201: Teleconnections in the Earth System

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This article illustrates the large-scale connectivity of the atmosphere–ocean coupled system and generalizes the concept to regional scales and to other components of the earth system. Connections at a distance, or teleconnections, can occur by the direct transfer of mass by changes in regular circulations or by propagating waves initiated by a variety of mechanisms. Questions as to what extent recognized teleconnection patterns can be associated with identifiable forcing mechanisms, to what extent these patterns are interrelated and how they might cause, react to, or interact with changing forcing such as changes in atmospheric composition, land cover, or the distribution of sea ice to produce climate changes are examined.

INTRODUCTION

EQ1 •The term teleconnection is usually defined as a coherent atmospheric response to remote forcing such as particular sea surface temperature or atmospheric pressure patterns. The term is generally applied to a disturbance in the atmospheric circulation that is persistent and of large spatial scale (continental and above). However, a more complete definition should refer to a teleconnection as any transmission of a coherent effect beyond the location at which a forcing occurred. Seasonal weather forecasters noticed certain persistent atmospheric circulation features and were using these patterns for seasonal weather forecasts by the 1950s based on theoretical development by Bjerknes and Rossby in the previous decades (Namias, 1953, 1959).

Circulating fluids, such as the atmosphere and oceans, communicate information over large parts their volume and these teleconnections can be defined to occur in two ways. First, the atmosphere and oceans organize themselves into coherent circulations on a variety of time and spatial scales. These include the Hadley cell, subtropical jet streams, monsoons, sea and mountain breezes, and the oceanic thermohaline circulation. A change to the overall strength or position of the circulation will generally be noticeable over a wide area. Secondly, disturbances associated with these coherent circulations generate waves of several kinds that propagate in fluids in different ways and can be quite persistent. These waves do not necessarily follow the path of the coherent circulations mentioned above and can generate regional climate anomalies far from the source of the original disturbance.

The atmosphere–ocean system appears to oscillate in certain quasi-periodic teleconnection patterns that typically move between different states on a variety of timescales (Barnston and Livzey, 1987). These transitions between states can be quite abrupt or rather gradual, both indicative of the nonlinear character of the climate system (Rial *et al.* 2003). Recognizable climate anomalies associated with each phase of a particular oscillation are then transmitted over wide areas of the globe through the mechanisms mentioned above.

The simplest way to identify such patterns in observational data is to choose points on the globe and correlate that point with every other point. In this way, coherent regions of correlation and anticorrelation may become apparent. More sophisticated statistical methods, such as empirical orthogonal function (EOF) analysis or rotated principal component analysis (RPCA), seek to isolate independent patterns and to maximize the variability associated with the major patterns. Recognized teleconnection patterns seem to result from the internal dynamics of the atmosphere and/or ocean rather than from forcing from outside the

Encyclopedia of Hydrological Sciences. Edited by M. Anderson.

earth system and for this reason they are often referred to as natural modes of variability. Teleconnections offer potential long-term weather predictability based on their persistence and oscillatory behavior and potentially hold the key to understanding the relation between natural and anthropogenic climate change.

Several critical questions as to the nature and mechanics of teleconnections, however, remain. These questions reflect uncertainty as to how to define more-or-less independent patterns and how individual patterns are related to each other, to what extent teleconnection patterns can be associated with a response to an identifiable forcing mechanism, what physical mechanisms are involved in a propagating pattern, and finally, how might teleconnection patterns react to, or interact with, changing forcing such as a atmospheric composition changes, land-cover changes, or changes in the distribution of sea ice? The United States Climate Prediction Center actively monitors 13 separate teleconnection patterns in the Northern Hemisphere for weather and climate forecasting purposes. We will not discuss each pattern extensively, but instead use several of the major teleconnection patterns as illustrations of the remaining uncertainties.

We begin with the apparently more complicated teleconnections, those involving both the atmosphere and the oceans including El Niño/Southern Oscillation and the Madden–Julian Oscillation (MJO).

TYPES OF TELECONNECTIONS

Ocean to Atmosphere/Atmosphere to Ocean

El Niño/Southern Oscillation

El Niño/Southern Oscillation (ENSO) teleconnection patterns can be thought of as resulting from the interannual warming and cooling of equatorial Pacific sea surface temperatures (SSTs) and associated atmospheric circulation changes. This is an arbitrary starting point in the cycle as the changes in SST are likely themselves the result of distant atmospheric and oceanic forcing. ENSO appears to be the result of a series of internal interactions and feedbacks between ocean and atmosphere. The opposing phases of ENSO, the warm El Niño and the cold La Niña, though occurring quasi-periodically with roughly a 3–7 year cycle, have not proved to be highly predictable (Landsea and Knaff, 2000) despite considerable effort.

The ENSO cycle has weather and climate implications in the tropics and across the extra-tropics of both hemispheres. Climatologically, the warmest water in the equatorial Pacific occurs in the western Pacific warm pool (Figure 1a). The tropical signature of El Niño include large, persistent, warm SST anomalies in the eastern and central equatorial Pacific (Figure 1b), a relaxation of the easterly, near-surface winds; an anomalous tilting of the thermocline along the equator towards the east and an associated reduction in cold, nutrient-rich upwelling waters in the eastern equatorial Pacific which in turn affects fisheries production. Warm SST anomalies in the central and eastern Pacific are thought to be caused by an eastward traveling oceanic Kelvin wave following the relaxation of surface easterlies. This shift allows the main Pacific convective storm center from the western Pacific warm pool to shift to the east following the warm SST anomalies. The reduction in cold, upwelling waters in the eastern Pacific further enhances the warm SST anomaly. The La Niña pattern can be thought of as an amplification of the climatological SST patterns with unusually cold SSTs in the central and eastern Pacific and warm SSTs in the west (Figure 1c).

Rising motion due to convective storms in regions of high SST form the starting point for the entire large-scale, tropical circulation, including the north–south Hadley cell and the east–west Walker cells. Changes in the magnitude and spatial pattern of tropical convection therefore alter the magnitude and pattern of the Walker cells and affect the upper-level tropical outflow in the Hadley cell which feeds the higher latitude zonal jet (e.g. Bjerknes, 1969; Krishnamurti, 1961; Chen *et al.*, 1988; Oort and Yienger, 1996). The altered position of the Pacific Walker cell is such that large shifts in atmospheric mass occur with pressure drops in the eastern Pacific and increases to the west. This east-west change in pressure is the basis for the Southern Oscillation index (SOI), a measure of ENSO phase and strength.

Climatologically, rising air and therefore heavy precipitation occur in the western Pacific while the eastern Pacific is under the subsiding branch of the Walker circulation and so is relatively dry. El Niño causes shifts in tropical circulation, which generally create drier than average conditions in the western Pacific including Indonesia, Australia, and India and above average precipitation over parts of South America. El Niños also tend to cause warmer than average conditions over parts of the tropics and into the extra-tropics (Halpert and Ropelewski, 1992). El Niño patterns are so powerful that these events can generally be seen in a general warming of the area-averaged tropics. This warming can also be detected in the globally averaged temperature. For instance, 1998, a year of a very large El Niño event, is the warmest year of the satellite record in the global average (Chase *et al.*, 2004). La Niña, on the other hand, is associated with enhanced rainfall in western Pacific regions and decreased rainfall in the central and east Pacific. La Niña is generally associated with cold regional anomalies that are less easily seen in the globally averaged temperature.

Individual El Niño events vary considerably from the average in terms of duration, time of onset and magnitude and appear to have certain longer-term fluctuations that hamper prediction. For instance, a strong and persistent correlation between reduced Indian monsoon rainfall

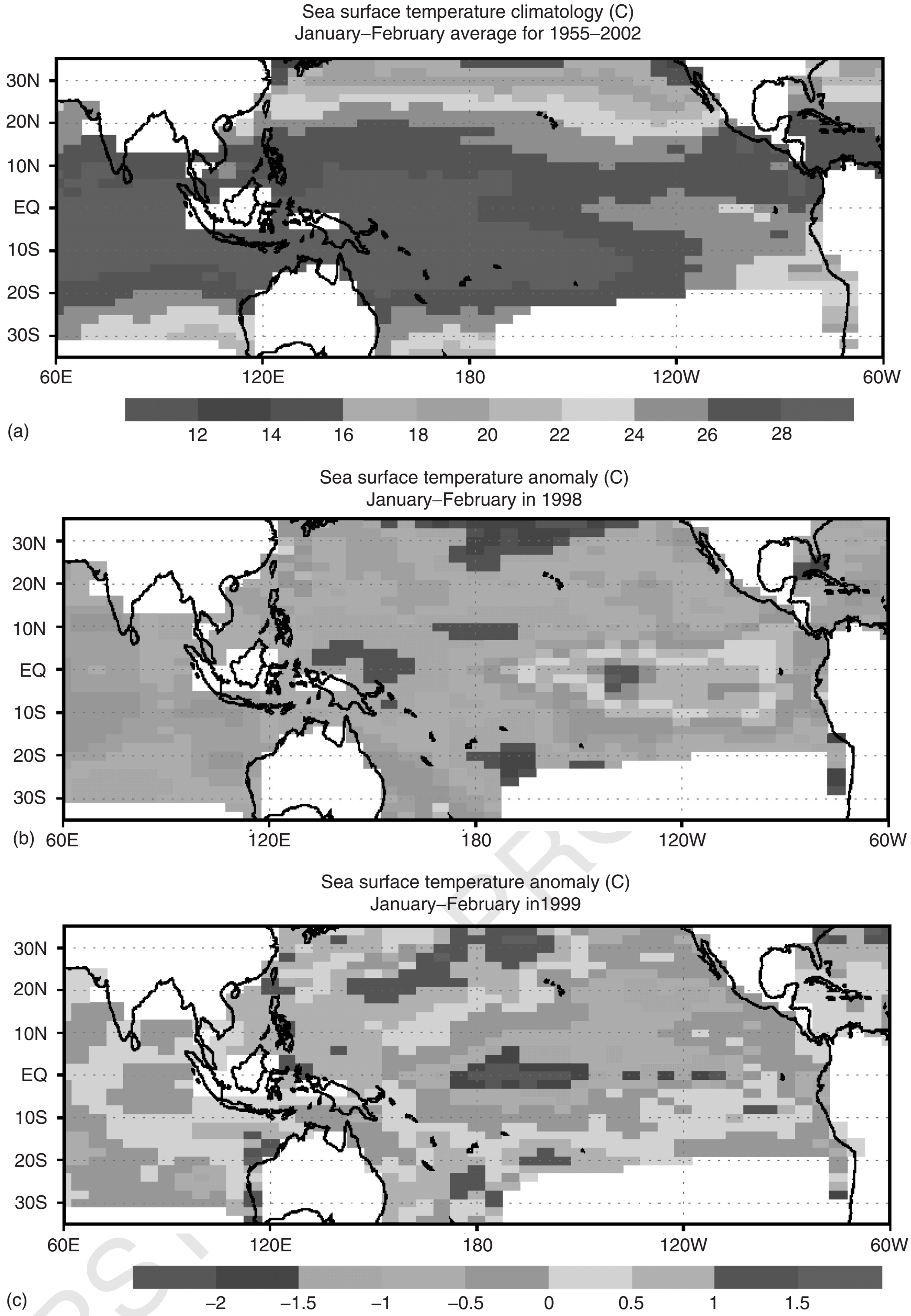

Figure 1 January and February tropical Pacific sea surface temperatures. (a) Climatology with the warmest temperatures in the western Pacific, (b) anomalies for 1998, a strong El Niño year with warmer than usual temperatures in the eastern Pacific, and (c) anomalies for 1999, a La Niña year with cool anomalies in the central and eastern Pacific

and El Niño has diminished in recent years for unknown reasons. Suggested mechanisms further illustrate the interconnectivity of the atmosphere–ocean system and include a higher latitude warming strong enough to enhance the monsoon and overcome the rain suppressing effects of El Niño or a small shift in El Niño convective anomalies, which in turn, shifts the downward branch of the Walker circulation away from India. (Kumar *et al.*, 1999).

Apart from affecting the mean zonal and meridional flow in the tropics, changes in upper-level outflow from tropical convection may also force anomalous atmospheric Rossby waves which can propagate to higher latitudes in a westerly background flow (e.g. Wallace and Gutzler, 1981; Tiedtke, 1984; James, 1994; Tribbia, 1991; Berbery and Nogues-Paegle, 1993). Such wave propagation out of the tropics into high latitudes in great arching patterns is a readily identifiable teleconnection pattern called the *Pacific North American Pattern* (PNA) which arches in a great circle northward from the tropical Pacific and eastward across North America and then southward towards the tropics. Discussion as to whether El Niño distinctly forces the PNA or simply modifies the statistics of an already existing mode of variability is ongoing (Straus and Shukla, 2002). Interestingly, details of each individual ENSO event may be very different in terms of season of onset, duration, strength, and exact location of convective anomalies. The extratropical patterns generated by Rossby waves tend to be roughly similar from event to event though the details of the pattern from event to event can be different (Hoerling and Kumar, 1997). This gave rise to the quite successful westerly duct hypothesis that Rossby waves can only escape the tropics at certain times of year and in certain locations because they cannot propagate in regions of ambient easterly winds. Winter season winds near Southeast Asia turn from easterly to westerly so waves generated within the tropics by shifts in convective activity can escape to higher latitudes from generally the same region (Webster, 1981; Hoskins and Karoly, 1981). It also appears that the extratropical waves may be more a function of the position and strength of the Southeast Asian jet on which the waves are excited, making the response less sensitive to the details of the tropical convective anomalies (Sardeshmukh and Hoskins, 1998).

Regionally, ENSO teleconnections can also be quite important.

In Northern Hemisphere winter, more intense storms occur farther north during El Niño years. Warmer than average conditions occur in the northern United States, eastern Canada, and near Japan. Extratropical effects for La Niña are, in some sense, the opposite of those caused by El Niño with warm conditions in the southern United States and cold, wet conditions in the northwest United States, Japan and southern Africa in northern winter. Correlations with ENSO in many climate variables have been reported across the globe though these correlations tend to be relatively weak and not highly statistically significant and therefore do not offer strong predictability in any single event. Strongly significant and repeatable teleconnections cover only a small portion of the area of the globe but are still highly important climatologically. In other regions, ENSO can offer probabilistic forecasting information.

While the chain of events constituting an El Niño or La Niña is well recognized and provides some statistical predictability in regions around the globe once the phase of ENSO is established (discussed in the Section "Predictability: numerical forecasts using teleconnection patterns"), actual understanding of the mechanisms which start the chain of events or stop it once started have been elusive, and the prediction of the onset of El Niños by both dynamical and physical models have yet to display skill relative to a simple climatology and persistence model of ENSO onset (Landsea and Knaff, 2000). One theory for ENSO is the delayed-oscillator theory (Suarez and Schopf, 1988; Battisti and Hirst, 1989) which posits an unstable atmosphere–ocean system where oceanic Rossby waves generated from previous El Niños or La Niñas act as the excitation for the next ENSO event. Other mechanisms such as monsoonal activity (Webster and Yang, 1992) and the MJO (discussed in the Section "Madden–Julian oscillation") have also been proposed as modulators of ENSO though such theories only lengthen the chain of causality as these phenomena are themselves even less understood than ENSO. Finally, Penland and Sardeshmukh (1995) have hypothesized that the tropical Pacific atmosphere/ocean system is not an unstable system waiting for triggering mechanisms but that the ENSO variability is best thought of as a response of the tropical Pacific system to stochastic climate noise.

Recent trends in ENSO and other teleconnection patterns will be discussed in the climate change section below.

Madden–Julian Oscillation

An example of the difficulties in associating an observed teleconnection pattern with physical mechanisms is the Madden–Julian Oscillation. First identified in the 1970s, the MJO is characterized by an observed, eastward moving atmospheric circulation anomaly and associated convection anomalies that can be identified in the wind, cloud, and outgoing long-wave radiation (OLR) fields along the equator with an approximate 40–50 day time period. The convective anomalies are strongest over the Indian Ocean and eastward over the west Pacific warm pool to the date line. Little sign of convective anomalies appear from the central through eastern Pacific. The MJO differs from the relatively spatially fixed teleconnection patterns such as the Arctic Oscillation (discussed below) in that it travels across the Pacific with a speed of approximately $5–10\,\mathrm{m\,s^{-1}}$.

The exact nature of the forcing of the MJO and its method of eastward propagation have eluded adequate theoretical

explanation as yet (Waliser *et al.*, 1999) and the oscillation is not well represented in model simulations (Slingo *et al.*, 1996). This is a problem in that the MJO dominates tropical climate variability at intra-annual timescales (while ENSO dominates interannual variability). Theories for the initiation and propagation of the MJO have centered on
Q1 the wave •CISK mechanism (Lau and Peng, 1987) and the wind evaporation feedback (Emmanuel, 1987; Neelin *et al.*, 1987). However, both have failed to produce adequate representations of the MJO. Wave CISK theory typically produces oscillations with phase speeds of 15 m s^{-1} or
Q2 greater, which is significantly faster •than observations. Wind-evaporative feedback mechanisms require easterly winds at the surface. While surface winds are easterly in much of the tropics, regions where the oscillation is most noticeable have climatological westerly winds at the surface.

The idea that the MJO is part of a coupled atmosphere–ocean oscillation, similar to ENSO, is the subject of active research (e.g. Waliser *et al.*, 1999; Woolnough *et al.*, 2000). Recent research (Seo and Kim, 2003) conclude that the MJO is a coupled oscillation of the ocean–atmosphere system and represents an interaction between two classes of waves, Rossby and Kelvin waves, leading to a self-generating and self-propagating disturbance.

The MJO is associated with the timing of the active and break period of both the Indian and Australian monsoons (Madden and Julian, 1994) and may have some role in triggering ENSO events (Kessler *et al.*, 1996; Zhang and Gottschalk, 2002) further complicating ENSO prediction. There does not appear to be a strong signal of the MJO in the extra-tropics (Madden and Julian, 1994).

Teleconnections in the Atmosphere

North Atlantic Oscillation-NAO/Arctic Oscillation-AO

Whether the major mode of mid and high Northern Hemisphere variability is better characterized as a regional oscillation known as the *North Atlantic Oscillation* (NAO) or a circumpolar mode referred to as the Arctic Oscillation (AO, Deser, 2000; Wallace and Thompson, 2002; Aambaum *et al.*, 2001) remains an open question illustrating the sometimes ambiguous way the atmospheric circulation organizes itself.

The NAO is a north–south oscillation of mass between the subtropical North Atlantic and Arctic. A measure of the NAO is an index generally defined as a pressure difference between a high-latitude station representative of the Icelandic low (Reykjavik or Stykkisholmur, Iceland) and a subtropical station (Lisbon or Gibraltar) representative of the other center of action in the Azores surface high-pressure system. A positive NAO index is an indication of more meridional flow across the Atlantic, which allows for warmer and more moist conditions in northwestern Europe while the negative phase is an indication of zonal flow and colder temperatures in western Europe and more moisture in southwestern Europe. The phase of the NAO also modulates climate in eastern North America (Wettstein and Mearns, 2002) and North Atlantic, particularly in winter months. The NAO, like ENSO, is an interannual oscillation with an irregular pattern of several years.

A• related pattern, the AO, has been recently thought to Q4
be a more general mode of variability that actually includes the oscillation in the North Atlantic but expands it to a more symmetric annular mode, meaning that mass oscillates between the Arctic and lower latitudes in a giant ring around the circumference of the globe (Figure 2). The Arctic oscillation is seen in the first EOF in sea level pressure as three main centers of action, one in the Arctic, and two in the lower latitude centers in the North Atlantic and the North Pacific (the oscillation is not perfectly annular). The North Pacific center is substantially weaker than the North Atlantic center, giving rise to controversy as to which pattern, the AO or NAO, is actually climatologically more significant, and whether the AO is simply an artifact of statistical analysis (Deser, 2000; Aambaum *et al.*, 2001). Pressure in the two lower latitude centers of action is observed to be anticorrelated with pressure in the Arctic

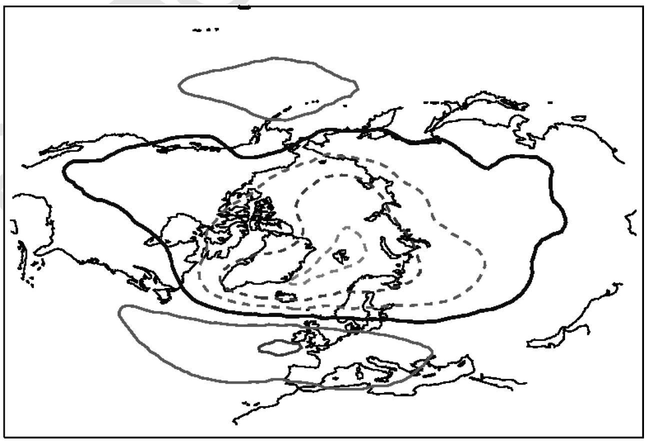

Figure 2 First• EOF of sea level pressure from NCAR/NCEP Reanalysis showing the major mode of variability in the Northern hemisphere circulation including both the NAO and the AO. EOF analysis shows the preferred spatial organization of variability over time. In this case, three nodes are visible, one centered in the Arctic Ocean and two others at low latitudes in the Pacific and Atlantic oceans of opposite sign (brown contour is zero). The interpretation of this figure is that atmospheric mass oscillates back and forth between the high-latitude node and the two low latitude modesTN If one only looks at the Arctic-North Atlantic nodes this is the NAO. All three nodes comprise the AO and suggest a more annular character as the zero line extends around the globe Q3

as would be expected in a coherent, annular movement of mass from high latitudes to lower latitudes. However, the two lower latitude centers of action are only very weakly correlated with each other suggesting that the AO is not really a globally coherent pattern. Wallace and Thompson (2002) suggest that other modes of variability are masking the coherence of the lower latitude pattern but it is still unclear which pattern will become favored.

In an effort to produce an idealized annular mode in a general circulation model, Cash *et al.* (2002) applied zonally symmetric surface boundary conditions and examined individual annular mode events (as opposed to a long-term average) and conclude that, even with no zonal changes in surface conditions, the primary mode is best conceived of as a series of regionally localized, north-south shifts in mass more in line with the NAO conception of Northern Hemisphere variability.

Monahan *et al.* (2001) suggest that the two patterns are not independent and the question may come down to the subjective judgment as to which paradigm organizes thinking most productively as suggested by Wallace (2000).

Teleconnection patterns are of interest because of the potential for long-term predictions if the source of the teleconnection can be understood. This is still not the case with the NAO/AO. Many studies have examined the factors involved in forcing variability in the AO/NAO and have found a variety of potential mechanisms within the earth system: SST (Rodwell *et al.*, 1999; Schneider *et al.*, 2003; Mehta *et al.*, 2000), snow cover (Gong *et al.*, 2002), volcanism (Stenchikov *et al.*, 2002), random stochastic variability (Schneider *et al.*, 2003; Tanaka, 2003; Wunsch, 1999), and stratospheric dynamics (Zhou *et al.*, 2001; Baldwin and Dunkerton, 1999; Black, 2002). Robertson (2001) concludes that the Arctic Oscillation is an inherent mode of atmospheric variability alone and that coupling a model to an interactive ocean does not change the simulated AO relative to a simulation with fixed SSTs suggesting limited predictability even with a knowledge of SST distribution.

Pacific Decadal Oscillation-PDO

The Pacific Decadal Oscillation (PDO) is a longer-term oscillation than those discussed previously. The average PDO phase persists for several decades though the period for an individual event is also quite a bit more variable than previously discussed patterns. PDO oscillations have energy peaks at both 15–25 year and 50–70 year timescales (Minobe, 1997) and is an example of interdecadal atmospheric variability. Such long-term patterns are of great interest because of the possibility of long-term predictive skill. However, as with other teleconnection patterns, the source of the PDO is not currently known and the predictability has not proved highly successful. It also remains unclear whether the PDO has been a consistently dominant mode of variability over long time periods. For instance, Gedalof and Mantua (2002) conclude that the PDO was less of a climatic factor in the nineteenth century than at present based on long-term proxy records.

While the PDO teleconnection pattern looks somewhat similar to El Niño, the strongest anomalies are in the extratropics with secondary signatures in the tropics, the opposite as observed with El Niño. The similarity in patterns may be explained by the observation that the PDO may actually be forced by ENSO anomalies, which are subsequently projected onto lower frequency variations by stochastic climate variability (Newman *et al.*, 2003). Such a forcing mechanism, if it proves robust, would make the PDO another coupled atmosphere–ocean mode of variability but we categorize it as atmospheric only until further evidence is accumulated. The PDO seems also to have utility in long-range forecasting. For example, Castro *et al.* (2001) have used a combination of ENSO and the PDO to diagnose summer precipitation patterns and temporal evolution in the western United States.

Teleconnections From Land to Atmosphere

The high interconnectivity of the atmosphere–ocean system suggests that other perturbations to the earth system might be reflected far from the original disturbance and may have some influence on previously discussed teleconnection patterns. Here, we examine the example of land-cover changes in detail but a variety of processes, such as perturbations due to atmospheric pollution including aerosol clouds, may be operating in very complicated ways which are only beginning to be appreciated or investigated.

Large-scale land-cover changes, particularly in the tropics appear to generate remote climatic effects and may interact with better-known teleconnection patterns. The three major tropical convective heating centers are associated with the land surfaces of Africa, Amazonia, and the maritime continent of Indonesia, Malaysia, New Guinea, and surrounding regions (e.g. Kreuger and Winston, 1973). Changes in this vegetation structure has major impacts on the momentum and radiant energy absorbed at the surface and its partitioning into latent and sensible forms which affect surface temperatures and the structure and strength of convective storms (e.g. Dickinson and Kennedy, 1992; Nobre *et al.*, 1991; Eltahir, 1996; Polcher and Laval, 1994; Baidya Roy and Avissar, 2002).

Teleconnections resulting from land-cover changes in climate models have been discussed by Franchito and Rao (1992), McGuffie *et al.* .(1995), Chase *et al.* (1996) and Zhang *et al.* (1996). Others have also noted isolated extratropical effects due to simulated tropical vegetation changes (Sud *et al.*, 1996; Sellers *et al.*, 1996). Chase *et al.* (2000) examined •GCM model simulations of the effect of observed levels of land-cover change globally and found strong evidence of changes in global scale circulations and for the propagation of Rossby waves into the mid latitudes. Pitman and Zhao (2000), Zhao *et al.*

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(2001), Bounoua *et al.* (2002) again demonstrated that the remote effects of observed levels of land-cover change were prevalent in a variety of models under a range of configurations and model assumptions and that remote temperature anomalies resulting from land-cover change could be similar in magnitude as effects of the historical increase of the radiative effect of increased CO_2 (Chase *et al.*, 2002). Gedney and Valdes (2000), also using a GCM, specifically examined the effects of a wholesale removal on the Amazonian rainforest on remote climates and found significant evidence for a reduction in large-scale circulations generated by tropical convection and for propagating Rossby waves which affected rainfall in Northern Hemisphere winter. Werth and Avissar (2002) and Avissar and Werth (2004) find statistically significant teleconnection patterns due to deforestation in Amazonia, Central Africa, and Southeast Asia (Figure 3). Defries *et al.* (2002) examined potential impacts of future land-use changes and found regional temperature anomalies of up to 1.5 °C in regions not directly affected by land-cover changes. Such teleconnection patterns due to human activity might be expected to interact with natural modes of variability and this is an ongoing area of research.

Teleconnection patterns also strongly affect the biosphere, which implies high levels of interaction and mutual self-adjustment between these components of the earth system. For instance, Asner *et al.* (2000) attribute changes in net primary production in Amazonian forests of up to 18% due to ENSO oscillations and found that El Niño years were responsible for large fluxes of CO_2 into the atmosphere in the tropics. Kitzberger *et al.* (2001) found that forest fires in the Southwest United States and in Patagonia, Argentina were related to phases of ENSO. El Niño years are wet in these regions allowing plant growth and accumulation of fuel. La Niña years are dry in these regions and so the high fuel loads become desiccated leading to high rates of burning. Additionally, the effects of teleconnection patterns are not limited to the primary producers. Nott *et al.* (2002) found that seasonal ENSO and NAO weather changes resulted in strong effects on the productivity of a variety of bird populations.

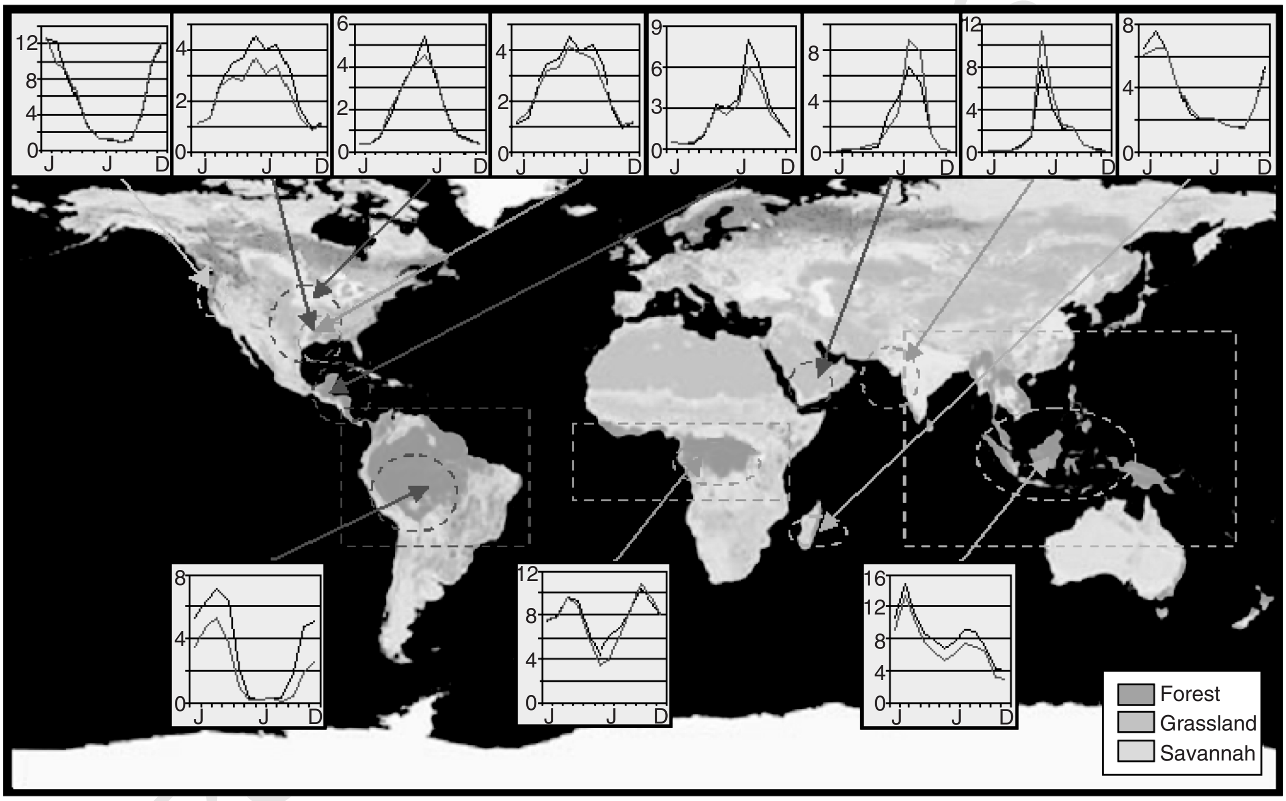

Figure 3 Annual cycle of precipitation (mm/day) in continental regions particularly affected by the deforestation of Amazonia (red arrows), Central Africa (green arrows), and Southeast Asia (blue arrows). The blue curves represent the mean monthly precipitation before massive deforestation started in tropical regions (i.e. the "control" case). The red curves indicate the corresponding precipitation following tropical deforestation. The size and location of the color-coded areas corresponding to the deforested regions are at scale. Color-coded ellipses indicate the regions in which tropical forest (in green on the 1-km resolution land-cover map used for the background) was replaced with a mixture of shrubs and grassland (derived from Avissar and Werth, 2004)

Regional Teleconnections

While the term teleconnection is usually applied to patterns with continental-scale variations that are long lasting, the term can also be generalized to distant influences resulting from changes in smaller scale circulations, or from changes in ecosystem function. For example, Chase *et al.* (1999) found weather influences in the high Rocky Mountains due to the presence of irrigated farmland in the plains below. Irrigated regions affected the daily summer mountain-plains breeze by altering temperature patterns thereby allowing communication between the two regions. Such changes in local circulation regime would be expected to alter the transport of pollutants or atmospherically transported micronutrients and so may be of importance in many locales. Along similar lines, Eastman *et al.* (2001) described a "biological teleconnection" where changed ecosystem characteristics affected local weather such that effects were communicated to regions to regions distant from actual changes in surface characteristics.

A final example of the complex regional nature of some teleconnections and how human effects on climate might be difficult to pinpoint is an observational study of the effect of irrigation on downwind rainfall patterns. Moore and Rojstaczer (2002) found a maximum increase in summer precipitation some 90 km away from the irrigated region.

PREDICTABILITY: NUMERICAL FORECASTS USING TELECONNECTION PATTERNS

The atmosphere-ocean system is nonlinear making long-term prediction of individual weather events impossible. Even assuming a perfect climate model, small errors in the observed initial conditions invariably grow exponentially in magnitude and spatial scale. Therefore, long-term weather and climate forecasts use expected probabilities of certain types of weather based on statistical relationships from past observations. These relationships often take the form of teleconnection patterns.

One major advance in long-range forecasts is the realization that ENSO has documented effects in many parts of the globe. Many regions show a statistical tendency towards more or less precipitation or higher/lower temperatures depending on the phase of ENSO. ENSO has a fairly regular periodicity allowing for some skill in predicting changes in phase just from climatology or persistence. Several dynamical models also try to predict the future phase and resulting teleconnections of ENSO though these have not been dramatically more successful than knowledge of the climatology and persistence (Landsea and Knaff, 2000). The phase of ENSO is the single most important factor going into long-range forecasts today.

A statistical technique called a *canonical correlation analysis*, used in long-range climate forecasts, combines a series of indicators, including teleconnection indices, to infer possible preferred future patterns. This technique uses model-simulated weather patterns, global SST patterns, surface temperature, and precipitation for the past year to infer information about persistence and trends over the year. ENSO is emphasized in this analysis but other natural modes of variability such as the NAO are also accounted for. This analysis makes use of the forecast for La Niña, El Niño, or neutral conditions in the equatorial Pacific and then takes into account the confidence that this one phase of ENSO will exist.

Such information is used in a series of forecast simulations that differ slightly in order to estimate the envelope of possible atmospheric responses under such conditions. The relative occurrence of a particular climate pattern in these ensemble forecasts determines the probability of an individual event being forecast.

CLIMATE CHANGE

"Greenhouse Gas Warming" and Projection on Natural Modes

The major teleconnection patterns such as ENSO, NAO/AO, and the PDO occur in an irregularly periodic manner. Longer-term structure characterizes each of these patterns with periods of stronger or weaker intensity, altering periodicity and shifts favoring one phase of the oscillation over the other. The variability of climate due to these teleconnection patterns is therefore variable over longer timescales. Such longer-term variability has yet to be explained and appears to be particularly important in assessing present-day and future human impacts on climate.

For example, recent shifts favoring the warmer phase of two natural teleconnection patterns, ENSO and NAO/AO have been directly linked to a large portion of the observed Northern Hemisphere winter warming signal (Palecki and Leathers, 1993; Hurrell, 1996; Corti *et al.*, 1999). A trend in the NAO index toward more positive values since the early 1960s has been documented (Hurrell, 1996). Similarly, the observed SO index has shown a tendency towards more negative (El Niño-like) values since the middle of the century with a steep change to more negative values in the mid 1970s. Hurrell (1996) demonstrates that when these two natural circulation influences are removed from the time series, no discernible upward surface temperature trend remains (See Figure 4 in Hurrell, 1996). While such observations might be taken as an indication that recently observed warming is natural rather than a result of rising greenhouse gases, Corti *et al.* (1999) argue that greenhouse warming might be expressed in terms of changes in natural modes of variability. Stone *et al.* (2001) do find a general projection of climate change on the most dominant modes of variability suggesting that these need to be actively monitored for future change.

Therefore, the question remains whether recent shifts towards more and larger El Niños is a reflection of natural variability or is forced by human activity. Cobb *et al.* (2003), examining isotope signatures in fossil corrals, conclude that past variability of ENSO cycles is unrelated to the mean temperature and that eras in the past 1100 years have seen ENSO cycles that rival present-day fluctuations. This observational study supports the statistical analyses of Rajagopalan *et al.* (1997) and Wunsch (1999) who both found the present trend toward more and larger El Niño events to be within the bounds of natural variability. Trenberth and Hoar (1996), however, in a differing statistical analysis, found recent trends to be statistically unusual and concluded that this was evidence for human influence on climate.

Reports from model simulations as to circulation changes due to increasing greenhouse gases are, at present, contradictory. There have been reports of changes, which favor a positive shift in the Southern Oscillation (more La Niña-like) (e.g. Timmerman *et al.*, 1999; Hu *et al.*, 2001) while others find a tendency for increasing negative phase (e.g. Meehl, 2000; Collins, 2000). Still others find no change (e.g. Tett, 1995) or an increase in amplitude in both phases of the SO but no clear favoring of one phase over the other. Additionally, reported changes in the SO typically occur at CO_2 levels far above present levels of forcing and are therefore not entirely applicable to present-day conditions.

Simulated changes in the NAO/AO under increased greenhouse gases and/or aerosols also have a quite complicated response between simulations. Q6 •Paeth *et al.* (2000) show a steadily increasing NAO index in climate change simulations starting at about the correct time but find no statistical significance. Shindell *et al.* (1999) show a positive trend in model-simulated NAO with present-day levels of CO_2 forcing, however, the trend between 1959 and 2000, the period of observed increase in the NAO index, is static (see Shindell *et al.*, 1999: Figure 2b). Fyfe *et al.* (1999), also show an increase in the NAO but only at much higher levels of CO_2 forcing than presently observed.

Further complicating the picture, Osborn *et al.* (1999) find the opposite effect with a decreasing NAO index in climate change simulations starting at present-day and continuing through the century. Zorita and Gonzalez-Rouco (2000), in a head-to-head comparison of two climate models, found highly variable results between the models. In the first model examined, they found positive AO trends in the first realization and negative AO trends in the second realization using different initial conditions. The second model had a clear positive trend in two realizations though at differing times in the simulation (i.e. under different greenhouse forcing) so that present observations are still not well explained.

Finally, it is unclear how robust the results from any single model are. For example, Collins (2000) found a shift towards a more El Niño-like state at four times natural CO_2 (approximately 12 times present levels) though when small details of the model formulation were changed the simulation produced the opposite change in circulation.

Other Human Influences on Teleconnection Patterns

There exists some evidence for a highly complicated human effect on natural climate variability. Chase *et al.* (1996) found that climate model-simulated tropical circulation shifts due to historical changes in vegetation were consistent with conditions favorable for inducing El Niño events at the expense of La Niña while Chung and Ramanathan (2003) found in model simulations that atmospheric haze originating in southern Asia and due mostly to human activity (such as clearing of agricultural land) also led toward conditions which favored El Niño at the expense of La Niña.

Human effects on teleconnection patterns may also be quite indirect.

For example, Alexander *et al.* (2004) find a NAO-like pattern in response to model-simulated changes in Arctic sea ice extent suggesting that should a warming climate cause large changes in sea ice, a large part of the effect would be seen in changes in circulation patterns. Similarly, changes in snow cover in a warming world would be expected to affect other large-scale circulations, such as the Indian monsoon system (Blanford, 1884; Fasullo, 2004a), which also interacts with ENSO. While such interactions require further confirmation, the potential effect of human activity on climate and circulation variability is apparently multifaceted and complex.

ISOLATED OR INTERCONNECTED?

A fundamental question concerning the major patterns of teleconnections is how independent they are. Because a definitive “cause” of any teleconnection pattern is elusive, it is possible that subsets of the patterns are in reality interrelated and part of a larger oscillatory phenomenon. Signs of interrelatedness are appearing more frequently in studies of teleconnection patterns.

For instance, there are indications that tropical Pacific SST patterns and hence ENSO may have some impact on the evolution of the NAO/AO pattern (Hoerling *et al.*, 2001; •Schneider, 2003). Q7 Further, it appears that South Pacific SST patterns may influence the development of tropical SSTs on decadal timescales (Bratcher and Giese, 2002). Hakkinen and Mo (2002) find that tropical Atlantic Ocean temperature anomalies in boreal winter are related to North Atlantic •forcing due to fluctuations in the North Atlantic Q8 oscillation that generate equatorward propagating Kelvin waves, and are also influenced by teleconnections from the tropical Pacific, which can either work in conjunction or in opposition to each other. Gong and Ho (2003), find a significant relationship between the AO and East Asian summer monsoon rainfall due to a northward shift of the East Asian jet stream. As discussed previously, the Asian summer monsoon is known to interact with ENSO and the MJO. Further, Yang *et al.* (2002) find a teleconnection between the strength of the East Asian jet stream and weather downstream in East Asia, the Pacific, and North America, which appear distinct from ENSO patterns. Branstator (2002) further highlights the importance of remote effects due to the East Asian jet by showing that perturbations to the jet can be circumglobal in nature (an indication that the regional analysis of teleconnection patterns may be fundamentally misleading) and may, in part, be responsible for the patterns associated with the NAO. Kiladis and Weickman (1992) find forcing of El Niño variability by high-latitude storms. Xie and Tanimoto (1998) find a decadal teleconnection pattern spanning both hemispheres from the southern subtropics to the high northern latitudes apparently unrelated to the other patterns mentioned here but suggesting that the major teleconnection patterns may be linked by a variety of mechanisms. Miller *et al.* (2003) find a statistical association between the phases of the AO and the MJO further suggesting regular tropical/extratropical interactions between modes of atmospheric variability.

Therefore, it appears that evidence is emerging that the climate system is coupled in a variety of complicated ways and that conceiving of variability in terms of a series of isolated teleconnection patterns may give way to a view that each of the patterns is interrelated in some way, each forcing and being forced by the others. Long chains of causality linking some or all modes of variability might improve predictability if the chains of events are regular, though past experience indicates that relationships between the modes vary with time.

SUMMARY

This discussion illustrates the large-scale connectivity of the atmosphere–ocean coupled system and generalizes the concept to regional scales and to other components of the earth system. These connections at a distance, referred to as teleconnections, can occur by the direct transfer of mass by changes in regular circulations or by propagating waves initiated by a variety of mechanisms.

We have not discussed in detail several processes, which could rightfully be included in this section such as the regional monsoon systems, local winds, or the oceanic thermohaline circulation that, if changed, could have large climate repercussions all around the globe. We have, however, addressed the basic remaining uncertainties as to the nature of teleconnection patterns with prominent examples. Questions remain as to what extent recognized teleconnection patterns can be associated with an identifiable forcing mechanism, to what extent these patterns are interrelated and how they might cause, react to, or interact with changing forcing such as changes in atmospheric composition, land cover, or the distribution of sea ice to produce climate changes?

Acknowledgments

This work was supported under the following grants: NSF ATM-0001476, ATM-0346554; NASA NAG5-11400, NAG5-11402, NAG5-13781, NAG5-11370; NOAA NA17-RJ1228 Amendment 6. We thank Eungul Lee and Aaron Rivers for graphics assistance and two anonymous referees for their helpful comments.

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Keywords: teleconnection; circulation change; atmosphere-ocean interactions; biosphere-atmosphere interactions; ENSO; NAO/AO

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