it is more than that. The significance of the Obukhov length L had already been deduced by Obukhov in 1943, though not published until after the world war, in 1946 (Obukhov, 1971). But Obukhov’s work was based directly on the mixing-length model of Prandtl, so its conclusions were linked to the notions of gradient diffusion and a mixing length that varied with height. Monin and Obukhov tried to place this theory on a more general foundation, and to point out its applications.

Their method of similarity analysis was based on finding the conditions for similarity of the differential equations that express local relationships at any point in the fluid, plus u_* and q, which described the momentum and heat flux boundary conditions at the ground. Monin and Obukhov (1954) then introduced the concept of an atmospheric surface layer, defined as the layer where momentum and heat fluxes are sufficiently constant with height that the surface fluxes can be taken equal to the local fluxes at height z. By this device u_* and q could be considered local variables within the surface layer. Monin and Obukhov also introduced height z as a parameter, explaining that "*it is natural to assume that changes in mean velocity and temperature with height can be expressed by coordinate z*". This is a different kind of assumption since z expresses the difference between the local observation height and somewhere else (the ground), so z is not a local parameter. Monin and Obukhov (1954) had introduced z earlier in their paper, in a discussion of a neutral wind profile whose properties were self-similar with height. Though we might agree that z should be a parameter, its addition fits uncomfortably with the 'local' arguments used to choose the other parameters.

This difficulty with z comes to a head when Monin and Obukhov consider the asymptotic approach to windless (free) convection. Then u_* disappears from the list of parame-ters, and their methods identify only two parameters: g/T and q. They write "*We cannot form a length scale from the parameters q and g/T; therefore, the regime of purely thermal turbulence is "self-patterning"*". What they mean is that, in free convection, the turbulence organizes itself into patterns of motion (coherent structures perhaps) whose size depends on height above ground. One must admire their insight in coming to this conclusion because, until then, coherent structures had received very little attention in fluid dynamics. Had they gone further in this line of thinking they might have recognized that the self-similarity of neutral wind profiles is also an expression of the self-patterning nature of turbulence. Self-patterning occurs in real flows, and in well-formulated computer simulations, and so is an integral rather than a local property of the flow. If we admit z as a parameter, we may ask why other integral properties should not also be considered? Indeed, we might argue that only integral properties should be considered, since these are the ones that can be de-duced experimentally from observations of real flows. This brings into question the whole selection process used by Monin and Obukhov, including whether purely local properties, such as q and u_*, should be used at all.

3. The Deardorff similarity model

Early on it was recognized that Monin-Obukhov similarity does not apply to horizontal velocity spectra, since the length scale of their peaks is independent of z (*e.g.*, Bush and Panofsky, 1968). Kaimal (1978) argued that this could be explained by the effects of large eddies that obey mixed-layer scaling. A scaling theory for the large eddies was provided by Deardorff (1970), who was one of the first to perform large-eddy simulations of convection in the CBL. From his computations Deardorff found that the large coherent structures in a CBL can be scaled using the height of the capping inversion, z_i and the convective velocity scale $w_* = (z_i q\ g / T)^{1/3}$. The latter scale was compatible with Monin-Obukhov theory since the vertical velocity scale for the local free convection layer could be matched with the Deardorff scale simply by letting $z \rightarrow z_i$. This gave a consistent similarity model for the lower CBL, up to the bottom of the entrainment layer (Kaimal, 1976; Panofsky, 1977). The original Monin-Obukhov formulation still applied to vertical motions.

We cannot criticize Deardorff for neglecting integral properties of the CBL, since his results are based on results from integrations of the flow equations, but we can have concerns about the boundary conditions used in those integrations. Deardorff (1972) maintained his flow against surface drag by adjusting the horizontal pressure gradient at each time step. This adds energy to the mean flow throughout the CBL and so maintains the shear stress near the ground, but it contributes nothing to the energy of the large eddies which must, therefore, be driven by buoyancy alone. In real CBLs the flow is maintained principally by momentum entrained through the capping inversion (Stevens, 2002). If the entrainment velocity is w_e [$=dz_i/dt$-s, where s the subsidence velocity] then the momentum flux into the CBL is $w_e u_g$ (neglecting wind turning), where u_g is the geostrophic wind above the CBL. This momentum flux is associated with a flux of kinetic energy down into the boundary layer, $w_e u_g^2/2$, of which $w_e u_m^2/2$ goes to maintain the mean flow, u_m, while the remainder, $w_e(u_g^2-u_m^2)/2$, goes to maintain the large-scale turbulence. That is to say, the energy of the large eddies derives from entrained kinetic energy as well as buoyant production within the CBL, while the Deardorff model has only buoyancy.

4. Tests of the Monin-Obukhov / Deardorff similarity model

Despite these theoretical concerns about MO/D theory, the real test is whether the theory can reduce experimental data to universal constants or relationships? In this the MO/D scheme can work reasonably well, if not perfectly. For example, wind and temperature profiles from a range of careful experiments show generally similar shapes when scaled according to the Monin-Oukhov scheme, though the dimensionless gradients spread over a range of about 30% for given $-z/L$ (Högström, 1996). Statistics like the scaled tempera-ture variance, σ_T/T_*, from different experiments also display generally similar relationships with $-z/L$ in unstable conditions, but scatter about the trend is typically large at about 50% (Kader and Yaglom, 1990, Fig. 4), and the means differ between experiments. Other statis-tics and functions behave similarly failed to collapse exactly onto well-defined universal values and functions.

These limitations are well known, and most researchers simply accept that the scatter reflects the differences between real conditions encountered during field experiments and the ideal conditions of perfect atmospheric steadiness and land homogeneity required by the theory. Perhaps so, but this argument would be more convincing if there were studies to show how unsteadiness and inhomogeneities affect compliance. Instead, these arguments often simply provide an excuse for bad performance whenever results are not as expected.

More demanding tests have been used. For example, one can look at higher-order moments (*e.g.*, Högström, 1990), or for systematic relationships between the residuals from a MO/D analysis and other parameters (Johansson *et al.*, 2002). The results are difficult to interpret, but generally weaken our confidence in the MO/D theory. Other results suggest that some of the universal curves of MO/D theory are not universal at all. Thus Smedman *et al.* (2007), in near-neutral conditions over land and sea, observed temperature spectra that display two peaks: one at a wavelength normally associated with the z_i-scale eddies that fill the CBL, and the other where one would expect to see small-scale shear processes. Heat flux cospectra with two peaks present a similar problem. Most damaging of all are the results of McNaughton *et al*. (2007) for very unstable conditions: these show that the position of the peak of the temperature spectrum depends on the mixed length scale $z_i^{1/2}z_s^{1/2}$, which is not a possibility with the MO/D model.

The Deardorff scaling theory may also be tested. That z_i height scale seems to be correct, but there has been no direct experimental tests to show that the velocity scale of these eddies is w_*. One test is that the energy of the large eddies ($\propto w_*^2$) should be constant when scaled with $z_i gq/T$. Writing the former as $z_i\varepsilon_o$, where ε_o is the dissipation rate in the bulk of the CBL, this test is that $gq/T\varepsilon_o$ should be constant. Results from the literature show $gq/T\varepsilon_o$ to vary from 0.4 to more than 1.7 (see summary in Laubach and McNaughton, 2009).

5. A new approach to similarity modeling

There seems to be no alternative to similarity modeling. Fortunately, atmospheric flows, with their very high Reynolds and Rayleigh numbers, seem particularly well suited to this approach. The key is to find the right set of basic variables and the right way to use them. This involves choosing the right conceptual model.

A new conceptual model has been used by Laubach and McNaughton (2009, and references therein). This model views the CBL as a complex dynamical system in which the turbulence at all scales forms a single, interconnected system. The basic parameter set is not very different to the MO/D parameter set. Where the MO/D model has $\{u_*, z, gq/T, z_i\}$, with $L=-ku_*^3/gq$ as an important derived parameter, the new model has $\{u_\varepsilon, z, \varepsilon_o, z_i\}$, with as an important derived parameter. Here is related to the energy produced by the shearing action of the wind rather than to the momentum transfer, and the energy dissipation rate in the bulk CBL replaces the narrower buoyant production gq/T of the MO/D model.

With such a similar parameters set, one might expect the similarity relationships to be quite much the same, but this is not so. Unlike MO/D theory, where scaling is applied to the whole flow, the new model applies empirical scaling analysis separately to the different kinds and sizes of eddies. The most remarkable outcome is that eddies and heat plumes can have mixed length, energy and velocity scales. Mixed scales are the geometric mean of the scales that arise when different kinds of eddies interact. For example, the position of the peaks of temperature spectra in the surface friction layers occurs where $kz_i^{1/2}z_s^{1/2}$=4.5 and k is wavenumber. A variety of other mixed scales are found, with different mixed scales applying within the surface friction layer and above it.

The new scheme explains many of the anomalies of MO/D theory. However, it is not a local theory so the flow cannot be described in terms of experimental parameters measured at just one point. Remote sensing instruments, such as sodar, radar or lidar, will be needed to supplement the sonic anemometers etc. of a typical experiment. The first round of such experiments will be to verify the new model, and that will be a major job in itself.

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A Short Report on ChinaFLUX Training Course 2009 and Field Campaign of A3 Foresight Program “CarboEastAsia”

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Background

Terrestrial ecosystems in Asia cover large land area and they play a critical role in global carbon cycle. Therefore, knowledge of the carbon cycles in terrestrial ecosystems in Asia is essential to advance our understanding of global carbon and water budgets and prediction of impacts of climate change. Over the past decade, more than 100 flux sites have been set up in Asia for studying the mass and energy exchanges between ecosystem and the atmosphere, and several regional flux networks have been established in Asia. Many new flux sites have been set up in China in recent years, which greatly enhanced the intensity of flux research not only in China but also in Asia. As an important part of AsiaFlux, ChinaFLUX has taken the lead of flux observation and research in China and has developed close communication and cooperation with other regional flux networks.

ChinaFLUX has organized six domestic training courses since its establishment in 2002, aiming at training young scientists and technicians for the long-term flux observation and research, enhancing the capacity building, and promoting the communications among young scientists in China. Under the request of AsiaFlux Steering Committee, the 7th training course of ChinaFLUX (ChinaFLUX Training Course 2009) was open to all participants from Asia. During July 28~August 1, 2009, ChinaFLUX Training Course 2009 was jointly held with the Field Campaign 2009 of the A3 Foresight Program “CarboEastAsia” in Xining, China.

ChinaFLUX Training Course 2009

About 100 participants from six countries joined ChinaFLUX Training Course 2009. The introduction session (July 28, Morning) started with the welcoming addresses and congratulations conveyed by the celebrities from the host and sponsor organizations. As director of the host institute, Prof. Huai-Gang Zhang made a brief introduction to the Northwest Institute of Plateau

Figure 1. Group photo of ChinaFLUX Training Course 2009

Biology of CAS and sent a warm invitation to all participants to visit and collaborate with the Northwest Institute of Plateau Biology, CAS. The Director of the Bureau of International Cooperation of National Natural Science Foundation of China (NSFC), Prof. Qing Chang, gave a general introduction of the international cooperation program funded by NSFC and wished a fruitful success of the CarboEastAsia program through the 3-year close cooperation and communication among ChinaFLUX, JapanFlux and KoFlux, followed by the AsiaFLUX.

The lectures on ChinaFLUX Training Course 2009 covered various flux-related topics such as the basics of eddy flux measurements, flux data QC & QA, methodology for soil respiration, flux data-model fusion and remote sensing. The first morning (July 28) was started with the AsiaFlux visions and missions presented by the current AsiaFlux chair Prof. Joon Kim and ended with an integrated introduction to the basic micrometeorology for flux measurement by Prof. Jiemin Wang. The afternoon session focused on the theory and techniques of flux calculation, data quality control & auality assurance (QC & QA), flux gap-filling and flux partitioning, with lectures from ChinaFLUX, JapanFlux anf KoFLux. Soil respiration measurement is an important issue for ecosystem carbon budget estimation. Three keynote speeches were presented in the second morning (July 29) by Dr. Ming Xu, Dr. Naishen Liang and Dr. Dave Johnson that emphasized the critical considerations on soil respiration measurements. Three lectures conveyed the principles and applications of carbon and water vapor stable isotope flux measurement in the second afternoon, and some new developments in flux instrumentation and analyzer were also introduced.

One hot topic relating to flux research is the combination of remote sensing and ecosystem modeling with eddy fluxes. During the training course, Prof. Jingming Chen from Toronto University gave two keynote speeches, one systematically introduced the theory and instruments for measuring LAI and the other presented the method of mapping global GPP using remote sensing inputs. Prof. Weimin Ju's lecture gave the participants a guidance of using eddy flux data for ecosystem model validation and improvements.

Special session of CarboEastAsia

Special session of A3 Foresight Program "CarboEastAsia" was organized on the afternoon of July 30. CarboEastAsia is one of the Asia A3 Foresight Programs co-funded by National Natural Science Foundation of China (NSFC), Japan Society for the Promotion of

Figure 2. Opening Ceremony of ChinaFLUX Training Course 2009

Science (JSPS), and Korea Science and Engineering Foundation (KOSEF) in 2007, which has been implemented to support international collaboration among global change scientists from China, Japan and Korea. “CarboEastAsia” is aiming for the capacity building among ChinaFLUX, JapanFlux and KoFlux to cope with climate change protocols by synthesizing measurement, theory and modeling in quantifying and understanding of carbon fluxes and storages in East Asia. The CarboEastAsia special session was started with a general introduction of Haibei alpine meadow ecosystem station presented by Prof. Shiping Wang, followed by other 9 presentations by colleagues of ChinaFLUX, KoFlux and JapanFlux. Most lectures focused on the research questions of CarboEastAsia, covering topics about carbon, water vapor and nitrogen fluxes research progresses in grassland, forest, and paddy field in Asia. The participants had an extensive discussion about the issues brought during the training course.

Field Campaign 2009 of CarboEastAsia

On July 31, the Field Campaign 2009 of CarboEastAsia was held at Haibei alpine meadow ecosystem long-term ecological research station, which is a member site of ChinaFLUX and Chinese Ecosystem Research Network (CERN) and is about 150 km away from Xining city. About 80 participants joined this field campaign and visited the observation site of an alpine shrub-meadow and alpine meadow. Prof. Shiping Wang and Dr. Huajun Fang introduced the experimental fields for research on how alpine meadow communities respond to warming (OTC and FATE), clipping, and grazing and nitrogen deposition, through eddy flux observation and controlling experiments. On August 1, about 70 participants made a field trip to Qinghai Lake, which is the largest inland lake in China. The vasty alpine meadow and the golden pasture on Tibet Plateau impressed our participants very much.

ChinaFLUX Training Course 2009 provided an excellent communication platform for the young students and scientists in Asia who are interested in flux observation and research to strengthen their knowledge, and widen their visions. Finally, the organizing committee of the training course appreciates the financial support from sponsors in China, Japan and Korea including government agencies and private companies. The organizing committee also thanks all the valued lecturers for sharing their knowledge and experiences with all the flux communities in Asia. And lastly, we appreciate all the participants for their sincere support to the success of our training course.

Figure 3. Field Campaign 2009 of CarboEastAsia at Haibei alpine meadow station

An Afternote on ChinaFLUX Training Course 2009 and Field Campaign of A3 Foresight Program "CarboEastAsia"

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We were selected from AsiaFlux and ChinaFLUX Committees for attending ChinaFLUX Training Course 2009 during July 28 to 31, 2009 in the town of Xining, China. We are very excited and happy to be selected as training fellows, as there were only two from outsides China, Korea and Japan that were supported by the organizers. The objective of fellowship was 1) to provide an opportunity for the young students and scientists in Asia who were interested in flux measurements; 2) to consolidate their knowledge; and 3) to widen their vision of the flux research. Through participating in this training course, we have learnt about several major topics such as basic of micrometeorology, flux measurement and calculation, gap filling technique, basic and measurement of soil respiration, methane, and isotope measurement.

We arrived in Xining on 27 July 2009, so late from our scheduled itinerary because of bad weather in China. However, we were delighted and forgot about the tiring journey when arriving at Xining because of the wonderful weather there and warm welcomes from the host.

At the training opening, Prof. Joon Kim, chair of the AsiaFlux, reminded us of past, present and future of flux observation in Asia. We have learned that the number of AsiaFlux tower sites has been increasing significantly only for a few years. As the new comers in this field, we believe that in the near future, we will be able to add one more site to the AsiaFlux since we are working on a new flux tower under ThaiFlux network in Thailand.

Throughout the training course, we have learned several important topics. These include;

- Basic of the canopy-atmospheric boundary layer meteorology. This is very important aspects and considered the foundation of flux measurements. We realized that we needed to understand this subject thoroughly for the correct flux measurement. But this was the first time we have experienced such sciences. Indeed, we have to confess that we understood only some parts but we could fathom the depth of it. Coming back to Thailand, we will make more efforts and take more courses in order to improve our understanding about it.
- Flux calculation, data quality control (QC)

Figure 1. With friends from KoFlux and MalysiaFlux at Haibei Statation (left), ChinaFLUX (right), Xining, China

& quality assurance (QA), gap fillings, and flux partitioning.

- Soil respiration and its measurement methods. This is one of the most important processes in the terrestrial carbon cycle because it releases carbon at a rate that is more than one order of magnitude larger than the anthropogenic emission at the global scale. We learned about both conventional and advance techniques of measuring soil and ecosystem respiration such as automated chamber and open-top chamber and Li-6400 model. Our learning on this topic could help develop and improves our chamber technique for measuring soil respiration in Thailand.
- New development in flux measurement. We have come to realize that real time methane flux measurements are currently possible by using open-path CH_4 analyzer. We also learned that isotope flux measurement is now practicable. We are excited to have new opportunity to expand our study in a Thai forest to include such measurements in the future.
- Eddy flux data-model fusion, assessing tower flux footprint climatology and scaling issue between remotely sensed and eddy covariance measurements.

The field excursion to Haibei Alpine Meadow Ecosystem Station on 31 July 2008 was a lot of fun and we saw the currently operating flux measurement system. The site is about 250 km away from Xining city with an elevation of 3300 m. Here we looked at the records of CO_2 emission through soil respiration correlated primarily with soil temperature. On the way from Xining city to the Station, we were impressed with the yellow color landscape of the rapeseed flowers in fields.

On August 1st, we traveled to Qinghai Lake, which is the largest lake in China, and was ranked top of China's five most beautiful lakes in a latest competition activity by the magazine of China National Geography. This lake is located at about 3,200 meters above sea level and covers 4,300 square kilometers. It has abundant fish and other aquatic creatures, which in turn attracts large flocks of birds to perch in the islands of the lake.

In conclusion, the training course was both academically stimulating and geographically attractive to us. We have to admit that, as the persons who started to begin our research on flux measurement, the training course had provided us with a lot of knowledge. We could feel the depth of the science. We also realized that what we learned many important knowledge on the flux measurement and we hope to contribute to its advancement in the future. Moreover, we have got involved in the network of young scientists, which is important for our future work. Importantly, we met good friends, which may be the most important step for solving the global warming. We all needs to share some responsibility for it and no single one could do it alone. We believe that our first step should be good relationship among all of us.

Finally, we would like to thank the AsiaFlux and ChinaFLUX for giving us this good opportunity to learn and improve our knowledge on the science of flux measurements. The training opens our mind to the flux measurement community and we got acquainted experts on the flux measurement. Without such supports, we would not be able to participate in this training and would miss such important experiences in our research life.

Figure 2. At Qinghai Lake

Diurnal Variations of Thermal Roughness Length and Its Importance for Land Surface Modeling in Dry Regions

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Parameterization of turbulent flux from bare-soil and under-canopy surfaces is imperative for modeling land–atmosphere interactions in arid and semiarid regions, where heat flux from the ground is dominant or comparable to canopy-sourced flux. Using data archived in the Coordinated Enhanced Observing Period (CEOP) project, Yang *et al*. (2007) evaluated the predictive skill of five General Circulation Models (GCMs) and three Land Surface Models (LSMs). They pointed out that these models systematically underestimate the diurnal range of surface–air temperature differences in arid and semiarid regions (Fig. 1). They further showed that heat transfer resistances are underpredicted by these models, due to inappropriate parameterizations for bare-soil and under-canopy heat transfer. In this letter, we address the importance of diurnal variations of thermal roughness length for modeling land surface processes in arid and semi-arid regions as well as in the Tibetan Plateau.

Aerodynamic roughness length (z_{0m}) and thermal roughness length (z_{0h}) are two crucial parameters for bulk transfer equations to calculate turbulent fluxes. A number of studies have shown z_{0m} varies slowly and can be estimated according to the geometry of surface roughness elements, whereas z_{0h} or kB^{-1} [defined as $\ln(z_{0m}/z_{0h})$] is much variable and needs a parameterization.

Diurnal variations of z_{0h} were found for homogeneously vegetated surfaces (Sun, 1999), sparse canopies (e.g. Kustas *et al*., 1989), and bare-soil surfaces (Kohsiek *et al*., 1993; Verhoef *et al*., 1997; Ma *et al*., 2002; Yang *et al*., 2003). Generally, z_{0h} over bare-soil surfaces is small in the daytime while large in the nighttime. Kustas *et al*., (1989) suggested that the diurnal variations for vegetated surfaces are associated with the diurnal cycle of solar zenith angle, as it may cause a vertical movement of the source of heat in a canopy. How-

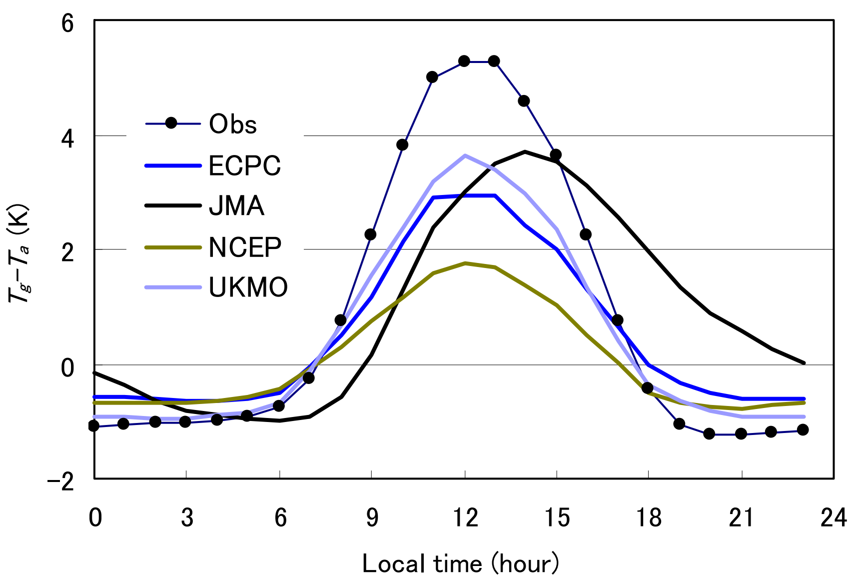

Figure 1. Composite diurnal variation of surface-air temperature difference from in situ data and GCMs (ECPC, JMA, NCEP, UKMO) at 14 CEOP sites for the period of 2002/10-2003/9 (after Yang *et al*., 2007).

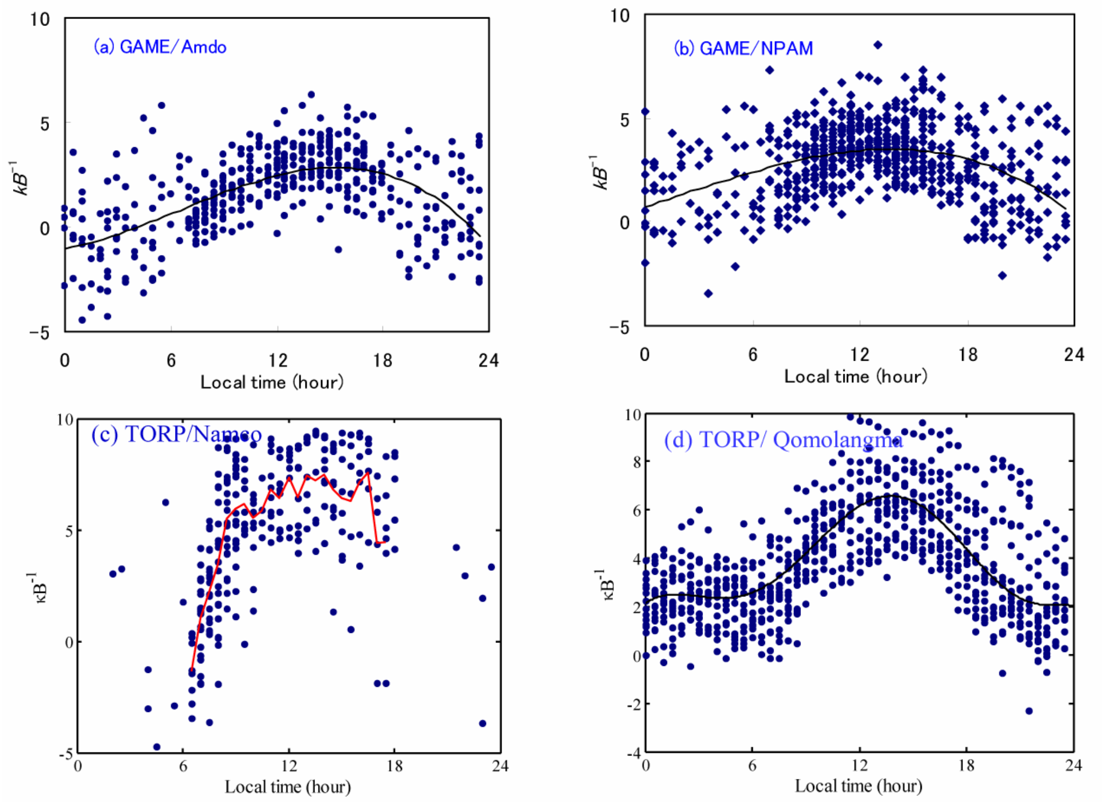

Figure 2. kB^{-1} derived from observed heat flux, temperature and wind speed at four Tibet sites: Amdo (after Yang *et al*., 2008), NAPM (after Yang *et al*., 2008), Namco (courtesy of Dr. Degang Zhou), and Qomolangma (courtesy of Mr. Shuzhou Wang).

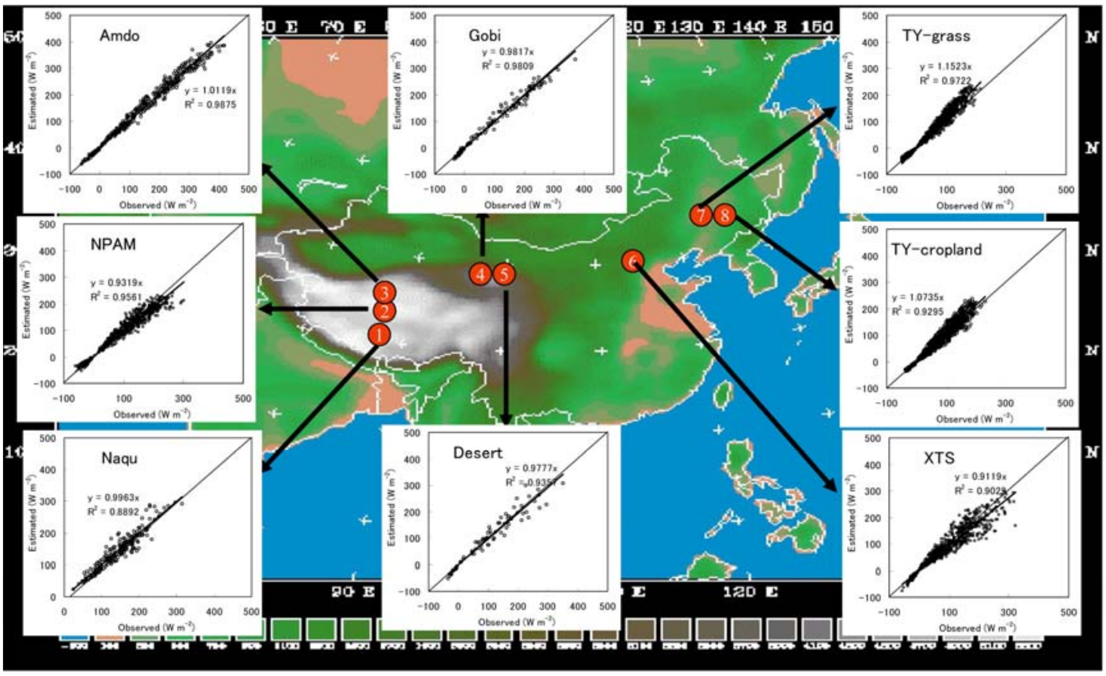

Figure 3. Comparison of sensible heat fluxes between observation and parameterization by Y08 (Eq. (1)) at eight bare-soil sites.

ever, this cannot explain the diurnal variations of z_{0h} over bare-soil surfaces (Verhoef *et al*., 1997), and Yang *et al*. (2008) speculated that z_{0h} is flow state-dependent.

In order to clarify the characteristics of heat transfer, Yang *et al*. (2008) analyzed fluxes data at eight bare-soil surfaces in China and indicated that z_{0h} exhibits diurnal variations at all sites but the variations are most outstanding at Tibet sites. Using new data of Tibetan Observation and Research Platform (TORP; Ma *et al*., 2008), Zhou *et al*. (2009) and Wang *et al*. (2009) also found outstanding diurnal variations at other Tibet sites. Fig. 2 shows typical results of the diurnal variations at four Tibet sites.

As heat transfer is sensitive to the diurnal variation of z_{0h}, parameterization of the diurnal variation over bare-soil surfaces is important for modeling surface energy budget in arid and semi-arid regions. Yang *et al*. (2008) evaluated seven typical schemes in the literature against flux data for bare-soil surfaces. Somehow surprisingly, two widely used schemes in land surface models do not perform well at these sites: Brutsaert (1982) (B82 hereafter) scheme underestimates heat fluxes and Zilitinkevich (1995) (Z95 hereafter) scheme much overestimates heat fluxes. Yang *et al*. (2002) scheme, with a correction for the definition of potential temperature in Yang *et al*. (2008) (Y08 hereafter), performs rather well at all bare-soil sites, as indicated by the good agreements between observed sensible heat fluxes and parameterized ones in Fig. 3.

Y08 introduces a temperature scale and a turbulence-related length scale to parameterize z_{0h}, in addition to the fractional velocity, as shown below:

$$z_{0h} = h_T \exp\left(-\beta u_*^{0.5} \left|T_*\right|^{0.25}\right) \quad (1)$$

where $h_T = 70\nu/u_*$ is a turbulence-related scale (m), β = 7.2 $m^{-1/2}s^{1/2}K^{-1/4}$, u_* is the frictional velocity (m s^{-1}), $T_*(\equiv -H / \rho c_p u_*)$ is a tempera-

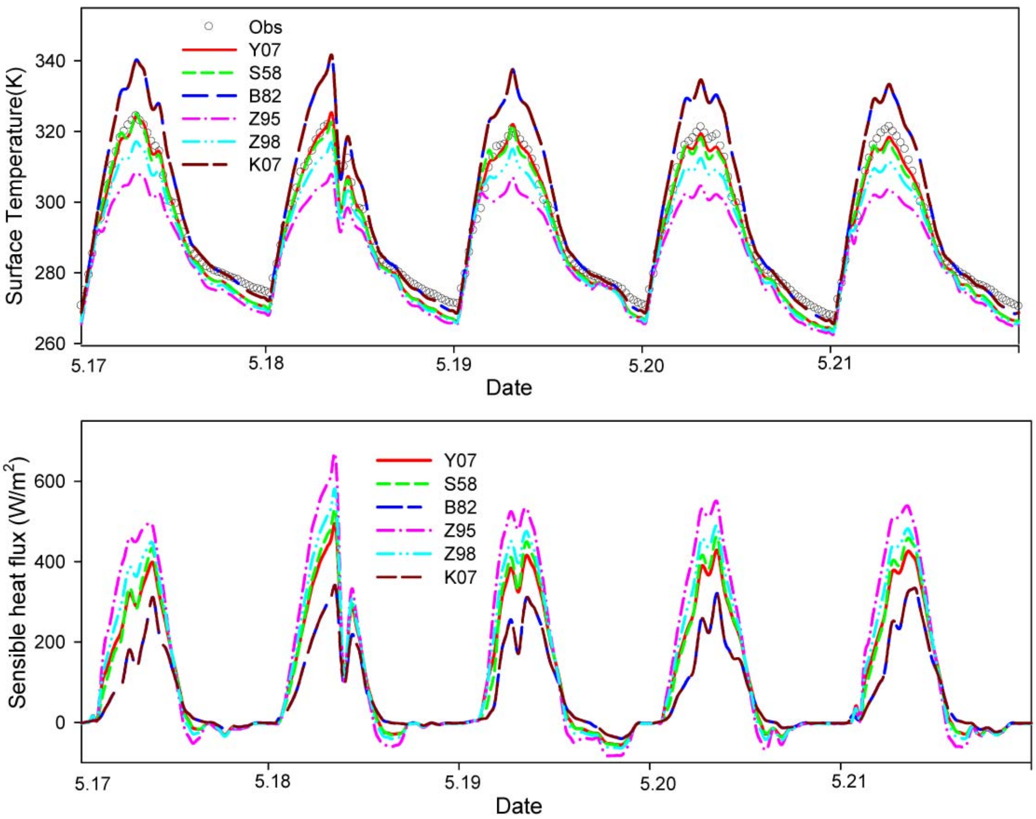

Figure 4. Sensitivity of Noah-simulated surface temperature and sensible heat fluxes to z_{0h} schemes for a dry site (Shiquanhe) in the western Tibet during 17–21 May 1998. Y08, S58, B82, Z95, Z98, and K07 are parameterization schemes summarized in Yang *et al*. (2008) (Courtesy of Dr. Yingying Chen).

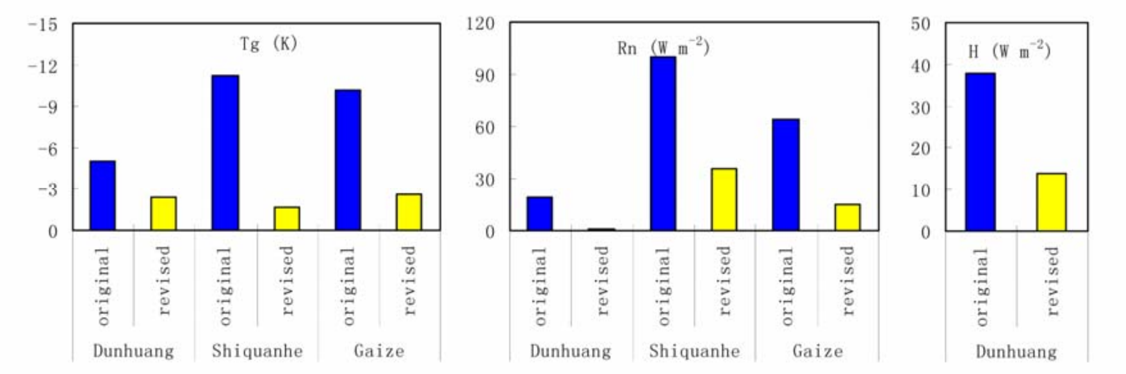

Figure 5. Mean biases of the original Noah model and the revised one for three dry sites during the daytime (0900-1600 LT), calculated from 30-minute observations and simulations. Sensible heat flux was not observed at Shiquanhe and Gaize sites (Courtesy of Dr. Yingying Chen).

ture scale (K), and v is the fluid kinematical viscosity ($m^2\ s^{-1}$).

Equation (1) has three features: (1) z_{0h} tends to decrease with respect to u_*; (2) T_* is introduced to reflect the diurnal variation of z_{0h}; (3) it can produce negative values of kB^{-1} that often observed in the nighttime for relatively smooth surfaces (z_{0m} <1 mm). By contrast, other scheme that parameterizes z_{0h} only by $Re_* \equiv z_{0m}u_* / v$ is neither sufficient to produce the diurnal variation of z_{0h} nor able to produce negative values of kB^{-1}.

Though Equation (1) works well when estimating heat fluxes from observed surface skin temperature, it is not clear how important such a scheme can be in a land surface model. Yang *et al*. (2009) implemented Eq. (1) into SiB2 and showed that the revised SiB2 indeed well produces diurnal ranges of surface skin temperature observed at very dry sites. To show its applicability in a more general sense, Chen *et al*. (2009) implemented six z_{0h} schemes into Noah model and tested the modeling sensitivity to the parameterization of z_{0h} at a dry site (Shiquanhe) in western Tibet. Figure 4 shows that the simulated skin temperature and fluxes are very sensitive to the choice of the paramterization of z_{0h}. The uncertainty in the simulated daytime temperature can be 30 K, and the heat flux can vary from 300 W m^{-2} up to 600 W m^{-2}.

The original Noah model and the revised one with Y08 were then applied at three dry sites (Shiquanhe, Gaize, and Dunhuang). To separate the effects of z_{0h} parameterization from parameter specification uncertainties, key parameters related to surface radiation and energy budgets modeling (surface emissivity, albedo, soil thermal properties) are given according to observations. The simulations show that the original Noah model often underestimates daytime surface temperature by 10 K or more, whereas the revised one well produces surface skin temperature at all sites. As the under-estimation of surface skin temperature is corresponding to lower upward longwave radiation (and thus high net radiation) and lower ground soil heat fluxes, the underestimated skin temperature implies that sensible heat fluxes are much over-estimated. Figure 5 shows mean biases of modeled surface temperature (T_g), net radiation (R_n), and sensible heat flux (H) for the daytime period (0900-1600 LT), when surface temperatures were high. At two Plateau sites (Shiquanhe and Gaize), the daytime skin temperature is underestimated by 10 K on average in the original Noah model while they are much reduced in the revised one. Similarly, the simulated net radiation is significantly improved and the modeled heat flux is improved in the revised model.

In summary, understanding the characteristics of thermal roughness length over bare-soil surfaces is crucial for parameterizing and modeling turbulent fluxes over both bare-soil surfaces and partially vegetated surfaces. Based on data collected on the Tibetan Plateau, an initial success from field experiments to model developments has been achieved by the hydrometeorological group at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences.

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An essay about the 2nd iLEAPS conference

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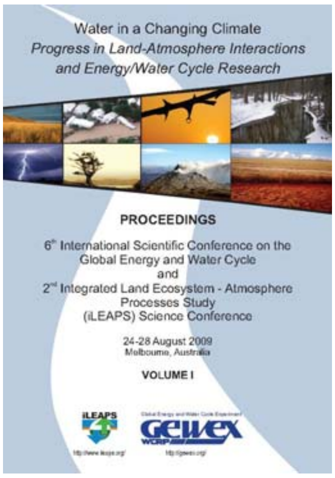
The 2nd Integrated Land Ecosystem – Atmosphere Processes Study (iLEAPS) Science Conference was held in Melbourne, Australia from August 24th to 28th and it was a joint conference with the 6th International Scientific Conference on the Global Energy and Water Cycle with their common title of "Water in a Changing Climate: Progress in Land – Atmosphere Interactions and Energy/Water Cycle Research". There were joint sessions as well as regular sessions for each part with regards of the role of land surface processes in the climate system, aerosol, cloud, precipitation and climate interactions, and future synthetic system with observation and modeling.



It was impressive that iLEAPS encouraged young scientists. They held a workshop a week ahead the conference for early career scientists and offered a lunch table on the midday of the conference, where they could meet and talk with senior scientists. They also honored several excellent posters presented by graduate students and post-docs.

Presentations by senior scientists have always inspired me though their talks are usually of general idea and broad aspect. It is still in my mind that observational research team and modeling team should have more conversation together. It reminded me of being often told that uncertainties in analysis results were attributed either to simulation data or to observational data. In general, uncertainty in simulation data comes from parameterized or approximated processes while uncertainty in observational data comes from environment or calibration method. I agree that modeler s and observation scientists should respect more each other.

Regarding a changing climate system, researches on carbon cycle and biogeochemical processes were paid attention more than before. In my personal view, in the last 20th century, land surface processes and their interactions with climate had been studied primarily focused on their physics and thermodynamic processes though there were pioneering studies on biogeochemical processes. In 21st century, climate scientists have growing concern about biodiversity as well as extreme weather events which will be brought out as global warming has increased. To me, it has been considered as a signal that people started looking after the environment. There is no doubt that without managing the environment well, human beings cannot sustain modern civilization, either.

Owing to advanced remote sensing technology especially with satellites, climate scientists at the conference showed their efforts to derive as many variables as possible from the satellite images such as soil properties, sea surface level, and even age of accumulated snow. Not only remote sensing but also in-situ flux measurement showed off progress. A research team from Max-Plank Institute in Germany brought an issue on "upscaling of data using Flux-Net dataset in worldwide". They took advantage of "neuron network method" to get a global dataset on a uniform resolution, which make usage of the Flux-Net dataset feasible to global modeling as input and boundary conditions.

Downscaling from global scale to local scale was introduced with applications for dam management for example mainly by Japanese scientists. They used Earth Simulator to calculate the model with fine resolution. I hope we can catch up their capability with great computing power. However, I must recall that Prof. Hye-Yeong Chun at Yonsei University gave me advice that we have to develop our own strength in meteorological research just as European scientists show off their strength in theoretical background and its application in parameterization even though they do not have Earth Simulator.

Probing the Atmospheric Boundary-layer with a Cost-effective Mini-UAV

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1. Introduction

The atmospheric boundary-layer (ABL), its structure and its height are essential to the understanding of the physical system of climate. They play a key role in virtually every human activity, in the biogeochemical cycles, and in the quality of the air.

Not surprisingly, then, airborne measurements of different physical quantities within the ABL have been tried and ultimately successfully implemented throughout the Modern and Contemporary Ages: their history proceeds apace (and gets confused with) the history of Meteorology itself.

Indeed, in 1804 Gay-Lussac ascended to approximately 6000 m of altitude in a balloon, taking air samples to determine the proportion of oxygen and nitrogen in the atmosphere. Other balloon ascents followed by Barral and Bixio in 1850 and Glaisher and Coxwell in 1862. A high altitude flight by Tissandier, Croce-Spinelli and Sivel in 1875 ended tragically with the deaths of the latter two; in the early 1890's, automated measurement systems were devised that could be floated or parachuted back to the ground (Strangeways, 2007; Goebel, 2008).

In the early 20th century, L. F. Richardson became interested in soundings and devised quite a few ingenious approaches: "Lizard balloons" and "Cracker balloons" (the last exploding at a pre-set temperature and the height being computed from theodolite observations) (Richardson, 1921b,a). He also shot spheres upward to measure the wind and temperature profiles (Richardson, 1923, 1924a,b,c). At this time, pilot balloons were already being used to measure the wind (Richardson *et al*., 1925).

At the end of the 1920's, the radiosonde was invented independently in France and in the Soviet Union (Wikipedia, 2009), and more reliable profiles of temperature, humidity and wind could be obtained.

The radiosonde remains an expensive system to this day, however, and more cost-effective systems have continued to be tried. Airborne measurements complementary to radisoundings have matured to the point of being part of the WMO global monitoring system (WMO, 2003). Alternative systems can be a particularly attractive option when the goal is to probe only the ABL, and not the whole troposphere: the most common types are probably tethered balloons and kites: tethered balloons are still actively used to investigate, among others, properties of the nocturnal boundary layer (Deanmead *et al*., 1996; Mathieu *et al*., 2005), and kites have been shown to be able to probe the convective boundary layer (Kaimal *et al*., 1976). Variations on the idea of the pilot balloon have also been tried (Gage and Jasperson, 1974).

It is only natural, then, that with the availability of relatively inexpensive UAV's (unmanned aerial vehicles) they are becoming a popular platform for measurements in the ABL.

The application spectrum is quite wide. To cite but a few recent developments, McGonigle *et al*. (2008) used an unmanned helicopter to measure the chemical composition (CO_2 and SO_2) of a volcanic plume; Piess et al. (2007) and van den Kroonenberg *et al*. (2008) developed a sophisticated mini-UAV, capable not only of measuring mean wind, mean temperature and mean wind profiles but also velocity and temperature turbulence fluctuations; and Hobbsa *et al*. (2002) used a small UAV to

Table 1. Characteristics of *Aerolemma-1*

Manufacturer	*Ultimate Models*, Presidente Prudente, SP, Brazil
Materials	Wood, aluminum, styrofoam and fiberglass
Engine	Aeronautical fuel
Flight Autonomy	20 minutes
Wing span	3,0 m
Length	1,8 m

study atmospheric structure, via air temperature and humidity fields, over heterogeneous terrain. A more complete overview of mini-UAV developments over the last decade can be found in van den Kroonenberg *et al*. (2008).

2. Early efforts

Our first effort at developing an UAV was a relatively large aircraft, with a payload of up to 9 kg. At the time, this size and payload were considered necessary to carry different types of sensors, including air-quality sensors which are usually heavier and bulkier. A research proposal to Brazil's Federal Science Funding Agency, CNPq, resulted in a small grant that allowed the plane to be built. It was in essence a big radio-controlled airmodel, built by an airmodel manufacturer (*Ultimate models*, Presidente Prudente, SP, Brazil). The aircraft, named *Aerolemma-1* (Fig. 1), flew for the first time at the factory site, on 2006-05-09. *Aerolemma-1*'s main characteristics are shown in Table 1.

The plane was fitted with a temperature-humidity sensor Campbell Scientific Instruments (CSI) HMP50, and a barometric sensor CSI CS100. The data were logged on-board with a CSI CR10X datalogger with a measurement frequency of 1 Hz. Fig. 2 gives an idea of sensor layout in the spacious fuselage.

For almost a year, we made several flights with *Aerolemma-1* without an autopilot system that would make it a true UAV. The plane would be flown to the limit of visual radio-controlled flight, which amounted to a maximum height of approximately 800 m above ground. Initially, all sensors were mounted inside the fuselage, and ventilating holes were

Figure 1. The first UAV, *Aerolemma-1*.

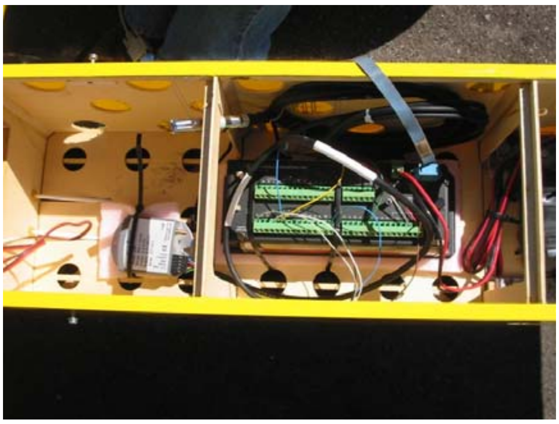

Figure 2. Sensor and datalogger layout inside *Aerolemma-1*.

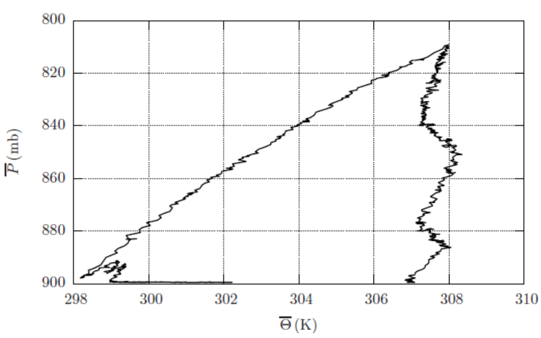

Figure 3. Histeresis on the temperature measurements due to sensor positioning inside the fuselage

Figure 4: External shield for housing the temperature sensor

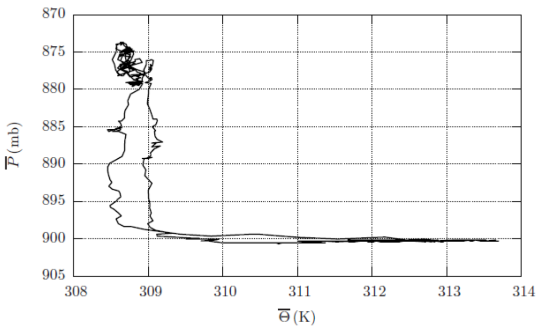

Figure 5. Potential temperature measured by *Aerolemma-1* with an external temperature shield.

assumed to be enough to expose the sensors to the surrounding atmospheric conditions while at the same time shielding the temperature sensor from solar radiation. This, however, induced a severe histeresis on the air temperature measurements, as shown in Fig. 3 for the potential temperature.

The problem was in great measure solved by placing the HMP50 on the plane's belly, inside a cylinder protecting it, among other things, from reflected radiation from the tarmac (Fig. 4). Potential temperature measurements with the new arrangement are shown in Fig. 5.

Without an autopilot system, radio-controlled models cannot climb high enough to identify clearly the height of the inversion *zi* that usually serves as the definition for the ABL height. At the end of 2007, *Aerolemma-1* was equipped with an autopilot system (*Micropilot* MP2028g) that enables the plane

Figure 6. Crash of *Aerolemma-1*.

to follow a pre-determined flight plan.

Unfortunately, on the first trial of the autopilot, on 2007-11-20 at 11:00 am, a radio link fault caused by human error triggered the system's emergency procedure: the plane descended on a spiral trajectory and crashed in the woods (Fig. 6). All sensors, the datalogger and the autopilot system, as well as the engine, were not damanged in the crash, and could be transfered to a new airframe, *Aerolemma-2*.

Several flights were attempted during 2008 with *Aerolemma-2*. Soon it was clear that it was too big and too difficult to set up. Moreover, its size (which was approximately the same as *Aerolemma-1*'s) required an airstrip to take off safely. Attempts to land on grass invariably resulted in breaking the landing gear. Even when landing on the airstrip, the plane's weight often caused the landing gear to break.

3. The mini-UAV design and adaptations

A new design that allowed more flexibility to take off and land virtually at any site was needed. A new research project with CNPq allowed to buy a commercial air model (*Hobbico* Hobbstar 60 Mk3) which was then adapted for the required mission. The same air temperature, humidity and pressure sensors were transferred to the new model together with the MP2028g, but the datalogger (the CR10X) was too heavy and had to be replaced by a lighter CSI CR216. Buying an off-the-shelf model substantially reduced the time needed to have the mini-UAV flying.

The "cargo bay" is considerably more cramped, see Fig. 7, but still enough to carry all the equipment. Learning from the experi-

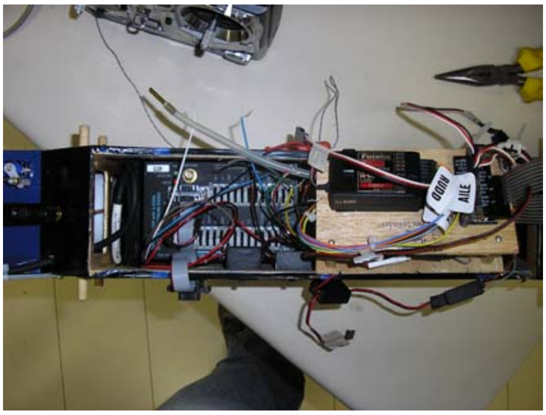

Figure 7. *Aerolemma-3*'s "cargo bay".

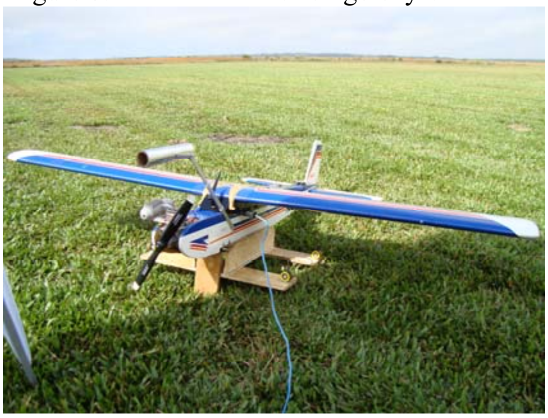

Figure 8. Temperature shield in *Aerolemma-3*.

Figure 9. Catapult-assisted take-off.

ence with the *Aerolemma-1* temperature measurements, a boom was fitted with a cylindric cardboard shield wrapped in aluminum foil to house the HMP50 (Fig. 8); to make take-offs safer and faster, a sling catapult was added to the system. The new plane, *Aerolemma-3*, finally got ready to fly. A take-off from the catapult is shown in Fig. 9. The plane is light enough, however, to allow launching from the hand. Fig. 10 shows a typical sequence.

Figure 10. Hand-thrown take-off.

4. Experimental site and ABL measurements

Aerolemma-3's first micrometeorological measurement flights have taken place at Tijucas do Sul, PR (20° 50' 28.47" S, 49° 7' 16.82" W, altitude 940 m). The objective of the campaign is to establish the plane's ability to fly above the elevated inversion; make the required measurements, and keep flying through the day in order to follow the daytime growth of the ABL. Because the main forcing of the ABL comes from the surface virtual sensible

Figure 11. Micrometeorological station for momentum and virtual sensible heat surface flux measurements.

heat flux, a micrometeorological station was mounted at the site and has been kept running without interruptions since 2009-04-07. The station, shown in Fig. 11, measures air temperature and humidity, net radiation, and velocity and sonic temperature with a CSI CSAT-3 sonic anemometer. Data are logged every 10 minutes with a CSI CR-23X datalogger. Besides the mean wind component and sonic temperature, momentum flux and virtual sensible heat flux are also measured.

Aerolemma-3's flights began in 2009-02-10. Ascensions were gradually programmed to 500m AGL, then 1000m, 1500m and finally 1800m. In all, we have flown *Aerolemma-3* 77 times, and on two occasions more then 10 flights were made on the same day, demonstrating the plane's ability to probe the growth of the ABL during the day when operated by a small and well-trained crew.

On Fig. 12, we show the sounding made by *Aerolemma-3* on 2009-06-04, starting at approximately 10:45 am and ending at approximately 11:03 am. This was a very cold and dry morning, after the passage of a frontal system.

At the time of the flight, the inversion is located a little below 500m above ground. Notice also that the inversion is effectively trapping water vapor resulting from the surface latent heat flux. Fig. 13 shows the progression

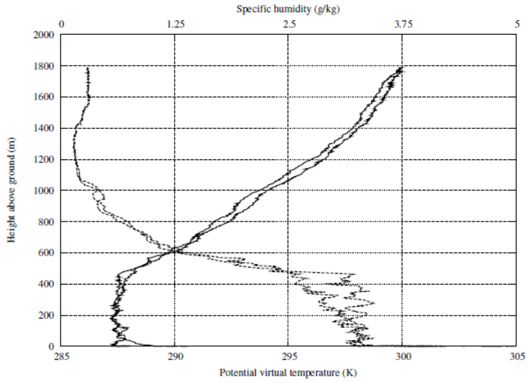

Figure 12. Sounding made by Aerolemma-3 on 2009-06-04 at 10:45–11:03. The solid line is the virtual potential temperature profile, and the dashed line is the specific humidity profile.

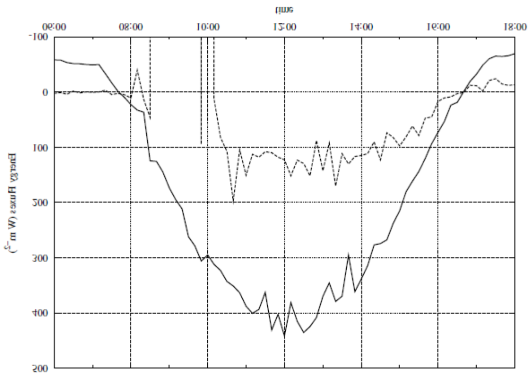

Figure 13. Net radiation (solid line) and virtual sensible heat flux (dashed line) at Tijucas do Sul, PR, on 2009-06-04, showing the effect of the surface energy fluxes on the temperature and humidity profiles in the ABL below the inversion.

of net radiation and sensible heat flux during the day at the site. In the early morning hours, the CSAT-3 was not measuring the virtual sensible heat fluxes properly due to dew deposition on its transducers. At 10:30 am, however, the transducers had dried and the virtual sensible heat flux was in excess of $100 Wm^{-2}$: the ABL grew very fast to nearly 500 m, and the effect of the large surface latent heat flux, apparent from the difference between the curves on Fig. 13, is the noted accumulation of water vapor below the inversion.

5. Ongoing measurements and possible applications

Measurements at the Tijucas do Sul site continue, conditioned by weather conditions (this has been a particularly wet year in the region), and when air traffic control clearance is granted. Flying the mini-UAV with full knowledge from the aeronautical authorities has been a *sine qua* condition from the start, and air safety restrictions are an integral part of the project.

With our unmanned planes, and particularly with *Aerolemma-3*, we intended to develop a cost-effective solution for ABL soundings. The main motivation was the importance of accurate values of z_i to scale variables such as σ_u/u_*, and for air quality studies as well. To keep the sophistication of the plane itself to a minimum, on-board instrumentation is the same as is standard in balloon soundings: pressure, temperature and humidity. With the small model adopted the cost of the airframe is minimal; however, work is needed to adapt the plane's interior. The most expensive item in the package is the autopilot, but the overall cost compares favorably with balloon-based measuring systems.

A very attractive feature is the possibility of carrying different scalar sensors, therefore adapting the vehicle for different missions. Currently, we are actively investigating the possibility of carrying CO_2 and O_3 sensors, because of their obvious importance for ABL studies of surface CO_2 fluxes and air quality analyses.

The ability to fly our mini-UAV enhances substantially our knowledge of ABL processes aloft, that surface micrometeorological measurements are unable to "see". The round-up time to re-fuel and re-launch the system is very small (no more than 15 minutes): a flight frequency of one every 30 minutes is possible in theory. Using an electrical engine this time can be further reduced. This opens up the possibility of accompanying the ABL evolution at a much better time resolution, making it particularly suitable for scalar budget methods.

Acknowledgements

Technical support from *Micropilot*, the manufacturer of the autopilot system, is gratefully acknowledged. We thank the support of Brazil's CNPq through Research Grants 475953/2004-5 and 471445/2008-8; this work has been partially supported also by the City of Curitiba via Research Contract FUNPAR 1984.

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Forthcoming events...

8th AsiaFlux Workshop (Sapporo, Japan, 27-29 October, 2009)
For more details, please visit http://www.japanflux.org/asiafluxws2009/

Young Scientist Meeting
- Date & Time: 18:30-21:00, 28 Oct, 2009
- Venue: Conference Hall, Hokkaido University

Youth AsiaFlux Meeting in Sapporo will be a great opportunity to carve out the glorious future through speeches by leading senior scientists. For more details, please visit http://www.japanflux.org/asiafluxws2009/youth/

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Inspiration, cultural diversity and education, which cannot be measured by the impact factor, were my motto of this volume. Thank all contributors for their wonderful and arduous works and I wish that many people enjoy the articles in this letter.

The Editor of AsiaFlux Newsletter No. 30
Jinkyu Hong
(Department of Atmospheric Sciences, Yonsei University, Korea)

The Editor of AsiaFlux Newsletter No. 31 will be Dr. Leiming Zhang (China Academy of Science, China)..