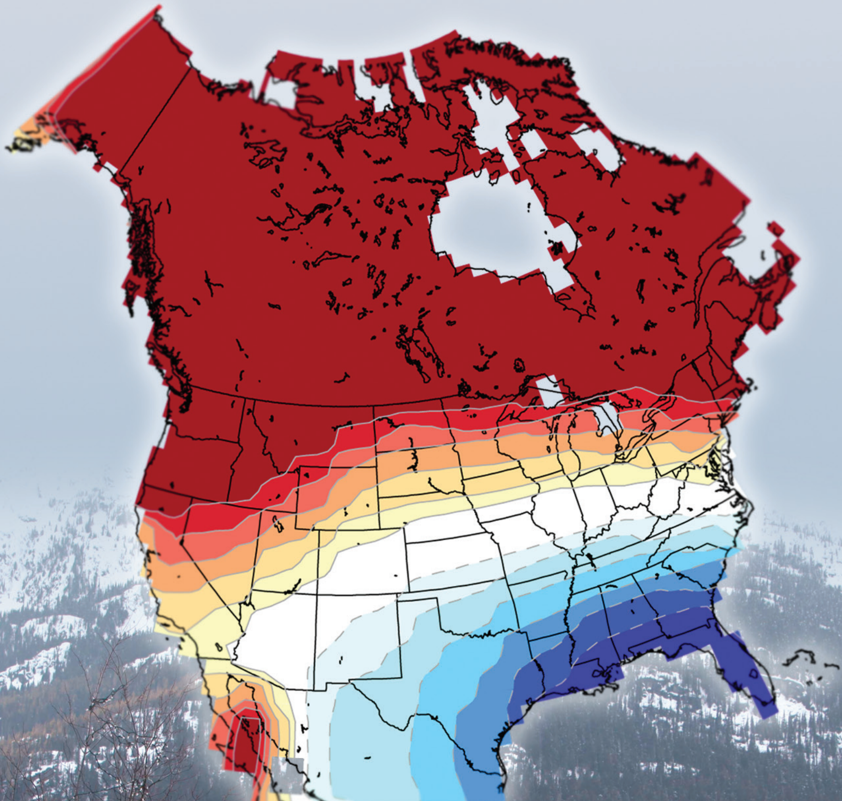
STATE OF THE CLIMATE IN 2010

J. Blunden, D. S. Arndt, and M. O. Baringer, Eds.

Associate Eds. K. M. Willett, A. J. Dolman, B. D. Hall, P. W. Thorne, J. M. Levy, H. J. Diamond, J. Richter-Menge, M. Jeffries, R. L. Fogt, L. A. Vincent, and J. M. Renwick



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1. INTRODUCTION—D. S. Arndt, J. Blunden, and M. O. Baringer

The primary goal of the annual *State of the Climate* collection of articles is to document the weather and climate events of the most recent calendar year and put them into accurate historical perspective, with a particular focus on unusual or anomalous events. This is the 21st annual edition of this effort, including its origin as NOAA's *Climate Assessment*, and the 16th consecutive year of its association with the *Bulletin of the American Meteorological Society*. The *State of the Climate* series continues to grow in scope and authorship. This edition presents contributions from the largest body of authors to date and brings several new sections to the readership.

The year 2010 was notable for its globally-averaged warmth and for the far-reaching impacts related to significant behavior of several modes of climate variability. These modes have unique influences and impacts throughout the climate system. Indeed, each chapter in this document contains special mention of ENSO, or the various hemispheric indices such as the Arctic Oscillation or Southern Annular Mode. Sidebar 1.1, which was coordinated by the Chapter 2 (Global Climate) editors, is intended as an introductory overview of selected known modes of variability. More practically, it serves as a data-laden reference for readers of later chapters. The online supplement includes additional data that allow the reader to investigate further.

Different regions have different sensitivities and thus varying definitions of ENSO. This, combined with the global authorship of the *State of the Climate in 2010*, led to various descriptors of the peak strengths of the early-2010 El Niño episode and the late-2010 La Niña. This was standardized, where possible, using NOAA's description of "strong" for El Niño and "moderate-to-strong" for La Niña. In more regional discussions, these descriptors have not been changed.

In order to build a broader description of the climate system, this report aims each year to increase the number of represented Essential Climate Variables (ECVs), as defined and maintained by the climate observing community through the Global Climate Observing System (GCOS 2003; Fig. 1.1) . To that end, new editors representing expertise in two broad disciplines (terrestrial processes and atmospheric composition) were added to the panel serving Chapter 2.

The following ECVs included in this edition are considered "fully monitored", such that they are observed and analyzed across much of the world, with a sufficiently long-term dataset that has peer-reviewed documentation:

- Atmospheric Surface: air temperature, precipitation, air pressure, water vapor*.
- Atmospheric Upper Air: earth radiation budget, temperature, water vapor, cloud properties.
- Atmospheric Composition: carbon dioxide, methane, ozone, nitrous oxide, chlorofluorocarbons, hydrochlorofluorocarbons, hydrofluorocarbons, sulphur hexafluorides, perflurocarbons*, aerosols.
- Ocean Surface: temperature, salinity, sea level, sea ice, current, ocean color.
- Ocean Subsurface: temperature, salinity*.
- Terrestrial: snow and ice cover.

ECVs in this edition that are considered "partially monitored", meeting some but not all of the above requirements, include:

- Atmospheric Surface: wind speed and direction.
- Atmospheric Composition: long-lived greenhouse gases not listed as fully monitored above.
- Ocean Surface: carbon dioxide.
- Ocean Subsurface: current, carbon.
- Terrestrial: soil moisture, permafrost, glaciers and ice sheets, river discharge, groundwater*, lake levels, fraction of absorbed photosynthetically-active radiation, biomass, fire disturbance.

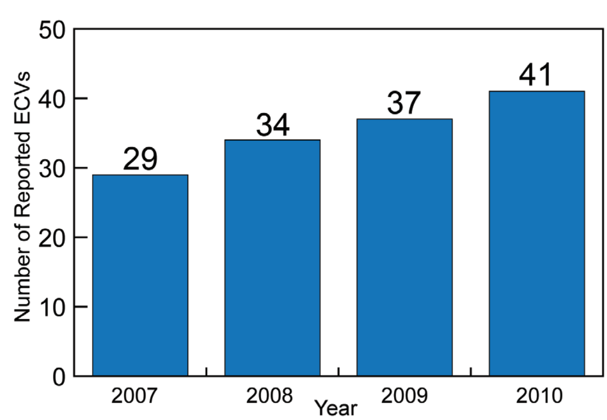


Fig. 1.1. Number of fully or partially monitored Essential Climate Variables (ECVs) reported in the annual *State of the Climate* editions since 2007. Atmospheric surface water vapor, atmospheric perfluorocarbons, oceanic subsurface salinity, and terrestrial lake levels have been introduced in this current edition.

ECVs that are expected to be added in the future include:

- Atmospheric Surface: surface radiation budget.
- Atmospheric Upper Air: wind speed and direction.
- Ocean Surface: sea state.
- Ocean Subsurface: nutrients, ocean tracers, phytoplankton.
- Terrestrial: surface ground temperature, subsurface temperature and moisture, water use, albedo, land cover, leaf area index.

**These ECVs were introduced to the report in this edition.*

A brief overview of the findings in this report is presented in the Abstract and shown in Fig. 1.2. The remainder of the report is organized starting with global-scale climate variables (Chapter 2) to increasingly divided geographic regions described in Chapters 3 through 7. Chapter 3 highlights the global ocean and Chapter 4 includes tropical climate phenomena such as El Niño/La Niña and tropical cyclones. The Arctic and Antarctic respond differently through time and hence are reported in separate chapters (5 and 6). Chapter 7 provides a regional perspective authored largely by local government climate specialists. Sidebars included in each chapter are intended to provide background information on a significant climate event from 2010, a developing technology, or an emerging dataset germane to the chapter's content.

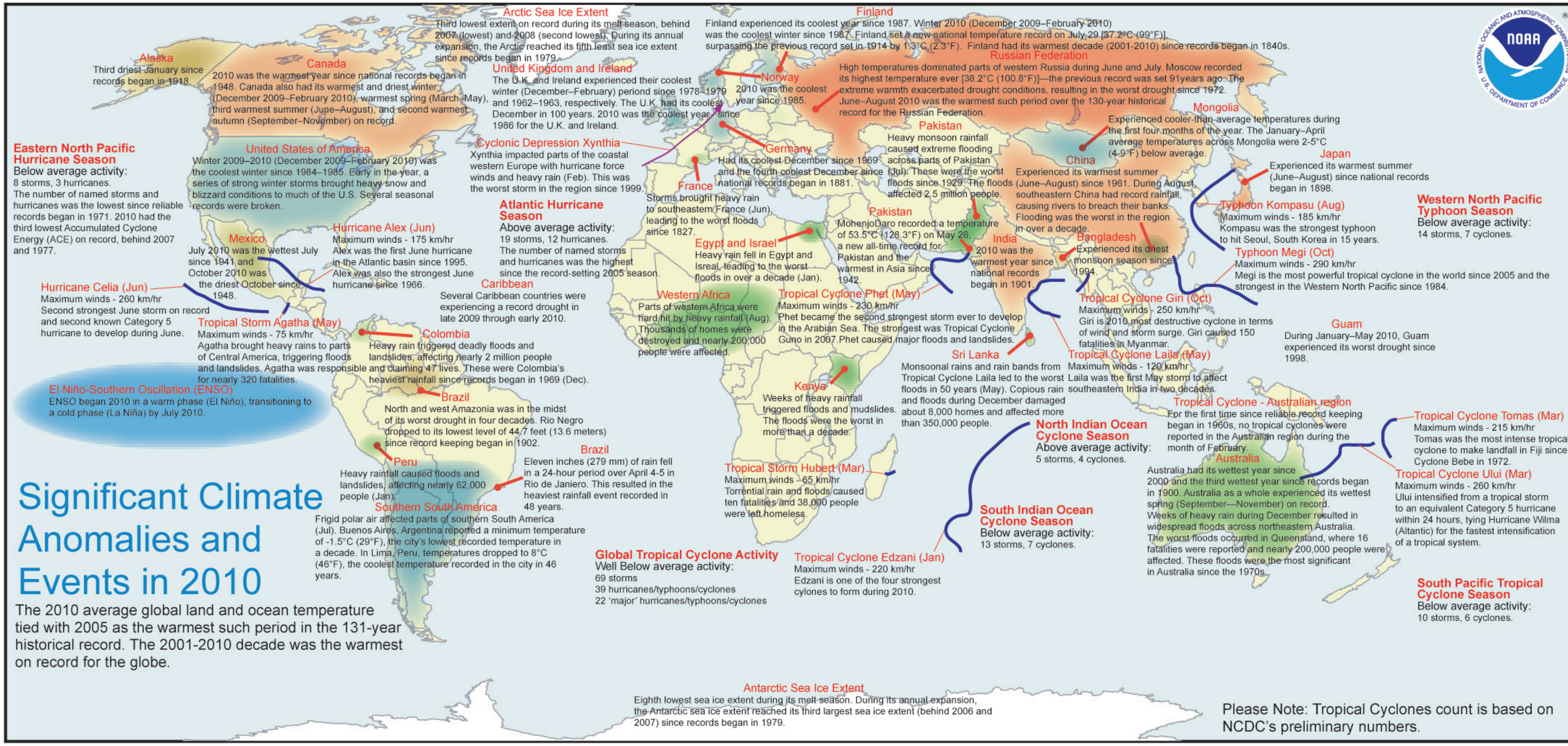


Fig. 1.2. Geographical distribution of notable climate anomalies and events occurring around the planet in 2010.

SIDEBAR 1.1: PATTERNS AND INDICES OF CLIMATE VARIABILITY— A. KAPLAN

Climate variability is not uniform in space; it can be described as a combination of some "preferred" spatial patterns. The most prominent of these are known as modes of climate variability, which affect weather and climate on many spatial and temporal scales. The best known and truly periodic climate variability mode is the seasonal cycle. Others are quasi-periodic or of wide spectrum temporal variability. Climate modes themselves and their influence on regional climates are often identified through spatial teleconnections, i.e., relationships between climate variations in places far removed from each other.

For example, Walker (1924) named the Southern Oscillation (SO) and associated its negative phase with Indian monsoon failure. Later, Bjerknes (1969) connected negative SO phases with El Niño occurrences episodes of amplified seasonal ocean surface warming in the eastern equatorial Pacific and coastal Peru (Fig. 1.3a). Subsequently, the El Niño—Southern Oscillation (ENSO) was observed to be a powerful, demonstrably coupled tropical ocean-atmosphere variability with a global set of climate impacts. In recent years, ENSO events were separated into canonical (Eastern Pacific) and Central Pacific ENSO events (a.k.a. "Modoki", Fig. 1.3b; see Ashok et al. 2007).

Walker (1924) also noticed a smaller-scale (compared to the SO) seesawing surface pressure between the Azores and Iceland (Fig. 1.3c) and named it the North Atlantic Oscillation (NAO; Stephenson et al. 2003). A positive phase of the NAO strengthens the Atlantic storm track and moves it northward, resulting in warm and wet European winters, and cold and dry winters in Greenland and northeastern Canada. In the negative phase the storm track is weaker and more eastward in direction, resulting in wetter winters in southern Europe and the Mediterranean and a colder northern Europe (Hurrell et al. 2003).

Traditionally, indices of climate variability were defined as linear combinations of seasonally-averaged anomalies from meteorological stations chosen in the proximity of maxima and minima of the target pattern. Since gridded fields of climate variables are now available, appropriate regional averages often replace station data. The strongest teleconnections in a climate field are also identified by pairs of grid points with the strongest anti-correlation (Wallace and Gutzler 1981). Table 1.1 defines the most prominent modes of largescale climate variability and the various indices used to define them; changes in these indices are associated with large-scale changes in climate fields. With some exceptions, indices included in Table 1.1 generally have been (1) used by a variety of authors and (2) defined relatively simply from raw or statistically analyzed observations of a single surface climate variable, so that observational datasets longer than a century exist.

Climate variability modes sometimes force other modes of climate variability. For example, a principal component analysis of the North Pacific sea surface temperature (SST) anomaly field (20°N–70°N), relative to the global mean, gives a pattern and index of the Pacific Decadal Oscillation (PDO; Mantua et al. 1997; Zhang et al. 1997), illustrated in Fig. 1.3d. It is different from ENSO but thought to be connected to it through atmospheric bridges and/or internal oceanic wave propagation (Newman et al. 2003; Newman 2007; Schneider and Cornuelle 2005). Despite being defined with Northern Hemisphere data only and being similar to the simple mean sea level pressure-based North Pacific Index (NPI; Trenberth and Hurrell 1994), the PDO index captures well variability in both hemispheres and is similar to the Interdecadal Pacific Oscillation (IPO; Folland et al. 1999; Power et al. 1999).

Principal component analysis of the entire Northern Hemisphere extratropical sea level pressure field identifies a leading mode known as the Northern Annular Mode (NAM) or Arctic Oscillation (AO), which turns out to be very similar to the NAO (Thompson and Wallace 1998, 2000). The Pacific North American pattern (PNA; Fig. 1.3e) also appears as one of the leading variability patterns in the Northern Hemisphere. A Southern Hemisphere analogue of the NAM is the Southern Annular Mode (SAM, Fig. 1.3f), also referred to as the Antarctic Oscillation (AAO), calculated using mean sea level pressure, 850 hPa, or 750 hPa geopotential height in the extratropical Southern Hemisphere (Gong and Wang 1999; Thompson and Wallace 2000).

Atlantic Ocean meridional circulation is affected by the Atlantic Meridional Oscillation (AMO; Fig. 1.3g), which is indexed by the average Atlantic Ocean SST from which the long-term trend is removed (Enfield et al. 2001; Trenberth and Shea 2006). Regional modes of tropical climate variability were identified in Atlantic and Indian Oceans: Atlantic Niño mode and tropical Atlantic meridional mode, Indian Ocean Basin Mode, and Indian Ocean Dipole mode (Fig. 1.3h-k). These modes dominate SST variability in these regions (Deser et al. 2010). The "Cold Ocean-Warm Land" (COWL, Fig. 1.3l) variability is not thought to represent a "true" climate variability mode (Wallace et al. 1995) but has proved very useful for interpreting variations in the hemispheric-scale surface temperature means (Thompson et al. 2008).

The multiplicity of indices defining the same climate phenomenon arises because no index can achieve a perfect separation of a target phenomenon from all other effects in the real climate system [e.g., see Compo and Sardeshmukh (2010) discussion for the ENSO case]. As a result, each index is affected by many climate phenomena whose relative contributions change with time periods and data used. Limited length and quality of observational record compounds this problem. Thus the choice of indices is always application specific.

Table 1.1: Established indices of climate variability with global or regional influence.

Climate Phenomenon	Index name	Index Definition	Primary References	Characterization / Comments
El Niño – Southern Oscillation (ENSO) - canonical, Eastern Pacific ENSO	NINO3	SST anomaly averaged over (5°S–5°N, 150°W–90°W)	Cane et al. (1986); Rasmusson and Wallace (1983)	Traditional SST-based ENSO index
	NINO3.4	SST anomaly averaged over (5°S–5°N, 170°W–120°W)	Trenberth (1997)	Used by NOAA to define El Niño/La Niña events. Detrended form is close to the 1st PC of linearly detrended global field of monthly SST anomalies (Deser et al. 2010)
	Cold Tongue Index (CTI)	SSTA (6°N–6°S, 180°–90°W) minus global mean SSTA	Deser and Wallace (1990)	Matches "cold tongue" area, subtracts effect of the global average change
	Troup SOI	Standardized for each calendar month MSLP difference: Tahiti minus Darwin, x10	Troup (1965)	Used by Australian Bureau of Meteorology
	SOI	Standardized difference of standardized MSLP anomalies: Tahiti minus Darwin	Trenberth (1984)	Maximizes signal to noise ratio of linear combinations of Darwin/Tahiti records
	Darwin SOI	Standardized Darwin MSLP anomaly	Trenberth and Hoar (1996)	Introduced to avoid use of the Tahiti record, considered suspicious before 1935.
	Equatorial SOI (EQSOI)	Standard difference of standard MSLP anomalies over equatorial (5°S–5°N) Pacific Ocean; east (130°W–80°W) minus west (90°E–140°E)	Bell and Halpert (1998)	
Central Pacific El Niño (Modoki)	El Niño Modoki Index (EMI)	SSTA: [165°E–140°W, 10°S–10°N] minus ½[110°W–70°W, 15°S–5°N] minus ½[125°E–145°E, 10°S-20°N]	Ashok et al. (2007)	A recently identified ENSO variant: Modoki or Central Pacific El Niño (non-canonical)

cont. SIDEBAR 1.1: PATTERNS AND INDICES OF CLIMATE VARIABILITY—A. KAPLAN

Climate Phenomenon	Index name	Index Definition	Primary References	Characterization / Comments
Pacific Decadal and Interdecadal Variability	Pacific Decadal Oscillation (PDO)	1st PC of the N. Pacific SST anomaly field (20°N–70°N) with subtracted global mean	Mantua et al. (1997); Zhang et al. (1997)	
	Intedecadal Pacific Oscillation (IPO)	The 3rd EOF3 of the 13-year low-pass filtered global SST, projected onto annual data	Folland et al. (1999); Power et al. (1999)	
	North Pacific Index (NPI)	SLP (30°N–65°N, 160°E–140°W)	Trenberth and Hurrell (1994)	
North Atlantic Oscillation	Lisbon/Ponta Delgada-Stykkisholmur/Reykjavik North Atlantic Oscillation (NAO) Index	Lisbon/Ponta Delgada minus Stykkisholmur/Reykjavik standardized MSLP anomalies	Hurrell (1995)	A primary NH teleconnection both in MSLP and Z500 anomalies (Wallace and Gutzler 1981); one of rotated EOFs of NH Z500 (Barnston and Livezey 1987) . MSLP anomalies can be monthly, seasonal or annual averages. Each choice carries to the temporal resolution of the NAO index produced that way.
	Gibraltar - Reykjavik NAO Index	Gibraltar minus Reykjavik standardized MSLP anomalies	Jones et al. (1997)	
	PC-based NAO Index	Leading PC of MSLP anomalies over the Atlantic sector (20°N–80°N, 90°W–40°E)	Hurrell (1995)	
Annular modes: Arctic Oscillation (AO), a.k.a. Northern Annular Mode (NAM) Index and Antarctic Oscillation (AAO), a.k.a. Southern Annular Mode (SAM) Index	PC-based AO index	1st PC of the monthly mean MSLP anomalies poleward of 20°N	Thompson and Wallace (1998, 2000)	Closely related to the NAO
	PC-based AAO index	1st PC of 850hPa or 700hPa height anomalies south of 20°S	Thompson and Wallace (2000)	
	Grid-based AAO index: 40°S–65°S difference	Difference between normalized zonal mean MSLP at 40°S and 65°S, using gridded SLP analysis	Gong and Wang (1999)	
	Grid-based AAO index: 40°S–70°S difference	Same as above but uses latitudes 40°S and 70°S	Nan and Li (2003)	
	Station-based AAO index: 40°S–65°S	Difference in normalized zonal mean MSLP at 40°S and 65°S, using station data	Marshall (2003)	

Climate Phenomenon	Index name	Index Definition	Primary References	Characterization / Comments
Pacific/North America (PNA) atmospheric teleconnection	PNA pattern index	¼[Z(20°N, 160°W) - Z(45°N, 165°W) + Z(55°N, 115°W) - Z(30°N, 85°W)], Z is the location's standardized 500 hPa geopotential height anomaly	Wallace and Gutzler (1981)	A primary NH teleconnection both in MSLP and Z500 anomalies
Atlantic Ocean Themohaline circulation	Atlantic Multidecadal Oscillation (AMO) index	10-yr running mean of de-trended Atlantic mean SST anomalies (0°–70°N)	Enfield et al. (2001)	Called "virtually identical" to the smoothed first rotated N. Atlantic EOF mode
	Revised AMO index	As above, but subtracts global mean anomaly instead of de-trending	Trenberth and Shea (2006)	
Tropical Atlantic Ocean non-ENSO variability	Atlantic Niño Index, ATL3	SSTA (3°S–3°N, 20°W–0°)	Zebiak (1993)	Identified as the two leading PCs of detrended tropical Atlantic monthly SSTA (20°S–20°N): 38% and 25% variance respectively for HadISST1, 1900–2008 (Deser et al. 2010)
	Atlantic Niño Index, PC-based	1st PC of the detrended tropical Atlantic monthly SSTA (20°S–20°N)	Deser et al. (2010)	
	Tropical Atlantic Meridional Mode (AMM)	2nd PC of the detrended tropical Atlantic monthly SSTA (20°S–20°N)		
Tropical Indian Ocean non-ENSO variability	Indian Ocean Basin Mode (IOBM) Index	The 1st PC of the IO detrended SST anomalies (40°E–110°E, 20°S–20°N)	Deser et al. (2010)	Identified as the two leading PCs of detrended tropical Indian Ocean monthly SSTA (20°S–20°N): 39% and 12% of the variance, respectively, for HadISST1, 1900–2008 (Deser et al. 2010)
	Indian Ocean Dipole mode (IODM), PC-based index	The 2nd PC of the IO detrended SST anomalies (40°E–110° E, 20°S–20°N)		
	Indian Ocean Dipole Mode Index (DMI)	SST anomalies: 50°E–70°E, 10°S–10°N)-(90°E–110°E, 10°S–0°)	Saji et al. (1999)	
Cold Ocean – Warm Land (COWL) Variability	COWL Index	Linear best fit to the field of deviations of NH temperature anomalies from their spatial mean; the COWL pattern itself is proportional to the covariance pattern of the NH spatial mean with these deviations.	Wallace et al. (1995); Thompson et al. (2008)	Useful for removing some effects of natural climate variability from spatially averaged temperature records.

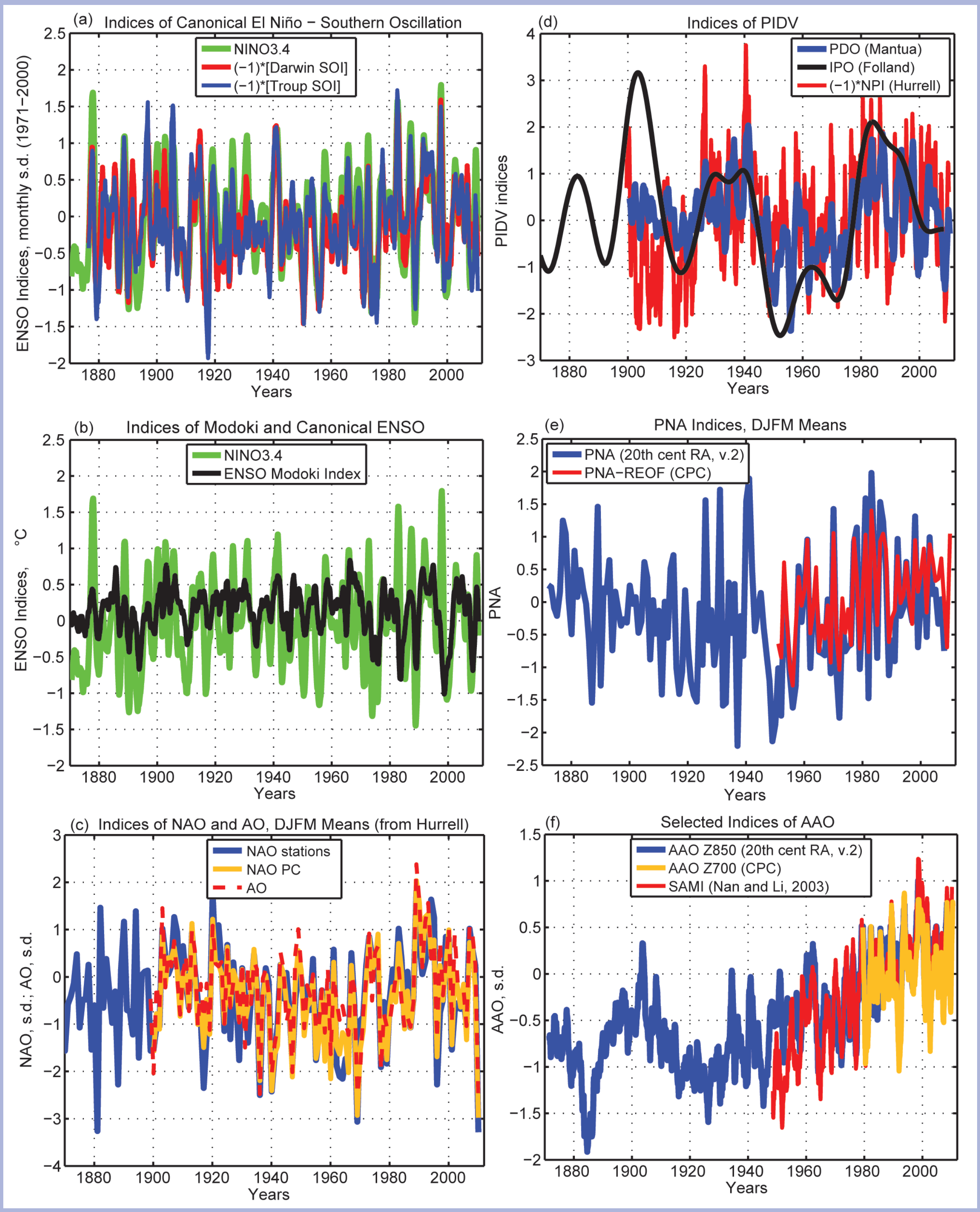
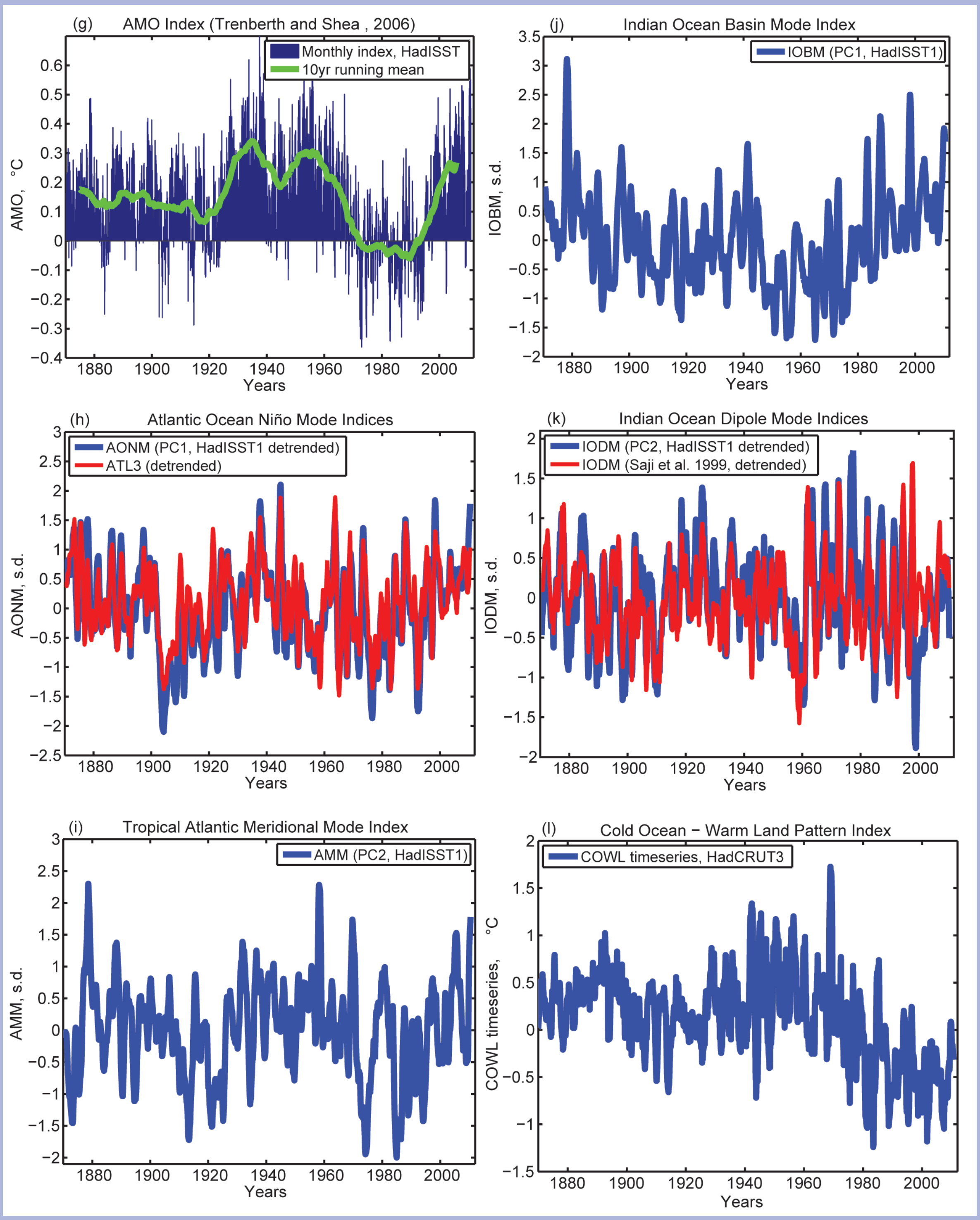


Fig. 1.3. Selected indices of climate variability, as specified in Table 2.3, for the period 1880–2010, grouped into categories: (a) Canonical El Nino -Southern Oscillation (ENSO); (b) the Modoki variant of ENSO; (c) Northern Hemisphere oscillations (NAO, AO, NAM) for the boreal cold season; (d) indices of Pacific Inter-decadal Variability; (e) Pacific-North American indices for the boreal cold season; (f) Southern



Hemisphere oscillations (SAM, AAO) for the austral cold season; (g) Atlantic Meridional Oscillation index; (h) Atlantic Niño Mode indices; (i) Tropical Atlantic Meridional Mode Index; (j) Indian Ocean Basin Mode Index; (k) Indian Ocean Dipole indices; and (l) Cold Ocean— Warm Land pattern. Unless otherwise noted in their panel, 13-month running means of monthly data are shown.

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