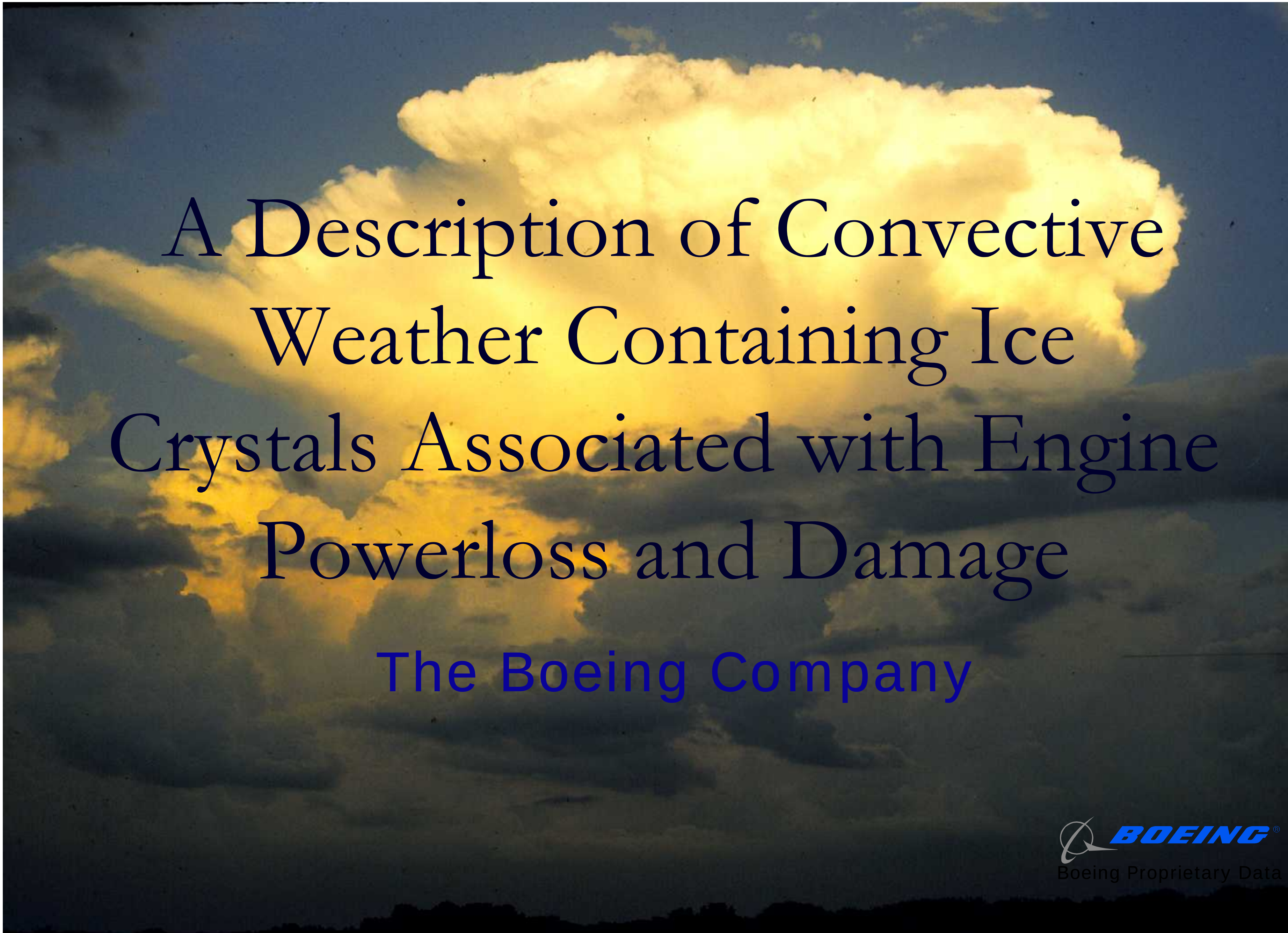


Photo: courtesy of Ian McPherson

The Boeing Company acknowledges the contributions of J. Walter Strapp, Environment Canada, to this presentation

Introduction

- This presentation is intended to enhance pilots' awareness of ice crystal icing conditions where engine events have occurred
- High altitude ice crystals in convective weather have been recently recognized to be a cause of engine powerloss and engine damage
- The term "icing conditions" has always been used to refer to conditions where supercooled liquid drops adhere to airframe surfaces – typically altitudes 22,000 feet and below
- "Ice crystal icing" does not affect cold airframe surfaces, only engine surfaces
- Traditional thunderstorm avoidance procedures may help avoid ice crystals, but...
- It is not practical to avoid all ice crystal conditions, as the particles may not be detected by aviation radar
- There are clues to watch for to recognize these crystal icing conditions

Reference: AIAA 2006-0206 "Ice Particle Threat to Engines in Flight"

What is convective weather?

Convective weather is caused by deep lifting and condensation of air in an unstable atmosphere, sometimes resulting in one or more of the following:

- deep cloud and large anvil regions
- areas of strong wind shear and turbulence
- lightning
- high condensed water contents
- heavy precipitation and hail

Photo: courtesy of Ian McPherson

Types of Convective Weather

Deep convective clouds can be found on a variety of scales:

- Isolated Cumulonimbus (CB), often thunderstorms, and can be thought of as the building block for convective weather.
- CBs can organize into mesoscale convective complexes (MCCs) and squall lines, spanning hundreds of miles
- Tropical storms are usually composed of convective elements rotating around a central low pressure center, leading to vast areas of mid-to-high altitude cloud ejected from convective cores
- More severe tropical storms are known as hurricanes or typhoons

Boeing includes all these types of clouds in the term convective weather; all contain ice crystals

Where do the ice crystals occur?

- Convective storms lift high concentrations of moisture to high altitude. In the mature stages of a thunderstorm, as the moisture passes through the freezing level, observations show that there is a rapid conversion of liquid to ice crystals – this is known as glaciation
- Vigorous circulation may cause ice crystals which are established in cloud at high altitude, to grow, redistribute, and deplete water droplets at lower altitudes. Therefore, deep convective cloud is dominated by ice crystals.
- These ice crystals exist at temperatures just colder than the freezing level, to well below -60C at the very top of the convective cloud
- Near the freezing level in a convective cloud, an airplane may encounter both supercooled liquid and frozen ice crystals – this is known as mixed phase conditions. In the early stages of convection, the cloud may be dominated by liquid.

What are ice crystals?

- Measurements have shown that ice crystals near the cores of deep convective clouds span micron (1 meter x 10^{-6}) to millimeter sizes, but the mass may be concentrated at very small sizes, with a mean mass “diameter” as small as 40 microns – or about the particulate size of flour.
- In this context, small crystals are speculated to have been created by freezing of small water droplets. Particles this small do not fall as precipitation.
- Other ice particles in a convective storm grow to larger sizes through:
  - vapor diffusion, although somewhat slowly. Vapor is supplied by the condensation of water vapor in the ascending air.
  - collision and sticking of individual crystals into ‘aggregates’ that can reach centimeters in size (snow). This process is highly active in most winter storms, but is also active in deep convective clouds. It does not require liquid cloud to be present. This is the major mechanism for particle growth in anvils.
  - sweeping out supercooled liquid droplets if they are present. The resulting particles, ultimately hail or graupel (small hail) tend to be more spherical, vary in size from 10ths of a mm to several centimeters, and have much higher mass than snowflakes of the same size. Supercooled liquid is therefore required sometime in their life-stage. Found in core updraft area of cloud system.

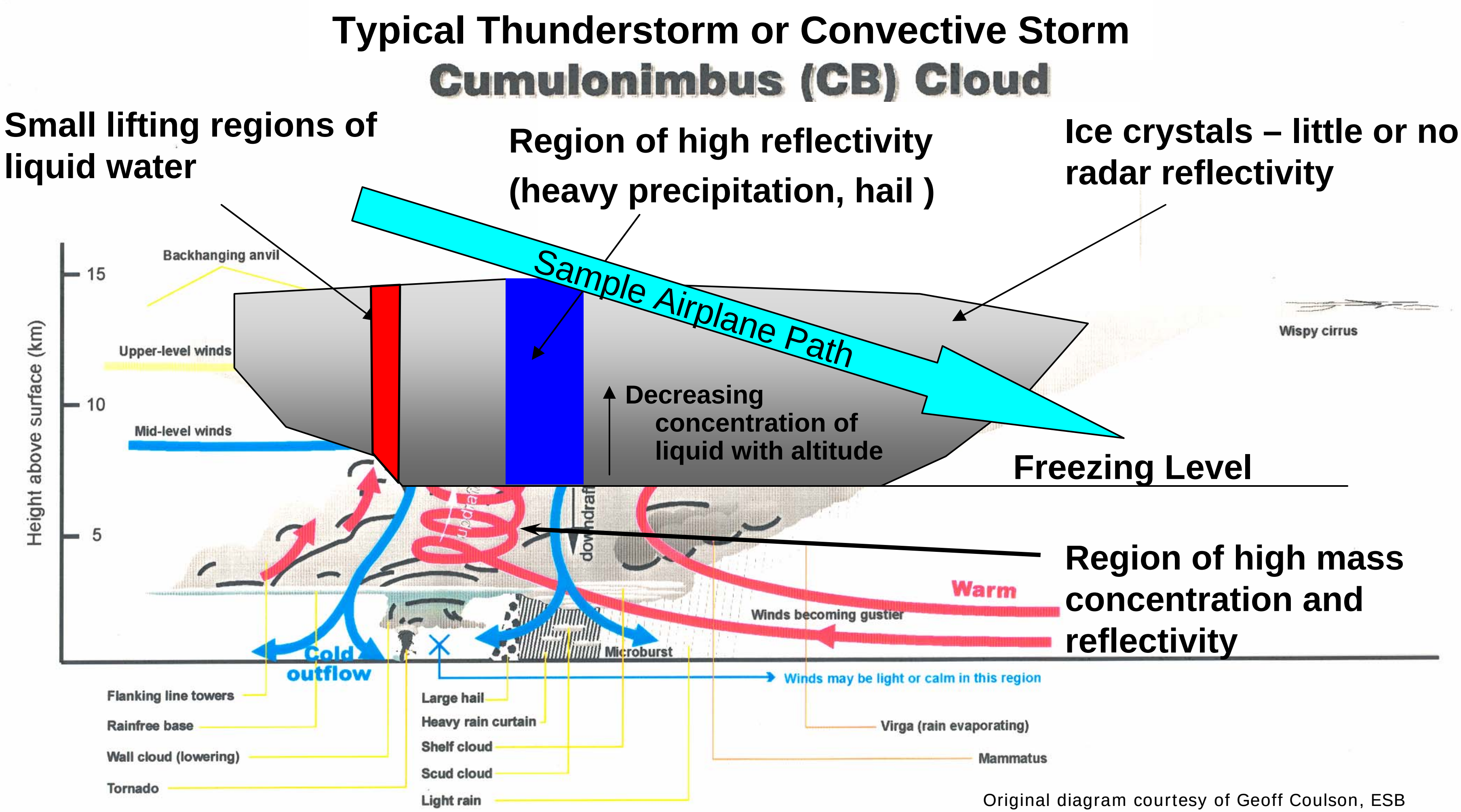
Hypothesis of the Environment that Causes Engine Events

- Typically found in regions with deep convective lifting and probable high ice water content
  - While diverting around reflectivity of isolated thunderstorm cores
  - In the broad outflow region of clouds associated with convective storms, convective storm complexes and tropical storms
  - Ice water contents can in theory reach 9 g/m3,
  - It is unknown what IWC/duration combination will cause an engine event
  - Liquid water need not be present

Using On-board Weather Radar to Detect Crystals

- Radar echoes have not been reported by the pilot at the location of the airplane in these engine events.
- In many cases, the aircraft was diverting around red echo regions of thunderstorms, at temperatures too cold for liquid water to exist
- Radar responds to particles according to the 6th power of their diameter, and is therefore able to detect large particles. Small particles, such as those 40 micron diameter particles in high concentrations near thunderstorms, are invisible to pilot's radar, even though they may compose a major fraction of the total mass of the cloud.
- Regions of hail, graupel, and ice crystal aggregates convected to high altitude, can still display high reflectivities due to their large size. Research indicates these are very localized regions at high altitude.
- Areas of high mass concentration invisible to the radar can still exist away from these high reflectivity areas. This is graphically represented in the next figure.

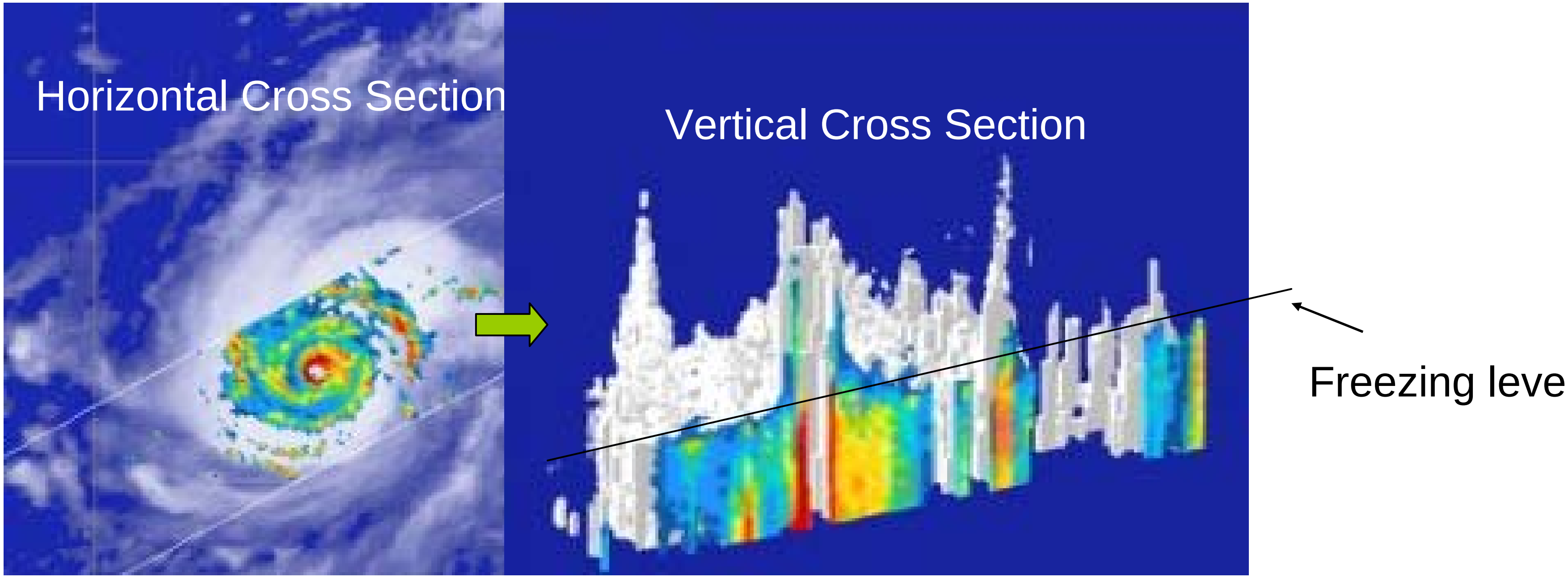
Diagram of Ice Crystals in a Convective Cloud



Original diagram courtesy of Geoff Coulson, ESB

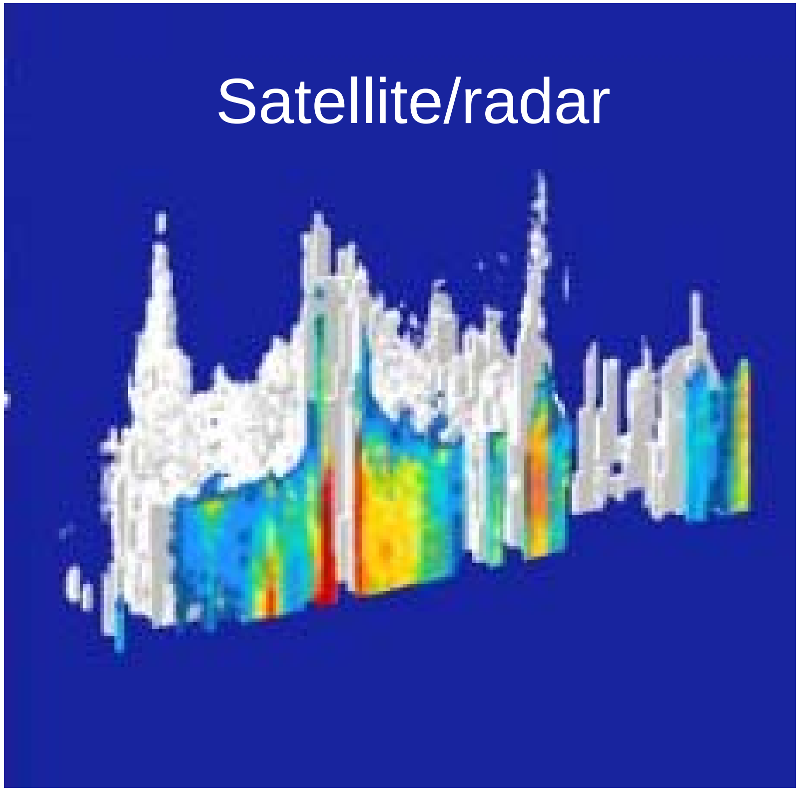
Above the freezing level, the convective cloud may be dominated by small ice particles, invisible to onboard weather radar

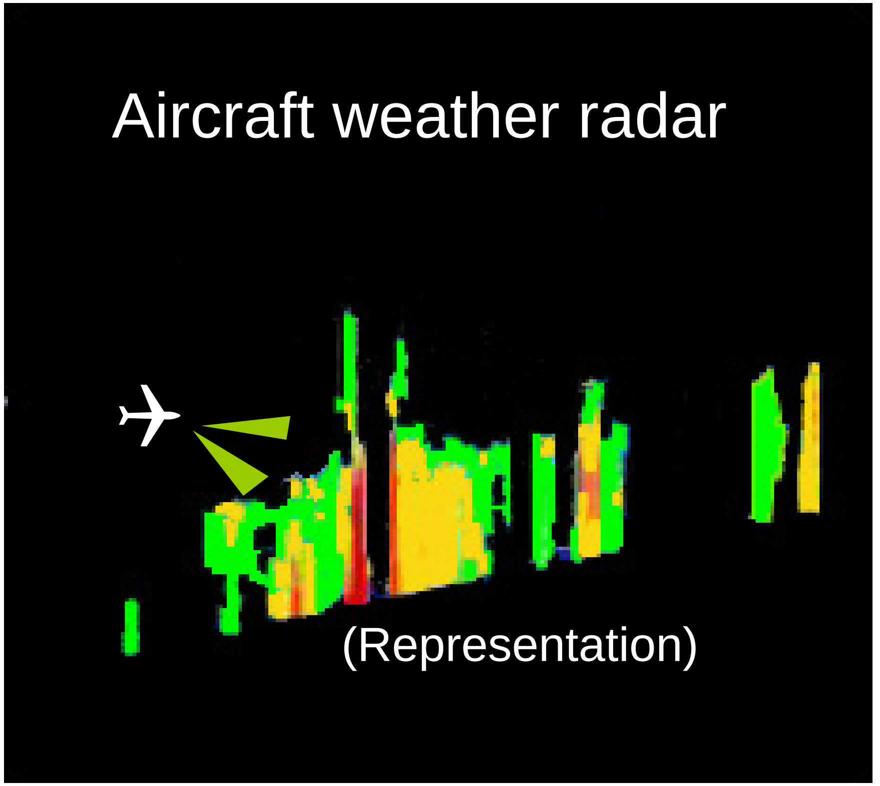
Satellite/Radar Can Detect Ice Crystals



•NASA TRMM satellite/radar combined space-borne sensors show the nature of a convective storm - colors are used for larger reflective particles such as hail, heavy snow, and rain.
• Satellite/radar infers regions of particles with low reflectivity such as ice crystals of mean diameter of 40 microns – these appear white on the cross section
•Even in this very vigorous storm few large reflective particles – rain, hail and graupel – occur at high altitude above the freezing level (limit of colored region).

High Altitude Flight in Convection where Ice Crystals Exist

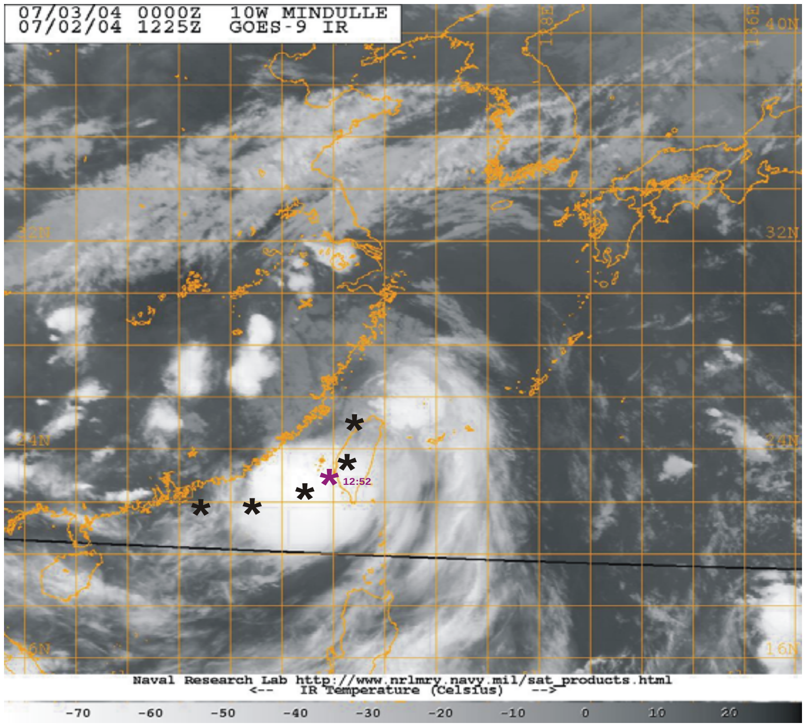


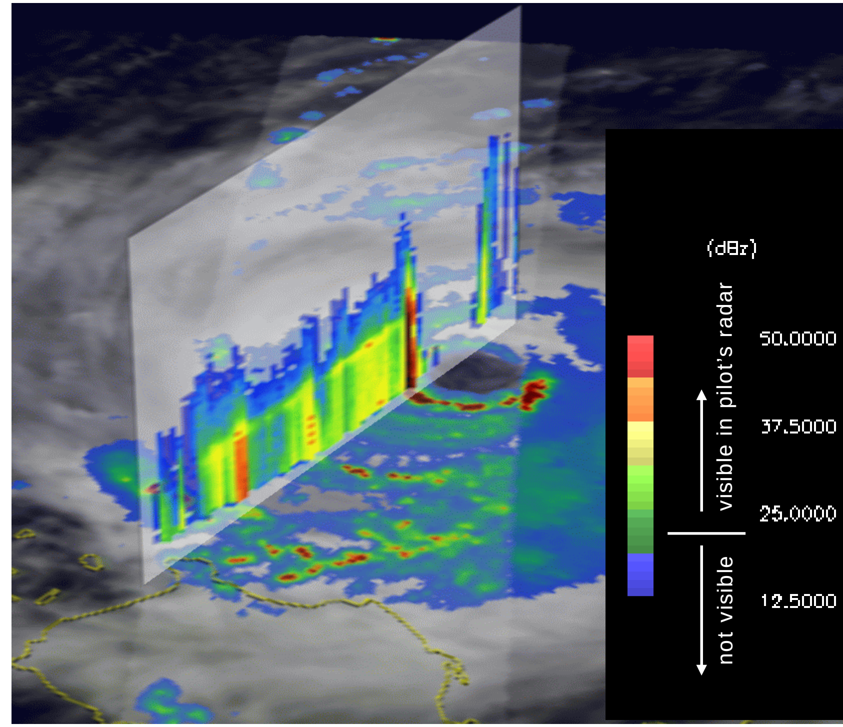


Flight in ice crystals will look like visible moisture, but will not produce significant radar returns. Isolated high reflectivity targets ahead may be detected.

Using tilt feature on radar should identify heavy rain below – a good indicator that dense ice crystals may exist above.

Images from a Tropical Storm Which Caused an Engine Event





- In the infrared image (left), the aircraft flight path is indicated by asterisks, through the high altitude regions of a tropical storm. The event location is indicated in purple.
- The accompanying satellite radar image (right) of the same storm, taken earlier than the engine event, shows that the upper altitudes of the storm, where the aircraft flew, were composed of small ice particles (blue), which would not have been visible on the onboard weather radar.

Ice Crystal Icing in an Engine

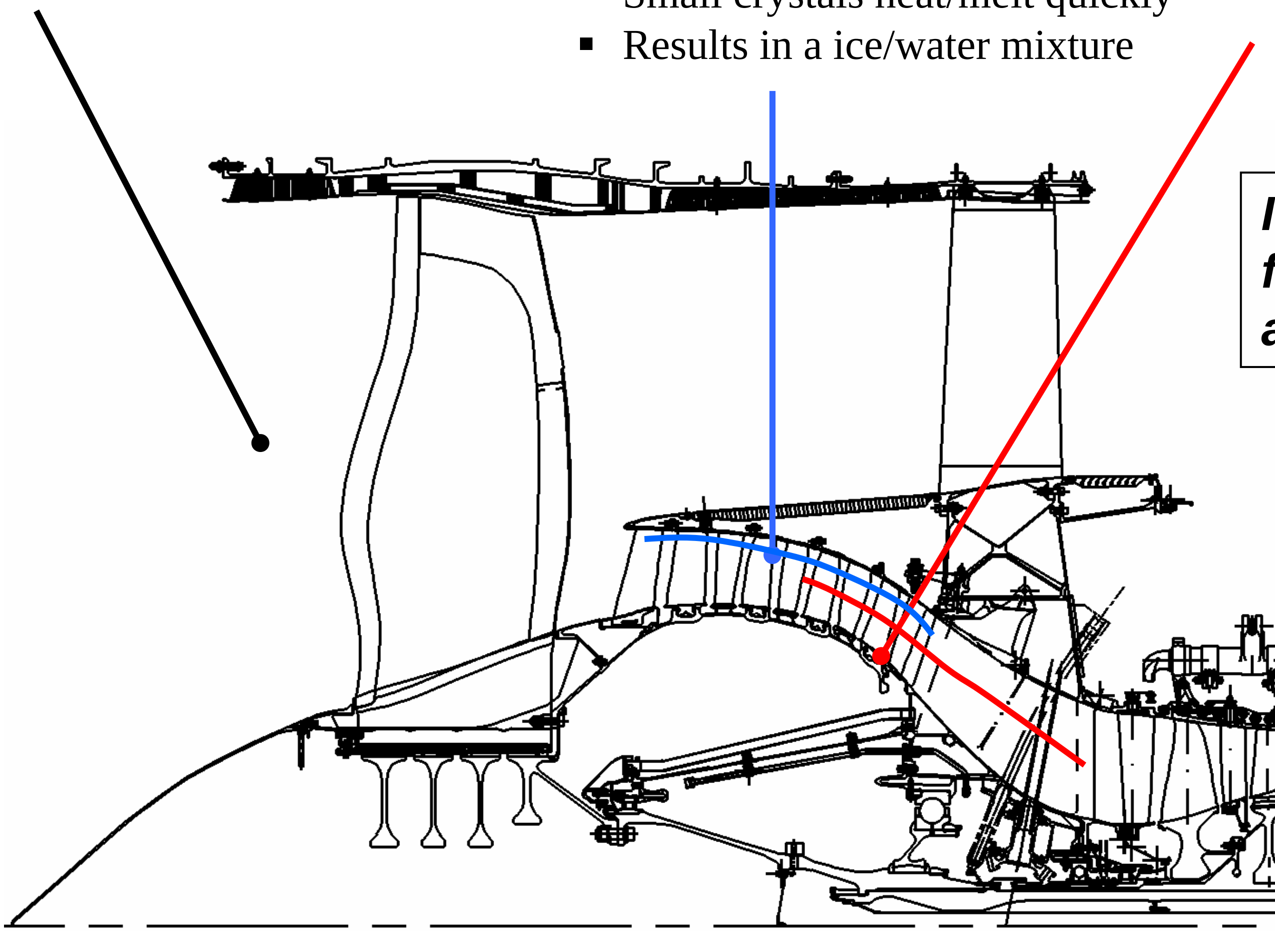
- Frozen ice crystals bounce off cold surfaces, this is why airframe icing is not noticed during aircraft encounters with high altitude ice crystals.
- The physics of ice crystal accretion in the engine is not completely understood, however the accretion mechanism is thought to be:
  - High concentrations of crystals impinging on a warm surface such as a compressor vane melt and cool the surface. When the surface reaches zero degrees centigrade, ice accretion can begin to occur.
  - This phenomenon means ice accretion can occur well behind the fan in the core of the engine
  - Ice shed from compressor surfaces can cause engine instability such as surge and flameout, or engine damage.

Ice Crystal Engine Icing -- Theory

Ice Crystals Bypass Fan
- Bounce off cold parts
- No threat

Ice Crystals Cool Booster
- Small crystals heat/melt quickly
- Results in a ice/water mixture

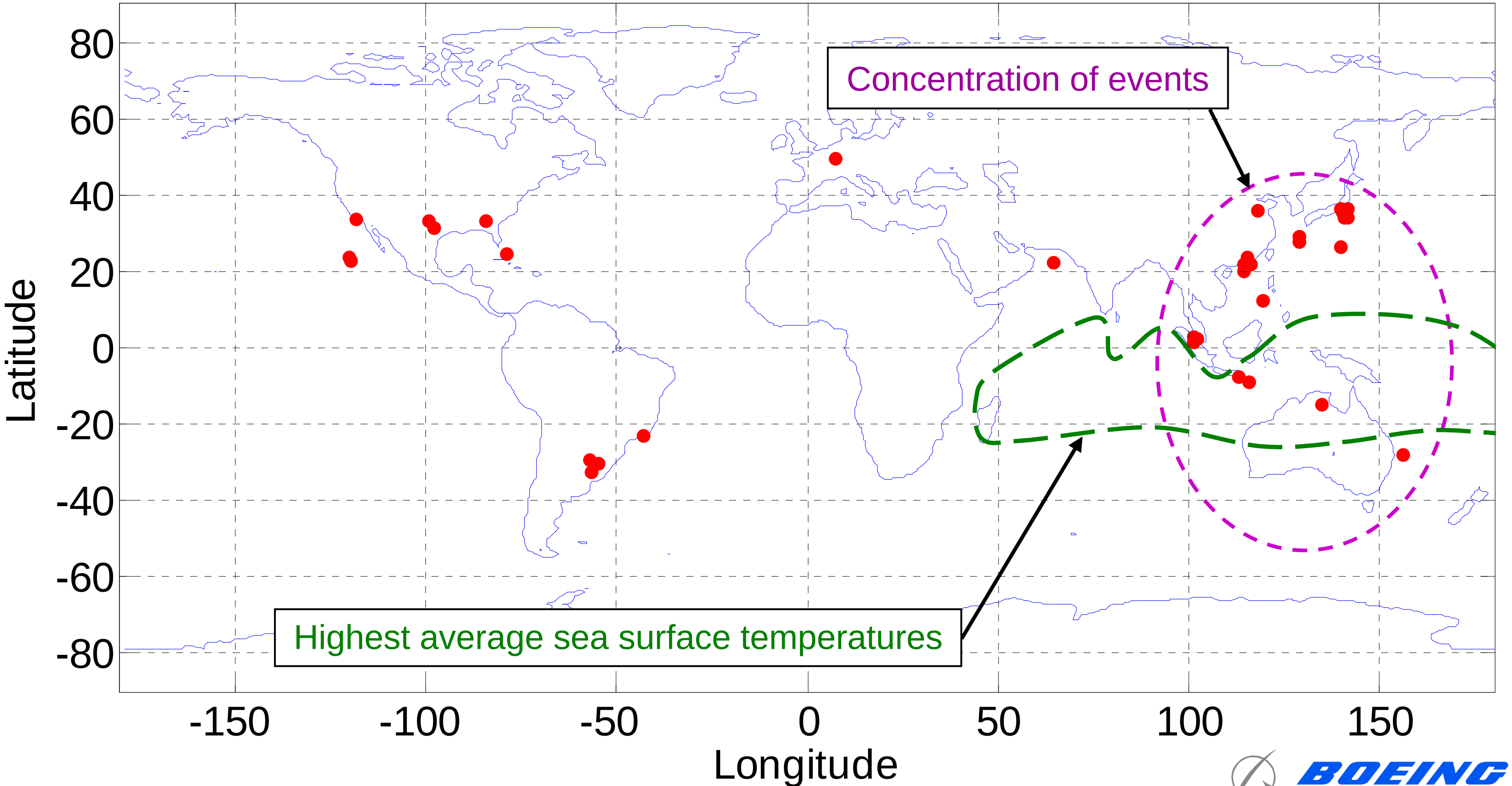
Ice Accretion
- Water/ice cools parts to 32F
- Wetness allows ice to "stick"
- Ice collects / accretes



Ice crystals penetrate fan and booster and accrete downstream

Global View of Engine Powerloss Events

- A large number of events are occurring in the Asia Pacific region – this may be due to the fact that the highest sea surface temperatures are also found in this region
- High temperature air can contain more moisture – hence high concentrations lifted to high altitude and condensed
- Typically the engine powerloss events have occurred on days with temperatures 10-20 degrees centigrade above standard day.



TAT Anomaly

- TAT anomaly has occurred in many cases near the time of the engine powerloss events.
- The airplane total air temperature probe (TAT) erroneously reporting zero degrees C is known to be evidence of ice crystals in the atmosphere.
- This anomaly is due to ice crystals building up in the area where the thermocouple resides, where they are partly melted by the heater causing the zero degrees C reading
- In some cases, TAT has “flat-lined” at zero during a descent, and may be noticeable to pilots. In other cases, the error is more subtle, and not a reliable indicator to provide early warning to pilots of high concentrations of ice crystals.
- The TAT, although used as engine parameter, has been determined not to be a contributor to the powerloss events. Under these conditions, the engine control compensates for loss of TAT.

Pilot Reports

- Pilots have reported rain, sometimes ‘heavy rain’ on the windscreen
  - Sometimes at impossibly cold temperatures,
  - This is believed to be the result of these small ice crystals melting on impact with the heated windscreen
- No observations of significant airframe icing
- Turning on landing lights at night and seeing reflective precipitation
  - It is likely they were seeing the larger particles even though they make up a smaller fraction of the population
- Hearing a different sound from rain
  - Ice crystals hitting the airframe sounded different than rain or hail
- Light to moderate turbulence

Recap – Ice Crystal Environment

- Above the freezing level in deep convective clouds, high concentrations of small ice crystals dominate the mass
  - These concentrations exceed 2 g/m3, which if it were a conventional icing threat, would be very severe
  - The majority of the crystals exist at small size – perhaps as small as flour.
  - Particles up to millimeter size do exist
- These small crystals are not visible on the pilot's radar, however the pilot will see visible moisture

Summary: Indicators of Ice Crystal Encounters

- Flight in visible moisture near deep convective weather, without radar returns, and at temperatures below freezing is very likely ice crystal conditions.
- These conditions may also include:
  - Flying in the vicinity of a convective weather system / thunderstorm and above a region of heavy rain
  - No significant airframe icing
  - TAT probe frozen
  - Ice detector not detecting ice (when installed)
  - Appearance of rain on the windshield
  - Light to moderate turbulence

Recommendations

- It is not practical to avoid all ice crystal conditions; crystals may not be detected by aviation radar
- Normal thunderstorm avoidance procedures may help avoiding high ice crystal content regions
- These include:
  - Plan a flight path that avoids storm cells by at least 20 nautical miles.
  - Fly upwind of the storm
  - Avoid flying over a storm cell. A fully developed thunderstorm can reach altitudes of more than fifty thousand feet. Even when there are no radar returns, there may be significant moisture in the form of ice crystals at high altitudes.
  - Utilize the radar antenna tilt function to scan the reflectivity of storms ahead. Recognize that heavy rain below indicates likely high concentrations of ice crystals above.
- ATC permitting, make a continuous descent at idle thrust. This decreases the exposure time to the ice crystal conditions.

Reference: AIAA 2006-0206 “Ice Particle Threat to Engines in Flight”