Tropical cyclone forecasting: theory and practical application - case study of tropical cyclone Olaf 2005

Sala Sagato Tuiafiso*

Tropical cyclone is among the most dangerous of our natural disasters. Forecasting of its track and intensity is a business with high stakes. Within the last fifteen years, the communities throughout the Pacific and beyond have suffered devastating tolls of destruction from cyclones. Occasionally these cyclones also result in horrific casualties. Forecasts have to be accurate to enable responsive actions to minimise damage and loss of lives. Under-warning would mean inadequate preparation and consequently dramatic losses. Over warning would mean community wasting enormous time and effort in preparations?

This paper attempts to look at the evolution of tropical cyclone and mechanisms that influence their movement, a case study on Tropical Cyclone Olaf 2005 and what might be done to improve the capability of Samoa Meteorology Services to improve tropical cyclone forecasting

Introduction:

Tropical cyclone is ranked as one of the most destructive of all natural disasters, capable of destroying topography and infrastructures and causing major loss of lives and properties. Some authors have stated that tropical cyclones causes four times more damages than any other disasters. Tropical structural damages can be caused by damaging winds and storm surges, huge amount of rainfall dumping onto the land as it makes landfall, or when its convective cloud bands covers a huge land area.

According to certain authors such as Gray and Sara, a cyclone that swept through Bangladesh in 1970 killed at least 300,000 people, and a similar disaster occurred in the same region in 1991 when 140,000 people lost their lives. In 1992, at the United States territory, Hurricane Andrew caused widespread devastation in the southern Florida and Louisiana, recording 74 deaths; with damaged bill estimated to exceed US$26.5 billion dollars.

Samoa, a very small island nation consists of two main islands and four small islands had experienced a similar fade in 1990, 1991 and 2004. Seven casualties were recorded for the 1990 and 1991 tropical cyclone events and had a huge impact on Samoa's economy. The changes of sea surface temperature within the region and tropospheric winds lead to alterations in the frequency of TC occurs around Samoa. Most of the tropical cyclone that affected Samoa was emerges during an ELNINO period. The 2003-2004 EL NINO have produced five tropical cyclones within 300 nautical miles from Samoa and most were located to the northeast and east of the islands. The most notable and most threatening of them to Samoa island group is TC Olaf, a category five Hurricane system which Regional Tropical Cyclone Warning Centres (RSMC) found it difficult to analyse (RSMC, Nadi; Joint Typhoon Warning Centre (JTWS), Hawaii; NZ Met. Services; MNRE Meteorology Division).

*S.S. Tuiafiso is the Principal Officer for Weather Services, Ministry of Natural Resources & Environment

The public demand for the most precise track and timing of arrival of a tropical cyclone would not be fully met at due to lack of tropical cyclone research in this part of the region, limitations in the science of meteorology and other factors. This paper briefly discusses some of the areas that need explanation in order to get some understanding on why tropical cyclone Olaf changes its course.

Formation of tropical cyclone

The location of Samoa within the area (I always called it the pivot point) of the ENSO seesaw make it vulnerable to tropical cyclone during any ENSO conditions and more frequent during EL NINO period. The statistical analysis of past years tropical cyclones states that Samoa has been directly struck by a tropical cyclone in every five and half year. However, the 1997/1998 and 2004/2005 EL NINO period has shown the increased number of tropical cyclones emerging within 300 nautical miles from Samoa.

The formation of a tropical cyclone is complex and depends on the availability of dynamics (forces) and thermodynamics (energy) parameters (Gary, 1979: WMO, 1995). The dynamics parameters are - the existence of low-level vorticity (mechanical circulation), coriolis (planetary) force of the earths rotation and minimal vertical winds shears (differences of lower & upper level winds) or less than 25 knots (12.5 m/s). The thermodynamics parameters are very vital in the starting of the evolution of huge area of convective cloud band into a tropical cyclone. That is why TC originates from an ocean area with sea surface temperature of more than 26.5° degree Celsius with the depth of that warm ocean layer to be at least 60 metres. It also needs moist instability between the ocean surface and the 500-hpa level with at 40 to 60 percent moisture at the middle atmosphere.

The purpose of the low-level vorticity is to transports low level moist air into the atmosphere and condensed into clouds and has to support by two stages of wind surge in order to develop into a tropical cyclone within five days if all other mechanisms are favourable. The winds surges can originate at any side of the convergence zone or both and some time calls trade wind surges. The first stage of wind surge helps to accelerate the convection inside an existing cloud band of the convergence zone and evolutes this cloud band into a disturbance. This process continues when a vertical circulation is increasingly well and condensed vapour released latent heat and drives the wind system. An extreme convective cloud would form a chimney if vertical wind shear between the low levels (850-750 hpa) and upper level (300-100 hpa) were below 26 knots or 13 m/s.

The second wind surge supports the upward forcing for an exhausted mechanism of high-altitude, low levels would fill up the chimney and slows down the process and ending in dissipation of the system. In nature, an existing upper level high or high-altitude anticyclone act as the exhausted mechanism which transports the upward air well away from the disturbance, before sinking occurs further away from the tropical cyclone. The latent heat released by the ascending moisture when condensed at cooler upper air contributes in dropping of surface pressure and completes the vertical circulation. This produces the steep pressure gradient along which winds reach gale, storm and hurricane proportions. The Coriolis force initiates and maintains the tropical cyclone rotational movement while the weak wind shear is needed for sustaining the vertical chimney or structure.

Theoretically, it is easy to know how a system organises itself but in practical forecasting, there are a lot of complications ranging from interpretation on how the variable fields affect each other, including its evolution and steering. Many authors have identified several difficulties in predicting unusual systems and these researches have helped in improving models output.

Tropical cyclone forecasting

The Weather Services Section of the Meteorology Division has three main principles for its tropical cyclone warning operations: First, the collection and analysis of the necessary observational data and guiding products, and the production of a consensus model; Secondly, the preparation of warning forecasts, and finally, the efficient distribution of advisories, warnings, and all other relevant information.

Tropical cyclone forecasting demands a good meteorological and analytical background, vast amount of climatological knowledge, a keen mind's eye that can observe the most minute deviation in a mass of nearly homogeneous data, diligence and dedication in the approach to the forecast. The meteorologists or operational forecaster assesses the output from various models and based on present and historical performance of the models, as well as personal experience, arrives at the official forecast and more complex when less information is available especially with the lack of real time surface data.

The evolution of technology enables the forecasters at the Meteorology Division to practically issue daily forecasts. However, reliable assistance of a Meteorologist with vast experience and knowledge in tropical cyclone forecasting is needed during the tropical cyclone season. There are many rules in tropical cyclone forecasting which requires a lot of theoretical knowledge.

Estimation of intensity and locating of tropical cyclone centre

The availability of satellite images in every thirty minutes makes it useful to find centre location and the intensity of tropical cyclone, using the Dvorak Technique. One huge limitation is increase of error if no surface data is available to confirm the exact location of the centre at the surface. The only surface data that are more meaningful for locating centre at the surface are the quick scat winds from various NOAA websites and its disadvantages is the limited number of passes a day.

Finding Tropical Intensity at night is more difficult due to lack of visible satellite images and Enhanced Infrared Images (EIR) is available only on SATAID systems that need downloading from the Bureau of Meteorology Server. The Meteorology Division are still on the learning board and the problem of forecasting tropical cyclone intensity change continues to be a challenge for all tropical meteorologists despite the recent advances in numerical weather prediction. Tropical cyclone intensity change remains as one of the atmospheric science's greatest mysteries. Measuring of tropical cyclone intensity is still a challenge in small tropical cyclone warning centres and it involves a challenging blend of experience, intuition and creativity and improved understanding.

Tropical cyclone track forecast

The software called SATAID, developed by the Japanese Meteorological Agency has been used for fixing the current cyclone position and intensity, as this is the first step in making a track and intensity forecast. Since the forecast quality is dependent on the accuracy of this data, considerable care is needed in the analysis stage. During the 2004-2005 season the SATAID have improved the accuracy of finding the centre of tropical cyclones. The staffs require lots of in-depth knowledge and experience before fully eliminating major forecasting errors in critical conditions. The Meteorology Division tropical cyclone warning office has to justify/verify its findings (tropical cyclone centre position, intensity, direction of movement, movement speed, radius of winds) by comparing with values provided by JTWC, RSMC Nadi and NOAA NWS Honolulu if available before next Special Weather Bulletin for Samoa is issued.

The lack of surface observation on the vast ocean, this problem is still a major challenge for a frontline forecaster; satellites, and land-based automatic weather stations are the most common methods used to locate the centre and determine the intensity. If initial positions of tropical cyclones were poorly defined, a major forecast error would contribute in the forecast tracking and could be from 30 km to 180 km in the case of a satellite fix of a poorly defined centre. The initial intensity estimates may be in error by as much as 30 knots, particularly when using satellite imagery.

The simplest method used to forecast the track of a tropical cyclone is to extrapolate the motion of the tropical cyclone during some past period, say 12 to 24 hours, for the next 12 to 24 hours. Another method uses historical data to determine the average direction and speed of motion of similar tropical cyclones passing close to the given location. Another technique employs current and forecast atmospheric variables in a set of statistical equations to predict the motion. The final set of track forecast techniques makes use of computer models of the atmosphere to predict the motion of the cyclone from an observed initial state of the atmosphere.

The Meteorology Division just recently employed a new tool call tropical cyclones Module from the Bureau of Meteorology Australia, which can both produce a consensus track and threat area map. This special package was developed and is widely used by the Australia Bureau of Meteorology and was given to the countries small with some capability in Tropical cyclone Forecasting and has Meteorologist working on site.

According to the following Author, Elsberry (1987), Velden and Leslie (1991), Shapiro, 1992, Jones (1995), DeMaria (1996) the motion of TC is the result of the deep layer flow in which resides, usually 850 to 200 mb; also moderate changes in the magnitude or vertical shear of the mean winds can alter the storm in ways that could potentially affect the structure and intensity of the cyclone, as well as its path. Moreover, a few stated that existent of a mid troposphere Tropospheric Upper Tropical Trough (TUTT) can often influence the current and future motion of a nearby Tropical cyclone

Case study – Tropical cyclone Olaf

On the 9th of February 2005, a series of satellite images had shown an area of Mesoscale Convective System (MCS) within 8.0 souths 179.0 west and 10.0 south 175.0 west. The satellite images of the 11th and 12th February indicated the developments of Extreme Convection (EC) within the MCS.

The Fiji Meteorological Services' evening surface chart of the 12th February indicated a closed isobar within the area MCS is located. The satellite images showed that the area of convection have moved northeast by 15 to 25 nautical miles with increasing organization and persistent convection around a developing low level circulation. The EC band was estimated to be located at about 460 nautical miles northwest of Apia and satellite images after midnight indicated a sign of banding eye. The CIMMS upper analysis showed favourable conditions for development of the system.

Tropical cyclone OLAF forecast track

The Tropical Disturbance reached Gale Force on 131500Z and named by the RSMC Nadi a double of hours later. The RSMC at Nadi initially forecasted Olaf's centre to go past the southwest of Savaii. The JTWC predicted Olaf to cross over Upolu. The Samoa Meteorology Division projected TC Olaf centre to cross about 60 nautical miles north of Apia and expecting to travel between Upolu and Tutuila. This was a result of comparison of NOGAPS, AVN, GFS and BOM GASP models, average centre position but there with inclusion of human bias based on surface chart analysis. The original track was altered by minus 0.5 degree latitude to take into account the increase pressure advection from southwest. This was purely based on experiences and knowledge learned from tropical cyclone Ron (1997) and Heta (2004).

The availability of a new tropical cyclone forecasting models like the tropical cyclones Module has made it possible the compare the average centre position to produce a projection track. The same method used to compare the three tracks produced by the RSMC, Nadi, JTWC and the Meteorology Division. The three projection tracks were used to construct a consensus track. The first consensus track put the centre of Olaf at about 20 nautical miles direct north of Apia by Tuesday Morning. The position of the consensus track produced by the tropical cyclones Module was more biased towards the Division's projection track and that showed how divert the tracks were in their first run. The difference of tracks produced by each centre depends on output of the models employed and office perception.

The Meteorology Division ran a number of projection tracks for every twelve hours and consensus tracks for every six hours. The Division projection tracks was purely based on observations and the output of the latest run models available and surface analysis with consideration of surface high pressure system that located east of New Zealand and the developing midlevel ridge over Fiji to become active and move northeast ward within matters of time 12 to 24 hours. Most of the models accessed to at the time have had their projection tracks over and close to north of Samoa. The first two consensus track put the centre of Olaf about 20 and 10 nautical miles direct north of Apia on Tuesday morning.

4.3 What causes tropical cyclones Olaf to divert eastward?

From Monday night to early Tuesday morning Olaf had slowed down to 3 to 5 knots due to its interaction with tropical cyclone Nancy. At 141500Z, Olaf was located at about 9.6 south 176.8 west or 350 nautical miles northwest of Asau with estimated intensity of 80 knots close to centre, with the models expecting an increase to 110 knots within three to six hours. At 142100Z or 10am Monday morning, a mid-level steering ridge had driven Olaf and the satellite images exhibited a good outflow to the northeast (Figure1).

Samoa was ready for Olaf's destructive winds that could hit most of the islands within 12 to 24 hour period as shown in Figure 2. Is it a miracle or just the caused of nature? At 150900Z, TC Olaf was located at 12.3 South and 173.6 west and was moving southeast at about 10 knots. TC Olaf was expected to strike northwest of Savaii around 4 to 5 am Tuesday morning.

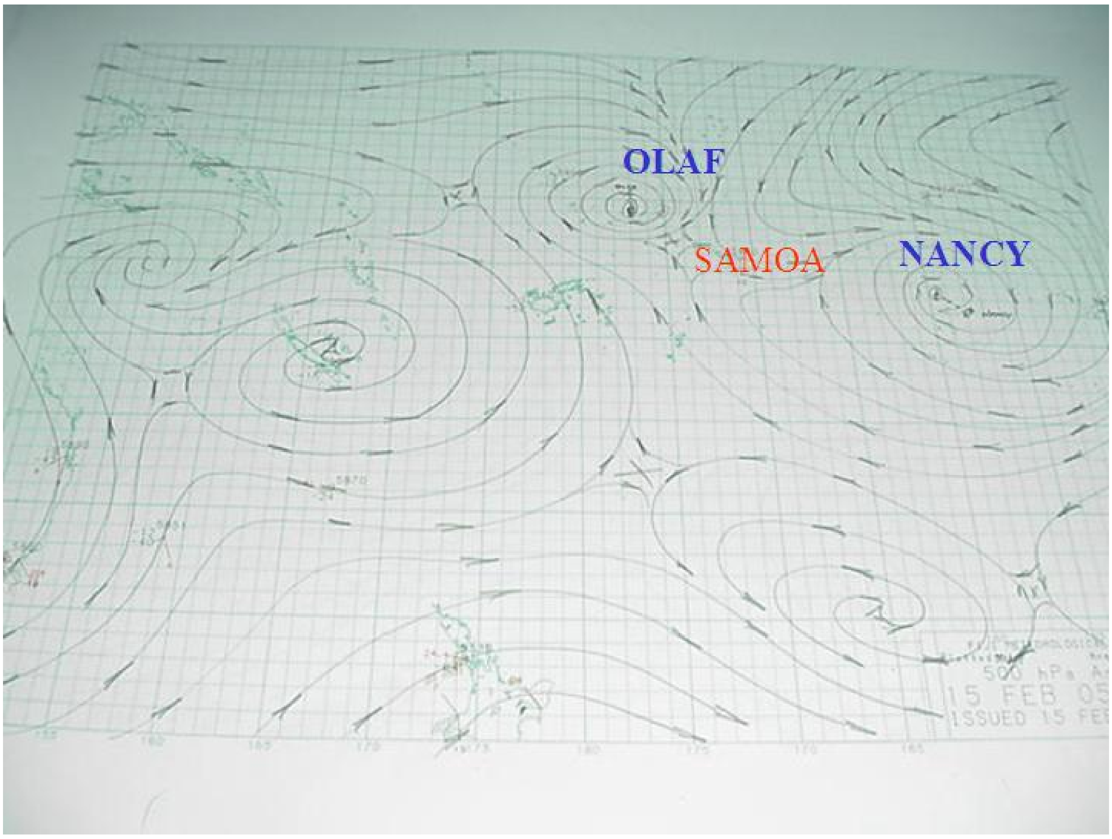

Figure 1: Tropical cyclone Olaf is steering southeast by a midlevel ridge to its northeast (Chart courtesy of RSMC Nadi)

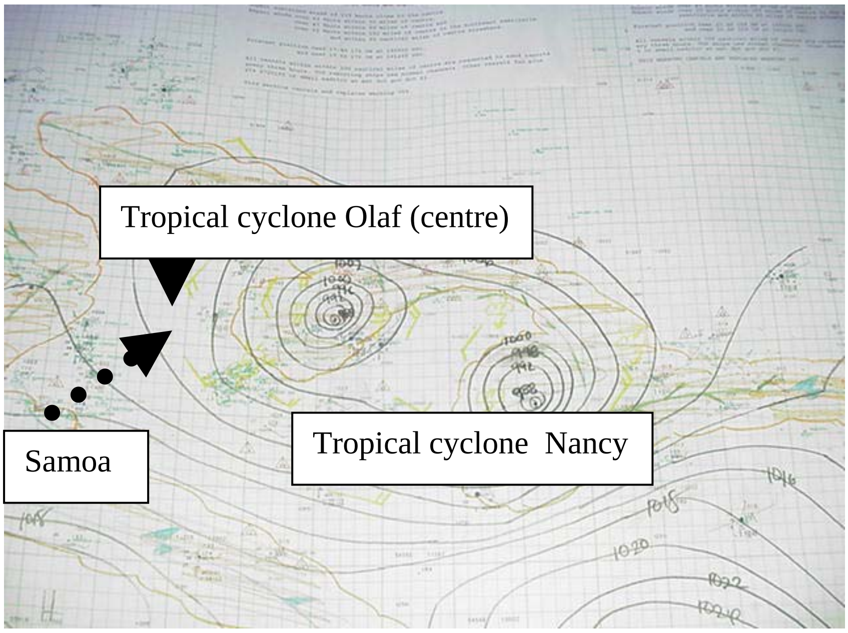

Figure 2: Location of Olaf centre from Samoa (Courtesy of RSMC NADI)

The system was almost stalling and undecided on which way to go between 151100Z and 15121300Z. The first suspect was an interaction between Olaf and Nancy (Figure 3). According to Chan, Gray and Kidder, the most popular kind of interaction of any dual system in the northern hemisphere has to be within 5 to 10 degrees. No studies have been done on this area of the South Hemisphere with regards to interaction of dual system, and having TC Olaf and TC Nancy more than 10 degrees apart, the only possible interaction was a repulsion between the two and this was one possible reason it held Olaf further north Samoa than previously predicted.

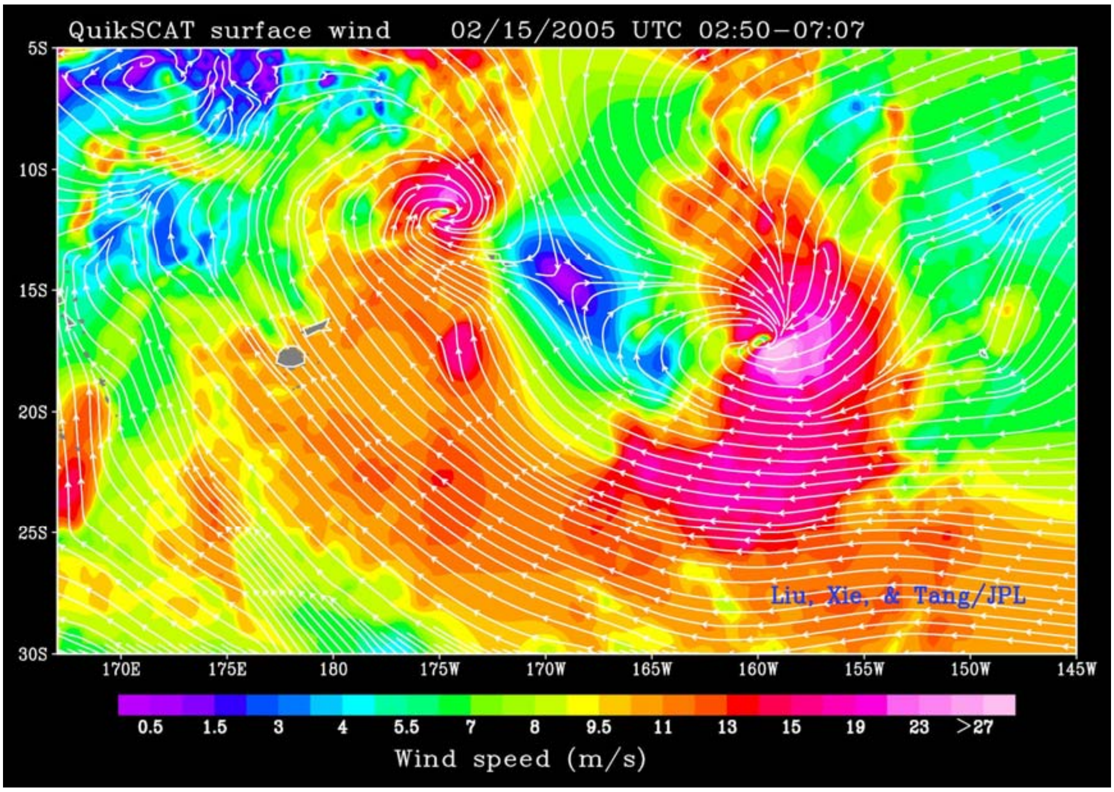

Figure 3: Tropical cyclones Olaf and Nancy interaction (Courtesy of NASA)

Chan and Gray reported that according to Lander and Holland (1993) – "storms that were unable to approach each other at distances smaller than a certain minimum distance (of about 450-500 km) without being mutually stretched out. The initial attraction of the storms in this regime was replaced by repulsion, in agreement with observations. One of the possible causes hindering further storm attraction is the displacement of the maximum latent heat release to the opposite sides of the interacting storms. The storms can be pushed away from each other due to the tendency of tropical cyclones to displace toward the areas of maximum heating."

Many authors had discussed that the result of any dual tropical cyclones depend on certain elements such as comparably small changes in structure and strength of interacting storms, Coriolis force, Sea Surface Temperature and vertical and horizontal shears of the background flow can also lead to different scenarios of their interaction. Predicting results of any dual system interaction is rather difficult and requires a lot of room for research.

With Olaf and Nancy competing over available energy, the satellite images showed that most of the convective clouds were located east of Olaf and that was where most of the latent heat required for feeding Olaf was brewing (Figure 4).

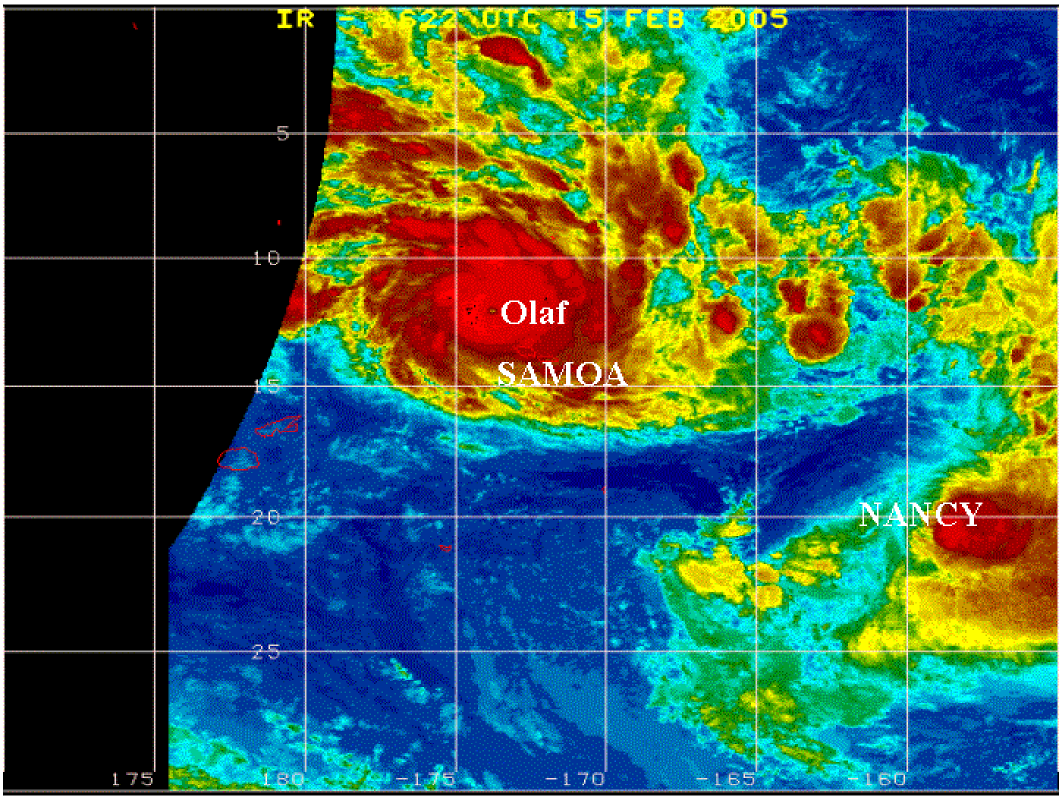

Figure 4: Satellite image of tropical cyclones Olaf and Nancy

The surface pressure was falling at this area of active convective clouds so Olaf was moving towards this area of falling pressure. At the same time a midlevel ridge to the northeast steering Olaf southeast although the wake of a ridge of high pressure to the west of Fiji extended to the northeast of the Fiji group holding Olaf just less than 100 miles north of Samoa. This means that a tropical cyclone goes through the low pressure area and avoid high-pressure area. This southeast ridge was also vertically extend to the 700 mba contributes to shrinking of Olaf gale and storm force winds radius on its southern quarters. There was a possible repulsion between Olaf and Nancy) slowing Olaf's movement from 190900z to 192000z. At the time, this wave interaction was occurring, an upper trough approaching in from the southwest (Figure 5), accelerating Olaf eastward after 200000z with it centre pass north of Apia at about 70 nautical miles and its closest point to Samoa land. Samoa would still have received destructive forces of Olaf gale and storm winds if two of the mention synoptic features not arrived on time.

According to Chan, Gray and Kidder "Most of numerical models fail to predict cyclone with turning motion beyond 24 hours. In addition, same authors found that the largest tropical cyclone track forecast errors usually associated with them undergoing a turning motion" like Olaf. This is one of the reasons why forecasting of Olaf's track was far out from its actual track in the first 48 hours of its lifetime.

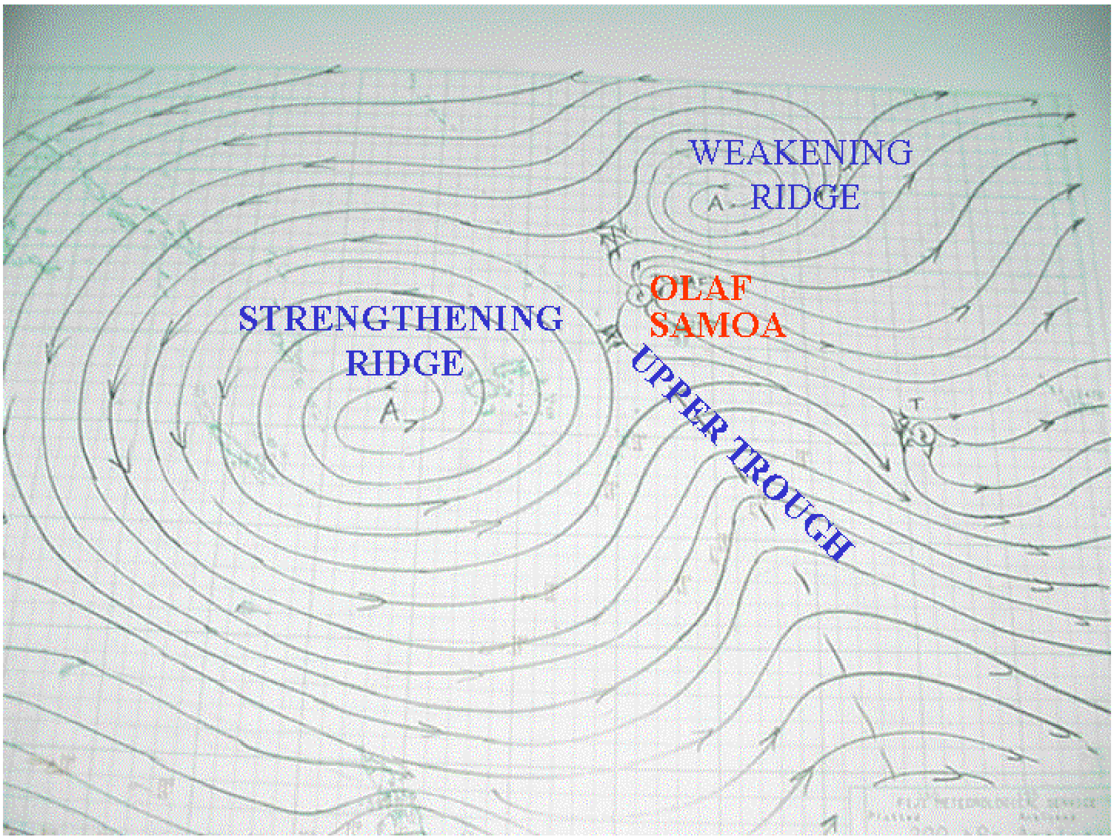

Figure 5.0 Courtesy of RSMC Nadi

Tropical cyclone Olaf was a most CHAOS system that most professional meteorologists would agree with. Olaf's destructive and damaging storm to hurricane winds never reached the Samoa islands. Despite winds of 115 to 125 knots close to centre, the southern quadrant gale and storm force winds radius were greatly reduced as Olaf got closer to Samoa (Figure 6). The southeast of Upolu and northeast of Savaii had experienced gale winds within a very short period, approximately from 2 to 3 hours with only minor damages reported. Sustained southeast winds of 35 to 40 knots with gusts of 47 knots were recorded at Tafitoala (southeast east of Upolu island) automatic weather station on Tuesday night while Olaf was moving closer to Tutuila and over Manua Island (American Samoa) early next day.

Tropical cyclone Olaf was also accompanied by heavy rainfall from Monday afternoon to Thursday morning with a total of 171.8, 170.0, and 82.3 mm for Apia, Faleolo and Maota respectively. Lowest pressure recorded in Samoa was at Avao (northwest of Savaii) with 990 hpa while Apia and Faleolo recorded pressures of 991.3 and 991.2 hpa respectively.

Challenges and recommendation

Tropical cyclone forecasting has a lots of challenges and does requires a lots of commitment and determination. The Meteorology Division needs more tropical cyclone meteorologist to consults our forecasters in critical situation where deeper understanding of the dynamics, hydrostatics and kinematics of the atmosphere require.

The professional meteorologist would dedicate their time to researches on weather systems and climate pattern in our region and they could collaborate with Samoa National University staffs of the Mathematics, Science and Computer Departments in developing systems that could promote both disciplines within the region and globally. Strongly recommended the integration of knowledge from related science field for various researches.

There is also a great need to bridge the gaps in our knowledge and observations of the early tropical cyclone rapid development processes. This is a real problem globally and the tropics here in the pacific is the most difficult to deal with due to the lack of research in such area. Also need to observe and investigate the scale interactions that lead to controlling the motion of tropical cyclones. There is a great need to improve our understanding of the complex interactions leading to changing tracking and motion of tropical cyclones.

The RSMC and JTWC are the other two meteorological agents that also issue tropical cyclone information for area from equator to 25 degree south. The Meteorology Division is the official tropical cyclone warning office for Samoa. Many users of weather information have access to other tropical cyclone warning centres websites, comparing forecast options and question the differences, especially when divergence of the forecast is significant. These results may degrade credibility and create pressure to mimic the other agency's forecast. The convergence of forecasts is in the best interest of overlapping agencies and is based on fact and not political considerations. This should encourage close collaboration and coordination among meteorological agencies.

When the tropical hurricane warning was issued for all of Samoa on Monday morning 15th February, all private businesses and government ministries closed down to allow people to prepare for the worse. Should Olaf have hit Samoa without any warnings, the public would not be able to mitigate any impact of hurricane winds and could result in a bigger economic loss.

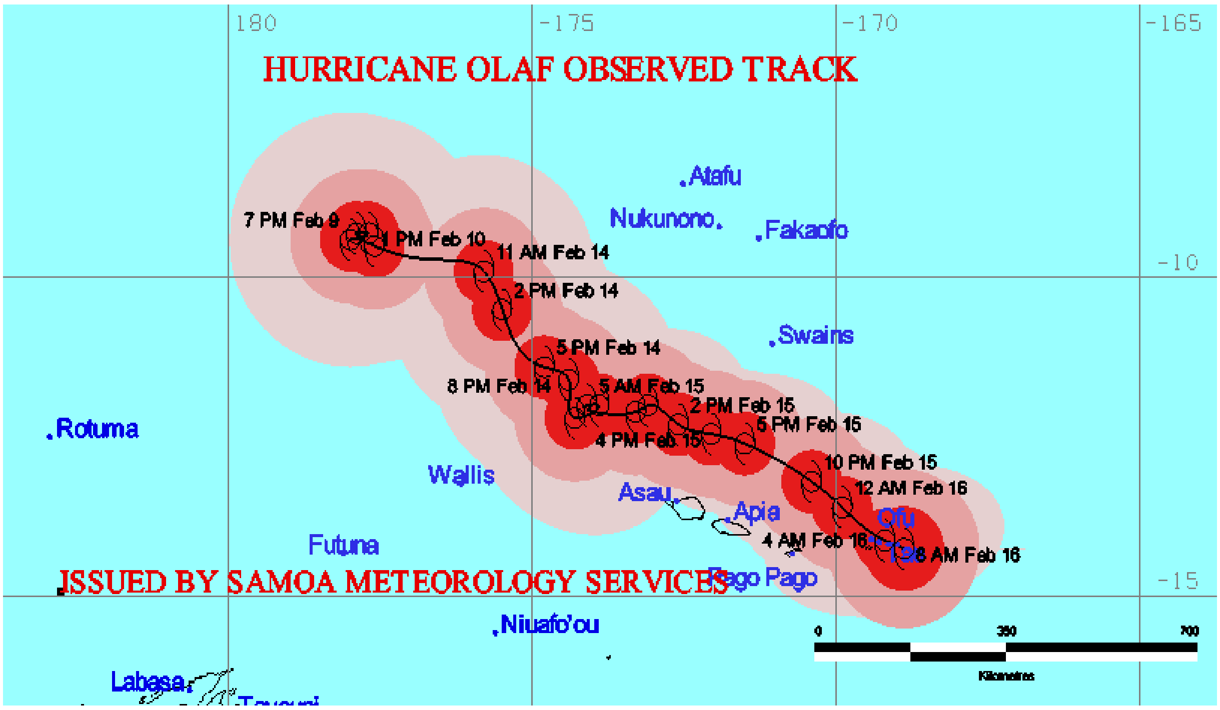

Figure 6: Tropical Cyclone Olaf Track and estimated wind radius (hurricane, storm, gale force) (courtesy of MNRE Weather Services)

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