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Monitoring and Understanding Changes in Extremes: Extratropical Storms, Winds, and Waves

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Abstract

This scientific assessment examines changes in three climate extremes (extratropical storms, winds, and waves), with an emphasis on U.S. coastal regions during the cold season. There is moderate evidence of an increase in both extratropical storm frequency and intensity during the cold season in the Northern Hemisphere since 1950, with suggestive evidence of geographic shifts resulting in slight upward trends in off-shore/coastal regions. There is also suggestive evidence of an increase in extreme winds (at least annually) over parts of the ocean since the early-to-mid 1980s, but the evidence over the U.S. land surface is inconclusive. Finally, there is moderate evidence of an increase in extreme waves in winter along the Pacific coast since the 1950s, but along other U.S. shorelines any tendencies are of modest magnitude compared with historical variability. The data for extratropical cyclones are considered to be of relatively high quality for trend detection whereas the data for extreme winds and waves are judged to be of intermediate quality. In terms of physical causes leading to multidecadal changes, the level of understanding for both extratropical storms and extreme winds is considered to be relatively low while that for extreme waves is judged to be intermediate. Since the ability to measure these changes with some confidence is relatively recent, understanding is expected to improve in the future for a variety of reasons, including increased periods of record and the development of “climate reanalysis” projects.

Capsule

This scientific assessment examines changes in three climate extremes (extratropical storms, winds, and waves), with an emphasis on U.S. coastal regions during the cold season.

1. Introduction

Weather and climate extremes profoundly affect society and the environment, resulting in the loss of life, property, and habitat. For example, since 1980 the United States has sustained well over 100 weather and climate disasters where damage exceeded one billion U.S. dollars (<http://www.ncdc.noaa.gov/billions/>). Given the obvious importance of extreme events, a working group of the National Climate Assessment (NCA) convened a series of workshops in 2011-2012 to address the state of scientific knowledge regarding changes in such extremes. The goal of each workshop was to document observed changes on multidecadal timescales, assess the suitability of the underlying data, explore the potential causes of any observed changes, and rate the overall level of evidence (i.e., as strong, moderate, suggestive, or inconclusive, per NCA guidelines; Moss and Yohe 2011). The first workshop focused on climate hazards, including tornadoes and heavy precipitation (Kunkel et al. 2012). The second workshop focused on larger-scale events, such as heat waves and droughts (Peterson et al. 2012). This paper summarizes the findings of the third workshop, which addressed extratropical storms, winds, and waves, with an emphasis on U.S. coastal regions during the cold season.

In this assessment, storm-related extremes refer to short-duration events that are uncommon for a particular place and time of year (Peterson et al. 2008). The extremes discussed herein are causally related: extratropical storms account for the majority of extreme winds during the cold season, and extreme waves are largely driven by extreme winds. For assessment purposes, extremes are defined based on meteorological principles rather than physical destructiveness. Nevertheless, each of these extremes can result in substantial societal impacts. Wind is illustrative in this regard; for example, one study reported that a 25% increase in peak gust causes almost a seven-fold increase in building damages (Kezunovic et al. 2008), and

another study found that insurance losses increased by 44% with only a 6% increase in the average winter gust (Schwierz et al. 2010).

2. Extratropical Storms

The term “extratropical storm” refers to any synoptic-scale low pressure system developing in mid- and high-latitudes. Such storms generally form in zones of marked temperature contrasts and account for the majority of all cyclonic systems affecting the United States, particularly in winter. Strong extratropical storms (such as the classic Nor’easter) can have significant impacts over large regions, accounting for heavy precipitation, severe icing, and high winds. Coastal areas are especially at risk as onshore winds accentuate tides and enhance storm surge, battering shorelines and damaging structures. Increasing sea levels extend the impact zone inland.

Estimates of extratropical storm activity primarily derive from two sources: atmospheric reanalyses and pressure-based indices. Reanalysis products have the advantage of uniform space and time fields on which to locate pressure minima or vorticity maxima, facilitating the identification of storm tracks. In contrast, pressure-based indices have the advantage of being directly computed from in situ observations, which often extend further back in time than most reanalyses. The two approaches generally exhibit comparable trends in data-rich areas (Wang et al. 2009, Wang et al. 2012), though the actual number of storms identified can vary.

There is moderate evidence of an increase in both storm frequency and intensity during the cold season in the Northern Hemisphere since 1950 (Fig. 1). Increases are now evident in both mid- and high-latitude zones, in contrast to the 2009 U.S. NCA report (Karl et al. 2009), which noted a decrease in mid-latitude storm frequency (a result obtained using a shorter analysis period). Generally speaking, storm tracks have shifted slightly poleward (Wang et al.

2006, 2012). From a littoral perspective, there is suggestive evidence of a shift toward off-shore activity (as well as an overall increase in storm activity around U.S. coastlines) during the second half of the 1950-2010 period (Fig. 2). The increase along the Atlantic coast likely commenced before 1950, as the frequency of damaging storms was considerably lower in the early- to mid-20th century according to in situ storm reports (Mather et al. 1964).

Most research on changes in extratropical storms has focused on mean frequency and intensity, with comparatively little attention on changes in extremes because of their sporadic occurrence. Theoretically, however, extremes should be readily detectable in the historical record simply because of their size, and thus virtually any data source (reanalysis or other) could be scrutinized for trends therein. For example, when the reanalysis-based record of Fig. 2 is stratified by intensity, the extreme extratropical storms (i.e., those exceeding the 90th percentile) are found to exhibit changes comparable in pattern to the overall extratropical storm record (though the trends themselves are smaller). In short, there is at least some indication of an increase in extreme extratropical storm activity during the cold season in the Northern Hemisphere since 1950, but the evidence overall is limited and thus inconclusive.

Neither climate model projections nor our understanding of the physical climate system leads to any conclusive answers regarding extratropical cyclone activity in a warming climate. As discussed by Bengtsson et al. (2009), a decrease in the meridional temperature gradient at the surface would decrease the amount of available potential energy for extratropical storms. At the same time, stratospheric ozone depletion in polar latitudes and increasing tropospheric greenhouse gas concentrations lead to a cooling within the stratosphere and an increase in the meridional temperature gradient, resulting in intensification of systems (Bengtsson et al. 2009). The additional latent heat available in warmer air is a factor that could result in greater

extratropical storm intensity. Finally, an expansion of the Hadley cell would cause a subsequent poleward shift of the polar front, though there is as yet no evidence for a significant expansion in the Hadley cell during the Northern Hemisphere winter (Hu and Fu 2007; Seidel et al. 2008). In short, the balance and interactions among these factors are not well understood. Projections into the 21st century generally show a slight poleward shift in extratropical storm tracks, while different conclusions (increase, no change, decrease) have been reached for changes in intensity (Bengtsson et al. 2009; Neu 2009; Catto et al. 2011).

The frequency, intensity, and location of extratropical storm activity are also greatly influenced by large-scale circulation patterns such as the El Niño Southern Oscillation (ENSO) and the North Atlantic Oscillation (NAO). For example, during the warm phase of ENSO there is enhanced storm activity along the East coast (Hirsch et al. 2001) and Gulf of Mexico, an equatorward shift in the North Pacific storm track, and decreased storm activity in Pacific Northwest (Eichler and Higgins 2006). The positive phase of NAO is associated with a poleward shift of storms tracking across the Atlantic (Wang et al. 2011). When the negative phase of NAO coincides with the warm phase of ENSO, East Coast winter storms are weaker but tend to move more slowly, enhancing the impact of coastal flooding and beach erosion (Bernhardt and DeGaetano 2012). Climate model simulations vary in their depiction of future changes in atmospheric circulation patterns, increasing uncertainty regarding both the frequency and distribution of extratropical storm activity during the 21st century.

3. Winds

Extreme winds impact numerous aspects of society, ranging from structural engineering (Jensen et al. 1992) to energy production (Pryor and Barthelmie 2011). Extreme winds also contribute to other high-impact phenomena, such as extreme waves (Wang et al. 2009a) and

storm surge. While the exact definition varies by economic sector, “extreme” generally implies a return period >1 year and/or an event in the upper tail (e.g., $\geq 90^{\text{th}}$ percentile) of the probability distribution. From the perspective of engineering design, both short-term, high-magnitude perturbations (1-3 second gusts) and sustained, positive excursions (e.g., ≥ 10 -minutes) are of practical importance.

Estimates of extreme winds are available from four distinct sources: in situ observations, satellite data, atmospheric reanalyses, and pressure-based indices (i.e., geostrophic winds derived from pressure fields; Wang et al. 2009). Each source covers a different period, represents a different spatial scale, and has a different accuracy and precision. In general, both wind speed and direction are available from most sources, with the latter sometimes being more important from an impacts perspective (e.g., bridge closures are functions of both speed and direction).

There is suggestive evidence of an increase in extreme winds at the annual time scale over parts of the ocean since the early-to-mid 1980s, but the evidence over land is inconclusive. In particular, both atmospheric reanalyses (Pryor et al. 2009) and radar altimeters (Young et al. 2011, 2012) generally depict increases in extreme winds along many parts of the Atlantic and Pacific coasts since the early-to-mid 1980s, though the accuracy of the altimeter trends has been debated (e.g., Wentz and Ricciardulli 2011). In contrast, atmospheric reanalyses and in situ data exhibit little consistency over the conterminous United States since the 1970s. For example, one comprehensive analysis of annual 90^{th} percentile wind speeds found reanalysis products generally depicted increases while the in situ record depicted substantial decreases, particularly in the eastern half of the nation (Pryor et al. 2009) (Fig. 3). Additionally, there were large differences in the actual magnitude of the 90^{th} percentile across the various datasets (Pryor et al. 2012b).

There are several ongoing challenges in identifying trends in the historical record. For example, the record itself is short compared with the entire spectrum of time scales on which wind regimes vary (Barring and Fortuniak 2009). There are substantial inhomogeneities due to changes in surface instruments and siting (Pryor et al. 2009; Wan et al. 2010) and algorithms applied to derive wind speeds from remotely sensed data. Land-based data may not be archived at a resolution that is always sufficient for climate change detection (e.g., wind speeds may be truncated to the closest knot). Quality control and assessment procedures often focus on mean conditions and may erroneously remove extreme values. Finally, reanalysis products do not explicitly model conditions at 10-m and may contain biases resulting from changes in assimilated datasets.

Mechanistic understanding of how extreme winds might evolve in a non-stationary climate has improved since the 2009 U.S. National Climate Assessment report (Karl et al. 2009). This is largely attributable to recent enhancements in global and regional climate models, such as the increases in spatial resolution and improved characterization of topography (Pryor et al. 2012a, Pryor et al. 2012b, Pryor et al. 2012c). Nevertheless, challenges remain in making robust assessments of both past tendencies and future projections, and the level of understanding is still largely a function of the spatial scale of the phenomenon generating the extreme (McInnes et al. 2011, Najac et al. 2011, Pryor et al. 2012a, Pryor et al. 2012c). In essence, uncertainty is larger for smaller-scale events than for larger-scale cyclonic systems.

There is higher confidence in generating *a priori* expectations for extreme winds from synoptic-scale phenomena (e.g., extratropical storms), as these are most likely to be resolved in climate models. In particular, tracking of extratropical storms is predominantly dictated by large-scale thermal gradients, which are reasonably well resolved in climate models (including

reanalyses), which in turn generally depict a poleward shifting of mid-latitude storm-tracks in the future (Bengtsson et al. 2009). This change has already been noted in the historical record (McCabe et al. 2001, Wang et al. 2012), though attribution is confounded by ENSO and other internal climate modes (Klink et al. 2007, Pryor and Ledolter 2010) that account for much of the interannual variability in extratropical storm activity (and thus extreme winds).

There is much lower confidence in generating *a priori* expectations about changes in extreme winds that derive from smaller-scale systems. For example, mesoscale systems (e.g., polar lows, sea-breeze fronts) are strongly linked to dynamical forcing and thermodynamic processes, the scales of which are not finely resolved in most reanalyses and climate models (Condrón et al. 2008) and are undersampled in the sparse surface observing network. For extreme winds associated with even smaller-scale phenomena (e.g., thermo-topographically forced Chinook winds), the level of understanding is essentially nascent from a climate-change perspective (Hughes et al. 2011). Furthermore, irrespective of the dynamical mechanism, local features (e.g., roughness elements, soil moisture and stability) will continue to influence the magnitude of extremes.

4. Waves

During the cold season, extreme waves generally result from extratropical storms passing along the coast. Multiple storm attributes (e.g., wind speed, storm fetch, and storm duration) collectively govern the energy imparted to such waves, which can have large coastal impacts. Damage is primarily a function of wave energy, storm track, and event duration/timing (e.g., when storm surge and high waves combine to produce erosion and flooding). As with extratropical storms and intense winds, extreme waves are usually characterized as events in the upper tail of the probability distribution (generally $\geq 99^{\text{th}}$ percentile).

Estimates of extreme waves are available from three general sources: in situ observations (buoys, ships, tide gauges); satellite data; and wave models (driven primarily by wind fields, e.g., Wang and Swail, 2001; 2002). In situ observations are well suited to regional-scale analyses, with buoys having the advantage of high temporal resolution while ship data and tide gauges have relatively long historical records. Satellites and wave models both have good spatial coverage over the oceans, but the record length is relatively short for satellites. The reliability of the data ranges widely across the sources, data homogeneity being an acute example (Gemmich et al. 2011).

There is moderate evidence of an increase in extreme waves in winter along the Pacific coast since the 1950s, but evidence along other U.S. shorelines is inconclusive (Figs. 4 and 5). In particular, non-tidal residual data (Bromirski et al. 2003), visual ship reports (Gulev and Grigorieva 2004), and reanalysis ocean wave models (Uppala et al. 2005, Dee et al. 2011) all depict increases in extreme waves along the Pacific coast over the past half century. Buoy data (Bromirski et al. 2005, Allan and Komar 2006, Menedez et al. 2008, Ruggiero et al. 2010) generally corroborate these increases over the past several decades, though some buoy trends (particularly in the northeast Pacific) may be suspect because of historical changes in observing practice and analysis procedures (Gemmich et al. 2011). In contrast, the various data sources exhibit less consistency along the Atlantic and Gulf coasts. For example, reanalysis wave models depict longer-term decreases along the East coast whereas visual ship reports exhibit increases, and buoys along the central Atlantic coast have no net trend in winter in the past three decades (Komar and Allan 2008).

Several ongoing challenges remain in analyzing observed wave climatological changes and in making future projections. From an observational perspective, wave extremes themselves

are difficult to measure; ships often avoid the worst conditions, buoy mooring cables can break, tide gauges can be submerged, and an individual storm may not encounter a sensor. Likewise, most observing systems (particularly buoys and satellites) have only been in place since the 1980s, a relatively short period for assessing multidecadal variability and trends. In addition, wave models depend upon accurate wind fields, which can be uncertain in data-sparse regions of the ocean, and thus wave extremes are often underestimated (Semedo et al. 2011). From a projection perspective, changes in extreme waves will be driven largely by future changes in extratropical storms and the resulting extreme winds, but robust predictions for both remain elusive for a myriad of reasons (e.g., uncertainty regarding future storm tracks and internal climate modes such as ENSO). Other ongoing environmental changes will also contribute to future extremes; for instance, decreases in permanent sea ice have already increased the frequency of extreme wave activity in parts of northern Alaska, the village of Shishmaref being a widely publicized example (U.S. Congress 2012).

5. Conclusions

This scientific assessment examined changes in extratropical storms, winds, and waves, with an emphasis on U.S. coastal regions during the cold season. The main conclusions are:

- There is moderate evidence of an increase in storm frequency and intensity during the cold season in the Northern Hemisphere since 1950. There is suggestive evidence of a shift toward off-shore activity, with slight upward trends along U.S. coasts.
- There is suggestive evidence of an increase in extreme winds at the annual time scale over parts of the ocean since the early-to-mid 1980s, but evidence over land is inconclusive.

- There is moderate evidence of an increase in extreme waves along the Pacific coast in winter since the early 1950s, but evidence along other U.S. shorelines is inconclusive.

Figure 6 summarizes the authors' collective assessment of the state of knowledge regarding changes in each extreme. Two complementary concepts are represented: trend detection (i.e., how useful the data actually are for assessing historical changes), and physical causes (i.e., how well the mechanisms driving changes are understood, and thus how extremes are expected to change in the future). The assessment in each case was determined through extensive discussion at a meeting of the author team to reach a group consensus. In terms of trend detection, the data for extratropical cyclones were considered to be of relatively high quality, roughly on par with phenomena such as extreme precipitation and heat waves. The data for extreme winds and waves were judged to be of intermediate quality, roughly comparable to hurricanes and snow. In terms of physical causes leading to multidecadal changes, the level of understanding for both extratropical storms and extreme winds was considered to be relatively low, similar to thunderstorm winds and ice. The level of understanding for extreme waves was judged to be intermediate, the justification being that reasonable projections could be made given realistic projections of storm activity and extreme winds.

Like the climate system itself, the state of knowledge on extremes is evolving, and a variety of measures can be taken to increase the level of understanding in the future. For example, improved observations are always useful, and in fact Fig. 7 shows a positive correlation between confidence in the observations and the ability to understand changes. At present, most observations are geared toward weather forecasting, and a transition toward a dual weather forecast/climate change applications would benefit detection and attribution studies. New data

283 analysis techniques focused on non-stationarity in extremes (Katz et al. 2002) are increasingly
284 available, as are open source statistical software applications to fit trends in one or more
285 parameters of the generalized extreme value distribution (Gilleland and Katz 2011). Finally,
286 innovations in high-resolution numerical modeling and the development of new reanalysis
287 products (Thorne and Vose 2011) with improved boundary-layer parameterizations will also
288 greatly help in data homogeneity and thus the assessment of extremes.

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475

List of Figures

- Figure 1 Time series of extratropical storm frequency and intensity during the cold season (November – March) for high latitudes (60-90 °N) and mid-latitudes (30-60 °N) of the Northern Hemisphere. The time series represent standardized departures, which are deviations from the long-term average that have been divided by the spread in the data (e.g., the standardized departure of frequency in a given year/location is computed by subtracting the long-term average frequency at that location from the actual frequency in that year/location, then dividing the difference by the standard deviation of the frequency in that location). The time series were derived from the NCEP/NCAR reanalysis (Kalnay et al. 1996) using a modified version of Serreze (1995) as detailed in Wang et al. (2012). Each series has an increasing trend from 1948-2010 that is statistically significant (0.01 level). Overall, there is good agreement between these series and those of McCabe et al. (2001), which were presented in the previous National Climate Assessment report (Karl et al. 2009). Generally speaking, the NCEP/NCAR reanalysis is consistent with other reanalyses in terms of extratropical cyclone activity (Hodges et al. 2011).
- Figure 2 Difference in extratropical storm activity between 1979-2010 and 1948-1978 during the cold season (November – March). Activity is defined using a standardized index that represents the seasonal total of cyclones in a given area, multiplied by their mean intensity (Wang et al. 2012). As in Fig. 1, extratropical storms were derived using the NCEP/NCAR reanalysis (Kalnay et al. 1996) as input, and the term “standardized” implies deviations from the long-term average

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Figure 3 Temporal trends of 90th percentile 10-m wind speed at the annual time scale. Frames (a) and (c) depict trends from two station-based data sets archived at the National Climatic Data Center (NCDC): NCDC-6421 (a homogeneity-adjusted data set by Groisman 2002) and DS3505 (an unadjusted data set by Smith et al. 2011). The remaining frames depict trends from four atmospheric reanalyses: ERA-40 (Uppala et al. 2005), NCEP/NCAR (Kalnay et al. 1996), NCEP/DOE (Kanamitsu et al. 2002), and the North American Regional Reanalysis (NARR; Mesmer et al. 2006). In each frame the size of the dot scales linearly with the magnitude of the trend [see frame (a)]; red depicts increases, and blue depicts decreases. In frames (a) and (c), stations with statistically insignificant trends are depicted with a plus symbol. In other frames, reanalysis grid points with statistically insignificant trends are not depicted with any symbol.

521 Figure 4 Time series of 99th percentile significant wave heights in winter (December –
522 February). The column on the left depicts area-averaged time series computed
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526 depicts time series from high-quality, spatially representative buoys mapped in
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530 gauge (Bromirski et al. 2003).

531 Figure 5 Data sources for extreme waves. Squares denote buoy locations, red indicating
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539 causes of the observed changes – i.e., how well the mechanisms driving changes
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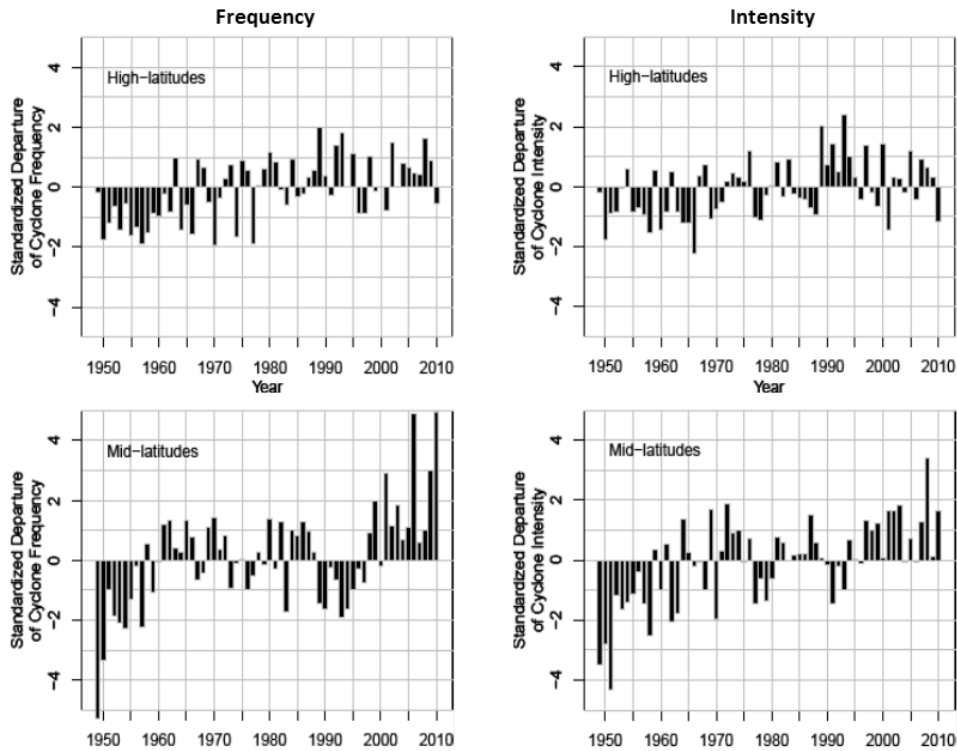


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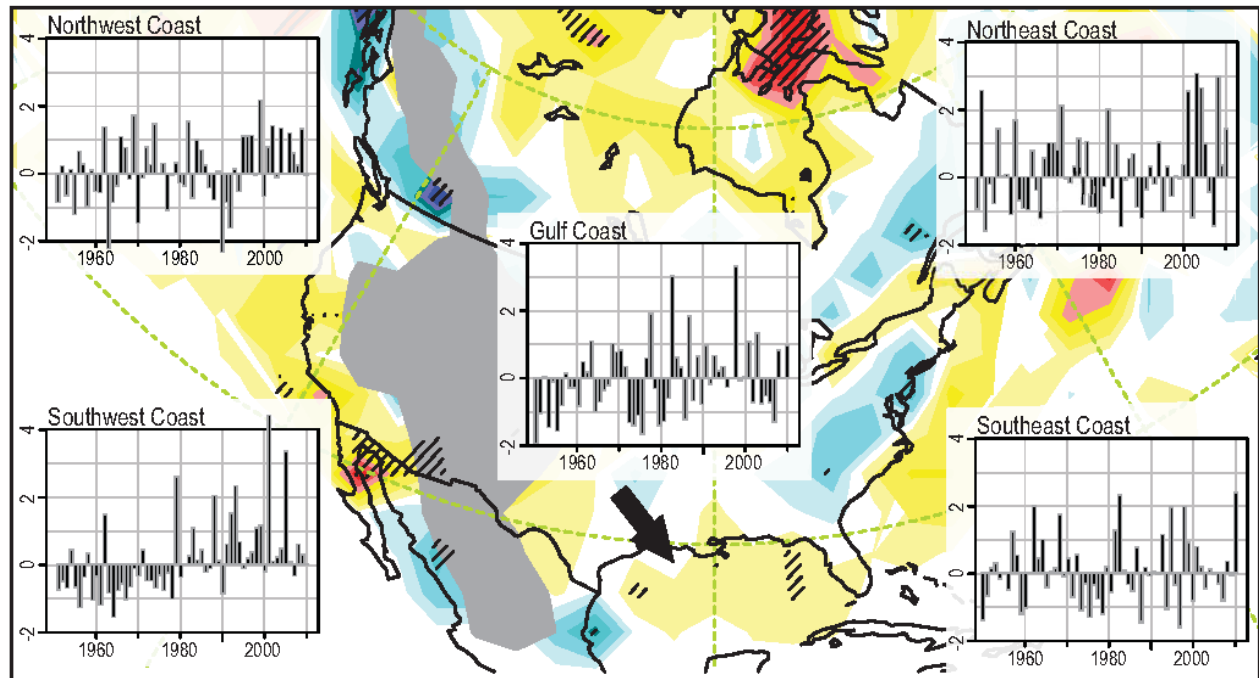


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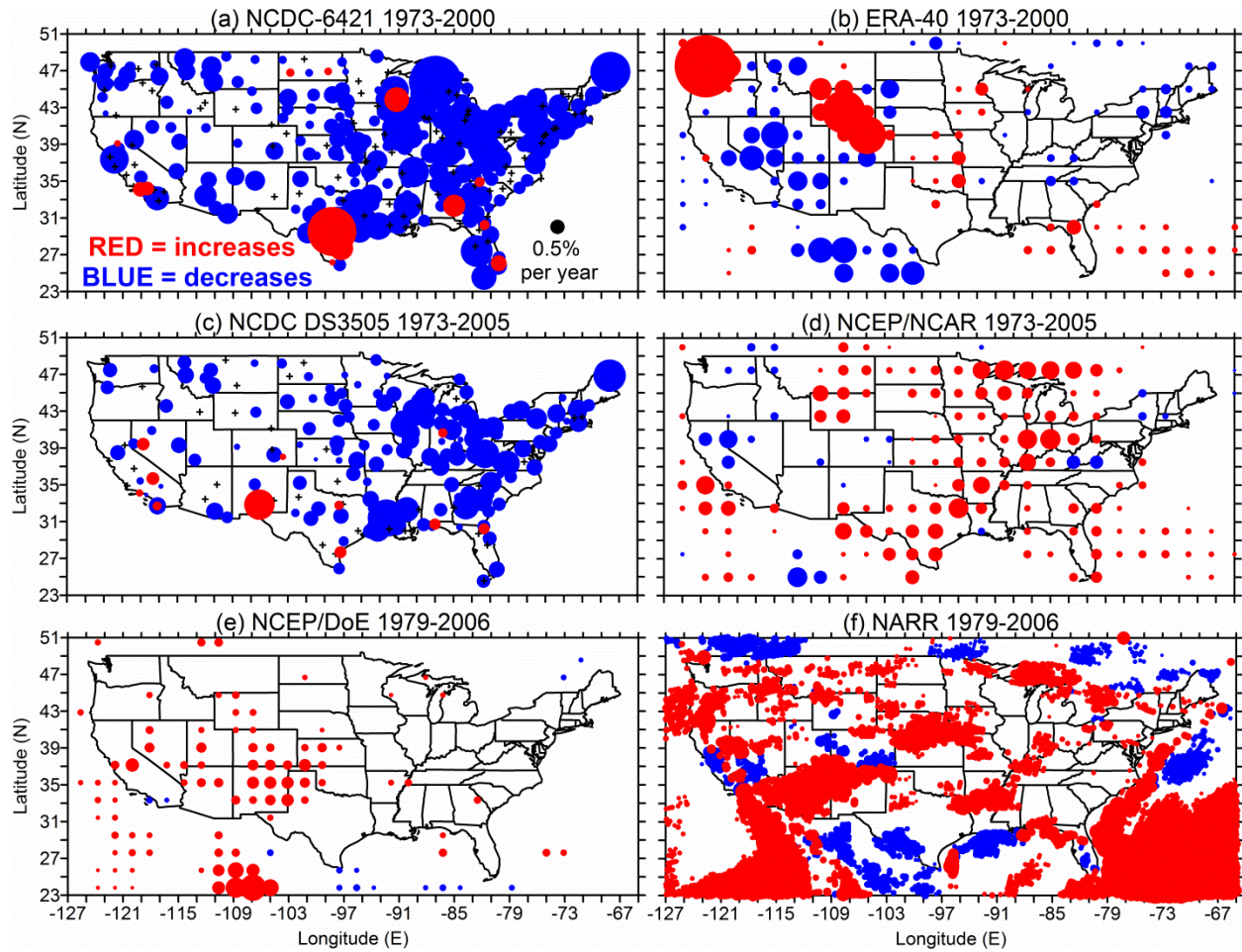


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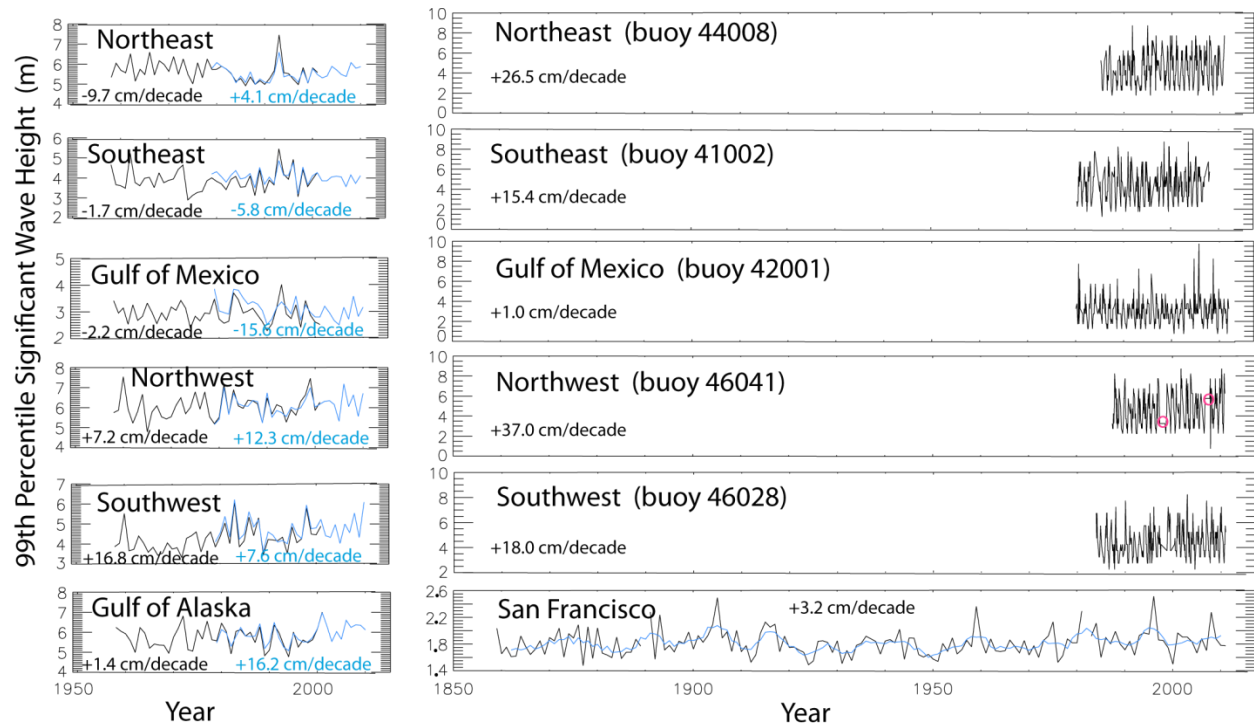
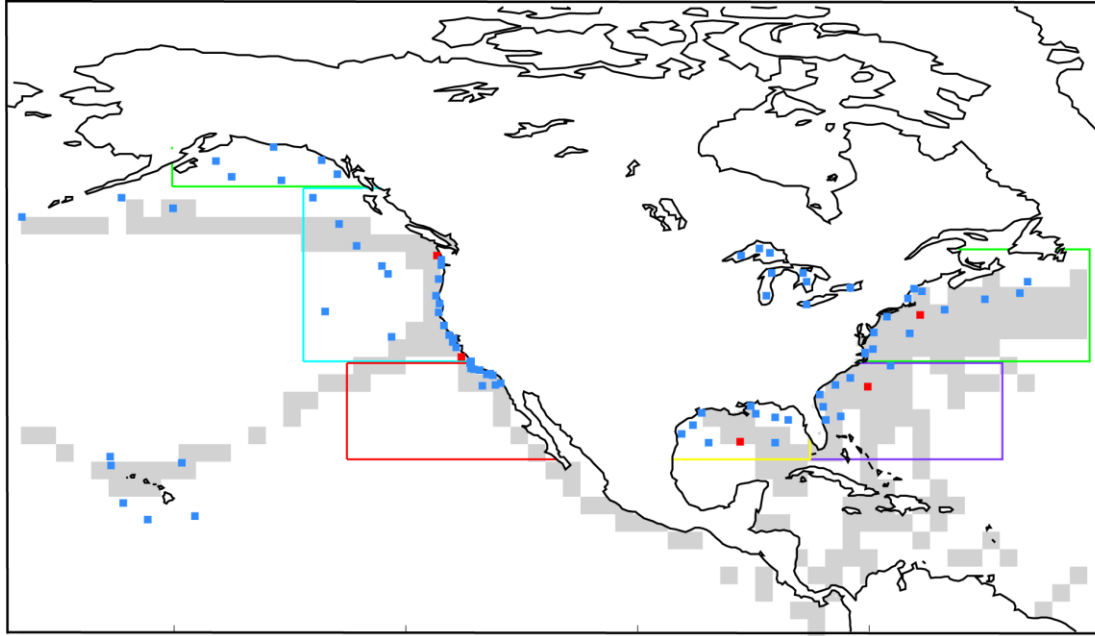
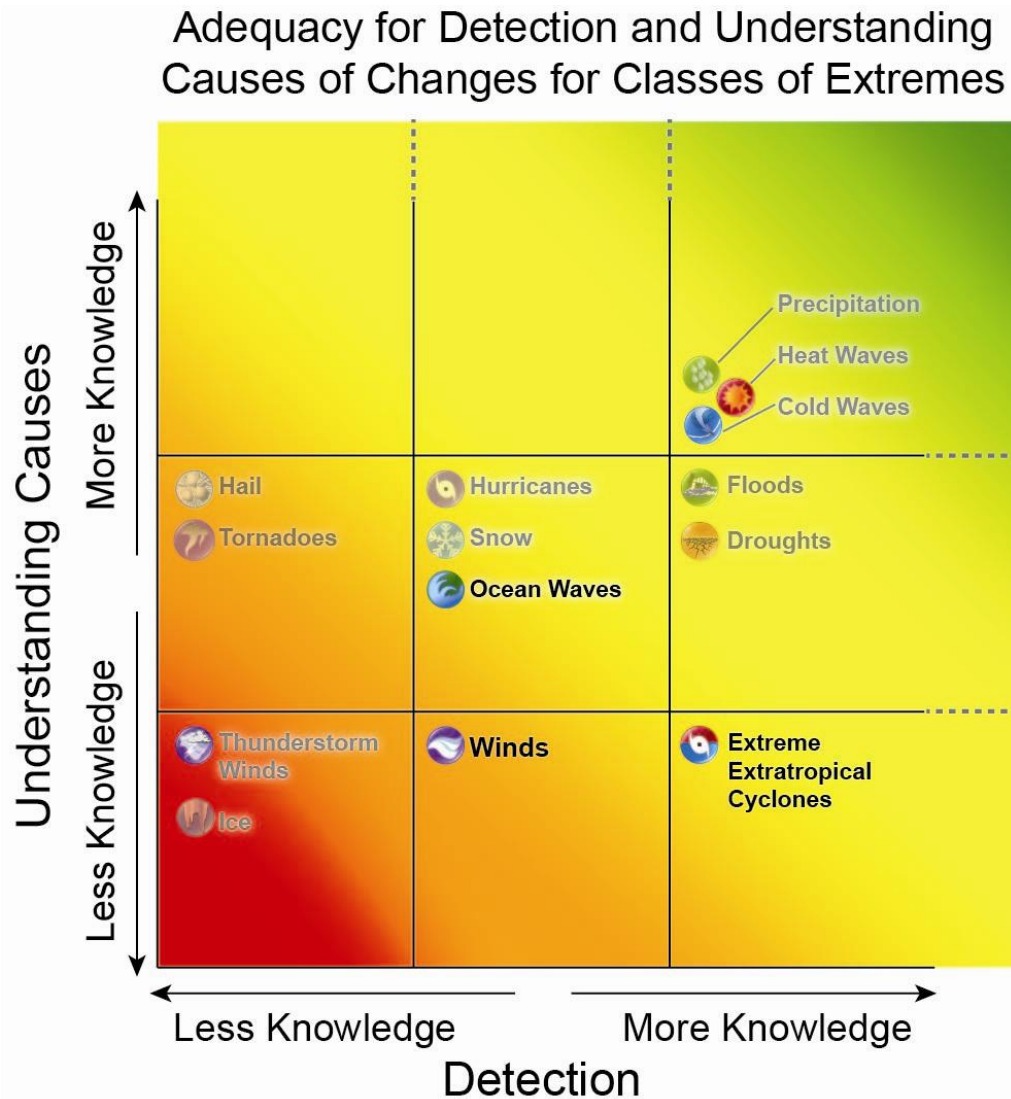


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