

# **Intensive “porpoising” with a research aircraft to determine atmospheric structure during the SALLJEX and NAME programs**

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## **ABSTRACT**

Two recent field programs have focused on describing aspects of low-level jets in the Americas. Both programs have used NOAA WP-3D research aircraft to make mesoscale measurements about the jets, with the object of describing the 3-dimensional structure of the flow over relatively large areas. During both field programs the WP-3D was used as a probe, with the aircraft moving vertically while carrying out flight patterns that were mostly predetermined. The object was to describe both the horizontal structure of the jets while also describing the vertical variation of the flow. This involved trade-offs in the design of the flights. The SALLJEX flights sampled a deeper jet flow, necessitating greater vertical coverage and lesser horizontal resolution. The NAME flights were intended to sample a shallow jet that was confined in part by topography. This presentation summarizes the advantages and disadvantages of using the aircraft in a porpoising mode, with examples drawn from both experiments. The objective is to explain the benefits (and limitations) of the porpoising procedure and discuss how it may be employed most effectively.

## **1. Introduction**

There are many strategies to sample the atmosphere with an instrumented aircraft. Research aircraft have been used to deploy dropsondes, to carry airborne meteorological radars or other remote sensors, or to directly measure meteorological quantities from the aircraft itself. In this paper we discuss some observing strategies that have been used for years, but not discussed in the formal literature. Specifically, we will describe the use of meteorological research aircraft to measure the three-dimensional structure of the atmosphere through special flight patterns. These patterns were extensively employed during the recent SALLJEX and NAME field programs. Although we focus on NOAA WP-3D aircraft activities and characteristics, the concepts are applicable to any turboprop aircraft, and, to a somewhat lesser degree due to performance differences, to jet aircraft.

There are a variety of possible sampling strategies for an aircraft to measure the atmosphere. The aircraft can carry remote sensors, such as a meteorological radar or radiometers to indirectly measure certain characteristics of the atmosphere. This has certain advantages, such as the ability to remain away from dangerous weather or terrain conditions, or to sample larger areas than in-situ measurements. Other approaches to sampling the atmosphere with a research aircraft include deploying dropwindsondes (DWS's) to obtain profiles and using the aircraft itself as a probe. The advantages and disadvantages of these strategies form the topic of the next section.

Before discussing the details of aircraft operating strategies, it is important to stress one point. *Use the aircraft for what it can uniquely provide.* Given the high cost of operating a research aircraft its time should be used as effectively as possible. Over the ocean an aircraft may be the only in-situ measurements platform, but over land areas there may be many other possible potential observing systems. The aircraft excels at providing high horizontal resolution measurements, but cannot provide deep soundings effectively. A mix of radiosonde soundings (providing deep tropospheric thermodynamic soundings), wind profiler measurements (providing high time resolution winds) and surface measurements (to measure what the aircraft cannot) is always a desirable complement to an aircraft program, and often at a much lower cost than the aircraft component. These should all be considered as part of a field program to compliment aircraft operations, so that the aircraft is used efficiently.

## **2. Overview of different strategies for sampling the atmosphere with research aircraft**

Many research flights have the objective of measuring both the horizontal and vertical structure of the atmosphere over a region. There are perhaps three main procedures for measuring the atmosphere in 3-dimensions from an aircraft flight pattern. The relative benefits and disadvantages of each are discussed in this section.

### *Dropwindsonde (DWS) deployment*

This procedure has the notable advantage of being able to provide the greatest vertical coverage of the strategies to sample the atmosphere. Since the aircraft usually flies faster at higher altitude and also operates more efficiently in most cases, the range of the aircraft is improved and the time required to fly a specific pattern is reduced. Specialized jet aircraft exist to provide DWS coverage, most notably the NOAA Gulfstream IV, used for hurricane reconnaissance.

Despite the obvious advantage for synoptic-scale coverage, the DWS mode of operation does have some significant limitations. The aircraft generally flies at the highest altitude possible, not the level of greatest scientific interest. Thus the aircraft's flight level measurements are of secondary value during the flight. The cost of DWS's is not entirely insignificant, at ~\$600 each, and they cannot be dropped at a sustained rate more often than about every 5 minutes, which limits the spatial separation of soundings to 30-50 km or more. Another, less readily recognized problem is that if a sonde fails during descent it is difficult to make another sounding in the desired location, and a less-than-desirable gap in the data results. Error detection depends on comparison with neighboring measurements, so the effective resolution is several times the drop interval, so that mesoscale investigations with DWS's is not always satisfactory.

### *Multi-level sampling*

In this approach the feature of interest is identified geographically and flight patterns at discrete levels decided upon. The objective of maintaining fixed flight levels is to provide continuous measurements at these levels. The primary advantage of this sampling strategy is to measure sharp horizontal gradients as accurately as possible, since the aircraft data is usually recorded at least once per second, giving a spatial sampling of ~ 100m. Constant flight levels also ideal for

locating centers of circulation, such as the position of a hurricane eye. This approach is also necessary if the aircraft is to make turbulent flux measurements at multiple levels.

A significant drawback to the multilevel sampling strategy is that the separation in time between the first part of the first flight level and the last time of the last level can approach the duration of the flight. This makes interpreting the vertical structure of the atmosphere difficult if there are rapid changes taking place. This is commonly the situation in the middle latitudes, where it may be difficult to fully account for the evolution of the synoptic flow during a flight of perhaps 8 hours. If the feature of interest is primarily translating - a hurricane would be a good example, then all of the observations can be adjusted in space to produce an analysis valid for a particular time. However, with multiple aircraft flight levels, even a small error in estimating the translation could lead to serious errors in the vertical structure of a mesoscale feature. Even worse, evolution of the atmospheric patterns also usually is observed and simple translation is usually not sufficient. This is most evident where the flight tracks at different times of the flight overlap - and show differing observations.

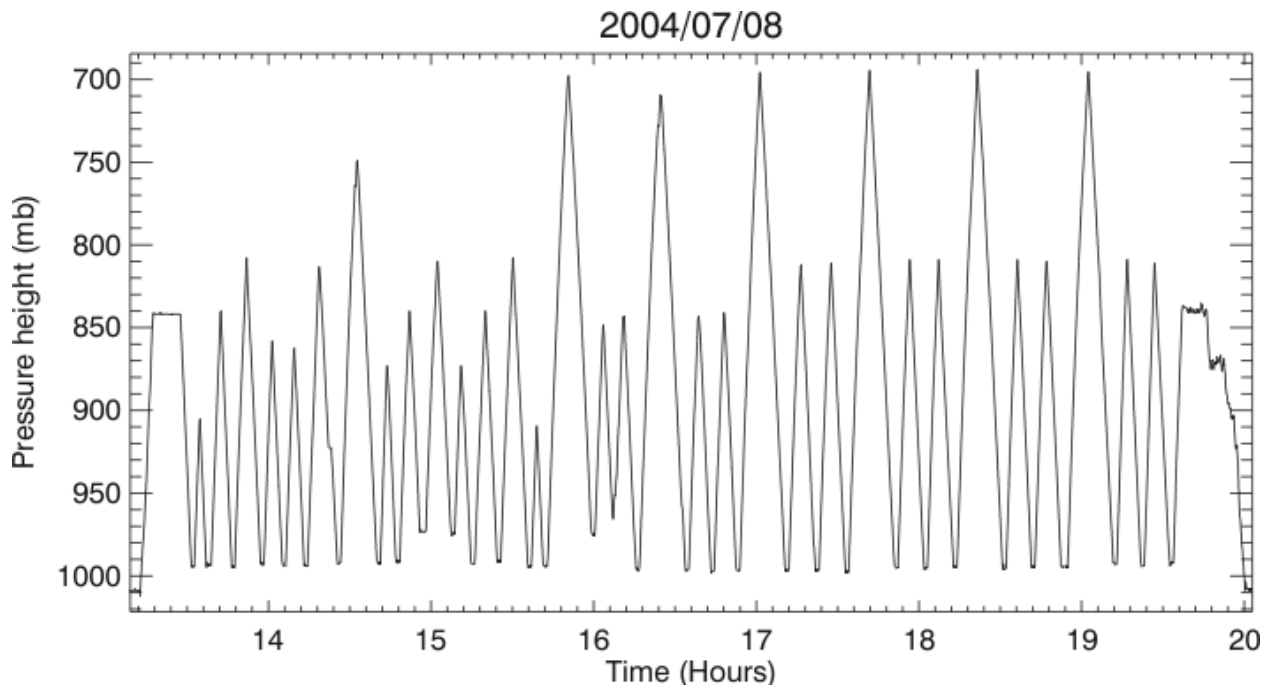


Fig. 1. Pressure versus time plot from the NOAA WP-3D during a flight on 08 July 2004. Note the porpoising between about 990mb (500ft ASL) and ~700mb. The climbs to 700mb were made only every third ascent to maintain better spatial sampling at lower levels; these were done over a uniform region without strong gradients.

### *The porpoising, or vertical sawtooth pattern*

A flight pattern that has some advantages over the multi-level approach is commonly called the porpoising pattern, as the aircraft flies a pattern that resembles the motion of a porpoise. The aircraft ascends and descends between selected levels, so that along a chosen track data is

collected throughout a layer. Figure 1 shows such a flight carried out during the NAME campaign. The porpoising pattern has a significant advantage over DWS patterns in that all of the meteorological measurements are made by the same set of sensors, whereas each DWS profile is made by a separate set of sensors. This makes measurement of small meteorological gradients easier with the porpoising data, since only one set (one for each measured parameter) of systematic sensor errors is involved. For many tropical measurement campaigns this is a crucial advantage that is often overlooked.

### **3. Porpoising flights -some details**

#### *Capabilities of the aircraft*

(Note: In the discussion below we use, based on our experience, the NOAA WP-3D research aircraft as the example. However the results we discuss are applicable to a wide variety of aircraft. )

The climb rate of the aircraft and the horizontal speed of the aircraft are key factors in determining how rapidly soundings can be made with the aircraft and what the final spacing of sounding will be. For example, if a horizontal spacing of soundings of 50km is the minimum acceptable, then with an ascent rate of 5m/s and a horizontal aircraft velocity of 100m/s it will be possible to ascend or descend approximately 2500m in the time required to fly 50km (500s). Precise planning requires specific knowledge of the particular aircraft to be used, this is sometimes not always available to those not already experienced in aircraft operation. For a NOAA WP-3D aircraft, a 4-engine turboprop aircraft, the horizontal velocity during an ascent can vary from 100-135 m/s, depending on altitude (and power setting of the engines). In the SALLJEX and NAME activities the aircraft ascended and descended near 1200 ft/min (~365m/min); note that English units of feet and knots are generally used in aircraft operations. This ascent rate was sustainable up to about 10 Kft (~3000m), a fully-fueled aircraft early during a flight could not climb this fast at higher altitudes. Although fuel consumption is greater than during level flight it is not excessively so, with nearly continuously porpoising 8-hr flights having been carried out by the P-3.

Examining Fig. 1 shows that there is a special characteristic of porpoising flights – the observations are not uniformly spaced at each level (as might be DWS observations). Near the top of each ascent and the bottom of each descent the observations will be close together in space, while half way up or down a sounding the observations will be most uniformly spaced. Because the uppermost observations were considered less useful than the lowest part of the soundings during SALLJEX and NAME the aircraft did not remain long at the highest altitude, but essentially began to descend immediately upon reaching the intended altitude. However, because the lowermost observations in a sounding were more valued, and also more variable (due to their boundary layer nature), the aircraft remained at the lowermost level usually one or two minutes. This allowed for the bottom values to be averaged, and also provided some spatial separation between the end of the descent and the beginning of the ascent, so that the measurements would not sample the same microscale conditions. An appreciation for the spatial separation of the data can be seen in Fig. 2, which shows the observations near the top, bottom, and middle of most of the soundings made during one flight.

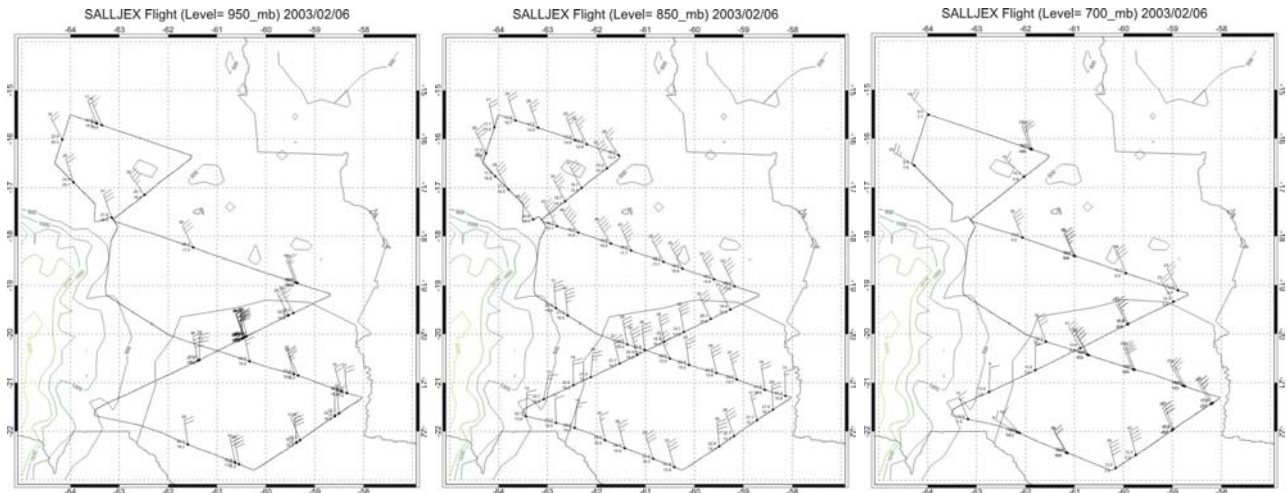


Fig. 2. Winds from NOAA WP-3D during porpoising pattern over eastern Bolivia and western Paraguay, 06 Feb 2003. Left panel is at 950mb, center panel is at 850mb and right panel is at 700mb. Note the more uniform spacing of the observations at 850mb, near the midway point between the top and bottom of the soundings.

Other factors to consider when planning a porpoising mission would include the impact that porpoising might have on other aircraft sensors, such as radars or other remote sensors that might require a particular orientation.

Given that a knowledge of the aircraft climb rate and speed is presupposed, the design of a porpoising pattern requires an expectation of the most valuable layers to sample with the aircraft. Usually this is from the lowest-level that can be flown (safety requires certain minimum altitudes during the daytime over land and at night) to some higher level. The higher the maximum altitude of the porpoise, the longer it will take and the greater the horizontal separation of each sounding. There is a trade-off between maximum depth of the sampled layer and the horizontal spacing of the soundings and these two need to be adjusted to satisfy the desired research objectives. Usually the depth of the porpoise can be adjusted during the flight, depending upon the conditions observed, so that finer spatial sampling is possible in some areas and less in others (Fig. 1).

#### *Horizontal track of the aircraft*

A porpoising transect provides two-dimensional data, while the variation of the aircraft's track across the study region provides the opportunity to obtain three-dimensional structure. Although there are infinite possibilities, often the flight track is chosen normal to the anticipated strong meteorological gradients. If done in several locations this provides sufficient data to describe both the along-gradient and across-gradient structure. An example of this is shown in Fig. 2, where the objective was to sample both along and cross-flow gradients.

#### *Time changes during the flight*

Unless the flight is intended specifically to describe the evolution of an atmospheric feature, the flight track should be designed to minimize the analysis complications that might be introduced

by synoptic or diurnal changes that take place during the flight. The objective is usually to obtain a “snapshot” of the atmosphere for diagnostic purposes. Naturally, the shorter the flight segment that will be analyzed, the better. It is often a productive use of aircraft time to repeat a small portion of the main pattern, so that the extent of time-changes can be assessed. This can often be done during the return to the aircraft’s base of operation, but before the aircraft has left the region of primary scientific interest.

### *The diurnal cycle*

Unless the diurnal cycle is the focus of the flight, it is usually desirable to minimize its effect on the measurements. Over ocean flights, far from land are the least susceptible to significant diurnal effects, those these still exist – especially with cloudiness. There are always small (~ a few mb) diurnal pressure tides that affect the flight level of the aircraft (since most flights fly on a constant pressure surface rather than radar (or geometric altitude), but these can be adjusted for (thought rarely done). Over land surfaces the diurnal changes are usually largest, and this can be in all parameters. Commonly, the depth of the boundary layer changes rapidly during the morning hours, clouds may form, and the temperature and humidity profiles change. These changes are unavoidable if the flight is long enough. However, flights can often be designed to be divided into segments that can be treated as occurring at the same time to simplify the analysis of the data.

### *Nighttime and daytime flights*

Although in principal research flights may be carried out either at night or during the daytime, and in fact night flights may be essential for many objectives, there are some adverse consequences of night operations that should be recognized beforehand. First, minimum altitudes above the ground are higher at night; they are usually 2000 ft above the highest topography in the sector. Since a navigation error could lead to the aircraft hitting a peak, this restriction is particularly serious and makes aircraft research in mountainous areas essentially a daytime activity. During daytime, 1000 ft above the surface is generally permissible anywhere, even if mountains are nearby, provided visibility exists.

A second advantage of daytime flying is the possibility of using visual cues to adjust the flight. Cloud features are much more evident during the day, and smoke from the surface and similar such features can help interpret the meteorology of the near surface layer. Also, cloud photography, either video or still, is usually not useful at night.

### **The SALLJEX and NAME experiences**

Two recent field experiments that used the NOAA WP-3D aircraft illustrate the procedures discussed above and further discuss steps that can be used to analyze the data.

#### **SALLJEX**

The focus of the South American Low-Level Jet Experiment (SALLJEX) was to describe the structure and variability of the strong but variable low-level jet found frequently over parts of

Bolivia, Paraguay and northern Argentina. In spatial scale and variability it is similar to the feature found over the US Great Plains. A NOAA WP-3D was based in Santa Cruz, Bolivia during SALLJEX. This location was very near the climatological position of the jet, as peak winds were found near a bend in the Andes close to Santa Cruz.

The SALLJEX aircraft operations relied heavily on aircraft porpoising for describing the structure of the low-level flow during the experiment. Using average ascent/descent rates of ~360m/min the aircraft made an average of 40-46 soundings per flight (fig. 2), most extending from 300m AGL to about 3000m ASL. These limits were chosen to map the vertical extent of the region of strongest winds, while maintaining good horizontal resolution. Higher soundings were occasionally carried out, but the aircraft could not often climb to 5 km, as the spatial separation of the soundings would have been compromised.

If aircraft operations are restricted to one base, as is most commonly the case, the aircraft must necessarily return to base at the end of the flight. This restricts the efficiency of the flight track – some duplication of track is difficult to avoid. The SALLJEX departure and return soundings were useful in showing diurnal changes, but additional track overlap took place during the typical butterfly patterns flown over western Paraguay (Fig. 2).

## **NAME**

The North American Monsoon Experiment (NAME), carried out over northwestern Mexico during July-August 2004, was similar to SALLJEX in exploiting the porpoising mode of operation. However, the layer most intensively sampled during NAME was shallower, and most ascents did not exceed 2 km ASL. Several lower porpoises alternated with a higher sounding, so that some information was obtained at higher levels, but without reducing horizontal sampling in priority locations (e.g. Fig. 1).

The geography and climate of the NAME region, which was focused on the Gulf of California, required that most soundings be shallow, rarely extending above 2000m ASL. Fig 1 shows a flight over the eastern Pacific, where climbs extending to almost 700 mb alternated with two shorter soundings to about 800 mb. The moist layer, and region of greatest interest was between the surface and about 900 mb. Thus the most uniform spacing of the soundings was near the top of the moist layer, the region of perhaps the greatest interest.

If the data is being monitored in real-time during the flight it is possible to adjust the vertical extent to optimize the sampling. For example, during the flight of 13 July, 2004 an objective was to provide a cross section of the low-level jet over the northern Gulf of California with the highest spatial resolution possible. To do this the aircraft altitude was varied from the minimum operating altitude (without life vests) of 500 ft above the surface to an altitude where the jet had decreased substantially from the level of maximum wind (Fig. 3). This level was subjectively determined, but the procedure permitted higher horizontal resolution of the jet than might have otherwise been possible if a uniform (but higher) profiling depth been used.

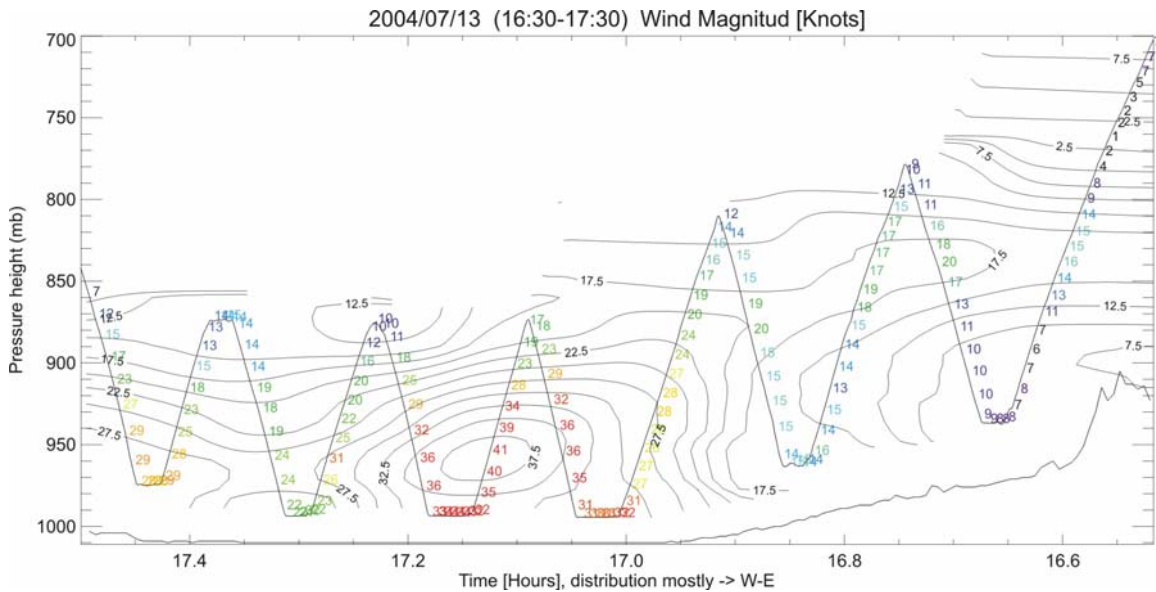


Fig. 3. NOAA WP-3D flight level winds (20-s averages, knots) across northern Gulf of California on 13 July 2005 during “Gulf surge” event. An objective analysis of the winds, with contours every 2.5 kts, is superimposed. (Note max winds are stronger than indicated by analysis). Note decreasing depth of porpoises from right to left, intended to provide finer spatial resolution of the region of strongest winds (sacrificing vertical extent of sampling).

#### *Data quality concerns*

The aircraft activities during SALLJEX and NAME revealed some problems associated with with porpoising procedure. Although there were insignificant differences between ascent and descent soundings on most flights, on a flight over the eastern Pacific there was sensor wetting of the hygrometers, which led to a systematic differences near the cloud layer between ascent and descent sounding through stratocumulus layers over the ocean.

A more difficult problem to deal with, and one which is most apparent in actively convecting daytime boundary layers over land, is that a particular ascent or descent sounding can be affected by the presence of horizontal roll vortices in the boundary layer. The aircraft, in making a sloping ascent, can cut through one or more such rolls during its traverse through the boundary layer. The resulting wind profile can show maxima and minima in the BL as the aircraft passes through descending and ascending currents respectively. These were of considerable amplitude during SALLJEX (Fig. 4a), and the shear in the BL (see Fig. 4b) was difficult to determine from many soundings. In comparison, a radiosonde sounding might sample either a region of ascent (weaker winds) or descent (stronger winds) but not as likely both during its quick passage through the BL. Thus the radiosonde might give a better estimate of the BL shear, though it might not be better in determining the mean wind than the aircraft. Many SALLJEX flights were carried out in strongly heated boundary layer conditions, whereas the NAME flights, mostly over water, showed much less BL wind variability (Fig. 4c).



Although averaging the data can help provide smoother horizontal fields when the aircraft is flying at a constant level, it naturally is less desirable when the aircraft is ascending and descending. Averaging over 20s might smooth out the roll vortex windfield signature, but limits the vertical resolution of the data set to ~100-150m. This may or may not be acceptable. If the vertical shear in a turbulent boundary layer is a critical quantity then the aircraft will have to ascend slowly, or make a series of multi-level passes to collect the required data that, when averaged, will provide a stable mean.

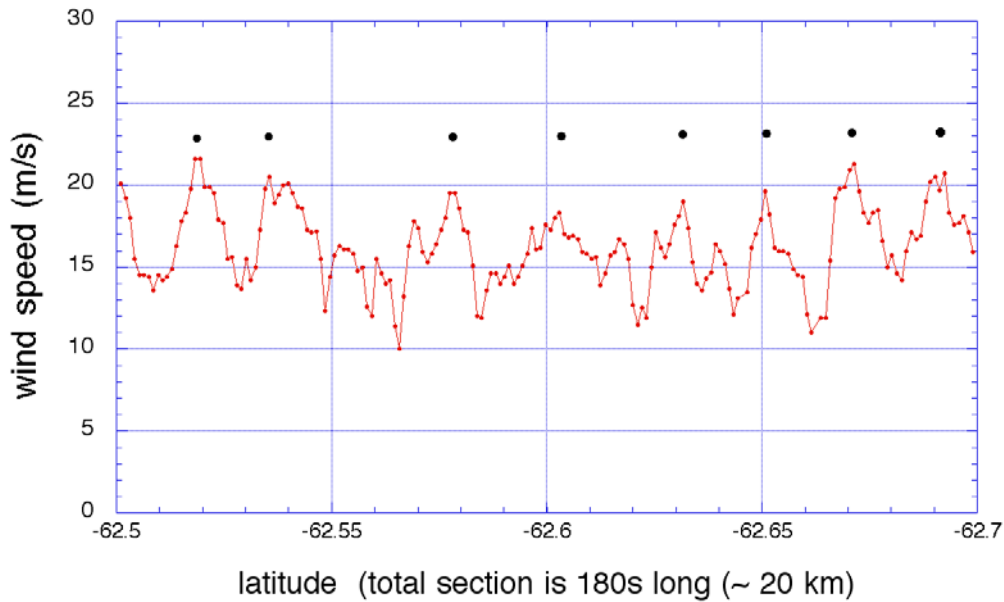


Fig 4a. One-second wind data from the NOAA WP-3D during level flight at 1000 ft above the ground during an afternoon SALLJEX flight. Note the large wind speed variations, range of 5-10m/s, associated with boundary layer roll vortices. Flight direction was approximately normal to wind direction.

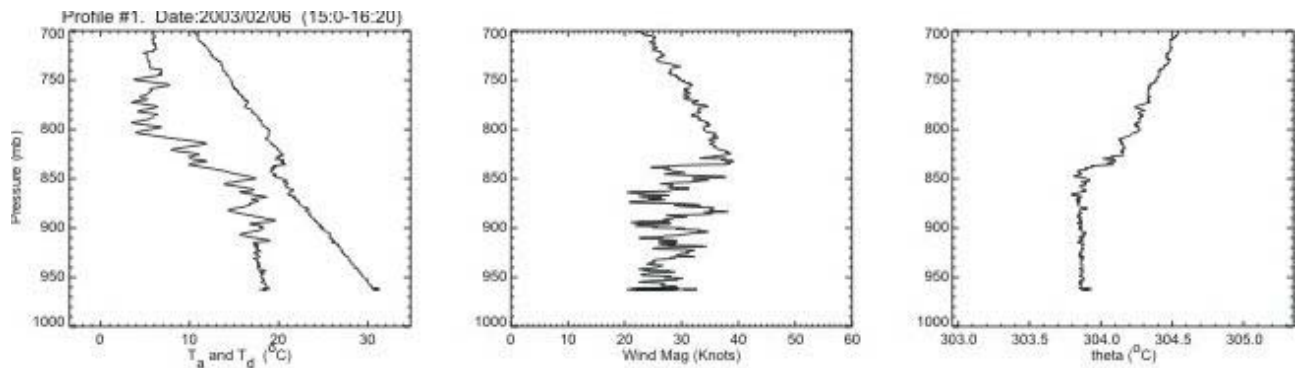


Fig. 4b. Aircraft sounding over Paraguay during SALLJEX on 06 Feb 2003, showing the highly turbulent winds observed in the mixed layer (top about 850mb from the temperature sounding on the left panel). Right figure is the potential temperature profile. During the descent from 850mb to 960mb the aircraft took ~ 4 minutes and could have passed through ~10 horizontal roll vortices.

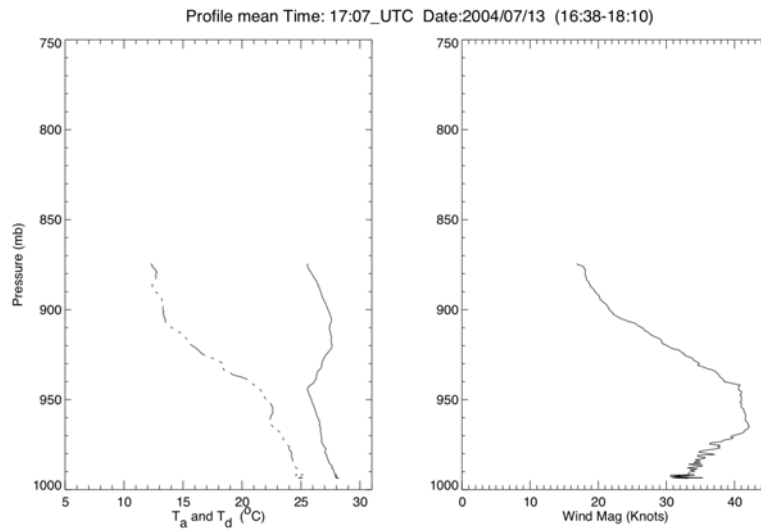


Fig. 4c. Thermodynamic and wind speed soundings made by the NOAA WP-3D over the Gulf of California during the strongest low-level jet event of the NAME. Although there is variability in the wind profile, it is small compared with Fig. 4b.

### Concluding Remarks

More details of the aircraft operations during the SALLJEX and NAME field campaigns can be found at:

<http://www.nssl.noaa.gov/projects/pacs>

and by selecting the appropriate links on this page.

### Acknowledgments

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