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Global and hemispheric climate variations affecting the Southern Ocean

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Abstract: The hemispheric and regional atmospheric circulation influences the Southern Ocean in many and profound ways, including intense air-sea fluxes of momentum, energy, fresh water and dissolved gases. The Southern Ocean ventilates a large fraction of the world ocean and hence these influences are spread globally. We use the NCEP-2 reanalysis data set to diagnose aspects of the large-scale atmospheric structure and variability and explore how these impact on the Southern Ocean. We discuss how the 'Southern Annular Mode' and the 'Pacific–South American' pattern influence the Southern Ocean, particularly in the eastern Pacific. We review the importance of atmospheric eddies in Southern Ocean climate, and the role they play in the transport of mechanical energy into the ocean. The fluxes of fresh water across the air-sea boundary influence strongly the processes of water mass formation. It is shown that climatological precipitation exceeds evaporation over most of the Southern Ocean. When averaged over the ocean from 50°S to the Antarctic coast the annual mean excess is 0.80 mm day^{-1}. The magnitude of the flux displays only a small measure of seasonality, and its largest value of 0.92 mm day^{-1} occurs in summer.

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Introduction

The Southern Ocean (SO) has a number of special characteristics which differentiate it from the rest of the global oceans. It is a region of intense air-sea exchanges of momentum, energy, fresh water and dissolved gases. The magnitude of these regional fluxes of momentum (and the implications for currents), kinetic energy (wave activity, near-global swell propagation, and mechanical mixing in the mixed layer), heat (vertical oceanic stability), moisture (near-surface salinity and water mass formation), gas transfers (CO_2 drawdown) etc. determine many aspects of global ocean structure. The physical, chemical and biological attributes of the SO are strongly influenced by these processes, and the manners in which they vary in space and on a broad spectrum of time scales are of great importance. The SO may be defined to have its southern boundary at the Antarctic continent and its northern limit at the Subtropical Front, the latter lying roughly along 40°S around much of the hemisphere. Defined in this way it occupies about 20% of the surface area of the global ocean. A reflection of the global importance of these fluxes is that water masses formed in the SO account for more than 50% of the volume of the world ocean (Godfrey & Rintoul 1998).

The SO has a well deserved reputation for having some of the strongest winds and largest waves over the global ocean. The wind waves impact on many aspects of the surface ocean, as outlined by Swail *et al.* (2001). Part of the reason for this strength is the great 'exposure' and minimal continentality at mid and high latitudes in the Southern Hemisphere (SH). The SO is unique among the world's oceans in that it links all the ocean basins. The feature which ensures strong connections between the southern Pacific, Atlantic and Indian Oceans is the Antarctic Circumpolar Current (ACC) which is a deep-reaching current which transports large volumes of water. The transport of this current near 140°E has been estimated at as much as 147 Sv (Rintoul & Sokolov 2001) and Cunningham *et al.* (2003) have reckoned the baroclinic ACC transport (above 3000 m) through Drake Passage to be 107 Sv. These numbers may be contrasted with the 1.2 Sv estimate for the flow of all the world's rivers combined (Dai & Trenberth 2002).

There are significant consequences of the absence of continental barriers in the latitude band encompassing Drake Passage. In ocean basins in general continental boundaries to the east and west mean that basin-wide zonal pressure gradients, and hence basin-average geostrophic meridional flow, are possible. The associated mean overturning circulations play an important role in the meridional fluxes of heat etc. The latitude belt centred on 60°S represents the exception to these characteristics, and hence cannot support a mean geostrophic meridional flow. It is believed that the meridional heat fluxes there are most likely accomplished by transient eddies (Godfrey & Rintoul 1998). (See also the recent discussion of Borowski *et al.* (2002).)

The importance of obtaining a good understanding of the workings of the SO is emphasised by the fact that it has displayed considerable changes in recent decades, and it is highly likely that these have been driven from the atmosphere. For example, Gille (2002) has reported significant mid-depth SO temperature increases between the 1950s and the 1980s, and Cabanes *et al*. (2001) have shown that the SO has made a disproportionate contribution to global sea level rise through thermal expansion.

Given the importance of these considerations, our principal goal in this paper is to survey large- and regional-scale atmospheric structure and variability, and to explore the manner in which these impact on the SO, and particularly on some of the fluxes mentioned above.

Atmospheric structure over the Southern Ocean

Because of its remoteness and hostile environment the SO has always presented a problem for the collection of meteorological and climatological data to provide quantitative information on the broad range of ways in which the atmosphere impacts on the SO (Hines *et al.* 2000, Simmonds 2003a, 2003b). These problems have been ameliorated to some extent over the past few decades. While remote oceans present a problem for the gathering of conventional observations, satellite remote sensing can fill in some of the gaps. One of the great advances in monitoring the SO and its atmosphere came with the advent of the 'modern satellite' era in 1979 (Kistler *et al.* 2001). At that time data from the TIROS Operational Vertical Sounder started to provide reliable information on the three-dimensional structure of the atmosphere. Progressive sophistication of satellite sounding units and of the algorithms to deduce atmospheric and oceanic structure from their outputs has meant that the SO atmosphere can be monitored at high frequency in both space and time. Operational satellites are able to provide a broad range of products, including quality temperature retrievals and cloud motion vectors (Kanamitsu *et al.* 1997) and scatterometer winds (Marshall & Turner 1999) and these have been shown to have very beneficial effects on deducing the structure of the atmosphere at high southern latitudes (Mo *et al.* 1995).

Another important advance in the assembling of reliable and physically consistent pictures of the atmosphere has been the development of 'data assimilation' and 'four dimensional analysis'. The seeds for this approach were planted by the remarkable study of Charney *et al.* (1969). That paper, written over three decades ago, ends with the prescient sentence 'We are publishing these incomplete results to arouse interest in a type of interpretive problem which we believe has potentially great significance for observational and theoretical meteorology and oceanography.' This procedure uses a numerical model of the global atmosphere to 'assimilate' individual data as they are inserted into it, and the physics of the model ensures that this is done in a consistent manner and in a way that satisfies all the (strong and weak) constraints pertaining to atmospheric structure (Stern 1974, Simmonds 1976, Seaman 1997, Kalnay 2002). Clearly, this system is of great value where the data network is not so dense. A recent use of the data assimilation concept has been in the construction of 'reanalyses'. In this procedure historical data may be inserted into the data assimilation cycle of a state-of-the-art model, which in turn can provide what is arguably the best analysis from those data. An extended period of such reanalyses can provide an 'optimum' time series of the large-scale three dimensional atmospheric structure. Many studies have shown that the quality of analysis products derived from these modern techniques is very high, even in regions when the data coverage is limited (Kalnay *et al*. 1998, Connolley & Harangozo 2001, King 2003). It follows that such reanalyses are appropriate sets with which we can explore the mean climatological aspects of atmospheric forcing of the SO.

In this paper some of our investigations are based on the 'NCEP-2' reanalysis set (generated by the US National Centers for Environmental Prediction and the Department of Energy) covering the period from 1 January 1979 to 31 December 2002 at 6-hourly intervals (Kanamitsu *et al.* 2002). While the NCEP reanalyses represent a dataset of high quality it should be mentioned that there are uncertainties in this (and indeed any analysis) in the data sparse region of the SO. Recently, Marshall (2002) undertook a critical assessment of trends apparent in the NCEP reanalysis over the 40 year period 1960–99. In a comprehensive investigation Marshall & Harangozo (2000) validated fifty years of NCEP reanalyses against station observations in the extratropical South Pacific, and found that a lack of surface observations entering the assimilation model caused the reanalyses to be poorly constrained prior to the availability of GTS-based data (in 1967), and significant improvements were found with the advent of satellite sounder data. The work of Sturaro (2003) is especially relevant here. He identified marked changes in the coefficients of the leading principal components of atmospheric structure (as diagnosed in the original NCEP reanalysis) at the end of 1978. This behaviour was particularly noticeable for the components which reflected atmospheric structure over the Southern Ocean, and is thought to be associated with the introduction of quality satellite data. These and other considerations (e.g. the comments made above on the work of Kistler *et al.* (2001)) have led us to make use of the NCEP product only since 1979.

Unless stated explicitly otherwise the investigations we undertake with reanalyses are based on the NCEP-2 set. In this work we will also make some use of the ERA-40 reanalysis from the ECMWF (European Centre for Medium-Range Weather Forecasts) (Simmons & Gibson 2000, Uppala 2002). For reasons similar to above we only use these data for the same period 1979–2002. Marshall (2003) has commented that the ERA-40 reanalysis can be used with high confidence to study SH high-latitude atmospheric circulation variability at least as far back as 1973.

Circulation characteristics above the Southern Hemisphere and Southern Ocean

Dominant modes of large-scale variability

We begin our investigation by exploring the mean climatological structure of the mean sea level pressure (MSLP). This parameter is arguably the single most valuable variable for diagnosing atmospheric circulation and in studying weather and climate. Its pattern allows an estimate of the low-level wind, which in turn is a critical factor in determining the air-sea fluxes mentioned above.

The average MSLP pattern over the SH has an interesting seasonal cycle which has been explored in reanalysis products in a number of papers (e.g. Simmonds 2003a, Simmonds *et al.* 2003) A significant proportion of the seasonality is due to the presence of the 'semiannual

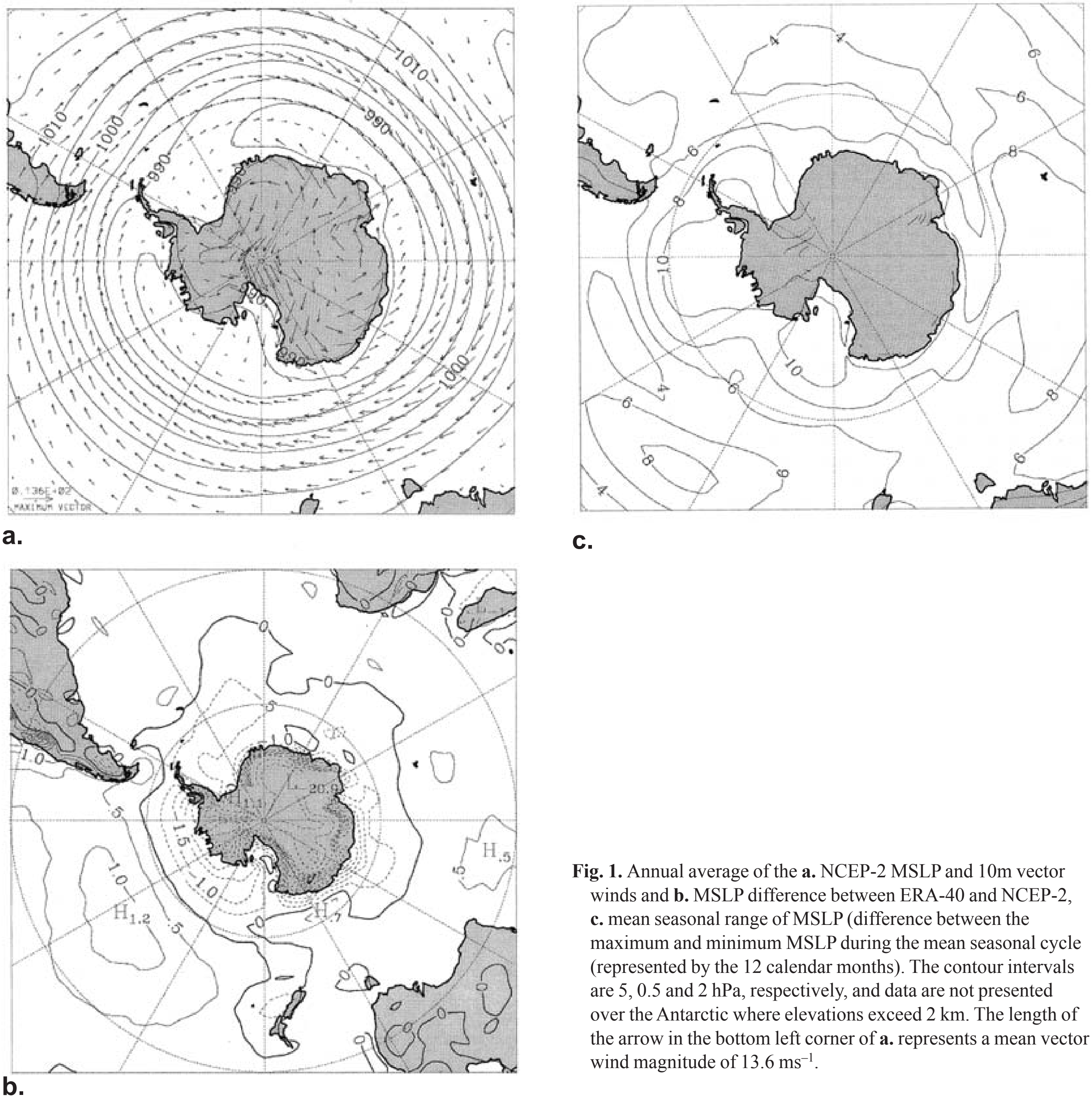


Fig. 1. Annual average of the **a.** NCEP-2 MSLP and 10m vector winds and **b.** MSLP difference between ERA-40 and NCEP-2, **c.** mean seasonal range of MSLP (difference between the maximum and minimum MSLP during the mean seasonal cycle (represented by the 12 calendar months). The contour intervals are 5, 0.5 and 2 hPa, respectively, and data are not presented over the Antarctic where elevations exceed 2 km. The length of the arrow in the bottom left corner of **a.** represents a mean vector wind magnitude of 13.6 ms^{-1}.

oscillation'. The complex thermodynamics and dynamics of the SH ocean-atmosphere system, result in differing annual cycles of temperature in the mid latitude ocean and Antarctic regions (e.g. van Loon 1967, 1972, Meehl 1991, Simmonds & Jones 1998). These differences lead to a strong semiannual component to tropospheric meridional temperature gradients over the SO, with the consequence of a strong signal in the baroclinicity and MSLP at this periodicity. The strength of this oscillation has undergone considerable variability over recent decades (Meehl *et al.* 1998, Simmonds & Jones 1998, Walland & Simmonds 1999, Burnett & McNicoll 2000, van den Broeke 2000).

The *annual average* NCEP-2 MSLP and 10m vector winds are presented in Fig. 1a. The westerlies which cover much of the SO and the circumpolar trough (CPT) off the Antarctic coast are features found in all seasons, and hence it is not surprising they appear in the annual average. The latitudes of the axis of the mean trough shows considerable variation with longitude, extending almost to 60°S in the Indian Ocean sector to south of 70°S in the vicinity of the Ross Sea. The mean MSLP distribution in the ERA-40 analysis is very similar to that displayed above. To allow a critical comparison of the two we present in Fig. 1b the difference between the ERA-40 and NCEP-2 products. The disparities are very small (excluding the differences over the Antarctic continent where the concept of MSLP has little meaning). In general the pressures in ERA-40 are lower south of 60°S and somewhat higher to the north. The largest divergence is found in the Amundsen and Bellingshausen seas, and only just exceeds 2 hPa. The difference pattern shows very little seasonality (not shown), with the magnitudes being only slightly larger in winter and spring.

A perspective on the magnitude of the mean seasonality of MSLP may be obtained by subtracting the minimum MSLP during the mean seasonal cycle (represented by the 12 calendar months) from the maximum pressure. This mean seasonal range is presented in Fig. 1c. The largest values in excess of 10 hPa are only found in the region to the north of the Amundsen and Bellingshausen seas and to the north of the Ross Sea. This behaviour is associated with the (longitudinal) movement of the climatological low from the former position in summer to the second location in winter. Ranges in excess of 8 hPa in the Indian sector reflect the winter trough in this region. Notwithstanding these features, the seasonal range of the MSLP is rather small, reflecting, of course, only a modest amount of seasonality in this parameter. (This behaviour can be contrasted with the magnitude of the seasonal range over Northern Hemisphere (NH) oceanic regions, which exceeds 17 hPa to the south of Greenland and 20 hPa to the south of the Alaska Peninsula.)

We now turn our attention to exploring the modes of low-frequency variability which the SH atmosphere displays and which impact on the SO. These characteristics have been explored in past studies which have made use of less comprehensive data sets (e.g. Rogers & van Loon 1982, Mo & White 1985, Kidson 1988, Kiladis & Mo 1998). Many features of SH variability exhibit a barotropic structure and such aspects of variability can be explored with upper level data, which has the advantage of not being artificially distorted by the presence of the Antarctic massif. To identify the dominant hemispheric modes we have undertaken a Principal Component Analysis (PCA) of the 200 hPa height

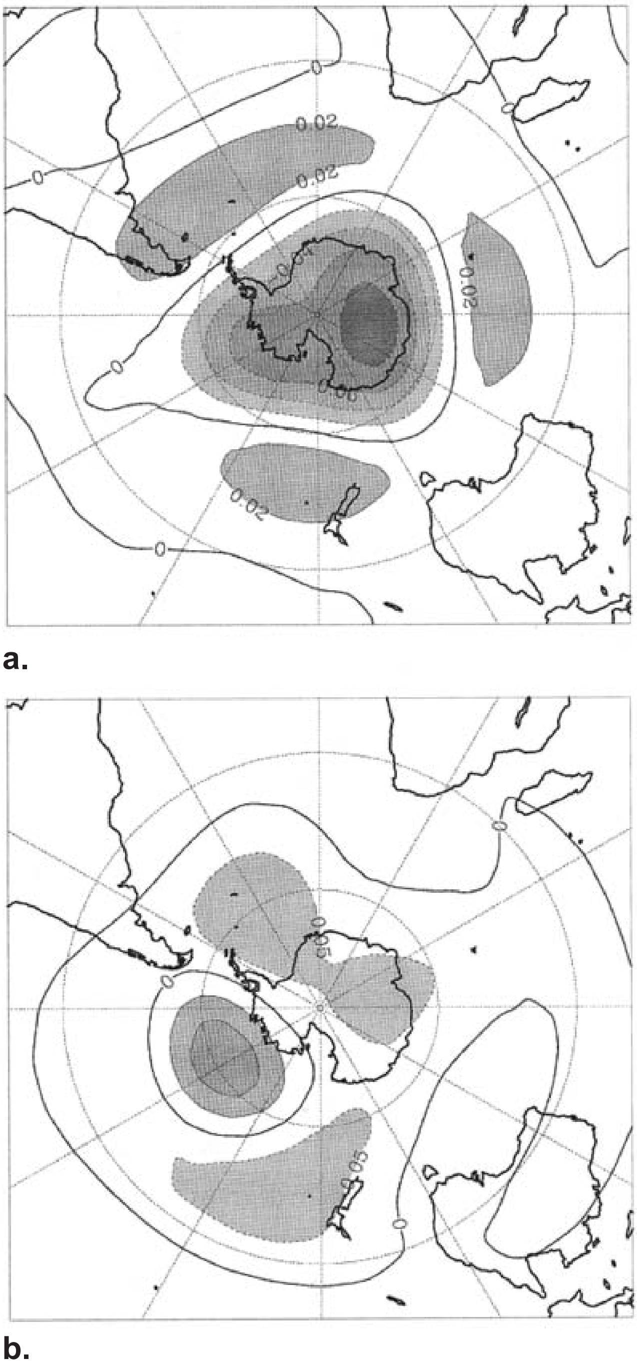


Fig. 2. The **a.** first, and **b.** second mode of 200 hPa height variability identified from a PCA analysis of data between 20 and 90°S.

field between 20 and 90°S. The six-hourly height fields were deseasonalised by removing both the linear trend and the first four annual harmonics. The data were then low-pass filtered to retain only fluctuations having periods greater than 50 days. The first mode of variability (Fig. 2a) is the so-called Southern Annular Mode (SAM) (Thompson & Wallace 2000, Thompson & Solomon 2002, Hall & Visbeck 2002) and explains 20.2% of the variability. (In the literature cited above the SAM has also been referred to as the 'Antarctic Oscillation' and as the 'High-latitude Mode'.) This mode represents an exchange of mass between the mid and higher latitudes. It should be pointed out, however, that the component is not zonally symmetric, but has significant structure in wavenumber 3 (Kidson 1999). In particular, large loadings are found over, and to the north of, the Amundsen Sea. This mode of variability is known to have assumed an increasingly positive polarity over the past few decades (e.g. Simmonds & Keay 2000a, Thompson *et al.* 2000). Figure 2b shows the second mode (10.4% of the variance) which reflects a teleconnection pattern across the Pacific. It has nodes of alternating sign to the east of New Zealand, to the north of the Amundsen Sea, and to the north of the Weddell Sea. This pattern is known as the 'Pacific–South American' (PSA) pattern, and its presence has been shown to be closely associated with ENSO (Mo & White 1985, Karoly 1989, King 1994, Chen *et al.* 1996, Karoly *et al.* 1996, Marshall & King 1998, Renwick 1998, Harangozo 2000). It is of interest to note that both these orthogonal modes have centres of action in the eastern Pacific sector of the SO. This conjunction establishes the potential for complex interactions between El Niño and the SAM, and for regionally specific SAM impacts. It is well known that this region displays significant levels of variability in all climate parameters (e.g. King & Comiso 2003, King *et al.* 2003, Turner *et al.* 2003). Recently Silvestri & Vera (2003) have commented that in spring their ENSO index (surface temperature anomalies in the Niño 3.4 region) has a significant (negative) correlation with the SAM index. One can appreciate, therefore, that the high southern latitude responses to El Niño can be modulated by the state of the SAM.

The two modes (and their near-surface reflection) are associated with anomalies of the surface wind field over the SO. We had discussed earlier some of the many ways in which changes in atmospheric circulation can impact on ocean properties. One of these is the interaction with sea ice and thermal properties. The interaction between SO sea ice and circulation depends to a considerable extent on the relative positions of the CPT and the sea ice edge, and the implications of these for anomalous Ekman ice transport (Enomoto & Ohmura 1990). With respect to the influence of the first mode, Hall & Visbeck (2002) recently conducted a model experiment which showed that the SAM can generate significant sea ice and ocean circulation anomalies. As far as forcing from the second mode is concerned, studies, including those of King (1994), Harangozo (1997), King & Harangozo (1998), van den Broeke (2000), Kwok & Comiso (2002), and Renwick (2002), have discussed the interaction of the atmospheric circulation and sea ice in the east Pacific sector of the SO, and the role played by El Niño teleconnections in the associations. Other studies to have demonstrated a link between El Niño (and hence by implication the PSA pattern) and sea ice in the Pacific sector are Simmonds & Jacka (1995), Yuan & Martinson (2000), and Hanna (2001).

Given the ability of these two key atmospheric modes to influence strongly the SO it is of interest to consider to what extent their variations are predictable. The SAM appears as the first mode of variability in a range of atmospheric models of varying complexity (Robinson 1991, 1996, Robinson & Qin 1992, Lee & Feldstein 1996, Watterson 2002). This universal presence signifies that this mode is an important physical and robust aspect of southern extratropical vacillation, and that it results from the internal (wave-mean flow) dynamics. This latter point may indicate that it is essentially unpredictable. This mode of variability is known to have assumed an increasingly positive polarity over the past few decades (e.g. Simmonds & Keay 2000a, Thompson *et al*. 2000, Marshall 2003). Thompson & Solomon (2002) argue that this trend may have been driven, at least in part, by the recent decline in stratospheric ozone at high southern latitudes. Modelling studies (Sexton 2001, Polvani & Kushner 2002, Gillett & Thompson 2003) lend some support to this view. However, model experiments indicate that circulation changes associated with increasing greenhouse gases also project strongly onto this leading mode of variability (Fyfe *et al*. 1999, Kushner *et al*. 2001). It should be pointed out, however, that the recent study by Jones & Widmann (2003) has indicated that a SAM index based on tree rings has exhibited similar decadal trends in the past. By contrast, variations in the PSA mode appear to be strongly influenced by tropical Pacific sea surface temperature (SST) anomalies associated with El Niño events. Since these anomalies have considerable persistence the PSA can be regarded as partly predictable.

Synoptic environment over the Southern Ocean

It is well appreciated that transient eddies play a key role in the energy and momentum budgets of the atmosphere over the SO (e.g. Peixoto & Oort 1992). As indicated above, these eddies also are also intimately tied up with the vacillations in the SAM (see also Karoly (1990), Limpasuvan & Hartmann (1999, 2000), Lorenz & Hartmann (2001), Rao *et al.* (2003) and Rashid & Simmonds (2004)). The characteristics (including the seasonality) of SH cyclone activity are known to be different to those in the NH. One of the reasons for this is the seasonality of the baroclinicity and of the changes in SST. To quantify accurately these changes we have made

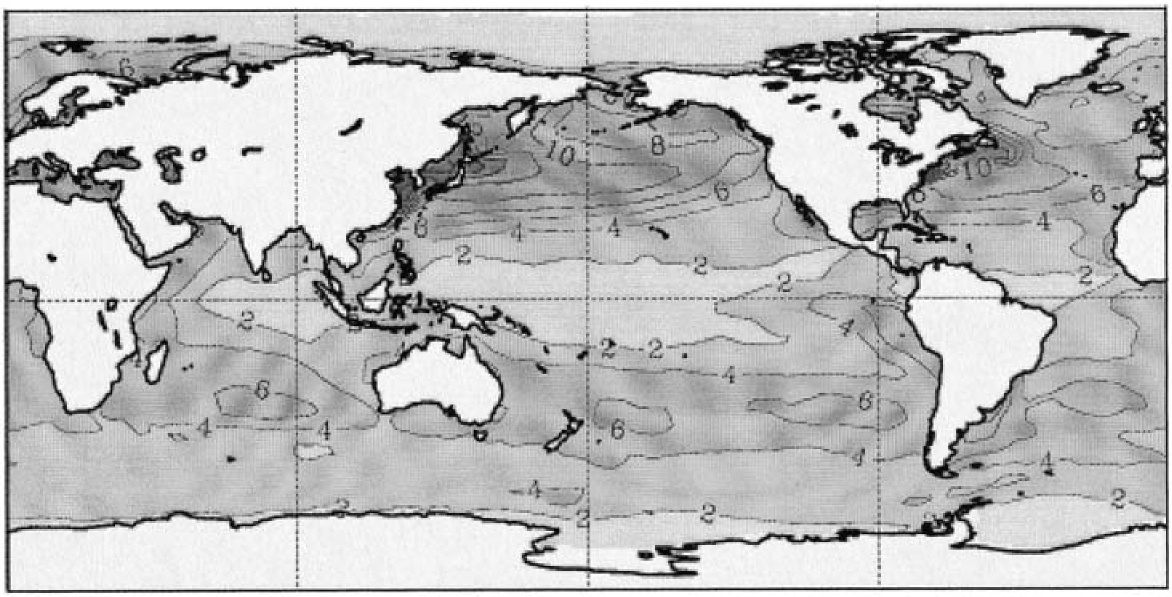


Fig. 3. Mean seasonal range of SST (difference between the maximum and minimum SST during the mean seasonal cycle (represented by the 12 calendar months). The data are taken from the HadISST1 dataset (Rayner *et al.* 2003) over the period 1901–2000. The contour interval is 2°C.

use of one of highest quality data sets of twentieth century monthly mean temperatures, namely the 'HadISST1' set produced by the UK Met Office Hadley Centre (Rayner *et al.* 2000, 2003). This compilation supersedes the 'GISST' datasets. The SSTs are reconstructed using a two-stage reduced-space optimal interpolation procedure, followed by superposition of quality-improved gridded observations onto the reconstructions to restore local detail. The data cover the global domain on a 1° latitude x 1° longitude grid. Shown in Fig. 3 is the mean seasonal range (as defined above for MSLP) of the HadISST1 data set over the period 1901–2000. The range shows considerable zonal symmetry,

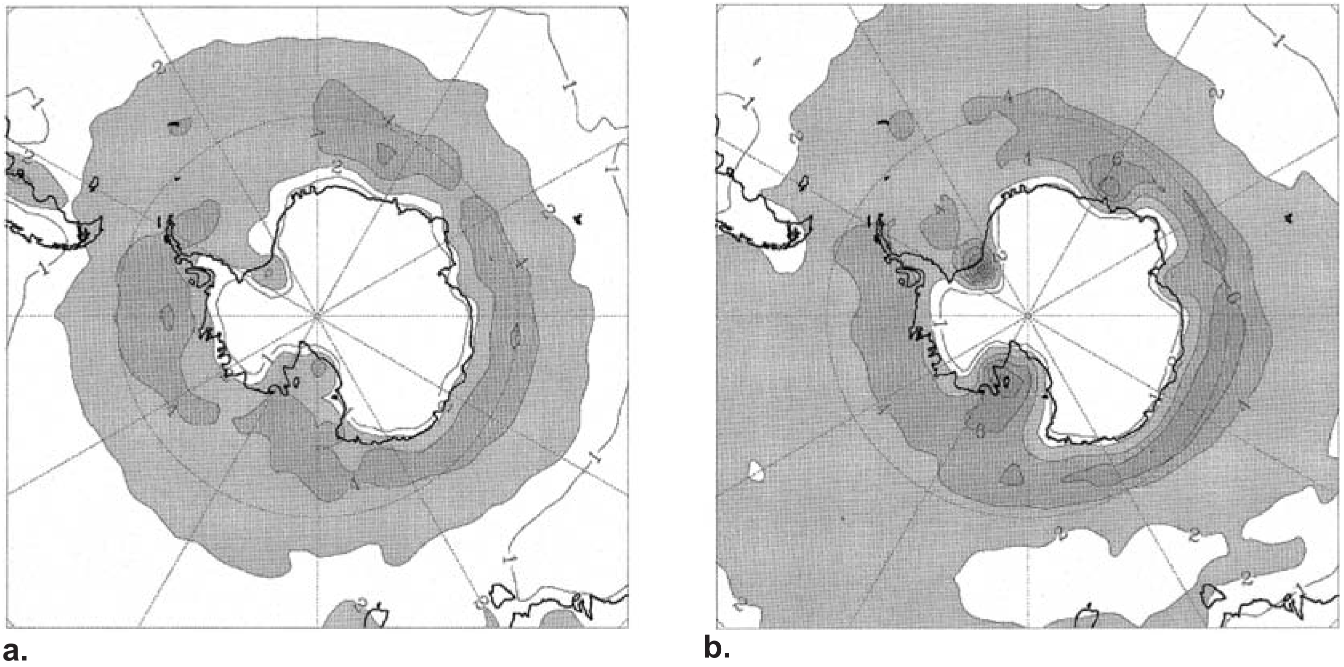


Fig. 4. Cyclone system density (the mean number of cyclones per analysis found in a 1000 (deg. lat.)^2 area) in **a.** DJF and **b.** JJA. The contour interval is 2.

and its value only exceeds 6°C in the relatively low latitude band of 30–35°S. Over most of the SO the range is less than 4°C. This structure can be contrasted with that in the NH which displays little zonality, largest values at mid latitudes and exhibits values in excess of 10°C in the west Atlantic and west and central Pacific. The modest magnitude of this facet of seasonality partially explains why the seasonal cycle of cyclone frequency is much smaller than in the NH. Figure 4 displays the mean December to February (DJF) and June to August (JJA) frequency of cyclones over the SO, diagnosed from the NCEP-2 analyses with The University of Melbourne cyclone tracking scheme (Simmonds & Keay 2000b). The patterns are similar with axes of maxima lying at about 60°S in the Indian sector, and located somewhat further south elsewhere. The cyclone counts are relatively modest over much of the Weddell Sea. Almost everywhere, the counts in winter exceed those in summer. A number of studies (e.g. Simmonds & Keay 2000a) have shown that the frequency of cyclones over the SO has decreased since 1970, while their mean depth has increased. Climate change model simulations exhibit trends consistent with these (e.g. Fyfe 2003).

These characteristics of cyclonic activity have many implications for the forcing of the SO. One of these is the 'directional constancy' of the low-level wind. Clearly, if these winds are consistently from a given direction currents may be set up more easily than if the direction undergoes considerable variation. An appropriate measure of directional constancy may be given by

$$C = \frac{|\overline{\boldsymbol{u}}|}{\overline{|\boldsymbol{u}|}}$$

where $\boldsymbol{u}$ denotes the instantaneous near-surface wind vector, and the overbar the time average. C assumes values of between 0 and 1, the former corresponding to the case where the (speed weighted) wind direction is completely variable and the latter where the wind direction is constant. Figure 5 presents this statistic for all the 10 m NCEP-2 data. It displays very low values in the region just offshore from the continent, with values dropping as low as 0.2. It is appreciated that in this region of high cyclone density wind directions are very variable. To the north of about 60°S there is a band (particularly wide in the Indian) over which the 'constancy' exceeds 0.6. This behaviour in these latitudes can be understood as the westerlies (Fig. 1a) being unaffected when there is no cyclone to the south or being strengthened when a cyclone is so-placed. Throughout this latitude belt one can appreciate that the passage of cyclones in the south influences the strength but not greatly the direction between about 45 and 60°S. Further to the north the directional constancy is seen to decrease as the influence of the subtropical ridge becomes more apparent.

Flux of kinetic energy into the Southern Ocean

The scalar wind stress acting on the ocean can be expressed as

$$\tau = \rho C_D u^2$$

(e.g. Simmonds 1985) where ρ is the atmospheric density, u the wind speed at some (near-surface) reference level, and C_D the drag coefficient with respect to that level. While the density and the exchange coefficient vary with space and time, our main interest here is in the characteristics of the square of the wind speed. Hence below these are treated as constants, and as convenient shorthand one can refer to u^2 as simply the wind stress (or momentum flux). (We remark that Ponte *et al.* (2003) recently suggested that uncertainties in seasonal oceanic torques are related mostly to the wind fields rather than to the specific parameterizations of the surface stress in the boundary layer.)

In a similar vein it is convenient to refer to the cube of the wind speed (u^3) as the rate at which mechanical (i.e. kinetic) energy is deposited in the ocean. As discussed earlier, this flux is of direct relevance to wave setup and the development of the fully-developed sea.

Dividing the wind speed into a mean and turbulent part

$$u = \overline{u} + u'$$

where the overbar again denotes the temporal mean and the prime is the deviation from that mean, we may express the time mean of u^2 as

$$\overline{u^2} = \overline{u}^2 + \overline{u'^2}$$

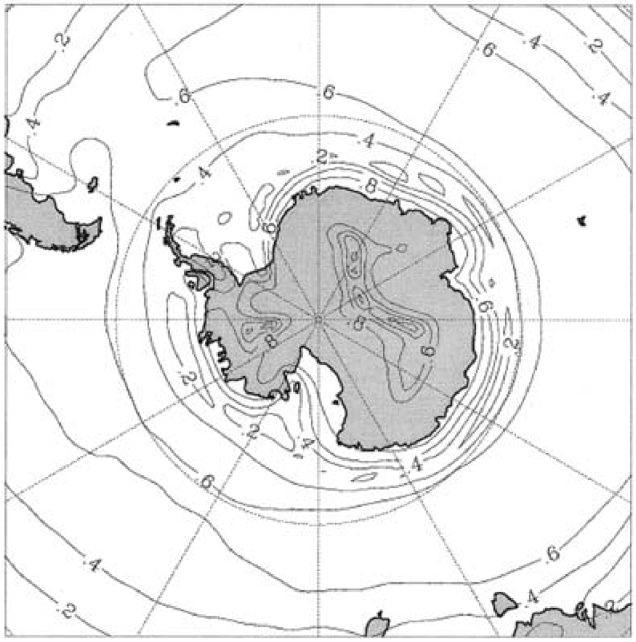
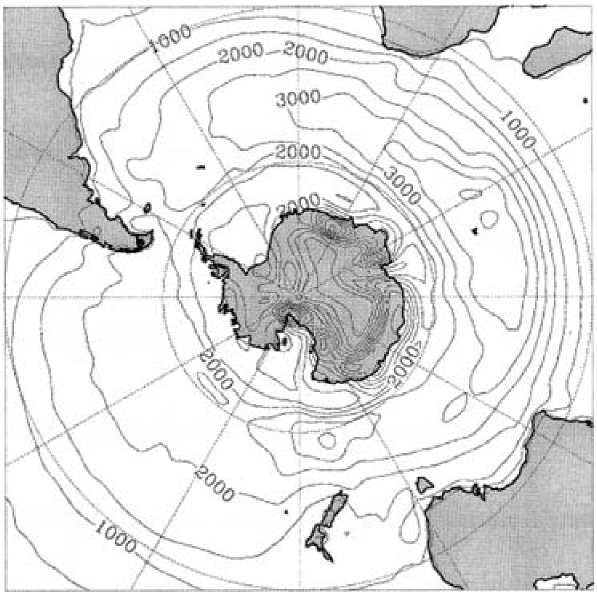
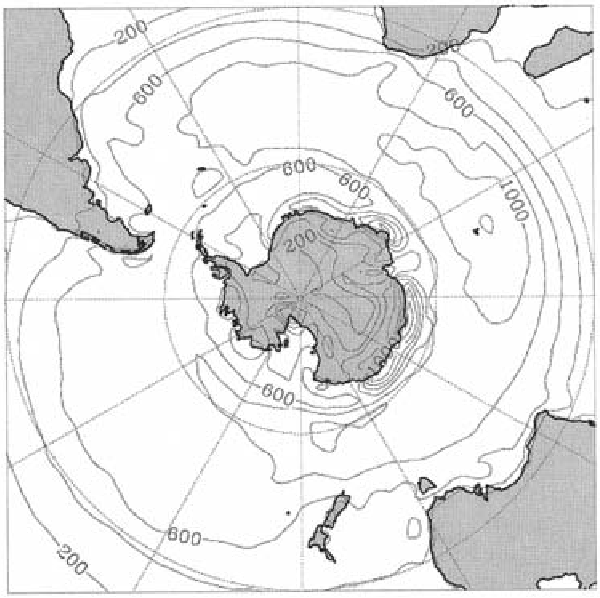


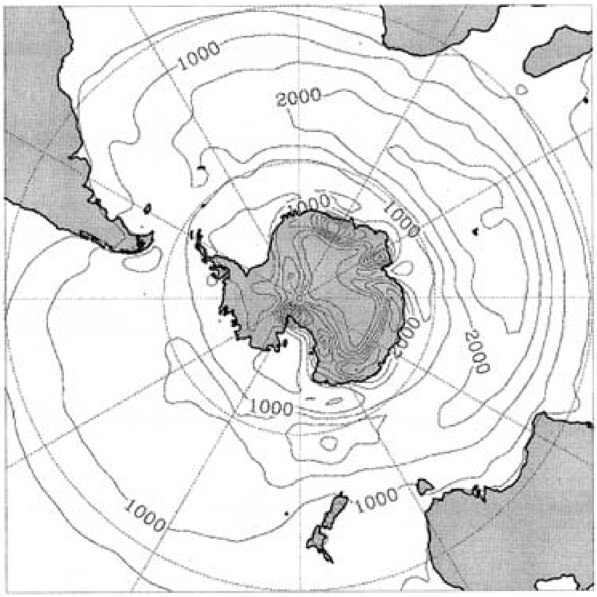
Fig. 5. Annual mean directional constancy (see text).



a.



c.



b.

Fig. 6. JJA mean values of **a.** *UC*, **b.** *UC*1 and **c.** *UC*2 (see text). The contour intervals are 500, 500, and 200 m^3s^{-3}.

Performing a similar decomposition for u^3 leads to

$$\overline{u^3} = \overline{u}^3 + 3\overline{u}\,\overline{u'^2} + \overline{u'^3}$$

(Simmonds & Keay 2002). For convenience, we refer to the left hand side term in the above equation as *UC*, and the three terms on the right hand side as *UC*1, *UC*2, and *UC*3, respectively.

The mean of the JJA *UC* (Fig. 6a) (calculated from the 10 m winds) shows a band of high mechanical energy input at about 45°S from the eastern Indian to the west Pacific Ocean. This attains its maximum (in excess of 4000 m^3 s^{-3}) in the vicinity of Kerguelen. Figure 6b shows that the rate of mechanical input to the SO due to the mean wind speed (*UC*1) possesses a pattern very similar to that of *UC*, and both show relatively small values in the eastern Pacific and at lower latitudes. The first term to involve the transients (*UC*2) also displays a similar pattern (Fig. 6c). Inspection of the plots reveals that about two thirds of *UC* is contributed by *UC*1 and one third by *UC*2. Overall, the triple covariance term contributes very little, but does assume some sizeable values over limited areas near the Antarctic coast. This sizeable contribution from the eddy terms underscores our earlier comments on the importance of these transients features in the SO environment.

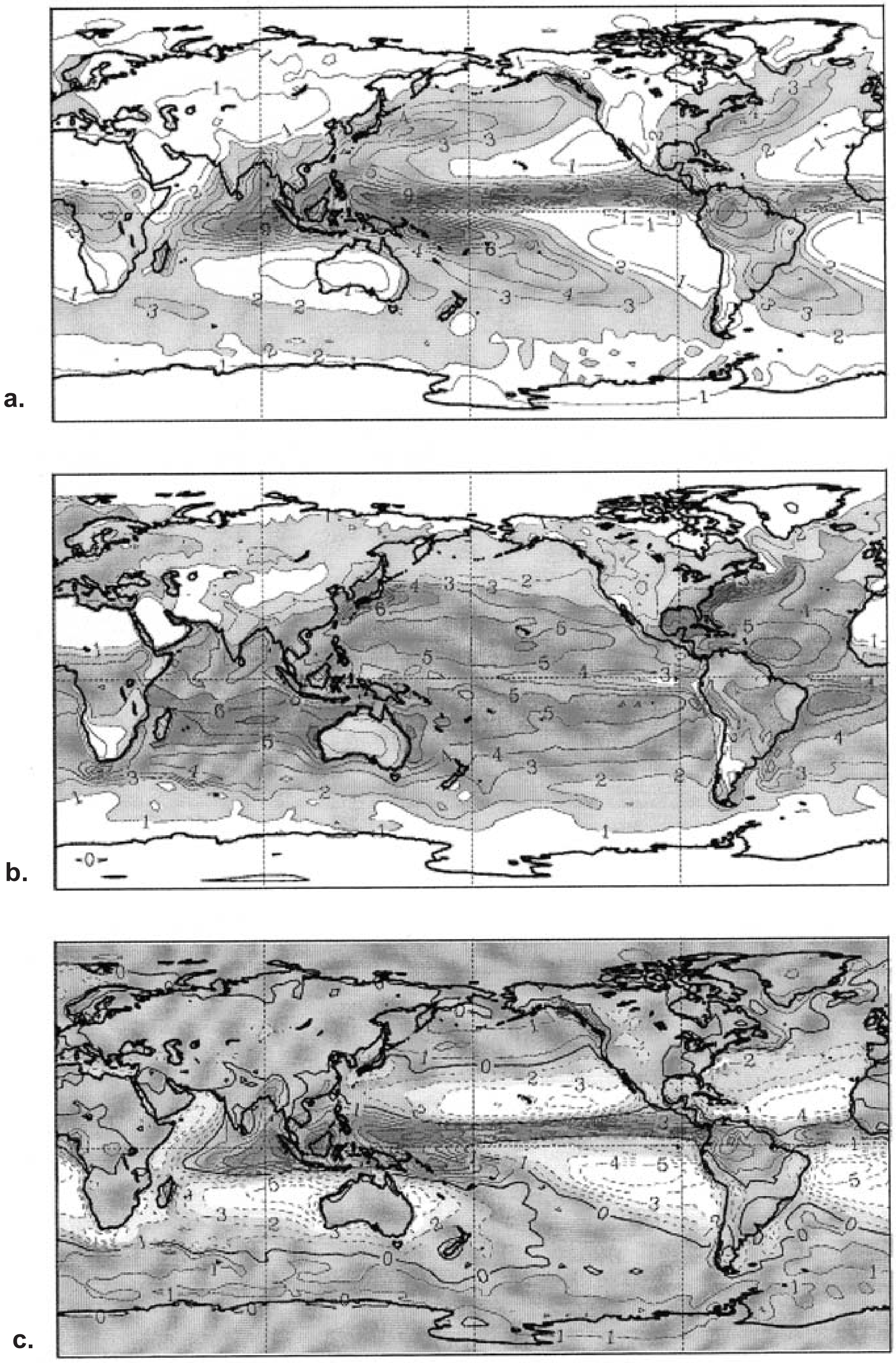


Fig. 7. Annual mean rates of **a.** precipitation (CMAP), **b.** evaporation (NCEP-2), and **c.** precipitation minus evaporation. The contour interval is 1 mm day^{-1}.

Southern Ocean air-sea freshwater fluxes

The moisture fluxes across the atmosphere-ocean interface play an integral part in determining the surface salinities over the world's oceans and in understanding the processes of water mass formation. Given the constraints of conservation the hydrological cycle over a given region (e.g. the SO) must be seen in a global context and, in particular, changes in high southern latitudes are most profitably interpreted in terms of changes in the character of the global hydrological cycle. The vertical stability and sea ice cover of the SO is very sensitive to the freshwater flux. For example, Marsland & Wolff (2001) found in their model study that a large-scale open ocean polynya develops in the Weddell Sea when the regional flux falls below about 350 mm yr^{-1}. Coupled ocean-atmosphere models of transient climate change due to greenhouse warming predict increases in freshwater flux over the SO. Hirst (1999) found the SO response to global warming in his transient model simulation to be very profound, simulating marked reductions in surface density and salinity and consequent major reductions in the depth and extent of convective mixing. Wong *et al*. (1999) made a detailed comparison of historical hydrographical data and concluded there to be freshening of surface waters, over approximately 22 years, in the SO, suggesting that precipitation minus evaporation has increased by about 31 mm yr^{-1} between 55 and 65°S, with a pattern of change consistent with models.

In view of these considerations, it is of relevance to diagnose the terms in the present-day SO freshwater budget and how these relate to the global hydrological cycle. Accordingly, in Fig. 7a, we show the annual mean precipitation rate over the globe, as estimated by the CMAP (Xie & Arkin 1997) for the period 1979–2001. Noteworthy features are the high precipitation rates in the ITCZ and the SPCZ. The rates over much of the SO assume values of between 1 and 3 mm day^{-1}. The annual mean evaporation rate distribution, taken from the NCEP-2 reanalysis, is presented in Fig. 7b. Over the open ocean the greatest evaporation is found somewhat equatorward of the subtropical ridges. These are the locations where the trade winds are strong. In the SO it will be noted that the meridional gradient of evaporation is larger than that of precipitation. The freshwater flux to the ocean may be deduced from the difference between these two plots. Figure 7c makes apparent the dominance in the hydrological budget of the precipitation in the convergence zones, and of evaporation in the tropics at locations where the trades are strong. A consequence of the magnitude of these contributions is that there is a net freshwater flux into the SO of a typical magnitude of 1 mm day^{-1}. This positive balance extends to lower latitudes in the central Pacific. By contrast, in the New Zealand sector evaporation exceeds precipitation almost down as far as 60°S. Shown in Table I are the annual means of P, E and P–E calculated over the ocean domain (including the sea ice region) between the Antarctic coast and 50°S. The long-term precipitation and evaporation rates are 1.86 and 1.05 mm day^{-1}, and a freshwater input of 0.80 mm day^{-1}. The table also shows the means of these quantities by season. Autumn and winter are the seasons of greatest precipitation and evaporation, which would have been expected from the cyclone distributions presented earlier. The smallest P and E values occur in summer; it is worth noting that the regional mean evaporation is least in summer (at 0.71 mm day^{-1}) despite this being the time when the sea ice extent is approaching its minimum. The area-average freshwater flux (P–E) exhibits only a modest amount of seasonality, with a maximum (of 0.92 mm day^{-1}) in summer.

Table I. Climatological annual and seasonal means of P, E and P–E calculated over the ocean domain (including the sea ice region) between the Antarctic coast and 50ºS. Units are mm day^{-1}.

	P	E	P–E
Annual	1.86	1.05	0.80
DJF	1.63	0.71	0.92
MAM	2.03	1.22	0.82
JJA	2.03	1.28	0.75
SON	1.75	1.01	0.74

Concluding remarks

We have emphasised in this paper the many important ways in which the atmosphere over the SH influences the SO and its properties. This ocean covers only about 20% of the world's oceans, but the nature of the forcings is such that their consequences are felt over much of the globe. Reliable and robust estimates of many of the important fluxes over the vast expanses of the SO have only recently become possible with the use of relatively long records of reanalysis products.

Some of the analyses presented here have been based on the NCEP-2 reanalysis set. This has revealed relatively modest magnitudes of the mean seasonal range of MSLP over the SO. Our work has confirmed many earlier studies in identifying the SAM and the PSA as the first two hemispheric modes of time-filtered 200 hPa height. These two modes have high loadings over the SO, and particularly in the 'hot spots' of the Amundsen, Bellingshausen and Weddell seas. We have commented on how large-scale forcings (e.g. El Niño) can influence these modes and dramatically change oceanic forcings in the high southern latitudes, and clearly the SAM and PSA are able to interact in complex (and probably nonlinear) ways in the eastern Pacific and western Atlantic.

We stressed that eddies in both the atmosphere and ocean play a central role determining climate and how such climate may change in future. The atmospheric eddies are intimately tied up with the structure of the near-surface wind directional constancy. Results presented here document that enormous amounts of kinetic energy are imparted to the SO by the atmosphere at about 45°S from the eastern Indian to the west Pacific Ocean in winter. These fluxes are responsible for the massive SO swells whose signature may be found over much of the world's oceans. It has been shown that the covariances associated with transient systems make a significant contribution to the fluxes of mechanical energy.

We have finally examined the SO surface freshwater budget in the context of the global structures of the budget terms. We have commented that this global view is important, as it allows us to obtain an appreciation of how changes in the intensity of the overall hydrological cycle may impact on the source and sink terms at high southern latitudes. Our analysis of the freshwater input (precipitation minus evaporation) to the ocean shows this to be positive over virtually all of the SO. When calculated over the SO between the Antarctic coast and 50°S the annual means of P, E and P–E are 1.86, 1.05, 0.80 mm day^{-1}, respectively. The freshening term shows only a modest amount of seasonality, and is largest in summer.

Most of the discussion presented here pertains to conditions from the last two decades of records. While we have made some comments on trends and outlooks for the SO we have, in the interests of brevity, not explored such matters. It is worth commenting, however, that many of the future climate scenarios involve significant changes over and in the SO, including major alterations in high latitude synoptic behaviour, oceanic convective mixing, Antarctic Bottom Water production and sea ice. Given the importance of the SO in global climate it is of the utmost importance we continue to enhance our understanding of how atmospheric changes can influence this key ocean.

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