P8.2 VALIDATION OF TROPOSPHERIC AIRBORNE METEOROLOGICAL DATA REPORTING (TAMDAR) TEMPERATURE, RELATIVE HUMIDITY, AND WIND SENSORS DURING THE 2003 ATLANTIC THORPEX REGIONAL CAMPAIGN AND THE ALLIANCE ICING RESEARCH STUDY (AIRS II)

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1. INTRODUCTION

The Tropospheric Airborne Meteorological Data Reporting (TAMDAR) sensor is designed to measure winds, temperature, humidity, turbulence and icing from regional commercial aircraft (Daniels, 2002). AirDat, LLC, developed the sensor under contract for NASA (Daniels, et al., 2004). A system of TAMDAR sensors and datalinks on a sufficient number of aircraft would provide high temporal- and spatial-resolution wind and temperature data in the lower troposphere. Such a system has the potential to substantially improve weather forecasting. Moreover, the high-resolution humidity data produced by TAMDAR is unprecedented, and may provide substantial benefits. The meteorological community is keenly interested in additional observations of the lower troposphere and in particular moisture data as evidenced by the American Meteorological Society Statement (AMS Council, 2003).

The University of North Dakota (UND) Cessna Citation II and the NASA ER-2 participated from November 19 to December 14, 2003, a period of overlap between two separate field campaigns, the 2003 Atlantic THORPEX Regional Campaign (ATReC) and the Second Alliance Icing Research Study (AIRS II). ATReC flights originated from Bangor, Maine, and were typically over the North Atlantic, while AIRS II flights were over Ottawa, Ontario and the Mirabel Airport outside Montreal, Quebec.

To support both campaigns, it was necessary to identify suitable cases for targeting, provide information on the location of sensitive areas, and have the facilities to control each observing system at short notice. Trans-Atlantic routing of commercial aircraft was a daily consideration. Early morning meteorological reports were used for daily aircraft routing. Additional information can be found on the website (Murray and Nguyen, 2003).

As part of the development process, the TAMDAR sensor has been tested in various ground-based facilities and on different atmospheric research aircraft (Daniels, et al., 2004). The subject of this report is validation of TAMDAR sensor using data other instruments installed on the UND Citation. Additional validation data came from GPS dropsondes (from the UND Citation). In addition, other data from two sounding instruments is used for comparison purposes.

Among the various instruments installed on the NASA ER-2 aircraft, the NPOESS Atmospheric Sounder Testbed Interferometer (NAST-I), MODIS Airborne Simulator, and the Scanning High-resolution Interferometer Sounder (S-HIS), are of particular interest (Murray, et al., 2003). NAST-I is designed to support the development of future satellite temperature and moisture sounders such as the IASI (Interferometer Atmospheric Sounding Instrument) on the METOP satellite (2005), the CrIS (Cross-track Infrared Sounder) on the NPP (2006) and NPOESS (2008–2010) satellites, and the HES (Hyperspectral Environmental Sensor) on the GOES-R satellite (approximate launch 2013).

The Atmospheric Infrared Sounder (AIRS) instrument is an infrared sounder on the AQUA satellite. Among the important parameters derived from AIRS observations are atmospheric temperature and humidity profiles. These parameters (used in this paper) are retrieved with the same methodology as that used with NAST-I data.

Sounding data from the AIRS and NAST-I instruments is used for comparison to TAMDAR and UND Citation in-situ data.

2. ATLANTIC THORPEX REGIONAL CAMPAIGN

The primary aim of the 2003 ATReC was to test the real-time quasi-operational targeting of observations using a number of platforms (including AMDAR, ASAP, ships, extra radiosonde ascents, research aircraft and

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meteorological satellites) (Truscott et al., 2003). ATReC was the first time that the real-time adaptive control of such a complex set of observing platforms was attempted.

ATReC had the goal of testing the hypothesis that the number and size of significant weather forecast errors over Europe and Eastern seaboard of the USA can be reduced by targeting extra observations over oceanic storm-tracks and other remote areas, determined each day from the forecast flow patterns.

3. ALLIANCE ICING RESEARCH STUDY II

AIRS II objectives were to: a) develop techniques to remotely detect, diagnose and forecast hazardous winter conditions at airports, b) improve weather forecasts of aircraft icing conditions, c) improve characterization of the aircraft icing environment and d) improve our understanding of the icing process and its effect on aircraft (Hallet, et al., 2003).

In order to support the AIRS II operational objectives, data was collected to: a) investigate the conditions associated with supercooled large drop formation, b) determine conditions governing cloud glaciation, c) document the spatial distribution of ice crystals and supercooled water and the conditions under which they co-exist, and d) verify the response of remote sensors to various cloud particles, and determine how this can be exploited to remotely determine cloud composition.

4. CASE STUDY

This paper examines data from a particular day during the two campaigns: December 5, 2003. As shown in figure 1, the aircraft flew through medium-level altocumulus associated with the mesoscale convective complex off the eastern seaboard of North America also depicted in the GOES visible image with flight tracks overlay. The ER-2 (at 65,000 ft.) and UND Citation (at 36,000 ft) flew a southward leg along a known Aqua ground track, then reversed course. Both aircraft then flew back along the same track while the Aqua satellite passed over at 17:46, local time. (This is also 63960 seconds from midnight, SFM). The overlapping flight tracks of interest have a time duration or "period of interest" from 16:35 to 18:30 (59400 to 66600 seconds from midnight), corresponding to the interval as described above.

A depiction of the flight configuration is shown in figure 2, where the UND Citation is shown flying directly below the NASA ER-2. The NAST-I instrument was carried onboard the NASA ER-2. In this manner, the UND Citation in-situ data would coincide with the NAST-I centermost (or nadir) downward pointing infrared retrieval.

The UND Citation aircraft is instrumented for in-situ cloud physics research. For these field campaigns the TAMDAR sensor package was installed, and the aircraft was equipped to deploy NCAR GPS dropsondes. The UND Citation, shown in figure 3, dropped four GPS sondes at various times during the period of interest.

The NASA ER-2, shown in figure 4, carried the NAST-I instrument. The temperature sounding data are retrieved from NAST-I infrared hyperspectral radiances (Zhou et al., 2002). NAST-I data were searched for the location where and time when the ER-2 and the Citation were collocated within a delta Latitude <= 0.05º, delta Longitude <=0.05º, and delta time <= 5 min. Mean values for temperature of NAST-I retrievals within the matching criteria are computed and reported as NAST-I temperature data.

Flight tracks of the two aircraft for the period of interest are shown in figure 5. Note that the UND Citation deviates from the ER-2 track slightly (as pilots tried to underfly the 17:46 overpass track of the Aqua satellite). This slight deviation results in the loss of available comparison data from the NAST-I instrument.

No icing was detected during the flight period of interest. As a result, the TAMDAR de-icing heaters remained off, and all TAMDAR data is valid.

On the case study day, a lack of UND Citation RH data was discovered. Both moisture instruments were not functioning properly. The EG&G dewpoint hygrometer was miscalibrated. Although not listed in table 1, a tunable diode laser (TDL) was also installed on the UND Citation. The TDL measures water vapor concentration via IR absorption of water vapor. An examination of dewpoint temperatures from the TDL results in values of -60º C and lower. This instrument was not calibrated for values below -60º C, and data "dropouts" were occurring.

4.1 Temperature

The temperature accuracy for the TAMDAR sensor is ±1°C. To verify this value, a comparison to UND Citation Rosemount Model 102 Probe sensor data over the period of interest and also over the entire day's flight is made. The Rosemount sensor accuracy is 0.5° C.

Figure 6 is a plot of the temperature as compared between the UND Citation and TAMDAR over the period of interest. Both sets of values are corrected for dynamic heating. A percent difference was computed between the TAMDAR and UND Citation values. From this difference, the mean and standard deviation were computed. A comparison to the UND Citation temperature yields a mean difference of -0.38°C and a standard deviation of 0.5°C.

In addition, GPS dropsonde data is also shown in the comparison plot of temperature on figure 6. Dropsonde temperature values are valid about 20-30 seconds after launch. The initial value of temperature as reported by the dropsonde is used here. Also shown in figure 6 is available NAST-I and AIRS temperature data.

A temperature correlation between UND Citation and TAMDAR for the entire duration of this day's flight, from take-off to landing, is shown in figure 7. A linear regression line is also plotted with correlation $R^2 = 0.99$.

4.2 Humidity

The TAMDAR sensor has two independent RH sensors. As both were reporting very similar values, only data from one is used for this comparison. The reported RH accuracy is +/- 5%. To verify this value, a comparison to GPS dropsonde data is made as shown in figure 8 over the period of interest.

The initial dropsonde values for relative humidity are often reported about 60-75 seconds after launch. The values shown in figure 8 are converted using the Hyland and Wexler formulation (Hyland, 1983). Using the four values of RHi, a mean difference with TAMDAR is computed as 3.4% and the standard deviation of the differences is 4.9%.

Moisture sounding data is also retrieved from NAST-I infrared hyperspectral radiances. A comparison for NAST-I relative humidity (computed with respect to ice) is also shown in figure 8. Measurements for relative humidity at corresponding altitude are unavailable from the AIRS instrument.

Since the times of the satellite and aircraft observations were not close enough to account for the same moisture variation, the AIRS relative humidity data set is not used here.

4.3 Wind Speed and Direction

The TAMDAR sensor computes wind speed and direction from measured airspeed, aircraft (UND Citation) magnetic heading, and GPS ground track. TAMDAR wind vector magnitude accuracy is +/-3.08 m/s (+/- 6 knots). To verify this value, a comparison to UND Citation nose probe sensor winds is made.

Figure 9 is a plot of wind magnitude comparison between TAMDAR and the UND Citation. The mean difference between the UND Citation and TAMDAR for wind magnitude is only -1.02 m/s and the standard deviation of this difference is 3.1 m/s.

Initial values from each of the four NCAR GPS dropsondes is shown in the comparison figure along with corresponding data from the UND Citation and TAMDAR sensor. Initial dropsonde wind values are typically reported about 20-30 seconds after launch.

A wind magnitude correlation plot is shown in figure 10 for data over the entire day's flight. A linear regression is computed and shown on the same plot. The correlation for wind magnitude is $R^2 = 0.98$.

Figure 11 is a comparison plot of wind direction. The mean difference between TAMDAR and the UND Citation for wind direction is only -0.22° and the standard deviation of this difference is 0.85°.

Figure 12 is a correlation plot of TAMDAR to the UND Citation over the entire day's flight. The correlation for wind direction is $R^2 = 0.90$.

5. CONCLUSIONS

The intent of this paper is to use in-situ temperature, relative humidity, and winds aloft data from the UND Citation as a reference to compare all other measurements against. With the exception of the problems noted with the UND Citation relative humidity data, the reference data it provided proved to be highly valuable.

While the dropsonde values are also considered reference values, the individual measurements usually start reporting after some time delay. The assumption is made that each different sensor measured air samples of sufficient similarity to make a comparison. Since some corrections due to pressure are made to the temperature, relative humidity, and winds values, it is understood that there will be some deviations from the dropsonde data.

The TAMDAR sensor performed within its specifications for accuracy. Sensor specifications are listed in (Daniels, et al. 2004). Data from both UND Citation and TAMDAR sensors compare favorably to the four dropsondes. NAST-I temperature values compare favorably to UND Citation and TAMDAR data. The AIRS data also compares favorably with the results from the other instruments.

In summary, the TAMDAR sensor performed very well over the entire period of the two field campaigns. The data from this new sensor compares favorably with the other instruments.

6. ACKNOWLEDGMENTS

The authors would like to express their gratitude to the Bangor Airport staff and the ER-2 and Citation flight crews and pilots.

7. REFERENCES

American Meteorological Society Council, "Support for Automated Observations from U.S. Commercial Aircraft," *Bull. Amer. Met. Soc.*, 84, 515—517, Adopted by AMS Council on 9 February 2003.

Daniels, Taumi, "Tropospheric Airborne Meteorological Data Reporting (TAMDAR Sensor Development," 2002-02-153, *SAE General Aviation Technology Conference and Exposition*, April 16-18, 2002, Wichita, KS.

Daniels, T. S., G. Tsoucalas, M. Anderson, D. Mulally, W. Moninger, R. Mamrosh, 2004: "Tropospheric Airborne Meteorological Data Reporting (TAMDAR) Sensor Development," *11th Conf. on Aviation, Range, and Aerospace Meteorology*, Oct. 4-8, 2004, Hyannis, MA.

Hallet, John, G. Isaac, M. Politovich, D. Marcotte, A. Reehorst, C. Ryerson, "AIRS II Science Plan," July 2003,http://www-angler.larc.nasa.gov/bangor/docs/AIRS_SciencePlan_July7.pdf

Hyland, R. W. and A. Wexler, "Formulations for the Thermodynamic Properties of the saturated Phases of H2O from 173.15K to 473.15K," *ASHRAE Transactions*, 89(2A), 500-519, 1983.

Murray, John, L. Nguyen. NASA Langley ATReC & AIRS-II Satellite Page, http://www-angler.larc.nasa.gov/bangor/ , November 2003

Murray, John, W. Smith, Sr., T. Daniels, P. Minnis, M. Kapitzke, M. Poellet, M. Avery, H. Revercomb, M. McGill, J. Myers, "Alliance Icing Research Study II, Science Plan Appendix E," November 14, 2003, http://www-angler.larc.nasa.gov/bangor/docs/NASA_LangleyAIRSII.pdf

Truscott, Bruce, D. Richardson, "Atlantic THORPEX Observing System Test Project Plan," August 22, 2003, EUCOS/SP/105

Zhou, Daniel K., W. L. Smith, J. Li, H. B. Howell, G. W. Cantwell, A. M. Larar, R. O. Knuteson, D. C. Tobin, H. E. Revercomb, and S. A. Mango, 2002: "Thermodynamic product retrieval methodology for NAST-I and validation," *Applied Optics*, 41, 6957–6967.

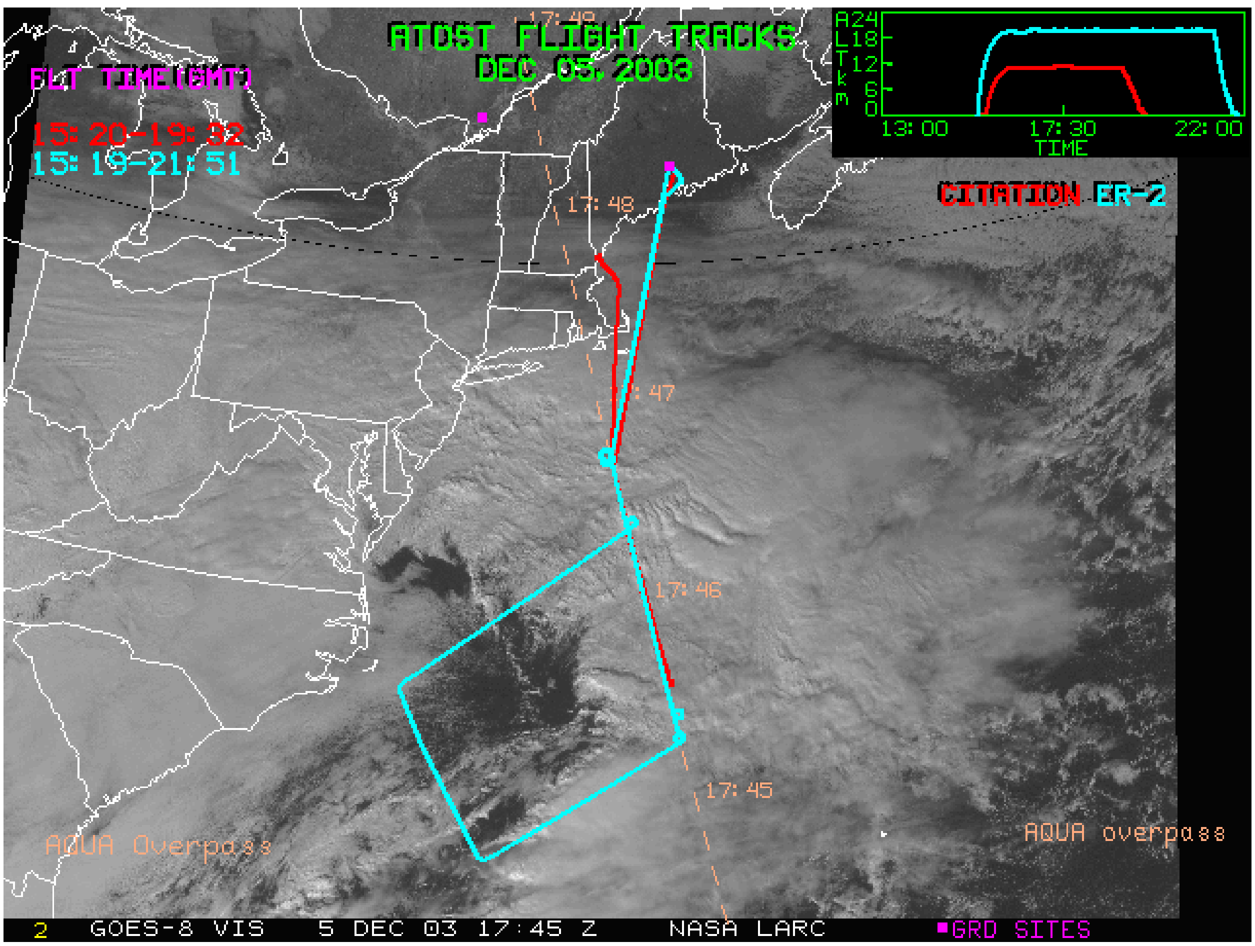

Figure 1. Case Study GOES Image and Flight Tracks

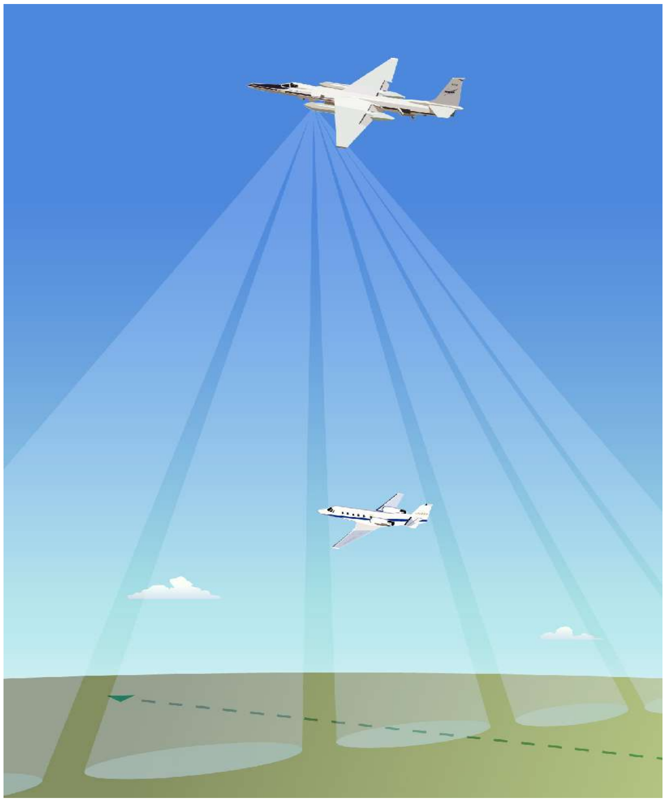

Figure 2. NASA ER-2 Over-flight of the UND Citation

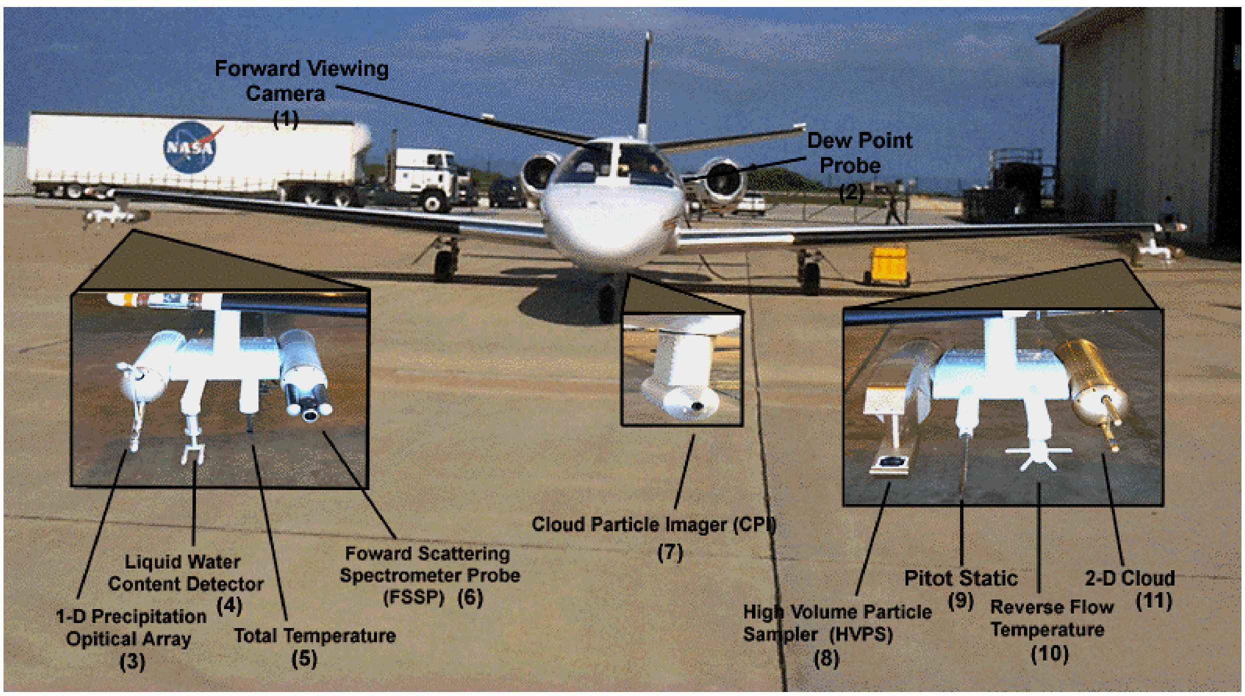

Figure 3. UND Cessna Citation II with Instrumentation

Figure 4. NASA ER2

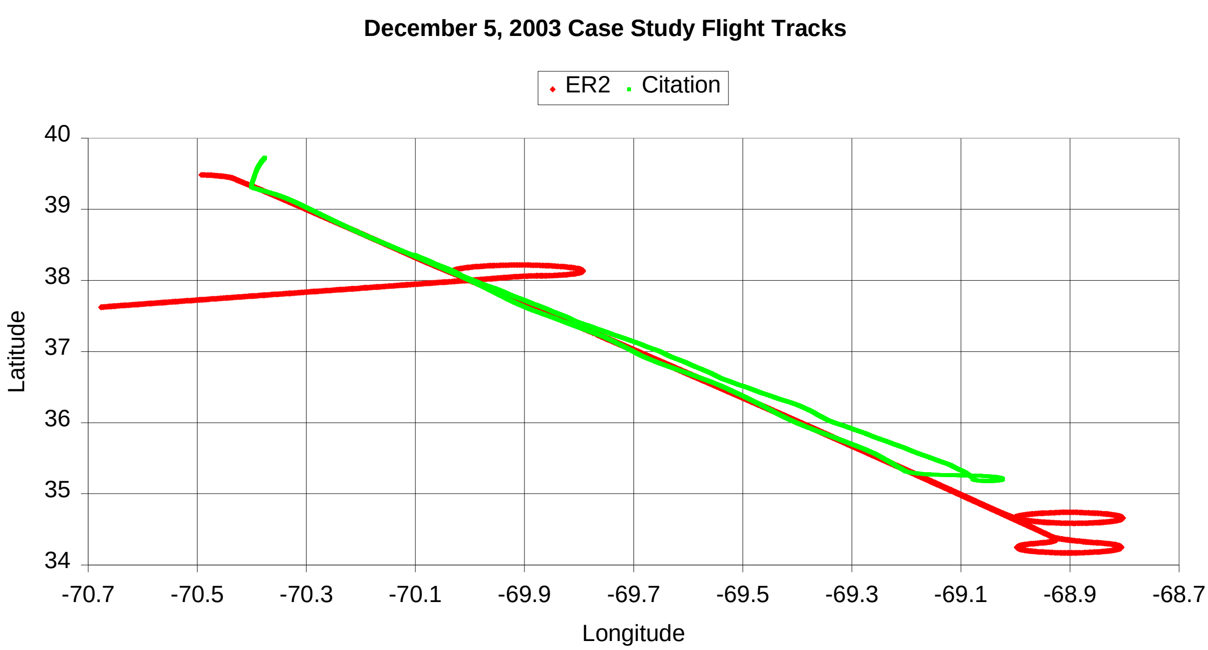

Figure 5. Flight Tracks from 59400 SFM to 66600 SFM

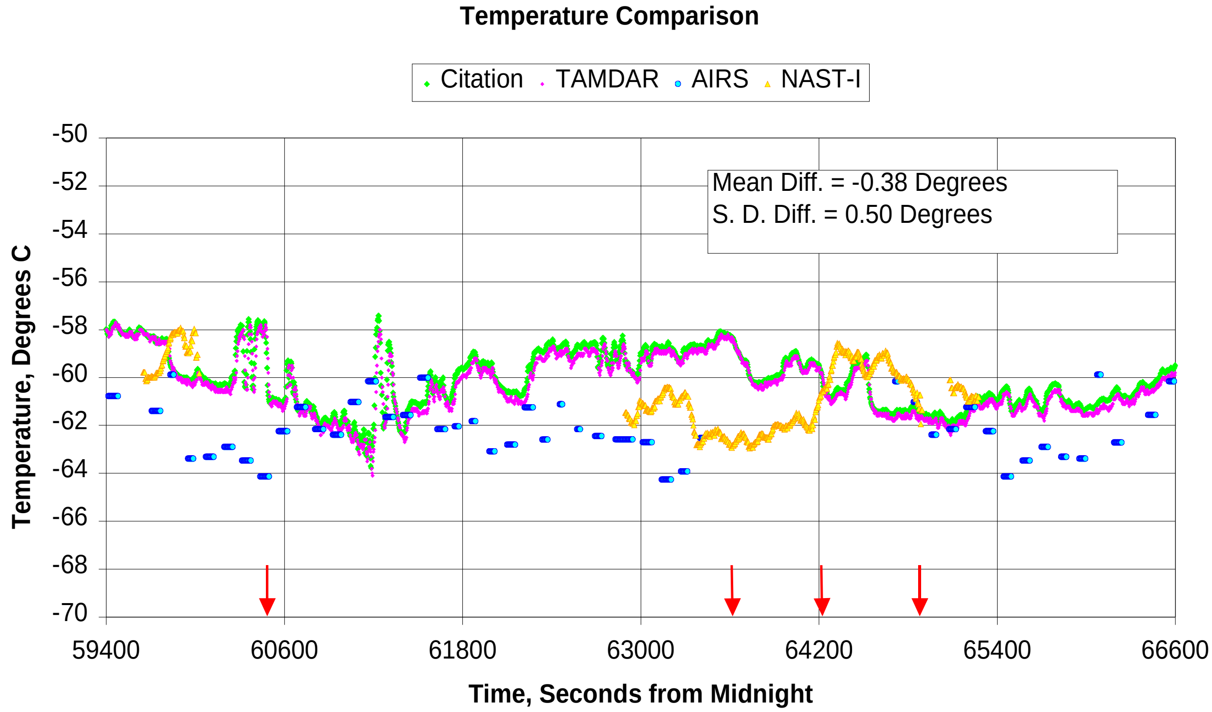

Figure 6. Temperature Comparison

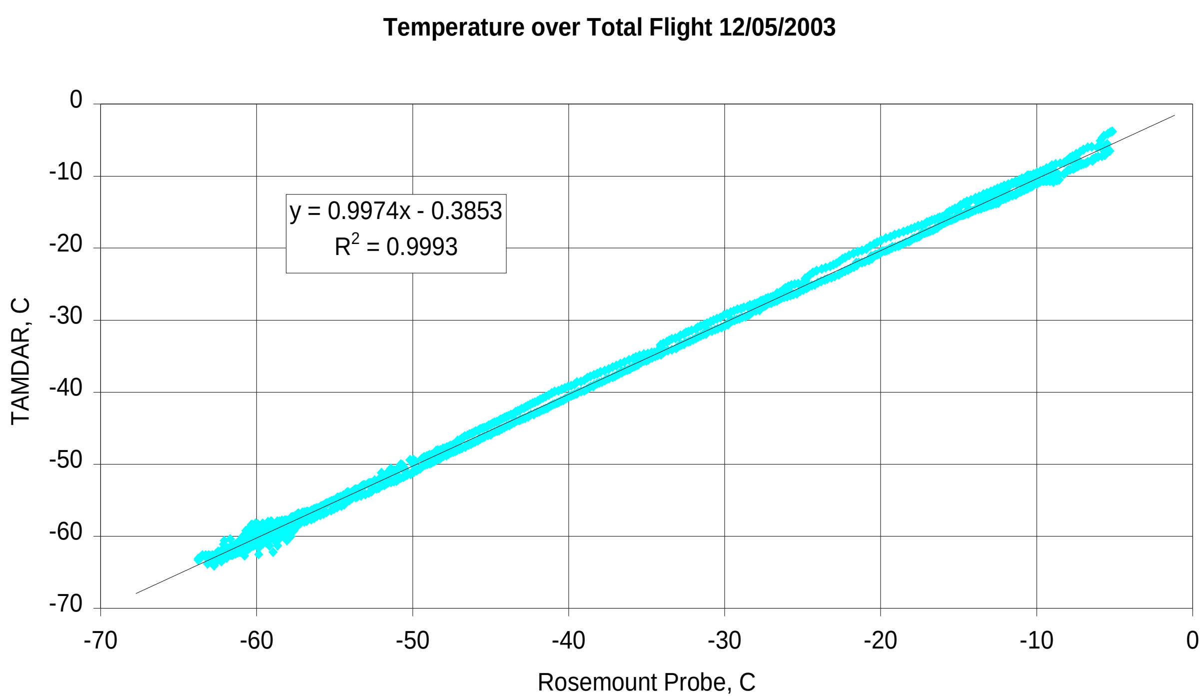

Figure 7. Temperature Correlation

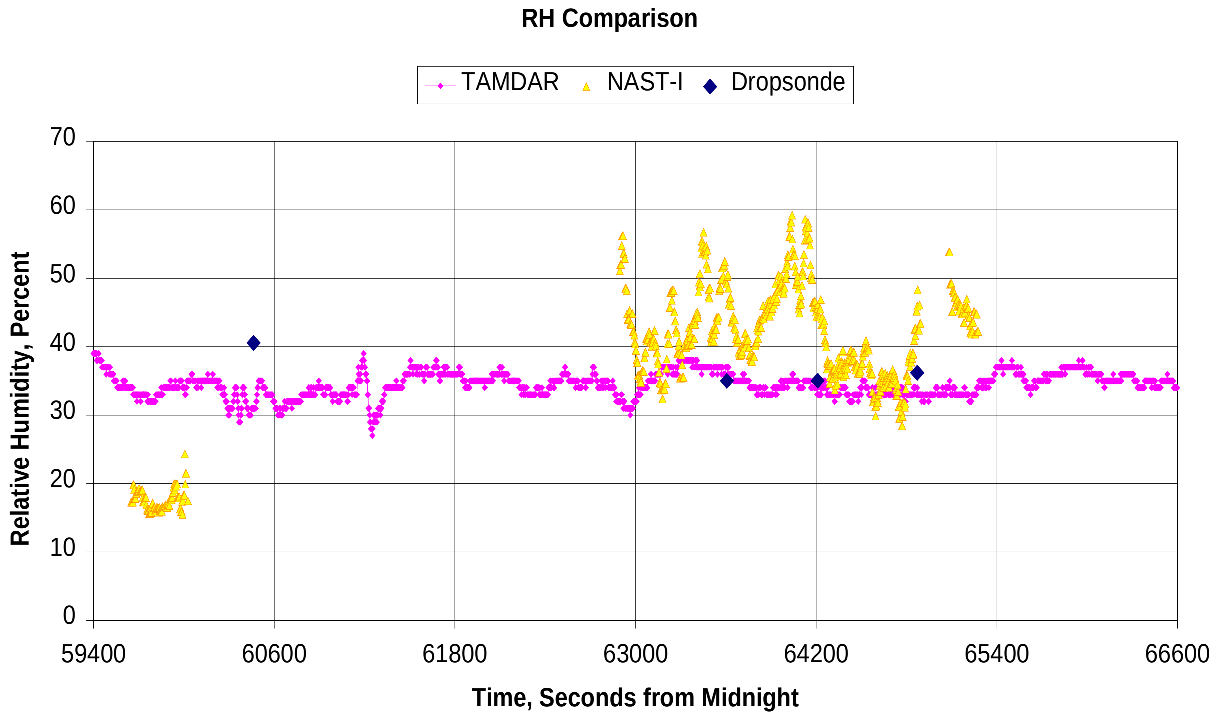

Figure 8. Relative Humidity Data

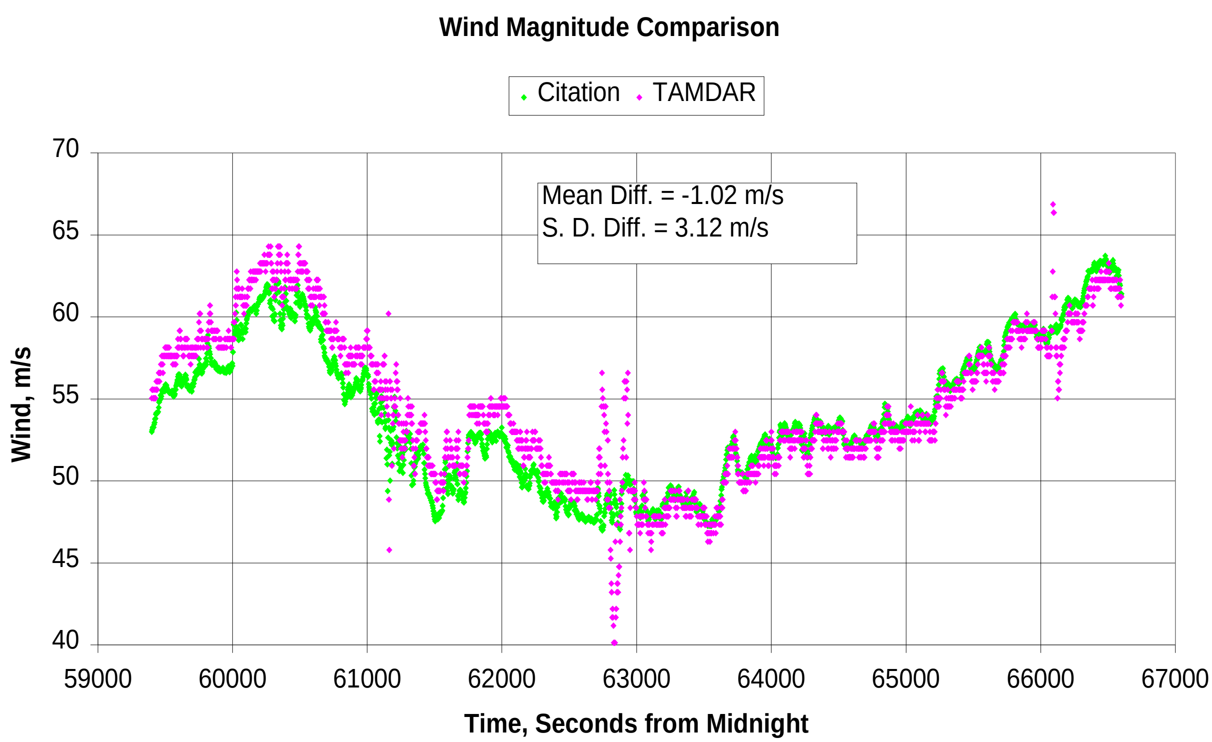

Figure 9. Wind Magnitude Comparison

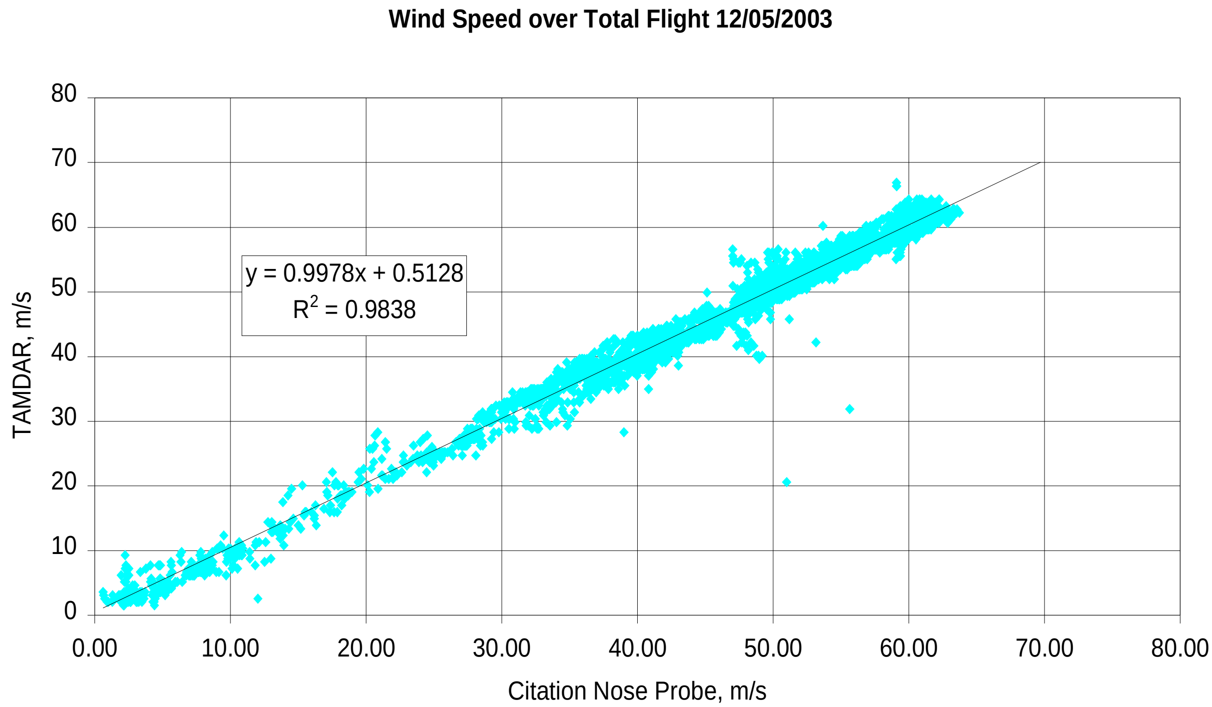

Figure 10. Wind Magnitude Correlation

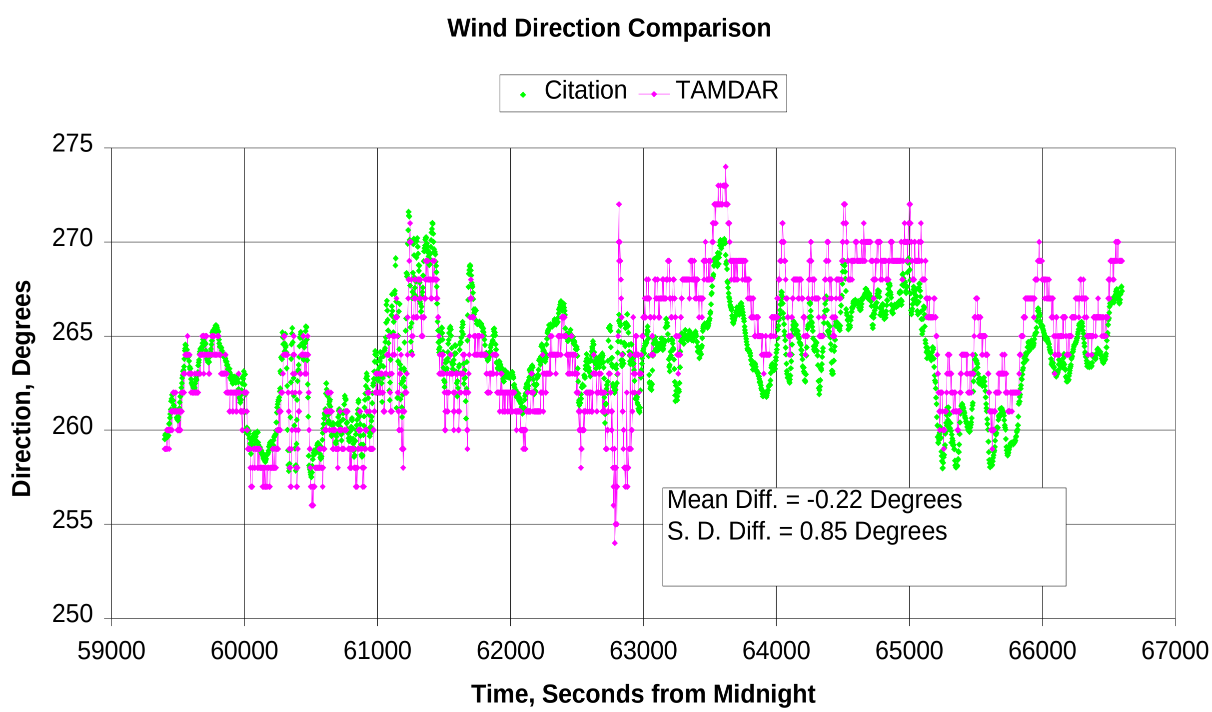

Figure 11. Wind Direction Comparison

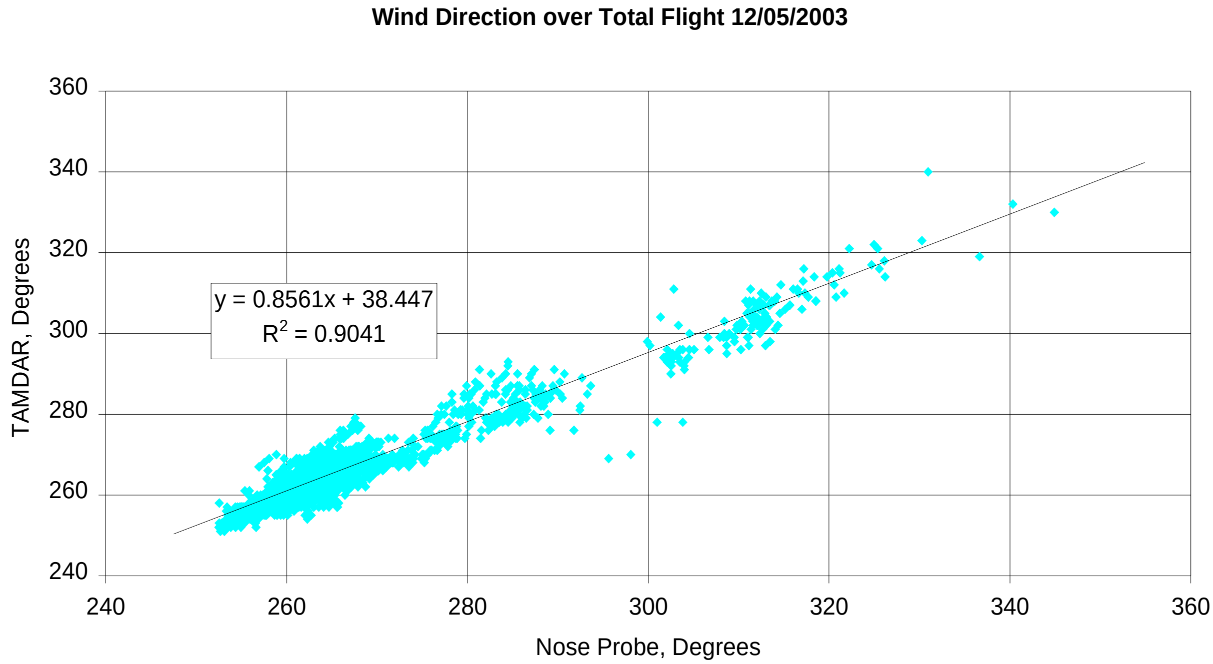

Figure 12. Wind Direction Correlation