Atmospheric variability and extreme Autumn rainfall in the UK

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Autumn 2000 was exceptionally wet over England and Wales and much of western Europe. The extreme weather prompted a public debate about a possible increased frequency of such extremes due to climate change. We investigate the patterns of atmospheric variability and underlying mechanisms associated with this record-breaking season and previous wet Autumns, and we identify a particular pattern of anomalies extending from the mid-Atlantic over Eurasia (the Scandinavia pattern). Using analysed data and an idealised atmospheric model, we show evidence for a catalytic role played by conditions over the tropical Atlantic and South America in the anomalous European weather in Autumn 2000. We briefly investigate the historical data for evidence of trends in England-Wales Autumn precipitation.

Characteristics of Autumn 2000

The Autumn season of 2000 (the period September to November, SON) saw record precipitation and severe flooding in western Europe. It was the wettest Autumn in England and Wales since records began in 1766 (Alexander and Jones, 2001), while several regions from France to Norway received double their average rainfall and there were severe floods and mud-slides in the southern Alps (Lawrimore et al, 2001; WMO, 2001).

The season was characterised on average by a displacement of the Atlantic jetstream eastward from its climatological position. The region in which air exits from the jet was more marked than usual over western Europe and displaced south of the UK (Fig. 1). Individual weather systems tend to move in the sense of a vertically-averaged flow, and this anomalous jetstream brought intense systems into western Europe, where they slowed, repeatedly leading to prolonged precipitation events. Dynamical considerations (Hoskins et al, 1978) also suggest that the poleward side of a jet exit region is one of preferred near-surface cyclone growth and dynamically forced ascent. In Autumn 2000 the southward displacement of the jet exit moved this preferential region south from its normal elongated position near 55°N to lie, instead, directly over England and Wales.

The anomalous jetstream was associated with a train of anomalies in geopotential height extending from the subtropical Atlantic across Eurasia, with a cyclone over the UK and strong anticyclone over Scandinavia (Fig. 2). This wavelike pattern was present through the depth of the troposphere, with an equivalent-barotropic structure (Charney and Eliassen, 1949; Thompson, 1961), indicative of a train of quasi-stationary Rossby waves. The persistence and coincidence of this anomalous pattern with the wet period in the UK, from mid-September to mid-December, were notable. It also recurred later in the winter together with further wet periods.

Previous wet Autumns and the Scandinavia pattern

To test whether this pattern was relevant to previous wet UK Autumns, we have correlated the

Autumn seasonal England-Wales precipitation (EWP, Jones and Conway 1997, Alexander and Jones 2001) with global geopotential height, point by point, for the preceding 42 years for which gridded data are available from the National Centers for Environmental Prediction - National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kistler et al, 2001). The regressed height anomalies in Fig. 3 are remarkably similar to the anomalous pattern in Autumn 2000, except over the Pacific Ocean, with correlations in excess of 0.40, significant at the 99% level, in the four peaks of the pattern over Eurasia. A similar regression pattern appears in other fields, including, for example, sea-level pressure. The seasonal EWP data are slightly skewed relative to a Gaussian distribution but a square root transform (Box and Cox, 1964), which minimises skewness, and detrending make no discernable difference to the regressions. We conclude that wet UK Autumns have not only been associated (unsurprisingly) with low pressure in situ, but also with a particular pattern of anomalies stretching over a wide area.

The regressed height field for wet UK Autumns and the anomalous pattern for Autumn 2000 are very similar to the Scandinavia or Eurasia-1 pattern, which was originally identified in a rotated principal component analysis of the preferred patterns of northern hemisphere variability by Barnston and Livezey (1987). Subsequently NOAA's Climate Prediction Centre (CPC) have created monthly indices of the Scandinavia and other teleconnection patterns from 1950 to the present day (Bell and Basist, 1994; CPC, 2001). A scatter plot of CPC's Autumn Scandinavia index and the EWP anomaly is shown in Fig. 4. The correlation between the two time series for 1950-1999 is 0.60, statistically highly significant given the almost zero 1-year lagged correlations of the individual series. There is evidence of variability on decadal timescales, with a tendency for predominantly positive Scandinavia index in the Autumns of the 1950s and 1960s, followed by two decades of large variability, then low variability in the 1990s preceding the extreme 2000 season. This correlation between positive Scandinavia index and wet UK Autumns can be understood through modification of the Atlantic jetstream and its subsequent effect on individual weather systems, as already discussed for Autumn 2000. However, although over one third of the Autumn EWP variability is associated with variability of the Scandinavia pattern, individual years show that, for example, a Scandinavia index greater than unity has coincided with a large range of EWP anomalies, from slightly negative to the record 2000 value.

A tropical catalyst?

We now investigate possible forcing mechanisms for the Scandinavia pattern. In recent years, most discussions of seasonal climate anomalies have been based on the atmospheric response to slowly changing sea surface temperature (SST) anomalies, usually in the tropics. There is ample observational and modelling evidence (e.g. Bjerknes, 1966, 1969; Horel and Wallace, 1981) for generation of teleconnection patterns by heating associated with anomalous deep convection overlying tropical SST anomalies, particularly for the Pacific and North American sector. Idealised modelling (Hoskins and Karoly, 1981; Sardeshmukh and Hoskins, 1988) has identified horizontal divergence, at the upper-tropospheric outflow level above a region of tropical convection, as a vorticity source. This drives a wave-packet response which is baroclinic in the tropics and equivalent-barotropic in the extra-tropics and which propagates, to a first approximation, on great circle paths with a component in the eastward direction. Arguments for forcing by mid-latitude SST anomalies are more complex and will be discussed later.

(a) Observational evidence

During Autumn 2000, raingauge and satellite cloud observations (NOAA, 2000) implied the presence of reduced convection and precipitation compared with climatology over parts of the tropical Atlantic and South America. There were associated anomalies of horizontal divergence in the upper-troposphere, shown in inverse Laplacian form as anomalous velocity potential for October (Fig. 5), from analyses by the European Centre for Medium-Range Weather Forecasts (ECMWF). Both the October and November fields showed strong (in the historical context) horizontal convergence anomalies over the tropical Atlantic and South America. The reality of these anomalies can be questioned, because the divergent flow is generally only a small component of the total flow and is not well observed, and because the climatology, from which the Autumn 2000 fields were subtracted, was created using a previous version of ECMWF’s forecasting system. However, the ECMWF velocity potential anomalies are in very close agreement with those derived from analyses at NCEP during Autumn 2000 (NOAA, 2000), produced independently of those at ECMWF.

Although the recent velocity potential anomalies appear realistic, we do not consider their historical time-series, from either the ECMWF or NCEP reanalysis systems, to be sufficiently reliable or temporally stable to warrant their use in a regression analysis with either EWP or the Scandinavia index. The two velocity potential time-series do not correlate well with each other over South America and there is evidence of temporal inhomogeneity in each series. Instead, we have used a new monthly precipitation dataset for the South American continent (Webber and Willmott, 1998), available for the period 1960 to 1990. Fig. 6 shows the map of point correlations between SON seasonal precipitation over South America and the seasonal Scandinavia index for this period. Correlations with EWP are similar but weaker. The regions of negative correlation in the tropics are consistent with the relationship implied by the velocity potential in Autumn 2000, with positive correlations being limited to the southern sub-tropics. Although the point correlations are only marginally significant at the 95% level (±0.37) the large-scale pattern of negative and positive correlation regions does suggest a weak historical relationship between tropical South American precipitation and European weather patterns in Autumn.

Tropical South American precipitation in SON correlates more strongly with the Southern Oscillation Index (Walker and Bliss, 1932; Trenberth, 1976; Hastenrath, 1990), which is a measure of La Niña / El Niño variability in the tropical Pacific, with correlations in excess of 0.4 over much of Amazonia (not shown). This is in agreement with other studies (Ropelewski and Halpert, 1987, 1989: Kiladis and Diaz, 1989), which have found South American dryness during El Niño events. This historical relationship means that it may be impossible to separate any influences of South American and Pacific anomalies on the Scandinavia pattern and West European Autumn weather using statistical analysis of observational data.

(b) Evidence from an idealised model

We have instead used a global barotropic model (Sardeshmukh and Hoskins, 1988) to investigate the atmospheric response to anomalous convergence over the tropical Atlantic and South America. This very idealised model simulates the global response of the vorticity field to specified vorticity forcing associated with either divergence, orography or transient weather systems. In the tropics the model represents the upper tropospheric flow in the layer of divergent convective outflow, while in the extra-tropics it represents the deep equivalent-barotropic atmospheric structure. The model has been run in “seasonal anomaly” mode: the SON climatological 300hPa upper tropospheric flow has been held fixed in the model (by computing the climatological vorticity forcing necessary to maintain it against self-advection) and a specified anomalous divergence forcing has been added and the model integrated forward in time to obtain a steady state response. Linear damping of the vorticity anomalies is included to crudely represent non-adiabatic processes, including surface friction and radiation.

Fig. 7 shows the solution obtained for forcing by a region of idealised convergence over the tropical Atlantic (denoted by bold contours in the figure), its location based on that of the observed velocity potential anomalies during Autumn 2000 (Fig. 5). A linearised form of the vorticity source has been used which omits vorticity advection by the divergent flow ($-fD$, see Sardeshmukh and Hoskins, 1988), but the solution using the complete vorticity source differs only in the tropics, particularly local to the forcing region. The main result is the generation of a Rossby wavetrain propagating into the extra-tropics, which is remarkably similar to the observed fields in Figs. 2 and 3. The wavelength of the model response is longer than that observed, possibly due to omission of terms involving the vertical structure in the barotropic model, a hypothesis that could be tested by performing equivalent experiments in a baroclinic model. The model response does not change substantially for modest changes in the location of the forcing, over approximately 30° longitude or 10° latitude, or for replacement of the climatological background state with the 200hPa rather than 300hPa flow, or use of the October or November climatology rather than that for the SON season. However the response differs markedly using the September climatology, suggesting that the response depends on the presence of the stronger wintertime jetstream in the North Atlantic, which is usually largely set up by October. Changing the sign of the forcing (to anomalous divergence) results in a weaker extra-tropical response of the opposite sign. These results imply that anomalous horizontal convergence in the upper-troposphere and descent in the mid-troposphere over the tropical Atlantic and South America may have been the catalyst, not only for the anomalous pattern in Autumn 2000, but also for the index of the Scandinavia pattern in other years.

Barotropic model experiments have also been performed using ECMWF analysed divergence anomalies for October and November 2000, extracted for the Atlantic and American tropics and sub-tropics only. The model responses are moderately successful in reproducing the main observed anomalies of the individual months over the Atlantic and Europe (not shown). Experiments have also been performed using idealised divergence anomalies over the Indonesian region, to assess the possible effect of the strong precipitation and divergence anomaly seen there, most clearly throughout October 2000 (Fig. 5 and NOAA, 2000), associated with large amplitudes of the Madden Julian Oscillation (Lawrimore et al, 2001). These experiments (not shown) reproduce features of the observed Pacific anomalies in October, notably wavetrains in both hemispheres propagating into the Americas. It is possible that the anomalous convergence over tropical South America was associated with such remote forcing from Indonesia and the West Pacific, though this would not be consistent with the positive historical correlation of South American precipitation with positive Southern Oscillation Index, corresponding to La Niña conditions when it is also wet over Indonesia. Baroclinic model experiments using condensation heating anomalies over Indonesia could help to shed light on any such connection.

We have also briefly considered the boreal Winter (December to February, DJF) situation. A barotropic model result similar to that in Fig. 7, but with a slightly longer wavelength, is obtained using the DJF climatological flow as basic state. Moreover, a regression of monthly geopotential height against EWP for January (but not for the DJF season), for 1958-2000, reveals a pattern very similar to that in Fig. 3. This confirms the recent finding by Massacand

and Davies (2001) of this teleconnection pattern in January (they called it the "midlatitude hemispheric pattern", MAT: it does not project well onto any individual teleconnection pattern computed for January by CPC).

The role of the extra-tropics

We now consider possible forcing of the Scandinavia pattern by heating above anomalous SSTs in the extra-tropical Atlantic, around 30°-40° latitude in the region of the Atlantic anticyclonic anomaly in Figs. 2-3. An observational study by Ratcliffe and Murray (1970) found that warm SSTs off Newfoundland in October preceded a pattern of sea level pressure strikingly similar to the Scandinavia pattern, together with wet weather over the UK and western Europe, one month later in November.

Subsequent modelling studies found evidence for forcing of the atmosphere by SST anomalies in the region identified by Ratcliffe and Murray, albeit with a weaker response than for tropical SST anomalies. Linear modelling (Hoskins and Karoly, 1981) showed that the direct response to mid-latitude heating is locally baroclinic, which is not consistent with the observed structure of the Scandinavia pattern. However, studies using climate models (Palmer and Sun, 1985; Ferranti et al, 1994; Peng et al, 1995) have found a more barotropic local response, with an anticyclone immediately east of an imposed warm SST anomaly near Newfoundland. The current consensus appears to be that a weak positive feedback may be operating, involving atmospheric forcing of the ocean, with weak positive feedback by the induced SST anomalies onto the atmospheric anomalies (e.g. Watanabe and Kimoto, 2000). Changes in the storm-track and transient weather systems appear to be an important component of the atmospheric response in several of these studies.

We have regressed Autumn surface temperature globally against EWP, and found a pattern of surface temperature anomalies (not shown), marginally significant at the 95% level, roughly in quadrature with the height field anomalies in Fig. 3, and with a much larger amplitude over land than over the ocean. This pattern includes a warm SST anomaly in precisely the region identified by Ratcliffe and Murray. Regression against the Scandinavia index gives a similar result. A very similar SST anomaly pattern was also present in Autumn 2000 (NOAA, 2000). Although these observational correlations do not distinguish causality, our regressed surface temperature pattern is consistent with atmospheric forcing of surface temperature by two processes: first, meridional advection of the basic north-south temperature gradient by the anomalous flow leading to anomalous surface heat fluxes and, second, enhanced low-level winds in the north-east Atlantic leading to surface cooling through both enhanced surface fluxes and oceanic mixing with the cooler water below. The stronger response over land is consistent with the lower heat capacity of the land surface compared with the ocean mixed layer.

We have also performed barotropic model experiments, using prescribed vorticity forcing at various locations within the observed Scandinavia pattern, to investigate the possibility of its forcing in mid-latitudes. The barotropic model cannot directly address forcing by in-situ SST anomalies, but it can predict the atmospheric response to deep vorticity forcing, either by the transient weather systems or by a Rossby wavetrain propagating into the Atlantic from the west. These experiments suggest that deep forcing of anticyclonic vorticity near the location of the mid-Atlantic anomalous ridge in Figs. 2,3 could generate the Scandinavia pattern in Autumn. However, there is no evidence from the ECMWF analyses of anomalous transient vorticity forcing in this region in Autumn 2000, although there were large anomalies in transient activity in the jet exit region in Fig. 1 (not shown), which may have reinforced the Scandinavia pattern there.

Discussion

Our results, suggesting a link between UK Autumn precipitation, the Scandinavia pattern and weather over the tropical Atlantic and south America, have relevance to three areas of current research and public interest: Amazonian deforestation, climate change and seasonal forecasting.

Recent studies of tropical deforestation, particularly in Amazonia, have investigated the remote climatic impacts of the resulting decrease in local precipitation, latent heating and ascent (Zhang et al, 1996; Gedney and Valdes, 2000). Evidence was found in these studies of propagation of planetary (Rossby) wave activity into the extratropics, just as found in our barotropic model experiments, leading to significant regional changes in circulation and precipitation over the north Atlantic and Europe in boreal Winter (December to February: the Autumn and Spring seasons were not studied). In Autumn the wavelength and path of the response are expected to differ somewhat. Also, the primary descent region associated with the Amazonian ascent is situated in the south-east Pacific in Autumn, rather than in the northern sub-tropics in Winter: Gedney and Valdes (2000) found that it was changes in this sub-tropical descent that led to their Atlantic/European response. The implication is that changes in Amazonian precipitation, whether due to natural variability or deforestation, are likely to have climatic impacts over the European region. Recent climate-change studies using the Hadley Centre climate model (Cox et al, 2000) have raised the possibility of Amazonian die-back occurring during the 21st century, due to climate change itself rather than direct human influence on land-use.

It is impossible to say that a single extreme season is evidence of climate change, but Autumn 2000 was seen at the time as a “wake-up call”, indicative of more extreme weather in the future (The Times, 21 November 2000). The England-Wales precipitation data show no significant trend in the Autumn seasonal total, either for the last half century used here or for the entire record from 1766. This contrasts with the winter period (December to February), for which there has not only been a significant precipitation increase in the instrumental record (Jones and Conway, 1997) but also prediction of a possible future increase in the frequency of extreme wet winters over much of central and northern Europe, from analysis of an ensemble of climate-change integrations (Palmer and Räisänen, 2001). The separate contributions of changes in the long-term mean and in the variability to this increased risk are not clear. The historical Autumn EWP data do show a possible increase in variability over the 19th and 20th centuries, with the standard deviations during the four half-centuries increasing monotonically from 58mm to 71mm (more robust measures of variability show similar trends). This influences return periods calculated for the record Autumn 2000 event, based on the statistics of the square-root transformed data, but all estimates are greater than the length of the instrumental record. Any future increase in Autumn variability would increase the frequency of extreme events such as that in 2000.

In the last decade, seasonal forecasting using coupled global atmosphere-ocean models has become feasible, and forecasts are now produced regularly by several operational centres (Stockdale et al, 1998; Barnston et al, 1999). These have shown skill in predicting the large-scale climate anomalies associated with the last El Niño, and it is extreme events such as the European weather of Autumn 2000 that they would aim to predict. However the ECMWF forecasts did not capture the extreme Autumn precipitation over Europe nor, interestingly, the anomalies over tropical America (T. Stockdale, personal communication). Seasonal hindcast experiments at ECMWF, and also at Reading using the observed sea surface temperatures in the

UK Met Office atmospheric model (B. Dong, personal communication), have also failed so far to capture the extreme weather. Our results offer a basis for attempts to understand this current lack of predictability in Autumn 2000 and so advance the burgeoning science of seasonal prediction.

Acknowledgements

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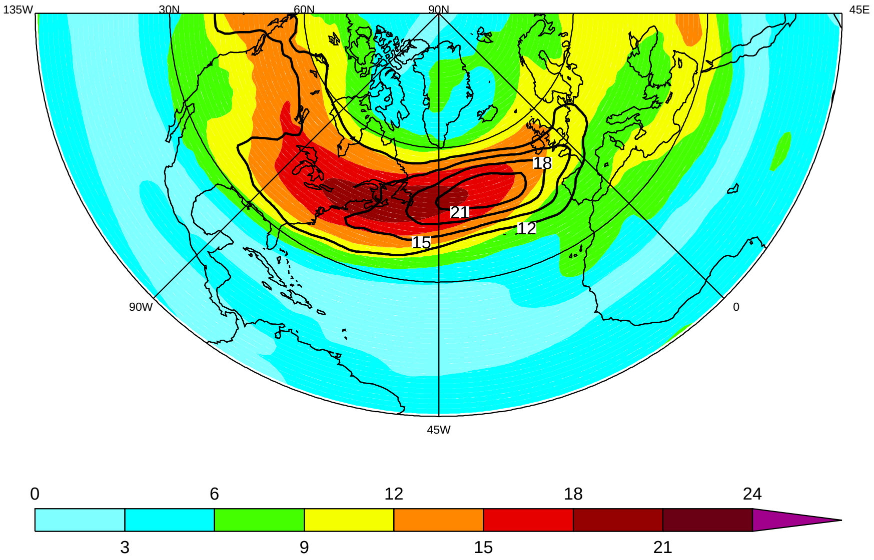

Figure 1. The Atlantic jetstream, depicted by the speed of the mean 500hPa wind, for the Autumn climatology (coloured) and for Autumn 2000 (contours) in ms^{-1}, showing the displaced Atlantic jetstream in 2000. The data are taken from global analyses at the European Centre for Medium-Range Weather Forecasts (ECMWF).

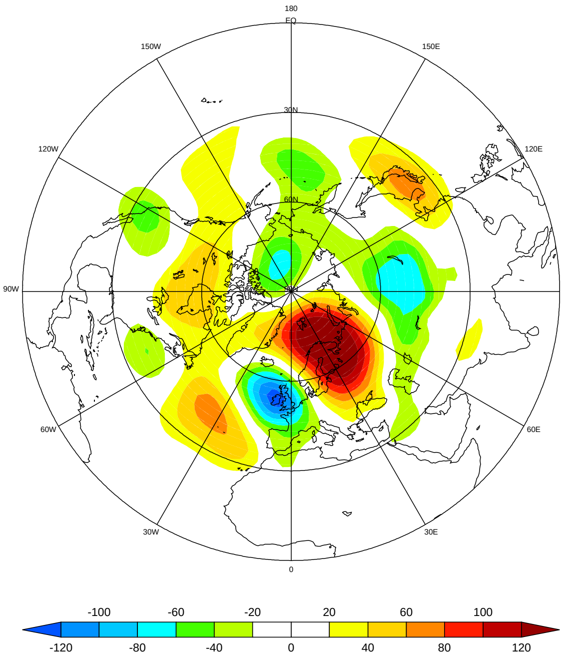

Figure 2. Autumn 2000 geopotential height anomaly relative to climatology at 300hPa, from ECMWF analyses (colour scale in metres). The pattern is dominated by a train of anomalies extending from mid-Atlantic over Eurasia.

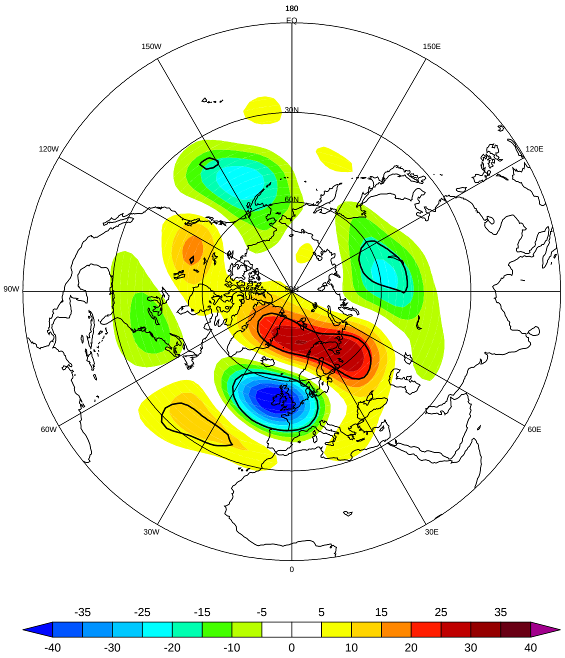

Figure 3. Regression of Autumn mean geopotential height at 300hPa against Autumn precipitation in England-Wales for 1958-1999. The bold contour denotes areas significant at the 99% confidence level. The regressed height field (in metres) corresponds to one standard deviation of precipitation (72mm).

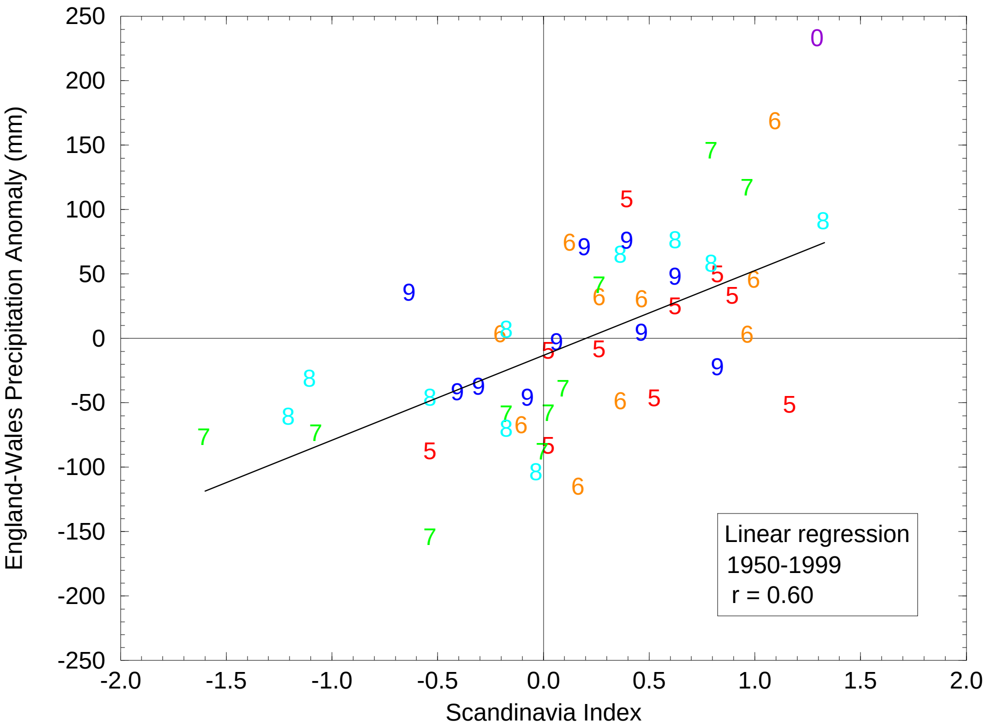

Figure 4. Scatter plot and linear regression for the index of the Scandinavia pattern and the England-Wales precipitation (EWP) anomaly, for Autumns from 1950 to 1999. Points are labelled by their decade and Autumn 2000 is included for comparison.

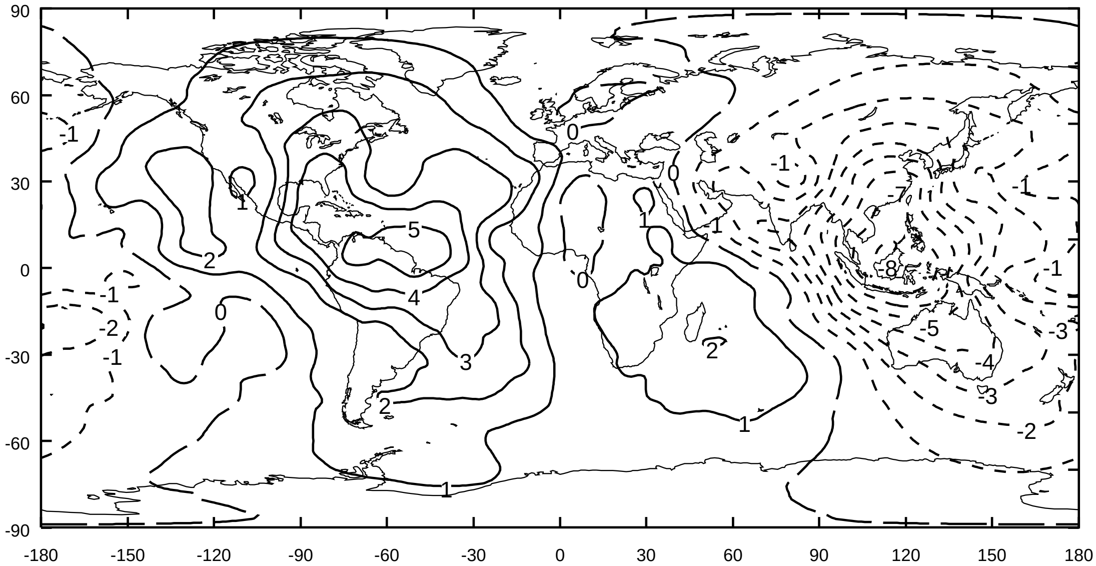

Figure 5. Velocity potential anomaly (inverse Laplacian of divergence) at 200hPa for October 2000, relative to climatology (1979-93), from ECMWF operational analyses. Contour interval $10^6 m^2 s^{-1}$. The dominant features of anomalous convergence over tropical South America and anomalous divergence over Indonesia show most clearly in October but were also present in the November and Autumn (SON) averages.

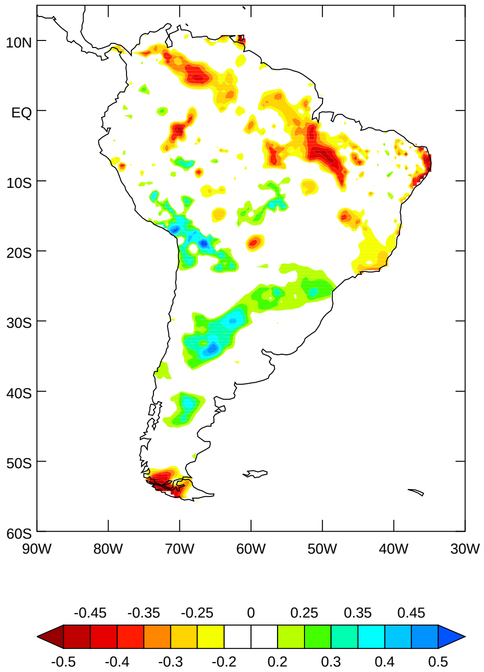

Figure 6. Correlations between South American precipitation and the Scandinavia index for boreal Autumn (SON), 1960-1990. Although 5% of points are expected to exceed a correlation of ±0.37, corresponding to the 95% confidence level, by chance, a coherent pattern of negative correlations occurs north of 10°S, coincident with the upper tropospheric convergence anomalies observed during Autumn 2000, depicted in Fig. 5.

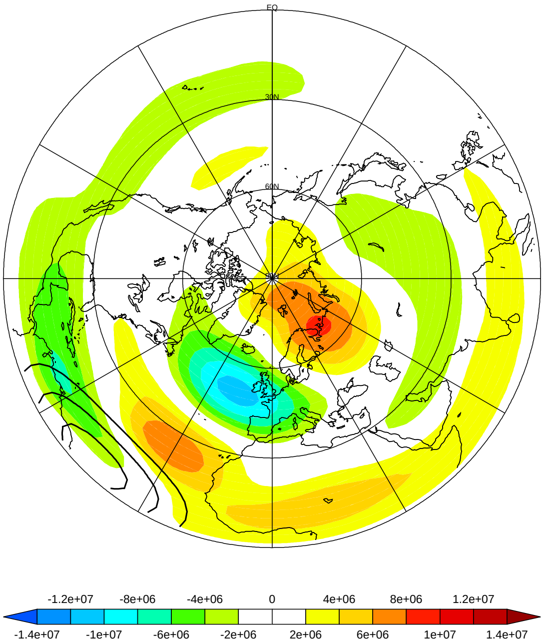

Figure 7. Barotropic model streamfunction anomaly (coloured in m^2s^{-1}) for idealised convergence forcing over the tropical Atlantic (bold contours, interval $10^{-6}s^{-1}$), using the 300hPa Autumn climatological flow as background state and a linearised form of the vorticity forcing (*-fD*). The anomaly is for day 15, approximating the steady-state solution. It is dominated by a Rossby wavetrain propagating northeast over the Atlantic and Europe, similar to the observed 2000 anomaly (Fig. 2) and the regression with wet UK Autumns (Fig. 3).