Climate Change, Atmospheric Rivers, and Future California Floods

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BIOGRAPHICAL SKETCH

Dr. Michael Dettinger is a research hydrologist for the U.S. Geological Survey, Branch of Western Regional Research, and a research associate of the Climate, Atmospheric Sciences and Physical Oceanography Division at Scripps Institution of Oceanography. He has degrees from the University of California, San Diego (Physics), Massachusetts Institute of Technology (Civil Engineering), and a Ph.D. from the University of California, Los Angeles (Atmospheric Sciences). Dettinger has monitored, evaluated, and researched the water resources of the West for over 25 years, focusing on regional surface water and groundwater resources, watershed modeling, causes of hydroclimatic variability, and climatic-change influences on western water resources. Among other activities, he was Nevada State Ground-Water Specialist for the USGS in the 1980s, received a Vice President's National Performance Review Award for physical-sciences leadership in Mojave Desert Ecosystems science and data management planning efforts in 1996, was an Associate Editor of the journal Water Resources Research from 1998 to 2000, was the program chair and fundraiser for the annual Pacific Climate (PACLIM) Workshops, 1998-2004, is a founding member of the multi-institution CIRMONT Western Mountain Climate Sciences Consortium, and served on the CALFED Water Management Science Board.

ABSTRACT

Historically, the most dangerous storms in California have been warm wet storms that strike in winter, producing intense rains over large areas and unleashing many of the State's largest floods. The most commonly recognized of these storms have been described as "pineapple express" storms because of the way that they appear (in weather satellite imagery) to draw warm, moist air from the tropics near Hawaii northeastward into California. Recent studies, though, have shown that pineapple express storms are just one version of a common feature of midlatitude weather, called "atmospheric rivers" (ARs). We now know that, globally, about 90% of all the water vapor transported towards the poles across the midlatitudes is transported within the narrow, intense filamentary bands of moist air that form these ARs. Because AR storms are increasingly understood to have been the source of most of the largest floods in California, an evaluation of the future of floods under climate change must attempt to project the future frequencies and intensities of ARs.

Using a locally-based strategy for detecting AR-type storms along the California coast, developed at the NOAA Earth System Research Lab, climate simulations from seven global-climate models (GCMs) were analyzed to compare frequencies and magnitudes of AR storms arriving in California under simulated historical and climate-changed conditions. First, numbers of AR episodes in the climate models and in the observational record were compared to find that, although on average most of the models generate more ARs than observed, the general distribution of AR days per winter were not so different as to preclude evaluations of the projected changes. Next, in comparing historical to future climate simulations, changes in AR storms in the models were found to occur mostly at the extremes: Years with many AR storms become more frequent in most of the climate-change projections, but the average number of such storms per year are not projected to change much. Similarly, although the average intensity of the storms is not projected to increase much in most models, occasional much-stronger-than-historical-range storm intensities are projected to occur under the warming scenarios. The simulated AR storms also warm along with the winter-mean temperatures in the seven models. Together these findings suggest that California flood risks from the warm-wet, atmospheric-river storms may increase beyond those that we have known historically, mostly in the form of occasional more-extreme-than-historical storm seasons.

CLIMATE CHANGE, ATMOSPHERIC RIVERS, AND FUTURE CALIFORNIA FLOODS

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Introduction

Major floods are a recurring theme in California's climatology and hydrology, and have a long history of being an important cause of death and destruction in California (Kelley, 1998). Even today, California's aging water supply and flood protection infrastructure, including more than a thousand kilometers of levees, is being challenged by punishing floods and increased standards for urban flood protection. Many Californians face unacceptable risks from flooding, both from where they live and work and from where they derive water supplies. In response to the risks and conflicts posed by flooding, the California Department of Water Resources Water Plan Updates in both 2005 and 2009 strongly recommend that water supply management, land use development, and flood management in the State be much more fully integrated (DWR 2005, 2009). The Delta Vision Task Force has identified improvements in floodplain and flood emergency management among its key recommendations for the future of California's Delta (Delta Vision Task Force, 2008). Perhaps most convincingly, the people of California passed Propositions 1E and 84 in 2006 to fund bonds intended to provide over $4.5 billion dollars specifically for flood management programs in the State.

Although uncertainties abound, a significant part of this focus has been motivated by the risks that flood may occur more frequently or become more extreme with climate changes due to increasing greenhouse-gas concentrations in the global atmosphere. Current climate change projections for 21st Century California uniformly include warming by at least a couple of degrees, and, although great uncertainties remain about future changes in long-term average precipitation rates in California (e.g., Dettinger 2005; Cayan et al. 2008), it is generally expected that extreme precipitation episodes may become more extreme as the climate changes (Trenberth, 1999; Cayan et al., 2009). As a step towards better understanding of the risks, this paper summarizes a preliminary analysis of the 21st Century future of a particularly dangerous subset of flood-generating storms—the pineapple-express or atmospheric-river storms—from seven current climate models.

Projections of Future Atmospheric-River Storms

Although warming may be expected to alter flood regimes in many snowfed settings (e.g., Dettinger et al., 2009), changes in California's storm types, frequencies, or magnitudes may provide more direct and pervasive opportunities for change. Probably the most dangerous storms in California have been warm and wet storms that historically strike in winter, producing intense rains over large areas and unleashing many of the State's largest floods. The most commonly recognized of these storms have been described as "pineapple express" storms because of the clear way that they appear (in weather satellite and other imagery, e.g., Fig. 1) to draw warm, moist air from the tropics near Hawaii northeastward into California (Weaver 1962, Dettinger 2004). More recently, studies have shown that “pineapple express” storms in California are just one version of a more common feature of the midlatitude atmosphere. It has been determined that about 90% of all the water vapor transported towards the poles across the midlatitudes is transported within narrow, intense filamentary bands of moist air, called atmospheric rivers (ARs, Zhu and Newell 1998), that together typically span less than about 10% of the Earth’s circumference at any given latitude. Ralph et al (2006) recently noted that all “declared” floods on the Russian River near Guerneville during the past 10 years have been associated with the arrival of an AR. Dettinger (2004) showed that, during the past 50+ years, flows in the Merced River near Yosemite Valley have typically risen by about an order of magnitude more following the pineapple express form of ARs than following other winter storms. From these and other examples, AR storms are now increasingly understood to be the source of most of the largest floods in California, and an evaluation of the future of floods must attempt to understand their future.

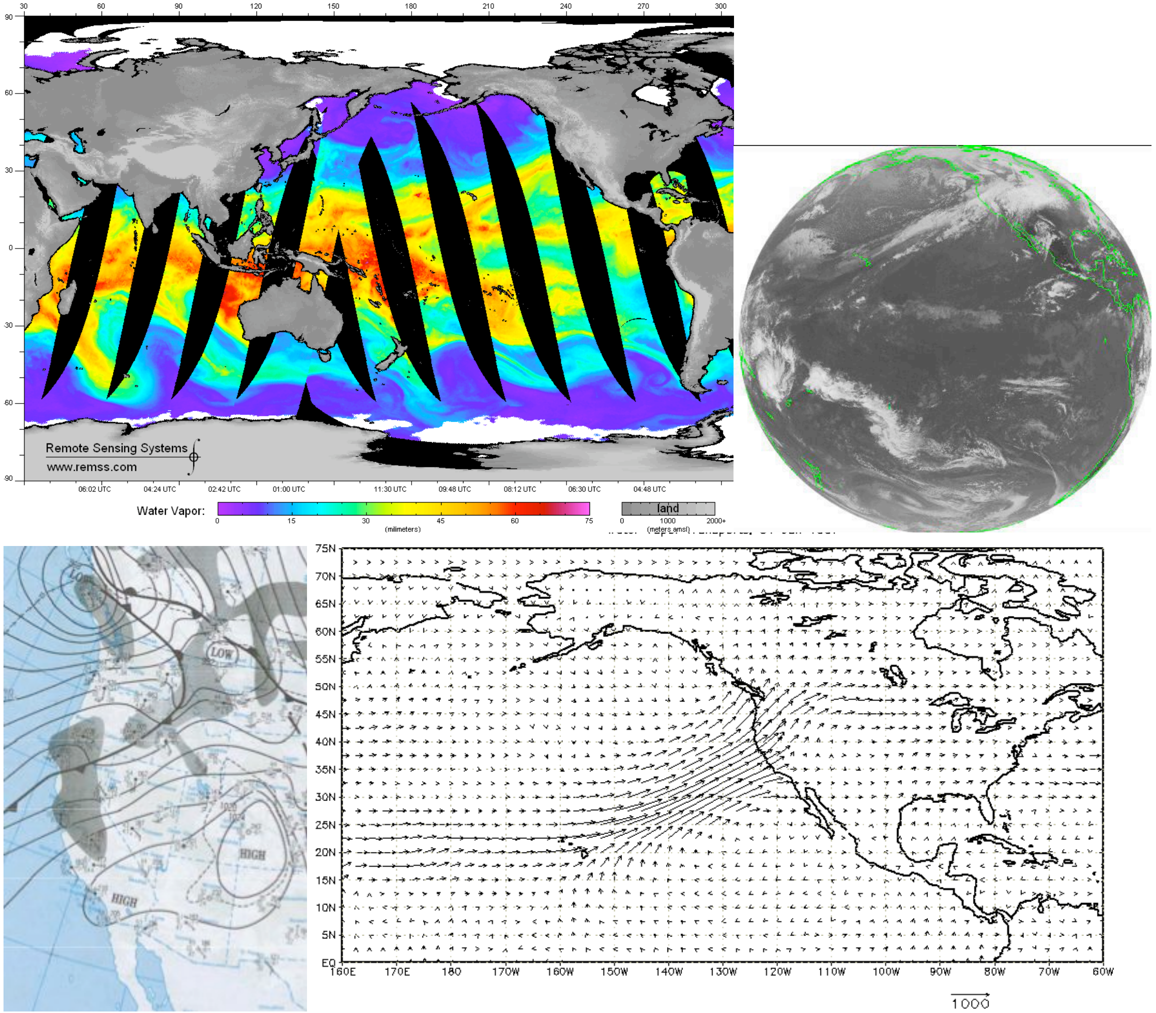

Fig. 1—SSM/I integrated water vapor imagery from GMT morning on 2 January 1997 (top left), infrared weather-satellite imagery of the Pacific Ocean basin (GOES-West) from 1800 hours GMT on 1 January 1997 (top right) and corresponding daily weather map (bottom left) and vertically integrated water-vapor transport directions and relative rates (bottom right); arrow at bottom indicates length of a 1000 kg/m/s vapor-transport vector.

The long thin band of gray (high water vapor amounts) between roughly Hawaii and central California in the top panel of Fig. 1 is the AR associated with the New Years 1997 storm and gives a sense of the scope and scale of these features. The other panels show other ways of visualizing the same episode. Investigations by Ralph et al. (2004, 2006), Neiman et al (2008a, b), and others have shown that, as they approach the west coast of North America, these ARs are typically 2000 or more km long and only several hundred kilometers wide (Ralph et al 2006). The air column within a typical AR will contain more than 2 cm of water vapor, with most of that vapor contained in the first 2.5 km above the sea surface and with a jet of intense and moist winds centered near about 2 km above the surface (Neiman et al 2008a). When the AR is oriented so that these intense winds carry their moist air directly up and over the mountains of California (that is, in directions nearly perpendicular and upslope into the mountain ranges), intense storms of orographically enhanced precipitation result (Neiman et al., 2002; Andrews et al., 2004).

Intense pineapple express storms can be identified in daily general-circulation model (GCM)-scale atmospheric fields by tracing back to sources of intense water vapor transport plumes to determine which begin in the subtropics or tropics near Hawaii (Dettinger 2004). However, this can be a cumbersome algorithm to apply to current projections of climate change, because of the large fields that must be manipulated and because some of the necessary variables are not available from most of the IPCC GCMs at daily resolutions. Thus a more locally-based strategy for detecting precipitation-rich AR-type storms along the California coast, designed and described by Neiman et al (2009), is applied to climate-change projections from IPCC GCMs in the analysis presented here. The GCM-friendly AR-detection approach used here is to calculate the vertically integrated of water vapor (IWV) in the atmosphere and the wind speed and direction at the 925 mbar pressure level (about 1 km above the surface) above a GCM grid cell just offshore from the central California coast. In this study, these variables were determined for each day from the periods 1961-2000, 2046-2065, and 2081-2100, and for a model-grid cell offshore from San Jose. The wind directions are evaluated to determine the component of wind that is directly upslope on the mountain ranges upon which the ARs are impinging, and when the upslope wind component is greater than 10 m/s while the integrated water vapor is greater than 2.5 cm, an AR storm is declared to be occurring. In nature, all storms that dropped more than 10 mm/hour of precipitation at the NOAA Cazadero meteorological station in the past decade have met roughly these criteria. Applying the criteria above to historical and future climate simulations by seven IPCC GCMs allows us to compare the frequencies and magnitudes of AR storms arriving in California in the models under simulated historical and climate-changed conditions.

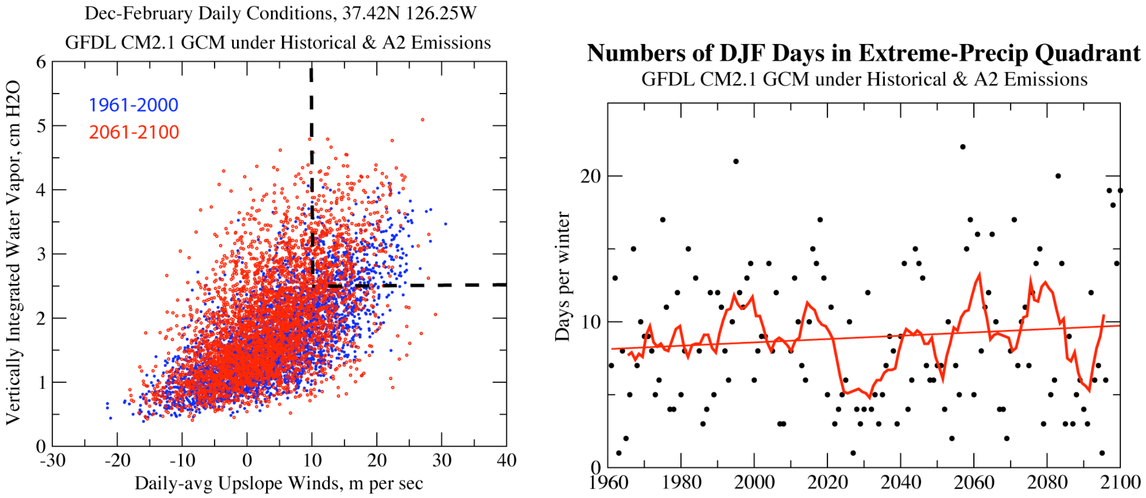

Fig. 2.—Plot of daily December-February integrated water vapor (IWV) and upslope wind values from GFDL CM2.1 climate model (left) and numbers of days per winter falling into the upper right quadrant of that plot (right), under evolving 20th and 21st Century climate changes with A2 greenhouse-gas emissions.

For example, the plot of daily IWV and upslope 925-mb wind speeds as simulated by a particular climate model (GFDL CM2.1) under historical (dark dots) and future 21st Century conditions (light dots) is shown in Fig. 2a. Conditions on a relatively few historical December-February days fall in the upper right quadrant of this figure, where IWV > 2.5 cm and upslope wind > 10 cm, and the number of such days increases slightly as the climate evolves under the influence of increasing greenhouse gas concentrations due to the A2 emissions scenario analyzed here (Fig. 2b). The A2 emissions scenario is a scenario in which global greenhouse-gas emissions accelerate quickly throughout the 21st Century. This scenario is investigated here because it provides the most greenhouse effects on climate among the scenarios for which climate projections are commonly available. The slight increase in number of winter days that meet the historical AR criteria (in this particular model) is a suggestion that opportunities for major AR storm with potentially attendant winter flooding might increase with warming of the climate. In this model, the upslope winds slacken notably (light dots are generally farther left on Fig. 2a than dark dots), perhaps due to the weakening of midlatitude westerly winds discussed in the Introduction. This slackening almost compensates for the tendency of the IWVs to be larger, so that only marginally more days appear in the "extreme-precipitation" upper right quadrant. By analyzing such figures from several models and by analyzing the corresponding projected weather conditions that prevail on the days that meet the ARs criteria, key factors that will determine the intensity and risks associated with individual AR events can be inferred.

The numbers of December-February days during the 1961-2000, 2046-2065, and 2081-2100 periods that have IWV > 2.5 cm and upslope winds > 10 m/s, in each of seven GCMs and in the observations-based NCAR-NCEP Reanalysis depiction of the historical weather record (Kalnay et al 1997), are shown in Fig. 3. The open (Reanalysis) circles represent real-world analogs to the simulated fields from the seven GCMs, and the number of Reanalysis AR episodes is on average lower than the numbers simulated by most of the GCMs (excepting the MIROC and MRI models). Nonetheless the range and general distribution of numbers of AR days per winter are not so different from the GCM counts as to preclude evaluations of the projected changes in the ensemble of GCM projections. Numbers of AR days during the 21st Century increase in most of the GCMs (compared to their respective historical counts). Most models simulate more winters with many opportunities for AR storms and floods, and fewer winters with few opportunities, so that changes in the frequency of these "extreme" winters are more notable than the changes in long-term mean numbers of AR storms.

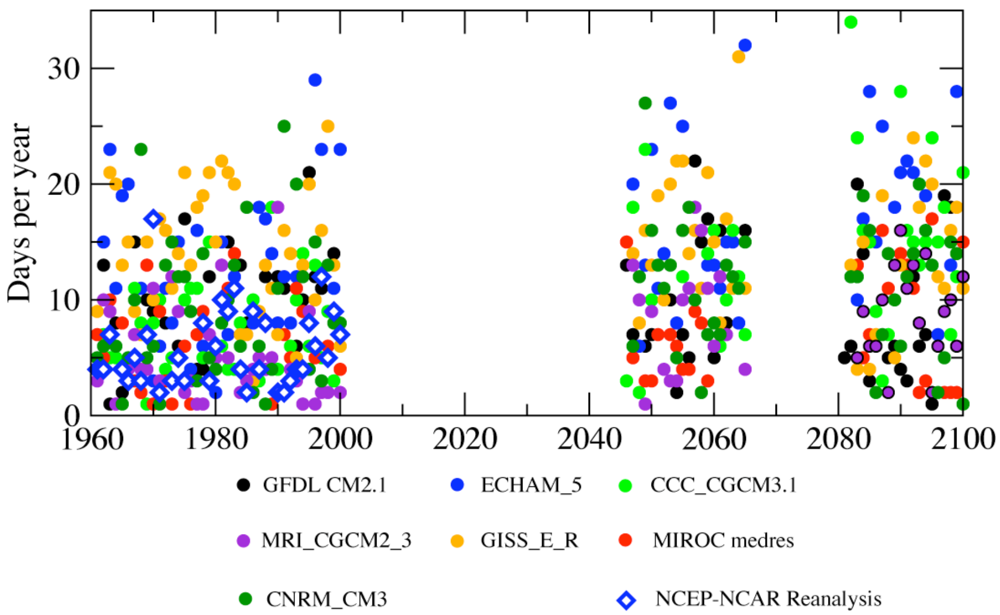

Fig. 3.—Numbers of December-February days per year in the upper-right quadrant of Fig. 2a, for seven climate models (listed at bottom of figure) and the NCAR-NCEP Reanalysis data fields; 21st Century counts are from projections made in response to A2 emissions scenarios.

To be more specific, Table 1 shows the numbers of AR days per winter change through time on a model by model basis, as indicated by linear regressions of the AR-day counts from all available winters (1961-2000, 2046-2065, 2081-2100) versus year. AR-day counts increase in 5 of the 7 models and counts in the remaining models remains at historical levels. The projected numbers of AR days in the 21st century average (across the ensemble of models) about +2.5 days, or about 30%, more by end of century. Thus opportunities for winter-flood generating storms in central California are generally (but not unanimously) projected to increase in frequency in projections of climate change.

The intensity and characteristics of these simulated (and observed) AR events may also be evaluated, in order to determine how AR episodes themselves may evolve in the 21st Century. Figures 4 and 5 compare distributions of IWV values and upslope wind speeds on AR days under the historical and projected-future climates from each of the seven models. Integrated water vapor on AR days increases in all of the models, as do the numbers of AR days with IWV values greater than about 3.5 to 4 cm. In the real world, AR days with such high IWV values have been associated with the very largest storms (Neiman et al, 2008b), and thus the increases at the rightmost edges of the histograms of

Fig. 4 suggest rather ominous changes in the amount of precipitation that many of the projected AR days may deliver in the future.

Table 1.—Trends in numbers of AR days / 100 yrs from seven climate models, with trends that rise to statistical significance at 95% level highlighted in boldface, and with (*) the trend in CNRM only just missing 95% significance level.

Climate model	Change in # AR days / 100 yr	R**2 of trend fit
CCC	**+7.2 days**	**30%**
CNRM	+2.4	4 *
ECHAM	**+4.5**	**10**
GFDL	+0.4	0.2
GISS	+0.3	0
MIROC	**+2.2**	**7**
MRI	**+3.6**	**15**

On the other hand, the histograms of upslope wind speeds in Fig 4 indicate that, in all of the models except perhaps CCC, the upslope components of the winds transporting the additional water vapor tend to weaken as the 21st Century proceeds. These weaker upslope winds will tend to work against the increased water vapor to reduce the orographic precipitation totals that the ARs might deliver. Indeed, the product of the upslope wind times the IWV gives an approximate sense of the water vapor delivered and available to be rained out of the AR storms as they pass over California's mountains. Fig 6 shows the distributions of this "intensity" product for each of the models, with the strong suggestion that in most models, although the numbers of AR days increase, the distributions of their overall (product) intensities may not change as much. Table 2 shows the regressed trends for these intensities on a model-by-model basis, indicating that 3 of the 7 models produce statistically significant increasing trends in the winter-average intensities of AR circulations, and 2 more models yield increases that are not statistically significant, with season-average intensities in the remaining two models remain more or less the same. Even in the models that produce significant trends in AR intensity, the changes are not (on average) more than about 10%, which might be interpreted to translate into an average of not much more than about +10% more rain from future AR storms. Nonetheless, notice that more-than-historical numbers of ARs fall into the most intense tails of the projected distributions (Fig 6) from all seven GCMs. This tendency towards the occasional future occurrence of ARs that are more intense than any that have been witnessed historically is an indication that, under projected climate changes, occasional AR storms are likely to be exceptionally intense.

AR storms are associated with floods because of their relatively warm temperatures as well as the intense precipitation they can deliver. The warm temperatures associated with the ARs commonly result in elevated snowlines and thus much larger than normal river-basin areas receiving rain rather than snow. The long-term AR-day and all-day averages of surface-air temperatures from the entire ensemble of projections are shown in Fig. 7 for the 1961-2000, 2046-2065, and 2081-2100 epochs. In the historical simulations, AR-day temperatures average 1.8C warmer than the average of all Decem-

Table 2.—Trends in intensity (IWV * upslope wind speed) of AR days / 100 yrs from seven climate models, with highlighting as in Table 1.

Climate model	Change / 100 yr	% change / 100 yr	R**2
CCC	**+5.7 cm H2O m/s**	**+11%**	**12%**
CNRM	**+4.0**	**+ 9%**	**8**
ECHAM	**+3.8**	**+ 7%**	**6**
GFDL	+0.1	0	0
GISS	+1.6	+ 4	3
MIROC	-0.3	- 1	0
MRI	+2.1	+ 5	3 *

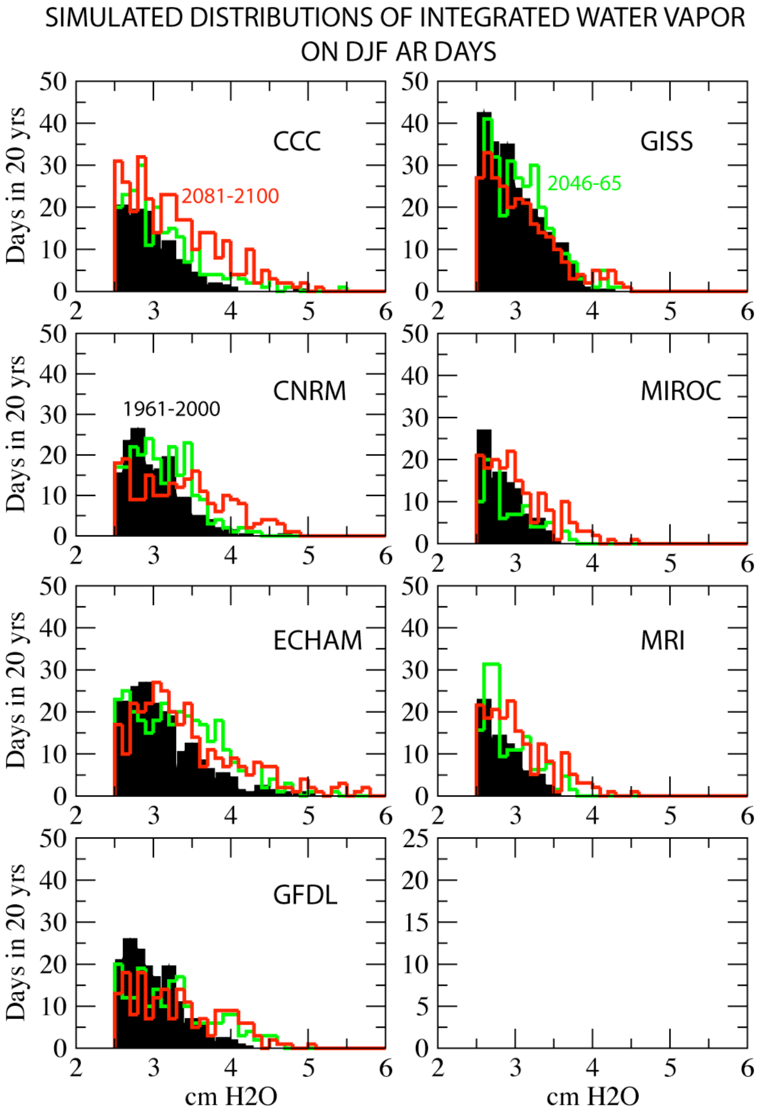

Fig. 4.—Histograms of simulated historical (20c3m, black) and future (A2, green and red) distributions of integrated water vapor values associated with AR-days in seven climate models.

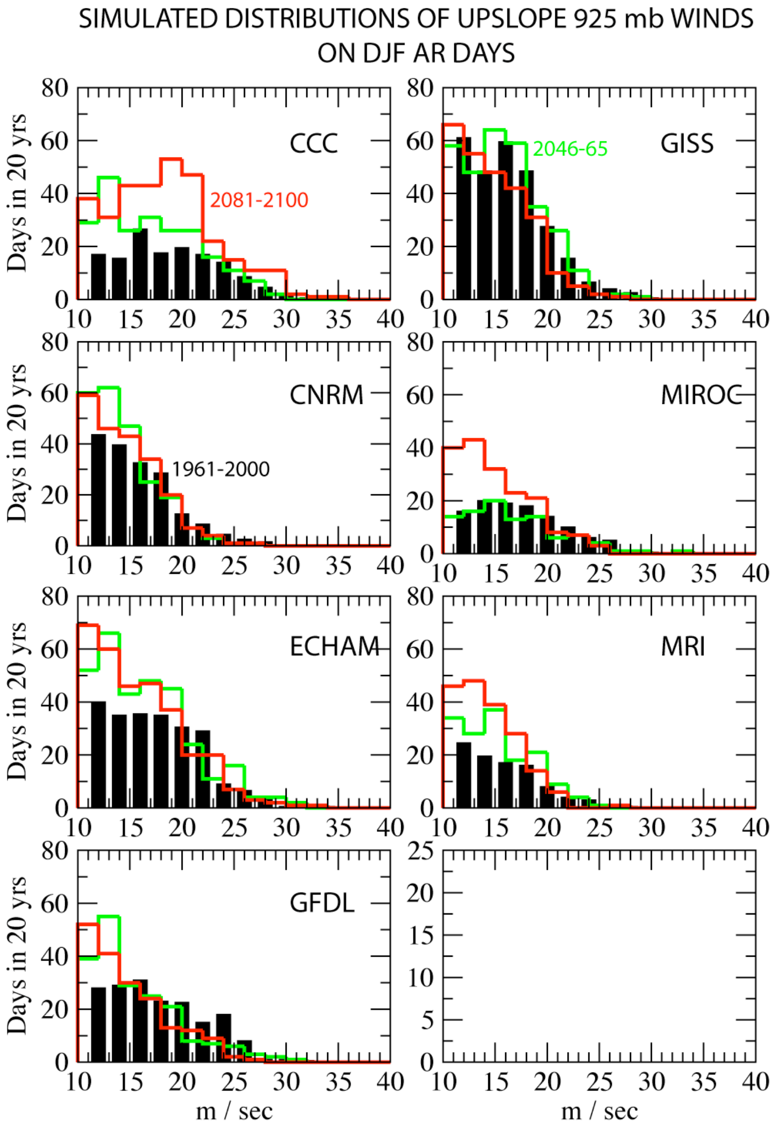

Fig. 5.—Same as Fig. 4, except for upslope winds on AR days.

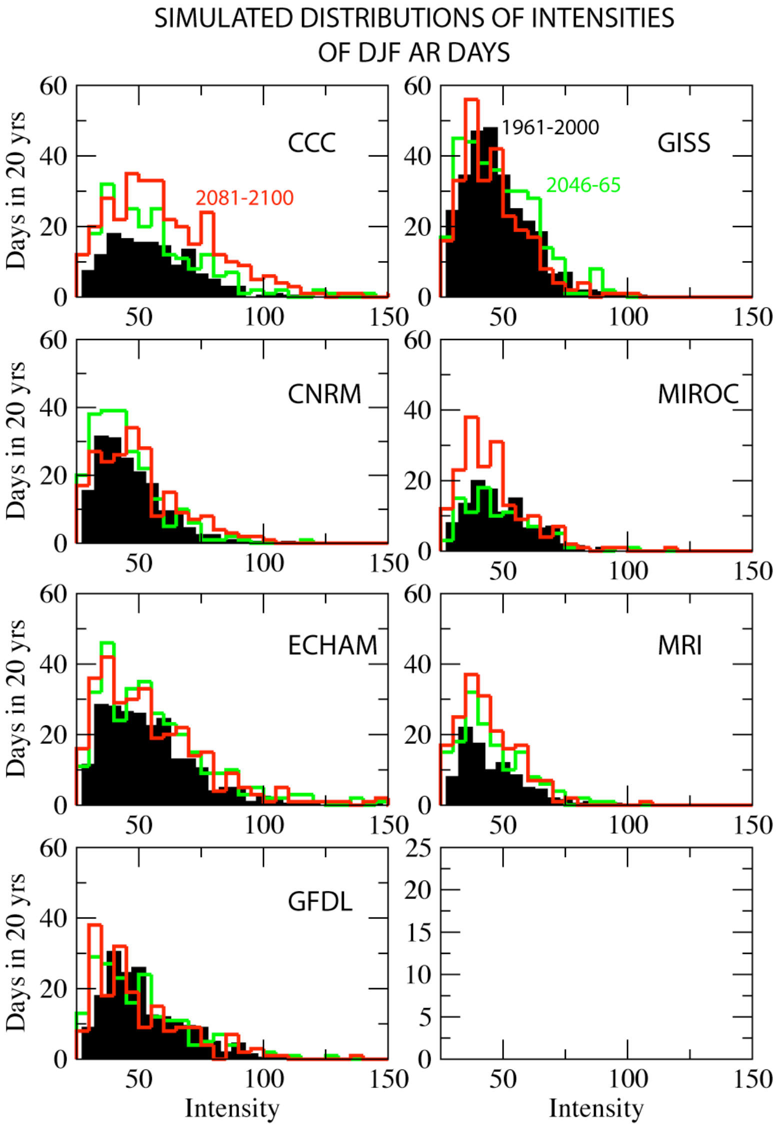

*Fig. 6.—Same as Fig. 4, except for intensities (IWV * upslope wind) on AR days.*

ber-February days, in close agreement with the observed (Reanalysis-based) average difference of 1.7ºC. In the 21st Century simulations, both AR-day average temperatures and all-day average temperatures increase, by about +1ºC in 2046-2065, and by about +2ºC in 2081-2100. Notice that the AR-day average temperatures warm somewhat less quickly than all days, with all days warming by about 0.1ºC more in 2046-2065 and by about 0.3ºC more by 2081-2100. This modest difference in the rates of average warming presumably reflects the fact that ARs involve transport of warm air from regions closer to the tropics, where overall rates of warming are less than in the midlatitudes (IPCC, 2007). Roughly, the +1.8C warmer AR storms by the end of the 21st Century might be expected to lift snowlines by about 1.8C * (1 km per +6.5C warming) or +330 m on average, thereby increasing the average basin areas that receive rain rather than snow in many mountain settings.

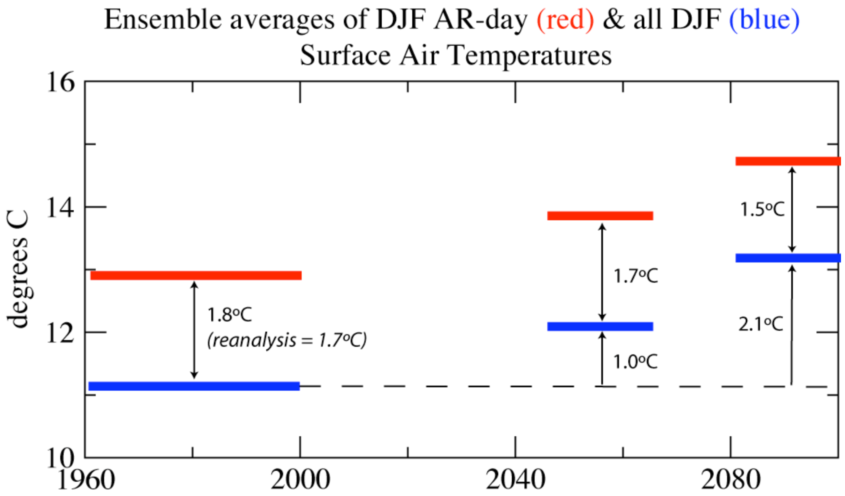

Fig 7.—Ensemble average temperatures on December-February AR days (light) and on all December–February days (dark) under conditions corresponding to Figs. 4-6.

Finally, the seasonality of AR days was investigated by counting the numbers of such occasions for each month of the year in the historical, 2046-2065, and 2081-2100 periods (not shown here; see Dettinger et al., 2009). Generally speaking (with primary exception being the GFDL simulation), most of the increases in numbers of AR days under climate change occurred in the winter months, from about December to February. In five of the seven models, however, AR days also are projected to become notably more common in spring (CCC, GISS, MIROC, ECHAM and MRI) and autumn (CCC, GISS, and MRI). Thus, there is a widely simulated potential for expansion of the season when AR storms might occur. This may imply more potential for increased early (pre-) and late (post-) historical flood-season flooding.

Conclusions

Major storms, in particular pineapple express or atmospheric river storms, were assessed here in the context of projected climate changes. Projected changes in these storms are mostly at the extremes: Years with many AR storms become more frequent in most climate change projections analyzed here, but the average number of such storm per year are not projected to change much. Likewise, although the average intensity of these storms is not projected to increase much in most models, occasionally much-larger-than-historical-range storm intensities are projected to occur under the warming scenarios. Finally the AR storms warm along with, but not quite as fast as, the general mean temperatures in the seven projections analyzed.

Together these findings suggest that California flood risks from the warm-wet, atmospheric-river storms may increase beyond those that we have known historically, mostly in the form of occasional more-extreme-than-historical storm seasons. More analysis is needed to increase understanding and certainties about this potential.

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Ecosystem (CASCaDE) Project. These results were presented and discussed more fully in a report to the California Climate Action Team's 2008 biennial climate-change impacts assessment (Dettinger et al., 2009).

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