

The Resurgence of Tropical Cyclone Reconnaissance Aircraft in the Far East and Western Pacific

By David Reade

With a current focus on the Atlantic, and US national remote sensing Unmanned Aerial Vehicles *(UAVs)* conducting surveillance trials in hurricanes, many tropical cyclone researchers have paid little attention to a growing resurgence of tropical cyclone reconnaissance and surveillance flights emanating from the Far East and Pacific flown by international weather agencies operating in the areas of the South China Sea, East China Sea and Western North Pacific *(Philippine Sea)* as well as the Indian Ocean now and in the near future.

Developed specifically for typhoon reconnaissance and / or surveillance, these recent aircraft operations are a part of a growing trend towards the utilization of modern numerical weather forecast models established to improve tropical cyclone forecasts and warnings in these regions.

In the last decade, organizations like the World Meteorological Organization *(WMO*), have been promoting the development of numerical *(computer)* weather prediction models as a means to improved forecasts and warnings of tropical cyclones - to better safeguard life and property. The establishment of these new weather prediction forecast models particularly associated with tropical cyclones, within various international weather agencies, ultimately benefits the WMO's wider-scale objectives of monitoring global climate change. However, this effort is a lot easier said than done. Often these modern computer weather prediction models require more accurate, higher-resolution data to be assimilated into them. The accuracy of the end products of these weather prediction systems, are only as good as the quality of information that goes into them.

As a component of the introduction of these modern computer models, the WMO has also been recommending aerial in-situ data collect as a means to get the most accurate results. It is generally accepted within the tropical cyclone research community, that aerial reconnaissance is the best method by-which to obtain high-resolution in-situ data, from the core of the storms, to provide for the most accurate forecasts and warnings. However, in the recent past, this concept was made further difficult given that there have been few if any tropical cyclone reconnaissance / surveillance aircraft flying storms in the Western Pacific, since the US Military disestablished typhoon reconnaissance flights in the Western Pacific and Indian Oceans in 1987.

The most immediate effects after the discontinuation of US typhoon reconnaissance operations in 1987, was a major increase in forecast errors of the regional typhoon forecasts products, specifically in the areas of position tracking, intensity forecasts and landfall predictions. In a study conducted by the Hong Kong Observatory, in the period immediately following the discontinuation of US typhoon reconnaissance flights, HKO researchers found upwards of a 30 % increase in errors within the 24-hour track, position and intensity forecasts during the first year without reconnaissance - as compared to the previous decades of typhoon tracking operations. It was also determined that the 48 and 72 hour forecasts of these storms suffered further errors, forcing military weathermen to rely more heavily on land-based radars, daily radiosonde *(weather balloons)* soundings and specifically on weather satellite imagery analysis.

As a result, over the next succeeding decades, US typhoon forecasters and researchers focused specifically on improving weather satellite technology as well as advancing their ability to better analyze *(visual)* satellite derived data. However, despite much effort devoted in this and other areas, today the United States' Joint Typhoon Warning Center *(JTWC)* currently experiences a high rate of forecast errors in its typhoon forecast products.

The JTWC's typhoon forecast errors are normally published in the organization's annual typhoon reports and are normally expressed as the actual nautical miles off in its track forecast estimates and knots of winds off in its intensity forecasts. Thus, the JTWC's actual 2013 track forecast were off by 46 nautical miles *(53 miles / 85 kms)* in the 24 hr forecast, 77 nm *(89 miles / 143 kms)* in the 48 hr and 106 nm *(122 miles / 196 kms)* off in the 72hr forecasts. The actual JTWC intensity forecasts errors for 2013, comprised 11 knots *(13 mph / 21 km/h)* in the 24 hr forecast, 15 Knots *(17 mph / 27 km/h)* in the 48 hr period and 16 knots *(20 mph / 32 km/h)* off in the 72hr forecasts.

Although JTWC forecast error rates have oscillated up and down since 1988, they have only incrementally declined *(by a few percent)* since 1999. In 2009, US Pacific Command *(USPACOM)* mandated a forecast error reduction scheme for the JTWC that comprise a 50% reduction in track forecast errors, a 20% reduction in intensity errors and 25% reduction in landfall estimates over 5 years. Based upon 2010 forecast error rates, the mandated percentages translate to actual error reductions on the order of 25nm *(29 miles / 47 kms)* off in the 24 hr track forecasts , 50 nm *(58 miles / 93 kms)* off in the 48 hr and 75 nm *(86 miles / 138 kms)* off in the 72 hr forecasts. With intensity forecast reductions to encompass 10 knots *(12 mph /19 km/h)* in the 24 hr forecast, 15 knots *(17 mph / 28 km/h)* in the 48hr and 16 knots *(18 mph / 30 km/h)* in the 72 hr forecasts.

Currently in the last year of its 5-year USPACOM error reduction mandate, the JTWC is clearly not even close to the proposed error reduction goals and still very far from zero errors which may only be achievable by the initiation or re- initiation of aircraft reconnaissance.

Its been firmly established by tropical cyclone researchers, and typhoon airborne surveillance operations *(conducted byTaiwan's DOTSTAR flights)* that modern GPS – equipped dropsondes can achieve forecast error reduction rates on the order of 20% or more. Translating into an immediate reduction of the average typhoon landfall warning area by 10% or 34 miles *(55 kms)*, a seemingly obvious step towards improved forecasts.

The JTWC's current efforts to improve their typhoon forecast errors are squarely focused on improvements *(and / or enhancements)* to existing computer models and the development of new ones, along with improvements in the processes of satellite data interpretation and analysis. No aircraft reconnaissance or surveillance capability seems evident in any of their near-term planning.

Note: *the JTWC's current development of new forecast models comprises the use of NOAA's Hurricane Forecast Improvement Program (HFIP), a group of developmental regional and global forecast models for tropical cyclones. HFIP is a NOAA program to accelerate improvements to hurricane forecasts (track, intensity, storm surge and landfall forecasts) with emphasis on the prediction of rapid intensity in Atlantic hurricanes. The goals of the 10-year program are principally to reduce track and intensity forecasts by 20% in the first 5-years and by 50% at the end of the 10-years (in the 1-5 day storm forecasts) while improving the service's capability to better predict rapid intensification. The HFIP program is seeking to accomplish this through the improvement of computing infrastructures and supporting the development of new regional and global (resolution) computer simulation models*

NOAA's HFIP program developmentally began running real-time "Hurricane Weather Research and Forecast" (HWRF) regional model forecasts (based upon satellite data) for the JTWC in 2012 ,from the program's supercomputing facility in Boulder, Colorado. (as well as for the Indian Ocean in 2013) Under this scheme, NOAA transmits HFIP generated forecast data directly to the JTWC for incorporation into its regional typhoon forecasts and warnings. There are some in the HFIP program that attribute the slight 1-2 % reduction in JTWC's 2012 – 2013 forecast errors to the incorporation of HFIP model data.

It would seem logical to assume that once a Western Pacific version of the HFIP forecast model is developed, the assimilation of aircraft reconnaissance data (critical storm core data) would significantly reduce the JTWC's forecast errors and provide ultra-accurate forecasts and warnings for the entire region.
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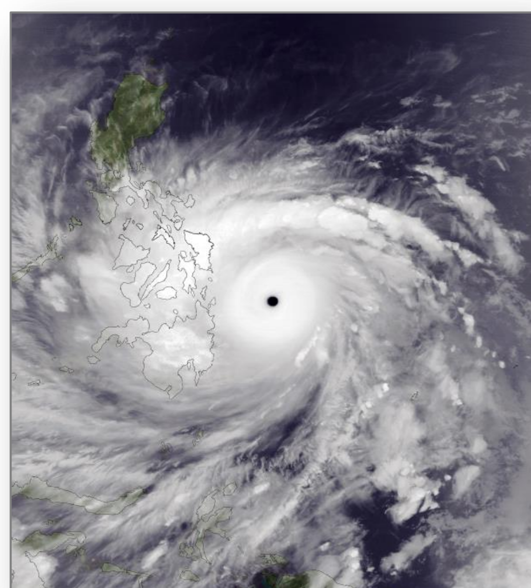
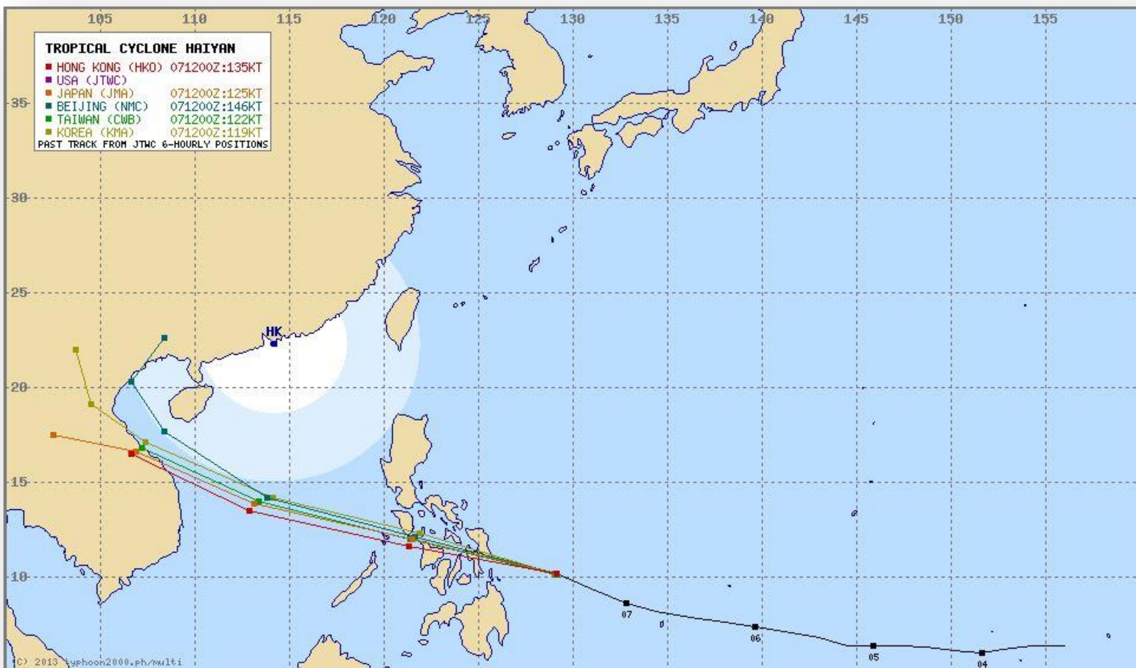
In the meantime, specific issues associated with current tropical cyclone intensity estimates, mostly based upon satellite imagery interpretation and subjective analysis, has contributed to the number of intensity errors in Western Pacific forecasts. These forecast errors remain at a high rate with a wide margin between what the storm's actual intensity was, experience on the ground, -vs- what was originally forecasted for the storm.
In fact, a recent paper *("Irreconcilable Differences" by M.A. Lander)* argues that JTWC intensity estimates are way too high, with its gale and hurricane *(or typhoon)* force wind distributions off by hundreds of miles or kilometers. These discrepancies are complicated by the JTWC's use of a variant Dvorak *(method)* technique used to assign wind speeds and directions to tropical cyclones from satellite data analysis derived from visual and infrared satellite imagery. The original Dvorak method was developed to identify visual characteristic associated with estimated wind speeds and directions in storms.

Like the JTWC, the various international weather agencies in the Western Pacific region all utilize their own modified versions of the Dvorak method of satellite data and imagery interpretations and analysis – which again are all estimates and are not the actual *"true"* intensity of the storms. These intensity discrepancies were never more evident than during the recent Typhoon Haiyan *(aka Yolanda / 3-11 November 2013)* event that devastated the Philippines in 2013.



Typhoon Haiyan at peak intensity near landfall in the Philippines in November 2013

Some in the media *(mostly internet based sites)* have suggested that Haiyan was the most powerful storm to have ever occurred in tropical cyclone history, while others debate if this is the case. The US JTWC estimated the peak intensity *(winds)* of this storm at 195 mph *(315 km/h – one minute sustained) with higher gusts*, while the Philippine's own Atmospheric, Geophysical and Astronomical Services Administration *(PAGASA)* estimated the storm's peak intensity at 145 mph *(230 km/h – ten minute sustained)* near landfall in Guiuan *(in eastern Samar)*. Other regional weather agencies also estimated the intensity of Haiyan before landfall in Samar. The Japanese Meteorological Agency *(JMA)* reported winds in excess of 145 mph *(230 km/h – ten minute sustained)*, the Hong Kong Observatory *(HKO)* estimated 170 mph *(275 km/h – ten minute sustained)* winds while the People's Republic of China's meteorological service, the China Meteorological Agency *(CMA)*, filed intensity forecasts on the storm at 175 mph *(280 km/h – two minutes sustained)*. All these weather agencies based their estimates on the same storm *(during the same period)* on different interpretations and analysis processes of visual satellite data.



The forecast model tracks for Typhoon Haiyan by the various regional weather agencies.

And there's the rub of the matter; with no reconnaissance aircraft flown during the storm to verify its true intensity at peak, near landfall, no one can know for sure what the intensity of the storm really was in those critical few hours before landfall. Had there been aircraft reconnaissance flights flown during the storm, the true nature of Haiyan as to the intensity, wind speeds and whether it was truly the most powerful storm in tropical cyclone history, would have been known.

In an effort to get everyone on the same page, the World Meteorological Organization *(through different sponsored meteorological sub-organizations)* has been promoting the sharing of tropical cyclone databases and captured datasets of storms under surveillance, between the regional weather agencies and the use of modern computer *(simulation)* modeling towards the improvement of regional typhoon forecasts and warnings. However, these computer model-generated forecasts are only as good as the

accompanying databases and the specific storm data assimilated into them. The more accurate the forecasts, requires better, higher resolution data to go into the models.
Thus; the WMO has taken the lead and is openly encourages the expansion of aircraft reconnaissance capabilities in the various tropical cyclone basins throughout the world – touting that "…. *Aircraft reconnaissance is still the best means of acquiring the storm data needed …."* In fact, the WMO has also been recommending that consortiums of nations cooperatively develop capabilities for aircraft reconnaissance and shared data to significantly improve regional typhoon forecasts and warnings.

Minimally, aircraft surveillance *(the deployment of GPS-Dropsondes in tropical cyclones)* could validate current satellite data analysis techniques and processes to provide the best possible resolution to support improved forecasts and warnings. Aircraft equipped with dropsonde vertical profiler systems, along with potential Stepped-Frequency Microwave Radiometer systems *(SFMR)* would be the best option. However, it has been clearly established within the tropical cyclone research community, that the best high-resolution data by which to populate computer models, is that derived directly from the inside of storm's core by reconnaissance aircraft penetration - whether manned or unmanned.

The principle typhoon reconnaissance aircraft in 1986.

In another study conducted in the period just before the disestablishment of tropical cyclone reconnaissance in the Western Pacific and Indian Oceans *(Tropical Cyclone Observation and Forecasting With and Without Aircraft Reconnaissance" by J.D. Martin, 1988 - reviewing tropical cyclone reconnaissance flights between 1979-1986)* demonstrated that satellites cannot provide tropical cyclone tracking, motion nor intensity measurements within storms as accurately as insitu aircraft reconnaissance.

Its interesting to note that this statement was made in the era before the introduction of GPS-Dropsondes, that are much more accurate, now in wide use and distribution.

As we will see in the pages ahead, there have been a number of international weather agencies that have heeded the WMO message and have recently fielded tropical cyclone reconnaissance and or surveillance aircraft to collect storm data towards forecast improvements. Additionally, there are other meteorological organizations that are currently in the process of establishing aircraft capabilities to improve forecasts and those in the beginning phases of internal justification and or authorization towards the establishment of potential new aircraft programs in the near future.

All this activity surrounding the establishment and utilization of tropical cyclone reconnaissance and or surveillance aircraft, constitutes a *"resurgence"*, since the discontinuation of typhoon reconnaissance by the US Military in 1987, on a scale never before seen in the history of hurricane hunting aircraft.

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"A Brief History of International Hurricane Hunting Aircraft"

In the unrealized history of Hurricane Hunting, the practice of utilizing aircraft for tropical cyclone reconnaissance towards the development of forecasts and warnings of approaching storms, there have been a number of countries that, out of necessity, took to the air and reconnoitred hurricanes, typhoons and or cyclones to gather the vital information needed to provide accurate forecasts - giving the public the timely warnings to make needed storm preparations and or evacuations to safeguard lives and property.

The US Military *(jointly with the US Weather Bureau)* pioneered Hurricane Hunting in the Atlantic in 1943, when both US Army Air Forces and US Navy aircraft first took to the skies to reconnoiter hurricanes far out to sea. The first official or *"authorized"* hurricane reconnaissance flight was flown by *a US AAF aircraft out of Trinidad on 19 August 1943, although some Navy aircraft had previously flown directed reconnaissance flights on several unnamed tropical depressions / storms earlier in July and August 1943.*

The principle US Navy patrol aircraft used for hurricane reconnaissance in the Atlantic between 1943 –1945.

The first tropical cyclone reconnaissance flights flown into Pacific storms commenced a little later, with tropical cyclone reconnaissance flights flown in the Southwest Pacific Area *(SWPA)* beginning in mid-1944 and typhoon reconnaissance flights in the Western Pacific starting in November of 1944.

The SWPA tropical cyclone reconnaissance flights were a component of much wider-ranging weather reconnaissance flights flown by a joint Royal Australian Air Force *(RAAF)* and US AAF Meteorological Service from bases in Australia, New Guinea and New Brittan. The first typhoon reconnaissance flights flown in the Western Pacific occurred in November and December 1944. These flights were flown by US AAF aircraft from Saipan, in a meteorological effort to support the first US military bomb strikes on Japan from the Marianas.

Note: *the December 1944 typhoon was actually flown by both a US AAF bomber and a couple of US Navy patrol planes from various bases. This was the same storm that struck Admiral Bull Halsey's 3rd Fleet with devastating results. Three destroyers capsized and were lost in the storm along with more than 790 crewmen.*

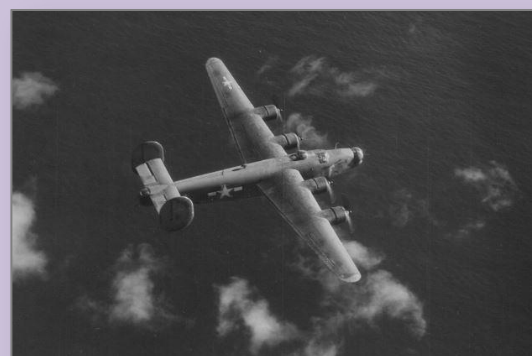
US typhoon reconnaissance flights continued in the Western Pacific until 1987, when the USAF disestablished its' Air Weather Service weather reconnaissance units. This effectively ended aerial typhoon reconnaissance support to forecast and warning in the Western Pacific after 42 continuous years.

Atlantic hurricane reconnaissance flights were also discontinued by regular Air Force weather squadrons, with the hurricane hunting mission transferring to the US Air Force's Reserve Command, that maintains one Hurricane Hunting squadron to this day.

US Navy Pacific typhoon reconnaissance flights were discontinued in 1971 with the Navy's Atlantic hurricane reconnaissance operations terminated in 1975.

The principle US AAF aircraft used for hurricane reconnaissance in the Atlantic between 1943-1945.

The principle US Navy patrol aircraft used for typhoon reconnaissance in the Pacific between 1944 -1945.



The principle US AAF aircraft used for typhoon reconnaissance in the Western Pacific between 1944-1945

But what is not generally known, is that a number of international aircraft have flown tropical cyclone reconnaissance and research flights over the past 70 years, some as early as WWII. One of the very first nations, other than the US, to fly tropical cyclones was the United Kingdom.

During the Atlantic Hurricane Season of 1944, British Royal Air Force *(RAF)* B-24 Liberators flew routine reconnaissance missions into hurricanes that threatened the United Kingdom's commonwealth of the Bahamas and the British Overseas Territory of Bermuda. The RAF B-24s located and tracked hurricanes for the area RAF Met Services, with the reconnaissance data factored directly into the British hurricane forecasts and warnings specifically generated for the local governments of the Bahamas and Bermuda – independently of the US Weather Bureau's hurricane forecast center.

The next country to become involved in flying tropical cyclones comprised Australia. Believe-it-or-not, Australia's Royal Australian Air Force *(RAAF)* meteorological service personnel, jointly with US AAF weathermen conducted cyclone reconnaissance flights on storms in the SWPA during 1944-45 on US aircraft.

According to a recent historical article, *"The History of Australian Weather and Cyclone Reconnaissance Aircraft: Australia's Cyclone Hunters" (by David Reade, P-3 Publications)* the history of Australia's participation in tropical cyclone reconnaissance flights has been revealed for the first time.

After the WWII joint flights, Australia continued to fly weather reconnaissance flights, in their own aircraft, that often encompassed flying on tropical cyclones.

In later post-war years *(during the mid-1950s)* the Australian Bureau of Meteorology *(BOM)* made an effort to establish a dedicated, routine, tropical cyclone reconnaissance capability utilizing high-altitude RAAF Canberra Jets, with BOM meteorologists on-board to locate the centers of the storms and gather visual weather information.

a British RAF B-24 used for hurricane reconnaissance in the central Atlantic in 1944 and cyclone reconnaissance in the Bay of Bengal 1944.

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One of the regional weather services in the Western Pacific that took the WMO message to heart and began an effort to acquire modern computer modeling capabilities was the Hong Kong Observatory. It was also this organization that further took the next step and began flying reconnaissance flights into Pacific typhoons in 2011.

Hong Kong's Typhoon Chasers

The most recent convert to the virtues of flying typhoon reconnaissance and the inspiration for the so-called resurgence in the Western Pacific, is Hong Kong; the special administrative region of the government of the People's Republic of China, and Hong Kong's associated weather agency, the Hong Kong Observatory.

Hong Kong, located along China's southeast coast, experiences more than 7 typhoons each year that affects parts or all of its territorial areas. These storms often generate severe wind-induced damage as well as catastrophic inundation *(and mudslides)* from heavy torrential rains and tsunami-like storm surges.

The Hong Kong government's SAR aircraft used for Pacific typhoon reconnaissance flights flown since 2011

In May 2011, the Hong Kong Observatory *(HKO)* partnered with Hong Kong's Government Flying Service *(GFS)* to initiated typhoon reconnaissance flights from Hong Kong. As of January 2014, the HKO-GFS team have flown approximately 14 reconnaissance missions into 10 typhoons and tropical storms *(as well as one low pressure system)* out over the northern South China Sea.

Notable storms flown comprised Typhoons Haima *(16-25 June 2011)*, Nesat *(23-30 September 2011)*, Talim *(16 -20 June 2012)*, Vicente *(18-25 July 2012)*, Kai-tak *(12 -18 August 2012)* and Tembin *(17-30 August 2012)* as well as Tropical Storms Bebinca *(19-24 June 2013)*, Rumbia *(27 June – 2 July 2013)* and Severe Tropical Storm Jebi *(26 July – 3 August 2013)* – before tangling with Typhoon Utor between 8-18 August 2013.

Three additional typhoons Hagibis *(13-23 June 2014)*, Rammasun *(9-20 July 2014)* and Kalmaegi *(11-18 September 2014)* and a tropical depression *(Karding / 5-8 September 2014)* have now been flown during the 2014 typhoon season.

Sporadically over the next 39 years, for various projects, program requirements and or events, RAAF military aircraft *(and some civilian ones)* conducted reconnaissance flights into Australian cyclones. Despite having never established an official routine *(dedicated)* cyclone reconnaissance capability, the BOM tried a number of times to do just that.

Even today, with reports on Global Climate Change touting the increases in the number and intensity of tropical cyclones from higher sea surface temperatures, there are recommendations for Australia to once again establish an airborne tropical cyclones reconnaissance or surveillance capability to improved cyclone forecasts and warnings.

With a resurgence of tropical cyclone reconnaissance aircraft on within the Pacific, the next great destructive Australian cyclone may make the case for the government to once and for all establish dedicated *"Cyclone Hunters"* in future.

Soviet Tropical Cyclone Hunters

The next country to have joined the hurricane hunting fraternity was the former Soviet Union. Little known and little understood, the USSR actually embarked on tropical cyclone research in the early 1950s and later in the 1970s, utilizing a fleet of oceanographic research vessels to investigate typhoons in the Western Pacific - jointly with the Socialist Republic of Vietnam, as a means to gather vital data for improved forecasts and warnings in Vietnam. This effort also provided research information for the Soviets to better understand these violent storms, as it related to Soviet Naval fleet deployments within the Western Pacific.

As these ship-borne cyclone research operations continued, other Soviet researchers took to the air to study typhoons in the Pacific *(between 1984-1990)* and hurricanes in the Atlantic *(between 1987-1990)*. Conducted by the Central Aerological Observatory *(of the USSR State Committee on Hydrometeorology and Monitoring of the Natural Environment)* and the Institute of Experimental Meteorology, the CAO's Flight Scientific Research Center, with support of the Flight-Test Complex of the State Scientific Research Institute of Civil Aviation; these airborne tropical cyclone flights were flown jointly with other regional meteorological agencies, including the Cuban Meteorological Service *(Atlantic)* and the National Hydro-Meteorological Service of Vietnam *(Pacific)* flew storms in Soviet weather / atmospheric research aircraft.

Hong Kong's Government Flying Services operates a variety of rotary-wing and fixed-wing aircraft supporting internal government taskings that comprise search and rescue, air ambulance / MedEvac, internal security / law enforcement agencies' operations as well as maritime surveillance, aerial survey / mapping and firefighting missions.

To facilitate the typhoon *(data collection)* reconnaissance missions, one of the GFS's two fixed-wing, twin-engine turboprop BAe Jetstream 4100 *(J-41)* SAR aircraft was configured with a flight-level meteorological measurement system *(measuring flight-level temperature, humidity, pressure and winds)* and an associated wing-mounted wind gust probe - that can collect three different components of wind speed. The aircraft was also equipped with a digital data-collection *(storage)* system that captures typhoon and tropical storm datasets, that are taken post-flight and assimilated into the HKO's numerical computer forecast models to build high-resolution databases as well as to support in-work forecasts and warnings for the active storms under surveillance.

The meteorological probe on the Hong Kong government's SAR aircraft used for Pacific typhoon reconnaissance flights

Flown along pre-determined flight track *(flight levels)* in and around the storms, between 10,000 feet *(3048 m)* and 1000 feet *(305 m),* the J-41's normal typhoon mission endurance is about 4-hours within *(minimally)* 125 miles *(200 kms)* of Hong Kong. During all the typhoon flights, the pilots used *(cockpit)* color weather avoidance radar to successfully navigate the severe thunderstorm cells in and around the storms. On flight tracks at 1000 feet *(305 m),* the GFS flight crews often experience moderated to heavy turbulence and at this low altitude can see the turbulent, white-capped seas below.

New Aircraft

In 2011, even before the Hong Kong typhoon flights actually began, the GFS announced that it was ordering two new *(Canadian)* Bombardier Aerospace Challenger 605 turbo-fan Jets as advanced multi-mission replacements for their existing J-41 turbo-prop SAR aircraft.

The new Jets encompass modern digitalization with full systems integration that will optimise mission performance, effectiveness and reliability. Given the subsequent GFS typhoon mission established by HKO, each of the new Challenger jets are to be configured with the AIMMS -20 flight-level meteorological system as well as a dropsonde vertical profiling system.

The Soviet aircraft used for Pacific typhoon and Atlantic hurricane research flights between 1984-1990.

The Soviets initially flew a specially equipped Ilyushin IL-18D aircraft *(nicknamed "Tsiklon" or Cyclone)* in Atlantic hurricanes and Pacific typhoons between 1984-88, flying from various bases in *(Cam Ruhn Bay, Da Nang and Saigon / Ho Chi Minh City)* Vietnam and from Camaquey, Cuba.

Then in 1988, another research aircraft was developed to fly the Cuban *"Hurricane Hunting"* flights. An Antnonov AN-12BPT *(also nicknamed "Tsiklon")* was introduced and flew both hurricane reconnaissance and research flights for a joint Soviet – Cuban hurricane program *(between 1988-90)*. Each aircraft had a variety of flight-level meteorological instruments, airborne weather radars, cloud physics systems and a 13 foot *(4 m)* long gust probe extending out from the nose.

The Soviet aircraft used for Atlantic hurricane research flights between 1988-1990

Some of the more notable storms flown by the Soviet Tropical Cyclone Hunters included; Pacific Severe Tropical Storm Warren *(23 August -2 November 1984)*, Typhoon Val *(14-19 September 1985)*, Hurricane / Tropical Storm Emily *(22-26 September 1987)*, Hurricane Floyd *(9-13 October 1987)*, Tropical Storm Chris *(21-30 August 1988)*, Super Hurricane Gilbert *(8-19 September 1988)*, Hurricane Gabrielle *(30 August – 13 September 1989)*, Hurricane Hugo *(10-25 September 1989)*, Tropical storm Iris *(16-21 September 1989)*, Hurricane / Tropical Storm Jerry *(12-16 October 1989)*, Hurricane / Tropical Storm Klaus *(3-9 October 1990)* and Tropical Storm Marco *(9-12 October 1990)*.

At the end of 1990, if you had asked, Soviet tropical cyclone research would have continued for the foreseeable future. Under Mikhail Gorbachev's policies of Glasnost *(openness)* and Perestroika *(government restructuring)*, exchanges were made

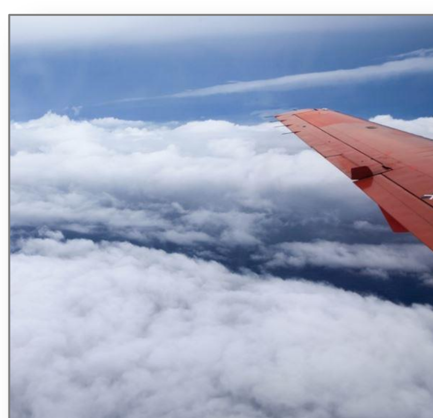
The aircraft's meteorological mission will be further enhanced by a real-time data-link / down-link system, of the SAR mission suite, that will be capable of transmitting all meteorological data directly to a HKO downlink station – where the high-resolution data can be quickly assimilated directly into the numerical

One of the two of the Hong Kong government's new SAR jet that will be utilized for Pacific typhoon surveillance flights in the Northern South China Sea.

forecast models. This will allow HKO to facilitate faster analysis and provide improved forecasts and warnings to the general public in a timely manner.

With both jet aircraft equipped with meteorological systems, this effectively doubles the HKO-GFS capacity to fly typhoons. The introduction of the new Challenger Jets will also see the HKO typhoon flights transition from of a rudimentary reconnaissance role, to that of a surveillance mission - capturing real-time storm datasets aiding improved forecasts. Now expected to be delivered in late 2015, the Challenger jets could be ready to fly typhoons by early 2016.

As a meteorological leader in the region, through various organizations such as the *(multi-national)* regional WMO / UN-sponsored Economic and Social Commission for Asia and Pacific *(ESCAP)* typhoon committee, HKO is sharing its typhoon datasets with other meteorological agencies in the region, to help promote development of those agencies' own numerical forecast models for typhoons as well as help advance cooperative research and analysis of tropical cyclones in the region. Through its participation in the regional Typhoon Committee, HKO has already provided Japan's Meteorological Agency *(JMA)* with storm datasets gathered during Typhoon Vicente in July 2012.



The Hong Kong's BAe J-41 SAR aircraft over Typhoon Utor between the US Hurricane Center and the Soviet CAO, where Soviet tropical cyclone scientists visited Miami and NOAA weathermen traveled to the Soviet Union. However, with the dissolution of the Soviet Union in December 1991, all CAO tropical cyclone research operations ceased and to-date have never been resumed by the subsequent Russian Government.

Canada's ET-Storm Hunters

Not widely known, but the next country to become involved in hurricane hunting was Canada. Between 2000 and 2005, Environment Canada's Meteorological Service of Canada, along with the Canadian Hurricane Center and the Canadian National Resource Council, joined forces to conduct airborne research surveillance flights into Atlantic hurricanes in Canadian waters as part of a study into *"Extratropical Transition"* storms.

Extratropical Transition storms *(ET storms)* are tropical cyclones that undergo transition from their tropical characteristics *(state)* to those of an extratropical cyclone with associated fronts, delineated cold air masses from warm air masses. During extratropical transition, tropical systems cease to draw their power from the ocean below *(known as thermodynamic decoupling)* and transitions to drawing energy from any frontal environments that the storms may be moving into or surrounded by.

These newly formed ET storms are often as intense or more intense than the hurricanes they

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Besides typhoon flights, the HKO-GFS aircraft has recently been participating in regional meteorological research projects supporting international weather research efforts. In early 2014, the Chinese Meteorological Agency *(CMA)* in cooperation with HKO, utilize the GFS's J-41 to gather airborne observations during the Southern China Monsoon Rainfall Experiment or SCMREX.

Initiated by CMA and the WMO, SCMREX studies the onset of the South China Sea Monsoon period of early summer, where the monsoon's associated torrential rain formations and intensity poses a serious threat to lives and property in southern China. To better understand the processes involved in the monsoon's rain formation and intensity *(to improve forecasts and warnings)* SCMREX introduced an airborne data collection element in 2014, which comprised the J-41. On 16 June 2014, the aircraft collected flight-level data at altitudes between 3280 feet *(1000m)* and 8202 feet *(2500m)*, during a period of intense observations conducted between April-June 2014.

With the expected delivery of the new GFS Challenger jets later in 2015, equipped with a modern dropsonde systems, its hoped that the new jets can contribute further to the SCMREX project and improve experimental airborne observations at altitudes upwards of 39,000 feet *(12 kms)*.

Along with the WMO, HKO is independently promoting the advantages of typhoon flights through the regional Typhoon Committee and has inspired others in the region to acquire typhoon reconnaissance / surveillance aircraft capabilities. One of Hong Kong's regional neighbors, South Korea, is now ready to follow in their foot-steps and has established a weather aircraft observation program that will include surveillance flights of typhoons.

South Korea Typhoon Reconnaissance

One nation set to begin typhoon surveillance flights in 2016 - 2017 is South Korea. The Republic of Korea's Meteorological Agency *(KMA)*, in an effort to monitor the effects of global climate change and investigate other aspects of weather modification, is acquiring an airborne meteorological observation platform equipped with 14 different meteorological instruments *(including a weather surveillance radar and a dropsonde system)* that can be utilized for typhoon surveillance.

Under the guidelines publicly put forth by the KMA, the multi-purpose aircraft will function in several key areas of weather research that includes Atmospheric *(air pollution)* monitoring, remote-sensing satellite data validation, climate change *(component)* research, precipitation enhancements experiments *(cloud seeding)* and severe weather observations - that will include flights into the advancing environments of tropical storms and typhoons.

Part of a much larger meteorological program to beef up its weather services and expand observation capabilities, the weather aircraft observation project was begun in late 2012 after a series of devastating typhoons and tropical storms that caused severe damages and devastating floods throughout the Korean Peninsula. In 2012, four disastrous storms; Severe Tropical Storm Kanoon *(aka; Khanun or Enteng / 14-19 July 2012)*, Typhoon Denbin *(aka; Tembin or Igme / 17-30 August 2012)*, Typhoon Bolaven *(aka; Julian / 19-20 August 2012)* and Typhoon Sanba *(aka; Karen / 10-18 September 2012)* devastated parts of South Korea and demonstrated an urgent need to improve Korea's typhoon forecast and warning capabilities.

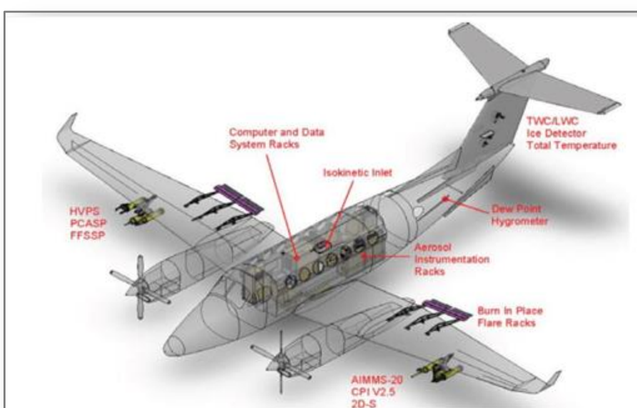
Note: *three additional severe storms in 2013; Typhoon Leepi (16-21 June 2013), Typhoon Kong-Rey (25-30 August 2013) and Severe Tropical Storm Danas (1-9 October 2013) caused further flooding that set new records not seen since 1962.*

In a proposed surveillance operation similar to the Taiwanese DOTSTAR typhoon flights, the KMA aircraft will deploy dropsondes in and around the periphery environments of typhoons to capture 3-dimensional storm datasets to aid in building tropical cyclone databases for their numerical forecast models. The flights will additionally provide near real-time surveillance data feeding forecast models, towards active forecasts and warnings of those storm under surveillance.

Much like HKO, and the other nations around the region *(with the help of the WMO)*, KMA initiated a new series of numerical analysis and weather forecast prediction models in 2012, that require high-resolution data collected from data sparse ocean areas *(of the Yellow Sea, Sea of Japan and the East China Sea)* and the sea approaches to the southern Korean peninsula.

Having participated in and received dropsonde information collected during international typhoon research projects, *(like The Observing System Research and Predictability Experiment or THORPEX and its associated Pacific Asian Campaign or T-PARC and its component, the Tropical Cyclone Structure or TCS-08 field experiments)* KMA recognised the value of such data and determined that aircraft are still the best method of collecting typhoon data needed to feed the computer models for both analysis and prediction.

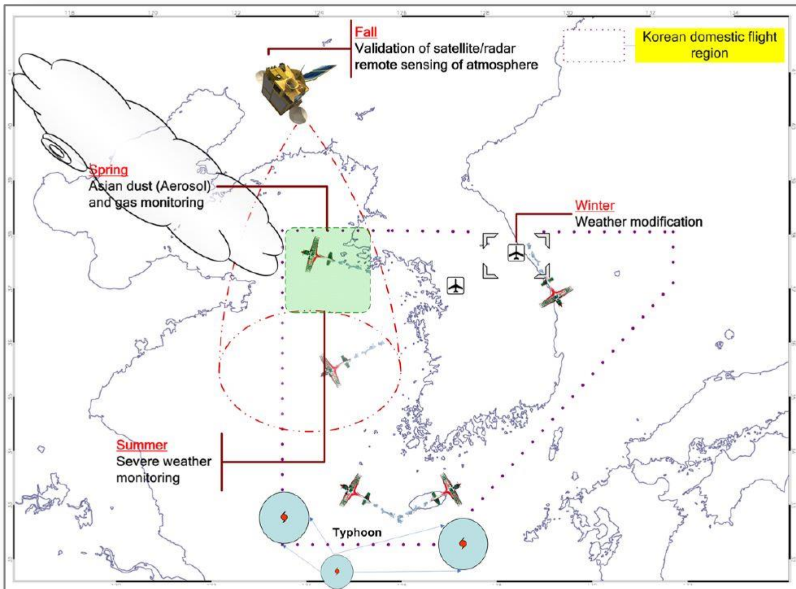
Note: *KMA and its Meteorological Research Institute (METRI) had previously flown data collection flights into Typhoon Nakri (7-13 July 2002) over a number of days, utilizing two Aerosonde UAVs. The storm datasets collected were used as a database for the initiation of KMA's Global Data Analysis and Prediction System (GDAPS) model at that time.*



The new South Korean meteorological observation aircraft to be used for typhoon surveillance flights in the ocean areas and sea approaches to the southern Korean peninsula

Thus, in May 2013, KMA ordered a multi-purpose aircraft consisting of a heavy-weight, twin turbo-propped, Beechcraft King Air 350 H/W aircraft as a meteorological observation aircraft. The KMA Beechcraft King Air will be equipped with more than a dozen meteorological sensors that will encompass flight-level meteorological instruments and a remote-sensing dropsonde system as well as cloud physics instruments, atmospheric aerosol and pollutant *(gas)* monitoring systems and *(glaciogenic / hygroscopic)* cloud seeding capabilities.

Korea has had considerable problems with air pollution and heavy-metal contamination drifting over the Korean Peninsula from unchecked Chinese Industries to the Northeast. It's believed that the utilization of cloud seeding techniques may help to remedy the air pollution problem, thus the KMA multi-purpose aircraft will be equipped to conduct cloud seeding operations.



The new South Korean meteorological observation aircraft's areas of operation and multi-mission applications, including its typhoon surveillance flights in the ocean areas and sea approaches to the southern Korean peninsula.

KMA has publicly indicated that the scarcity of observations over the open ocean is a limitation to its efforts of improving typhoon forecasts and warnings and that aerial observations in the storm's environment *(and ultimately the central core)* would go a long way towards any improved forecasts.

Under current plans put forth by KMA, their multi-purpose King Air observation aircraft is expected to be delivered sometime in 2016, with corresponding test flights conducted during that year. Typhoon observation flights could begin as early as the 2017 typhoon season.

Existing South Korean military aircraft proposed to be utilized for typhoon reconnaissance flights in the near future.

The Canadian atmospheric research aircraft used for North Atlantic hurricane research flights between 2000-2005.

transitioned from, with expanded wind fields and heavy rainfall distributions. The strongest winds typically occur on the right side of the storms, relative to their motion, with rainfall distributions often displaced, mostly on the left side of the storms. Both these aspects of the ET storms can extend out hundreds of miles *(or kilometers)* from the storms' center, permitting the interaction with other low pressure systems and fronts in the surrounding environment.

Side Note: *the term extratropical transition storm has caused considerable confusion to the public, given the different forecast products put out by the Canadian and American hurricane centers. Extra-tropical storms in the US have been traditionally considered to be tropical systems that no-longer possess sufficient tropical characteristics (organized convection) to be considered tropical cyclones and are in the process of weakening or dissipating.*

The Canadian Extratropical Transition storms denotes a tropical cyclone that has undergone the ET process, with

However, given the urgency to better serve their modern forecast models and improve typhoon forecast and warnings, South Korea is apparently in the initial process of considering a more viable and independent typhoon reconnaissance capability, to include eyewall penetration. Aside from their current multi-purpose meteorological observations aircraft *(the King Air)* acquisition program, KMA is considering the use of existing Korean military aircraft *(such as C-130 transports)* as typhoon hunting aircraft.

Something to keep an eye on.

US Pacific Command

One regional forecast organization in the Western Pacific, that you would expect to have a typhoon reconnaissance capability, is the JTWC in support of the US Pacific Command *(USPACOM)* – which currently has none.

Headquartered in Honolulu *(Oahu)* Hawaii, USPACOM is a unified combatant command encompassing Pacific-based elements of the US Navy, the US Air Force and other US armed forces components. USPACOM is responsible for the security of the Pacific Ocean Area. Under the current command structure, the USPACOM is ultimately responsible for providing reconnaissance *(flights)* of typhoons in the Western Pacific to support the JTWC typhoon forecasts. Unfortunately USPACOM does not have any dedicated typhoon reconnaissance aircraft to provide flight operations for the typhoon forecasting mission, leaving the JTWC to utilize satellite and land-based radar systems to help forecast typhoons in the region.

History

Routine typhoon reconnaissance flights, aiding Western Pacific area typhoon forecasts and warnings, began in June 1945 by US Army Air Force weather reconnaissance aircraft out of Guam. The US Navy soon joined in, officially beginning routine typhoon reconnaissance flights in August 1945 from the Philippines and various other Pacific Island bases.

Between 1947 and 1971, both US Navy and US Air Force *(Air Weather Service)* weather reconnaissance squadrons maintained continuous typhoon reconnaissance operations, before demobilization from recurring budget cuts in the wind-down of the Vietnam conflict, saw the Navy retire from conducing typhoon reconnaissance flights all together in 1971 – leaving the USAF sole responsibility for typhoon reconnaissance in the Western Pacific.

the resulting transitioned storm often termed a Post-tropical Storm by the Canadian Hurricane Center.

The US Hurricane Center never really had a dedicated term for those storms that underwent extratropical transition, as they rarely occurred in their area of responsibility. However, when they did occur in the past, US forecasters use semi-official terms to describe the results of these storms that underwent extratropical transition, such as "Weather Bombs", "Super Storms" or "Perfect Storm" – as in the case of the Halloween Storm of 1991 (28 October – 4 November 1991) which was also known as "The Perfect Storm" made famous by the Sabastian Junger book of the same name and subsequent movie (based upon the book) about loss of the fishing vessel; the Andrea Gail.

The use of the "Super Storm" term arose again during Hurricane Sandy (22-30 October 2012,) where the storm extratropical transitioned in a period just before landfall, in New Jersey and New York with devastating results. Another unofficial descriptor for Sandy, which was coined during the storm (traced back to a US Weather Service forecaster), was "FRANKENSTORM". Seized by the media, this term caused further confusion with the general public as they did not fully understand the extratropical transition process and the potential threat posed by these types of storms.

Another term also materialized during Sandy, when the US Hurricane Center use the term

The principle US Navy typhoon reconnaissance aircraft in the Western Pacific between 1952 - 1971.

The principle US Military typhoon reconnaissance aircraft (USAF WC-130s) used in the Western Pacific between 1971-1978

The USAF subsequently disestablished its' Air Weather Service weather reconnaissance units conducting typhoon reconnaissance flights in 1987, effectively ending aerial typhoon reconnaissance support to forecasts and warnings in the Western Pacific after 42 continuous years. Atlantic hurricane reconnaissance flights were also discontinued by regular Air Force squadrons about this time, with the hurricane mission

Continued on page 17

"Hybrid Storm" to describe the extratropical transitioning of Sandy in public warnings and its resulting landfall as a post-tropical storm with hurricane force intensity. (hybrid was mostly used in forecaster technical discussions and had little context to the public raised with standard hurricane, tropical storm, tropical depression designates)

After some consultation with the Canadian Hurricane Center, the US Hurricane Center began using the term "Post-Tropical" with regards to a storm that has undergone Extratropical Transition. However, they used accompanying sub-set terms such as "Post-tropical / Extratropical" that comprises tropical cyclones that no longer exhibit tropical characteristics and have undergone full ET transition into extratropical storms with attached low pressure fronts (-vs- the previous "Post-Tropical" storms where tropical cyclones have lost all tropical characteristics, but maintain winds of 35 knots or greater). Then there's "Post-Tropical / Remnant Low" which is the same as Post-Tropical storm, but with no ET transition and winds less than 40 mph (64 km/h) and weakening.

Another problem was the media / broadcast sector's use of these terms. In the Canadian Maritimes, local TV media and (meteorological) weather reporters often said "….. down-graded to a Post-Tropical storm …." with little true understanding of the terms (specifically the Canadian meaning of the terms) and the extratropical transition process. The use of incorrect adjectives and a limited understanding into the extratropical transition process, and the characteristics of the resulting powerful storms, gives the public a confused view to the posted warnings and the imperativeness to make preparations and or evacuations as needed. In an effort to foster a direct relationship with the media, improved understandings and provide training, the Canadian Hurricane Center conducted 1-day seminars for all regional broadcasters and media weather providers in Canada, to educate them on the extratropical transition process and the characteristics and dangers of the resulting Post-Tropical storms.

Today, the Canadian and American hurricane centers are more aligned with equal terms for ET transition resulting storms and both somewhat utizing the Post-Tropical designator. But regardless of what you call it, the bottom-line is that the public needs to be made aware of the difference between a tropical cyclone that is dissipating and a tropical cyclone that is undergoing extratropical transition into a resulting storm that is just as powerful and damaging as a tropical cyclone – as in the case of Sandy in 2012.
…. end ….

In an effort to better understand the extratropical transition process, capture extratropical transition datasets *(for forecast model development)* and improve forecasts and warnings for these storms, the Meteorological Service of Canada / Canadian Hurricane Center established the *"Canadian Hurricane Research Project"*

The Canadian Convair 580 hurricane research aircraft

Under this project, the participating Canadian National Research Council contributed one of its research aircraft, comprising a Convair CV-580 twin-turboprop, that was instrumented specifically for the hurricane research mission. The aircraft's meteorological instrumentation comprised standard flight-level pressure, humidity and temperature instruments as well as state-of-the-art cloud physics sensors and systems, GPS navigation and a vertical-profiling dropsonde system. The aircraft was also equipped with two types of radars, including a spotlight Synthetic Aperture Radar *(SAR)* and a *(W-band)* Polarimetric radar, to provide detailed cloud structures and rainfall concentrations.

The Canadian research project involved surveillance flights into 5 tropical systems over 5 years, that included Hurricane Michael *(15-20 October 2000)*, Hurricane / Tropical Storm Karen *(12-15 October 2001)*, and Hurricane Juan *(24-29 September 2003)* all off the coast of Nova Scotia, as well as the decaying remnants of Hurricane Isabel *(6-20 September 2003)* over Lake Erie and Ontario, Canada. The Canadian research project personnel also participated in a joint hurricane research mission with NOAA into Hurricane Ophelia *(6-23 September 2005)* on a NOAA Hurricane Research Division WP-3D Orion flown over two days off the US Coast between Virginia and Nova Scotia.

The Canadian research flights gathered high-resolution datasets on these storms that captured specific details of extratropical transition.

In the end, the Canadian Hurricane Research Project collected a spectrum of datasets of different hurricanes that transitioned into extratropical storms. Combined with datasets captured by Canadian ocean buoys, regional manned weather stations and off-shore automated surface (weather) stations *(mostly located on oil platforms and remote barrier islands)* the research program transitioned to one of data analysis and the development of computer models – with no additional flights required.

With a number of successful extratropical transition datasets acquired and numerous ET observations to incorporated into hurricane forecast models, the Canadian Hurricane Center began to develop and experimentally run storm forecasts with ET computer *(simulation)* models.

Since 2006, the Canadian Hurricane Center has tracked a number of extratropically-transitioned storms in Canadian waters, including Hurricane Florence *(3-13 September 2006)*, Tropical Storm Chantal *(31 July – 1 August 2007)*, Hurricane Noel *(28 October -2 November 2007 and 2-7 November 2007 as a post-tropical storm)*, Hurricane Bill *(15-26 August 2009)* as well as Hurricanes Earl *(25 August – 5 September 2010)*, Igor *(8-23 September 2010)*, Irene *(21-30 August 2011)*, Tropical Storm Jose *(27-29 August 2011)*, Hurricane Leslie *(30 August – 12 September 2012)* and most recently Hurricane Arthur *(1-7 July 2014)* in the Canadian Maritimes.

Today, the Canadian Hurricane Center uses a variety of computer prediction models to forecast for hurricanes that move into the cooler, mid-latitude waters of Canada. Some of those models comprise special weather phenomena native to Canada including the extratropical transition or ET process.

Although the desire is there to have an aerial reconnaissance or surveillance capability for tropical cyclones that transition in Canadian water, the Canadian Hurricane Center *(Environment Canada)* does not have any short-term plans for the establishment of hurricane surveillance aircraft.

But never say never.

Taiwan's Typhoon Hunters

Since September 2003, Taiwan *(the Republic of China)* has been conducting surveillance flights in the vicinity of typhoons that threaten Taiwan, in an effort to improve the computer forecast models that in turn improve the accuracy of typhoon forecasts and warnings for the Taiwanese populace.

The "Dropsonde Observations for Typhoon Surveillance near Taiwan Region" or DOTSTAR program is an interdepartmental project of the *(Taiwanese)* National Science Council *(NSC)*, the National Taiwan University *(NTU)*, the Taiwanese Central Weather Bureau *(CWB),* the National Central University *(NCU)* and the Private Chinese Culture University *(PCCU)* in cooperation with the Civil Aeronautics Administration *(CAA)*, and the Aerospace Industrial Development Corporation *(AIDC)* of Taiwan - in collaboration with the US National Oceanic and Atmospheric Administration *(NOAA),* its Hurricane Research Division *(HRD)* as well as the World Meteorological Organization (WMO).

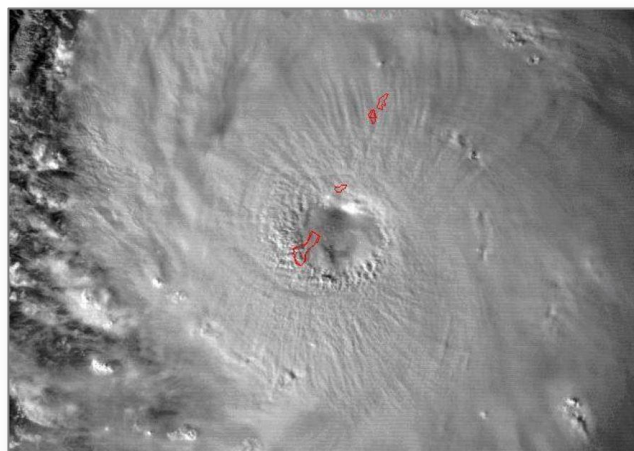
Astra Jet used for Pacific typhoon surveillance flights between 2003 – present

transferred to the US Air Force's Reserve Command that maintains one Hurricane Hunting squadron today.

<u>Note:</u> *the US Navy further discontinued hurricane reconnaissance flights in the Atlantic in 1975, after 32 continuous years of what was considered the longest humanitarian effort ever conducted by the US Military at the time.*

With a lack of weather reconnaissance aircraft, the JTWC has experienced a significant high rate of forecast errors with little direct over-water observations by aircraft. However, there have been incidents where USPACOM and its components have considered re-establishing typhoon reconnaissance in the Western Pacific.

Components of the US Pacific Command actually began looking at re-starting typhoon reconnaissance / surveillance flights back in the early 2000s. In 2003, the JTWC petitioned USPACOM to re-establish or resume Pacific synoptic weather reconnaissance and typhoon reconnaissance flights *(either manned or unmanned)* in the Western Pacific in the wake of destruction wrought by Super Typhoon Pongsona in 2002.



Super Typhoon Pongsona 2002, at a time when the storm's eye passed over the Marianas islands of Guam and Rota simultaneously.

Super Typhoon Pongsona *(2-12 December 2002)* struck in the Northern Marianas with sustained winds in excess of 150 mph *(240 km/h)* and stronger gusts upwards of 173 mph *(278 km/h)*. Some witnesses said wind gusts were as high as 184 mph *(298 km/h)*, that raked Guam with devastating results and affected other island in the Northern Marianas such as Rota, Tinian and Saipan. Damage was wide-spread with particular devastation wrought upon US Military bases and facilities belonging to US Pacific Command. On Guam alone, 1300 homes were destroyed, damaging another 1825, with power and communications cut off throughout the whole of the island. Anderson AFB was in the 65 mile *(40 km)* wide eye for over 2 hours. The eye passed over Guam and nearby Rota island *(just 30 miles / 48 kms away to the north)* simultaneously. The typhoon dumped more than 25 inches *(650 mm)* of rain on the island causing localized flooding.

Later, the lack of sufficient weather observation data at JTWC was further compounded by the pending loss of the QuikSCAT *(Scatterometer)* satellite, which aggravated the situation further

Under DOTSTAR, a Gulfstream G-100 *(Astra SPX)* turbo-fan jet flies in the peripheral environments around and over typhoons to deploy dropsondes from altitudes upwards of 43,000 feet (13,106m). Flown by test pilots of the Aerospace Industrial Development Corporation, the DOTSTAR jet is modestly equipped for the typhoon mission with an Airborne Vertical Atmosphere Profiling System *(AVAPS)* GPS - based dropsonde system, the aircraft's on-board weather avoidance radar and a commercial satellite phone system, to transmit the dropsonde surveillance data in near real-time to the Taiwanese Central Weather Bureau *(CWB)*, for assimilation into the numerical forecast models.

The DOTSTAR program flew its first operational mission on Typhoon Dujuan *(27 August – 3 September 2003)* on 1 September 2003, deploying 11 dropsondes into the storm. After the first year of operation, DOTSTAR flights were providing improved forecast accuracies on the order of between 14% to 22% or an overall average improvement in forecasts by 18%. Today that number has increased to approximately 20% (the program's original goal) with the potential of further improvements as developmental computer forecast models progress.

The Taiwanese DOTSTAR jet out over a typhoon in the Western Pacific

As of May 2014, the DOTSTAR Jet has flown more than 69 surveillance sorties on 54 typhoons, deploying more than 1141 dropsondes, to gather invaluable datasets that have not only helped with the development of improved forecasts and warnings for the public, but has also aided continued typhoon research improving new computer simulation numerical forecast models to advance our knowledge of these tempestuous storms.

The DOTSTAR typhoon surveillance program is another shining example of the benefits that can be derived through the initiation of tropical cyclone reconnaissance / surveillance flights. The DOTSTAR program further demonstrates the ability to establish a tropical cyclone flight program with minimal resources, such as leased aircraft operations and minimally required equipment to get the data need to improve forecast and warnings. _End_

DOTSTAR 2002-2005

driving increases in forecast errors in the JTWC's typhoon forecast products.

The NASA QuikSCAT *(short for Quick Scatterometer Satellite)* was a specialized weather satellite used to record sea-surface wind speeds and directions over the data-sparse areas of world's oceans. QuikSCAT itself had been developed as a quick or fast replacement for a NASA scatterometer instrument that, onboard a Japanese earth-observation satellite, failed in June 1997. This system had in-turn been providing the JTWC with remote-sensing wind speed and direction estimates for typhoons in the Western Pacific since the US military ceased aircraft reconnaissance in 1987. Fully operational in June 1999, the QuikSCAT satellite experienced a mechanical failure in November 2009, when the primary onboard *"SeaWinds"* instrument's antenna stopped rotating and could no longer provide viable wind information. This failure seriously crippled the JTWC's forecasting capabilities, further adding to a considerable level of forecast errors in the center's typhoon prediction products.

Note: *unfortunately scatterometer derived data has limitations and built in errors that compound to produce inherent forecast errors. Based upon the JTWC's own reports, scatterometers provide a good view to low-level circulation and outer wind structures in weak tropical cyclones, but are actually unreliable for determining wind speeds above 58 mph (93 km/h) in mature tropical cyclones. These scatterometers can also depict false centers in storm wind fields by as much as 138 miles (222 kms). Because of this, scatterometer derived center positions of storms have not been used by the JTWC since 2002. The JTWC however, does utilize data derived from scatterometers to determine the radius of 40 mph (65 km/h) winds in the mature storms in forecasts estimates. Thus, given the lack of aircraft reconnaissance, scatterometers are one of the few tools for developing JTWC forecast estimates.*

Although the US Military procured access to the Indian Government's Oceansat-2 scatterometer satellite *(known as OSCAT)* as well as some other foreign satellites as a temporary stop-gap measure, no viable replacement for QuikSCAT was forthcoming.

A subsequent planned replacement for QuikSCAT has only now been made operational in 2014. Launched by NASA in September 2014, the new instrument known as ISS-RapidSCAT *(built from existing QuikSCAT spare-parts)* was mounted to the International Space Station on 1 October 2014 and began collecting operational wind data on or about 6 October 2014.

But back in 2005, with pressure mounting, the US Air Forces' Pacific Command sponsored a demonstration and evaluation project of the recently developed long-range meteorological drone known as the *"Aerosonde UAV"*.

UAV Surveillance

In 2005, under a project called "*WEATHERSCOUT" (or WSUAV)*, a miniature Aerosonde UAV was evaluated in the Western Pacific as an inexpensive means by which to jump-start typhoon reconnaissance again and improve the accuracy and quality of weather forecasts *(including Tropical Cyclone forecasts and warnings)* in all areas of the Pacific. The Aerosonde, is a small meteorological robotic unmanned aerial vehicle specifically designed for highly flexible and inexpensive meteorological surveillance operations. While under development, Aerosondes had flown a series of meteorological collection flights, that included previous tropical cyclones missions flown in Australia, Taiwan, Japan, South Korea and in the United States.

During a six week trial period, between October – November 2005, WEATHERSCOUT Aerosonde UAVs were evaluated in a series of weather mission profiles in the Western Pacific. Operating out of Anderson AFB on Guam, several Aerosondes accumulated more than 282 flight hours flying in different weather collection profiles. Unfortunately, no typhoons materialized during the trial period out of Guam. However, USAF representatives had been on hand earlier in the year during flight trials by NOAA, evaluating the capabilities of Aerosondes to fly hurricane surveillance flights in the Atlantic – where a Aerosonde flew into Hurricane Ophelia *(6–23 September 2005*) with positive results.

Having successfully completed the WEATHERSCOUT trials, the Aerosonde proved to be a flexible meteorological survey platform capable of operating in the data sparse areas of the Pacific. However, the US Military never adopted the Aerosonde for the WEATHERSCOUT application and no comparable vehicle has ever been acquired for this application in the Pacific since.

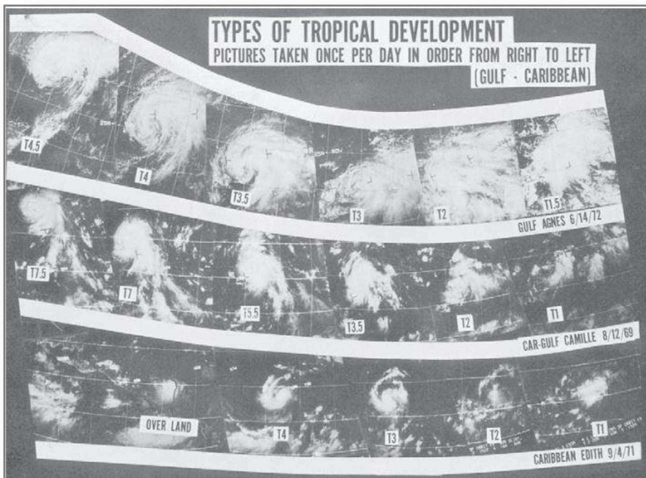
Note: *about this time or shortly thereafter, Aerosonde's parent company (AAI Corporation) ran into some financial issues that pushed any acceptance of the UAV off the table for consideration in the WEATHERSCOUT project. AAI Corp was subsequently acquired by Textron Systems and the Aerosonde continues to be marketed as a viable platform for scientific and military surveillance applications.*

The US Pacific Forces' WEATHERSCOUT (Aerosonde) UAV, trialed in the Western Pacific as a weather reconnaissance observation platform, which included typhoon surveillance applications in 2005

Still with no viable reconnaissance capability to help revitalize typhoon forecasts and reduce errors, the forecasters and researchers working for the JTWC bean looking at more objective ways of improving analysis of satellite imagery. One of the primary tools available to them; was *Dvorak analysis.* As indicated before, the original Dvorak technique uses visual cues *(cloud types and motion)* to derive storm data from satellite imagery. This technique of visual analysis is very subjective and subject to individual interpretation by the various analysts.

An *"objective"* Dvorak Technique was instituted to include the visual analysis of IR *(infrared)* satellite imagery. Under this type of analysis, visual cues *(contrasting brightnesses)* corresponding to temperature differences, were derived and then applied to known formulas to determine intensity estimates. This subsequently led to the advancement of the automated version of the objective Dvorak technique, or the

Advance Objective Dvorak Technique, which is associated with automatically locating the center of circulation and identifying weak storm signatures during analysis of infrared satellite imagery. The fact is that the objective analysis of visual satellite data is still subjective and when combined with other data estimates fed in to forecast models, magnify inherent errors that affect the final forecast products – often by wide margins. These revisions to the original Dvorak Technique require validation or ground-truthing, which can only be done by tropical cyclone reconnaissance aircraft. Thus, through a series of recent typhoon research projects *(T-PARC / TCS-08 and ITOP 2010)* US Military and other countries research aircraft flew typhoons in the Western Pacific to gather the data subsequently needed to verify the revised satellite imagery analysis techniques and processes developed to improve the JTWC and other regional weather agencies typhoon forecast.



An example of visual analysis cues associated with the Dvorak Technique

As mentioned earlier, the JTWC still produces forecast products with inherent forecast errors. In order to further reduce these errors and significantly improved typhoon forecasts and warnings, the JTWC *(via USPACOM)* needs to develop a typhoon reconnaissance capability.

Some of the logistical issues associated with USPACOM potentially establishing a typhoon reconnaissance capability encompasses the funding needed to acquire and modify a new specialized meteorological aircraft, the establishment of a dedicated unit to operate any proposed aircraft and maintain it over the long term, and the time it will take develop an aircraft acquisition program - especially when the need for such a capability has existed for some time and has never been more needed than at the present time.

However, as we have seen with Hong Kong, Canada, Taiwan and others, there are alternatives to a large and expensive aircraft program. There are existing tactical aircraft within USPACOM, with inherent operational capabilities, that can be minimally equipped *(with flight level and or dropsonde systems)* for the typhoon reconnaissance or surveillance mission. Existing multi-role aircraft such as Maritime Patrol and or Search and Rescue aircraft, once suitably equipped, can provide the means to capture storm data required to reduce forecast errors and greatly improve typhoon forecasts and warnings in the Western Pacific, sooner than later.

In fact, there is even precedence for this in JTWC history. Between the 1950s and 1980s, due to a series of weather reconnaissance aircraft maintenance issues, reductions in force and limited availability of typhoon reconnaissance aircraft, the JTWC would press into service regional tactical aircraft to perform typhoon investigations and tracking missions. Sometimes designated as USOA *(US Other Aircraft)* in JTWC records, these aircraft comprised a mix of tactical airlift, military transport, tactical reconnaissance *(photo reconnaissance)* and search and rescue aircraft as well as maritime patrol *(ASW)* planes assigned to Western Pacific US Navy and US Air Force units.

There was even one occasion in 1985, when a USAF F-15B Strike Fighter was used to fly a reconnaissance mission into Typhoon Jeff *(21 July – 2 August 1985)* out of an urgent necessity. Even US civilian contracted aircraft performing regional military transport duties in the Western Pacific, *(known as Aircraft Of Opportunity or AOO)* also provided limited synoptic weather reconnaissance and typhoon positioning / tracking information to the JTWC at different times.

A number of the various USOA aircraft utilized by the JTWC for augmenting typhoon reconnaissance between the 1950s and 1980s.

All the different operators and various typhoon aircraft approaches, past and present, represent potential alternative methods to the various weather organizations considering the development of their own future aerial reconnaissance or surveillance capabilities. Existing *(current)* US military aircraft in the Western Pacific region could be minimally equipped for JTWC's typhoon reconnaissance or surveillance mission and in operation sooner than later**.**

Potential future US "Typhoon Chasing" aircraft from various existing tactical aircraft within USPACOM already in the Western Pacific

Something USPACOM could consider as it looks for solutions to reduce its forecast errors and improve forecasts and warnings accuracies in the Western Pacific to safeguard its facilities, deployed aircraft assets and personnel.

India's Cyclone Reconnaissance Program

In 2008, the Indian Government announced a plan to establish wide-ranging scientific research to enhance its national weather collecting capabilities and to provide improved forecasts and warnings of approaching cyclones in the Indian Ocean and the Bay of Bengal.

The Indian Ocean, and specifically the Bay of Bengal, is one of the most active tropical cyclone regions of the world, with more than 5 severe cyclones per year making landfall along regional coastal areas that have the highest density of population on the Indian subcontinent. India has experienced some of the most deadliest cyclones to have ever challenged mankind. Of the top ten deadliest tropical cyclones to have ever occurred in history, eight out of the ten have occurred in the area of the Bay of Bengal. In fact, fifteen of the top twenty deadliest storms have occurred in the Bay of Bengal.

10 Worst Tropical Cyclones in History *(based upon fatalities)*

No.	Name	Region / Country	Fatalities
1	*the* Bhola Cyclone *(7-13 November 1970)*	Bay of Bengal / East Pakistan *(now Bangladesh)*	300,000 - 500,000
2	*the* Hooghly River Cyclone *(11 October 1737)*	Bay of Bengal / India & Bengal region *(now Bangladesh)*	300,000 - 350,000
3	Haiphong Typhoon *(27 September – 8 October 1881)*	Western Pacific / Indochina *(now Vietnam)*	300,000
4	Coringa Cyclone *(16 or 25 November 1839)*	Bay of Bengal / India	300,000
5a	*the* Backerganj Cyclone *(1584)*	Bay of Bengal / Bengal region *(now Bangladesh)*	200,000
5b	*the* Great Backerganj Cyclone *(29 Oct – 1 Nov 1876)*	Bay of Bengal / Bengal region *(now Bangladesh)*	200,000
6	Chittagong Cyclonic Storm *(28 October 1897)*	Bay of Bengal / Bengal region *(now Bangladesh)*	175,000 - 200,000
7	Super Typhoon Nina *(30 July – 6 August 1975)*	Western Pacific / China & Taiwan	171,000 - 229,000
8	Cyclone 02B *(24-30 April 1991)*	Bay of Bengal / Bangladesh	138,000 - 143,000
9	Cyclone Nargis *(27 April – 3 May 2008)*	Bay of Bengal / Myanmar	138,000 - 140,000
10	*the* Great Bombay Cyclone *(6 June 1882)*	Bay of Bengal / India	100,000

An important component of this significant Indian scientific weather research project is the establishment of a cyclone reconnaissance capability through the procurement of *"Hurricane Hunting" (type)* aircraft for the reconnaissance of Indian basin tropical cyclones, to provide the high-resolution storm information needed by which to feed modern computer forecast models.

The proposed establishment of cyclone reconnaissance by India ends a 27-year hiatus since cyclone reconnaissance flights were flown in the region.

History

The first routine cyclone reconnaissance flights flown in the Indian Ocean and Bay of Bengal occurred during WWII. In 1944 British Royal Air Force *(RAF)* aircraft assigned to maritime patrol and other tactical reconnaissance squadrons flew weather reconnaissance flights for the Indian Meteorological Department *(IMD)* that included reconnaissance flights into tropical storms, cyclones and cyclonic *(frontal)* storms that hampered wartime operations and wrought devastation to allied military bases and facilities within the China-Burma-India Theater of war.

These RAF weather flights prompted the US AAF's 10th Weather Region to request its own weather reconnaissance unit to fly synoptic weather reconnaissance flights out in the Bay of Bengal, looking for areas of low pressure that would become cyclones and or other cyclonic storms.

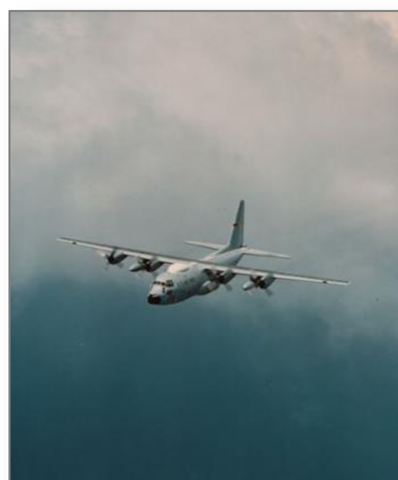
Although that unit, the US AAF's 2nd Weather Reconnaissance Squadron, would become famous for flying the weather over the Himalayas or the so-called *"Hump"* into China, this squadron was originally established specifically to fly synoptic weather reconnaissance and cyclone hunting flights out over the Bay of Bengal – which it did right up through the end of the war and until the end of 1945.

Later in 1963, India hosted an international study of the Indian Ocean that saw a number of cyclone flights flown by international aircraft. The International Indian Ocean Expedition *(IIOE)* was a three month investigation into the general large – scale atmospheric circulation over the northern Indian Ocean, that included the Bay of Bengal and Arabian Sea. During the IIOE period, participating US Weather Bureau hurricane hunting aircraft flew into several tropical storms and cyclones that materialized. Indian Meteorologist were invited to participate in the cyclone reconnaissance fights and several proposals for a domestic cyclone reconnaissance capability were developed and presented to the Indian Government in the immediate aftermath of the IIOE.

In 1974 the Indian Military identified an interest in supporting cyclone reconnaissance flights in the Bay of Bengal. As part of a proposed Foreign Military Sales case for US surplus C-121 Super Constellations, it became the US Navy's understanding that India would utilize some of the aircraft requested for tropical cyclone reconnaissance operations in the Bay of Bengal. The sale never materialized.

Earlier in 1971, the JTWC established additional areas of responsibility *(AORs)* that included the Indian Ocean and began tasking cyclone reconnaissance flights in the Bay of Bengal flown by USAF Air Weather Service *(AWS)* WC-130 aircraft from the 54th Weather Reconnaissance Squadron – flown from bases initially in Thailand. The JTWC Indian Ocean AOR was further expanded in 1975, adding weather and cyclones reconnaissance flights in to the Arabian Sea.

These flights continued until 1987, when all US weather and tropical cyclone reconnaissance operations in the Pacific, Indian Ocean and Arabian Sea were terminated by the US Government.



USAF flew tropical cyclone reconnaissance flights in the Indian Ocean / Bay of Bengal between 1971 - 1978

Indian Ocean Cyclone Reconnaissance

To address the critical lack of observations from tropical cyclone's core environment over the waters of the Indian Ocean, interfering with Indian Government efforts to improve cyclone forecasts and warnings for the northeastern Indian Ocean and Bay of Bengal, the Indian government proposed to implement cyclone reconnaissance flights to collect high-resolution storm data needed to feed new numerical *(computer)* forecast models.

The proposed program's goals are to significantly reduce current tropical cyclone forecast errors by 30% *(by between 16% and 33%)* in the track, intensity and landfall predictions.

Thus, reducing the current cyclone landfall warning areas from between 155 – 186 miles *(250 -300 kms*) down to 62 miles *(100 kms)* in the 48-hour cyclone forecasts - while further improving the accuracy of storm intensity estimates and storm surge level predictions.

Initially conceived by the Indian Ministry of Earth Sciences in 2008, based upon a set of guidelines established by the Indian National Disaster Authority *(NDMA)* in 2005, the Indian scientific weather research plan was part of a much wider government disaster mitigation program designed to reduce the vulnerability of coastal communities to hydro-meteorological hazards associated with cyclones, safeguarding the lives of its populace in these coastal areas.

With participation by the Indian Ministry of Earth Sciences and the National Cyclone Risk Mitigation Project *(group),* the IMD is to be the lead agency for the Indian Cyclone program and is assigned high-priority for the establishment of a reconnaissance aircraft - to be under the operational control of and maintained by the Indian Air Force.

Indian Cyclone Reconnaissance Aircraft

For the eventual cyclone reconnaissance mission, the Indian Government is looking for an aircraft that has the meteorological capabilities to that of the American WC-130J Hurricane Hunting plane with flight level weather reconnaissance systems *(sensors and instruments)* and associated data management *(computer data control, display and data storage)* system as well as a vertical profiling *(GPS)* dropsonde system – with the structural airframe toughness to withstand eye penetrations. Whether that means the Government actually wants to acquire a WC-130J remains to be seen. The notion that they wanted a WC-130J comes from the fact the Indian Air Force recently took procession of 6 new-production tactical airlift C-130J Hercules form Lockheed Martin. Under an estimated $2 billion dollar aircraft acquisition program, India would purchase up to 12 C-130J transport Hercules, with potential options to acquire a number of maritime patrol variants of the C-130J *(currently designated SC-130J Sea Hercules)* for the Indian Navy and Coast Guard as well as an additional specially configured C-130Js for the IMD *"Cyclone Hunting"* mission.

India is looking to establish a typhoon reconnaissance capability similar to the American WC-130J Hercules hurricane hunting aircraft

It was also recognized that the advance technological capabilities of UAVs could also be of some benefit to the Indian aircraft reconnaissance program, providing wider-range area surveillance augmenting the manned reconnaissance aircraft mission during storm tracking.

Although the proposed cyclone hunting aircraft are to be primarily established as a cyclone reconnaissance asset towards improved forecasts and warnings, the IMD ideally views any proposed aircraft as meteorological platforms, that can be utilized in support of regional tropical cyclone research as well as those research operations associated with global climate change monitoring.

The IMD has further suggested that the introduction of proposed cyclone reconnaissance aircraft flights will additionally benefit the meteorological agencies of other Indian Ocean regional countries, including Madagascar, Sri Lanka, Bangladesh, Myanmar *(Burma),* Thailand, Pakistan and Oman, with storm data shared by the IMD with the various other regional meteorological agencies. The IMD further asserts that this might include flying storms and cyclones out over the Arabian Sea if need be.

Forecast Demonstration Project

Under the proposed Indian cyclone project, there are to be several initial incremental phases to demonstrate improvements in the overall IMD forecast and warnings leading up to the implementation of cyclone reconnaissance flights. The Forecast Demonstration Project was subsequently established specifically to demonstrate the IMD's ability to gather high-resolution storm data needed to feed sophisticated weather prediction models, to improve forecast and warnings from the data collected over sparse areas of the Bay of Bengal.

Broken down into several sub-projects or phases, the first *"Pre-Pilot phase"* comprised a short term investigative period *(between 15 October and 30 November)* whereby a variety of existing land-based and ship-borne meteorological systems, sensors and remote – sensing *(satellite)* capabilities were employed during tropical cyclones events in 2008 and 2010 to gather as much data as possible to essentially baseline the current capability of the IMD.

The next *"Pilot Phase"* conducted in 2011-12, was similar to the first except it employed a series of Indian Ocean Tsunami early warning ocean buoys, a new network of coastal Doppler radar *systems (with a range of 186 – 249 miles / 300-400 kms)* as well as specialized satellite and new numerical prediction models during cyclone activities in the planned October – November investigative period.

Although some of the IMD's forecast errors were reduced somewhat during the initial phases, they were not comprehensive enough to provide the significant improvements in the national and regional forecasts and warnings established by the guidelines. For this, data from the storm's internal core-environment is required, which can only be accomplished by aircraft reconnaissance.

The *"Final Phase"* of the demonstration project *(originally scheduled for 2012 and then 2013)* was to have included a contracted aircraft used to probe Bay of Bengal cyclones and deploy dropsondes into the storms periphery environment. The proposed surveillance aircraft was to have had a suitable dropsondes capability and additional cloud micro-physics instruments. Although the proposed contracted aircraft was to fly into Bay of Bengal cyclones environments, it is not expected to penetrate the eyes of the storms. The insitu – data collected was planned to be assimilated into forecast models as a final demonstration of the improvements to IMD's tropical cyclone forecasts.

Currently this phase of the Demonstration Project has not been completed and apparently on hold.

In February 2014, India submitted a proposal request to NASA for a joint scientific research project, whereby NASA's earth resources DC-8 flying laboratory would fly cyclone research flights out over the Bay of Bengal. This NASA DC-8 has for years supported US national hurricane research efforts to improve hurricane forecasts in the Atlantic and has a dropsonde system as well as cloud physics capabilities.

This request was erroneously reported in the Indian Press *(and on the internet)* as the IMD's attempt to acquire NASA's DC-8 for the cyclone reconnaissance program. Having established that their DC-8 was not for sale, NASA reported that the Indian proposal comprised their DC-8 flying high-altitude data-collection flights to capture *(steering)* wind patterns and provide the means needed for the deployment of dropsondes as part of the final demonstration phase of the Indian cyclone project - for a predicted period of cyclone activity in October – November of 2015 or 2016. However, as of December 2014, NASA Headquarters *(Washington D.C)* reported that it had no plans in the DC-8's 2015-16 project schedule to investigate tropical cyclones in the Indian Ocean.

Under the original cyclone reconnaissance program outline, the Operational Test Phase was to have taken place by now, whereby operational test flights were to have been flown into Bay of Bengal cyclones to develop reconnaissance *(and research)* flight patterns and to practice penetrations of storm eyes – presumed with the operational reconnaissance aircraft acquired for the program. However delays in the final demonstration phase, is pushing further delays in the subsequent operational flight test phase. Thus, currently the Indian cyclone reconnaissance project is running between 2 and 4 years behind proposed schedule and its unclear exactly what the future is for the entire program.

At the end of December 2014, the Cyclone Warning Division *(of the IMD)* reported that despite technical difficulties and insufficient responses to its global tender for a *(leased)* dropsonde-capable aircraft, the Indian Government has allocated the funds to support the continuation of the Operational Test Phase *(dropsonde aircraft)* and the subsequent acquisition of a cyclone reconnaissance aircraft in the near future.

More recently, its been reported that the IMD is in the process of developing its own domestic dropsonde-capable aircraft for the final phase of the Demonstration Project, potentially based upon a King Air airframe with dropsonde and cloud physics instruments.

Stay tuned, I'm sure that we will hear more from India soon.

It was also during 2014, that it was learnt that a number of other regional countries in the Pacific have expressed vague interests in the potential of establishing typhoon reconnaissance aircraft capabilities. One country potentially in the throes of an internal justification of such an aircraft program is mainland China *(the People's Republic of China)*.

China: Typhoon Reconnaissance

China, through its meteorological service the China Meteorological Agency or *CMA*, is currently undergoing an internal proposal for the establishment of an airborne capability to conduct reconnaissance of tropical cyclones, specifically typhoons out over the northern extent of the South China and East China Seas.

Mainland China is one of the worst countries in the Asia - Pacific region to be severely affected by tropical cyclones. *(The Philippines is the second worst)* Each year, China can expect to experience between 8 and 10 typhoons on average, with more than 6 storms making landfall along coastal provinces – based upon statistical observations during a period between 1949 and 2002. More recent observations suggest that land-falling typhoons in China has increased to 7.6 storms per year. *(The maximum number of storms to have ever affected mainland China per year peaked at 16 during 1974)*

In more recent years, CMA has been looking to improve its tropical cyclone forecasting and warning services. In 2006, in an effort to further reduce the annual fatalities from typhoon encounters, the CMA revised their typhoon warning system by instituting two new storm categories; *"Severe Typhoons and Super Typhoons"* to help motivate the populace to make appropriate preparations and or evacuate low-lying coastal areas when ordered by officials. The revised CMA storm category system now comprises; **Typhoons,** *that includes previous severe tropical storms, 73.0 - 92.6 mph (117.5 -149.0 km/h),* **Severe Typhoons** *92.8 – 113.9 mph (149.3 – 183.3 km/h) and* **Super Typhoons** *114.1 - plus mph (183.6 - plus km/h)*

Not generally known, China has actually ventured into airborne surveillance of typhoons during 2008, with a CMA project that saw unmanned aerial vehicles or drones, fly several low level observations into the boundary layers and inner cores of typhoons near mainland China.

China's UAV Flights

Due to perceived limitations in tropical cyclone forecasts, especially storm tracks, landfall predictions and intensity forecast accuracies, CMA decided to evaluate the potential of UAVs as a surveillance platform to collect storm data, towards improving typhoon forecast and warnings. Under this project, Chinese UAV drones flew a number of flights into Typhoon Kalmaegi *(13-22 July 2008)* and Typhoon Sinlaku *(8-23 September 2008)*.

China flew several UAV flights into Pacific typhoons in 2008

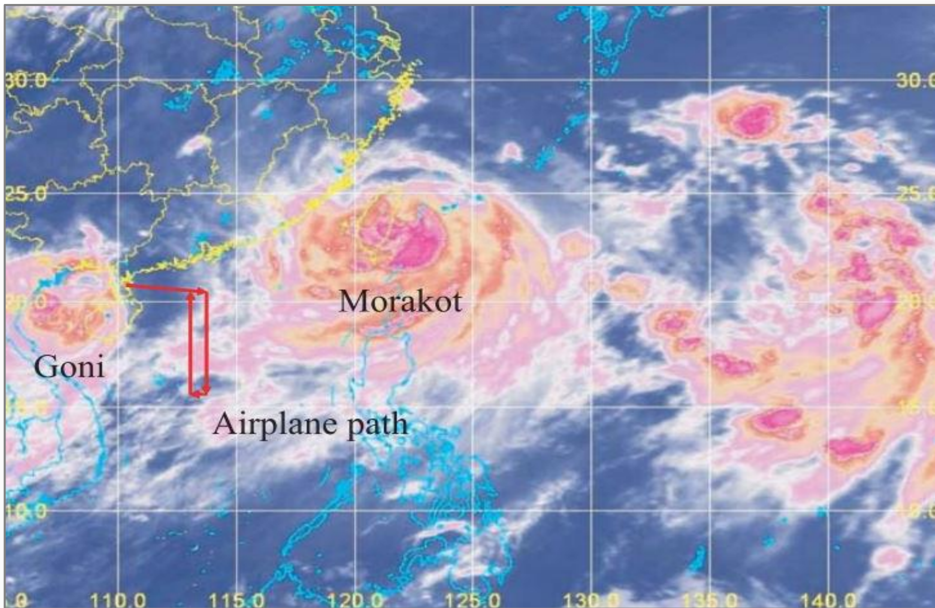
The CN-1 Drone UAV *(also known as; "the Early Bird 1")* was a domestically produced Chinese fixed-wing, long-endurance miniature UAV, of a twin-boom *(inverted)* V-tail design with a rear-mounted *(pusher)* propeller engine. The Drone was equipped with GPS navigation and an 11 pound *(5 kg)* payload, capable of carrying a variety of meteorological instruments. Standing 2 feet *(0.71m)* high, 6 feet *(1.75m)* long and wingspan of more than 9 feet *(2.9m)* wide, the CN-1 was capable of speeds upwards of 75 mph *(120 km/h)* and a range between 700 -1100 miles *(1200 -1800 kms)* – providing a maximum extended endurance of approximately 20 hours or about 7-12 hours normally.

The Chinese CN-1 UAVs flew three 7-hour long missions in and around Typhoon Kalmaegi on the 18th and 19th of July 2008, before and after the storm made landfall into China's Fujan province. Launched out to sea, the drones flew towards the northeast into the right-front quadrant of the storm over the ocean, while the center eye was over land.

The flights into Kalmaegi occurred during the same period that Chinese government agencies called for the evacuation of the populace of Fujan and Zhejiang provinces.

The CMA UAVs gathered temperature, pressure, humidity and wind speed and direction measurements during the flights in the two storms. The UAVs cruised at altitudes of approximately 1640 feet *(500m)* in and around the storms, mostly in the typhoon's wind fields or boundary layer. During Kalmaegi, one of the drones came within 62 miles *(100 kms)* of the storm's center. The drones flew into areas of heavy precipitation, severe convection and turbulent conditions – further verifying the water-tightness and durability of the aerial probes. Later during Typhoon Sinlaku *(on 15 September 2008)* a CN-1 UAV flew one 4-hour mission into the core of the storm, through the heaviest rain and turbulent areas of the typhoon.

The next year *(2009),* CMA conducted another set of experiments testing the application of dropsonde data into forecast models, evaluating the reliability of dropsondes data on typhoon track forecasts as well as a theoretical attempt at real-time targeting.



China flew typhoon surveillance / dropsonde flights into Typhoon Morakot 2009 in a Chinese military aircraft

In this effort, CMA utilized a Chinese military aircraft to deploy *(GPS)* dropsondes into Typhoon Morakot *(2-13 August 2009)* and parts of Tropical Storm Goni *(30 July – 9 August 2009)* during the 2009 typhoon season. This is the first time a manned PRC Chinese aircraft has been known to have flown on a tropical cyclone and the first time mainland Chinese dropsondes have ever been deployed into tropical cyclones. The aircraft is believed to have been a Chinese Air Force Shaanxi Y-8 medium-range transport aircraft. The Y-8 is a *(Chinese)* domestically manufactured version of the of the Russian Antonov AN-12BP military transport aircraft, that is roughly equivalent to the American C-130 Hercules. Flown between 7 & 9 August 2009, the Chinese Y-8 deployed upwards of 20 –plus dropsondes into the two storm systems, 11 in the cloud-shrouded areas between Typhoon Morakot and Tropical Storm Goni *(while Goni was still a tropical depression)* in the East China Sea - in an area to the north of Taiwan and east of Fuzhou China.

China flew a typhoon surveillance / dropsonde flight into Typhoon Morakot 2009 in a Chinese military aircraft

The area between the two storms was deemed a *"sensitive area"*, believed better for gathering the best storm data *(via dropsondes)* as part of the experiment into real-time targeting.

One of the most devastating storms to have struck Taiwan in recent history, Morakot carried on over the central part of the island nation, later making landfall in eastern mainland China - causing more than 1 million people to be evacuated from low lying and coastal areas in a number of eastern and southeast provinces. More than 49 inches *(1240 mm)* of rainfall fell causing wide-spread flooding. Ultimately, forecast model simulations were run with and without the assimilated dropsonde data collected.

Among a number of differences between the two model runs, was the subsequent reduction in the

48-hour forecast track errors (*for typhoon Morakot)* by 18%, and significant forecast improvements with the dropsonde data assimilated into the models. Forecasters were able to located the storm's center more accurately and better capture intensity changes. In fact, the dropsonde data subsequently identified that Tropical Storm Goni, at one point, had achieved typhoon intensity.

Today, the CMA is seemingly preparing to take the next step in its evolution of improving typhoon forecasts and is in the process of implementing a typhoon research project to explore the parameters of tropical cyclone intensity. Called *"the Experiment on Typhoon Intensity Change in Coastal Areas"* or *EXOTICA*, this project's aims are to study typhoon intensification and its associated characteristics via the utilization of a network of synergistic observation techniques, including land-based, seaborne and airborne platforms, to collect datasets to improve Chinese typhoon intensity forecasts – particularly rapid intensification near landfall. Although a variety of observation platforms will be employed, including land-based mobile wind chasing vehicles *(with microwave radiometer and wind profilers)*, offshore moored ocean buoys and weather towers, shore-based radars, *"meteorological rocket dropsondes"* and potentially developmental UAVs, the project hinges on the use of an integrated dropsonde - capable aircraft to collect inner core storm data.

Note: *the Chinese "rocket dropsondes or dropsondes deployed by rockets" is a proposed concept (or technique) of making atmospheric soundings via the use of Chinese meteorological rockets that are capable of deploying stratospheric radiosonde balloons or dropsondes while in flight. Known as the "Zhi Nu" or ZN series of meteorological sounding rockets, the ZN-1 is a rocket capable of gathering meteorological sounding data (wind speeds and direction as well as barometric pressure, temperature and humidity) from specialized GPS dropsondes automatically deployed by the rocket. CMA has proposed to position these rockets to launch and track over (or through) the tops of typhoons to deploy a series of dropsondes to make vertical soundings down through the storm. Although a number of these rockets have been test-launched on high-altitude atmospheric winds and wind shear soundings, they have yet to be tested on a typhoon at this time.*

To be conducted by CMA through the regional Typhoon Committee, with some of their area weather agency partners, EXOTICA is expected to be implemented sometime in 2015 and run through 2017-18. Under the latest EXOTICA draft plan *(released February 2015)* CMA expects to utilize Hong Kong's new dropsonde-equipped Challenger 605 Jets to collect inner core storm data on 1-2 typhoons in 2015 and 3-5 typhoons in 2016-2017. However as previously stated, delays in the development of the Hong Kong replacement Challenger jets have pushed delivery of these aircraft to late 2015 with operational readiness to fly typhoon missions as late as the spring of 2016. This issue may greatly impact the effectiveness of EXOTICA with the lack of a dropsonde capable aircraft upon implementation. Given this situation, the EXOTICA project is minimal justification for the CMA to establish its own typhoon reconnaissance capability, either a temporary one just for the project or a more permanent solution towards future improvements in CMA's typhoon forecast and warnings.

A potential Chinese typhoon reconnaissance aircraft capability could see the use of existing Chinese Military Shaanxi Y-8 transport aircraft as viable *"typhoon stalkers"* in the near future and may already be in the works.

Potential future Chinese military typhoon reconnaissance aircraft, in support of Project EXOTICA.

The Philippines

Sometimes it takes a devastating storm to make a government realize that they need to improve their observational capabilities and expand their capacity to provide more accurate forecasts and warnings of tropical cyclones.

The Philippines is at that point now, in the wake of the devastating Super Typhoon Haiyan *(aka; Typhoon Yolanda / 3-11 November 2013)*. Originally detected as an area of low pressure southeast of Pohnpei *(Micronesia)*, Haiyan developed in unusually favorable conditions throughout its track to become a large and powerful storm, more than 300 miles across at peak – which occurred just before landfall in the early morning hours of 8 November 2013 on the east coast of Samar Island with winds in excess of 145 mph *(230 km/h)*.

With high winds and torrential rains, it was the storm surge that caused most of the 6,000-10,000 fatalities and left more than 4-million homeless throughout the more than 7000 islands that make up the Philippine Archipelago. Although the storm surge was believed to have been no more than 20 feet *(6m),* ocean floor and landward contours as well as other factors magnified the surge into a mountainous tsunami that drove fishing vessels 5-miles *(8 kms)* inland and completely inundated whole cities and towns such as Tacloban.

As previously discussed, there are some that view this storm as the most severe tropical cyclone in history. Satellite imagery analysis provided forecasters estimates as to the storm's pressure in the neighborhood of 895 mb *(26.43 inches) or lower*, although not quite surpassing Super Typhoon Tip *(4-24 October 1979)* which had an aircraft measured central pressure of 870 mb *(25.69 inches)* via dropsonde at peak. However, the true measurement of this potentially record setting storm Haiyan is unknown.

There is no denying that Haiyan was an unusual and extremely powerful storm. The question is *"how powerful"* ? Without reconnaissance aircraft having flown the storm, there is no way of truly knowing.

In the wake of this storm, the Philippines will have to reassess their weather services and typhoon forecasting capabilities. And like Hong Kong and Korea, they may come to the determination that an airborne reconnaissance or surveillance capability is needed *(either manned or unmanned)* to provide the data required to maintain new forecast models to improve typhoon forecasts.

This is not the first time the Philippines has had to make this decision. Back in the mid-1970s, under the Marcos Government, PAGASA had developed plans to establish an airborne typhoon research / reconnaissance capability in support of its previously "*Typhoon Moderation Research and Development Council's" (TMRDC)* approved typhoon modification project - to lessen the severity of typhoons via cloud seeding. Under the TMRDC's *"Typhoon Moderation"* project *(also known as Project TYMOD)*, a small fleet of Philippine military aircraft were to have conducted reconnaissance and tracking flights to collect storm data for PAGASA, during seeding operations. The data collected would have been provided to PAGASA forecasters to be used to improve the accuracy of typhoon forecasts and warnings.

With the subsequent fall of the Marcos Government in 1986, and the reorganization of the PAGASA in 1988, any progress on the TYMOD project activities and the opportunity for typhoon reconnaissance aircraft disappeared.

Note: *although the TYMOD project seemingly never officially progressed beyond some rudimentary experiments with cloud seeding flights in thunderstorms, utilizing different trial seeding equipment, no typhoon reconnaissance flights were ever officially flown. However, there is some significant evidence to suggest that a Marcos ordered typhoon seeding mission was flown during Typhoon Olga (10-28 May 1976) with mixed results – that just may have actually caused additional destructive flooding in Manila had the storm not been tampered with.*

Beyond the contributions of American *"Typhoon Chasing"* aircraft, often operating from the Philippines between 1945-1987, the Philippines has never maintained an organic typhoon reconnaissance capability. Thus, the establishment of typhoon reconnaissance or surveillance aircraft capability in the Philippines remains to be seen.

Japan's Typhoon Hunters

One of the regional Western Pacific meteorological organizations that has a vital typhoon tracking responsibility is Japan's Meteorological Agency or *JMA*.

Japan experiences the effects of between 3-5 typhoons making landfall each year, that can cause severe wind damage and devastating flooding. The Japanese Meteorology Agency is the sole national authority responsible for monitoring and forecasting typhoons in the Western *(North)* Pacific and the South China Sea. All the principle typhoon analysis, tracking, and forecasting is done through a forecast center in Tokyo. This center was further designated a Regional Specialized Meteorological Center *(RSMC)* in 1984 under the World Meteorology Organization *(WMO)* as part of the World Weather Watch. The Tokyo RSMC was further designated a WMO Data Collection or Production Center *(DCPC)* for the WMO information systems *(WIS)* in June 2011.

In order to detect and track typhoons, JMA utilizes a network of weather radars and numerous satellites to monitor these storms in its area of responsibility. JMA has a network of 20 *(C-band / 5.6 cm)* weather radars covering the expanse of the main home islands as well as the Rykyus Islands with meteorological radar facilities positioned at Okinawa *(at Nase and Ishigakijima islands)* and a radar facility on top of Mt. Fuji.

<u>Note:</u> *as of 2013, the Japanese network of 20 weather radar stations were to have been replaced by newer Doppler weather radar systems to improve radar monitoring of typhoons.*

JMA additionally owns, or has access to, more than a dozen weather satellites of different configurations that provide data on cloud heights and distribution, upper-air wind speeds and sea-surface winds estimates as well as sea-surface temperature measurements. Its data from these satellites that provide JMA with most of its typhoon observations that are assimilated into various forecast models. JMA has some of the most advanced weather prediction systems in the region and currently utilizes an advanced modified version of the Dvorak method for typhoon analysis

Lacking insitu coverage over the open ocean, JMA's forecast estimates have a measure of variation that lend themselves to forecast errors. Thus, in 2006-07 JMA recognises the need for forecast improvements *(error reduction)* and embarked on a number of efforts to do just that. One focused plan was to use new developmental computer simulation prediction forecast models, with data solely derived from improved satellite data analysis. In this effort, JMA began to utilize a super computer system known as *the "Earth Simulator"*, housed at the Yokohama facility of the Japan Agency for Marine Earth Science and technology *(Japan's equivalent of NOAA,)* to aid in high-resolution typhoon forecast modeling.

Also during this time, JMA began contemplated adding an aerial surveillance capability to support improved typhoon forecasts and warnings. JMA explored an airborne surveillance capability through a series of experimental research projects and field experiments under the project name *"Typhoon Hunter"* in the early 2000s.

Established in late 1999, the first planned flight operations of Typhoon Hunter field experiments were conducted by JMA's Meteorological Research Institute *(MRI)* between September – October 2000, utilizing the commercially available miniature *(autonomous)* meteorological UAV *"Aerosonde"* to collect

Japan flew the Aerosonde UAV towards typhoon surveillance in 2000-2001.

high-resolution *(fine structure)* storm datasets for assimilation into new forecast models - towards the improvement of public typhoon forecast and warnings in Japan. This field experiment, conducted out of Okinawa from Shimojishima airport, gave the JMA an opportunity to operationally evaluate the capabilities of the Aerosonde UAV as a potential typhoon surveillance platform. Unfortunately, no storms materialized during the experimental period and no typhoon reconnaissance flights were actually flown.

But during Typhoon Hunter 2001 *(TH2001)* a number of Aerosonde flights were flown. Conducted over 5-days, between 25-30 July 2001, several Aerosondes flew more 50 flight hours in the near vicinity of Typhoon Toraji *(25 July – 1 August 2001)*, from the Shimojishima Airport on Okinawa. The UAVs flew exclusively in the right-front *(northeast)* quadrant of the storm to collect vital storm data. On one overnight continuous flight, one Aerosonde flew for more than 18-hours and made more than 10 vertical soundings of the Toraji between 13,000 feet *(4000m)* and 1300 feet *(400m)* – coming within 248 miles *(400 kms)* of the storm's center.

JMA / MRI also conducted Aerosonde flights from Palau *(Micronesia)*, 804 miles *(1,295 kms)* southwest of Guam *(or 434 miles / 700 kms east of the Philippines)*, in November 2001. At least one flight was flown into an unnamed tropical depression *(later developing into Tropical Storm Ondoy; 16-25 November 2001)* with mixed results.

Although the Aerosonde performed admirably in its scientific missions under the Typhoon Hunter experiments, there was apparently problematics staying in direct *(line of sight)* communication with the vehicle, due to the curvature of the earth as it flew southwards. It was suggested that if the UAV had had a more stable communication system during its' flights over the Western Pacific, such as via satellite, the vehicles would have made a viable long-range typhoon observation platform for the JMA in future. At the time, the Aerosonde was only equipped with UHF radio communications subject to particular limitations.

During another JMA field research experiment, known internally as Typhoon Hunter 2008, JMA utilized a *(contracted)* German Dassault Falcon 20E-5 Jet to conduct typhoon surveillance as part of their contribution to T-PARC / TCS-08.

Under T-PARC, four different research aircraft flew on Typhoons Nuri *(17-23 August 2008)*, Sinlaku *(8 - 21 September 2008)*, Hagupit *(18-25 September 2008)* and Jangmi *(23 September – 1 October 2008)*, including a USAF (Res) Hurricane Hunting WC-130J, a US Navy *(NRL)* RP-3D Orion, the Taiwanese DOTSTAR typhoon surveillance jet and the Japanese *(leased)* Falcon 20E-5 Jet.

The German Falcon Jet, owned by Deutsches Zentrum fur Luft – und Raumfahrt *(Germany's National Research Center for Aeronautics / Aerospace and Space)*, is a specialized atmospheric research aircraft based upon the popular French Dassault business jet. The Falcon is equipped with LIDAR *(pulse)* laser and dropsonde systems as well as cloud physics instruments to capture high-resolution datasets of vertical profiles of winds and water vapor distributions.

During an extended program called Typhoon Hunter, Japan flies a German Atmospheric research jet in a number of storms in 2008

The goals of JMA's project *(some aligned with its T-PARC participation)* were to collect comprehensive typhoon datasets for the implementation of new forecast models to improve regional typhoon forecasts and warnings. They additionally wanted to investigate regional cyclogenesis, rapid intensification and particularly areas of typical recurvature in the Western Pacific as well as Extratropical Transition *(ET)* of tropical cyclones within the region. The Falcon Jet flew 25 flights around Japan *(85 flight hours)* mostly around Typhoons Nuri, Sinlaku and Jangmi collecting rare storm structure datasets – some during extratropical transition. More than 328 dropsondes were deployed.

Given the experience gained during these projects, it would be expected to see JMA leverage off its *"Typhoon Hunter"* efforts and pursue some kind of aircraft program of its own to routinely fly typhoons that threaten or affect Japan - and to gather the vital data needed to significantly improve Japanese forecasts and warnings. Apparently, JMA has considered a surveillance aircraft in the past, that was to have been based upon a business type corporate jet. However this proposal never materialized.

Despite the *"Typhoon Hunter"* efforts, today the JMA continues to improve its analysis capabilities of visual satellite data. Since 2012, RSMC Toyko has been developing new objective satellite analysis techniques utilizing MTSAT satellite data. The center has also been improving its storm surge forecasts, sharing them with other regional weather agencies to verify accuracies.

However, its now been learned that the JMA is quietly considering the possibility of establishing a typhoon reconnaissance or surveillance capability and is said to be in the very early stages of justification and analysis for a proposed aircraft – given the growing resurgence of typhoon chasing aircraft within the Western Pacific.

The future will tell.

In Closing

It's been said recently, that the *Golden Age* of the weather satellite is passing and that the end of their significance as a viable weather prediction tool *(at least for tropical cyclones)* is soon drawing to an end. The majority of the various types of weather satellites in operational use today are fast exceeding their design lives with no viable replacements on the horizon and limited launch capacity temporarily delaying any replacement programs. There are many that believe that current technology weather satellites just cannot provide the level of data needed by researchers or forecasters to feed the modern numerical computer models required to improve tropical cyclone forecasts.

The bottom line is that you can analyze all the space-based visual data from satellites you want, but all you can derive is an interpretation, an estimate, a guess as to what the pressure is in the core of a tropical cyclone; what the surface winds might be and what the intensity might be in several hours; Its all just a bunch of guesses!

With the establishment of tropical cyclone reconnaissance or surveillance aircraft, you are no longer dealing with estimations or guesses. You can collect hard *(high-resolution)* data that can provide you with the actual answers to your questions as to what the pressure is, what the winds are and how intense the storm is or will be.

In the end, the number of countries that are in operation of tropical cyclone reconnaissance and / or surveillance aircraft is growing, with an equal or greater number of nations in the throes of establishing aircraft capabilities towards typhoon or cyclone flights in future. This increase in tropical cyclone aircraft activity constitutes *a resurgence*.

In this sense, tropical cyclone reconnaissance flights have come full circle and remain the only viable way to collect the vital data needed to assimilate into computer forecast models to generate the desired improved forecasts and advanced warnings required in future; that ultimately save lives and property.

… the end …