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Turbulence forecasts based on upper-air soundings

By

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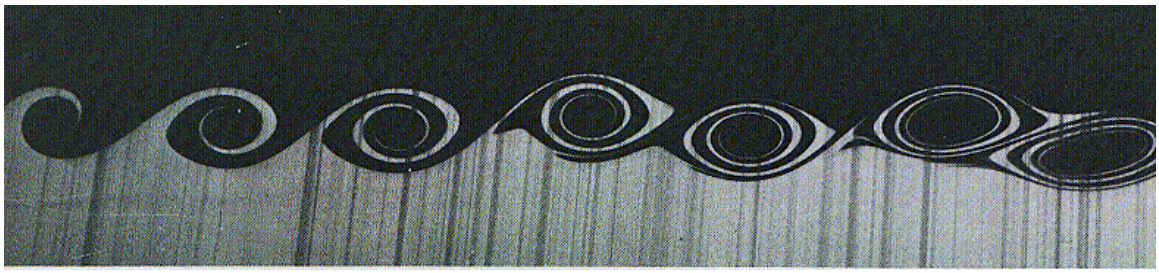

Introduction

The objective of this paper is to make turbulence forecasts from upper-air data by making Richardson's number calculations and to verify those conditions through the use of pilot reports (PIREPS), significant meteorological information reports (SIGMETS), airman's meteorological information reports (AIRMETS), and flight crew data.

While there exists 23 indexes to forecast turbulence, most of which has been based on Richardson's number, Reynolds number, Froude number and others, I was unable to fine where anybody had actually defined criteria based on Richardson's number. While interesting, the data acquired for this paper is not sufficiently detailed enough to make a determination. Therefore, only generalities can be made.

All of the upper-air data has been provided from the ongoing PACJET[1] research team operating out of Monterey airport during the months of January and February, while limited data is available from the R/V Point Sur research vessel sea cruise of 5-8 February. Data was limited from the Point Sur due to the failure of the GPS unit on the mini-rawin-system (MRS) that resulted in a lack of upper-level winds, lack of aircraft verification, and bad weather (high seas - 12-20ft).

SIGMET and AIRMET verification were mainly out of the San Francisco weather office. Other verification techniques were notes taken from PACJET flights and personal observations during those flights.

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1. PACJET is a California coastal research mission that utilized a NOAA P-3 to investigate land-falling fronts for the presence of a low-level jet stream, frontal structure, and microphysics.

Background

Anyone who's made more than a few flights has almost certainly had at least one bumpy ride when the airplane felt like a car on a rough road, except that the airplane might have rolled from side to side as well as bouncing up and down. That's turbulence.

Meteorologists define turbulence as a state of fluid flow in which the instantaneous velocities exhibit irregular and apparently random fluctuations. Those irregular fluctuations of the air create the bumps. As a side note, most people have heard of a or even experienced a phenomenon called an air pocket. This is where an airplane feels like it has run out of air and falls for a short distance. Air pockets don't exist, the sensation is simply turbulence, but more on the order of a long-wave fluctuation.

a. Turbulence defined

Light Turbulence and Light Chop. Turbulence that momentarily causes slight, erratic changes in altitude and/or attitude (pitch, roll, yaw) is reported as light turbulence. Turbulence that causes slight, rapid and somewhat rhythmic bumpiness without appreciable changes in altitude or attitude is reported as light chop.

Moderate Turbulence and Moderate Chop. Moderate turbulence is similar to light turbulence but of greater intensity. Changes in altitude and/or attitude occur but the aircraft remains in positive control at all times. It usually causes variations in indicated airspeed and is reported as moderate turbulence. Moderate chop is similar to light chop but of greater intensity. It causes rapid bumps or jolts without appreciable changes in aircraft altitude or attitude.

Severe Turbulence. Severe turbulence causes large, abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be *momentarily out of control*.

Extreme Turbulence. Extreme turbulence is when the aircraft is violently tossed about and is practically impossible to control. It may cause structural damage.

Both severe and extreme turbulence is rare in the atmosphere outside of thunderstorms. While the ride may feel like it is worse, odds are one is only experiencing moderate turbulence.

b. Causes

Mechanical turbulence is common near the ground as wind blowing over or around buildings create eddies. In fact, most turbulence involves eddies. The faster the wind, the stronger the turbulence. They are examples of the random fluctuations in instantaneous velocities in the scientific definition.

Turbulence caused in clear air by thunderstorms can extend from the ground to above 30,000 feet. A thunderstorm acts like to solid object to winds blowing over it or around it. Like a mountain, a thunderstorm can create waves in winds flowing over it. At lower levels, thunderstorms can create eddies as winds flow around it. The most violent winds are likely to be in clear air downwind from a thunderstorm.

Mountains create some of the most dangerous turbulence. It can affect pilots' large airliners cruising above 30,000 feet. When conditions are right winds blowing across mountain ridges take on a wave motion as the air flows upward over the mountains and

then drops down the other side. This up and down motion can continue for 100 miles or more downwind from the mountains and can extend high above them.

The final cause of turbulence and the one focused on in this paper is wind shear, a large change in wind speed, direction, or both over a short distance. Such changes help create eddies, or swirls of air, that cause turbulence. Wind shear can be both vertical and horizontal and can cause anything from minor turbulence to tornadoes, depending on the scale of shear. At high altitudes, shear is encountered when an airplane flies into a jet stream with the wind speeds increasing from less than 50 mph to maybe 150 mph over a few miles. The major cause of the air turbulence that sometimes makes planes bounce up and down in flight is wind shear.

c. Methodology & Calculations

Static instability in the atmosphere leads to spontaneous vertical mixing (convection) in the form of thermals and possibly cumulus clouds vertical mixing may occur in a stable environment, in particular in the form of breaking waves. The instability in question is the Kelvin-Helmholtz instability, which occurs when the kinetic energy in a sheared flow exceeds the potential energy stored in a stably stratified layer of atmosphere. In particular, observations suggest that a stable layer of air is unstable when the Richardson's number (the ratio of the stability over the wind shear) is less than 0.25, i.e. the mechanical wave production exceeds the buoyancy damping by a factor of 4. CAT is often observed in the vicinity of jet streaks, where the vertical wind shear is large. The breaking waves are a major cause of turbulence aloft, especially just above the planetary

boundary layer, in and around frontal zones, and near the jet stream, where they often produce clear-air turbulence (CAT).

Kelvin and Helmholtz have described the evolution of breaking waves mathematically, hence the term Kelvin-Helmholtz billows. The likelihood of Kelvin-Helmholtz instability can be evaluated by means of the Richardson's number (Ri), the ratio of the static stability (N^2) to the square of the wind shear (dU/dz):

$$Ri = N^2/(dU/dz)^2 \text{ where } N^2=(g/\theta)(d\theta/dz)$$

Here U is the wind speed, g the gravitational acceleration (about 9.8 m/s^2), θ the potential temperature, and z height. N the Brunt-Vaisalla frequency, or static stability parameter: the higher N, the more stable the flow. Both stability and wind shear were calculated locally, and Ri may vary rapidly across a sheared boundary, such as a frontal zone. Even under statically stable conditions, instability is possible, when the wind shear is strong enough to break up the stable layer and produce breaking waves.

Observations show that CAT is common in anticyclonic flow. This may be because flow around an upper-level ridge is super-geostrophic, therefore enhancing the vertical wind shear. Another explanation is that anticyclonic vorticity is inertially unstable. This instability occurs when the centrifugal and pressure gradient forces exceed the Coriolis force. It leads to secondary circulations, which offset the geostrophic balance in an attempt to restore geostrophic balance ('geostrophic adjustment'). This layer of air may produce gravity waves.

See table 1 for Richardson’s number calculations.

Summary

42-drop sondes were made during the month of February off the California coast. See figures 1-8. No soundes were dropped during the four flights in January, one of which I was aboard for.

It appears, while the flights incurred turbulence and weather at times that the crew considered severe enough to avoid, all the drop sondes were made in the cold sector that preceded the warm front or the warm occlusion. Only one sounde from IOP #8 of 10 February approached instability as defined by Richardson's number and that appeared to be associated with the upper limits of the boundary layer.

Numerous comments by the onboard scientist stressed the stability of the layer though measurements and the lack of turbulence. Additionally, several lapse rate calculations were made as a double check to Richardson's number calculations to confirm the stability of the atmosphere and basically the modified maritime polar air mass.

The NOAA P-3 did not fly high enough to investigate shear produced by the jet stream. All drop-soundes were confined to 20,000ft and below. As a consequence, this paper is limited to that respect.

Conclusion

The modified maritime polar air mass, in which all the drop soundes were made, showed consistent atmospheric stability as determined by Richardson's number and lapse rate calculations and was verified in part by crew notes and observations. It was clear that Richardson's number alone was not a clear indication of turbulence. Atmospheric

stability played a large roll in this type of calculation. On rare occasions, the flights did experience light chop in very stable conditions. Believe this was due to significant wind shear over a short distance, while at other times; weak embedded cumuliform clouds were present. It should be noted that wind shear and turbulence are *not* synonymous. Each can occur independently of the other.

While the San Francisco weather office issued numerous AIREPS for coastal regions due to light to moderate turbulence being reported and forecasted that were mainly due to mechanical turbulence (interaction with coastal mountains) and shear associated with the cold frontal zone, PACJET data was lacking. It was frustrating in the sense that measurements were not made in turbulent air.

Flight #	Date	Sounding(s) location & time	Ri #	Comments
IOP 8	10 Feb	41.5N 126.1W 0513 UTC 37.59N 123.0W 0103 UTC	.63 >1	Approached instability near top of boundary layer. Little wind shift evident. Mostly stratiform clouds. Very Stable. No discernible structure.
IOP 10	12 Feb	33.0N 120.5W 0610 UTC	>1	Found warm frontal and stability in heavy precip. Widespread stratiform precip Interpret this as a warm frontal over-running area.
IOP 11	17 Feb	35.3N 122.0W 2253 UTC 34.4N 122.0W 2242 UTC 33.9N 123.2W 2230 UTC 33.4N 124.5W 2212 UTC 35.3N 123.0W 2128 UTC 34.54N 123.0W 2121 UTC	>1 >1 >1 >1 >1 >1	Developing low. Light precip. Pre warm frontal occlusion. Stratiform clouds.

Table 1. Comments are taken from crew notes.

Flight #	Date	Sounding(s) location & time	Ri #	Comments
IOP 11	17 Feb	34.24N 123.0W	>1	
Con't		2115 UTC		
		34.24N 124.0W	>1	
		2101 UTC		
		34.21N 124.58W	>1	
		2040 UTC		
IOP 12	18 Feb	35.6N 126.2W	>1	Wide cold frontal band trailing.
		0655 UTC		
		35.5N 125.3W	>1	No low level winds available.
		0635 UTC		
		35.5N 124.5W	>1	
		0627 UTC		
		33.05N 125.71W	>1	On warm side of NCFR (narrow cold frontal rain band). Winds 56kts, no turbulence.
		0300 UTC		
		33.97N 124.89W	>1	
		0235 UTC		
IOP 13	21 Feb	35.93N 122.02W	>1	Very stable.
		2339 UTC		
		35.95N 121.96W	>1	
		2240 UTC		
		Pt 14 2222 UTC	>1	Old remnants of "front" only evident in moisture gradient. Winds show no clear shifts in direction or speed.
		Pt 8 2015 UTC	>1	See fig 6 for locations.

IOP 14	24 Feb	31.35N 124.27W 0618 UTC 30.6N 124.0W 0604 UTC	>1 >1	Spiraled down north of rain band. South of rain band. Consider to be trailing cold front.
IOP 15	25 Feb	19 soundings taken. Not shown here for brevity.	>1	No crew comments wrt soundings. No turbulence reported. Very stable atmosphere. See figure 8 for flight location.

Table 1 concluded.

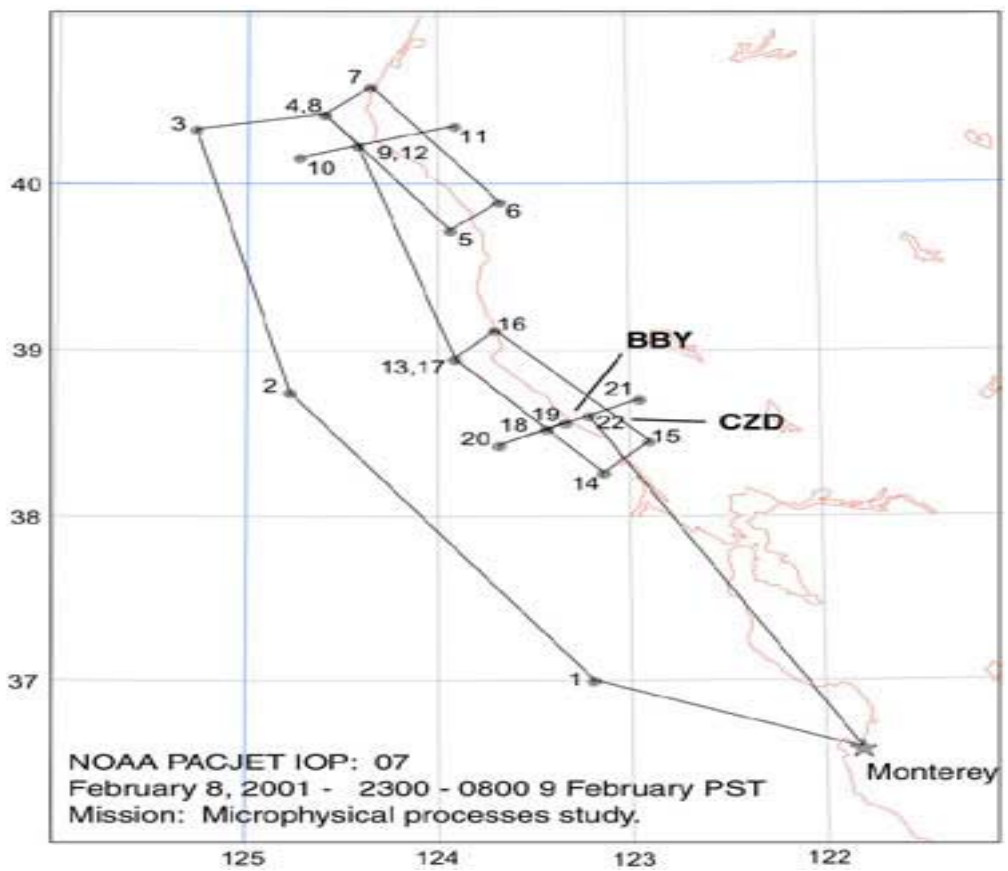

Fig 1. IOP 7.

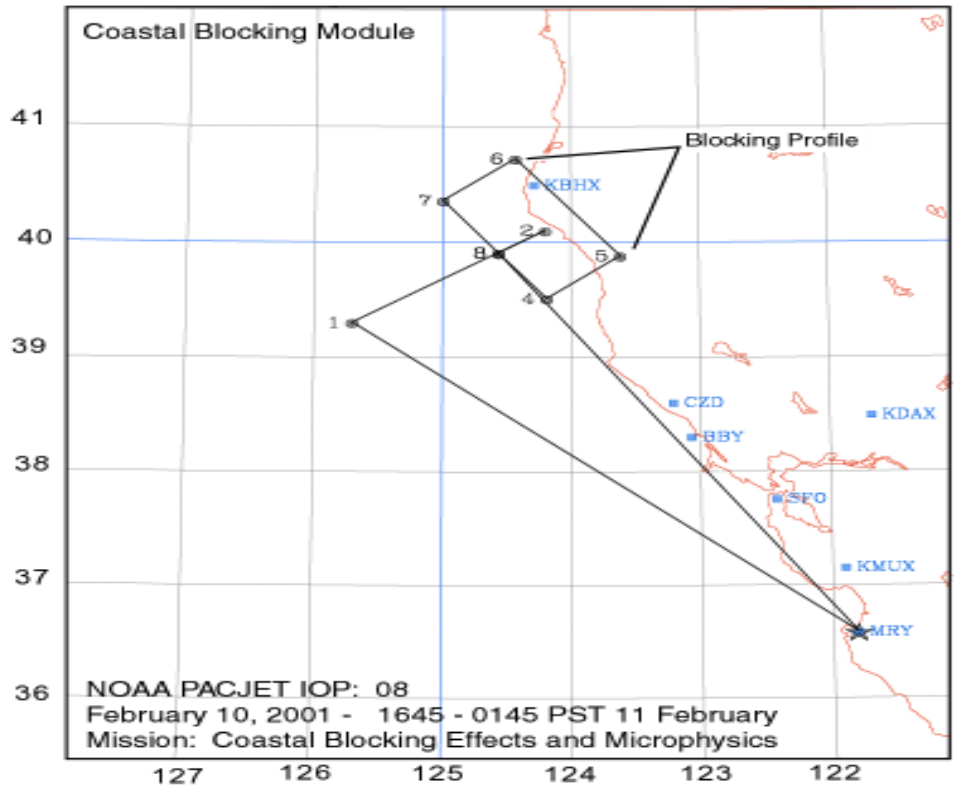

Fig 2. IOP 8.

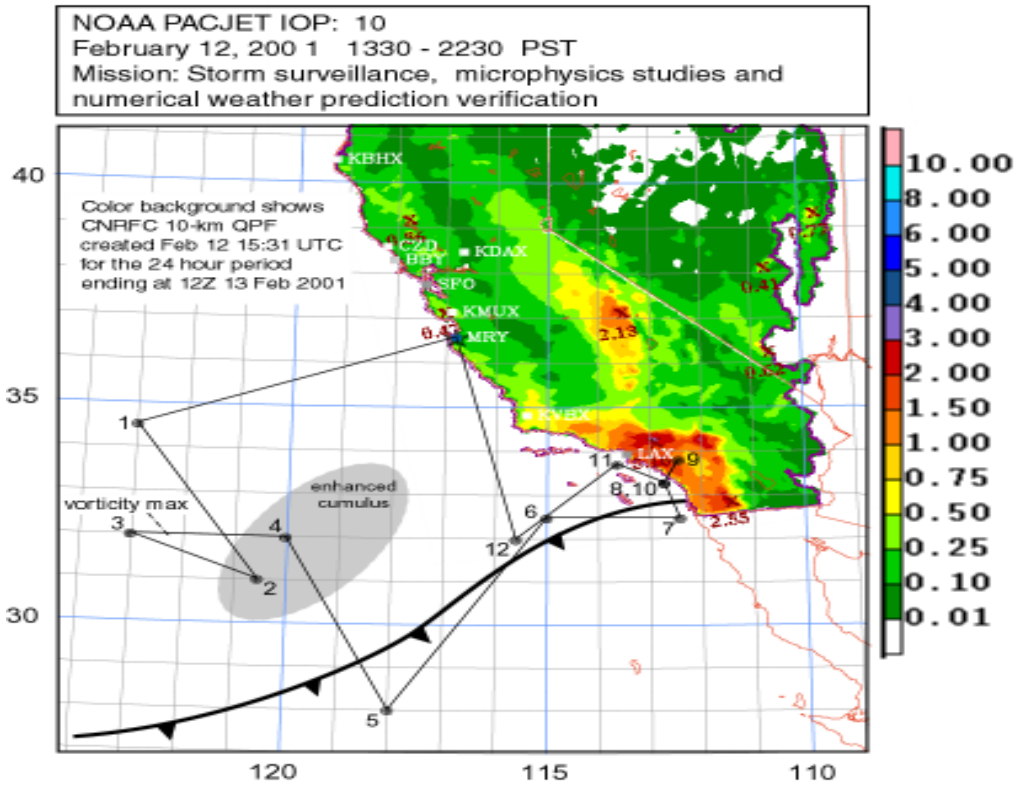

Fig 3. IOP 10.

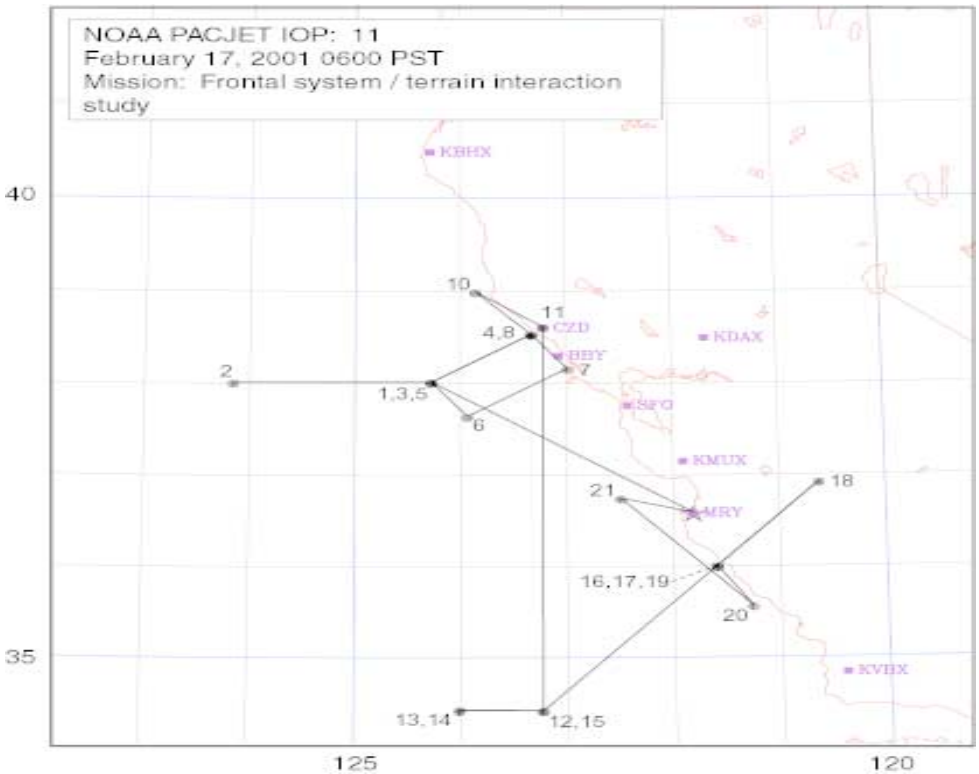

Fig 4. IOP 11.

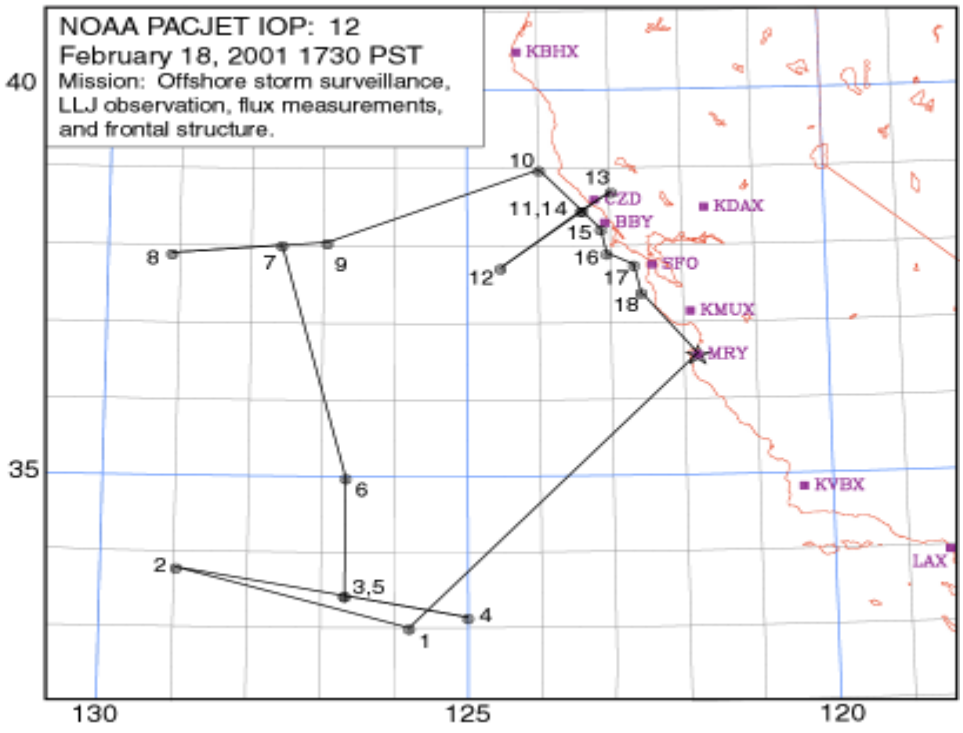

Fig 5. IOP 12.

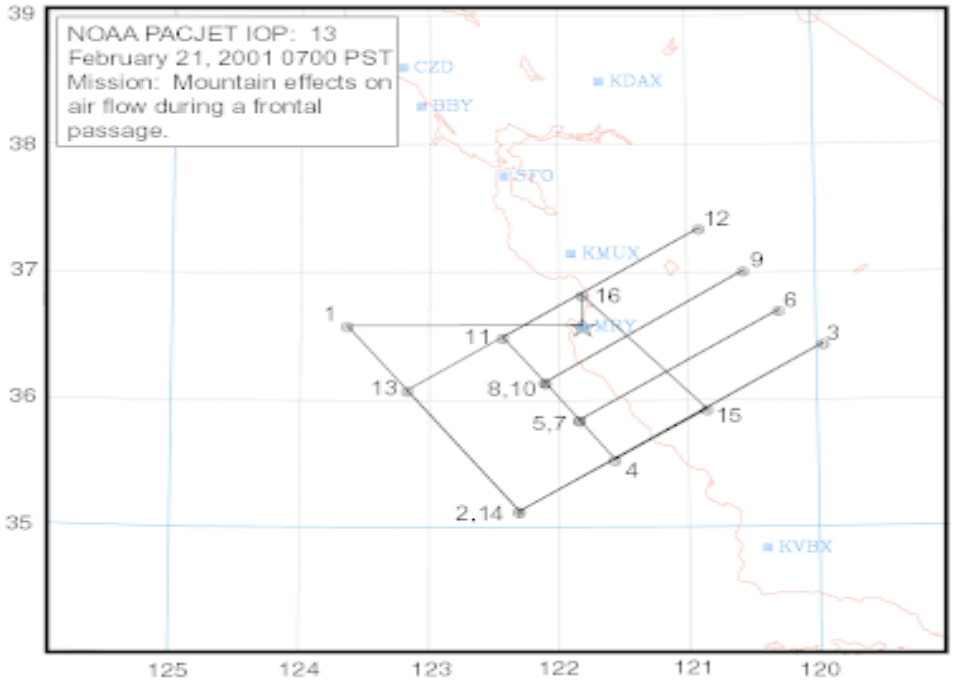

Fig 6. IOP 13.

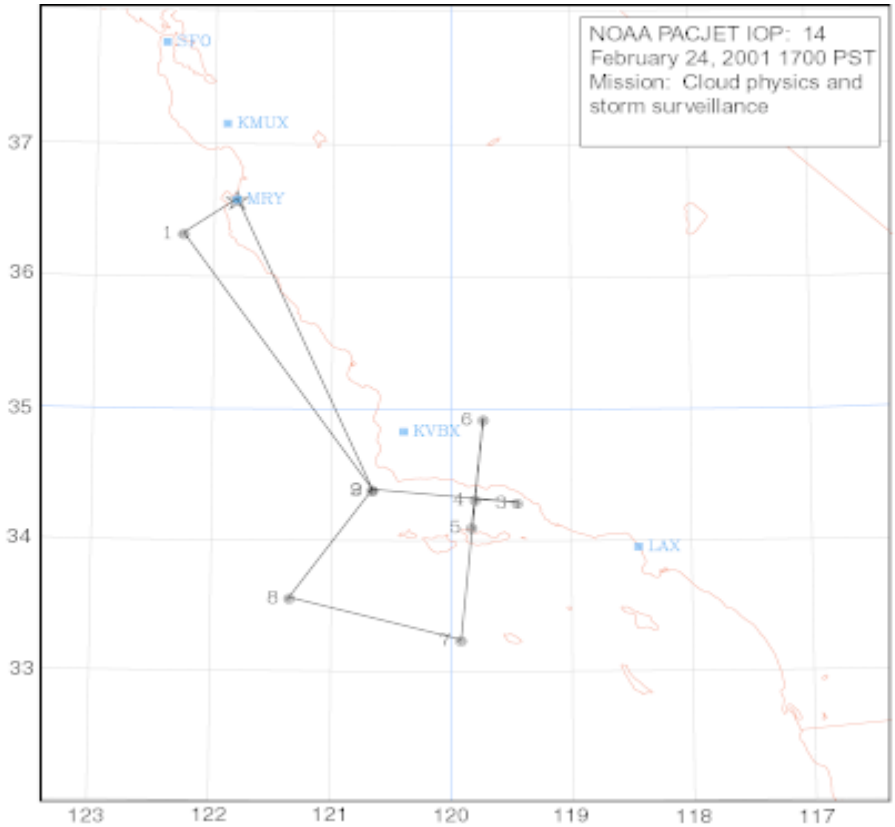

Fig 7. IOP 14.

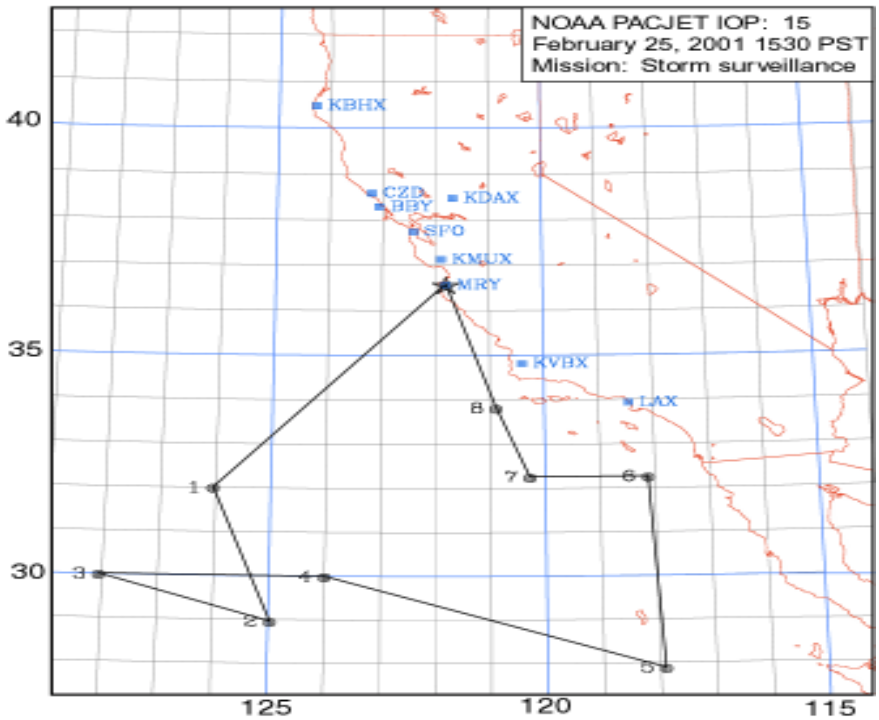

Fig 8. IOP 15.

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