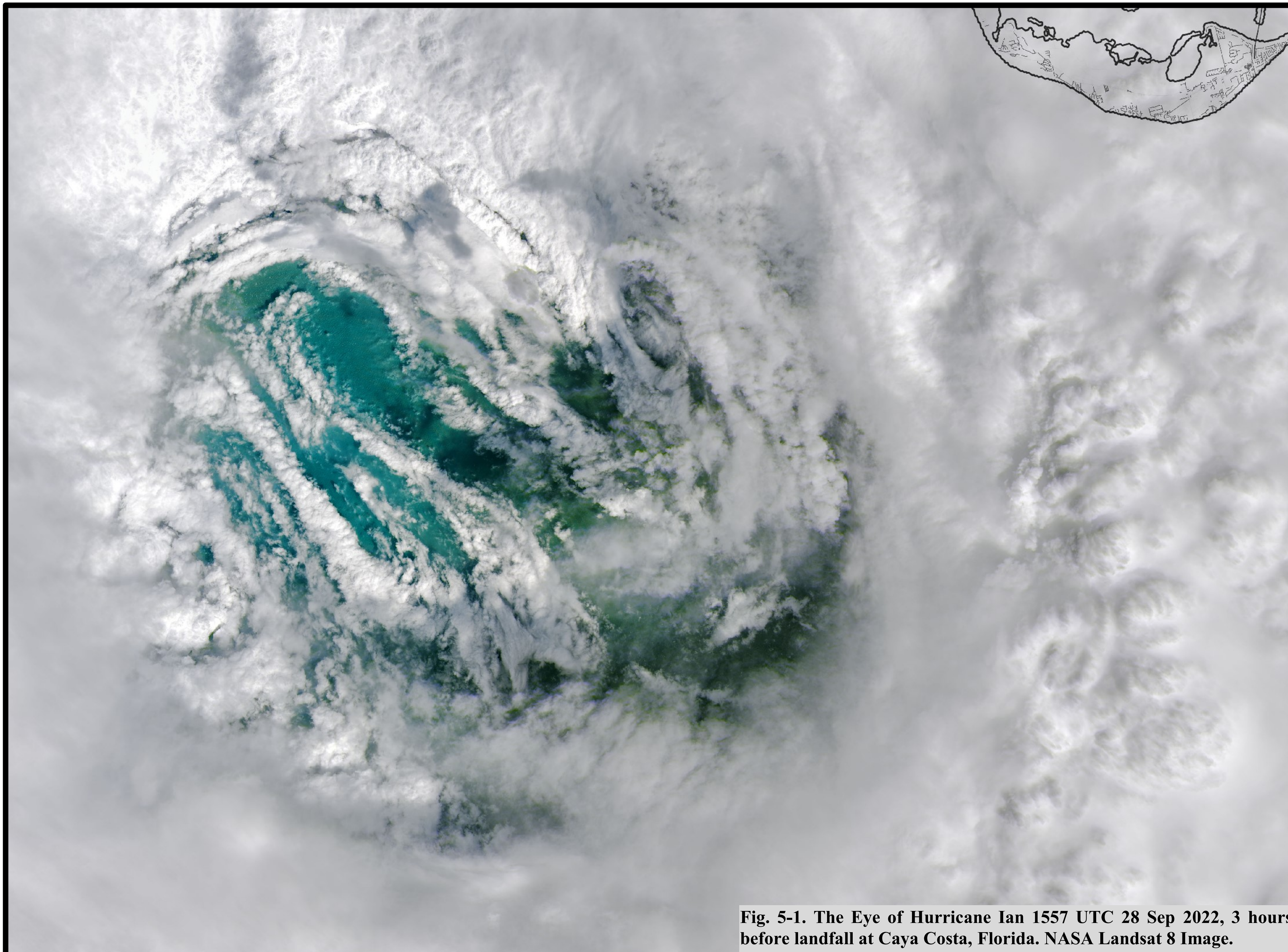

Fig. 5-1. The Eye of Hurricane Ian 1557 UTC 28 Sep 2022, 3 hours before landfall at Caya Costa, Florida. NASA Landsat 8 Image.

Wonders of the Atmosphere
Chapter 5: Cloud and Storm Systems: The View From Above

Started 25 July 2024

5.1 The View from Above

Throughout history humans have almost exclusively looked at clouds from below. This gave us little idea of their place and patterns in large scale storm and circulation systems. Now, with the conquest of the air and of space we routinely see clouds from above with a perspective that adds to our knowledge of the atmosphere, as, for example, the swirling cloud bands of Hurricane Ian's eye (Fig. 5-1).

Fig. 5-2. Flying amidst towering Cu over NC, 16 May 2009. A subsun is the bright spot directly below the Sun, indicated by the arrows. SDG.

The view from the air is more extensive than from the ground yet remains intimate and detailed. Nearby sights are fleeting but endlessly new. The view from space is less intimate, depending on the satellite's pixel size, but is so grand and extensive, even global, that we now see at a glance cloud and storm systems that took scientists centuries to suspect and then arduously piece together.

It is a joy to fly among the clouds, in the canyons between them, and rise above them. Breathtaking, close-up views of the turrets of cumulus, the anvils and mamma of thunderstorms, the streamers of cirrus, the mottled and wavy sheets of altocumulus, and a host of optical phenomena including a range of halos only seen by looking down, and 360° rainbows. In Fig. 5-2 the jet has just emerged into a clearing almost walled in by towering cumulus, while a subsun, a mirror image reflection of the Sun made by ice crystals that fall like horizontal mirrors appears as a bright dot indicated by the arrows.

Fig. 5-3. Valley Fog in San Mateo, CA on the morning of 24 Nov 2016. SDG.

5.2 Small-Scale Systems: Valley Fog

Fig. 5-4. Clear rifts in the fog at the centers of valleys in the Peruvian Andes 16 Jul 2015. NASA Earth Observatory, LANDSAT.

Even before aviation and space travel, anyone who climbed hills or mountains could look down upon a sea of fog filling the valleys (Fig. 5-3). Valley fog, essentially a form of radiation fog, forms best on clear, calm nights as the slopes radiate heat out to space and the cold ground cools the air just above by contact.

Fig. 5-5. The final ribbon of valley fog hugs the hillside. The view faces WSW to the Obaiu from Corps, France, around 10 AM, 03 Aug 1978. SDG.

The chilled, dense air sinks down the slopes as a mountain breeze, often in spurts, where it accumulates in the valleys and continues cooling as the valley floor also radiates heat out to space. If the air cools enough to become saturated, droplets condense to form valley fog. The top surface of the fog then radiates heat out to space and cools even more rapidly so that the fog becomes self-enhancing. At the same time, sinking air clears the sky over the summits.

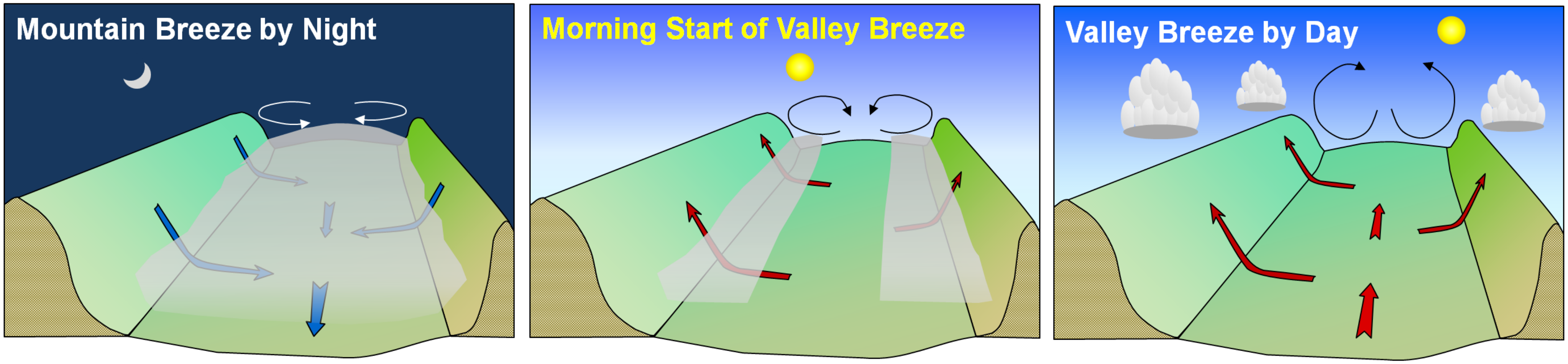

Fig. 5-6. The daily cycle of valley and mountain breeze circulations. Valley fog forms at night and evaporates from valley center outward as the Sun rises. Cumulus clouds form over the hilltops and summits during the day. SDG.

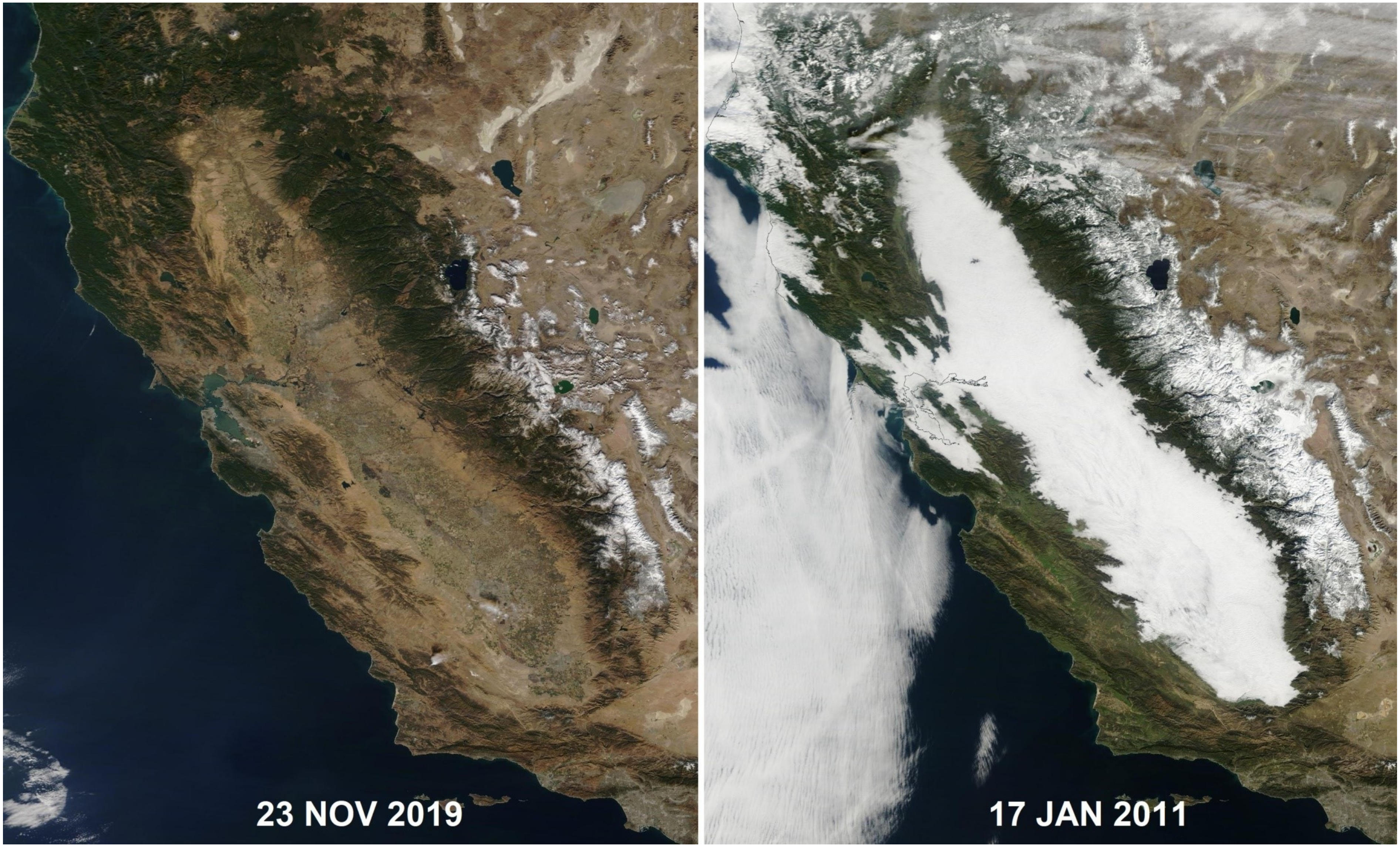

Fig. 5-7. Left: The Central Valley of California on 23 Nov 2019 during a dry period with a brown rim (NASA MODIS Terra). Right: The Central Valley filled with Tule Fog, which extends to the adjacent valleys including the San Francisco Bay on 17 Jan 2011, after a soaking rain. The visible parts of the rim are green and snow cover is greater. Advection fog, crossed by ship tracks, covers a large area of the Pacific Ocean.

As the Sun rises in the morning and heats the slopes, valley fog begins to 'burn off', but it does so in a curious way revealed by satellite images (Fig. 5-4). A clear rift in the fog forms in the center line of each valley and gradually broadens until the last remnants of fog hug the slopes like ribbons (Fig. 5-5).

This manner of clearing, from valley center outward, results because the circulation reverses direction. As heated air over the slopes slides upward as a valley breeze, cooler air in the center of the valley sinks, warms, and makes the fog evaporate faster.

As the day goes on if the air is heated and rises enough it will produce cumulus or even cumulonimbus clouds over the summits. The daily cycle of mountain and valley breeze circulations and the resulting daily cycle of fog and Cu or Cb are illustrated in Fig. 5-6.

Fog can also fill valleys on a grand scale, especially during winter's short days and low, weak Sun. Fig 5-7 contains two contrasting NASA MODIS Terra images of the Central Valley of California, one on 17 Jan 2011, when it was filled by the Tule Fog following a soaking rain. In this case, as in others, the fog persisted continuously for several days and nights even though it was quite shallow as the sounding at that time (Fig. 4-25) showed.

The Central Valley is so wide that Mountain Breezes play only a secondary role in the formation of the Tule Fog; cooling by radiation of heat to space by the ground is the primary driver. And, once the fog forms, it tends to be locked in by the surrounding mountains until a strong wind drives it out of the valley and dissipates it.

Without the rains, the Tule Fog seldom forms, as on 23 Nov 2019. A give-away of the dry conditions is the brown rim of the non-irrigated slopes around the valley. And, since drought has prevailed much of the past decade in California the slopes have more often been brown and the Tule Fog less frequent and less extensive.

Fig. 5-8. Hole punch cirrus in a field of Ac from Boynton Beach, FL to the Bahamas, 12 Dec 2014. NASA MODIS Terra image.

5.3 Satellite Pixel Size: Limits of Resolution

The extensive view provided by the meteorological satellites often comes at the cost of resolution. The smallest features of clouds or of the surface that are visible in any detail must be several times wider than the pixel size. Minimum pixel size for the geostationary satellites such as GOES that hover 22,236 miles over the equator is 1 km (but only for the red band). Minimum pixel size for Polar orbiting MODIS (MODerate resolution Imaging Satellites), Terra and Aqua (https://worldview.earthdata.nasa.gov/) is 250 m, but for only 2 of the 36 wavelength bands, 500 m for 5 bands and 1 km for the rest.

That is why Cu clouds appear as mere dots in MODIS images. It is also why many sheets of Sc and Ac clouds give little hint of the beautiful fine scale structure of their small cells and ripples.

The limitation due to a pixel size of 250 m can be seen by comparing the detailed structure of ground-based hole-punch cloud photo of Fig. 4-13 with the MODIS satellite image at the same time (Fig. 5-8), where the ripples are just visible and the cells appear as mottled shading. This is not surprising. An Ac cell or ripple 3 km above ground level that subtends and angle of 5° has a diameter of 262 m. Since the cells and ripples in cirrocumulus and the individual strands or fibers in cirrus are much narrower they cannot be detected

When pixel size is 30 m, as for LANDSAT more details of Ci streamers and Ac cells are clearly visible. The false color image of Fig. 5-9 was processed for a study of hole-punch clouds. The temperature in the sheet of Ac NW of Tampa on 09 Dec 2009 ranged between -5 and -20°C, yet it consisted entirely of supercooled water droplets (pink) until it was punctured by a plane, at which point ice crystals crystallized and formed the turquoise blue Ci in its center.

Many meteorological satellites now distinguish water and ice clouds. This is done by comparing the signals at several different wavelength bands given that the optical properties of water, such as reflection and absorption, vary with wavelength differently from those of ice.

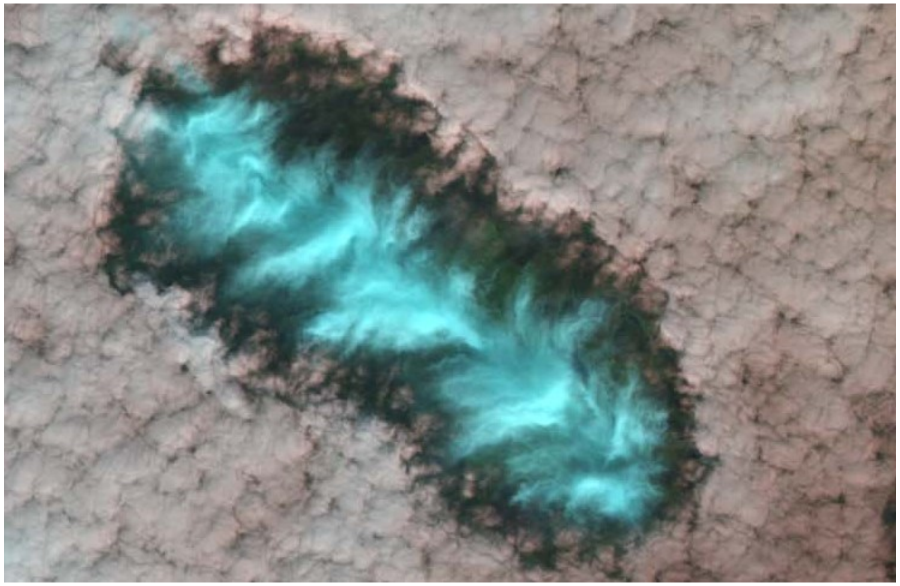

Fig. 5-9. Landsat image with 30 m pixels of hole punch cloud of 9 Dec 2009 showing ice crystal Ci (blue) in the midst of supercooled water Ac (pink).

Even though most satellites do not have such high resolution one look at the images constitutes proof that they give us breathtaking and informative views of the panoply of the clouds that grace the skies, and clothe the land. And many cloud features have a large enough scale so that the panoramas provided by satellite are superior to what we can see from the ground.

5.4 Small-Scale Systems: Sea Breeze

Flying over coastlines on many spring and summer afternoons reveals a striking but common pattern. In Fig 5-10, a field of Cu covers the land on the west coast of Florida just north of Tampa while clear skies reign over the Gulf of Mexico. Cu sprout up almost every day of the year over the land and some grow into Cb, making afternoon showers almost a byword in the tropics.

Fig. 5-10. A field of Cu covers the land north of Tampa, FL while the sky is cloudless over the waters of the Gulf of Mexico. SDG.

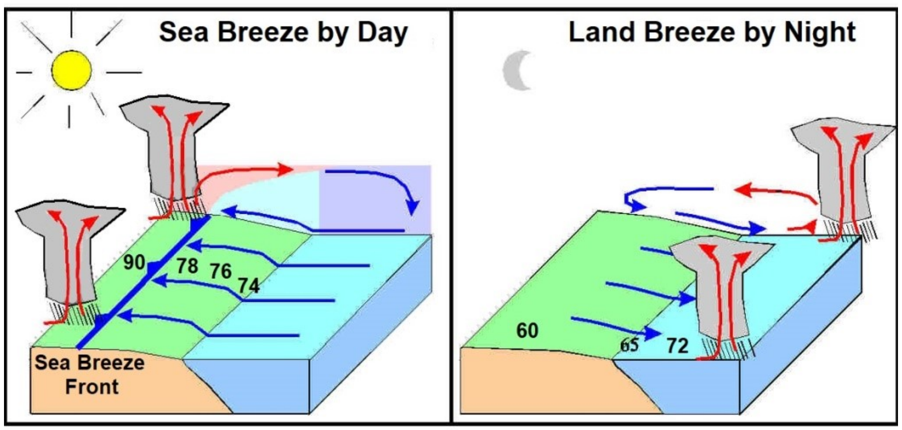

Fig. 5-11. The daily cycle of sea breeze and land breeze circulations. Clouds form over the land during the day and over the water at night. SDG.

This pattern is caused by the Sea Breeze, another classic local wind system with a daily cycle (Fig. 5-11). During the day all year long in much of the tropics and during spring and summer in many locations outside the tropics, the land quickly gets hotter than the sea and the hot, buoyant, air rises over the land. Cooler, denser air over the sea then blows in from the sea near the surface. The sea breeze typically penetrates 10 km or more inland before it is warmed enough to rise buoyantly, sometimes forming a sea breeze front with enhanced cloudiness. After rising between about 500 or 1000 m (except higher in Cu and Cb) the wind aloft returns to the sea and sinks over the ocean to complete a circulation cell and produce a clear aisle.

Fig. 5-12 illustrates these features to a tee! The near symmetry of clouds around the Yucatan on 16 Aug 2024 indicates that the large scale winds are weak. The sea breeze has cleared skies over the coastal waters and a short distance inland from the coast. Dots of Cu are spread throughout the interior of the Yucatan but are enhanced at their perimeter by the rising air at the inland edge of the sea breeze. A much larger popcorn Cb cloud has formed over the NE corner of the Yucatan, generated where updrafts are enhanced as sea breezes from two coasts clash.

In MODIS images, Cu appear as white dots because they are only a few pixels wide, but Cb, with their wide anvils appear as exploded white popcorn balls. Thus, comparing Cu and Cb is like comparing unpopped to popped kernels. Cb anvils are only circular when there are no strong winds around cloud top. When Cb's are embedded in strong winds aloft, such as the jet stream, they are elongated downwind like plumes from smokestacks. In most cases, the fuzzy, thin anvil edges thin out to Ci, and show that the anvils are composed of ice crystals and other frozen particles.

Myriad beautiful satellite images show the sea breeze and its clouds. Fig. 5-13 shows the Cu dots and popcorn Cb over Florida and the Bahama Islands while clear skies reveal the shallow turquoise and deeper cobalt blue waters, plus a well-defined coastal strip around southern Florida. Clear skies also typically reign over cooler Lake Okeechobee and the flooded grasslands of the Everglades.

The western half of Cuba is so narrow that sea breezes from north and south clash, often producing a string of popcorn Cb's over the land while the coastal strip remains mostly clear, as on 09 Sep 2023 (Fig. 5-13). This image contains at least two other interesting features. 1: Arcs of Cu dots south of two Cb's (Yellow arrows) mark outflow boundaries of thunderstorm downbursts, with rising air. 2: Narrow rings of Cu dots with clear centers in the SE quadrant of the image represent open convection cells often seen over warm waters.

Fig. 5-12. The Yucatan Peninsula covered by Cu dots and popcorn Cb, illustrating the sea breeze, 16 Aug 2024. NASA MODIS AQUAphoto.

Fig. 5-13. Cu dots and popcorn Cb over Florida and the Bahamas, while skies are clear over the coastal waters around Florida and over Lake Okeechobee. 10 Sep 2023. NASA MODIS AQUA image.

At night the land gets colder than the sea, the Cu and Cb evaporate, and the direction of circulation reverses to form a land breeze. The land breeze is generally weaker and shallower than the sea breeze, but if the ocean waters are warm enough, Cu or Cb can form over the water while the sky over the land remains clear, as in the NOAA VIIRS Image at 1300 UTC on 01 Sept 2019 (Fig. 5-25). Then, as the land warmed up during the day, Cb's sprouted up over Cuba and the Florida Peninsula by 2200 UTC (Fig. 5-29), where they were displaced to the west coast by easterly winds of Hurricane Dorian's periphery.

Among the prominent features in Fig. 5-14 are four storms over the subtropical oceans that resemble spiral galaxies – Hurricanes Juliette

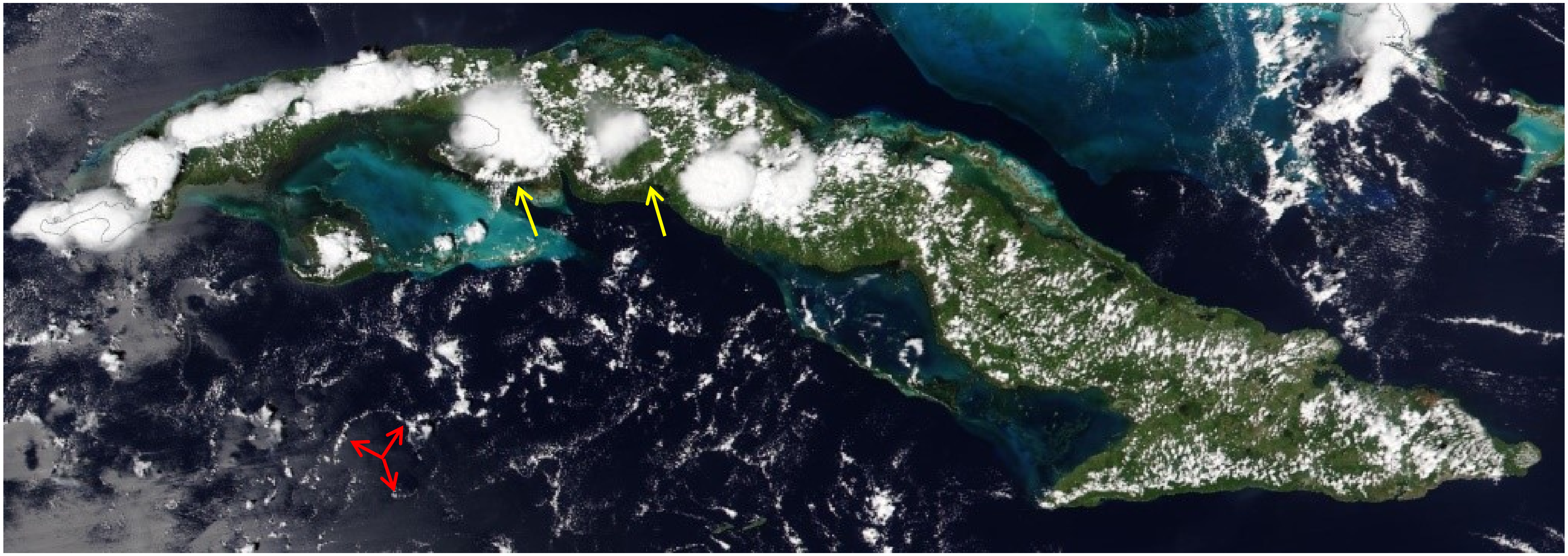

Fig. 5-14. Popcorn Cb and dots of Cu rise over the heated land of Cuba 09 Sep 2023. Rings of Cu form at the outflow boundaries south of two Cb's (yellow arrows). Rings of Cu dots mark the perimeters of open convection cells (red arrows). NASA MODIS AQUA image.

in the East Pacific and Dorian just east of Florida and Tropical Storms Fernand in the Gulf of Mexico and Gabrielle off the coast of Africa. At higher latitudes are cloud spirals or masses with long comma-shaped extensions that can resemble the profile of the human brain and spinal column. These are the extratropical, frontal cyclones that can in the depth of winter intensify into blizzards.

A distinct feature in both panels of Fig. 5-16 is the line of popcorn Cb clouds that stretches across the globe slightly north of the equator on 06 June and south of the equator on 01 Jan. This is the Intertropical Convergence Zone (ITCZ), a belt of low pressure that girdles the globe along the equator where surface winds converge and rise, for the most part in Cu and Cb clouds. (It can also be seen in Fig. 5-15 as the broad zone of abundant clouds over the Pacific

5.5 Large Scale Wind, Storm, and Cloud Systems

Local views are fine for identifying clouds but a picture of large-scale wind and storm systems is needed to tell where the different cloud genera are most likely to occur. Full disk images, such as on 04 Sept 2019 (Fig. 5-15) give that picture, while global videos such as the ones that Météo-France provides by stitching images from the various geostationary satellites of the high, thick clouds over Blue Marble surface features animate the weather and climate of the world for a year (Fig. 5-16 shows frames on 01 Jan and 06 Jun 2023).

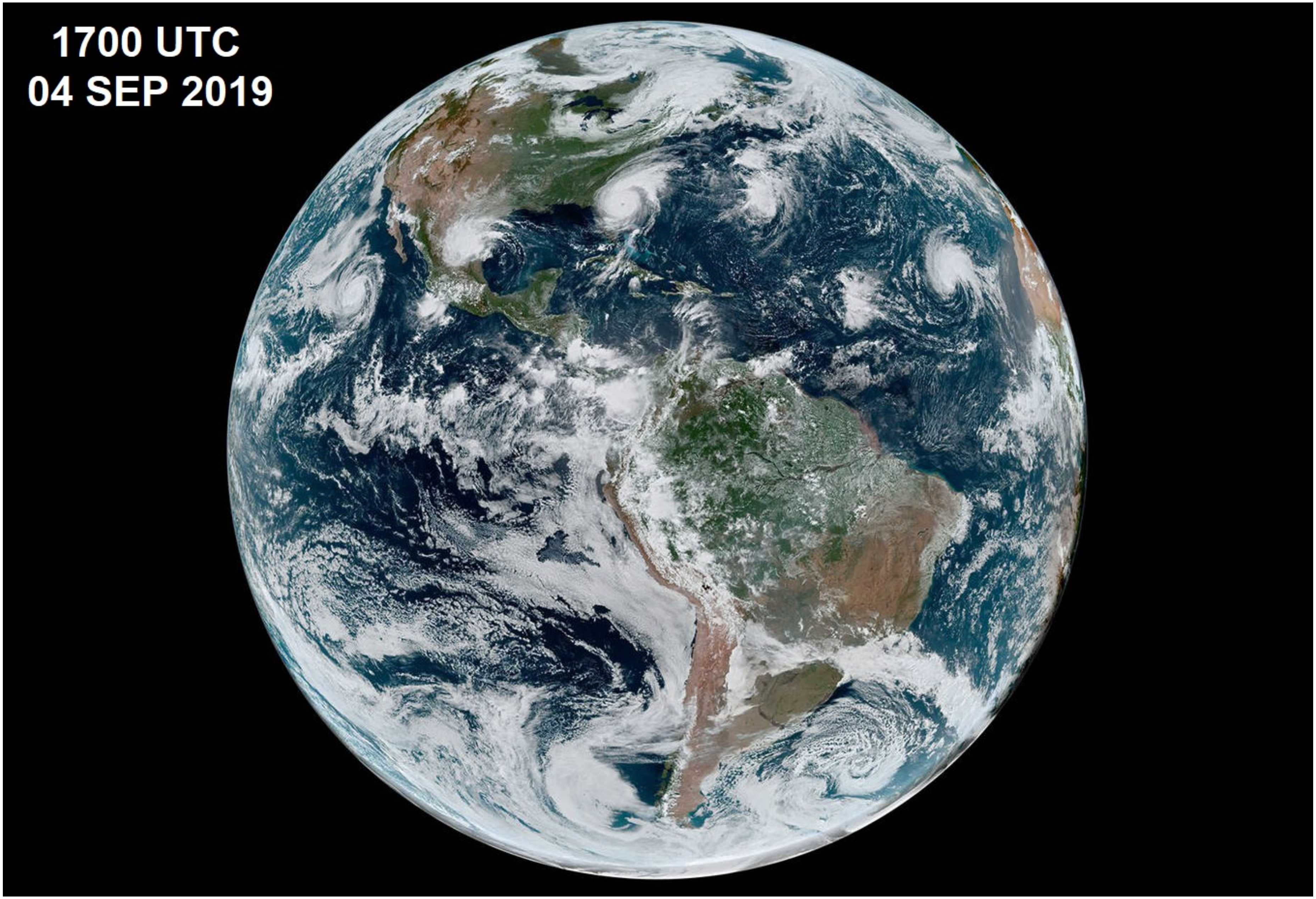

Fig. 5-15. Full Disk NASA GOES Image 04 Sept 2019 with many cloud genera and systems. Spiral pinwheels in the tropical oceans are Hurricanes Dorian and Juliette, and Tropical Storms, Fernand, and Gabrielle. Cloud swirls at higher latitudes ae extratropical cyclones. Dotted clouds over the Amazon Basin are cumulus and cumulonimbus. Cloud field over the Pacific Ocean west of the Atacama Desert are cellular stratocumulus clouds.

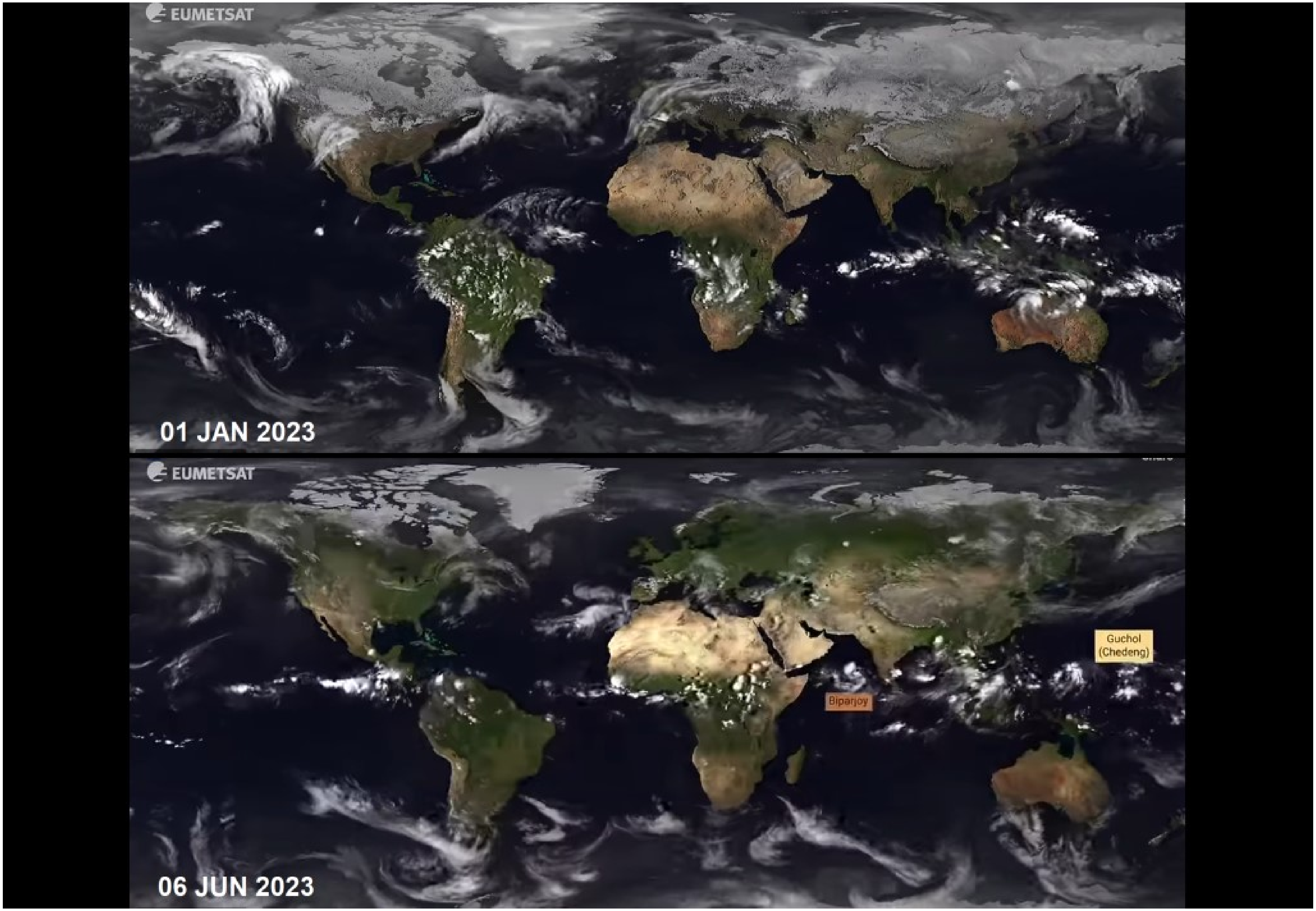

Fig. 5-16. Two frames (01 Jan and 06 Jun) from A Year of Weather 2023 by EUMETSAT (Video on YouTube). Low, thin clouds do not appear.

Ocean west of Ecuador.) The rising Cb towers of the ITCZ produce ample precipitation and result in Tropical Rainforests. After rising, the air aloft moves away from the tropics and sinks in the subtropics, typically between about 20° and 30° latitude, producing mostly clear skies and the world's Subtropical deserts, with hurricanes off the east coasts and extensive areas of low clouds off the west coasts of the continents as exceptions.

Earth's large scale surface winds are organized into high- and low-pressure areas. Air near the surface spirals out of highs (anticyclones) and air aloft sinks to replace it to form mostly clear skies. Air spirals into lows (cyclones) and rises to form abundant clouds and precipitation with distinctive patterns that often resemble spiral galaxies for tropical cyclones (hurricanes and typhoons) and spiral whirls with comma extensions for extratropical cyclones (frontal storms and blizzards). As pointed out above, Fig 5-15 contains four tropical cyclones or storms in subtropical latitudes north of the equator including Hurricane Doran and several distinctive frontal cyclones at the higher latitudes of both hemispheres.

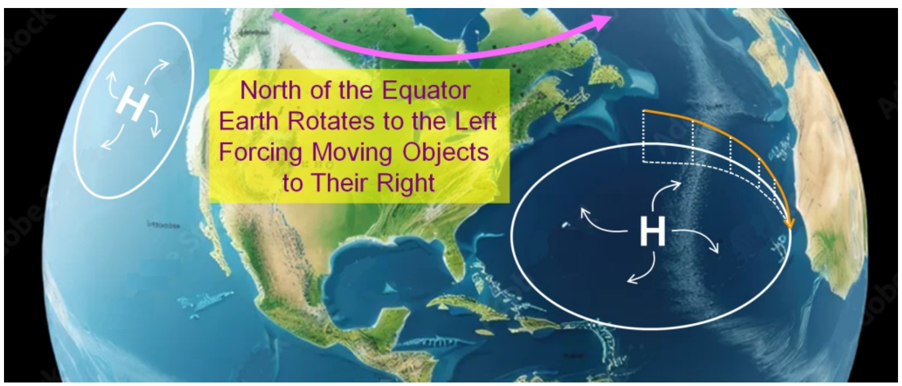

Fig. 5-17. Earth's rotation and wind around the Subtropical Highs. SDG.

The Earth's rotation via the Coriolis force is what causes the wind to spiral around the highs and lows. When viewed from space every point north of the equator turns to its left (Fig. 5-17). As a result, all moving objects in the Northern Hemisphere are forced to their right, so that,

North of the Equator, 1: wind spirals counterclockwise and inward toward the centers of low-pressure areas, (cyclones), and 2: wind spirals clockwise and outward from the centers of high-pressure areas (anticyclones).

South of the Equator, when viewed from Space, every point can be seen turning to its *right*. The result is that the winds around high- and low-pressure areas in the Southern Hemisphere spiral in the opposite direction from that of the Northern Hemisphere. Thus winds spiral clockwise and inward toward the centers of lows and counterclockwise and outward from the centers of highs.

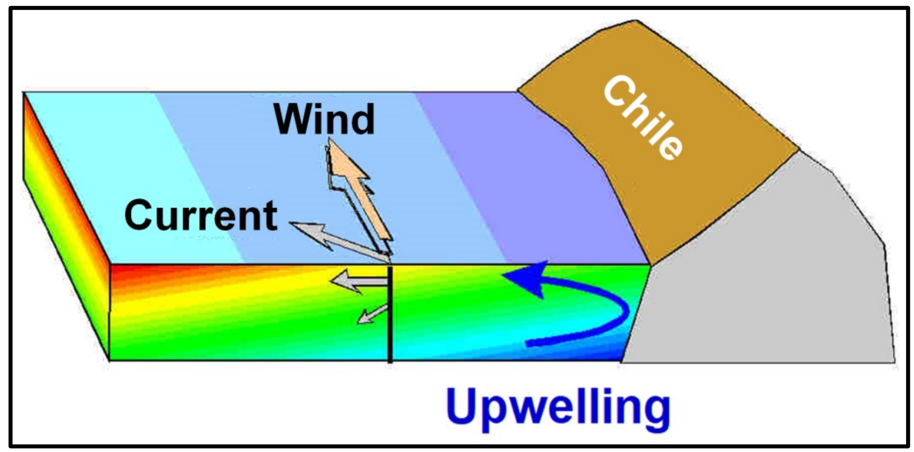

Fig. 5-18. Wind driven currents move to the left of the wind South of the Equator and force upwelling of cold, deep water. SDG.

Large, semi-permanent high-pressure areas centered at about 30° latitude dominate the world's subtropical oceans. Because the air near the surface spreads out from the highs and tends to sink, skies are generally clear and the climate is generally dry.

But the subtropical highs have great east-west asymmetry. Air on their eastern side (bordering the west coasts of the continents) blows from the direction of the poles and so, is cooler and experiences a stronger tendency to sink than the warmer, more humid air on the highs' western sides. Wind and weather are also more persistent on the eastern side of the subtropical highs. The western sides of the highs are frequently disturbed by cold fronts that pour off the continents mainly in the winter half of the year, and by hurricanes and thunderstorms, which form during the summer months.

The east-west asymmetry is enhanced by the interaction between the wind and the ocean currents. The wind drives the ocean currents but in an unexpected way, again because of the rotation of the Earth.

It is natural to think that ocean currents would be blown directly downwind, but this is not the case. The Earth's rotation forces the surface ocean currents to move to the right (left) of the wind in the Northern (Southern) Hemisphere, and thus away from the west coasts of the continents from about 10° to 45° latitude.

As the surface water moves away from the coast deep ocean water, which is frigid, upwells (Fig. 5-18) and chills the air near the surface. That enhances the tendency of the air to sink so that Cu and Cb cannot form and are absent over the coastal waters, and often for 100 km or more inland.

The air over the ocean is not only cooled but also charged with water vapor. This leads to the formation of widespread fog and S or Sc, whose tops seldom reach 2 km. As a result, extensive fields of low clouds and fog frequently form over the cold waters that dominate the oceans off the west coasts of continents in the middle latitudes, especially during summer, as at San Francisco. Patterns in the cloud field by mountains deflecting the flow are presented in Chapter 12.

When a sea breeze adds to the large-scale wind it drives the fog inland over valleys and makes it pour through straits such as San Francisco's Golden Gate, as on 26 Jul 2023 (Fig. 5-19), where a long tongue extended across San Francisco Bay (Fig. 4-24). On this day the fog topped out at about 350 m so it was blocked by the Coastal Range, but on the days the fog is thick enough, it will top the Coastal Range and pour down into the lowlands (Fig. 4-25 and Fig. 4-26).

Fig. 5-19. Fog and low clouds lodge against the Coast Range and pour through the Golden Gate as an extended tongue on 26 Jul 2023. NASA Modis image.

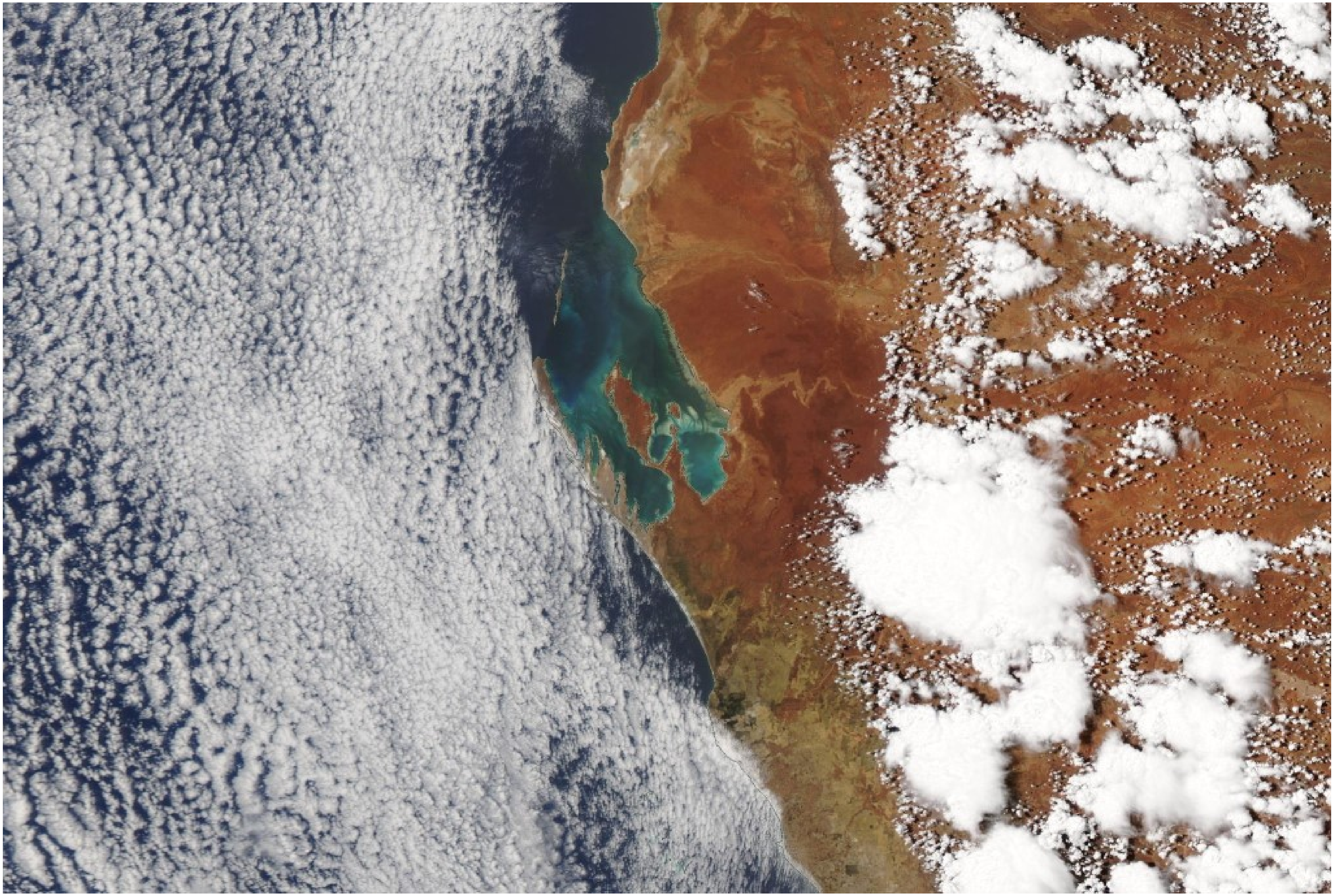

Fig. 5-20. Sc cells in a thin layer over the cool Indian Ocean, while popcorn Cb and dots of Cu rise over the hot Great Sandy Desert 29 Jan 2015. NASA MODIS/

If initially cool air from the subtropical highs acts in tandem with the sea breeze it can move far enough inland and be heated enough to produce Cu and Cb. This was the case over Australia's Great Western Desert on 29 Jan 2015 (Fig. 5-20). The cold, cobalt blue

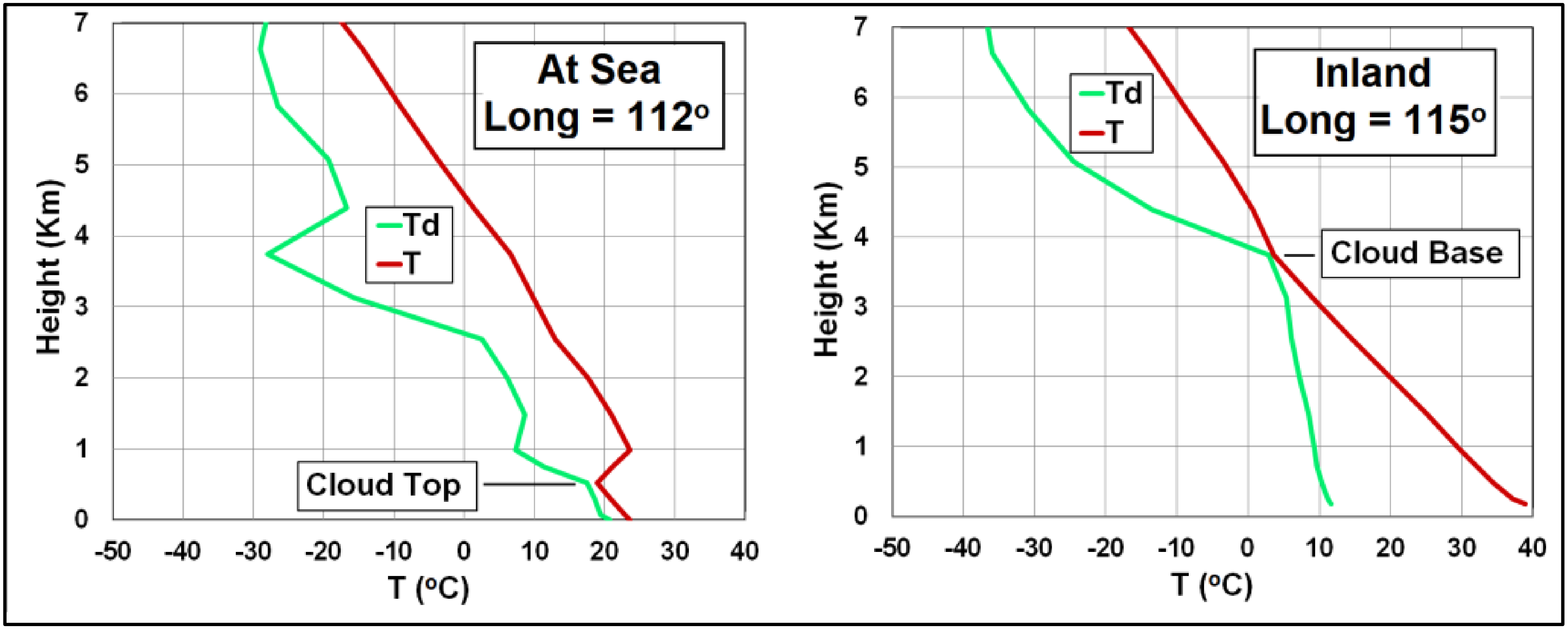

Fig. 5-21. Soundings over the cool Indian Ocean with Sc cloud cells (left), and over the hot Great Sandy Desert with Cu and Cb (right) 29 Jan 2015. SDG.

water of the Indian Ocean just west of Australia is covered by an extensive, patterned white sheet of stunted Sc cloud cells whose tops barely reach 500 m. above sea level.

As the cool, humid ocean air blew inland it was heated over the dry, desert land. Skies remained clear until the air was hot and buoyant enough to rise and form white Cu dots and popcorn Cb that towered above the deep red surface of iron-rich rock and sand punctured by lighter colored sediments in the meandering, dry stream beds.

This image of striking visual contrasts is mirrored by contrasting soundings over the sea and over the land (Fig. 5-21). The sounding over the sea had $\boldsymbol{T}$ = 23°C and $\boldsymbol{T}_d$ = 21°C, so $\boldsymbol{RH}$ = 90%. Five hundred m marked the cloud top because above it $\boldsymbol{T}$ increased and $\boldsymbol{T}_d$ decreased. The sounding over the desert 300 km to the east was markedly different. The air at the surface, $\boldsymbol{T}$ = 40°C and $\boldsymbol{T}_d$ = 12°C, was warmer and drier than when it had been over the sea. The sounding shows that temperature decreases with height at a rate near 10°C/km while the dew point decreases with height at a rate near 2°C/km. Both of these lapse rates match the physical cooling rates of rising, unsaturated air. Cloud base occurred at 3.6 km above the surface, where $\boldsymbol{T} = \boldsymbol{T}_d$. Though the ambient air was dry above this height Cu and Cb clouds were buoyant and continued to rise.

5.6 Tropical Cyclones

At the same time that fog and low clouds refrigerate summers on the eastern edges of the subtropical highs, towering spiral-galaxy shaped cloud systems of tropical cyclones roil the atmosphere and the warm sea surface waters that energize them on the tropical and western

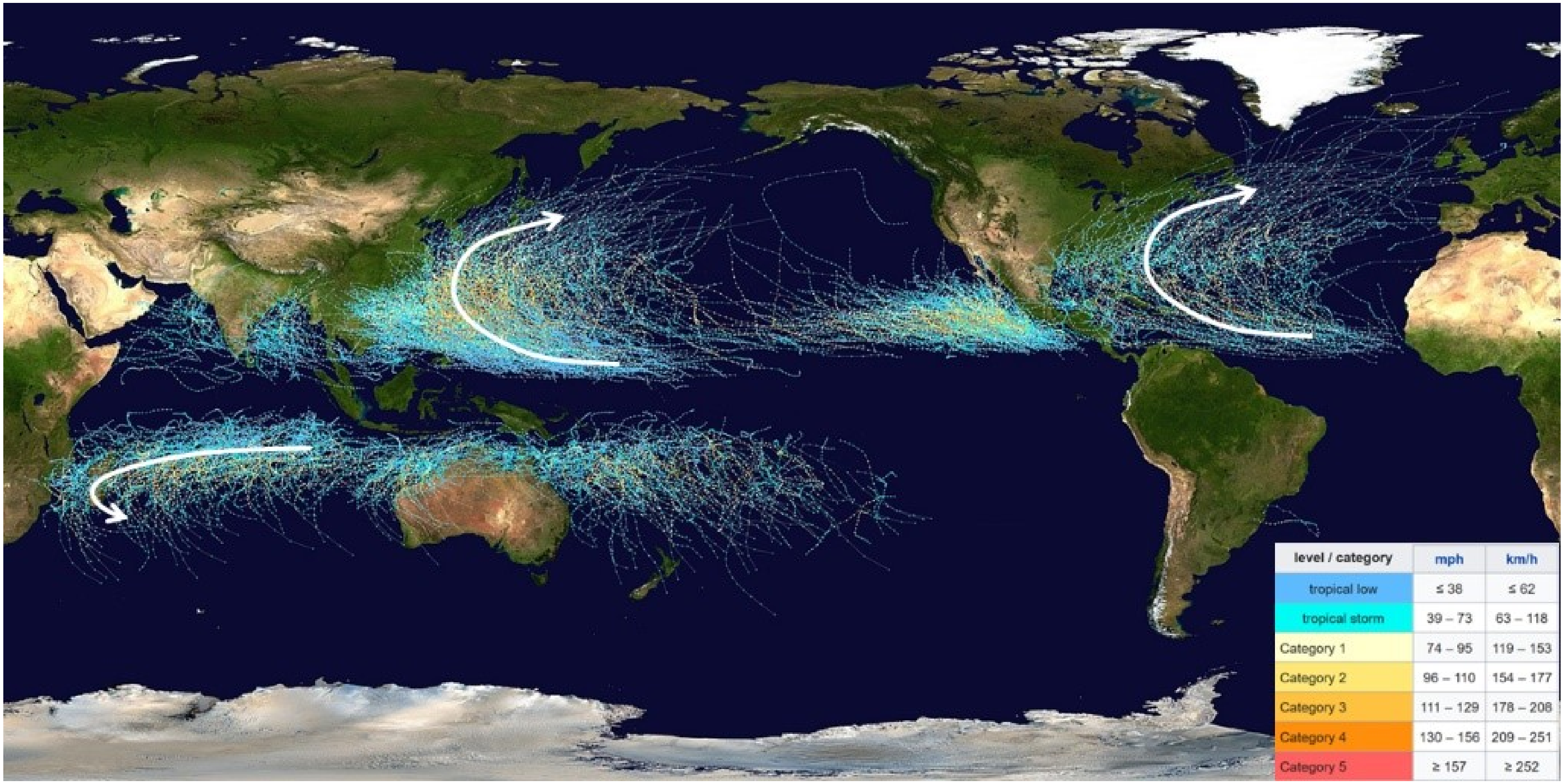

Fig. 5-22. Tropical cyclone tracks and intensity 1985-2005. White arrows show representative tracks around the subtropical highs. NASA image.

sides of the same highs. Tropical cyclones have various names depending on location but are all basically the same. They are called *hurricanes* in the North Atlantic and East Pacific Oceans, *typhoons* in the West Pacific, *bagyos* around the Philippines, and *cyclones* in the North Indian and South Atlantic Oceans.

Tropical cyclones are intense low-pressure areas between about 300 and 1500 km in diameter that rage over all the world's tropical and subtropical oceans (Fig. 5-22). The South Atlantic, long an exception to the rule, got its first in 2004 – Cyclone Caterina. They form over warm waters (T > 26.5°C) from about 3° to 33° latitude, avoiding the equator, mainly from late summer to early autumn, when the ocean waters are warmest.

To qualify as a hurricane or typhoon the surface wind speed must reach at least 118 km/h (74 mph) somewhere in the storm, though many greatly exceed that minimum standard with peak winds over 200 km/h. The greatest surface wind speed ever recorded in a tropical cyclone was 345 km/h (215 mph) in Hurricane Patricia (2015) in the Eastern Pacific Ocean. Hurricanes are ranked by maximum wind speed on the Saffir-Simpson scale from Category 1 to Category 5 (super typhoon). Storms of Category 3 or more considered major.

Tropical cyclones are the deadliest of all storms and, given that an average of almost 100 form every year, they are collectively the costliest of all natural disasters. They mete out damage in a range of ways. They can ravage the coasts they strike, raising sea level in a storm surge typically 2-3 m but up to 10 m, and produce enormous, ship-sinking waves that may exceed 15 m high at sea. Inland, their torrential rains that can reach 2 m transform babbling brooks into raging rivers and submerge wide swaths of lowlands while their ferocious winds mow down forests. For example, Hurricane Maria (2017) transformed emerald green Virgin Islands and Puerto Rico in its path into mountainous morasses of mud. Adding insult to injury, rotating thunderstorms, mostly on the hurricanes' advancing right quadrants can generate scores of tornadoes.

Hurricane Helene (2024) is a recent case-in-point. Helene, which reached Category 4 at its time of landfall, produced storm surges that exceeded 2 m along the Gulf Coast of Florida and topped out at almost 5 m in the panhandle region. Enormous rainfall totals exceeding 25 cm occurred from Florida to Virginia and topped out above 50 cm in the Blue Ridge Mountains of western North Carolina, where Helene was preceded by a front that produced an additional 25 cm. These enormous rainfall totals led to cataclysmic flooding in the river valleys, as in Asheville. Fierce winds trees toppled by the millions, blocking highways and knocking out electricity and internet for days. Helene's thunderstorms spawned a documented 33 tornadoes, most of which, fortunately were weak. The death toll from Helen exceeded 200 and monetary damage was almost $100 billion.

As the tropical cyclones spin furiously, they are enveloped in and guided by gentler anticyclonic winds to move along tracks around the giant subtropical highs. Eventually, tropical cyclones make landfall or move to higher latitudes, where they may approach extratropical cyclones and merge with or transform into them, where they often do further damage.

All these storms, which on the ground can be so devastating and leave behind scenes of almost unimaginable destruction and chaos, appear as wondrously beautiful objects when viewed from the air or from space.

For example, the beautiful satellite image of 03 Sept 2010 (Fig. 5-23) shows four distinct cloud systems and their relative sizes. Hurricane Earl, centered over the warm Gulf Stream waters of the Atlantic Ocean east of Virginia, was moving up the coast. It appeared in the pincers of the fronts of a larger extratropical cyclone centered in Ontario NE of Lake Superior. A cumulonimbus with a large anvil covering SE Florida and about the size of Lake Okeechobee shows how much smaller thunderstorms are than cyclones. At the same time, an extensive blanket of low stratus and fog covered the chilled Pacific Ocean west of California and pressed against the Coastal Range.

Tropical cyclones are so destructive that it is essential for forecasting purposes to obtain the most accurate data about their precise location, movement, and strength. This is done by flying into and through the heart of even the most violent hurricanes with instrumented airplanes. The result may be the most awesome of the atmosphere's sights – the eye of the hurricane (Fig. 5-1 and Fig. 5-24).

To get to the eye, the plane must penetrate the storm's most violent weather, the eyewall There it can be subjected to accelerations up to 6 g's with zero visibility in gushing rain or ice pellets.

The panoramic view inside the eye is called the stadium effect because it resembles the inside of a giant stadium, though it is some 300 times higher and wider than the Colosseum in Rome. When the eye is open, usually as the storm approaches maximum intensity, the sky overhead is deep blue. A circular wall of cloud rings, much like tiers in a stadium, extends from near the roiled sea surface to a height 15 km. Inside the eye shortly above the sea surface cloud vortices whirl. All this can be seen flying inside the eye of Hurricane Katrina

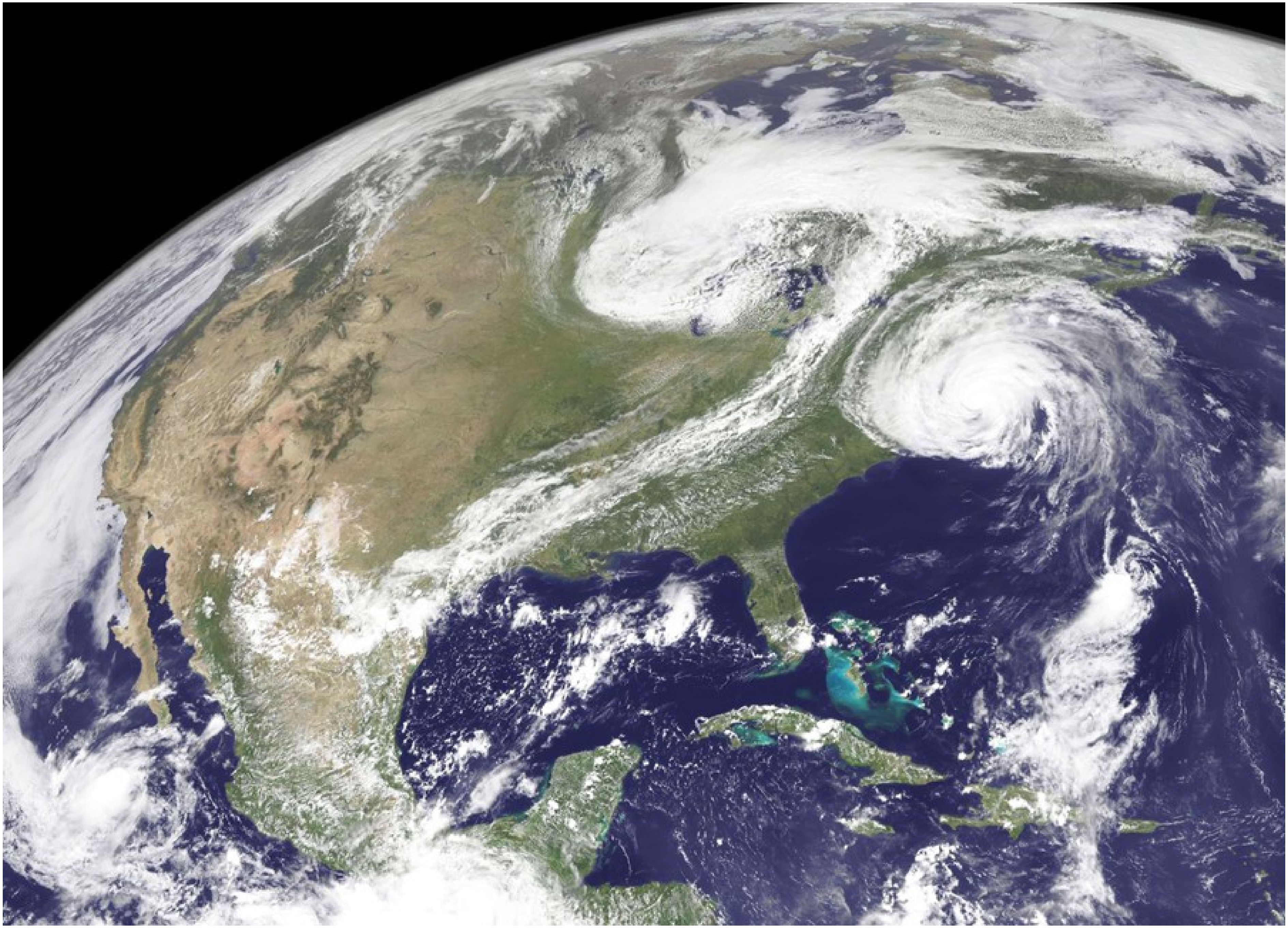

Fig. 5-23. Hurricane Earl in the warm sector of an extratropical cyclone. An extensive field of stratus and stratocumulus clouds cover the ocean west of California, 03 Sep 2010. Popcorn cumulonimbus and dots of cumulus cover Florida, Cuba, and the Yucatan Peninsula. NOAA GOES image.

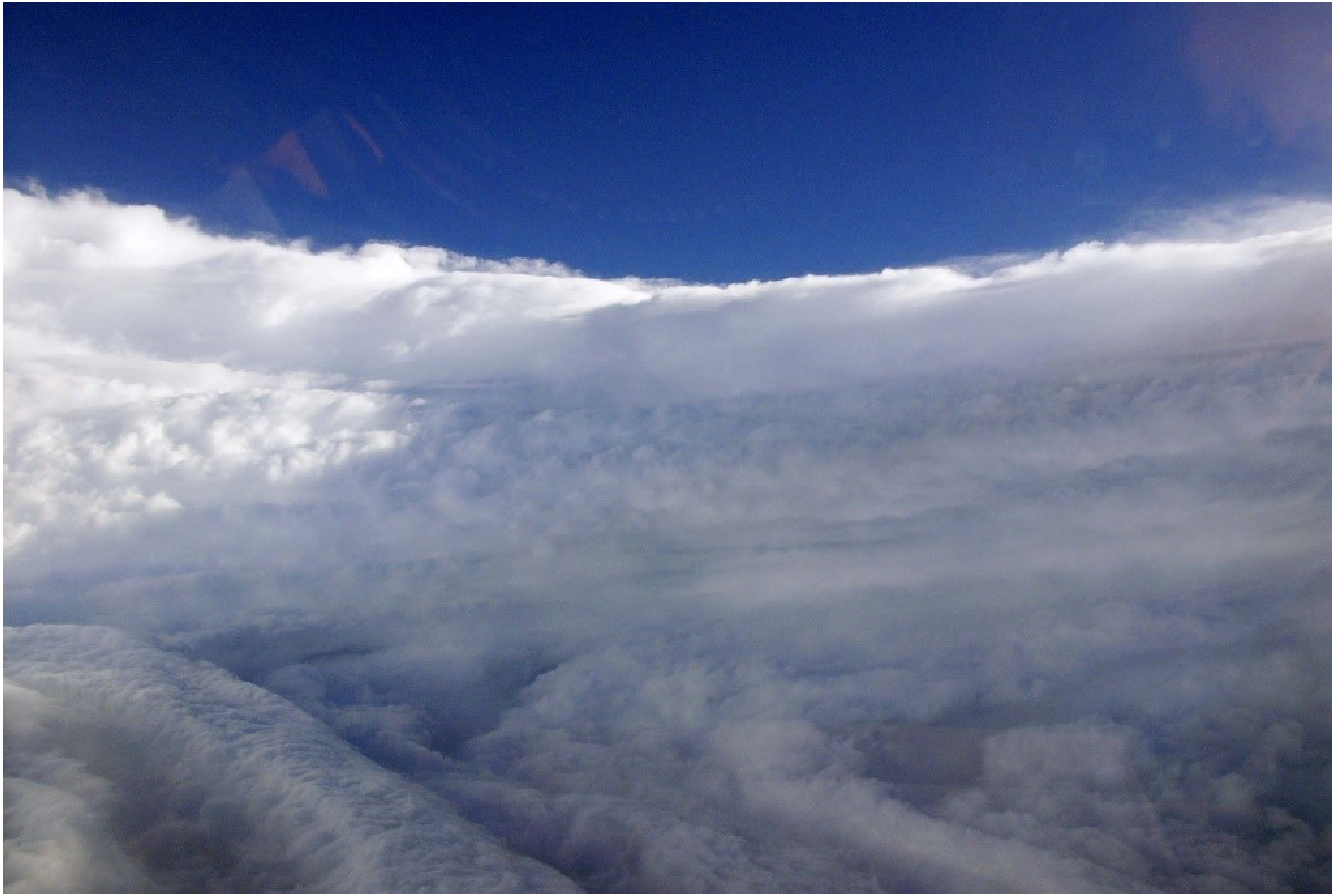

Fig. 5-24. Hurricane Katrina Eyewall with cloud bands inside the eye. NOAA Photo Library Fly 00449 28 Aug 2005.

(Fig. 5-24), except that the photo, magnificent as it is, conveys almost no idea of the scene's immensity.

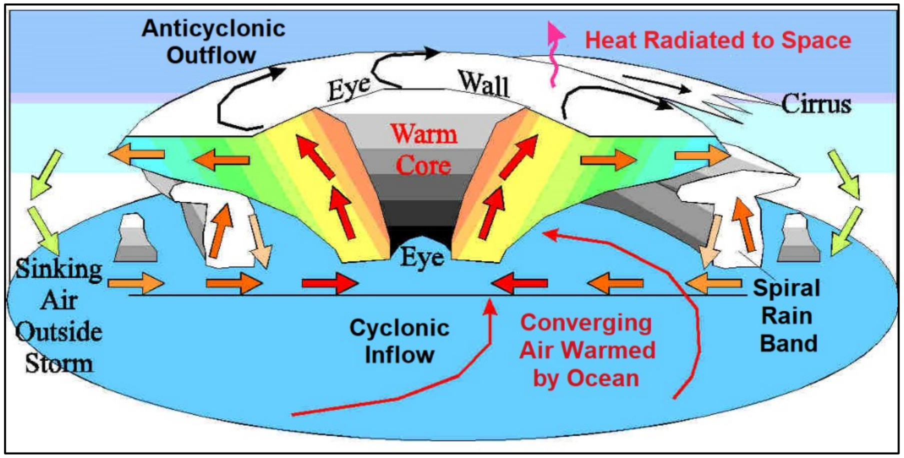

Fig. 5-25. Major structural features of tropical cyclones. SDG.

Tropical cyclones can only form and exist some distance from the equator because to spiral, the winds require that the Coriolis force have a horizontal component, which is zero at the equator and increases with latitude. The spiraling winds and clouds organize into a pattern whose features are illustrated and named in Fig. 5-25 and bear an almost uncanny resemblance to the features of spiral galaxies. The eye, which ranges from 10 to 100 km wide, a crude analog to the galaxy's central black hole, marks the low-pressure center. Moving out from the eye, the eyewall forms the inner edge of the central dense overcast, the region with the storm's fastest winds and heaviest precipitation. That corresponds to the dense central bulge of spiral galaxies, a region packed with old stars. Extending out to the periphery of the storm, spiral bands of Cu and Cb clouds with gusty winds alternate with quieter regions of partly cloudy skies. Like the spiral arms of galaxies, which are wavelike regions where mass converges to favor new star formation, the hurricane's spiral bands are wavelike regions where surface winds converge and rise to favor thunderstorm formation. Thunderstorms in the spiral bands (especially over the land) may spout tornadoes from their bases since they are immersed in the hurricane's rotating environment.

The hurricane can be considered a thermodynamic heat engine that generates the kinetic energy of winds. Air at the surface spirals in toward the low-pressure center spinning ever faster (conserving angular momentum except for losses to friction) until the wind spins so fast it cannot approach the center any closer. Hence the eye! As the converging air approaches that point, it turns up and rises in the central dense overcast. The hurricane has two main heat sources. The first is contact with the warm sea surface that keeps the converging air at an almost constant temperature despite the pressure decrease that would normally cool the by about 5 to 10°C.

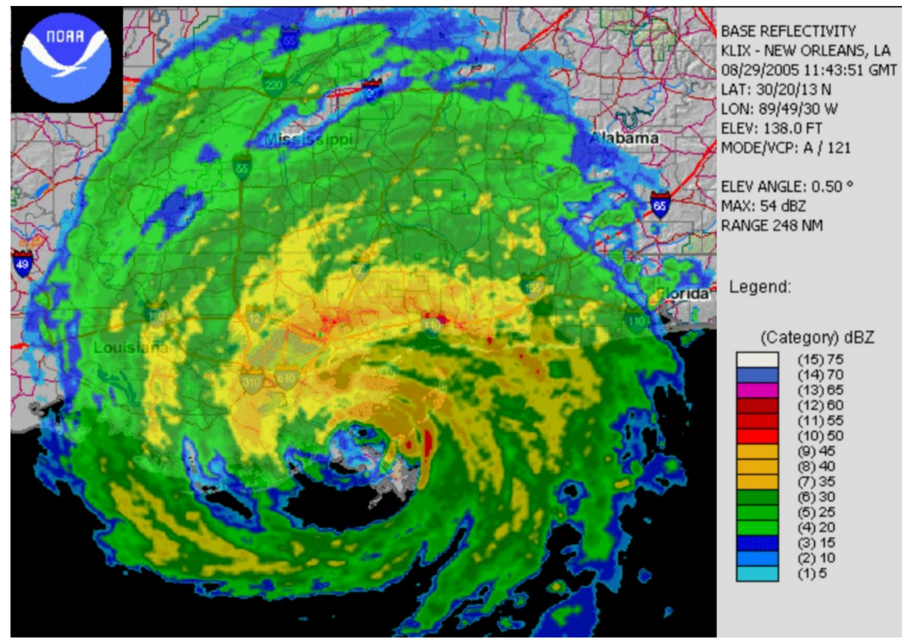

Fig. 5-26. Radar image of Hurricane Katrina at landfall on 29 Aug 2005, showing the eye and the banded nature of precipitation. NOAA.

Condensation in the rising air of the central dense overcast releases enormous quantities of latent heat into the air, ensuring that the hurricane is a warm-core storm, and that it is a high-pressure area at its top. Therefore, as the rising air in the central dense overcast approaches the stratosphere it is forced to turn outward. The air spins slower as it diverges, until beyond a certain distance the direction of spinning reverses and the air continues diverging anticyclonically (clockwise in the Northern Hemisphere). At the leading outer edge of the overcast the clouds may thin to beautiful bands of Ci, especially as the storm is intensifying. The contrast between the cyclonic rotation of the converging air near the surface and the anticyclonic rotation of the diverging air and Ci clouds aloft is displayed in magnificent fashion in animations of satellite images.

Radar images, such as that of Hurricane Katrina at 1200, UTC of 29 Aug 2005, the time it made landfall (Fig. 5-26), shows the eye with little precipitation surrounded by the eyewall and rainbands (which were first discovered by radar). Such images reveal the intensity of rainfall and the detailed structure of rainbands throughout the storm. These features are masked in satellite images by the almost uniform white cloud cover of the central dense overcast.

An EW cross section or panoramic profile of Katrina, produced by the WRF hurricane model, shows the calculated ascent rate (color contoured and expressed as a rate of pressure change) and the equivalent potential temperature (dashed white lines of the air's total heat content) in Fig. 5-27. Zones of rapidly rising air (deep red) of the eyewall surround the eye, tilting upward and outward, while a rainband of rising air appears about 180 km east of the storm center.

Morning (Fig. 5-28) and afternoon (Fig. 5-29) satellite images show Dorian, the most intense hurricane ever to strike the Bahamas, at its maximum intensity on 01 Sep 2019, Maximum sustained surface wind speed was 295 km/h (185 mph). Minimum pressure, 910 mb was 10% below mean sea level pressure, and more like the pressure 1 km above sea level!

Both images show the open eye spreading to a diameter about 50 km at the top (the size of Lake Okeechobee). The eyewall clouds were steep enough, given the low Sun to produce shadows on the eastern side of the eyewall angle at 1300 UTC and on the western side of the eyewall at 2200 UTC.

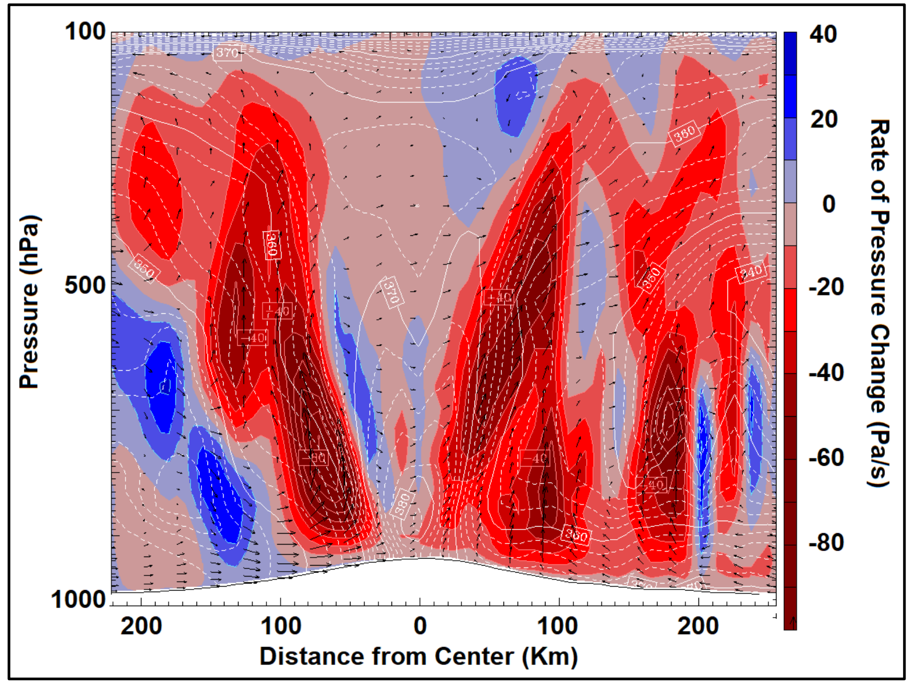

Fig. 5-27. Cross section view of vertical velocity (as rate of pressure change) for Hurricane Katrina prior to landfall. NOAA WRF Model.

In each image, Dorian's eye was surrounded by a wide, solid white ring of clouds of the central dense overcast. Here, the cirrus tops masked hints of structure, but in some storms, bands and even waves can be seen. Spiral bands extended from the central dense overcast to the storm's edge. Cb's with nipple tops do emerge from the cover of fuzzy Ci to give some hint of the structure below. In the afternoon image, distinct, streamers of Ci, fanned out in the radial direction, to indicate efficient venting, often during intensification. Near the surface, open convection cells, bounded by rings of Cu, covered the warm Gulf Stream waters north of Dorian and were blown over the Florida peninsula by Dorian's easterly winds.

The main difference between the morning and afternoon images was the intensity and location of convection. At 1300 UTC, a broad line of popcorn Cb clouds covered the warms waters just south of Cuba though the anvils stretched over the otherwise mostly clear land. The

Fig. 5-28. Satellite image of Hurricane Dorian at 2200 UTC, 01 Sep 2019. NOAA Photo Library.

Fig. 5-29. Satellite image of Hurricane Dorian at 1300 UTC, 01 Sep 2019. NOAA Photo Library.

skies over the Florida peninsula and a band of waters to the west were also mostly clear. By 2200 UTC, popcorn Cb's covered the heated land of Cuba and the west side of Florida's peninsula because of the sea breeze and easterly winds on Dorian's northern fringe.

5.7 Extratropical Cyclones = Winter Lows

So long as tropical cyclones remain in the tropics, they are reasonably symmetric storms with warm cores embedded in uniformly warm environments. But when they move out of the tropics, they are likely to encounter cold air. When they do, they entrain the cold air on their poleward and western sides. In that process they become asymmetrical and increasingly take on the characteristics of extratropical cyclones.

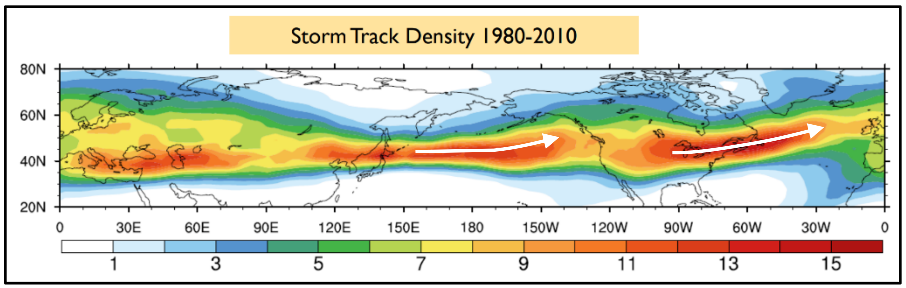

Fig. 5-30. Extratropical cyclone track density in the Northern Hemisphere from Dec through Feb of the winters 1980-2010. ©Katherine Lukens.

Extratropical cyclones, often called winter storms, are large, asymmetric storms between about 500 and 2000 km in diameter that form on the border of tropical and polar air (Fig. 5-30) and derive much of their energy as the cold, polar air sinks and the warm, tropical air rises over it. The storms move generally from west to east with a component towards the Poles at variable speeds averaging roughly 40 km/h. The structure and typical weather sequence, which typically lasts for about a day, are described on the next three pages.

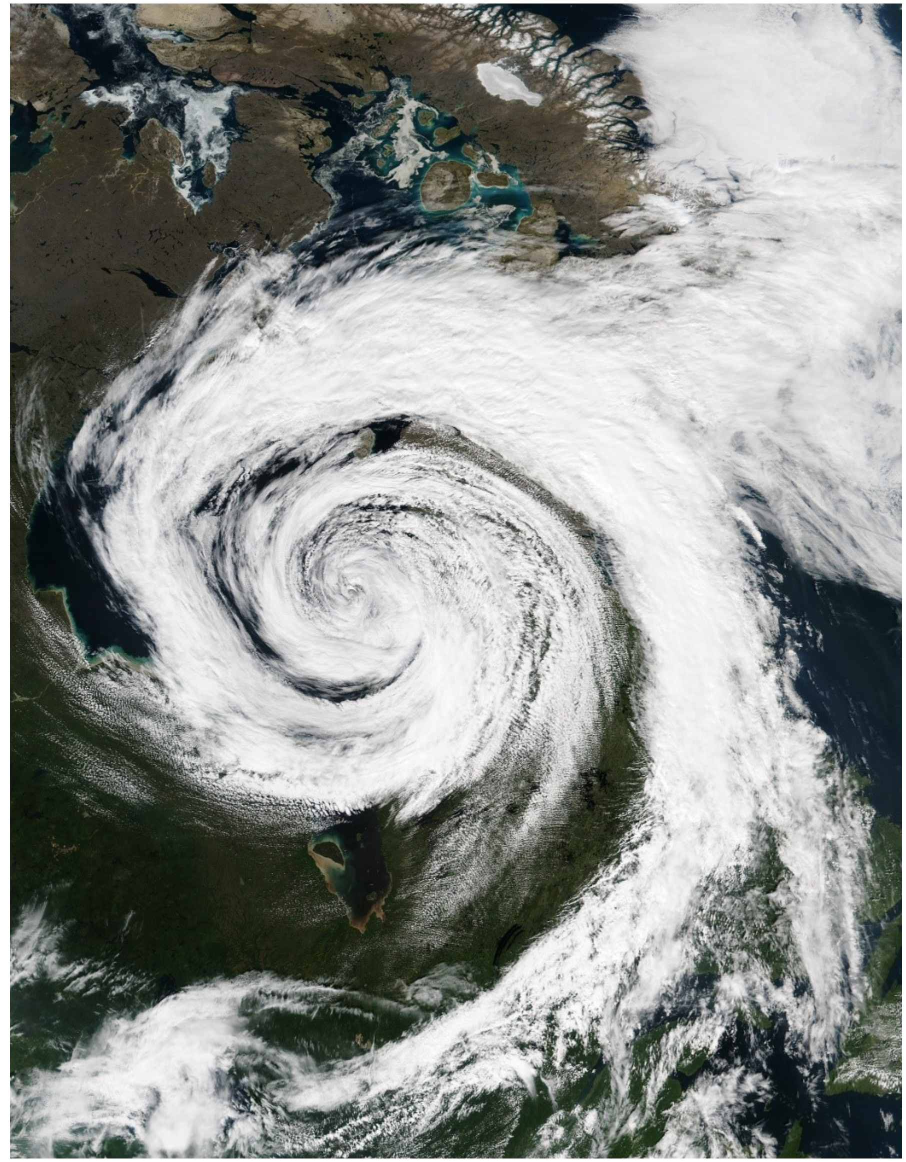

Fig. 5-31. The spiral cloud pattern of a dissipating extratropical cyclone centered over Hudson Bay, Canada on 10 Aug 2016. NASA VIIRS image.

Extratropical cyclones are not only larger, but far more numerous than tropical cyclones, so that almost any point in the mid latitudes will be at least touched by some part of one about once a week.

Extratropical cyclones, in association with thunderstorms they help generate, provide the middle latitude belt with most, if not all, of its precipitation in the winter half of the year. Though their precipitation intensity and winds (except in supercell thunderstorms) are much lower on average than in tropical cyclones, there are monster extratropical cyclones that are a match for hurricanes.

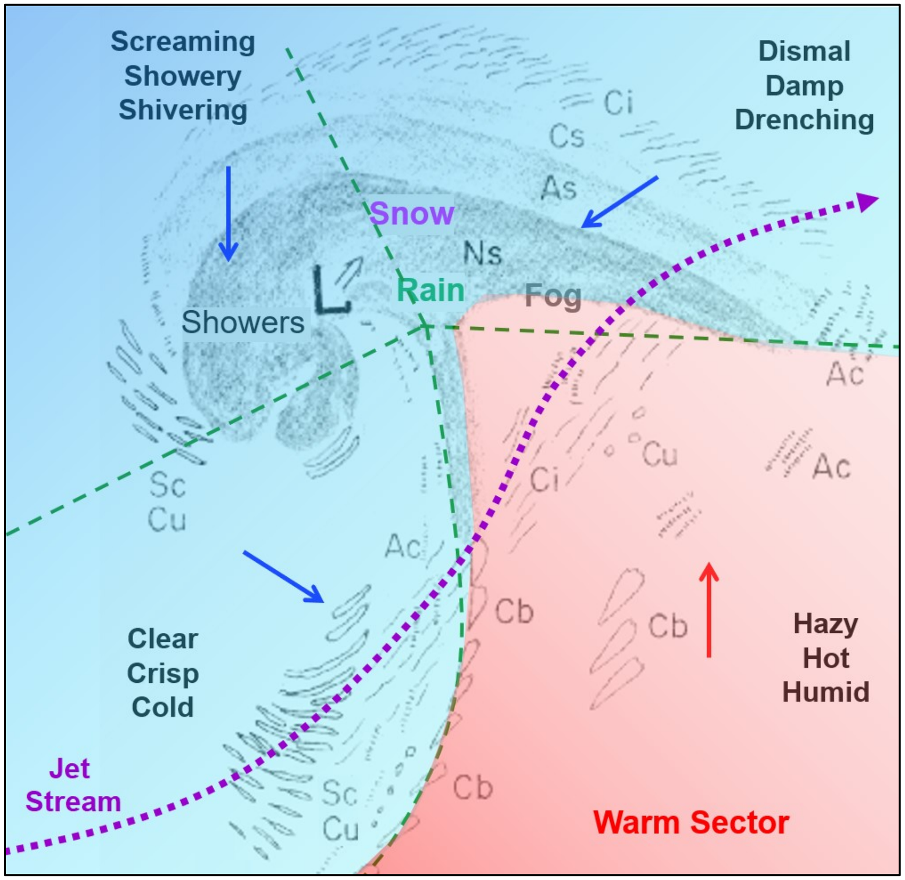

Fig. 5-32. Floor plan of clouds, wind, and weather sectors for a mature extratropical cyclone. Double arrow shows this storm moves to the NE.SDG.

Blizzards are extratropical cyclones with wind speeds faster than about 56 km/h and prolonged driving snow. They typically produce 10 to 40 cm of snow but have produced snow totals that greatly exceed 1 m and raised drifts over 5 m high. Sometimes, in the same

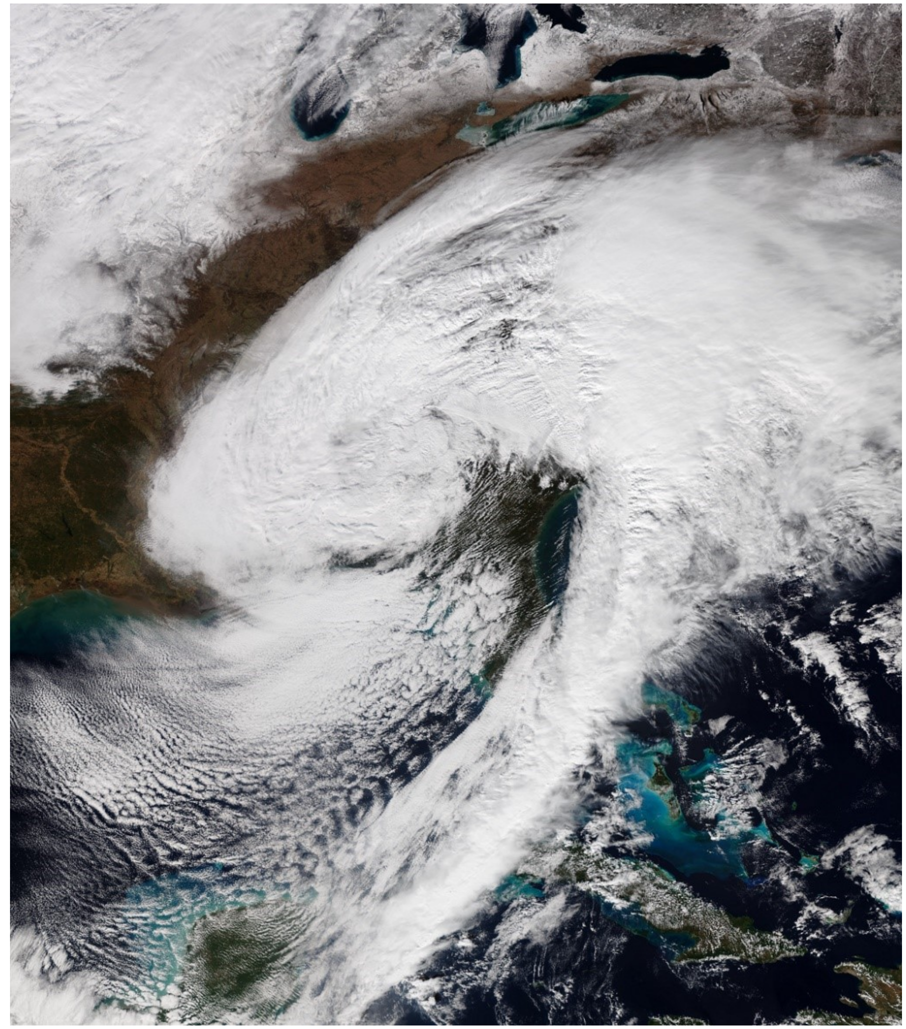

Fig. 5-33. Winter Storm Izzy, 16 Jan 2022. NOAA VIIRS

cyclone a short distance from where blizzard conditions are raging, ice storms produce freezing rain. Freezing rain is rain that freezes on contact. Ice storms can crack tree limbs, down trees and exposed power lines, and cover the ground with a layer of almost frictionless black ice that brings everything to a complete standstill. The coating of ice often gleams brilliantly in the sunshine after the storm has passed. What irony! And further equatorward, the same extratropical cyclone can spawn supercell thunderstorms with large hail and tornadoes!

Extratropical cyclones form in conjunction with and directly under the polar jet stream, which drives or steers the cyclones from west to east. The polar jet stream is the wavy band of the fastest mostly west to east winds near the top of the troposphere that girdles the globe in the middle latitudes of each hemisphere where the poleward temperature gradient is largest. It is a direct product of that temperature gradient due to a curious consequence of Earth's rotation and the Coriolis force called the thermal wind that,

> The west wind increases with height at a rate proportional to the gradient of poleward temperature decrease.

As air swirls around an extratropical cyclone, polar air on its western side sweeps equatorward, advancing on the tropical air and, being denser, undercuts it and wedges it aloft at the boundary called a cold front. At the same time, on the storm's eastern side, tropical air advances on the retreating polar air, and being lighter, rides over it at the warm front. All this occurs as the storm continues rotating, winding the cloud pattern in an ever-tightening spiral, as in Fig. 5-31 before all the tropical air has either moved aloft or mixed with the polar air, and the entire system ultimately dissipates.

The classic, mature extratropical cyclone averages about 1000 km in diameter and extends from the ground to the base of the stratosphere. As air spirals toward the storm center, the tropical and polar air masses are brought into ever closer contact, forming distinct fronts. The storm's floorplan map (Fig. 5-32), closely matched by the satellite image of Winter Storm, Izzy on 16 Jan 2022 (Fig. 5-33) shows its classical pattern of clouds and weather.

The radar and weather charts (Fig. 5-34) and satellite image (Fig. 5-33) of Winter Storm Izzy at 18 UTC, 16 Jan 2022 closely match the features drawn in the classical floor plan. The entire pattern bears resemblance to the human brain (the main cloud mass) and spinal column (the cold front).

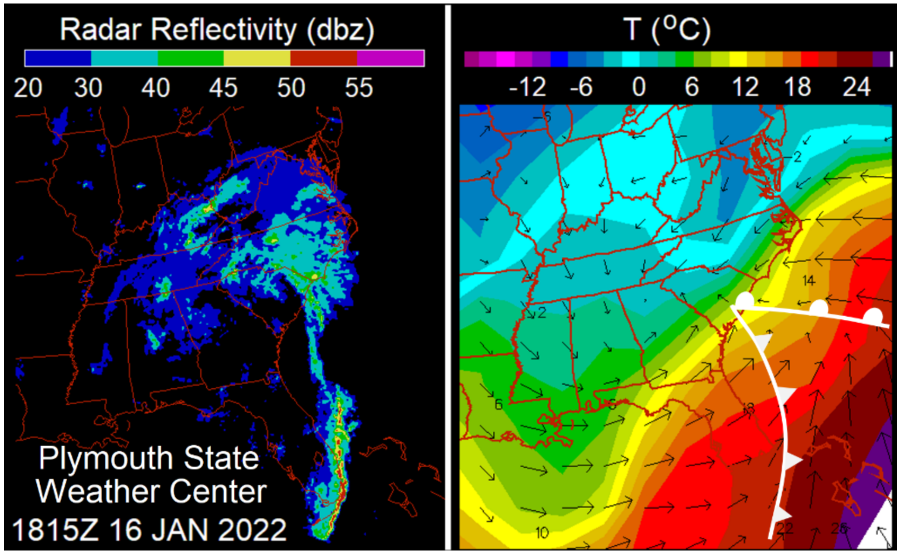

Fig. 5-34. Radar summary chart (left) and (right) surface weather map with wind arrows, fronts, and temperature for Winter Storm Izzy, 1800 UTC, 16 Jan 2022, modified from Plymouth State Weather Center charts.

Izzy's comma-shaped cold front, with a line of largely hidden, embedded thunderstorms over Florida, advances to the south and east. In its wake, long parallel streets of stunted Cu form as the polar air pours over the warm waters of the Gulf of Mexico, and is charged with water vapor and heated enough to become buoyant. The broad cloud mass that covers the cold, wet and the showery sectors contains a wide area of snow and rain north of the warm front and the storm center. The poleward edge of the stratiform cloud shield is covered by Ci and Cs. Finally, a dry slot has injected itself into the showery sector, just west of the storm center

Two small but telling features appear outside the poleward fringe of Izzy's cloud shield. 1: Cu streets appear over the open waters of Lake Erie, as tracers of the frigid N wind and, 2: The Adirondack Mountains near the NE corner of the image appear as a relatively dark region surrounded by white, snow-covered fields. This is a frequent sight in satellite images of the region during winter and is due to the largely forested nature of the Adirondack Park that covers the white ground.

The floor plan of Fig. 5-32 divides the storm into four quadrants or sectors, with fronts acting as two of the boundaries. The storm's vertical motions and relation to the fronts are shown in Fig. 4-20, with at least one caveat that the slope of the warm frontal surface and associated ascent rate of the air is too large and its width too narrow (each by a factor of about 50).

Each sector is filled by a giant conveyer belt of moving air. The cold, dry sector, located SW of the low-pressure center is filled by the polar conveyer belt from the northwest. It sinks as it wraps around the western side of the low to produce mostly crystalline skies, of clear, crisp, cold weather, though streets of Cu or Sc can form if daytime heating is sufficient or when the polar air pours out over the ocean. And, with the jet stream overhead near the cold front, mid and high clouds, that may be especially beautiful in this sector, are possible.

The warm sector, located SE of the low-pressure center and which extends into the tropics, is filled by a warm conveyer belt of tropical air. Weather of the warm sector tends to be hazy, hot, and humid. Mostly clear skies prevail, though mid- and high-level clouds are possible, and afternoon Cb's can develop from Cu, especially during spring and summer. Lines of possibly severe thunderstorms, with large hail and tornadoes, can develop near the western boundary of the warm sector, where the advancing cold front gives an extra upward shove to warm, unstable air.

The cold, wet sector, located north and east of the storm center, contains two conveyer belts, separated by the warm frontal surface that slopes upward towards the Poles. Below the frontal surface a conveyer belt of polar air slithers in from the NE. Above the frontal surface, the conveyer belt of tropical air from the warm sector ascends the dome of cold air, turning east as it does so to ultimately join the jet stream. The tropical air ascends at a gentle slope of about 1/100, spreading layer clouds that grade from Ns near the surface warm front, with stratiform precipitation, to As to Cs across an area several hundred km wide, and finally thinning out to Ci at the NE edge of the storm. The weather of this sector might well be termed dismal, damp, and drenching. It is where the majority of the prolonged rain, snow, and freezing precipitation occur.

In the showery and shivering sector north and west of the center of mature extratropical cyclones, the cold conveyer belt, previously soaked by the precipitation falling through it, final emerges and joins with the polar conveyer belt from the NW. The resulting weather is varied, but most often, especially in winter, can be described as screaming, showery, and shivering. Yet despite its threatening appearance, its intense showers tend to be brief and it is a region of generally lifting and clearing skies as the storm moves off to the east. And, as intense storms wrap up, a dry slot of clear skies whose air was warmed by sinking from jet stream levels, can protrude poleward into the cold air like a long tongue just west of the storm center.

The storm's typical eastward motion transforms the classical *pattern* of clouds and weather to a classical *sequence* in time for any fixed location. Thus, for example, the classical sequence of clouds and weather as storms approach from the SW begins with Ci (now often preceded by jet contrails), followed in order by Cs (often with a halo), As (with a 'milky' Sun), and Ns (often starting as snow, perhaps with a period of sleet and freezing rain, followed by rain). The halo has been recognized for millennia as a classical warning sign of an approaching winter storm (and hurricane), memorialized in poems such as Henry Wadsworth Longfellow's ***Wreck of the Hesperus***, and often appearing as a ring around the Sun or Moon some 6-24 hours before precipitation begins.

Extratropical cyclones are usually not soloists. They often form as the wave crests on a cyclone wave train, directly below waves in the jet stream. The connections are most distinct over the oceans where they are not masked and interrupted by mountains. A beautiful example occurred on 09 Nov 2024 (Fig. 5-35). Winter Storm Anya, which had dumped snow in the Rocky Mountains and sported a pronounced dry slot over the Central Great Plains and a gossamer veneer of sentinel Ci over the western Great Lakes, was attached to a cyclone over the Atlantic Ocean by an umbilical, long cold front. As

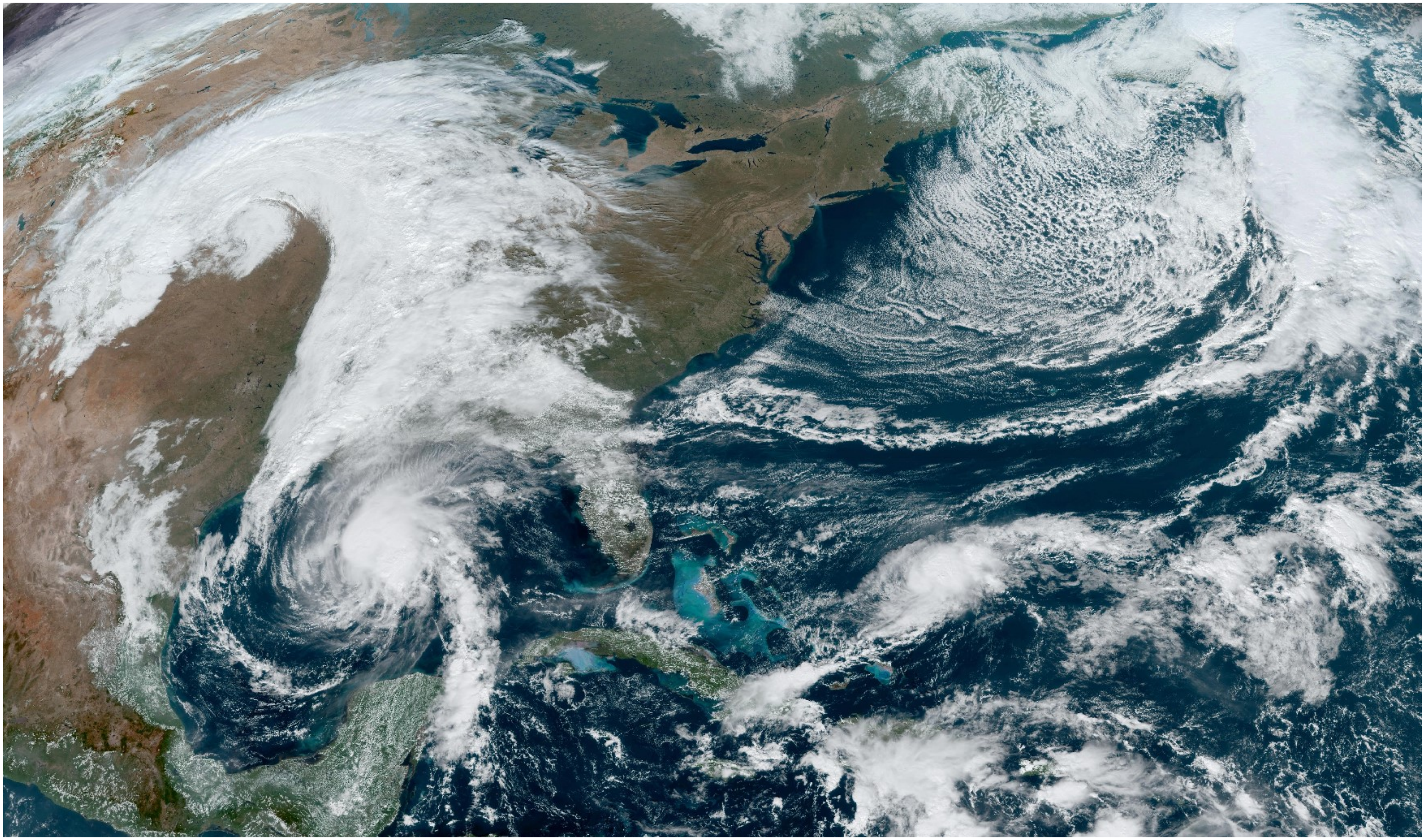

Fig. 5-35. Winter Storm, Anya over Kansas at 1800 UTC on 09 Nov 2024 connected by a cold front to a cyclone over the Atlantic Ocean, with the remnants of Hurricane Rafael over the Gulf of Mexico. NOAA VIIRS image.

cold, dry air poured over the Atlantic Ocean from the Eastern seaboard of the United States and the Maritime Provinces of Canada, Cu cloud streets and open convection cells formed and covered much of the cold, dry sector. In the warm sector, which extended into the tropics, Cu were dotted over all the land bordering the Gulf of Mexico and the Caribbean as well as over Cuba and Florida. At the same time, the remnants of Hurricane Rafael, swirling to its demise in the Gulf of Mexico, just happened to join the party by chance.

Fig. 5-36. Flying above a field of cumulus and below cirrus over the red earth south of La Mancha, Spain 22 Aug 2007. SDG.

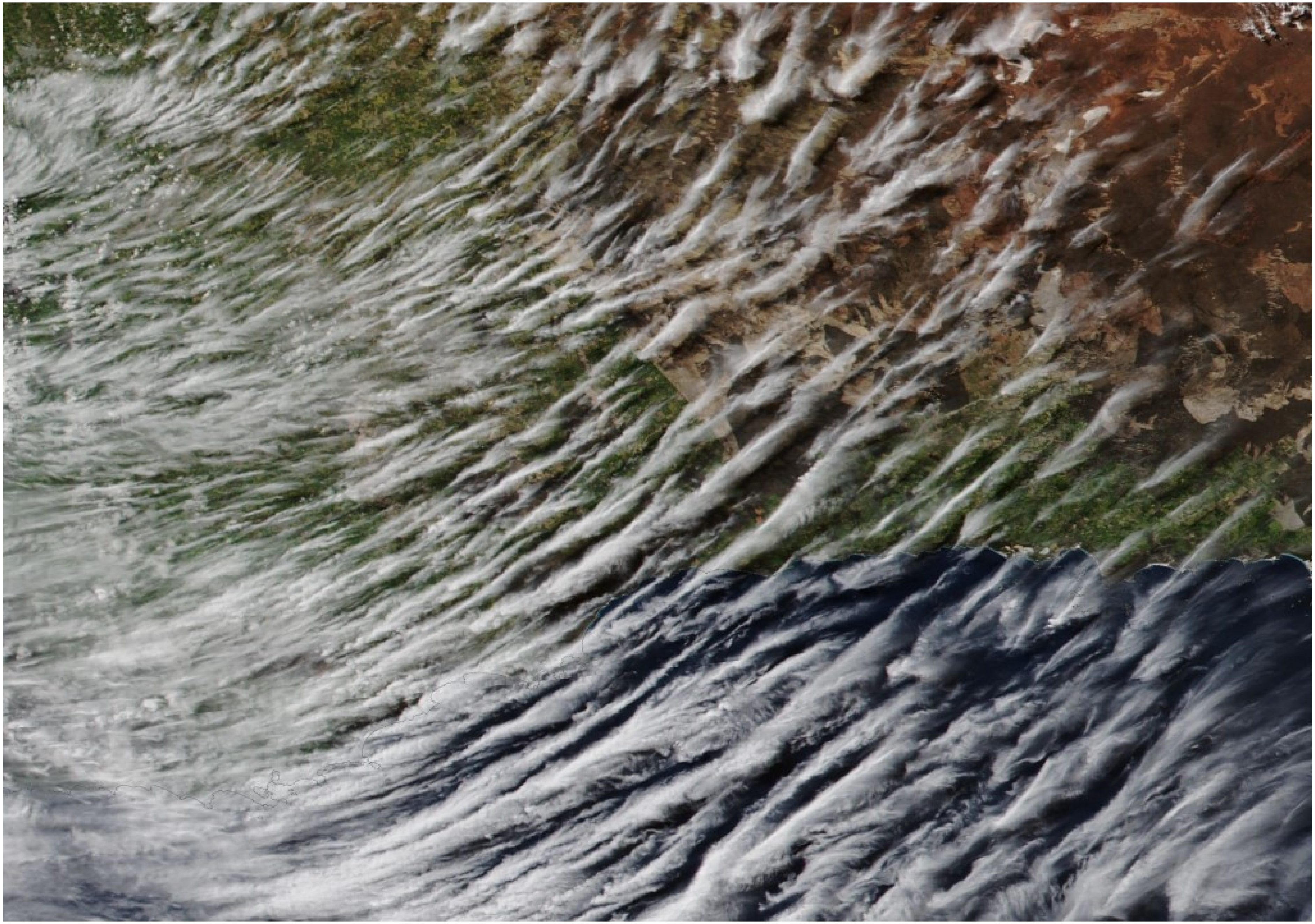

Fig. 5-37. Cirrus invasion over SW Australia, 09 Sep 2020. NASA MODIS.