

SIDEBAR 1.1: PATTERNS AND INDICES OF CLIMATE VARIABILITY—

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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 1 st 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: $\frac{1}{2}[165^{\circ}\text{E}–140^{\circ}\text{W}, 10^{\circ}\text{S}–10^{\circ}\text{N}]$ minus $\frac{1}{2}[110^{\circ}\text{W}–70^{\circ}\text{W}, 15^{\circ}\text{S}–5^{\circ}\text{N}]$ minus $\frac{1}{2}[125^{\circ}\text{E}–145^{\circ}\text{E}, 10^{\circ}\text{S}–20^{\circ}\text{N}]$ | Ashok et al. (2007) | A recently identified ENSO variant: Modoki or Central Pacific El Niño (non-canonical) |

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| 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 | $\frac{1}{4}[Z(20^{\circ}\text{N}, 160^{\circ}\text{W}) - Z(45^{\circ}\text{N}, 165^{\circ}\text{W}) + Z(55^{\circ}\text{N}, 115^{\circ}\text{W}) - Z(30^{\circ}\text{N}, 85^{\circ}\text{W})]$, 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 Thermohaline circulation | Atlantic Multi-decadal 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. |

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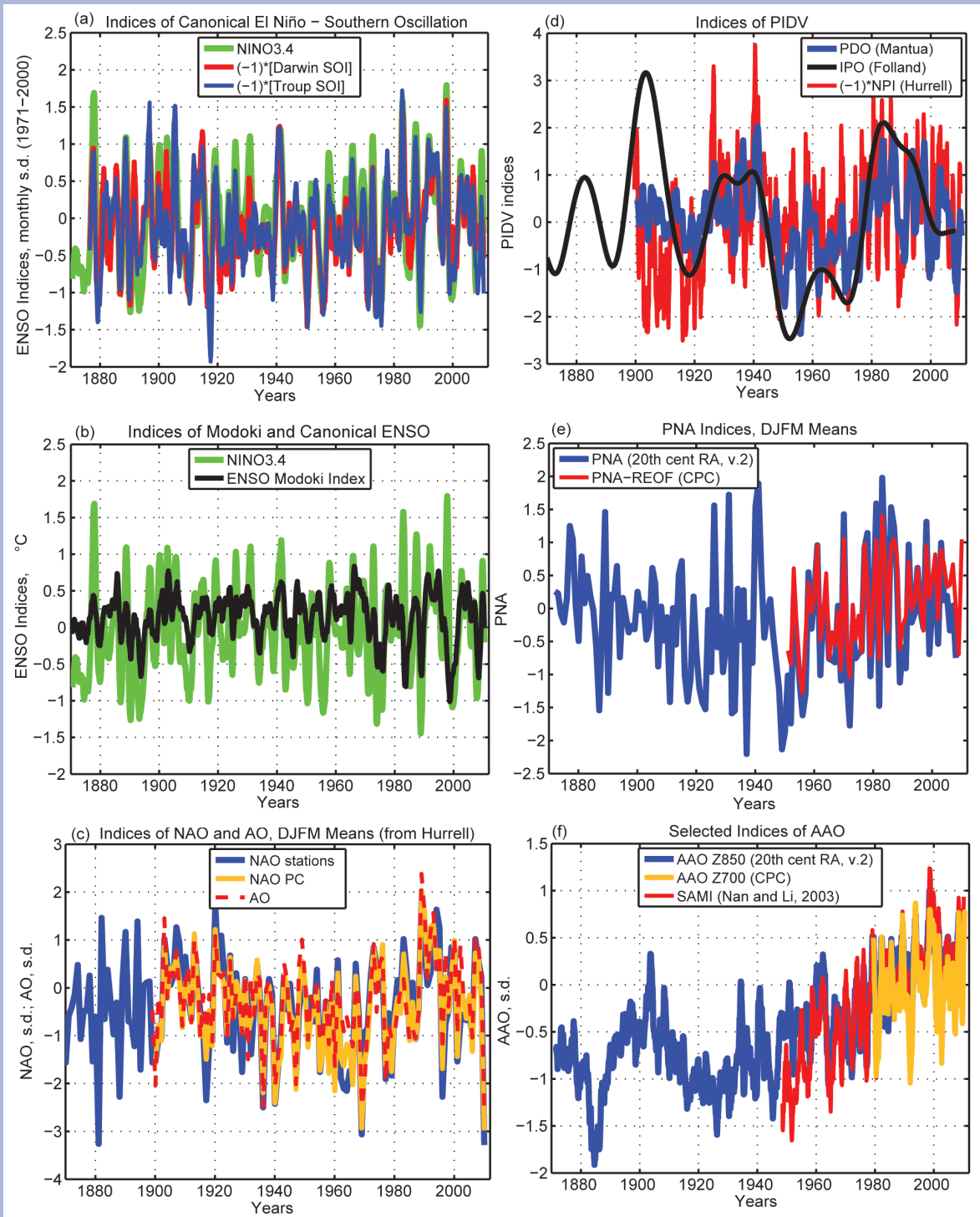
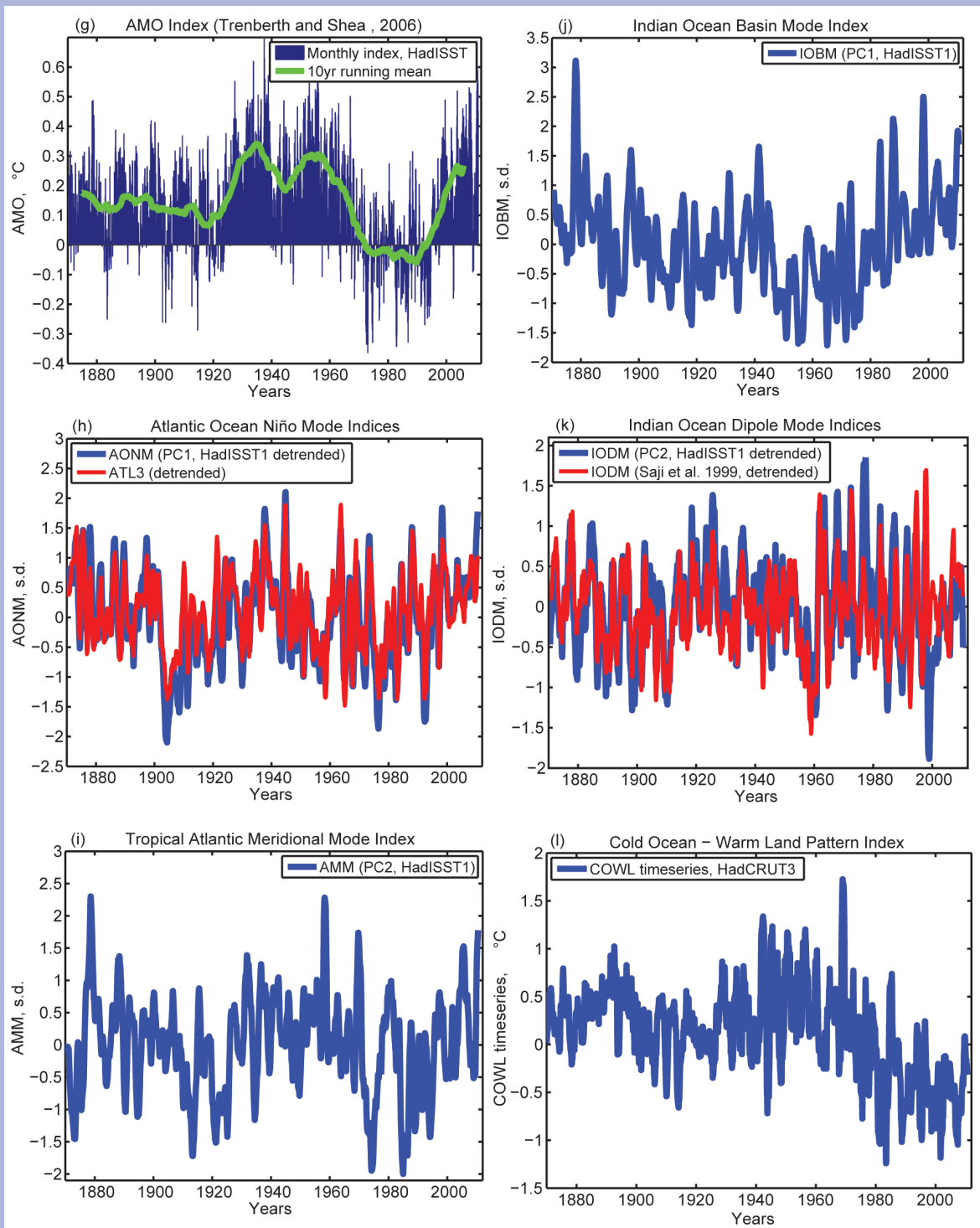


FIG. I.3. Selected indices of climate variability, as specified in Table 2.3, for the period 1880–2010, grouped into categories: (a) Canonical El Niño -Southern Oscillation (ENSO); (b) the Modoki variant of ENSO; (c) Northern Hemisphere oscillations (NAO, AO, NAM) for the boreal cold season; (d) indices 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.