Composite Analysis of Winter Cyclones in a General Circulation Model: Influence on Climatological Humidity

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Introduction

Baroclinic cyclones strongly influence the extra-tropical distribution of cloud, precipitation and water vapor. They do so via a combination of synoptic scale motions that should be resolved by climate general circulation models and mesoscale motions along fronts that are definitely not resolved by these models. The recent Atmospheric Radiation Measurement (ARM) intercomparison of climate general circulation models (Zhang et al. 2005) found that all models have a tendency to overestimate high-top, optically thick clouds and underestimate thin clouds in midlatitude winter. This suggests the possibility that unresolved features of the baroclinic cyclone circulation may adversely impact general circulation models cloud distributions in this region. As a first step in diagnosing the problem, we have developed a storm identification and tracking procedure and used it to compile storm occurrence and motion statistics, and composite dynamic and thermodynamic structure fields, for 10 years of Goddard Institute for Space Studies (GISS) general circulation models simulations and reanalysis products. We focus on the implications for the water vapor transport that is responsible for cloud formation in these storms. A more complete description can be found in Bauer and Del Genio (2005).

Data and Methods

We compile results for 6-hourly samples of 10 winters (December-January-February) of the GISS Model E GCM (Schmidt et al. 2005) run at 4° x 5° x 20L resolution. We also examine storm frequency characteristics for a 4-year run of an earlier version of the GCM at 2° x 2.5 x 32L. Storm properties are similarly aggregated for 10 winters of the European Centre for Medium-Range Weather Forecasts (Simmons and Gibson 2000) and National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) (Kistler et al. 2001) reanalyses, hereafter designated as ERA and NRA, respectively. Storms are defined between 30°-60°N latitude, and the discussion is restricted to maritime storms, although we expect the behavior to be qualitatively similar to midlatitude continental regions such as the Southern Great Plains.

The storm identification and tracking algorithm is similar to that of Chandler and Jonas (1999) and is defined as follows: Candidate storms are identified as local (within a 3 x 3 gridbox area) and regional (within a radius that captures features moving slower than 120 km hr-1) sea level pressure (SLP) minima. Candidates are successively paired with others from preceding timesteps and joined into a track representing the sequential path of a potential cyclone. The candidates are then screened to include only those that meet the following criteria: (1) Lifetime > 24 hr; (2) Lifetime minimum SLP < 1010 hPa; (3) Latitude-longitude propagation of > 700 km in each direction. In addition, cyclones that make a course change > 90° lasting 24 hr are identified as separate storms to capture secondary development events.

The resulting database of storms is sorted by a multivariate intensity index that combines measures of minimum lifetime SLP, deepening rate, and pressure gradient (Zielinski 2002) into weak, intermediate, and strong categories, with the first and last defined as the upper and lower quartiles of the intensity distribution. To facilitate general circulation models -reanalysis comparison, the ERA distribution intensities are used to define these boundaries. Composite fields for each intensity class are then produced by averaging the fields for each cyclone on a common grid centered on the location of the storm's lifetime SLP minimum.

Cyclone Statistics

Figure 1 shows the frequency distribution of cyclone intensities for both versions of the GCM and both reanalyses. Model E GCM cyclones are less frequent (~600 vs. ~900 per decade) and less intense (by ~20%) than are those found in the two reanalyses, whose distributions closely resemble each other. The general circulation models -reanalysis differences are most obvious for strong storms. One possible interpretation is that Model E's coarse 4° x 5° resolution inhibits cyclogenesis. However, the 2° x 2.5° earlier version of the general circulation models produces a similar number of storms (albeit a greater percentage of strong storms). This result is consistent with an analysis of 13 general circulation models by Lambert et al. (2002), who found that the finest resolution model was no better at matching the observed cyclone distribution than was the coarsest resolution model. Figure 2 shows the spatial distribution of cyclone occurrence in the general circulation models and the difference with respect to ERA. The GCM produces storm tracks in approximately the same locations as ERA, but it underpredicts the frequency along the east coasts of both continents and especially in the subpolar lows. The general circulation model also produces virtually no storms in the southeastern United States, an important region for North American cyclogenesis. We repeated the analysis with the search radius used to isolate individual cyclones doubled; this prevents cyclones from existing within 1500 km of each other. The reanalysis is much more sensitive to this change (Figure 2), losing ~1/3 of its cyclones, while the general circulation models lose almost none, i.e., the GCM lacks secondary cyclones, not surprising given the fact that secondary development is along fronts that are not resolved by climate general circulation models.

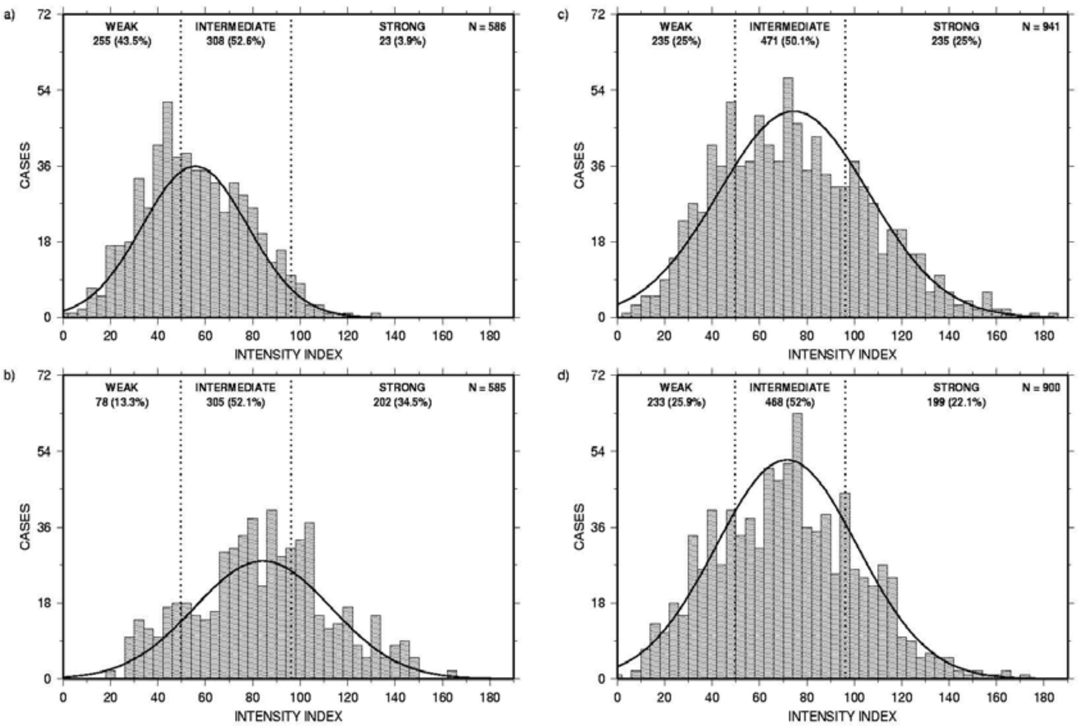

Figure 1. Frequency histograms of winter cyclone occurrence for 10 years as a function of intensity index in the GISS general circulation models at (a) 4° x 5° x 23L resolution and at (b) 2° x 2.5° x 32L resolution, and in the (c) ERA and (d) NRA reanalyses. The statistics for the higher resolution general circulation models come from only 4 winters and have been projected to 10 winters to facilitate comparison with the other histograms.

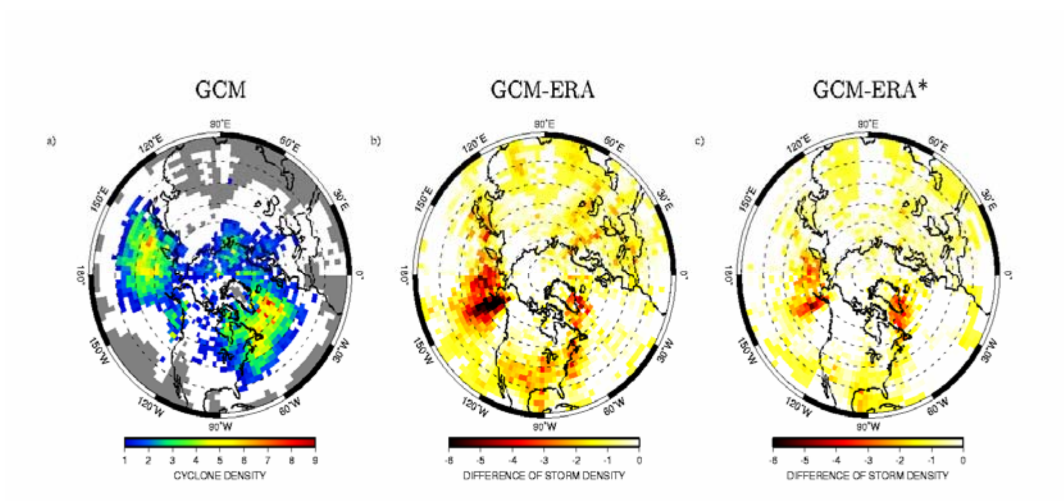

Figure 2. Climatological winter cyclone intensity (number per month) projected onto a 4° x 5° grid from statistics collected on an equal area grid. (a) GISS general circulation models. (b) general circulation models -ERA difference. (c) general circulation models -ERA difference with storms resulting from secondary cyclogenesis included.

Cyclone Composite Structure

Figure 3 shows the composite SLP and lower/middle/upper troposphere geopotential height fields for intermediate category cyclones at their time of peak intensity in the GCM and ERA. The SLP pattern in the general circulation models generally resembles that of ERA but is more symmetric around the surface low, understating the east and southwest extensions that mark the climatological positions of the warm and cold fronts. In the free troposphere, the general circulation model produces shallower depressions above the surface low and a less intense wraparound structure to the north and west. General circulation models storms also travel ~20% slower than their ERA counterparts, especially during the period of peak development just before peak intensity, and thus develop and dissipate over a shorter distance.

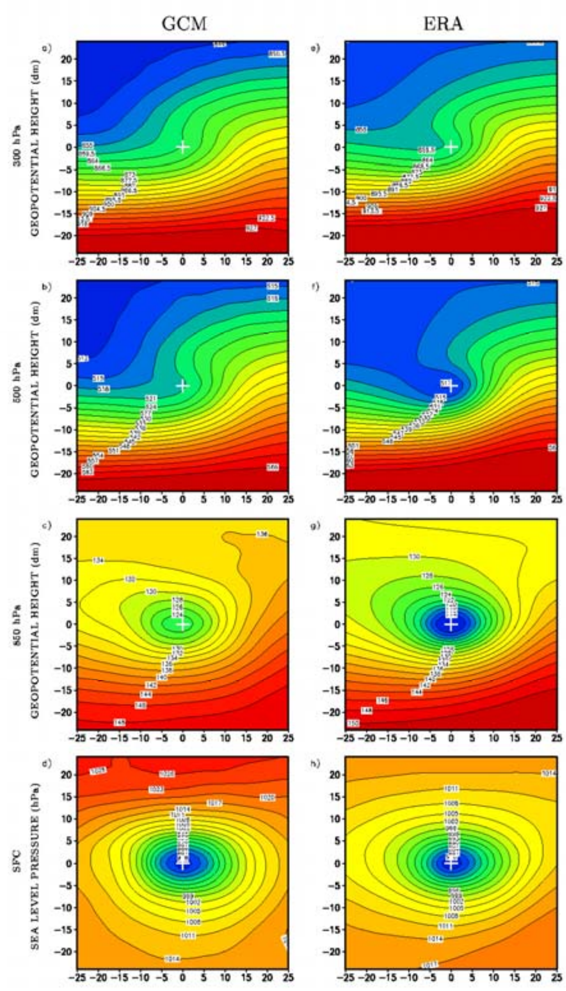

Figure 3. Composite fields for winter intermediate strength cyclones at peak intensity. Geopotential height (dm) at (a,e) 300 hPa, (b,f) 500 hPa, and (c,g) 850 hPa, and (d,h) SLP (hPa), in the general circulation models (left panels) an ERA (right panels). The fields are plotted in a latitude-longitude coordinate system centered on the position of the central SLP minimum of each cyclone (indicated by the +).

Consistent with the weak height anomalies, the general circulation models composite cyclone horizontal wind field is weaker than ERA's (Figure 4). Cyclone winds are more zonal in the general circulation models than in ERA, implying that meridional water vapor transports by the warm conveyor belt are less effective than in actual storms. This is tied to an apparently weak ageostrophic circulation in general circulation models storms. Figure 4 also shows that the GCM vertical velocity field is almost three times weaker than ERA's in ascending regions of the lower troposphere, lacks the mid-tropospheric maximum that ERA storms do, and is barely evident at 300 hPa, i.e., general circulation models storms are shallower than ERA storms. ERA ascending regions also extend east of the surface low at low levels and tilt further eastward from the low in the upper troposphere, while the GCM's ageostrophic circulation is almost upright, with peak ascending motion over the surface low at all levels. The long tongue of upward motion that extends south and west of the low in ERA, marking the cold front, is present only in abbreviated form in the general circulation models. General circulation models descending motion is spread over a broad region mostly west of the low rather than being concentrated southwest of the low, behind the surface cold front, as is seen in the ERA composite. Favorable conditions for rising motions are produced by warm low-level advection coupled with differential advection of positive (cyclonic) vorticity. Both of these are weaker in the general circulation models than in ERA, resulting in weaker SLP tendencies east and north of the surface low in the hours before peak storm intensity.

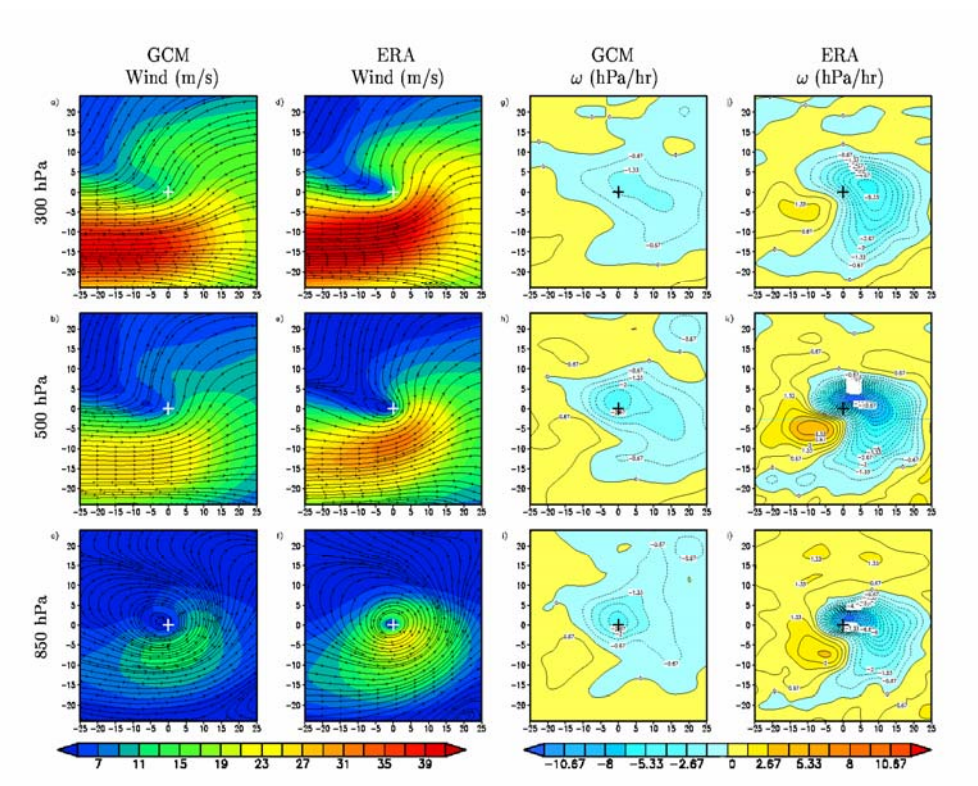

Figure 4. Intermediate cyclone composite horizontal wind (m s-1) fields for (a,b,c) the general circulation models and (d,e,f) ERA and pressure vertical velocity (hPa hr-1) fields for (g,h,i) the general circulation models and (j,k,l) ERA at (upper) 300 hPa, (middle) 500 hPa, and (lower) 850 hPa. The colors show speeds and the curves indicate streamlines in (a-f).

The composite temperature field of the general circulation models (Figure 5) reflects these dynamical deficiencies and shows an overall 2-3 K cold bias relative to ERA at all levels and a weaker meridional temperature gradient at upper levels. The combined result of the dynamics and temperature deficiencies is an anemic composite pattern of cyclone humidity advection (Figure 5). Positive (negative) humidity tendencies due primarily to upward (downward) motion east and north (south and west) of the low are 2-3 times stronger in ERA than in the general circulation models in the lower and middle troposphere. In the upper troposphere general circulation models cyclones are barely a source of humidity at all, whereas ERA cyclones moisten upper levels over a broad region due to both horizontal and vertical transports along the warm conveyor belt. The resulting cyclone composite humidity fields in the general circulation models (Figure 6) have an overall ~5% low bias relative to ERA, with less frontal organization, i.e., humidity extremes in general circulation models storms are not as moist or dry as those in ERA. Combined with the effect of the general circulation models cold bias, the general circulation models composite specific humidity field shows water vapor deficiencies of as much as a factor of 2 in the middle and upper troposphere east of the surface low. Thus, not only do general circulation models cyclones occur too infrequently, but in addition they do not move enough moisture upward and poleward when they do occur.

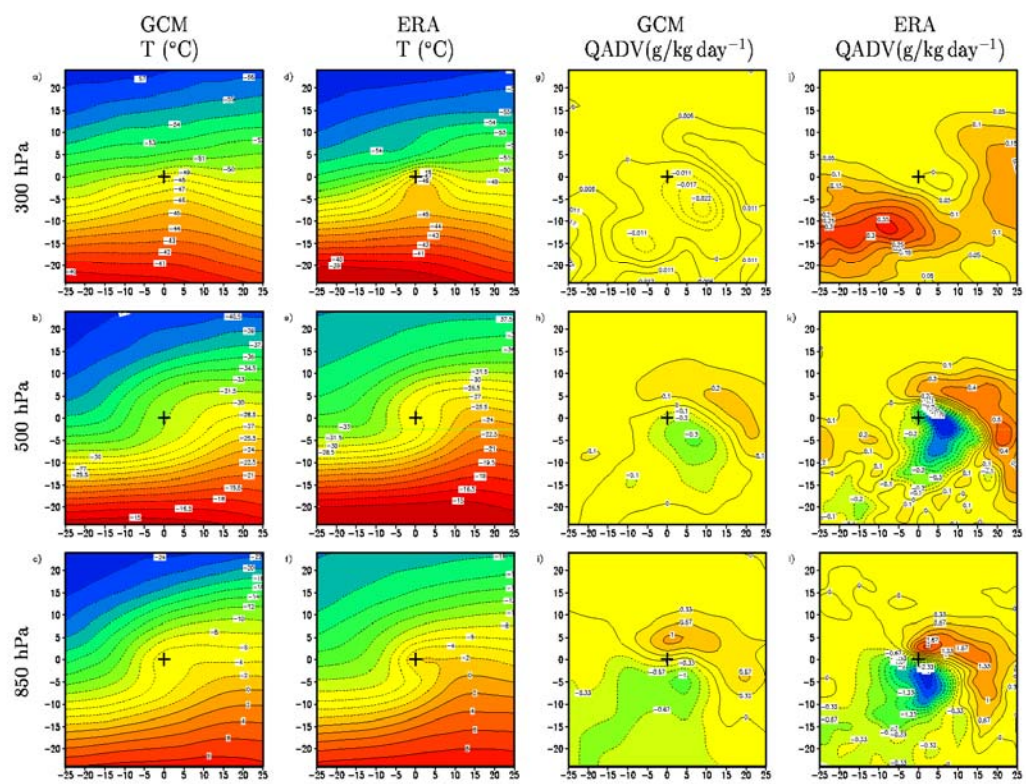

Figure 5. As in Figure 4 but for temperature (°C) and for specific humidity advection (g kg-1 d-1).

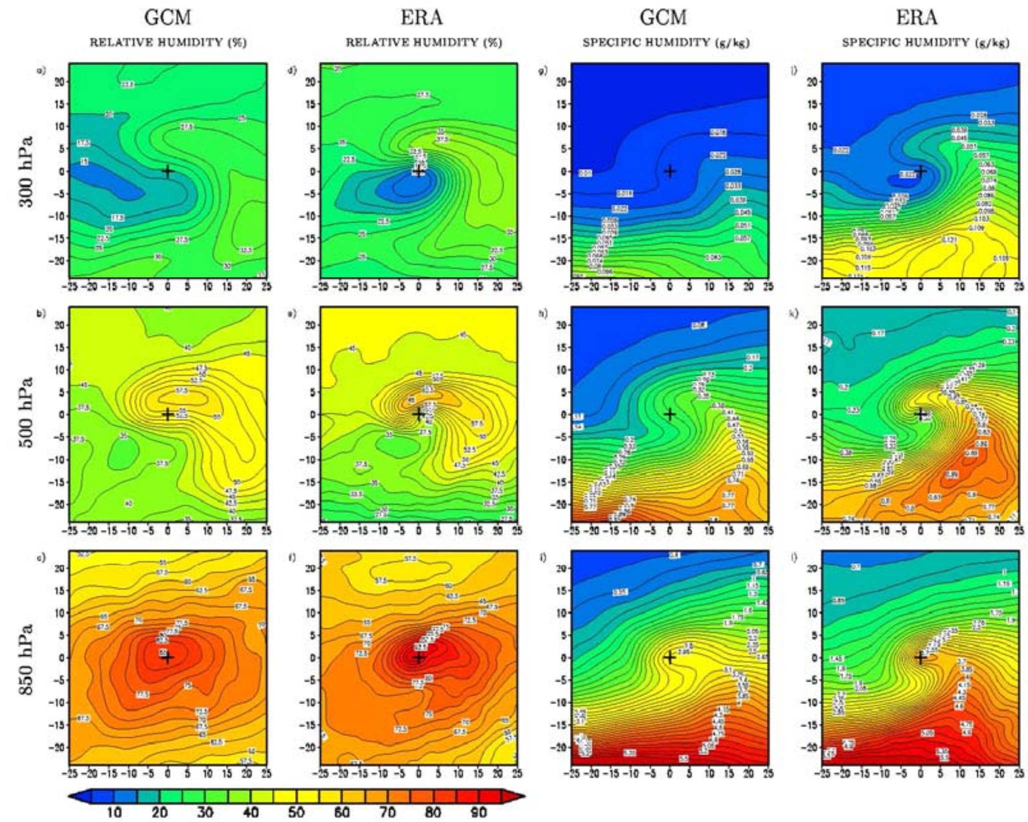

Figure 6. As in Figure 4 but for relative humidity (%) and for specific humidity (g kg-1).

Hypotheses for General Circulation Models Cyclone Deficiencies

The coarse resolution of climate general circulation models is a likely source of these errors, since they do not resolve the sharp frontal temperature gradients that are central to cyclone development. However, latent heat release in frontal zones is a non-negligible, if secondary, contributor to eddy available potential energy generation, and precipitation is a major moisture sink. Thus, it is possible that the general circulation model's problems are associated with cloud and precipitation parameterization deficiencies. We test this hypothesis in two ways. First, we compare the general circulation models cyclone composite precipitation fields to those produced by the reanalyses and derived from a 3-year global precipitation dataset (Huffman et al. 2003). Figure 7 shows that ERA and NRA have similar precipitation strengths and patterns to each other, and that the precipitation dataset composite has similar maximum precipitation rates but heavier rain east of the surface low than either reanalysis. General circulation models composite precipitation rates, by comparison, are weaker, more so as storm strength increases. Thus, the general circulation model is not too dry because its convection and stratiform cloud microphysics parameterizations overestimate rainfall.

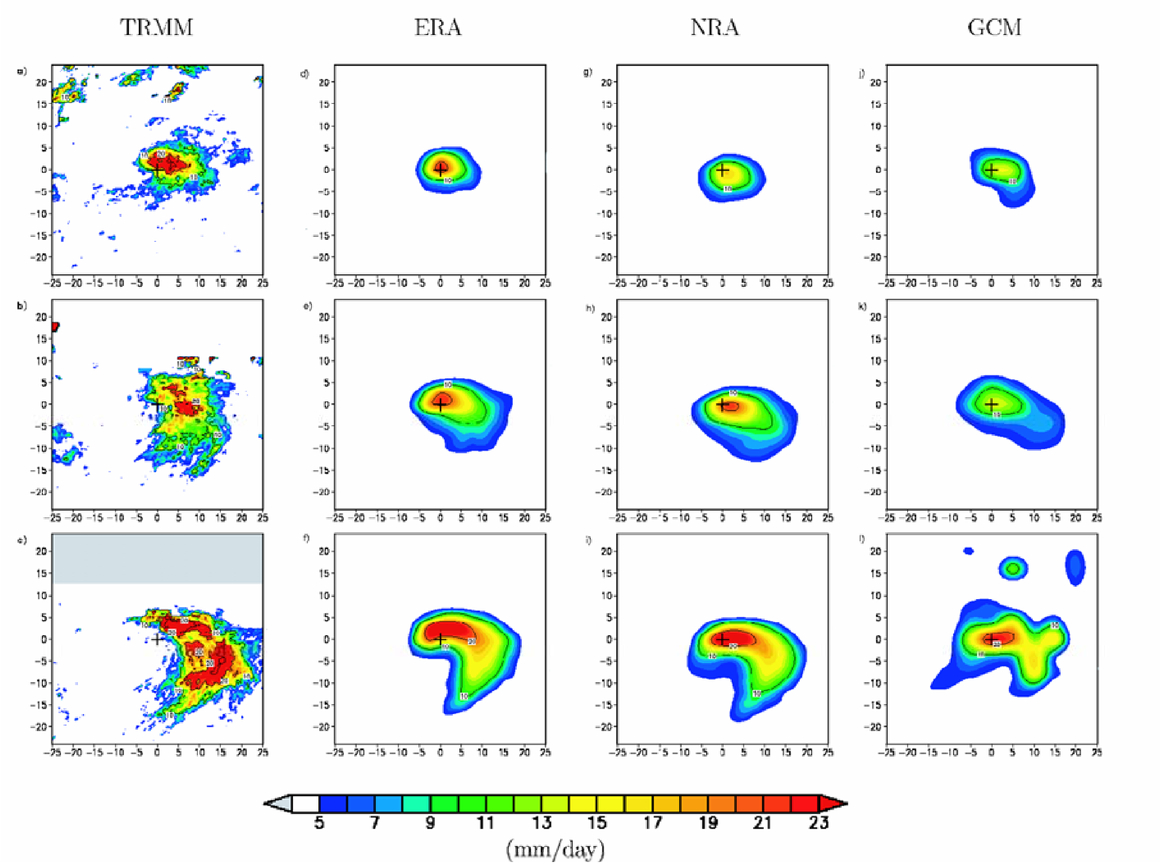

Figure 7. Composite cyclone precipitation (mm d-1) fields for weak (upper panels), intermediate (middle panels), and strong (lower panels) storms for (a,b,c) the satellite retrieval, (d,e,f) ERA, (g,h,i) NRA, and (j,k,l) the general circulation models.

On the other hand, if the general circulation models parameterizations underestimate rainfall early in the storm life cycle, this might suppress further development. If so, general circulation models storm structure should be more realistic in the early stages of growth, when diabatic heating is not yet important and baroclinicity is the only energy source. Figure 8 compares a variety of general circulation models and ERA 300 hPa composite fields for intermediate storms at the moment when the storm first formed closed surface isobars. Note that general circulation models storms lack a prominent short-wave to the northwest of the surface low compared to ERA. The general circulation models also forms its upper level low in place above the surface low, while the ERA upper level cyclone moves progressively closer to the surface cyclone center as the storm develops. This implies that their cyclogenesis and development are Type-A, dominated by low-level warm advection, rather than the Type-B characteristic of ERA, which couples this with upper level support due mostly to differential vorticity advection (Petterssen and Smebye 1971). Jet streaks are also more obvious in ERA than in the GCM, and their cyclonic curvature and diffluence more strongly favor ascending motion near the left-exit region (Keyser and Shapiro 1986). All of these factors are consistent with the general circulation model's weaker upper level vertical velocity field and suggest that the dynamic conditions required for cyclone development are more favorable from the outset in ERA than in the general circulation models, regardless of any cloud parameterization issues.

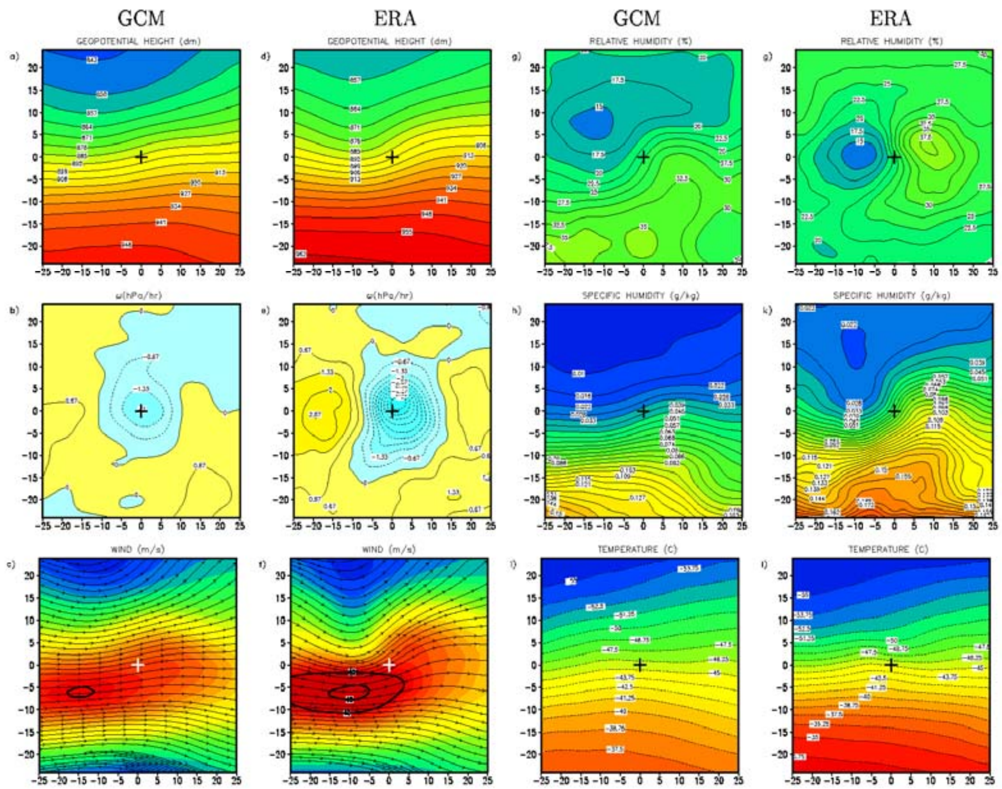

Figure 8. Intermediate cyclone composite fields at 300 hPa acquired at the time each cyclone was first detected by the storm tracking algorithm. (a,b,c) Geopotential height (dm), pressure vertical velocity (hPa hr-1), and horizontal wind (m s^{-1}) in the general circulation models. (d,e,f) As in the first column but for ERA. (g,h,i) Relative humidity (%), specific humidity (g kg-1), and temperature (°C) for the general circulation models. (j,k,l) As in the third column but for ERA.

Discussion

We conclude that the ageostrophic circulation in the GISS GCM, and most likely other climate general circulation models, is underestimated. This has consequences for the water vapor and cloud fields associated with general circulation models cyclones (cf. Tselioudis and Jakob 2002). Our analysis shows that general circulation models cyclones lack the classical tilted frontal structure that is present in the ERA composites. Frontal tilt is the distinguishing feature of semi-geostrophic frontogenesis, the tilt being produced by advection of thermal fields by the ageostrophic circulation. In the general circulation models the ageostrophic flow is so weak that frontogenesis is more quasi-geostrophic, i.e., advection is only by the geostrophic flow and can sharpen fronts but cannot change their orientation.

As a consequence, the general circulation models produces an excess of high-top, optically thick clouds over a small area in midlatitude storms and a deficit of optically thinner and midlevel clouds (Tselioudis and Jakob 2002). The fact that all general circulation models have the same cloud type biases despite their very different cloud parameterizations (Zhang et al. 2005) suggests that the so-called resolved dynamics of climate general circulation models is not actually adequately resolved for climate applications. To some extent these differences might be addressed indirectly via parameterization, e.g., by assuming minimum cloud overlap in diagnosed frontal regions. It might even be possible to diagnose the unresolved sharpening of grid-scale fronts in developing cyclones and parameterize the resulting subgrid ageostrophic motion response, including horizontal transport between gridboxes that generates frontal tilt. Ultimately, though, higher resolution than that characteristic of most current climate general circulation models will be needed to solve the problem. Whether a general circulation model's extra-tropical cyclone biases degrade its climate forecasts is an open question, but we suggest that inferences about climate changes in midlatitude cyclone frequency and strength, as well as regional climate impacts such as drought/flood occurrence and severity, be viewed with caution until these storms can be simulated with greater fidelity.

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Acknowledgements

This research was supported by the DOE Atmospheric Radiation Measurement Program, and the NASA Precipitation Measurement Missions and Radiation Sciences Programs.

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