3.4 Synergisms and comparisons between airborne Doppler Wind Lidar observations and other remote and in-situ wind measurements and model forecasts

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1. Introduction

Traditionally, direct observations of winds can be obtained from a number of measurement platforms including tower or tethered balloon mounted anemometers, drift balloons, rawinsondes, dropsondes, SODARs, profilers and, under special conditions, ground based radars. These methods of wind measurement, however, often suffer from one of three limitations: spatial representativeness, rapid deployment and adaptive mobility. The airborne Doppler Wind Lidar (DWL) can provide wind and aerosol profiles with high space and time resolution, and flown to specific targets of interest with various dwell options and measurement strategies.

Although airborne Doppler lidar is now mature enough to be called operational, the use of DWLs from airborne platforms is still very limited. Since 1999, the DLR (German Aerospace Center) have flown several wind lidars (both coherent and direct detection and particularly a coherent system named WINDS (Wind Infrared Doppler System)) on a Falcon aircraft to measure the 3-dimensional wind field over locales such as the Alps, Greenland, Africa and the North Atlantic (Reitebuch et al., 2003; Weissman et al., 2005). The NOAA Environmental Technology Lab has also flown a 2 micron coherent system on that same airplane as part of the IHOP campaign over the central plains of the United States (Tollerud et al., 2004; Hardesty et al., 2008).

Over the past ten years, the Integrated Program Office (IPO) of NPOESS (National Polar-orbiting Operational Environmental Satellite System) has funded the use of an airborne coherent DWL initially mounted in a Navy Twin Otter aircraft (Figure 1) to conduct a variety of investigations (see below). Since 2002, under the direction of Simpson Weather Associates (SWA) and operated by the Navy's Center for Interdisciplinary Remotely Piloted Research Studies (CIRPAS), this Twin Otter Doppler Wind Lidar or TODWL (Emmitt et al., 2005) has been the only on-demand lidar in the United States and has flown more than 125 hours of atmospheric missions with most of that over the Pacific Ocean and within 50 km of the shore. In particular, there were six dedicated wind lidar missions in 2002, 2003, 2004, 2006 and 2007. In many of these missions, one of the prime objectives has been the validation of the airborne lidar data and intercomparisons with other wind observations as well as numerical model output. This paper will focus on these activities.

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2. Instrument and data processing

The lidar is a 2 micron coherent system and Table 1 summarizes many of the technical details of the lidar. A defining capability of the TODWL is its ability to profile above and below the flight level. This is possible because the lidar includes a bi-axis scanner mounted on the side door of the aircraft (Figure 1) that allows vertical soundings of the wind profile above and below the aircraft as well as taking data with horizontal or vertical perspectives. In addition, the beam can be adaptively (in flight) directed in a variety of scan patterns including conical, nadir stares and flight level stares.

In most instances, a vertical profile is derived from a either an 8 point (45 degrees between stares) or 12 point step stare (30 degrees between stares) with a 20 – 30 degree nadir half angle. The dwells at each stare point vary from 1 – 2 seconds. Using this set-up, a 50 m/s ground speed for the aircraft, produces a complete profile of u, v and w every 1 – 2 km. However, complete profiles have also been obtained (at slower speeds) every 250 m along a flight path. Emmitt and O'Handley (2003) have developed software, scanning strategies and data processing algorithms that have resulted in high accuracy (< .05 m/s) in the wind observations and high resolution of aerosol features (< 5 meters in some instances). Using a sliding range gate in the processing we are able to achieve 25-50 meter vertical resolution.

3. Analysis and comparison with observations

Based out of Monterey, CA, the TODWL (Emmitt et al., 2005) has been flown over 125 flight hours since 2002. Some of the specific objectives included:

- Characterization and description of the of the low-level 3-D wind field over water and complex terrain and comparison with existing meteorological observations (cal/val)
- Study of returns from water surfaces
- Investigation of Organized Large Eddies (OLE) over the open ocean (Emmitt et al., 2005a)
- Validation of numerical model predictions of flow over complex terrain (Greco and Emmitt, 2005)
- Investigation of the interactions of aerosols and winds within the planetary boundary layer
- Validation of space-based wind sensors such as scatterometers and cloud motion vector imagers(Emmitt et al., 2004)
- Real-time on-board prospecting for vertical motions and regions of shear low level wind maxima

An example of a typical TODWL flight mission is shown in Figure 2. This sortie occurred during the most recent November 2007 campaign, on November 12th. Leg 5 of this mission took place between 1520 and 1537 LST and proceeded in a NE to SW direction. During this flight, 12-point step-stare scans were conducted each 1-1.5 km along the flight path. These profiles were used to help characterize the boundary layer in the coastal regions of central California near Monterey. Figure 3 shows the color contoured z-t plot for winds speed of all the vertical profiles taken during the leg while Figure 4 presents ten of the individual wind speed profiles. From both Figures 3 and 4, we can see the existence of an elevated jet or wind maximum (over 10-12 m/s) over both the inland and coastal terrain. However, the transition to a stronger jet and a deeper layer of high winds as we go from inland to the coast is also clearly illustrated.

During the last six years, flight missions near Monterey, CA were conducted to overfly locations where winds (surface or upper air) were routinely measured by other platforms. These included:

- surface networks
- ocean buoys
- rawinsondes (national network and campaign specific)
- microwave sounders
- ground-based lidars
- satellite underflights (QuikScat, WindSat)

Comparisons have been made between the lidar measurements and both surface (land and water) and upper air wind measurements. During the November 12th mission, the Twin Otter specifically flew over a Microwave wind sounder (part of the Coastal Profiler Network in California) located at Fort Ord, CA. An example of a comparison between the wind profiles (both speed and direction) measured by TODWL and those recorded by the Fort Ord sounder are shown in Figure 5a-b. The trends, shapes and vertical structure of the two independent wind profiles are very similar. This is true for both wind direction and wind speed. However, it is obvious that the Microwave sounder data, which is averaged over 30 minutes, can not capture the high resolution details provided by the one minute interval TODWL and thus misses the variability in the vertical, and the local jet, captured by the airborne lidar.

In the course of conducting flights, the TODWL has also underflown WindSat and QuikScat on several occasions by chance and, on numerous occasions, by design. The motivation behind these underflights was to not only obtain high spatially resolved wind profiles (50m vertical and 250m horizontal) within footprint and processing “pixels” of both a scatterometer (QuikScat) and a polarmetric radiometers (WindSat) but also to investigate the accuracy of PBL wind profiles derived for ocean vector winds (Cal/Val). There have been approximately 12 underflights in 2002, 2003, 2005 and 2007, with the ones in April 2007 being the best to date. Comparisons are being made between the ocean vector winds from QuikSCAT and WindSat, the co-located TODWL wind profiles and NOAA buoy data. Preliminary review of the TODWL data and comparisons with Quikscat and WindSat products suggests large discrepancies on several occasions.

4. Comparisons with models

As mentioned above, the TODWL system has also been used in validation studies of numerical model predictions of flow over complex terrain. The MM5 at the Naval Postgraduate School (Miller/Hale and Nuss) has been run during all the campaign missions, The NPS MM5 model was run twice daily, with a warm start and a MRF PBL scheme. The model contained 30 vertical levels with 12 levels at or below 850 mb. The NPS MM5 typically had a triple nested grid of 108, 36 and 12 km, but a 4 km nested grid was run special for the Monterey area.

After the field campaigns, output from NPS MM5 fine scale grid (4 km) analyses are compared with the nearest coincident TODWL soundings taken (within 1 km) over the water and complex terrain. Examples of these comparisons between model grid points (of a 6 hour forecast) and TODWL soundings for Leg 5 of the November 12th 2007 mission are shown in Figure 6. Once again, we can see that the model forecast of the MM5 captures the general sense of the direct observations taken by the airborne lidar but does not capture the high resolution vertical and horizontal variability that exist.

5. Summary

As show by the investigations described above, the TODWL can provide accurate, high space and time resolution wind profiles over open waters and complex terrain that can compliment and add to existing data networks or planned field campaigns. TODWL soundings of the wind field have been processed to obtain accuracies of <.10 m/s in each component (u, v, w). Comparisons with other sounders show very similar and encouraging results but must be interpreted with caution since integration times and sample volumes are different.

6. References

Emmitt, G.D. and C. O’Handley, 2003a: Processing airborne coherent Doppler lidar returns from the ocean surface and the layer adjacent to the surface, SPIE 5240, Barcelona, Spain, September.

Emmitt, G.D., C. O’Handley, S.A. Wood, R. Bluth and H. Jonsson, 2005: TODWL: An airborne Doppler wind lidar for atmospheric research. Annual Amer. Met. Soc. Conference, 2nd Symposium on Lidar Atmospheric Applications, San Diego, CA, January.

Emmitt, G.D., C. O’Handley, S. Greco, R. Foster and R. Brown, 2005: Airborne Doppler wind lidar investigations of OLEs over the eastern Pacific and the implications for flux parameterizations, Proc. Of the AMS Conference on Coastal Atmospheric and Oceanic Prediction and Processes, San Diego, CA, January, 2005.

Emmitt, G.D., S. A. Wood, C. O’Handley, S Greco, H. Jonsson, 2004b: Airborne Doppler lidar for WindSat Cal/Val WindSat Cal/Val and Science Meeting, Solomons MD, 17-18 November.

Greco, S. and G.D. Emmitt, 2005: Investigation of flows within complex terrain and along coastline using an airborne Doppler wind lidar, Annual Amer. Met. Soc. Conference, 2nd Symposium on Lidar Atmospheric Applications, San Diego, CA, January.

Hardesty, R.M., W.A. Brewer, C.J. Senff, B.J. McCarty, G. Ehret, A. Fix, C. Kiemle and E. Tollerud, 2008: Structure of meridional moisture transport over the US Southern Great Plains observed by co-deployed airborne wind and water vapor lidars, Proc. of the Annual Amer. Met. Soc. Conference, Symposium on Recent Developments in Atmospheric Applications of Radar and Lidar, New Orleans, LA.

Reitebuch, O., H.Volkert, C. Werner, A. Dabas, P. Delville, P. Drobinski, P.H. Flamant and E. Richard, 2003: Determination of air flow across the Alpine ridge by a combination of airborne Doppler lidar, routine radio-sounding and numerical simulation, *Q. J. R. Meteorol. Soc.*, 29,715-725.

Tollerud, E.T., B.D. Jamison, F. Caracena, S. Koch, D. Bartels, R.M. Hardesty, B.J. McCarty, C. Kiemle and G. Ehret, 2004, Multiscale Analyses of Moisture Transport By The Central Plains Low Level Jet During IHOP, Proc. of the Annual Conference of the Amer. Meteor. Soc., Seattle, WA, January.

Weissman, M., R. Busen, A. Dornbrack, S. Rahm, and O. Reitebuch, 2005b: Targeted Observations with an Airborne Wind Lidar, *J. Atmos. Ocean. Tech.*, 22, 1706-1719

Wavelength (microns)	2.05 (eyesafe)
Energy per pulse (mJ)	1 – 2
Pulse repetition frequency (Hz)	500
Pulse length (m)	90
Scanner	2 axis (+- 120; +- 30)
Telescope diameter (cm)	10
Range resolution (meters)	50-100
Total System Efficiency (%)	7-10
Power (KW)	.75
Weight (lbs)	750 including door mounted scanner
LOS measurement accuracy (m/s)	< .05 with .5 sec integration
Wind component accuracy (m/s)	u,v,w < .1 m/s nominal using a 30 degree VAD and LADSA

Table 1: Description and characteristics of TODWL

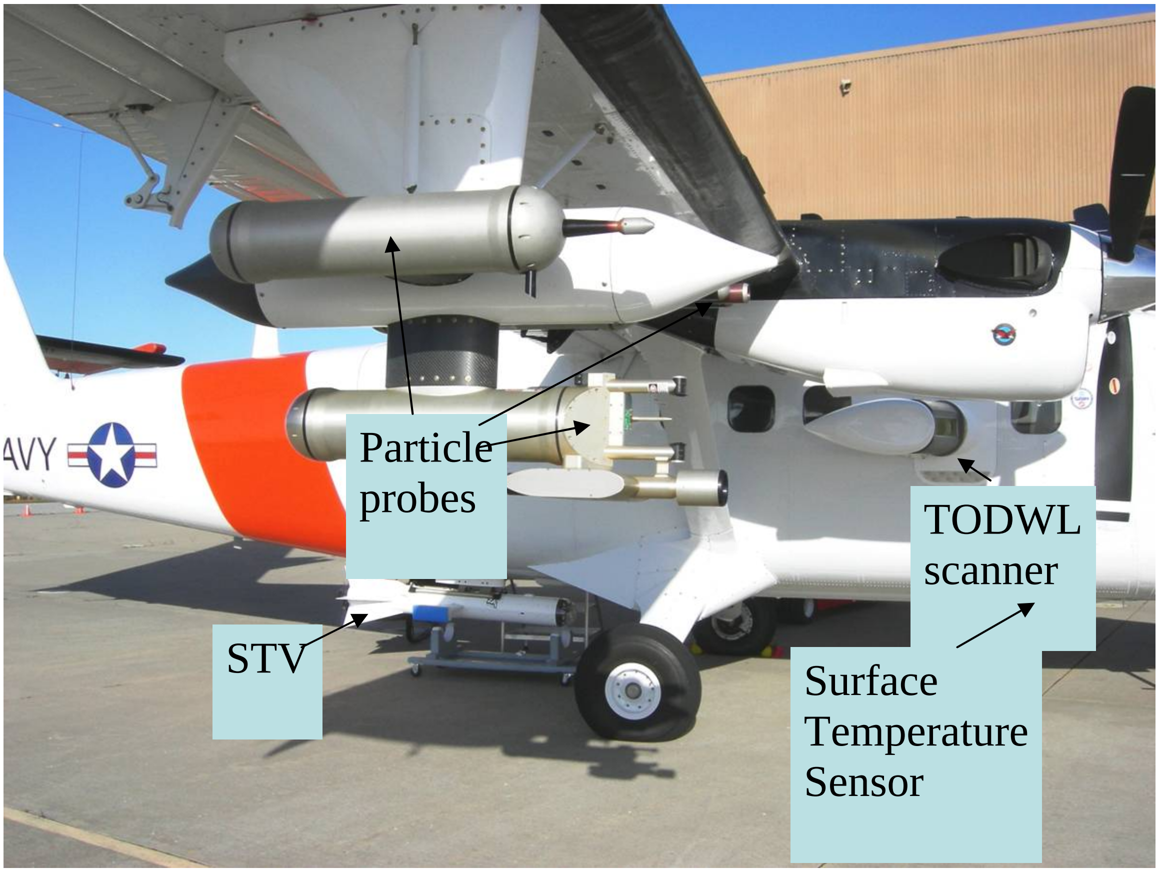

Figure 1. Navy Twin Otter with TODWL scanner in side door

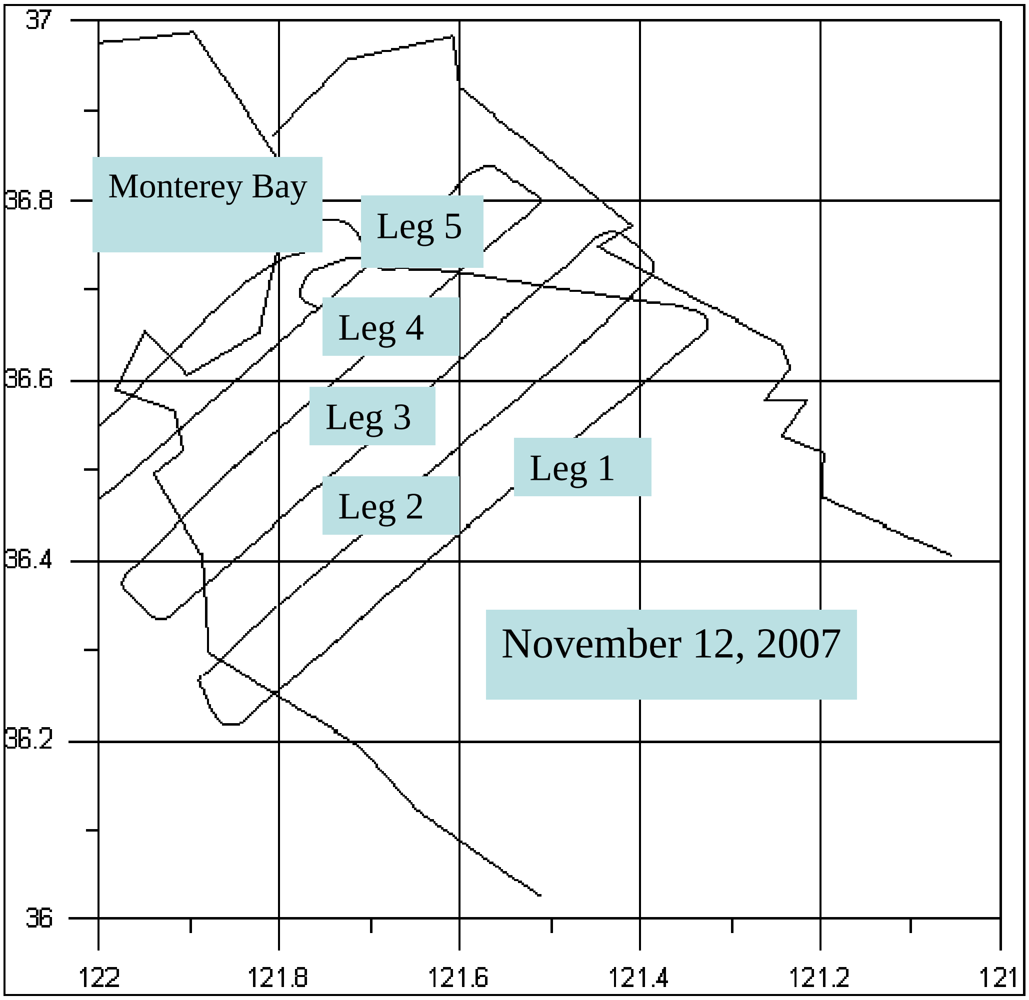

Figure 2: TODWL flight mission on November 12, 2007. Leg 5 of the mission was in a NE to SW direction.

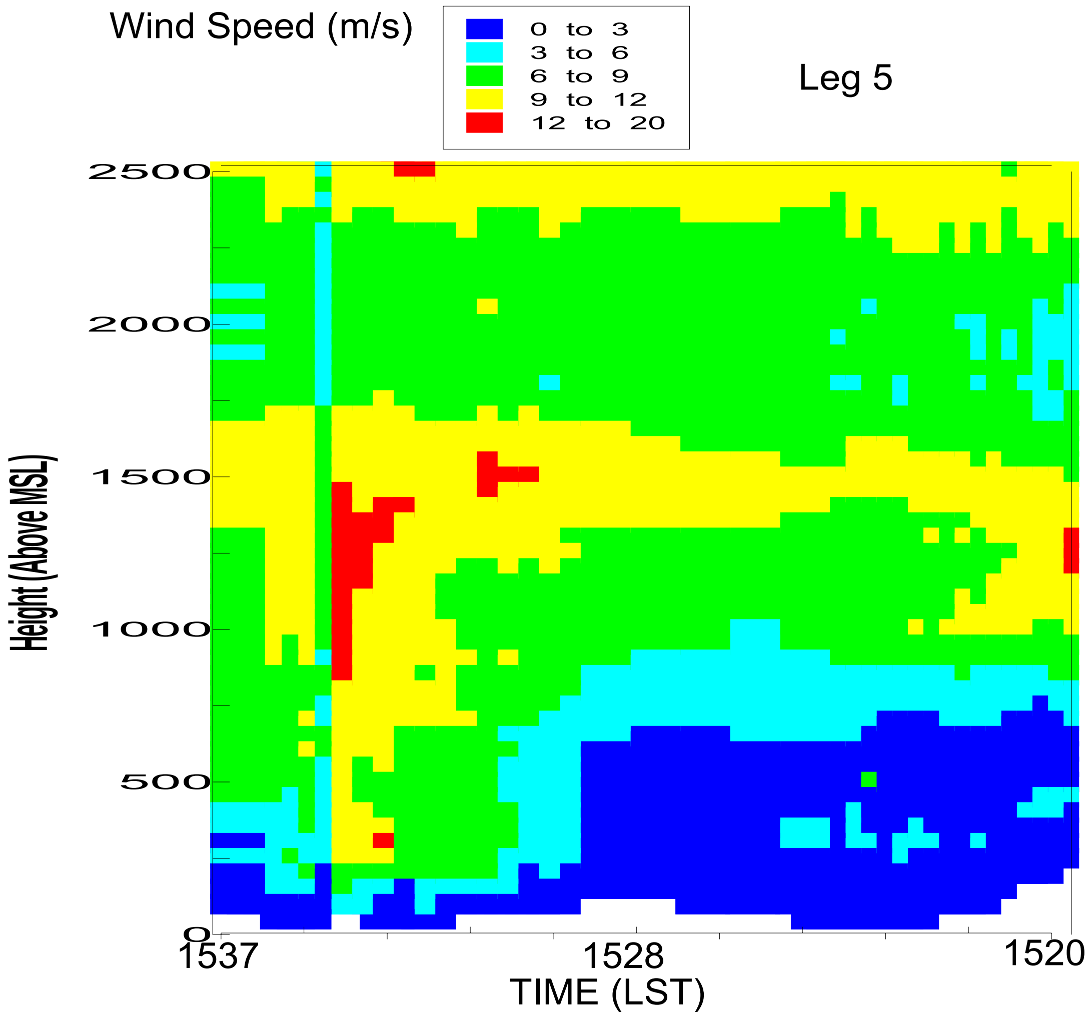

Figure 3: Z-t cross section of wind speed (m/s) along Leg 5 of November 12, 2007.

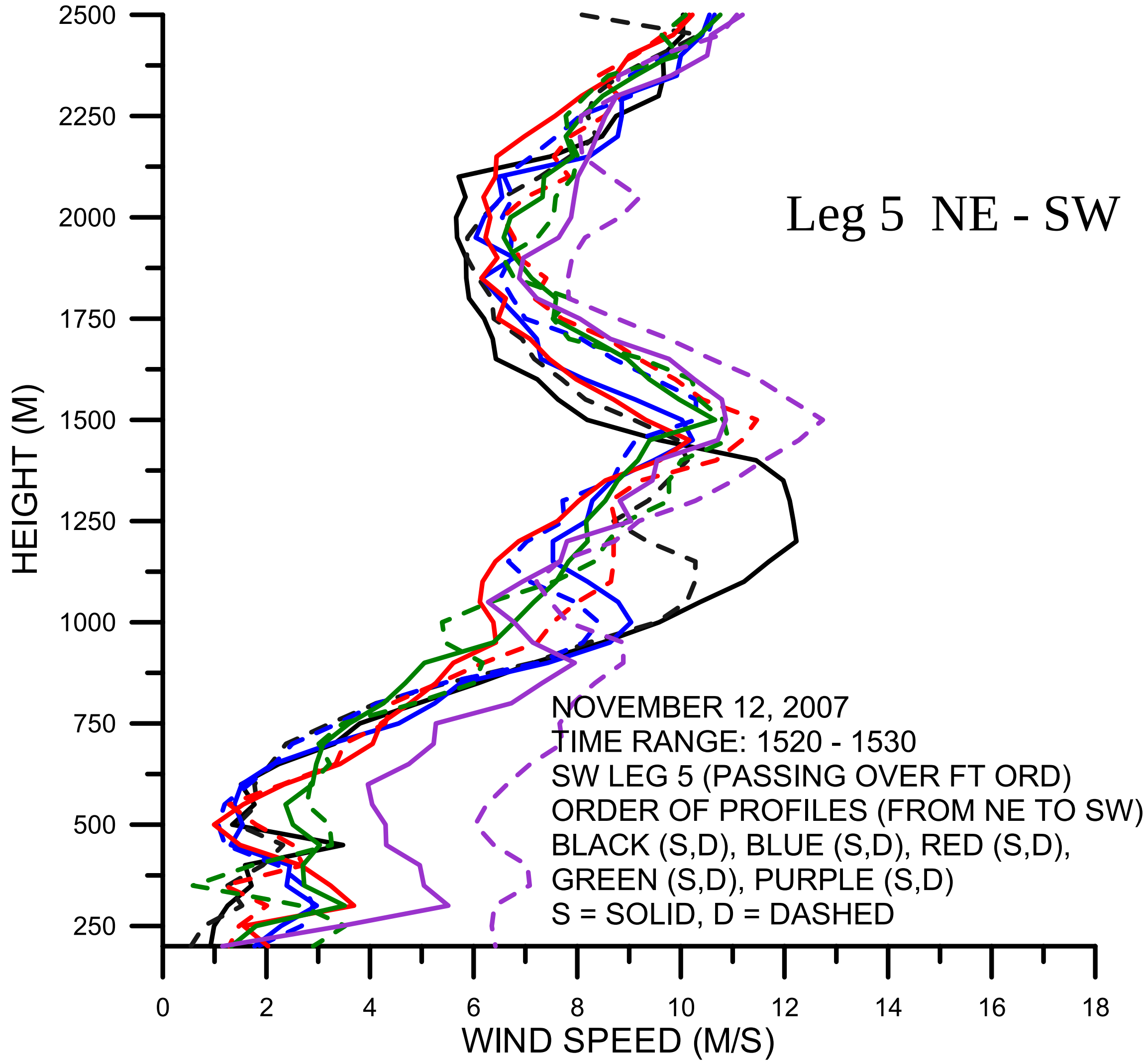

Figure 4: Individual profiles of wind speed (m/s) taken during Leg 5 of November 12, 2007.

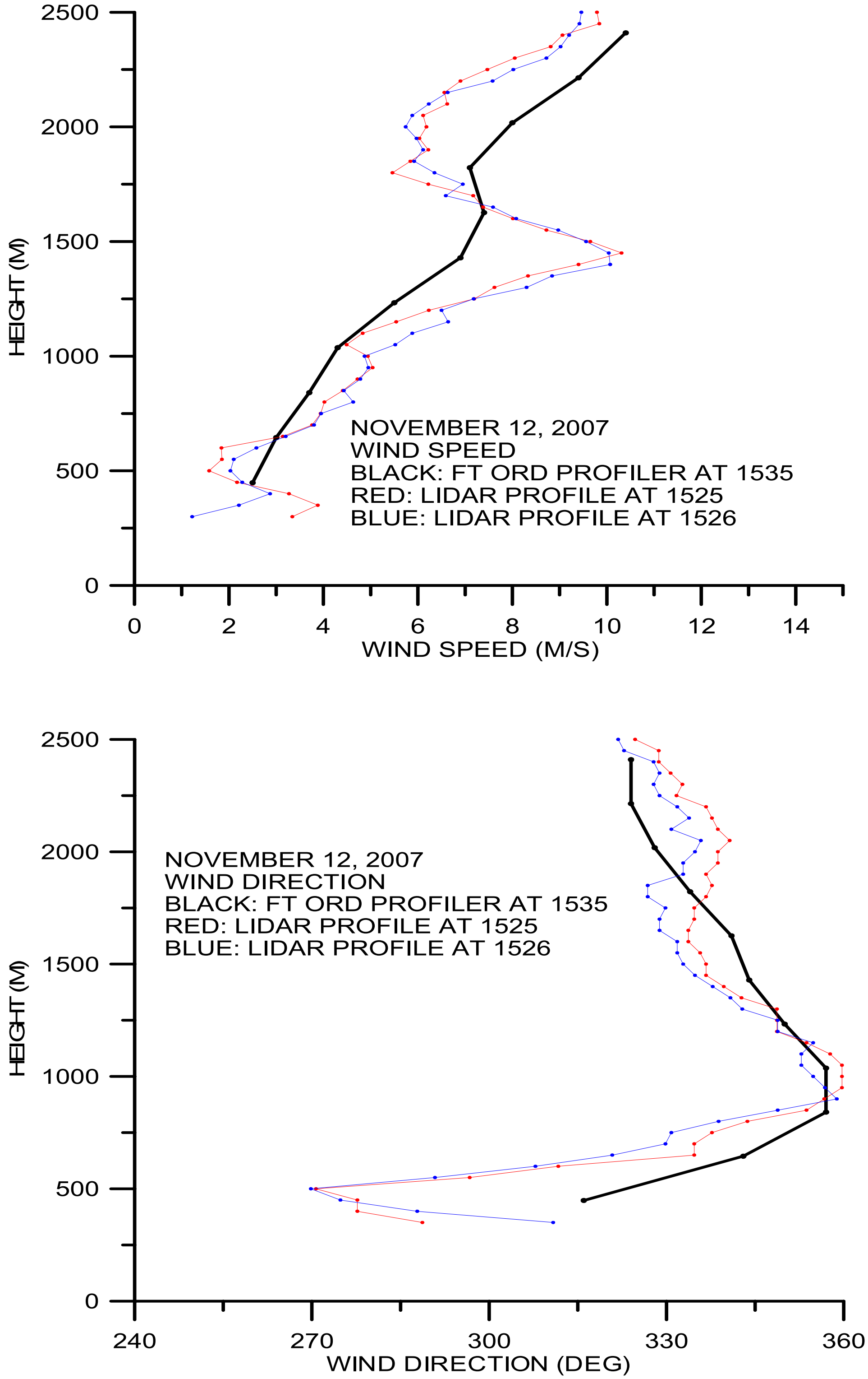

Figure 5: Comparison of TODWL sounding with an averaged sounding from the Ft Ord microwave sounder taken on November 12, 2002.

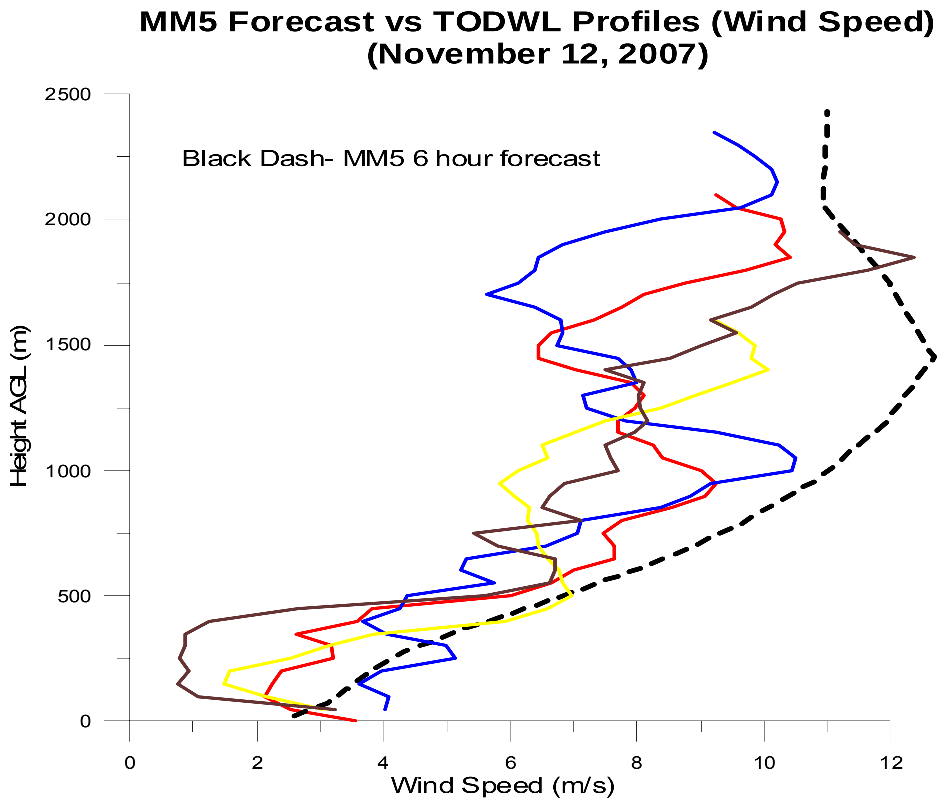

Figure 6: Comparison between MM5 6 hour forecast (black dash) at an individual grid point with a coincident and closest located TODWL profiles On Leg 5 of November 12, 2007.