United States Patent **7,714,767**
Kronfeld , et al. **May 11, 2010**

Storm top detection and prediction

Abstract

A radar system is configured to predict future storm cell characteristics and display an indication of the characteristics on an electronic display. The system has an antenna configured to receive radar returns from radar scans of storm cells. The system includes processing electronics configured to determine a characteristic of a first storm cell from the radar returns and identify at least one second storm cell. The at least one second storm cell is in the same weather system as the first storm cell. The processing electronics are configured to determine the characteristic for the at least one identified second storm cell, compare the characteristic of the first storm cell with the characteristics of the at least one second storm cell, determine a growth rate of the first storm cell, and calculate a predicted height of the first storm cell at a future time based on the comparison and determined growth rate.

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Appl. No.: **12/346,693**

Filed: **December 30, 2008**

Related U.S. Patent Documents

Application Number	Filing Date	Patent Number	Issue Date
11528829	Sep., 2006	7486220	

Current U.S. Class:	**342/26B** ; 342/26R; 702/3; 702/4
Current International Class:	G01S 13/95 (20060101)
Field of Search:	342/342R,342A-342D 702/3,4

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Parent Case Text

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of and claims priority to U.S. Ser. No. 11/528,829 entitled "Storm Top Detection and Prediction" and filed on Sep. 28, 2006, which is herein incorporated by reference in its entirety.

Claims

What is claimed is:

1. A radar system for use on an aircraft, the radar system configured to predict future storm cell characteristics and display an indication of the characteristics on an electronic display, the radar system configured to receive radar returns from a radar antenna and associated with radar scans of storm cells, the radar system comprising: processing electronics configured to: determine a characteristic of a first storm cell from the radar returns; identify at least one second storm cell, the at least one second storm cell being in the same weather system as the first storm cell; determine a characteristic of the at least one identified second storm cell; compare the characteristic of the first storm cell with the characteristic of the at least one identified second storm cell; determine a growth rate of the first storm cell; and calculate a predicted height of the first storm cell at a future time based on the comparison and the determined growth rate.

2. The system of claim 1, wherein the at least one second storm cell is the same type of weather as the first storm cell.

3. The system of claim 1, further comprising determining a maturity level of the first storm cell based on the comparison.

4. The system of claim 1, wherein the at least one second storm cell comprises a plurality of second storm cells and the plurality of second storm cells are part of the same weather system as the firsts storm cell.

5. The system of claim 4, wherein comparing the characteristic of the first storm cell comprises generating a maturity model based on the characteristics of the plurality of second storm cells and determining a maturity level of the first storm cell based on the maturity model.

6. The system of claim 5, wherein the generated maturity model includes a trend of the characteristics for the plurality of second storm cells.

7. The system of claim 4, wherein the characteristics of the plurality of second storm cells are determined at different times.

8. The system of claim 1, wherein the characteristic includes at least one of a storm cell volume, a storm cell vertical reflectivity profile, a storm cell lightning flash rate, a storm cell height, a storm cell vertically integrated liquid amount, a storm cell area above an isotherm level, a storm cell area above an altitude, a storm cell volume above an isotherm level, a storm cell volume above an altitude, a total reflectivity value, an average reflectivity value, a horizontal growth rate, a vertical growth rate, turbulence associated with a storm cell, hail associated with the storm cell, a speed of movement, a direction of movement, and an average growth rate.

9. A method for use on an aircraft, the method comprising: determining a characteristic of a first storm cell from the radar returns using processing electronics; identifying at least one second storm cell using the processing electronics, the at least one second storm cell being in the same weather system as the first storm cell; determining a characteristic of the at least one identified second storm cell using the processing electronics; comparing the characteristic of the first storm cell with the characteristic of the at least one second storm cell using the processing electronics; determining a growth rate of the first storm cell using the processing electronics; and calculating a predicted height of the first storm cell at a future time based on the comparison and the determined growth rate using the processing electronics.

10. The method of claim 9, wherein the compared characteristics represent an uncertainty of another

characteristic.

11. The method of claim 9, wherein the characteristic of the first storm cell comprises a predicted height of the first storm cell and calculating the predicted height of the first storm cell comprises adjusting the predicted height.

12. The method of claim 9, wherein the characteristic of the first storm cell comprises a growth rate of the height of the first storm cell and calculating the predicted height of the first storm cell comprises adjusting the determined growth rate.

13. The method of claim 9, wherein the characteristic of the first storm cell is received through a data link coupled to a second radar system.

14. The method of claim 9, further comprising determining if the at least one second storm cell is part of the same weather system as the first storm cell by comparing a distance between the first storm cell and the at least one second storm cell.

15. The method of claim 9, further comprising determining if the at least one second storm cell is part of the same weather system as the first storm cell by determining if the first storm cell and the at least one second storm cell are contiguous at or below an isotherm ***atmospheric*** layer.

16. The method of claim 9, wherein the predicted height is calculated for the future time when the aircraft is predicted to be within a predetermined distance of the first storm cell.

17. The method of claim 16, further comprising calculating an uncertainty of the predicted height and causing the calculated uncertainty to be displayed on an electronic display.

18. The method of claim 9, wherein the at least one second storm cell is determined to be decaying and the predicted height of the first storm cell is limited to not exceed a height achieved by the at least one second storm cell.

19. The method of claim 9, further comprising: calculating a first area of the first storm cell above an isotherm level at a first time; calculating a second area of the first storm cell above the isotherm level at a second time; and wherein the growth rate is determined based on a comparison between the first area and the second area and a time difference between the first time and the second time.

Description

BACKGROUND

The present application relates generally to weather detection and prediction. More particularly, the present application relates to the detection of and the growth prediction of storm tops.

Thunderstorms are a violent example of ***atmospheric*** convection with the uplift and cooling of air and subsequent cloud formation. As the cloud forms, water vapour changes to liquid and/or to frozen cloud particles resulting in a large release of heat that becomes the principal source of energy for the developing cloud. The cloud particles grow by colliding and combining with each other, forming rain, snow, and/or hail. High level winds may shear the cloud top into an anvil shape. When the droplets become heavy enough to fall against the updraft created as the cloud forms, precipitation begins. Once precipitation begins the updraft which initiated the cloud's growth weakens and is joined by a downdraft generated by the precipitation. This updraft-downdraft couplet constitutes a single storm cell. A typical storm is composed of multiple cells that form, survive for about half an hour, and then weaken and disperse. In some circumstances, new cells may replace old ones making it possible for some storms to continue for up to several hours.

Storm tops are hazards to aircraft. Conventionally, pilots use weather radar to detect and then avoid hazardous weather. Effectively and efficiently identifying and predicting storm tops using a weather radar is very beneficial for pilots that need to fly over the storm cell to avoid the hazardous weather. Meteorological radars are capable of detecting precipitation and variations of the refractive index in the atmosphere that may be generated by local variations of temperature or of humidity. The returned signal from the transmitted pulse encountering a weather target has an amplitude, a phase, and a polarization. The amplitude is used to determine the reflectivity and to estimate the mass of precipitation per unit volume or the intensity of precipitation through the use of empirical relations.

In general, modern weather radars automatically perform a volume scan consisting of a series of full azimuth rotations of the antenna at several elevation angles. The raw polar data may be stored in a three-dimensional array for further data processing and archiving. Using application software, a wide variety of meteorological products may be generated and displayed as images on a display. Grid or pixel values and conversion to x-y coordinates are computed using three-dimensional interpolation techniques. Each image pixel represents a color-coded value of a selected variable such as the reflectivity, the rainfall rate, etc. Vertically-integrated liquid can be displayed for any specified layer of the atmosphere as an indicator of the intensity of severe storms.

Turbulence is the leading cause of in-flight injuries to passengers and cabin crews on aircraft. A high turbulence region exists above a storm cell, but is difficult to detect with radar due to the low reflectivity. However, if a weather radar system can detect and predict the location of the high turbulence region with sufficient response time, aircraft can successfully avoid storm system hazards. Thus, there is a need for a system and a method for efficiently detecting the height of a storm cell. What is further needed is a system and a method to predict the change in the height of the storm cell for a forecast time period so that the aircraft can better respond to the changing conditions.

SUMMARY

According to an exemplary embodiment, the disclosure relates to a radar system for use on an aircraft and that is configured to predict future storm cell characteristics and display an indication of the characteristics on an electronic display. The radar system has a radar antenna configured to receive radar returns from radar scans of storm cells. The radar system includes processing electronics configured to determine a characteristic of a first storm cell from the radar returns and identify at least one second storm cell. The at least one second storm cell is in the same weather system as the first storm cell. The processing electronics are also configured to determine the characteristic for the at least one identified second storm cell, compare the characteristic of the first storm cell with the characteristics of the at least one second storm cell, determine a growth rate of the first storm cell, and calculate a predicted height of the first storm cell at a future time based on the comparison and the determined growth rate.

According to another exemplary embodiment, the disclosure relates to a method for use on an aircraft and that is configured to predict future storm cell characteristics and display an indication of the characteristics on an electronic display based on radar returns from radar scans of storm cells by a radar system. The method includes determining a characteristic of a first storm cell from the radar returns using processing electronics and identifying at least one second storm cell using the processing electronics. The at least one second storm cell is in the same weather system as the first storm cell. The method also includes determining the characteristic for the at least one identified second storm cell using the processing electronics, comparing the characteristic of the first storm cell with the characteristics of the at least one second storm cell using the processing electronics, determining a growth rate of the first storm cell using the processing electronics, and calculating a predicted height of the first storm cell at a future time based on the comparison and the determined growth rate using the processing electronics.

According to another exemplary embodiment, the disclosure relates to a radar system for use on an aircraft and that is configured to predict future storm cell characteristics and display an indication of the characteristics on an electronic display. The radar system has a radar antenna configured to receive radar returns from radar scans of storm cells. The radar system includes means for determining a characteristic of a first storm cell from the radar returns and means for identifying at least one second storm cell. The at least one second storm cell is in the same weather system as the first storm cell. The radar system also includes means for determining the characteristic for the at least one identified second storm cell, means for comparing the characteristic of the first storm cell with the characteristics of the at least one second storm cell, means for determining a growth rate of the first storm cell, and means for calculating a predicted height of the first storm cell at a future time based on the comparison and the determined growth rate.

According to another exemplary embodiment, the disclosure relates to a radar system for use on an aircraft and that is configured to predict future storm cell characteristics and display an indication of the characteristics on an electronic display. The radar system has a radar antenna configured to receive radar returns from radar scans of storm cells. The radar system includes processing electronics configured to determine a characteristic of a storm cell from the radar returns of a first time period, determine the characteristic for the storm cell from the radar returns of at least one second time period, compare the characteristic of the storm cell of the first time period with the characteristic of the storm cell of the at least one second time period, determine a growth rate of the storm cell, and calculate a predicted height of the storm cell at a future time based on the comparison and the determined growth rate.

Other principal features and advantages of the invention will become apparent to those skilled in the art upon review of the following drawings, the detailed description, and the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments of the invention will hereafter be described with reference to the accompanying drawings, wherein like numerals will denote like elements.

FIG. 1 is a diagram illustrating the spatial characteristics of an exemplary thunderstorm.

FIG. 2 is a flow diagram illustrating exemplary operations performed by a storm top detection application in accordance with an exemplary embodiment.

FIG. 3 is a diagram illustrating a vertical scan in accordance with an exemplary embodiment.

FIG. 4 is a diagram illustrating determination of a vertical scan axis and a vertical scan region in accordance with an exemplary embodiment.

FIG. 5 is a flow diagram illustrating exemplary operations performed by a storm top detection application to determine a maximum height of the storm cell in accordance with a first exemplary embodiment.

FIGS. 6-8 are flow diagrams illustrating exemplary operations performed by a storm top detection application to determine a maximum height of the storm cell in accordance with a second exemplary embodiment.

FIG. 9 is a block diagram of a storm top detection and prediction system in accordance with an exemplary embodiment.

FIG. 10 is a flow diagram illustrating exemplary operations performed by a storm top detection application to improve the maximum height determined for the storm cell in accordance with a first exemplary embodiment.

FIG. 11 is a flow diagram illustrating exemplary operations performed by a storm top detection application to improve the maximum height determined for the storm cell in accordance with a second exemplary embodiment.

FIG. 12 is flow diagram illustrating exemplary operations performed by a storm top prediction application in accordance with an exemplary embodiment.

FIG. 13 is flow diagram illustrating exemplary operations performed by a storm top prediction application to improve the prediction of the storm cell characteristics in accordance with an exemplary embodiment.

FIG. 14 is a diagram of an exemplary maturity model of a storm cell characteristic in accordance with an exemplary embodiment.

DETAILED DESCRIPTION

With reference to FIG. 1, a diagram illustrating the spatial distribution of a typical thunderstorm 100 is shown. The portion of thunderstorm 100 below a first altitude 102 contains water in liquid form. The portion of thunderstorm 100 below a second altitude 104 and above first altitude 102 contains a mixture of ice and water in liquid form. The portion of thunderstorm 100 above second altitude 104 contains only ice. Most of the reflectivity of a storm originates from the moisture that it contains and often the top of the storm is significantly higher than the moisture based radar reflectivity indicates. As a result, based on the geometry of thunderstorm 100, regions may be defined by their ability to be detected by radar, their visibility to a pilot, and their effect on an aircraft. Region 106, which includes the liquid water and the mixed ice and water portions of thunderstorm 100, is a region that is detectable by an aircraft radar system, due to the high and moderate radar reflectivity of those portions of thunderstorm 100. A storm top 108 (above region 106), which includes the ice portion of thunderstorm 100, is a region that is visible to a pilot, but is not detectable by radar at long range, due to the low radar reflectivity of the ice portion of thunderstorm 100. Region 110 (above region 108) is not visible or detectable by radar, but is a region of possible high turbulence which can affect the stability of an aircraft flying through region 110.

Thunderstorms may further be divided into isotherm layers based on temperature. For example, a generally horizontal scan of a thunderstorm may include an isotherm layer between approximately negative twenty degrees Celsius and negative forty degrees Celsius. Another generally horizontal scan of a thunderstorm may include an isotherm layer below zero degrees Celsius.

With reference to FIG. 2, exemplary operations in performing storm top detection are described. Additional, fewer, or different operations may be performed, depending on the embodiment without deviating from the spirit of the invention. In an operation 200, first scan data is received from a radar receiver. The scan data is formed from radar return signals received at a radar antenna as a result of a first horizontal scan of the atmosphere surrounding the radar. In an exemplary embodiment, a radar including the radar receiver and the radar antenna is mounted on an aircraft and the horizontal scan is in the direction of the aircraft's flight path. The scan data includes reflectivity data associated with the atmosphere that includes weather related phenomena such as precipitation. A radar scan generally includes a plurality of beam locations selected to "cover" a volume of space typically described by two angles and a distance along the beam of energy transmitted from the radar antenna. Exemplary angles are azimuth, elevation, and scan angles. In an exemplary embodiment, the first scan data is coincident with a first isotherm layer of the atmosphere. For example, the first scan may include the isotherm layer between approximately zero degrees Celsius and negative ten degrees Celsius.

Successive radar scan data is stored in memory as a function of time. In an operation 202, storm cells are identified in the first scan data. For example, a storm cell may be identified for one or more regions having a reflectivity value that exceeds a threshold reflectivity level. An exemplary threshold is 30 dBZ. No storm cells may be identified in the first scan data. Alternatively, a plurality of storm cells may be identified in the first scan data. In an operation 204, boundaries of the identified storm cells are determined based on the threshold reflectivity level encompassing a contiguous area. In an operation 205, a shape of each of the identified storm cells is determined. For example, image processing algorithms are applied to the scan data or image to determine the bounded reflectivity regions represented by polygons. In an operation 206, a first centroid of each of the identified storm cells is determined. For example, the first centroid may be determined based on the most reflective region that indicates a core of the storm cell. In another exemplary embodiment, the first centroid may be determined based on the shape of the storm cell.

With reference to FIG. 4, a first centroid 400 is shown as determined using the reflectivity data from the first scan data. In an exemplary embodiment, a first scan region may be defined relative to the first centroid. A first minimum azimuth angle 404 identifies the minimum azimuth angle of the reflectivity data that exceeds a reflectivity threshold in a decreasing azimuth direction relative to the first centroid. A first maximum azimuth angle 406 identifies the minimum azimuth angle of the reflectivity data that exceeds a reflectivity threshold in an increasing azimuth direction relative to the first centroid. The first scan region includes a plurality of beam locations that illuminate the area between the first minimum azimuth angle 404 and the first maximum azimuth angle 406. In an alternative embodiment, the first scan region is defined in the range direction. Additionally, the first scan region may be defined based on lightning data associated with the storm cell instead of reflectivity levels. The plurality of beam locations may be determined based on the pulse width, bandwidth, beamwidth, range to the centroid, width of the first scan region, etc.

In an operation 208, second scan data is received from the radar receiver. The scan data is formed from radar return signals received at the radar antenna as a result of a second horizontal scan of the atmosphere surrounding the radar. In an exemplary embodiment, the second scan data is coincident with a second isotherm layer of the atmosphere. For example, the second scan may include the isotherm layer between approximately negative twenty degrees Celsius and negative forty degrees Celsius.

In an operation 210, storm cells are identified in the second scan data. In an operation 212, boundaries of the identified storm cells are determined based on the threshold reflectivity level encompassing a contiguous area. In an operation 214, a shape of each of the identified storm cells is determined. In an operation 216, a second centroid of each of the identified storm cells is determined. In an operation 217, the storm cells identified in the first scan data and identified in the second scan data are correlated to identify a first centroid and a second centroid for the storm cell.

With reference to FIG. 4, a second centroid 402 is shown as determined using the reflectivity data from the second scan data. In an exemplary embodiment, a second scan region may be defined relative to the second centroid. A second minimum azimuth angle 408 identifies the minimum azimuth angle of the reflectivity data that exceeds a reflectivity threshold in a decreasing azimuth direction relative to the second centroid. A second maximum azimuth angle 410 identifies the minimum azimuth angle of the reflectivity data that exceeds a reflectivity threshold in an increasing azimuth direction relative to the second centroid. The second scan region includes a plurality of beam locations that illuminate the area between the second minimum azimuth angle 408 and the second maximum azimuth angle 410. In an alternative embodiment, the second scan region is defined in the range direction. Additionally, the second scan region may be defined based on lightning data associated with the storm cell instead of reflectivity levels. The plurality of beam locations may be determined based on the pulse width, bandwidth, beamwidth, range to the centroid, width of the second scan region, etc.

As stated previously, storm top 108 generally is not detectable at long range due to the lower reflectivity of ice. Additionally, at longer ranges the increasing width of the radar beam results in a reduced accuracy in a storm top determination. As a result, storm top 108 of the identified storm cells may not be determinable from the long range, horizontal first and second scan data. To address this issue, a third scan is performed to detect storm top 108 of storm cells that are located within a storm top detection volume. In an operation 218, storm cells within the storm top detection volume are determined from the identified storm cells. For example, the storm top detection volume may be defined by a range, a scan angle, an azimuth angle, and/or an elevation angle limit such as a minimum or a maximum. In an exemplary embodiment, the storm top detection volume is defined by a maximum range that is less than a maximum range of the first and/or second scans. For example, a maximum range of the third scan may be approximately half of the maximum range of the first and/or second scans. In an exemplary embodiment, the maximum range of the storm top detection volume is approximately 80 nautical miles (nm); whereas a maximum range of the first and/or second scans is approximately 320 nm.

In an operation 220, a scan order is determined for the storm cells determined to be located within the storm top detection volume. For example, storm cells that are near the aircraft and/or flight path may be scanned before other cells that are further away from the aircraft and flight plan. Additional parameters that may be used to determine the scan order of the storm cells determined in operation 218 include, but are not limited to, a last vertical scan time for the storm cells, a last vertical scan time exceeding a threshold, a level of storm maturity, i.e., a growing storm cell may be scanned more often than a decaying storm cell, a storm hazard level, an increased lightning rate, etc.

An operation 222 determines when the third scan(s) are complete for the storm cells determined to be located within the storm top detection volume. If the third scans are complete, processing continues at operation 200. If the third scans are not complete, processing continues at operation 224. In operation 224, a scan axis is determined for the third scan of the storm cell currently being processed. The scan axis is determined by connecting the first centroid and the second centroid of the correlated storm cells. For example, with reference to FIG. 4, a scan axis 412 is determined by connecting first centroid 400 and second centroid 402 of the correlated storm cells.

In operation 226, a plurality of beam locations for the third scan of the storm cell are determined based on scan axis 412 determined in operation 224. The plurality of beam locations may comprise a lowest elevation angle and a highest elevation angle along the determined scan axis. Thus, the third scan generally forms a vertical scan between the first centroid and the second centroid of the correlated storm cells. The third scan may further include a region surrounding the determined scan axis. For example, the third scan may include the plurality of beam locations determined for the first scan region and/or the second scan region. Additionally, the third scan may include a plurality of beam locations determined to illuminate the region bounded by a minimum azimuth line 414 and a maximum azimuth line 416 as shown with reference to FIG. 4. Minimum azimuth line 414 extends between first minimum azimuth angle 404 and second minimum azimuth angle 408. Maximum azimuth line 416 extends between first maximum azimuth angle 406 and second maximum azimuth angle 410.

In an operation 228, the determined beam locations for the third scan are sent to a radar controller. The third scan of the storm cell is conducted by transmitting a signal centered at each beam location and receiving returns from each beam location. The radar antenna may perform the third scan by steering to each beam location mechanically or electrically. In an operation 230, the third scan data is received from the radar receiver at a first time.

In an operation 232, the received third scan data is sampled to form pixel data that includes a reflectivity indicator for a plurality of pixels. Each pixel of the plurality of pixels identifies a segment of the received third scan data. The reflectivity indicator is determined for each pixel. The pixel data may be captured in a variety of formats. For example, the plurality of pixels may define a two dimensional region defined in a variety of coordinate systems as known to those skilled in the art both now and in the future. The plurality of pixels may be indexed using an x pixel number and a y pixel number. The reflectivity indicator may be a binary yes or no value such as a flag having a value of zero (false) or one (true), a value representative of the reflectivity level of the pixel, a value representing a color or intensity level for a graphical display, etc.

Preferably, the y pixel number is related to the height of the storm cell, and the x-pixel number is related to the range of the storm cell from the radar antenna or to the azimuth of the storm cell relative to the flight path. In general, the height of the storm cell is defined as a distance above ground or an altitude. Additionally, the pixel data may define a three dimensional region that may be indexed using an x pixel number (i.e., range), a y pixel number (i.e., height), and a z pixel number (i.e., azimuth). The pixel data may be rotated and/or translated to compensate for aircraft movement and/or to convert the data into a different coordinate reference system. In an operation 234, the pixel data including a time stamp at which the third scan data was received is stored in a memory.

In an operation 236, a maximum height of the storm cell is determined by processing the pixel data. Various methods exist for processing the pixel data to determine the maximum height or storm top of the storm cell. For example, a heuristic search technique may be used based on traversal of the pixel data. However, additional/different search mechanisms may be implemented (binary, tree, graph, blind, etc.) in processing the pixel data. The height of the storm cell is determined by searching the pixel data associated with the storm cell for the highest pixel that indicates a reflection which is defined based on a minimum reflectivity threshold. For example, if the pixel data includes a single storm cell, the pixel data can be traversed in row-major fashion starting at an upper corner until a pixel containing a reflective value exceeding the minimum reflectivity threshold is identified. If the y-pixel data is related to the height, the resulting pixel represents the highest point in the pixel data that contains reflectivity information "detectable" by the radar based on the minimum reflectivity threshold. Processing continues at operation 222 until the third scan has been executed for the storm cells determined to be located within the storm top detection volume. In another exemplary embodiment, processing may continue at an operation 1000 shown with reference to FIG. 10. In yet another exemplary embodiment, processing may continue at an operation 1100 shown with reference to FIG. 11.

Referring to FIG. 3, an aircraft 300 is depicted having a radar 302 mounted near the nose of aircraft 300. Radar 302 is capable of transmitting a plurality of radar beams 304, 306, 308, 310, 312, 314, 316 and receiving reflective energy from a thunderstorm 320. The plurality of radar beams 304, 306, 308, 310, 312, 314, 316 form a vertical radar scan. The plurality of radar beams 304, 306, 308, 310, 312, 314, 316 may be scanned in any order. If mechanical steering of the radar antenna is used, the plurality of radar beams 304, 306, 308, 310, 312, 314, 316 are preferably scanned in the order 304, 306, 308, 310, 312, 314, 316 or in the order 316, 314, 312, 310, 308, 306, 304. The location of the plurality of radar beams 304, 306, 308, 310, 312, 314, 316 can be adjusted for local winds in the area of the storm cell, which can create an anvil shape thereby creating a measurable radar top on a separate vertical axis as compared to the predominate core axis of the storm cell. In addition, an offset vertical scan can be executed on the downwind side of the storm cell to determine the existence of an anvil, which is an indicator of the maturity of the storm cell. Similarly, an upwind vertical scan can be performed to determine the existence of a supercell.

By performing a generally vertical scan in response to a determination that a storm cell is within a storm top detection volume, the time required to perform the third scan is reduced in comparison to a full or more complete three-dimensional radar scan. Various processing of the radar return data may be performed as known to those skilled in the art both now and in the future. For example, clutter rejection or suppression techniques may be utilized to reduce or remove the generally large returns that result from the ground.

The storm top height may be stored in a memory and/or displayed on an electronic flight information system display. Storm cells detected by the radar or other sources, but outside the storm top detection volume may be included on the display if received from other storm top detection sources. Other storm top detection sources may include other aircraft, ground based radars, satellites, etc. The storm top information may be transmitted to the aircraft and displayed to the pilot in conjunction with the storm cell information determined by the radar mounted on the aircraft to provide complete situational awareness. Other storm top sources can also be used to display storm cells within the storm top detection volume if the storm cells are obscured by other storm cells or other obscurations.

If multiple cells are present in the pixel data, a traversal of the pixel data in row major fashion starting at an upper corner is inadequate. With reference to FIG. 5, exemplary operations in determining a maximum height of the storm cell in pixel data that includes a plurality of storm cells are described in accordance with a first exemplary embodiment. Additional, fewer, or different operations may be performed, depending on the embodiment. In an operation 500, the pixel data formed from the third scan data is received from a memory. The pixel data includes a reflectivity indicator for a plurality of pixels. The plurality of pixels can be indexed using an x pixel number and a y pixel number. In an operation 502, a centroid of a first storm cell is identified. In an operation 504, a number of storm cells identified in the pixel data is determined. For example, by comparing the range and azimuth of the detectable storm cells with the range and azimuth extent of the plurality of radar beams used to generate the third scan, the number of storm cells can be determined. If the centroid of a plurality of storm cells is located in the vertical scan area, the height information for each of the plurality of storm cells can be determined from the single scan. Of course, the number of storm cells can be determined before executing the vertical scan to reduce the radar resources required to determine the height of each storm cell.

The pixel data is processed by traversing the plurality of pixels to identify a pixel associated with the maximum height of the storm cell. In an operation 506, an x-pixel number is initialized to an x centroid pixel number of the first storm cell and a y pixel number is initialized to a minimum y pixel number. In an exemplary embodiment, the x pixel number represents a range from the aircraft, and the y pixel number represents a height above ground. In another exemplary embodiment, the x pixel number may represent an azimuth angle from the aircraft flight path. In an operation 507, a pixel of the pixel data is selected by using the x pixel number and the y pixel number as an index into the plurality of pixels.

In an operation 508, a determination of whether or not the reflectivity indicator of the pixel indexed with the x pixel number and the y pixel number indicates a reflectivity value that exceeds the threshold is made. If the selected pixel is reflective, processing continues at an operation 510. In operation 510, a flag is set indicating that a reflective pixel has been found. In an operation 512, the y pixel number is incremented, and processing continues at operation 507. If the selected pixel is not reflective, processing continues at an operation 514. In operation 514, whether or not the flag is set indicating that a reflective pixel has been found is determined. If the flag is not set, processing continues at operation 512. If the flag is set, processing continues at operation 516.

In operation 516, a height associated with the y pixel number is identified. For example, a minimum (maximum) height may be defined for or calculable from the lowest (or highest) y pixel number and/or the x pixel number corresponding with the lowest (or highest) y pixel number. The height associated with the y pixel number can be calculated based on the minimum (maximum) height, the resolution of each pixel in the vertical dimension, and the offset from the minimum (maximum) y pixel number. In an operation 517, a height of the storm top (maximum height) is inferred using a reflectivity model. The reflectivity model describes the vertical reflectivity change as a function of altitude for storm cells. Using the reflectivity model, the reflectivity value associated with the pixel (or the threshold) may be used to infer an actual height of the storm top which was not actually "detectable" in the scan data. For example, the reflectivity model may assume a linear variation in reflectivity as a function of altitude and indicate a 300 meter altitude difference between 30 dBZ and 0 dBZ, which indicates the actual storm top. Thus, if the threshold is 30 dBZ, 300 meters is added to the height associated with the y pixel number to infer the height of the actual storm top which was not "detectable." In an alternative embodiment, a reflectivity model is not used to infer the height of the storm top.

In an alternative embodiment, the height is extrapolated from radar measurements performed immediately above the altitude of the freezing isotherm altitude. Because homogeneous radar beam filling is achieved at these altitudes, the extrapolation is based on reliable measurements. Input data include physical parameters associated with the storm cell and with the radar (e.g. reflectivity, Doppler parameters, etc.). Physical parameters, which are inputs of the principal components analysis process, are normalized using a statistical analysis as known to those skilled in the art both now and in the future. Nodes with a strong contribution in the global inertia are selected. For example, the inertia contribution is calculated for each node, and the inertia value of each node is classified into intervals of inertia contribution. Nodes with an inertia contribution between a median inertia and a maximal inertia are retained. A first grid criterion, which may be a function of the number of scans, the range to the node, the beam width, etc. is applied to the selected nodes to eliminate nodes with aberrant performance. A second grid criterion, which may be a function of the number of scans, the range to the node, the beam width, the distance between nodes, etc. may further be applied to detect and define outstanding areas (indirectly outstanding contour), which are a core of convective activity. An amplitude criteria may be applied to ensure that only relevant values are used. This core discrimination enables a vertical analysis of each core, and thus, a finer analysis of the convective activity within a cell. A vertical reflectivity profile has a typical shape: at low altitude, reflectivity is constant, and above an inflexion point, the reflectivity decreases with a characteristic slope. As a result, the turbulent height of the storm cell can be extrapolated using the characteristic slope and the inflexion point altitude determined using the radar measurements performed immediately above the altitude of the freezing isotherm altitude.

In an operation 518, the inferred (identified) height is saved in the memory. In an operation 520, whether or not another storm cell is within the pixel data is determined. If another storm cell is within the pixel data, processing continues at operation 506. If another storm cell is not within the pixel data, processing of the received pixel data ends.

With reference to FIGS. 6-8, exemplary operations in determining a maximum height of the storm cell in pixel data that includes a plurality of storm cells are described in accordance with a second exemplary embodiment. Additional, fewer, or different operations may be performed, depending on the embodiment. In an operation 600, the pixel data from the third scan data is received from the memory. In an operation 602, a centroid of a first storm cell is identified. In an operation 604, a number of storm cells identified in the pixel data is determined. The pixel data is processed by traversing the plurality of pixels to identify a pixel associated with the maximum height of the storm cell. In an operation 606, an x-pixel number is initialized to an x centroid pixel number of the first storm cell and a y pixel number is initialized to a minimum y pixel number. In an operation 607, a pixel of the pixel data is selected by using the x pixel number and the y pixel number as an index into the plurality of pixels.

In an operation 608, a determination of whether or not the reflectivity indicator of the pixel indexed with the x pixel number and the y pixel number indicates a reflectivity value that exceeds the threshold is made. If the selected pixel is reflective, processing continues at an operation 614. If the selected pixel is not reflective, processing continues at an operation 610. In operation 610, the y pixel number is incremented and processing continues at operation 607. In operation 614, the x pixel number is decremented, and a pixel of the pixel data is selected by using the x pixel number and the y pixel number as an index into the plurality of pixels. In an operation 616, whether or not the selected pixel is reflective is determined. If the selected pixel is reflective, processing continues at operation 614. If the selected pixel is not reflective, processing continues at an operation 618. In operation 618, a minimum x pixel number of the storm cell is initialized.

In an operation 620, the x pixel number is set to the x centroid pixel number. In an operation 622, the x pixel number is incremented, and a pixel of the pixel data is selected by using the x pixel number and the y pixel number as an index into the plurality of pixels. In an operation 624, whether or not the selected pixel is reflective is determined. If the selected pixel is reflective, processing continues at operation 622. If the selected pixel is not reflective, processing continues at an operation 626. In operation 626, a maximum x pixel number of the storm cell is initialized. Processing continues at A of FIG. 7.

With reference to FIG. 7, in an operation 700, the x pixel number is set to the x centroid pixel number. In an operation 702, the y pixel number is incremented, and a pixel of the pixel data is selected by using the x pixel number and the y pixel number as an index into the plurality of pixels. In an operation 706, whether or not the selected pixel is reflective is determined. If the selected pixel is reflective, processing continues at operation 708. If the selected pixel is not reflective, processing continues at an operation 710. In operation 708, the x pixel number is decremented, a pixel of the pixel data is selected by using the x pixel number and the y pixel number as an index into the plurality of pixels, and processing continues at operation 706. In operation 710, whether or not the x pixel number is less than the minimum x pixel number is determined. If the x pixel number is less than the minimum x pixel number, processing continues at operation 712. If the x pixel number is not less than the minimum x pixel number, processing continues at operation 714. In operation 712, the minimum x pixel number is set to the x pixel number.

In an operation 714, the x pixel number is set to the x centroid pixel number. In an operation 716, the x pixel number is incremented, and a pixel of the pixel data is selected by using the x pixel number and the y pixel number as an index into the plurality of pixels. In an operation 718, whether or not the selected pixel is reflective is determined. If the selected pixel is reflective, processing continues at operation 716. If the selected pixel is not reflective, processing continues at an operation 720. In operation 720, whether or not the x pixel number is greater than the maximum x pixel number is determined. If the x pixel number is greater than the maximum x pixel number, processing continues at operation 722. If the x pixel number is not greater than the maximum x pixel number, processing continues at operation 724.

In operation 722, the maximum x pixel number is set to the x pixel number. In operation 724, whether or not another row of pixels is included in the pixel data is determined. For example, an invalid y pixel number of a y pixel number greater than a maximum y pixel number may indicate that there is not another row of pixels to process. If there is not another row of pixels to process, processing may continue at B of FIG. 8. In an alternative embodiment, a height associated with the y pixel number is determined and the height is saved in a memory. Defining the height from the y pixel number after operation 724 does not include any additional storm height that may result from an overhang. If there is another row of pixels to process, processing continues at operation 700. The maximum x pixel number and the minimum x pixel number indicate the maximum extent of the storm cell in the dimension defined for the x direction. For example, the x direction may indicate a range from the radar antenna. The maximum range extent of the storm cell relative to the radar antenna can be calculated given a range resolution defined for the pixel data. In an exemplary embodiment, the range resolution can be multiplied by the difference between the maximum x pixel number and the minimum x pixel number to determine the maximum range extent of the storm cell.

To identify an overhang processing continues at operation 800. With reference to FIG. 8, in an operation 800, the x pixel number is initialized to the minimum x pixel number. In an operation 802, the y pixel number is initialized to a maximum y pixel number. In an operation 804, whether or not the selected pixel is reflective is determined. If the selected pixel is reflective, processing continues at an operation 814. If the selected pixel is not reflective, processing continues at an operation 806. In operation 806, whether or not the x pixel number is greater than or equal to the maximum x pixel number is determined. If the x pixel number is greater than or equal to the maximum x pixel number, processing continues at operation 810. If the x pixel number is not greater than or equal to the maximum x pixel number, processing continues at operation 808. In operation 808, the x pixel number is incremented and a pixel of the pixel data is selected by using the x pixel number and the y pixel number as an index into the plurality of pixels. In operation 810, the x pixel number is initialized to the minimum x pixel number. In operation 812, the y pixel number is decremented, a pixel of the pixel data is selected by using the x pixel number and the y pixel number as an index into the plurality of pixels, and processing continues at operation 804.

In operation 814, a height associated with the y pixel number is determined. In an operation 816, the height is saved in a memory. In an operation 818, whether or not another storm cell is within the pixel data is determined. If another storm cell is within the pixel data, processing continues at C of FIG. 6. If another storm cell is not within the pixel data, processing of the received pixel data ends. As known to those skilled in the art, modifications of the operations just described can be performed without changing the overall methodology. For example, the maximum x pixel number can be traversed before the minimum x pixel number.

With reference to FIG. 10, exemplary operations in improving a storm top height determination are described. Additional, fewer, or different operations may be performed, depending on the embodiment without deviating from the spirit of the invention. In an operation 1000, a beam location for a directed scan of the storm cell is determined based on the maximum height determined in operation 236. The beam location is positioned above the location of the determined maximum height of the storm cell. In an operation 1002, the determined beam location is sent to the radar controller. The directed scan of the storm cell is conducted by transmitting a signal centered at the beam location and receiving returns from the beam location. The directed scan increases the resolution and/or the sensitivity of the scan data. For example, the resolution and/or the sensitivity is increased by increasing the dwell time, increasing the gain, etc. as known to those skilled in the art both now and in the future.

In an operation 1004, the directed scan data is received from the radar receiver. In an operation 1006, a determination of whether or not the directed scan data indicates reflectivity is performed. If the directed scan data indicates reflectivity, processing continues at an operation 1008. In an operation 1008, the maximum height (storm top) of the storm cell is set to the height of the beam location of the directed scan. If the directed scan data does not indicate reflectivity, processing continues at an operation 1010, and the previously determined maximum height is not changed. In operation 1010, whether or not another storm cell is within the pixel data is determined. If another storm cell is within the pixel data, processing continues at operation 1000. If another storm cell is not within the pixel data, processing of the received pixel data ends.

With reference to FIG. 11, exemplary operations in improving a storm top height determination are described. Additional, fewer, or different operations may be performed, depending on the embodiment without deviating from the spirit of the invention. In an operation 1100, characteristic data for storm cells is received. In an operation 1102, a second storm cell different from the current storm cell is identified from the received characteristic data. In an operation 1104, whether or not the current storm cell and the second storm cell are part of the same weather system is determined. For example, a determination is made to identify if the current storm cell and the second storm cell are contiguous. If the current storm cell and the second storm cell are part of the same weather system, processing continues at operation 1106. If the current storm cell and the second storm cell are not part of the same weather system, processing continues at an operation 1116.

In operation 1106, whether or not the current storm cell and the second storm cell are classified as the same type of storm cell is determined. Exemplary storm cell type classifications include air mass, Orographic, Mesoscale system, squall ILine, etc. If the current storm cell and the second storm cell are the same type, processing continues at operation 1108. If the current storm cell and the second storm cell are not the same type, processing continues at operation 1116. In operation 1108, one or more storm cell characteristics are compared to determine the similarity of the current storm cell and the second storm cell. Exemplary storm cell characteristics include area, vertical reflectivity profile, lightning flash rate, etc. In operation 1110, whether or not the current storm cell and the second storm cell are similar is determined. For example, two storm cell may be determined to be similar by evaluating the trending characteristics of each storm cell as a function of time. If the current storm cell and the second storm cell are similar, processing continues at an operation 1112. If the current storm cell and the second storm cell are not similar, processing continues at operation 1116. In operation 1112, the maximum height of the second storm cell is identified from the received characteristic data. In operation 1114, the maximum height of the current storm cell is adjusted based on the identified maximum height of the second storm cell. In operation 1116, whether or not another storm cell is within the pixel data is determined. If another storm cell is within the pixel data, processing continues at operation 1102. If another storm cell is not within the pixel data, processing of the received pixel data ends.

With reference to FIG. 12, exemplary operations in performing storm top prediction for a storm cell are described. Additional, fewer, or different operations may be performed, depending on the embodiment. In an operation 1200, the storm top height, for example as calculated in operation 236, of the storm cell is received from the memory. The storm height data includes the time stamp which indicates the time at which the third scan data was received. In an operation 1201, the storm cells associated with each storm top height calculation are correlated with storm cells identified in a previous scan sequence as described with reference to FIG. 2. By correlating storm cells from scan to scan, a cell can be tracked over time as known to those skilled in the art both now and in the future.

An operation 1202 determines if a previous height is available for the storm cell. For example, previous height data is not available if the storm cell does not correlate with any storm cell identified in the previous scan sequence. If previous storm top height data is not available, processing continues at an operation 1214. If previous storm top height data is available, processing continues at an operation 1204. In operation 1204, the current storm top height is compared to the previous storm top height. In an operation 1206, a growth rate for the storm cell is determined based on a height difference between the current height and the previous height and a time difference between the third scans that resulted in each height determination. If the current height is larger than the previous height, the storm is "growing." Conversely, if the previous height is larger than the current height, the storm is "decaying." Thus, the growth rate may be positive or negative.

In an operation 1208, an updraft speed is calculated based on the growth rate as known to those skilled in the art both now and in the future. The updraft speed is indicative of the severity and area of the outflow hazards associated with the storm cell, such as turbulence, hail, lightning, etc. In an operation 1210, ***atmospheric*** instability information is received. Exemplary ***atmospheric*** instability information includes an estimate of the liquid content of the storm cell or cells in the region, an estimate of the ***atmospheric*** potential energy, etc. In an operation 1212, a height of the storm cell at one or more future times is calculated based on the determined growth rate and/or the ***atmospheric*** instability information. The storm top height prediction may use a linear extrapolation or a non-linear extrapolation. The predicted storm top height may be limited by the tropopause height or adjusted based upon the storm cells relative location to the frontal boundary layer, where cells that are crossing the frontal boundary layer will have reached maximum height and begin to decay shortly.

The growth rate may be used to predict a future height of the storm cell in the aircraft's anticipated flight path. For example, using the current heading of the aircraft, the current speed, the flight plan, etc. from the flight management computer, a time may be determined at which the aircraft will intersect with the storm cell or be within a predetermined distance of the storm cell. The resulting prediction time and growth rate may be used to predict the height of the storm at that time. If the storm cell is along the aircraft's anticipated flight path, and the storm top may create a conflict with the aircraft at the future time, a conflict area may be displayed along the flight path of the horizontal or vertical cockpit weather display. An uncertainty, standard deviation, or error amount may be calculated for the storm top associated with the detected storm cell height and the predicted height of the storm cell. The uncertainty amount may be calculated using one or more of the following inputs in addition to the storm top height: distance of aircraft to storm cell, radar pulse width, time of last update, duration of cell track, length of prediction time, etc. The uncertainty, standard deviation, or error amount may also be displayed along the flight path of the horizontal or vertical cockpit weather display.

Processing continues at operation 1214 which determines if another storm cell is to be processed. If another storm cell is to be processed, processing continues at operation 1201. If processing of the storm cells is complete, processing continues at operation 1200 to perform predictions using additional height data.

The storm top height and growth information may be stored in a memory and/or displayed on an electronic flight information system display. For example, U.S. Pat. No. 6,577,947, the entire disclosure of which is incorporated herein by reference in its entirety and for all purposes as if fully set forth herein, describes such a display. Storm cells detected by the radar or other sources, but outside the storm top detection volume may be included on the display if received from other storm top detection sources using a data link. Other storm top detection sources may include other aircraft, ground based radars, satellites, etc. The storm top information may be transmitted to the aircraft and displayed to the pilot in conjunction with the storm cell information determined by the radar mounted on the aircraft to provide complete situational awareness. Other storm top sources can also be used to display storm cells within the storm top detection volume if the storm cells are obscured by other storm cells or other obscurations.

With reference to FIG. 13, exemplary operations in improving a storm top height prediction are described. Additional, fewer, or different operations may be performed, depending on the embodiment without deviating from the spirit of the invention. In an operation 1200, characteristic data for storm cells is received. Exemplary storm cell characteristics include volume, vertical reflectivity profile, lightning flash rate, height, vertically integrated liquid amount, area above an altitude, volume above an isotherm level, volume above an altitude, a total reflectivity value, an average reflectivity value, a horizontal growth rate, a vertical growth rate, turbulence, hail, growth rates associated with various storm cell characteristics, speed and direction of movement (motion vector), etc. An additional storm cell characteristic may include an uncertainty associated with a characteristic. An additional storm cell characteristic may include calculation of an area of the storm cell above one or more predetermined isotherm levels or altitude levels coincident with the storm cell. For example, the reflectivity of pixels above the -15.degree. Celsius isotherm level may be summed using a weighted distribution (i.e., higher reflectivity pixel corresponds with higher weight) or integrated to form a total or average reflectivity amount above the -15.degree. Celsius isotherm level. Additionally, the reflectivity of pixels above the 0.degree. Celsius isotherm level may be summed using a weighted distribution or integrated to form a total or average reflectivity amount above the 0.degree. Celsius isotherm level.

In an operation 1302, nearby storm cells different from the current storm are identified from the received characteristic data. In an operation 1304, whether or not the current storm cell and the nearby storm cells are part of the same weather system is determined. For example, a determination is made to identify if the current storm cell and the nearby storm cells are contiguous. If the current storm cell and the nearby storm cells are part of the same weather system, processing continues at operation 1306. If the current storm cell and the nearby storm cells are not part of the same weather system, processing continues at an operation 1316.

In operation 1306, whether or not the current storm cell and the nearby storm cells are classified as the same weather type is determined. Exemplary storm cell type classifications include air mass, Orographic, Mesoscale system, squall line, etc. If the current storm cell and the nearby storm cells are the same type, processing continues at operation 1308. If the current storm cell and the nearby storm cells are not the same type, processing continues at operation 1316. In operation 1308, a local maturity model is generated using a storm cell characteristic(s) of the current and nearby storm cells of the same weather system and the same type. The local maturity model considers the growth and decay of storm cells that have been observed and are part of the same weather system to identify a maturity level of the current storm cell.

With reference to FIG. 14, a local maturity model 1400 of a storm cell characteristic is provided in accordance with an exemplary embodiment. For example, the storm cell characteristic may be a growth rate that increases until the storm cell reaches maturity and decreases thereafter. The growth rate may be determined based on a change in any dimension of the storm cell size. For example, the growth rate may be based on a change in height, in range, in cross range, in area at a particular altitude or at a particular isotherm layer, in volume, in volume above/below a particular altitude or a particular isotherm layer, etc. Additionally, a growth rate may be inferred based on a change in lightning flash rate or a reflectivity of the storm cell. For example, the area of the storm cell may be determined above a predetermined isotherm ***atmospheric*** level and compared to the area above the predetermined isotherm ***atmospheric*** level calculated at the previous time. An increase in the area above the predetermined isotherm ***atmospheric*** level may indicate a positive storm cell growth rate and a decrease may indicate a negative storm cell growth rate.

In the exemplary embodiment of FIG. 14, local maturity model 1400 includes a first growth rate curve 1402, a second growth rate curve 1404, a third growth rate curve 1406, and a growth rate maturity curve 1408. The growth rate curves may be defined as a function of a relative time since the storm cell was detected to define a common time reference for the storm cells which may have lifecycles that occur over different time periods. First growth rate curve 1402 defines the growth rate as a function of the relative time for a first storm cell that has just begun to decay. Second growth rate curve 1404 defines the growth rate as a function of the relative time for a second storm cell. Third growth rate curve 1406 defines the growth rate as a function of the relative time for a third storm cell. The first, second, and third storm cells have been identified as from the same weather system and of the same type as the current storm cell. Growth rate maturity curve 1408 is calculated from the data associated with first growth rate curve 1402, second growth rate curve 1404, and third growth rate curve 1406 as an estimate of the growth rate of the storm cells from the same weather system and of the same type. In an exemplary embodiment, growth rate maturity curve 1408 may be an average or a curve fit to the data determined from tracking the first, second, and third storm cells. A maturity model may include a plurality of storm cell characteristics tracked for a plurality of cells over time.

In an operation 1310, a maturity level of the current storm cell is determined based on a comparison of the current storm cell characteristic(s) with the local maturity model of the storm cell characteristic(s). For example, a current vertical growth rate of the storm cell may be compared to growth rate maturity curve 1408 to estimate the maturity of the storm cell in comparison with the first, second, and third storm cells. In an operation 1312, a characteristic(s) of the storm cell may be adjusted based on the determined cell maturity level and growth rate maturity curve 1408.

In an operation 1314, a height of the storm cell at one or more future times is calculated using storm cell characteristics adjusted from the local maturity model. Using growth rate maturity curve 1408, a prediction of the height can be improved based on an estimated variation in the growth rate during the prediction time window. For example, the current storm cell is determined to be at a maturity level A as shown with reference to FIG. 14. At the end of the prediction time period, the current storm cell is estimated to reach a maturity level B. Growth rate maturity curve 1408 indicates that the growth rate will increase and then decrease during the prediction time period. Thus, growth rate maturity curve 1408 can be used to vary the growth rate during the prediction time period to improve the height predicted for the future time. Smaller time windows with different growth rates estimated from growth rate maturity curve 1408 may be used to predict to the future time in an exemplary embodiment.

In an exemplary embodiment, the predicted height of the storm cell may be limited to not exceed the maximum height of nearby storms that have already reached their maximum growth and are part of the same weather system. In an exemplary embodiment, the predicted height of the storm cell may be limited to the tropopause height. Because a growth rate of the storm cell may be determined based on various storm cell characteristics, multiple growth rates may be determined for the storm cell. For example, a growth rate determined based on a change in the reflectivity level may indicate the storm cell is decaying while a growth rate determined based on a change in the height may indicate the storm cell is growing. As a result, a combined growth rate may be determined, for example, by weighting the growth rate determinations from the various storm cell characteristic data. The choice of weights for the various growth rates may vary based on a geographic region. In some situations, a weight associated with a growth rate may be zero effectively ignoring that growth rate determination in the combined growth rate. A combined growth rate also may be determined by weighting growth rate determinations from the various storm cell characteristic maturity growth rate curves.

In operation 1316, whether or not another storm cell is to be processed is determined. If another storm cell is to be processed, processing continues at operation 1302. If another storm cell is not to be processed, processing continues at operation 1300 to perform prediction improvements using additional cell characteristic data.

With reference to FIG. 9, a weather radar system 900 is shown in an exemplary embodiment. Weather radar system 900 includes a radar system 902. Radar system 902 may include a radar antenna 904, a signal generator/receiver 906, a processor 908, and an antenna control system 907. Radar antenna 904 may include one or more antenna element. In an exemplary embodiment, an antenna element is a transducer that converts electromagnetic fields into alternating electric currents and vice-versa. For example, radar antenna 904 may be a single antenna element, separate transmit and receive antenna elements, a phased array antenna, a linear array of antenna elements, dual band antenna, etc. A variety of antenna designs may be utilized depending on the application for the radar system. For example, the antenna design may be selected based on the types of objects to be detected, the distance at which detection of the object is desired, the speed, if any, of the object, whether or not an image is formed of the object and/or tracking of the object is performed, etc. as known to those skilled in the art both now and in the future. With reference to the exemplary embodiment of FIG. 9, radar system 902 detects information associated with weather.

Signal generator/receiver 906 generates signals that may be appropriately timed and shaped output pulses, discrete frequencies, chirp pulses, etc., as required for the type of radar application. The output signal of signal generator/receiver 906 may be provided through a power amplifier to radar antenna 904 that converts the generated signal to electromagnetic fields. Radar antenna 904 radiates the electromagnetic fields in a direction defined relative to an antenna boresight. An antenna boresight refers to the physical broadside axis of a directional antenna. The radiated energy may be centered about the antenna boresight or may be directed relative to the antenna boresight as in electronic steering of a phased array antenna relative to the antenna boresight. An antenna coordinate reference system is typically defined such that the antenna boresight corresponds to the positive z axis. The antenna coordinate reference system may be defined with respect to a coordinate reference system of the aircraft to which radar system 902 is mounted.

Additionally, a directional coupler may be used depending on the type of antenna system used. In an exemplary embodiment, signal generator/receiver 906 provides detection of a signal and conversion of the detected signal to digitized data, for example by sampling of the received signal. The digitized data may be provided to a digital signal processor within the signal generator/receiver 906 or to processor 908 appropriately programmed to process the digital signal.

Processor 908 executes instructions. The instructions may be carried out by a special purpose computer, logic circuits, or hardware circuits. Thus, processor 908 may be implemented in hardware, firmware, software, or any combination of these methods. The term "execution" is the process of running an application or the carrying out of the operation called for by an instruction. The instructions may be written using one or more programming language, scripting language, assembly language, etc. It is understood that any type of processor that can be programmed to carry out the signal/data processing set forth herein may be utilized. The digital signal may be saved in a memory 912 coupled to the processor as known to those skilled in the art. Processor 908 can receive the digital signal representing the radar return directly or through memory 912. Weather radar system 900 may include a plurality of processors that use the same or a different processing technology.

Antenna control system 907 controls the positioning of radar antenna 904. Antenna control system 907 may be an electronic system or an electro-mechanical system that physically moves radar antenna 907 without limitation. Antenna control system 907 couples to processor 908. Processor 908 provides signals to antenna control system 907 to control the position of radar antenna 904. The position or orientation of radar antenna 904 can be adjusted, for example, with respect to elevation, azimuth, and roll angles that define the location of the antenna boresight. If radar antenna 904 includes a plurality of antenna elements, antenna control system 907 may control the position or orientation of each antenna element individually or as an ensemble.

Weather radar system 900 may further include a display 910. Display 910 presents information to the user of radar system 902 including, but not limited to, information related to radar system 902 such as images of the weather detected. Display 910 may be a thin film transistor (TFT) display, a light emitting diode (LED) display, a Liquid Crystal Display (LCD), a Cathode Ray Tube (CRT) display, etc. as known to those skilled in the art both now and in the future. Exemplary images displayed with display 910 include representations of weather regions, rainfall densities, turbulence regions, etc. Weather radar system 900 may include a plurality of displays that use the same or a different display technology.

Display 910 can be a multifunction flight display (MFD).

Weather radar system 900 may further include memory 912. Weather radar system 900 may have one or more memories 912 that use the same or a different type of memory technology. Memory 912 stores information for access by other elements of weather radar system 900. For example, memory 912 may store pixel data 914, storm cell characteristic data 916, in addition to other information associated with weather radar system 900. Exemplary weather characteristic data includes storm cell height data, storm cell maturity data, storm cell hazard data, ***atmospheric*** instability information, etc. Memory technologies include, but are not limited to, random access memory, read only memory, flash memory, etc. and include both volatile and non-volatile storage.

Weather radar system 900 further includes storm top detection application 918 and/or storm top prediction application 920. Storm top detection application 918 performs operations associated with determining a height of a storm cell. Some or all of the operations described with reference to FIGS. 2 and 5-8 may be embodied in storm top detection application 918. The operations may be implemented using hardware, firmware, software, or any combination of these methods.

With reference to the exemplary embodiment of FIG. 9, storm top detection application 918 is implemented in software stored in memory 912 and accessible by processor 908 for execution of the instructions that embody the operations of storm top detection application 918. Storm top detection application 918 may be written using one or more programming languages, assembly languages, scripting languages, etc. A storm cell height is determined by execution of the instructions of storm top detection application 918. The operations of storm top detection application 918 may be performed periodically, in pseudo real-time, and/or in real-time. For example, a storm cell height may be determined at the end of a vertical scan sequence, every two seconds, etc.

Storm top prediction application 920 performs operations associated with predicting a height of a storm cell at a future time. Some or all of the operations described with reference to FIGS. 12 and 13 may be embodied in storm top prediction application 920. The operations may be implemented using hardware, firmware, software, or any combination of these methods. With reference to the exemplary embodiment of FIG. 9, storm top prediction application 920 is implemented in software stored in memory 912 and accessible by processor 908 for execution of the instructions that embody the operations of storm top prediction application 920. Storm top prediction application 920 may be written using one or more programming languages, assembly languages, scripting languages, etc. A storm cell height is predicted to a future time by execution of the instructions of storm top prediction application 920. The operations of storm top prediction application 920 may be performed periodically, in pseudo real-time, and/or in real-time. For example, a predicted storm cell height may be determined at the end of each storm cell height determination, every two seconds, etc. Storm top detection application 918 and storm top prediction application 920 may be embodied in a single application that performs some or all of the operations described with reference to FIGS. 2 and 4-8.

The elements of weather radar system 900 may be integrated or separated according to particular needs. For example, the functions of processor 908 and memory 912 may be provided using a single component. If processor 908 and memory 912 are separated, processor 908 may be coupled to memory 912 using a bus or other suitable link. Memory 912 may be local to or remote from radar system 902. In one preferred embodiment, the platform and software of a WXR-2100 weather radar system manufactured by Rockwell Collins, Inc. or an RDR 4000 weather radar system manufactured by Honeywell International can be configured to include the above-listed components of weather radar system 900.

The foregoing description of exemplary embodiments of the invention have been presented for purposes of illustration and of description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed, and modifications and variations are possible in light of the above teachings or may be acquired from practice of the invention. The embodiments were chosen and described in order to explain the principles of the invention and as practical applications of the invention to enable one skilled in the art to utilize the invention in various embodiments and with various modifications as suited to the particular use contemplated. It is intended that the scope of the invention be defined by the claims appended hereto and their equivalents.

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