USING CLOUD-MOTION WINDS TO UNDERSTAND KINEMATIC PROCESSES OF DEEP CONVECTION: ANVIL-LEVEL OUTFLOW AND MOMENTUM TRANSPORT

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ABSTRACT

Cloud motion-derived winds from geostationary satellite data are used to understand the kinematic flow fields within and surrounding deep convection. In particular, tropical cyclones and smaller, organized convective systems and ensembles are analyzed to assess upper tropospheric anvil-level outflow characteristics and tropospheric momentum fluxes.

Two hypotheses are tested in this work: First, deep convection will exhaust its upper-tropospheric outflow mass in the direction of least inertial resistance for lateral flow away from the parent cumulonimbus cloud. Second, cloud-motion winds, derived from the motion of anvil cirrus, accurately describe the wind flow in the upper portions of mature cumulonimbus clouds (when the effects of storm motion are taken into account). Following from these assumptions, techniques are devised that help forecasters and modelers understand the behavior and influence of moist convection across the tropics.

The first part of our presentation will demonstrate several real-time diagnostics, based heavily on the processing of geostationary satellite data, that may be used to predict tropical cyclone intensity and intensity changes. These diagnostics help assess interactions of storm outflow with upper tropospheric ($\theta \geq 340$ K) potential vorticity fields, and the formation of synoptic-scale outflow corridors for tropical cyclones. The second portion of this presentation will outline a theory for estimating deep-tropospheric convective momentum fluxes by combining 10-meter wind data from the NASA/JPL SeaWinds Scatterometer aboard the Quick Scatterometer (QuikSCAT) satellite, intercloud winds derived from Tropical Rainfall Measuring Mission's Precipitation Radar (TRMM PR) data, and GOES-derived cloud-motion wind information.

Results of both applications are very promising, exemplifying new remote sensing methods for diagnosing and monitoring convection across the tropics.

1. Introduction

This paper describes methods for using geostationary (infrared and water vapor) satellite data and derived "cloud-motion" wind vectors (Velden et al. 1998) to diagnose the structure and monitor deep cumulus convection. Specifically, this paper first describes procedures of combining cloud-motion winds with large-scale fields such as potential vorticity (PV) to evaluate favorable environments for the intensification of thunderstorm convection and tropical cyclones across mainly the tropical latitudes. This research, done in collaboration with the Tropical Cyclone Research Team at the Cooperative Institute for Meteorological Satellite Studies (CIMSS), focuses on the development of real-time diagnostic products for large oceanic basins that benefit forecasters of tropical cyclones. The second portion of this paper outlines new methods for using cloud-motion winds, in combination with the Tropical Rainfall Measuring Mission Precipitation Radar (TRMM PR) and 10-meter wind data from the NASA/JPL SeaWinds Scatterometer aboard the Quick Scatterometer (QuikSCAT), to evaluate full-cloud momentum fluxes. This portion of the research, in contrast, has to date focused on mesoscale case studies, considering several well-documented convection events during the Third Convection and Atmospheric Moisture EXperiment (CAMEX-3) as part of the TRMM validation done in 1998.

2. Motivation

The motivations for this research are to maximize use of remote sensing data sets toward understanding, diagnosing and forecasting deep moist convection over land, and especially over oceanic regions, between about 45° N and 45° S. Within this main theme, we are guided in two unique directions based on the two areas of research discussed above.

Two hypotheses are tested: First, deep convection will exhaust its upper-tropospheric outflow mass in the direction of least inertial resistance for lateral flow away from the tops of cumulonimbus clouds. This hypothesis has led to the formation of regional diagnostics for convection intensity forecasting. The second hypothesis is that cloud-motion winds, derived from the motion of anvil cirrus, accurately describe the wind flow in the upper portions of mature cumulonimbus clouds (when the effects of storm motion are accounted for). This hypothesis drives us to develop new techniques for evaluating convective momentum fluxes that take advantage of cloud-motion winds.

3. Convection-Intensity Diagnostics incorporating Cloud-Motion Winds

Real-time diagnostics of convective outflow are derived by combining 6-hourly GOES infrared satellite imagery, GOES cloud-motion winds, upper tropospheric potential vorticity (PV), and diagnostic quantities that describe the lateral outflow potential away from the anvils of deep convection (Mecikalski and Tripoli 1998; Sui and Yanai 1986). The PV and lateral-outflow diagnostics are derived from 6-hourly AVN model analysis grids. Isentropic levels between 340 and 365 K are analyzed for the purpose of evaluating the correlation between cloud motion-derived winds, low inertial stability, and intensity changes of tropical convection and tropical cyclones.

Low upper-tropospheric inertial stability has been shown to be important for determining the intensity of convective systems (Molinari et al. 1997; Dickinson and Molinari 2000). Issues of the influence inertial stability has on the behavior of deep convection are examined theoretically by Emanuel (1979), demonstrating that convection should grow most readily into regions of lowest inertial (or symmetric) stability. In addition, the observational and numerical modeling work by Blanchard et al. (1998) positively correlates regions of weak inertial stability with mesoscale convective complex development over the central US.

In the upper troposphere, surrounding deep convection, low inertial stability would result in a tendency for air parcels, exiting the top of the convective clouds, to spread outward from the updraft (at the parcel’s equilibrium level) with relative ease. In contrast, should air parcels exiting deep convection encounter high inertial stability, the rate of horizontal mass transport away from storm top may be significantly limited. This would result in either forced, dry subsidence immediately surrounding the convection, or a weakening of the convection’s vertical mass transport, or both. Given two deep convective clouds in similar vertical shear and convective available potential energy (CAPE) environments, the one extending into the less inertially stable upper troposphere would perform less work on its environment and thus should persist longer and achieve greater intensity compared to the convection encountering high inertial stability aloft.

Although the work of Blanchard et al. (1998) demonstrated that deep convection preferentially forms in conditions of low upper tropospheric (above about 30.0 kPa) PV (inertial stability), one unanswered question is how self-serving is low PV to enhancing the convection that may generate it?

In other words, and in addition, given that low upper tropospheric PV is a known prerequisite to the development (or invigoration) of deep convection, how does the production and re-distribution of this low PV influence the long-term behavior of mesoscale convection? Can "outflow corridors" be established via the perpetual generation of low PV aloft, or must low upper tropospheric PV be present prior to the establishment of such an outflow pathway?

These questions may best be answered by combining the above data sets. In particular, cloud-motion winds can provide information about the inherently un-(geostrophically) balanced flows exiting the anvils of thunderstorms, tropospheric levels that are in fact well sampled by geostationary satellites. By combining the PV-related products, computed from routinely available global AVN model analyses, with the cloud-motion wind data, real-time diagnostics and short-range (0-6 h) forecasts are provided. Three to twelve-hour convection-intensity forecasts are possible using the PV-related products alone.

Diagnostic products are computed for three oceanic basins: the Eastern Pacific, the Western Atlantic and the Eastern Atlantic to the African coast. Several of these products are available in real-time via the internet (*http://its.ssec.wisc.edu/~johnm/trmm_istc.html*). These products are being developed in collaboration with the Tropical Cyclone Research Team (headed by C. Velden of CIMSS).

The following categories of products have been developed during 2001-2002:

- Combined enhanced-satellite (identifying the most active, growing thunderstorms and tropical cyclones), inertial available kinetic energy (IAKE; Mecikalski and Tripoli 1998) and cloud drift winds to diagnose the low-PV–convective outflow correlation. IAKE is the horizontal (along-line) integration of PV in units of energy (m^2s^{-2});
- Vector differences between measured cloud-motion winds and IAKE vectors across isentropic convective outflow layers, used to determined whether convection, in fact, seeks the path of least horizontal resistance for its outflow;
- Combined IAKE, PV and cloud drift winds to determine whether pre-existing low upper-tropospheric PV causes convective enhancements, and the role convectively-generated low upper-tropospheric PV plays in invigorating new or existing convection;
- Combined IAKE and cloud drift winds to analyze the acceleration (or deceleration) of flow from the tops of tropical storm systems. Products like this will be used to assess intensity changes and/or storm tendencies.

Figure 1 shows a product that combines enhanced GOES-10 imagery, and contoured/shaded IAKE to demonstrate more or less favorable conditions for anvil-level outflow away from convection. Regions supportive of "more favorable" anvil-level outflow are regions in which deep convection may increase intensity based on a more efficient vertical mass transport through deep cumulonimbus clouds, and/or less-near storm subsidence. Tropical storms in these regions would exhibit an increased potential for growth, assuming other environmental conditions remain supportive for their occurrence (e.g., low vertical wind shears). Also in Fig, 1, the active convection nearer the region with the lowest inertial stability on θ=345° K (centered on 10° N 132° W), within the intertropical convergence zone (ITCZ) centered on about 8-10° N, may be expected to persist longer and reach greater intensity compared to convection further east near 100° W within the ITCZ.

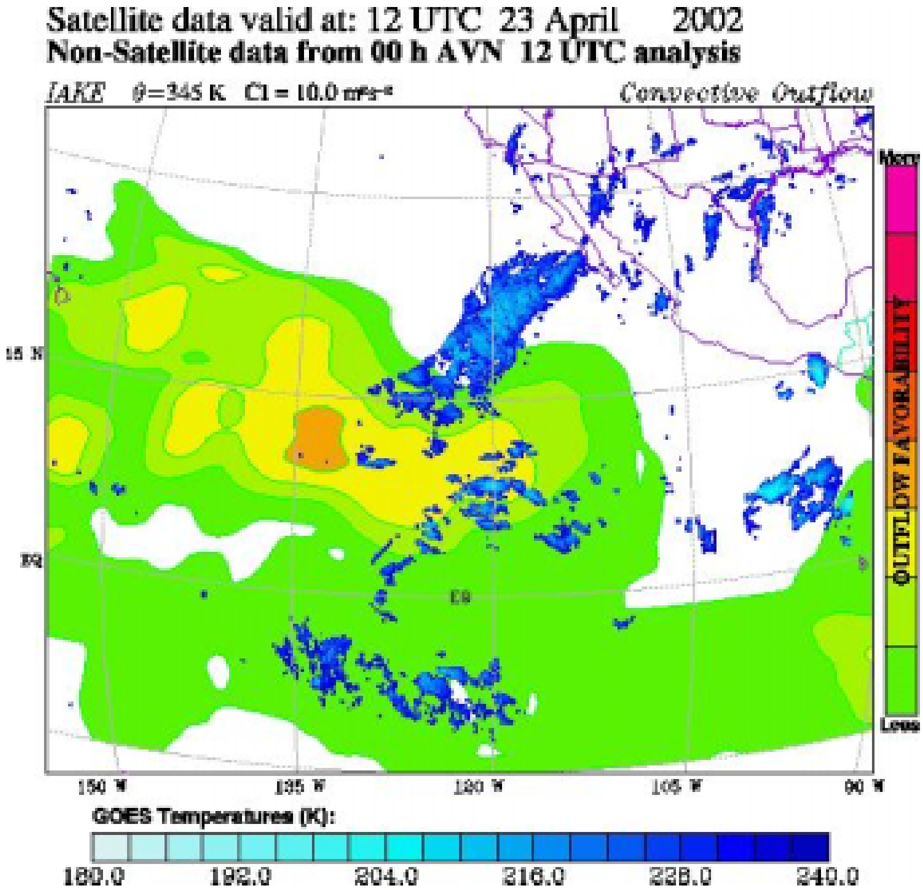

Figure 1. A composite of contoured IAKE>0 (no vectors, shading with scale to right), enhanced GOES-10 data (shading with accompanying scale on bottom denoting cloud temperatures, K), and infrared GOES-10 satellite-derived cloud motion vectors for 12 UTC 23 April 2002, with AVN model data (to derive the inertial stability, IAKE measurements) valid at the same time. The region with the highest IAKE is centered on 10° N 132° W.

Figure 2 presents an example of a product that may be used to assess the co-location of low-inertial stability (solid contours) and an upper tropospheric convective outflow, which is highlighted well by the satellite-derived winds. For the tropical cyclone centered near 20° N 125° W, and the newer tropical storm centered near 15° N 129° W, outflow "streams" appear in the cloud-motion winds extending southwestward, as well as northward from these two regions. The outflow is seen to occur within a region of low-inertial stability on this 345 K isentropic surface. The convective outflow likely forms and maintains the low inertial stability aloft. From diagnostics such as this a forecaster may gain confidence that the ambient environment for these two convective regions is and will remain generally supportive for their continued growth and development given the relative ease at which anvil-level outflow can occur.

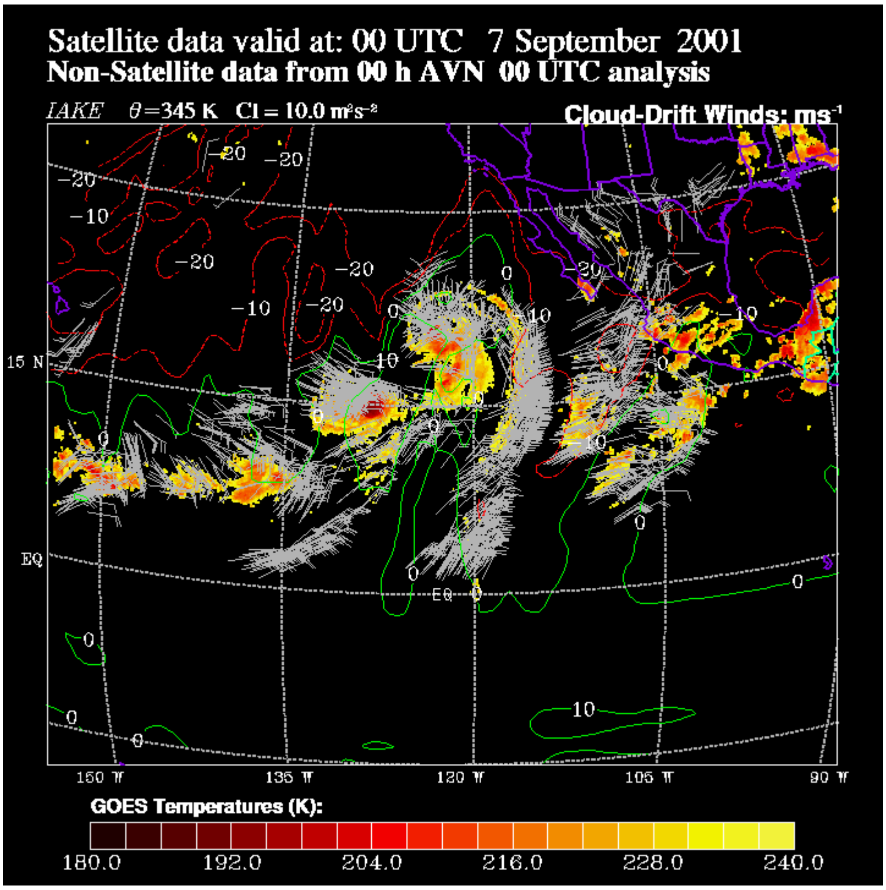

Figure 2. Derived product showing the relationship between the tropical storms off the Mexican coast, near 20° N 125° W and near 15° N 129° W, low upper-tropospheric inertial stability (IAKE; solid contours) and storm outflow aloft as highlighted by the cloud-motion winds (flags). The enhanced GOES-10 satellite image is valid at 00 UTC 7 September 2001, with AVN model data (to derive the inertial stability, IAKE measurements) valid at the same time. See text for description.

4. Using Cloud-Motion Winds to Diagnose Convective Momentum Fluxes

The goal of this portion of our study is to develop methods for estimating momentum fluxes of deep, precipitating convection using TRMM PR, GOES cloud-motion winds and QuikSCAT (0.5° x 0.5°) ocean-surface winds in combination. Until now, little to no work has considered such data sets for evaluating momentum fluxes, owing perhaps to the relative inadequacy or unavailability of them for accomplishing this task. The study by Mecikalski (2002) presents a method for estimating momentum fluxes using only vertically incident 915 MHz profiler radar data. The methods developed in that study apply immediately to the work outlined here, with TRMM PR used in place of the profiler radar in the Mecikalski (2002) work. We will overview the methods developed in Mecikalski (2002), as they are applicable. More attention will be given here as to how cloud-motion and QuikSCAT winds will be used to attain regional estimates of momentum flux, while paying attention to mesoscale processes of convective systems that these data measure.

From Mecikalski (2002), momentum flux terms (*u'w'*) and (*v'w'*), averaged over the domain of a radar-measured storm, were estimated for deep convection occurring during the TExas FLorida UNderflight-B (TELFUN-B) experiment conducted during CAMEX-3 in August and September 1998. These terms contain the most information on the momentum transported in the up- and downdrafts of cumulus convection. Key to the Mecikalski (2002) method is that the tilt and orientation of the convective drafts, relative to Earth's surface, are quantified from radar information into perturbation horizontal wind components once an accurate storm motion estimate is provided. For perturbation vertical velocities, the evaluation of drop size diameters from radar reflectivities, and the subsequent evaluation of terminal velocities of hydrometeors and draft motions are necessary information toward applying this technique. Doppler velocity measurements from the upward-looking Rd-69 Disdromet disdrometer (Joss-Waldvogel Disdrometer) calibrated 915 MHz profiler are used to demonstrate the procedures for estimating *w'*. The method has been proven by testing it against numerically simulated convection using the University of Wisconsin–Nonhydrostatic Modeling System (UW–NMS) mesoscale and cloud-resolving model. The radar-estimated momentum fluxes are found to match very well in sign and relative magnitude through the depth of the convective clouds studied to 11-km altitude (Mecikalski 2002).

Figure 3 demonstrates the radar-based momentum flux method as a schematic. Figure 4 presents results from Mecikalski (2002) as the radar-based method is compared to UW–NMS fluxes.

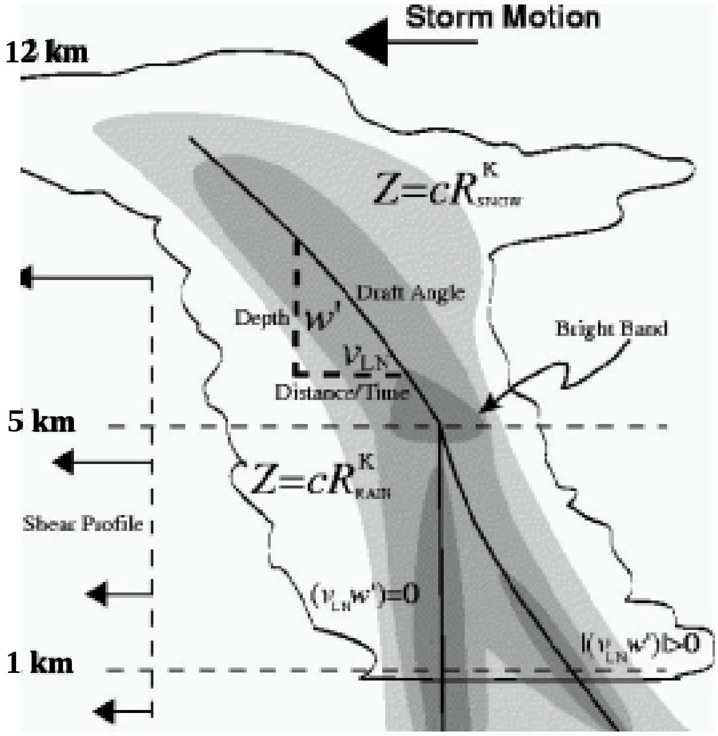

Figure 3. Schematic descriptions of the method outlined for estimating fluxes from profiler data. The significant features within deep, precipitating convection that are analyzed to determine momentum flux are illustrated. Shading denotes precipitation of varying intensities, darker shades denoting heavier precipitation. Updraft tilts, a representative shear profile, and the type of Z-R relationships used to evaluate drop sizes and terminal velocities are also depicted. In b) the mean air-flows through one type of organized convective system are presented to illustrate why our techniques work well for both up- and downdrafts, especially in the middle troposphere between ~2 and 9 km in this example.

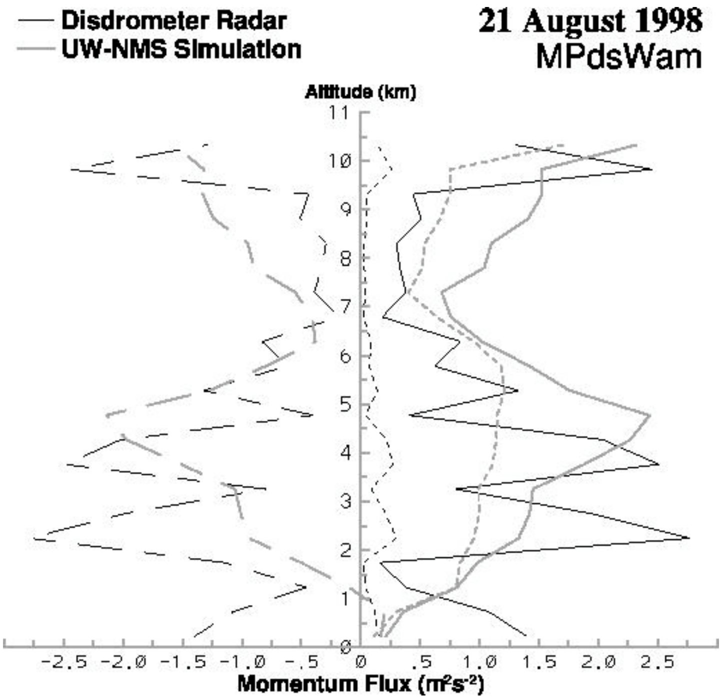

Figure 4. The method ("method 1") of Mecikalski (2002) results (black lines) for TEFLUN-B convection occurring on 21 August. In the figure, long-dashed lines are convection-averaged (*u'w'*), short-dashed lines are (*v'w'*), and solid lines are convection line-normal flux ($\boldsymbol{v}'_{LN}w'$), as compared against UW–NMS simulation results (grey lines; see key in upper-left for line labels). Fluxes presented are layer-averages, from the surface to 10.33 km, across the entire convective area as measured by the 915 MHz profiler. The identified "MpdsWam" represents the use of the Marshall–Palmer (Marshal and Palmer 1948) Z-R relationship to estimate drop sizes below the freezing level, the Gunn and Marshall (Gunn and Marshall 1958) Z-R relationship for estimating frozen hydrometeor sizes above the freezing level, and the Williams (2002) Sans Air Motion model for vertical air motion estimates.

The motivation for using 10 meter QuikSCAT and GOES cloud-motion wind data to evaluate momentum fluxes is that the Mecikalski (2002) method looses accuracy near the surface (below ~1.5 km) and near storm top (above about 10 km), for which these data a well-suited for measuring convective clouds. As we venture into the use of these new data, the following issues must be considered.

One main issue to be considered when processing TRMM PR data within the method developed in Mecikalski (2002), for quantifying convective up- and downdrafts into storm-relative winds, is how useful these three-dimensional data will be given the lower resolution of the TRMM data compared to the profiler. For TRMM PR vertical resolution is 250-meter and horizontal resolution is 4 km, which dictates that only meso-β (20-200 km) scale fluxes can be derived from these measurements.

For QuikSCAT data, these 0.5-degree data will help evaluate near-surface momentum fluxes caused by convection. Our methods will focus on small-scale wind perturbations within larger-scale wind patterns as provided by QuikSCAT. These wind perturbations will be used to assess meso-β scale, diabatically-driven outflows at Earth's surface. Since these data are relatively sparse, comparable in scale to TRMM PR data, they will also only measure the gross wind features associated with mesoscale convective systems. Since our flux retrieval methods will be most heavily focussed in regions near precipitating clouds, issues of rain contamination on the quality of QuikSCAT observations will have to be considered.

Finally, when using cloud-motion winds, useful information from these measurements of cloud-top features will only be provided if the cloud-motion winds are not smoothed by comparing them to a background field. Typically, cloud-motion winds are quality controlled against numerical model wind fields (e.g., from the AVN) to remove apparent spurious wind retrievals, namely those winds that are evaluated to be too disparate from a geostrophically-balanced atmosphere. Such spurious winds in fact contain the information our momentum flux methods require. Cloud-motions of anvil-level cirrus will be immediately used to construct storm-relative (perturbation) winds (i.e., u' and v'); upper-tropospheric divergence derived from these winds will be used to help estimate (perturbation) vertical motions. Similar assumptions as used in Mecikalski (2002) will be made as we determine perturbation velocities in the upper portions of convective clouds.

The accompanying talk will present many of the details regarding the evaluation of momentum fluxes by combining these three remotely sensed data sets, with more examples and details provided.

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